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Assessment of Remote Maintenance Technologies and Their Potential Application in the Federal Waste Management System

C. T. Kring
S. A. Meacham
F. L. Peishel

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ASSESSMENT OF REMOTE MAINTENANCE TECHNOLOGIES AND THEIR POTENTIAL APPLICATION IN THE FEDERAL WASTE MANAGEMENT SYSTEM

C. T. Kring
S. A. Meacham
F. L. Peishel
Fuel Recycle Division

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ABSTRACT

The Office of Civilian Radioactive Waste Management recognizes the potential that robotics and remote handling systems can have in meeting the design goals of the Federal Waste Management System (FWMS). An important issue is the extent of incorporation of this technology and its specific application to the Repository, the Monitored Retrievable Storage facility, if authorized by Congress, and the transportation elements of FWMS. The Oak Ridge National Laboratory (ORNL) with a comprehensive remote systems development program has been requested to assist in the resolution of this issue by compiling a technical data base summarizing remote handling systems, then assessing FWMS remote handling reqirements, and determining potential applications. This report addresses these issues.

The 40 plus years of remote operating experience in nuclear facilities are summarized, with emphasis on the evolution and capabilities of the remote systems. Current commercially available systems and major development activities are described. The advanced servomanipulator is described, which represents new remote technology that has been developed for the Department of Energy-Nuclear Energy and that can significantly improve remote operations by extending the range of admissible remote tasks and increasing remote work efficiency. Also, based upon past ORNL experience with remote facilities for reprocessing fuel, the guidelines and concepts that are utilized in the design, fabrication, and remote operation of mechanical process equipment and facilities are outlined.

The currently available remote handling systems that can be applied, in various combinations, to large-volume in-cell operations are described, and requirements for waste storage facilities are reviewed. A basic trade-off analysis of these remote systems considering waste plant requirements is given. Justification is given for selecting the overhead crane/servomanipulator-based maintenance concept as the option most desirable for future waste processing plant in-cell maintenance.

The Robotics/Remote Handling workshop that was implemented by the Office of Storage and Transportation Systems during the period that this assessment was being performed, helped focus the remaining time allocated to this effort on the future implementation of an overall program plan using a total systems approach. The concluding recommendation of this assessment is that this Robotics/Remote Handling program plan be developed and implemented as soon as possible.

1. INTRODUCTION

The Office of Civilian Radioactive Waste Management (OCRWM) is responsible for the development of a comprehensive national system for radioactive waste transportation and storage. This program has special needs that can be addressed by proper application of available technologies. One such technology is material handling techniques that can remove humans from hazardous environments. The term robotics and remote handling (R/RH) systems has been used to categorize these systems. The purpose of this report is to document existing technology associated with R/RH systems, assess the potential needs of the Federal Waste Management System (FWMS) in the R/RH area, and determine where beneficial matches between present technology and FWMS needs exist.

During the past decade, the Oak Ridge National Laboratory (ORNL) has been involved in multidisciplinary long-range research and development of remote maintenance technology for the Department of Energy-Nuclear Energy. More recently building upon ORNL's extensive experience in remote operations and human engineering, emphasis has been placed on artificial and machine intelligence with advanced control theory. This unique experience was the basis of this assessment.

The accessibility of humans to hazardous environments in the radioactive waste management system can be classified into two major groups: limited accessibility and totally remote operation. The Hanford Engineering Development Laboratory (HEDL) is conducting a preliminary design of a remotely operated cask handling system where limited accessibility is permitted. The ORNL effort is directed at the shielded cells in the proposed OCRWM facilities to which human access is denied due to the projected levels of radiation. It is within these zero-man-access areas that the greatest challenge exists for providing total system reliability by the application of remote manipulation capabilities for routine operations and maintenance as well as the ability to recover from unplanned events.

The recommendations in this assessment are based upon a review of conceptual design documents for the Monitored Retrievable Storage (MRS) facility and descriptions of proposed repositories and are considered applicable to all FWMS surface facilities because of the distinct similarities between many of the operations.

Two objectives of FWMS that can be addressed by remote handling are:

1. the reduction of radiation exposure to personnel to levels as low as reasonably achievable (ALARA)
2. the design of a waste management system with high confidence in its ability to maintain material throughput rates.

Several related but distinct manipulation technologies will be useful to address OCRWM objectives. These related technologies are generally referred to as robotics, but some important differences need to be highlighted. These technologies can be classified by the extent of human involvement required. Classifications include the following:

1. Teleoperated Manipulators — Manipulation devices developed for hazardous environments that allow man-in-the-loop control to provide the sight, feel, and intelligence of a human to direct the manipulation activities.
2. Industrial Robotics — Manipulation devices developed for commercial manufacturing applications that operate with a high degree of autonomy within structured environments. The ability of these devices to cope with unexpected events is limited to their sensory capabilities and the intelligence with which they are programmed.
3. Telerobotic Manipulators — A new generation of manipulation devices that is being developed to function with man-in-the-loop or automatic control. These devices consist of either an industrial robot with an improved operator interface or a teleoperated manipulator with automatic functions such as trajectory teach/playback.

During the past decade, ORNL efforts have focused on teleoperated manipulators for maintenance applications in totally remote environments, and the emphasis in this report will be directed toward this facet of the OCRWM facilities. Section 2 presents a historical review of plant maintenance and remote operations in high radiation fields as well as a review of the available types of remote manipulation equipment. Section 3 presents a description of current products and developments and specific organizations involved. Future research developments are described in Sect. 4. Section 5 presents an examination of OCRWM facility maintenance system requirements and an evaluation of the applicability of various remote handling systems. Section 6 discusses existing design guidelines for remotely operated equipment. Section 7 presents specific recommendations for potential applications.

It is recognized that readers of this report will possess a varied level of experience with remote operations and maintenance. Sections 2 and 3 have been directed at those individuals who have little experience in the field of robotics and remote handling and desire to delve into the subject in considerable detail. This material is intended to establish a background for ensuing sections. Those readers who are familiar with these topics may choose to only skim or skip these sections and start with Sect. 4.

In the future, advanced robotics and intelligent systems concepts will merge with teleoperator concepts into a new generation of remote systems technology. It is anticipated that this new technology will provide substantial improvements in remote work efficiency. These new concepts are discussed throughout the report and in the topical appendixes.

2. REVIEW OF ROBOTIC, REMOTE HANDLING, AND MAINTENANCE SYSTEMS DEVELOPMENT

2.1 EVOLUTION OF REMOTE OPERATIONS IN THE NUCLEAR INDUSTRY

In the more than 40 years that encompass nuclear history, one can observe a wide range of facility concepts that display differences in technical complexity and reflect varying dependence on human involvement. In examining the history of these nuclear facilities and the remote systems that evolved, this report focuses on the remote handling systems required for reprocessing plant maintenance. Fuel reprocessing plants are considered because the major experience base exists in these plants and, more importantly, because of their similarities to waste handling plants. The arrangement of equipment for manipulation in the remote environment needed for waste fuel handling is nearly identical to that required for preparing spent fuel for reprocessing. As an example, the preparation of reactor fuel for shearing prior to chemical dissolution is in many respects the same as preparing the reactor fuel for consolidation and containerization in FWMS.

2.1.1 History of U.S. Reprocessing Plant Maintenance

Large-scale reprocessing plants that have been built in the United States can generally be grouped into three basic categories of maintenance philosophy: (1) contact-maintained cells, (2) remote crane-canyon, and (3) combined remote/contact maintained cells. The historical evolution in the United States of these basic types of plants, listed in Table 1, is illustrated in Fig. 1.[1]

Two facilities at Hanford, Washington, the Bismuth Phosphate Plant (1944) and the Redox Plant (1946), were the earliest application of the crane-canyon concept for remote maintenance in large reactor fuel reprocessing plants. The Savannah River Plant (SRP),[2] started up in 1954 and operating today, and the Hanford Purex Plant,[3,4] started up in 1956 and currently back in service after shutdown in 1972, are also examples of the remote crane canyon maintenance concept. A cross section of SRP is shown in Fig. 2. Figure 3 illustrates the canyon equipment arrangement. A cross section of the Hanford Purex plant is shown in Fig. 4, and Figs. 5 and 6 illustrate the in-cell maintenance and process equipment arrangement, respectively. Equipment removal and replacement in these plants are accomplished by overhead cranes. An impact wrench carried by one of the auxiliary cranes supported from the main crane is used to loosen fasteners on equipment and piping connectors. The crane, controlled from a shielded cab with periscope viewing, provides all the equipment removal, transportation, and replacement capability. The remote crane-canyon maintenance technology has been demonstrated in these and other government reprocessing facilities for more than 40 years.

Table 1. Reprocessing facilities in the United States

Process	Plant location or name	Number of facilities	Date of construction	Type of maintenance
Bismuth phosphate precipitation	Hanford	3[a]	1944	Remote crane canyon[b]
Redox	Hanford	1	1946	Remote crane canyon[b]
Electrochemical and chemical dissolution; TBP and hexone solvent extraction	Idaho Chemical Processing	1	1953	Contact
Purex	Hanford	1	1956	Remote crane canyon[c]
Purex	Savannah River	2	1954	Remote crane canyon[c]
Pyromet	EBR-II Fuel Cycle Facility	1	1963	Remote
Transuranium recovery	Oak Ridge	1	1965	Remote
Chop-leach, Purex	Nuclear Fuel Services	1	1966	Remote/contact
Chop-leach, Purex	Barnwell Nuclear Fuels Plant	1	1976	Remote/contact[d]

[a]Only two were operated.
[b]Limited to removal and replacement.
[c]Minimal repair of process equipment and that only by contact means after decontamination.
[d]Never placed into operation.

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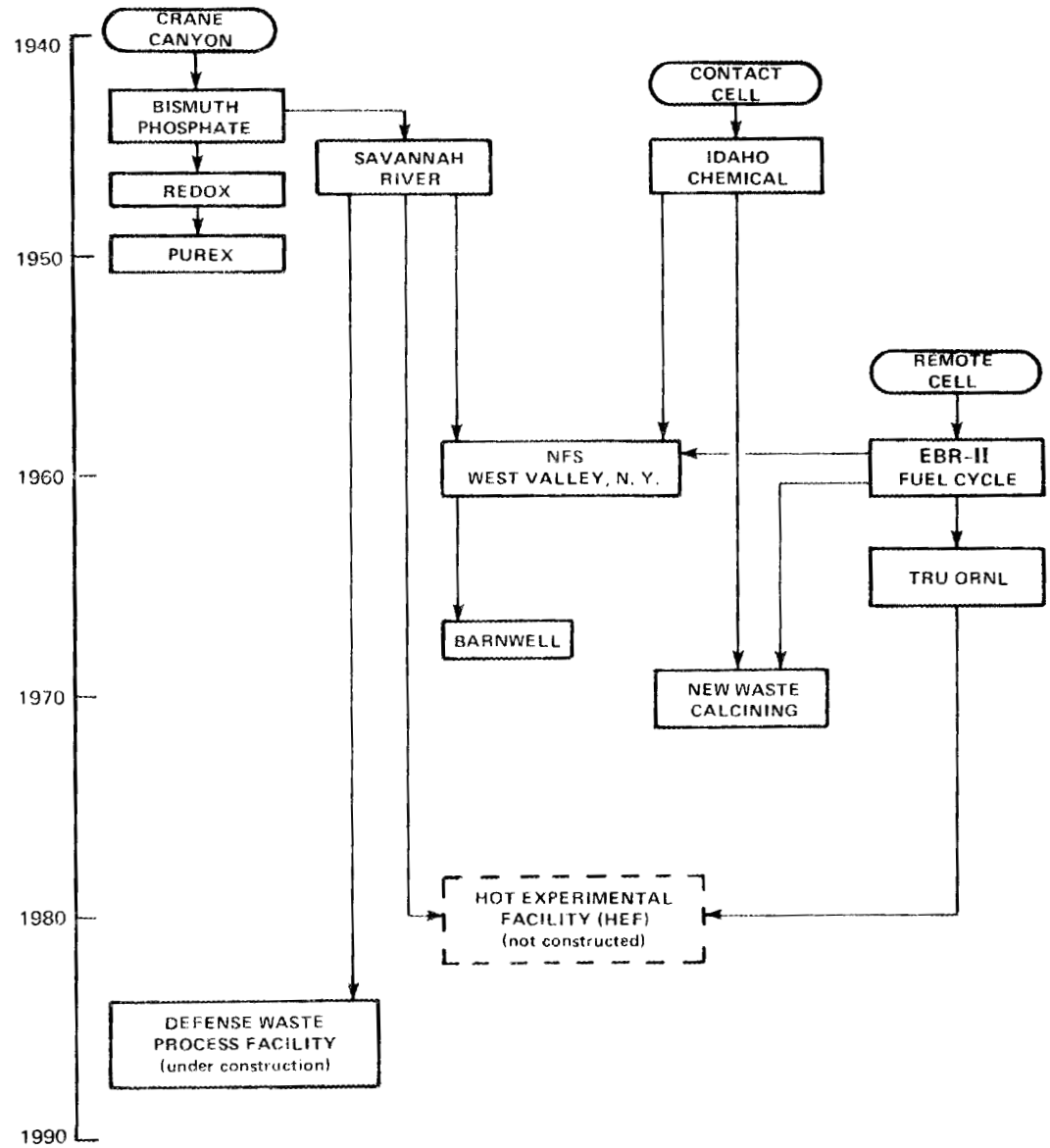

Fig. 1. Historical evolution of fuel reprocessing plant maintenance.

The availability of SRP during the first 25 years of operation is reported to have been over 80%. The average annual occupational radiation dose of workers ranged from 0.70 to 0.32 rem between 1965 and 1979.[2] The SRP, with the constraints of the existing structures, is engaged in efforts to upgrade the present facilities by improving the overhead maintenance cranes and using television systems to provide viewing. The Defense Waste Processing Facility (DWPF) is a major new addition to the SRP facilities for the vitrification of high-level waste. The DWPF will incorporate the crane-canyon arrangement for remote maintenance, but it will have a remote-controlled crane and television viewing.[5]

It should be noted that the government remote crane-canyon facilities have not previously required the complex mechanical systems for fuel disassembly associated with the head-end of

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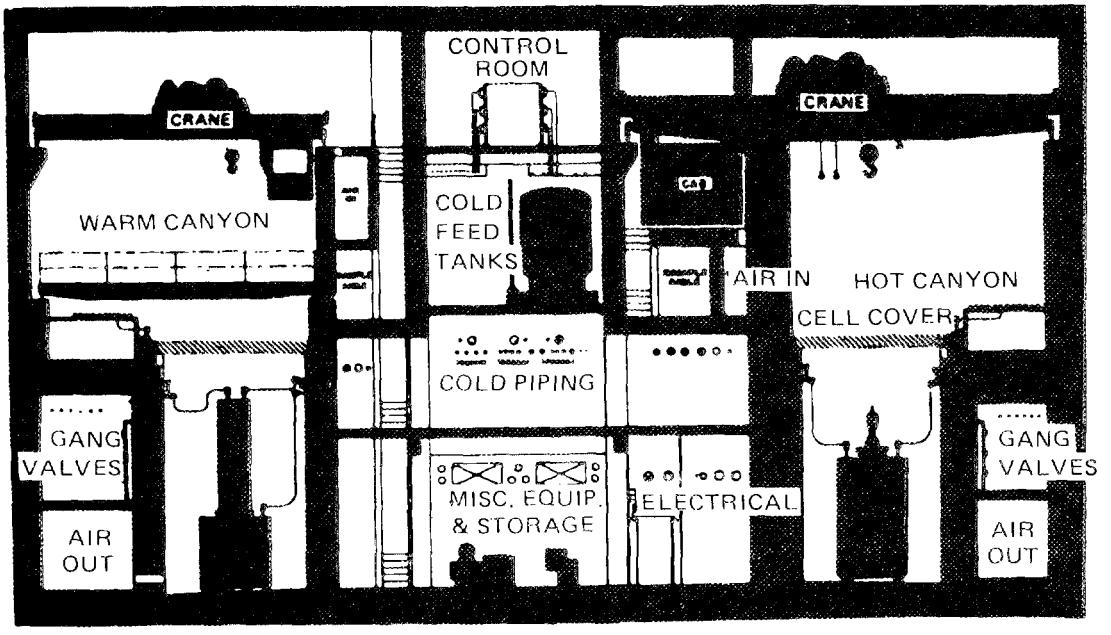

Fig. 2. Typical cross section of the Savannah River Plant.

commercial fuel reprocessing plants. However, the Hanford Purex Plant is presently overcoming this restraint by adding a new cell equipped with a teleoperated electromechanical manipulator (EMM) to accommodate the mechanical devices required to disassemble and prepare reactor fuel for reprocessing.

The Idaho Chemical Processing Plant (ICPP) is typical of a reprocessing plant designed for contact maintenance. The ICPP was started up in 1953 and remains in operation today. The ICPP was designed based on the successful experiences at the Oak Ridge Pilot Plant. Since the ICPP had much smaller throughput than the remote crane-canyon plants, a more conservative approach, which would minimize risk, was followed.[6] The radioactive process equipment is contained in a large number of separate small cells, each cell accommodating the process equipment for a process step. These cells are provided with equipment to effect decontamination of both the process equipment and cell walls prior to entry for maintenance. To keep plant availability high, some installed equipment redundancy is provided, and high-failure-rate components are located out-of-cell in shielded compartments. Although little information is available regarding the ICPP efficiency of operation, it should be noted that a new addition, designated as the Fuel Processing Restoration (FPR) Facility, is being planned which will replace aging equipment and upgrade process operations. The FPR will include grouping failure-prone equipment into common areas that will be designed for remote operation and maintenance to reduce personnel radiation exposure and improve contamination control.

The Nuclear Fuel Services (NFS) plant and the Barnwell Nuclear Fuels Plant (BNFP) are examples of the combined remote/contact plant design philosophy. The NFS plant, the first large-scale plant for reprocessing commercial light-water reactor (LWR) fuels, began operation in 1966 and shut down in 1972. Construction of BNFP was completed in 1976, but the plant was never started up. These plants were designed for recycle of commercial spent LWR fuels. The

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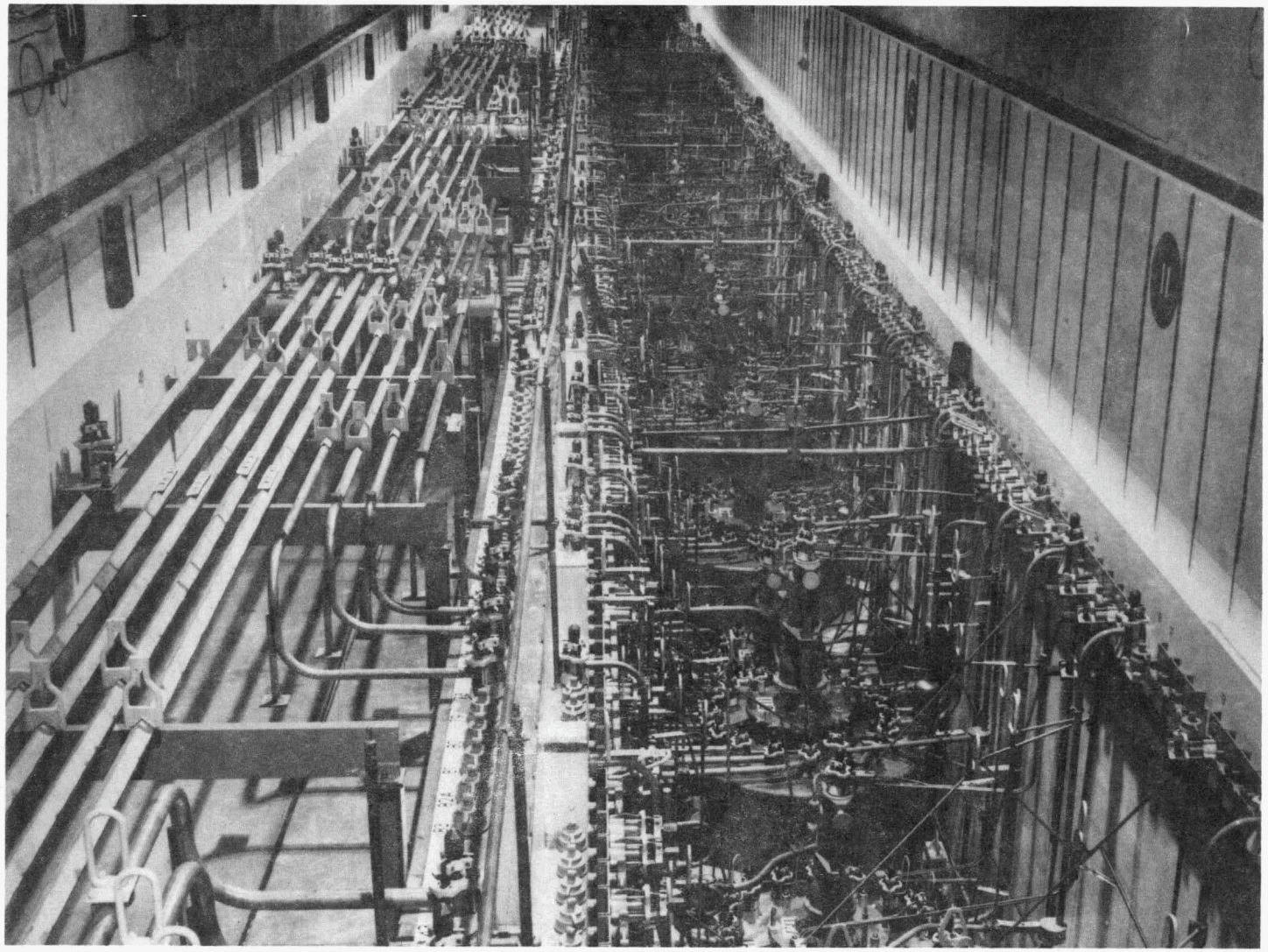

Fig. 3. Interior of the Savannah River Plant.

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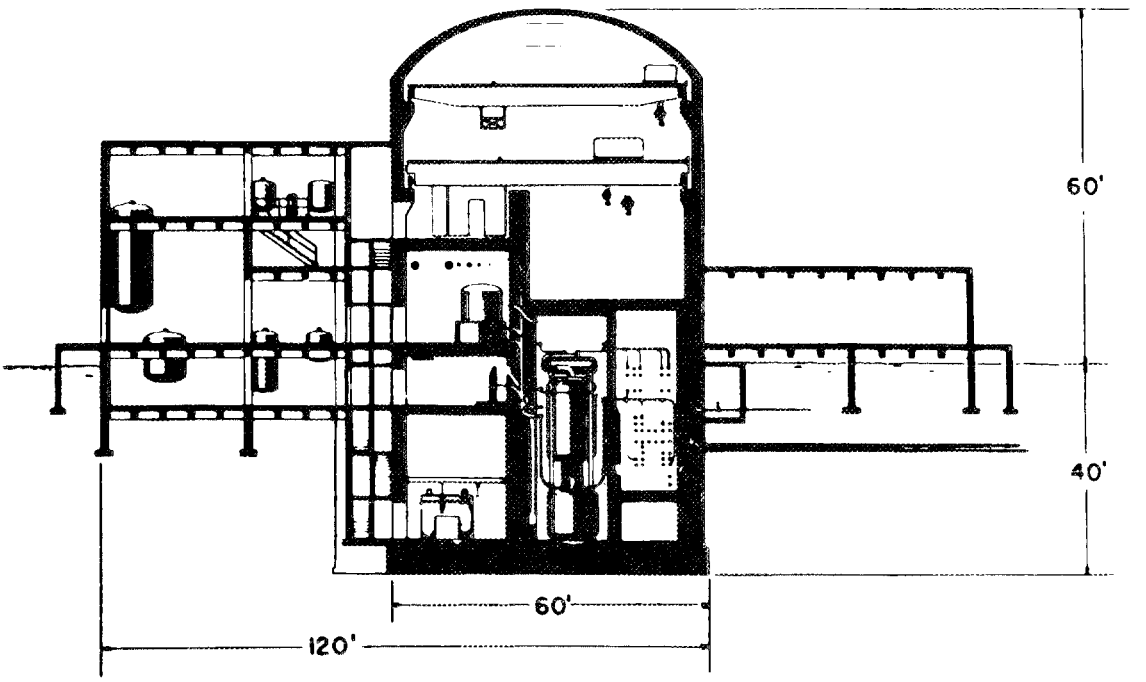

Fig. 4. Typical cross section of the Hanford Purex Plant.

mechanical complexity of the required head-end operations increases significantly when processing commercial LWR fuels. These operations consist of disassembly, shearing, and dissolving the oxide fuel out of the sheared tubes. The mechanical head-end portions and high-radiation chemical process portions of these plants were designed for maintenance using a combination of cranes, power manipulators, and mechanical master/slave manipulators. The downstream chemical process portions of these plants were judged to have high inherent reliability and were designed for contact maintenance. The average on-stream operating efficiency during the life of the NFS plant was apparently less than 60% of plant design capacity, although fuel availability may have influenced this to some extent. It appears from available data that the occupational radiation dose to workers was significantly higher than that experienced at the remote crane-canyon plants.

Based on experience and data from operations in the Waste Calcining Facility (WCF), ICPP undertook replacing the contact maintained WCF with the New Waste Calcining Facility (NWCF) which began operation in 1982 to process ICPP high-level wastes. The NWCF utilizes a combination of total remote maintenance for equipment expected to have higher failure rates and contact maintenance for equipment with lower expected failure rates.[7] The remote maintenance capabilities of NWCF have already demonstrated much improved plant availability and reduced personnel radiation exposure during unscheduled maintenance activities compared to the previous contact-maintained WCF.

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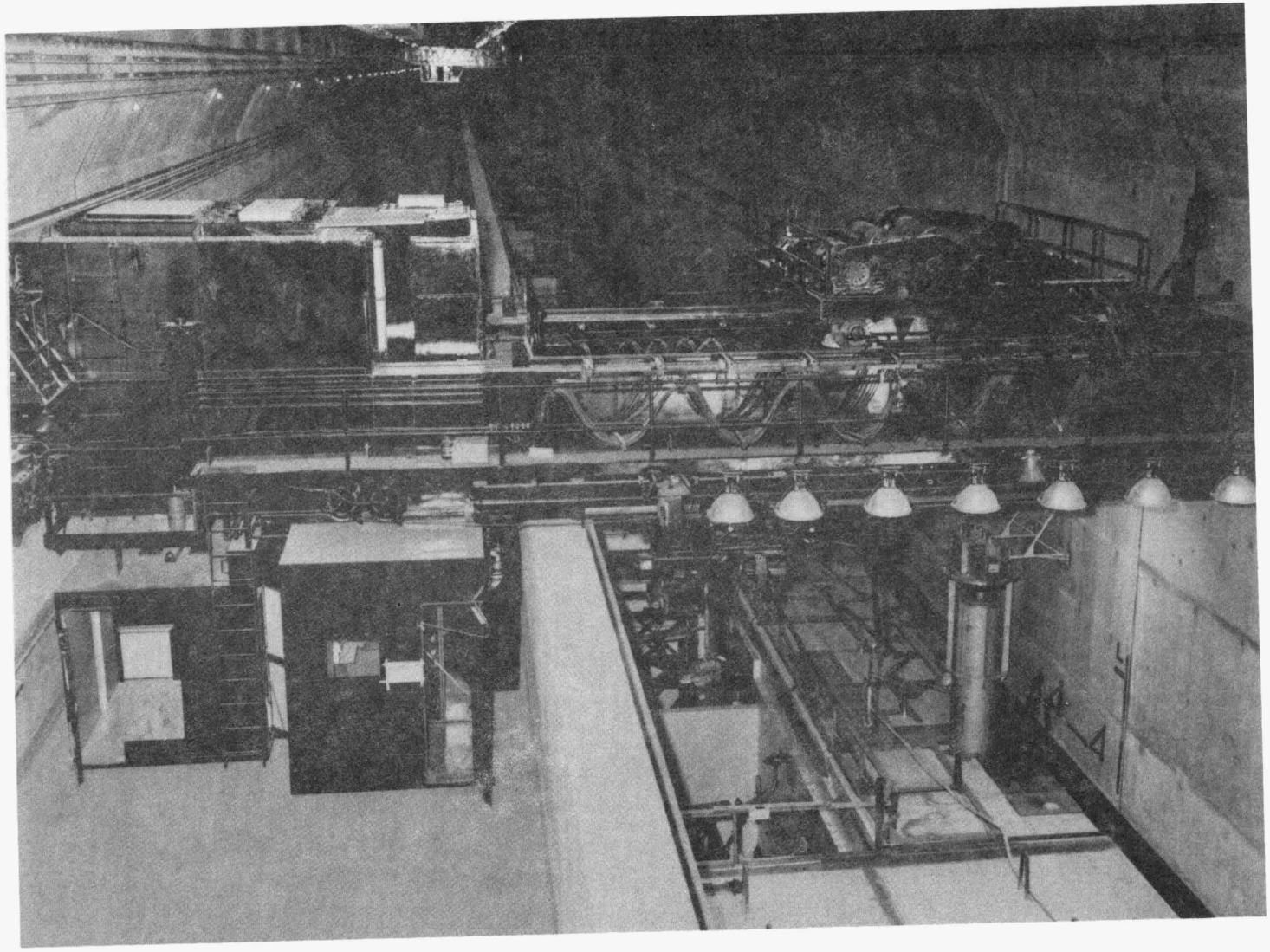

Fig. 5. Hanford Purex Plant maintenance crane.

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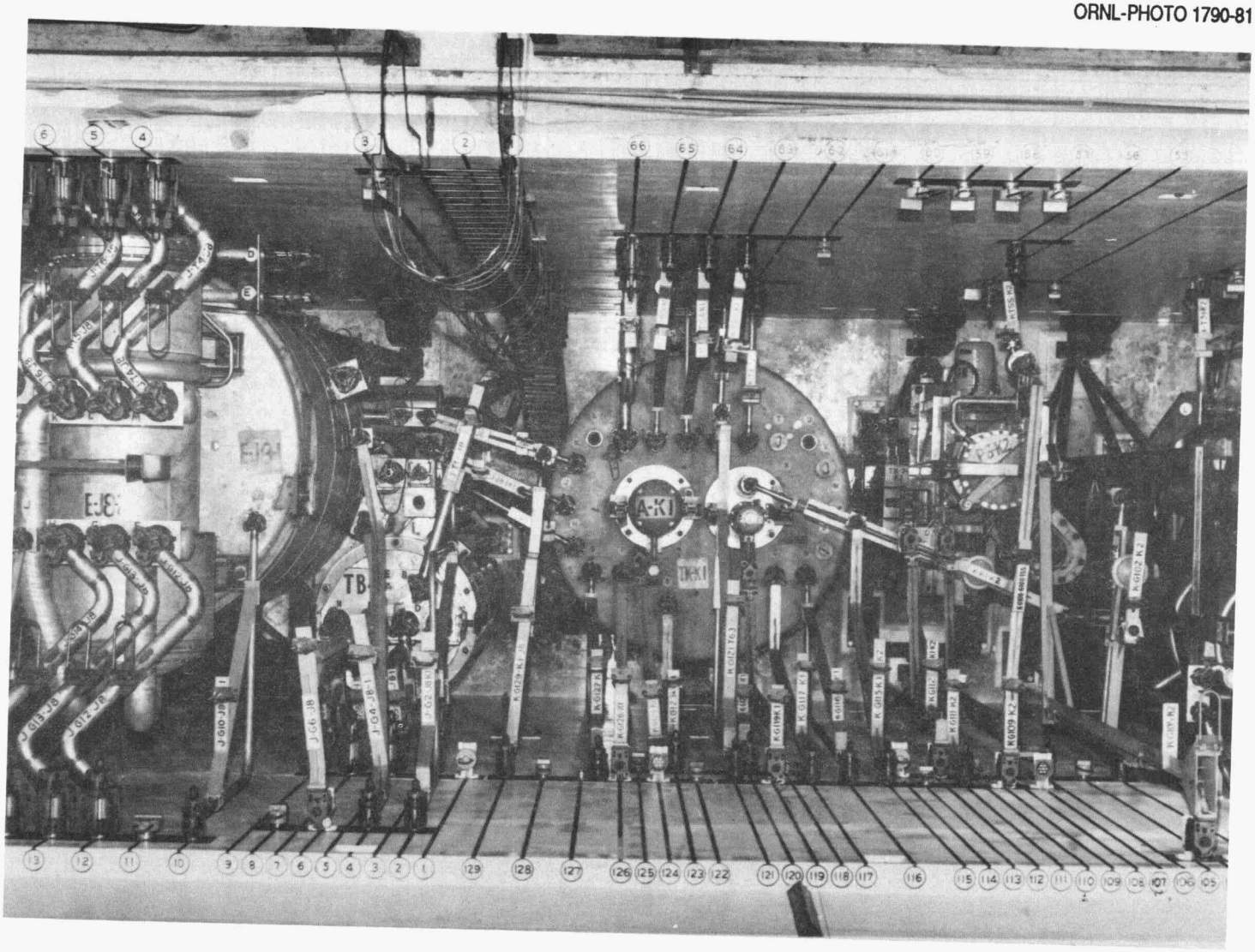

Fig. 6. Hanford Purex Plant typical remote equipment.

Techniques for total remote maintenance of a fuel reprocessing installation were successfully applied in the Fuel Cycle Facility (FCF)[8] at the Argonne National Laboratory (ANL) and the Transuranium Processing Facility (TRU)[9] at ORNL. The FCF used pyrochemical reprocessing techniques to recycle fuel from the Experimental Breeder Reactor-II from 1964 to 1969. Since 1964 TRU has been in operation recovering transuranium elements. These facilities incorporated remote maintainability initially into the design of the processing equipment and the remote handling equipment to improve overall plant availability. Experience with these facilities and the Hot Fuel Examination Facility/North, which was constructed adjacent to FCF and incorporated a similar maintenance philosophy, clearly shows that the more successful facilities have been based upon fully remote operations. As an example of the flexibility and ease of maintenance provided by designing for full remote operations, FCF and TRU have had all original equipment changed out with new or improved components, and in some instances a part of the facility was converted to a different mission altogether, all remotely. When total plant operating life is considered, data indicate that the increased capital cost of mechanized remote handling capability is justified, and personnel radiation exposure is minimized.

2.1.2 Evolution of Remote Handling Technology

The initial work to remove man from radioactive exposure began with simple mechanical tong handling devices. The first remote manipulators were, in effect, reach rods, which allowed working at a distance or behind walls. Primitive beginnings with these devices initiated a progression of developments that had the goal of replicating man's dexterity. Increasing radioactivity levels led to the ANL program,[10] whose greatest achievement is generally recognized as the mechanical master/slave manipulator (MSM).[11] These devices are 6 D.F. manipulators. The master and slave arms are mechanically coupled through a low friction and low inertia force transmission system which provides dexterity and sense of feel. When used in concert with shielding window viewing, MSMs project the human operator's two most important senses – sight and feel – into the remote environment and allows him to perform a very large fraction of the tasks he would be capable of doing directly with his hands. However, due to the direct mechanical coupling and the limited reach of the human operator while manipulating and viewing the work site through a shielded window, the distance and configuration between the master and slave of an MSM is limited to the small hot-cell work environment topography (approximately a 2.5-m cube).

The defense production plants, from the outset, dealt with large engineering-scale chemical equipment that dictated an entirely different approach.[12] If one considers the technical base that was available at the time, these plants represent an extremely innovative approach to totally remote operations. They are designed for complete remote operations and maintenance with the principal tool being an impact wrench hanging from a crane hook. The crane hook is controlled by an operator riding along in a shielded cab. The flexible-cable handling mechanism required that many special design provisions be incorporated into the facility and the equipment be maintained. All equipment and components must be designed for vertical access from above, and the canyon cells must be arranged with sufficient height for vertical clearance above the process equipment to transport all components. The time efficiency of this approach is limited by operator skill and the restricted maneuverability and control that is possible with a flexible lift member. The success of these plants, however, is an example of human innovation and the inherent adaptability of teleoperation.

While the crane-impact wrench system was adequate for the canyon approach, a need for more dexterity in large remote cells fostered the development of more sophisticated electromechanical systems. These developments progressed through various steps intended to offset the limitations of flexible crane cables and culminated in the design of the electromechanical manipulator (EMM) or power manipulator. These are sometimes referred to as a unilateral manipulator because the action of the end effector is not felt by the operator (i.e., non-force-reflecting). The EMM has been marketed in various configurations and capacities and typically has 6 to 8 D.F. It is also recognized that EMMs are much more difficult to use than MSMs because of their poor human interfaces. Individual switch control of each joint results in slow response relative to human arm movement and difficulty in coordinating the motion of multiple joints. Because the only feedback presented to the operator is visual, his perception of force interaction is limited to judging relative clearances and/or observing possible deflections of the manipulator or the object manipulated. Since the operator cannot sense the EMM load output, all process equipment must be designed to withstand the manipulator's full capacity or risk equipment damage.

With the success of the MSM development, in 1954 an ANL program was directed toward the development of an electrically driven equivalent that could be used in larger work volumes. The unit that evolved was mechanically similar to MSMs in that low friction/low inertia drives such as metal tapes or cables were used to transmit torque from the centralized motor actuators to the arm joints. Electrical servomechanisms that could reliably reproduce the force reflection quality achieved in MSMs were developed. The design was improved through several models and resulted in a servomanipulator that had a 25-kg capacity with force reflection and speed of operation comparable to MSMs. They were thus able to reproduce MSM-type dexterity and performance in a system that was interconnected with electrical wiring. However, cabling systems requiring hundreds of conductors and 1950s and 1960s electronics were not amenable to usage in corrosive and extreme radioactive environments, and therefore did not attract much interest among facility designers. They were used successfully in accelerator maintenance, which involves a lesser contamination environment.[13]

In spite of limited applications, the development of electrically driven master/slave manipulators did continue. The French were able to proceed with the development of a system that is being applied in operating plants. Carl Flatau developed a servomanipulator for Brookhaven National Laboratory and later formed TeleOperator Systems Corporation (TOS) which markets a servomanipulator.[14] In Germany, Kohler et al. developed an 8 D.F. servomanipulator for use in hot cells and on emergency vehicles.[15] Development is proceeding in other countries such as Italy and Japan.

The state of the art in advanced remote handling systems left some serious technical barriers in practical applications, especially in reprocessing-type applications. In addition to the high radiation from the fuel being processed, reprocessing plants subject equipment to corrosive fumes from the acids and other chemicals that may leak from the chemical process equipment. The MSM experience in hot labs set an important standard for all remote operations by establishing the significance of good viewing, speed of operation, and force reflection upon the effectiveness of teleoperations. Unfortunately, in addition to requiring the precise mechanisms of MSM, the achievement of equivalent performance with an electrically driven unit resulted in the addition of electrical complexity.

During the 1970s, work at ORNL was directed toward the design of a plant for reprocessing breeder fuels. Based on previous efforts and a decision in 1978 to design a plant using developing technology, a conceptual design evolved that adapted servomanipulators to perform maintenance in a large facility. The plant was referred to as the Hot Experimental Facility (HEF) and was planned to operate in the 1990s.[16] A parallel effort was begun at that time to develop servomanipulators and a transporter for these manipulators that would be able to better withstand the environment in a reprocessing plant. The effort has been successful due to developments in other supporting technologies, such as the rapid progress of the development of solid-state electronics. The HEF was cancelled, but the servomanipulator program was continued with testing presently in progress at ORNL for both the manipulators and the equipment items that interface with the manipulators. The primary difference in the manipulator developed at ORNL and previous designs is the use of gears and torque tubes instead of tapes and cables as the force transmission method. This difference allows in-cell remote maintenance of the manipulators' modular components.

2.2 TYPES OF MANIPULATOR SYSTEMS

Previous sections described nuclear facilities and operations and the remote handling systems that evolved in these facilities. This section will review each of the remote handling systems with emphasis on specific capabilities.

To determine the efficiency of using various manipulators to perform tasks relative to a human performing the tasks directly, a comparison or gauge has evolved. The gauge is based on a human performing a task in a certain amount of time, equalling one. The following tabulation is the result of many tests, independently performed, by a number of organizations and countries.

Manipulator type	Task completion time
Human	1
Suited human (airsuit or equal)	8:1
Force-reflecting servomanipulator or master/slave manipulator	8:1
Non-force-reflecting electromechanical manipulator	20-50:1
Crane/impact wrench	50-500:1

2.2.1 Teleoperated Manipulators

A teleoperator is a man-machine system that augments man by projecting his manipulatory capabilities across distance and through physical barriers into hostile environments. Each of the following are considered teleoperator systems.

1. Crane/impact wrench — A crane, coupled with a suspended impact wrench to tighten/loosen fasteners, has been used for remote operations for many years. This system relies on gravity to lower loads and the hoist to raise them. A rotatable hook is also employed for aligning components. Although massive pieces of equipment can be manipulated with this system, it is extremely difficult to do complex tasks or to operate very efficiently. Task time

ratios are in the range of 50 to 500:1 with this system. Because the hoist is capable of generating large forces at the work site, these systems usually employ some means of detecting this force. The cable can only exert upward forces, which in turn limits the type of manipulation available and where it can be applied. Various modifications have been performed on standard cranes to permit remote repairs to the crane, and materials of construction have been modified to resist the environment or permit easier decontamination to allow contact repairs.

2. Electromechanical manipulators — EMMs, sometimes referred to as power manipulators, have been commercially available since the early 1960s and have been applied in nuclear facilities throughout the world. When mounted on a telescoping tube suspended from a trolley and bridge system, the manipulator's working volume is limited only by the travel restraints of the bridge and telescoping tube. These single-arm manipulators are an improvement over the crane-impact wrench systems by providing multiple degrees of freedom and more dexterity than a hook on a cable. Lifting capacities up to 270 kg (600 lbs) of the arms permit reaching horizontally into or under equipment to perform tasks that cranes cannot do. This allows equipment designers to package their components more efficiently, since only total vertical access is no longer mandatory. Their slow speed (relative to the human) however makes them better categorized as a rigid articulated hoist. They are good for maneuvering large components but perform complex tasks poorly. Task/time ratios are in the range of 20 to 50:1 for these systems. The EMMs are not force-reflecting. As a result, equipment components can be easily damaged during maintenance. An approach that has been taken is to design all the equipment to resist the maximum manipulator force load, thereby making many parts larger than functionally required.

3. Mechanical master/slave manipulators — MSMs are the workhorses for performing remote maintenance tasks in hot cells throughout the world. They have 6 D.F. and mechanism capacities up to 45 kg (100 lbs). In this type of manipulator, the motions of the master are reproduced by the slave at a 1:1 ratio through mechanical linkages. If the slave encounters an impediment, the impediment is reflected to the master. These linkages therefore provide the operator with a sense of feel. The forces are generally transmitted through the linkages with steel tapes and cables. Such components minimize friction and inertia and also operator fatigue. The mimicking of motion and sense of feel of MSM provides the dexterity to disassemble or reassemble equipment components using ordinary hand tools. Commercially available components such as tube fittings, electrical connectors, and similar equipment can be manipulated easily in a remote cell. Task time ratio is about 8:1 for these systems. The mechanical nature of the master/slave manipulators, which use tape or cable drives to transmit force, has a history of requiring inordinately high maintenance. In the main, these maintenance requirements have resulted from use of the manipulators beyond their capabilities, which has been augmented by fatigue failures in the tendon drives. Booting for the slave portion, bagout, and decontamination techniques are available to reduce exposure to personnel during manipulator maintenance. Shortcuts in maintenance activities of these manipulators have resulted in high personnel exposure. The major disadvantage of MSM is the limited volumetric coverage that is obtainable because of being mounted through a wall. This can be compensated by using a crane-impact wrench or power manipulator system to remove and transport a failed component to a viewing window of an in-cell work station where detailed repairs can be made with MSMs.

4. Servomanipulators — The closest currently existing substitute for man that provides large volume coverage is the force-reflecting servomanipulator. This system has the same attributes, including task/time ratios, as MSM except that the master and slave arms are physically separated and linked electronically through servomotors. Full-volume coverage of the interior of a cell is limited only by the transporter coverage.

2.2.2 Industrial Robotics

The Robot Institute of America defines the robot as "a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through viable programmed motions for the performance of a variety of tasks."

The distinction between robots and teleoperated manipulators is the extent of human interface. Robots basically encompass those devices that are essentially autonomous, and teleoperated manipulators are those devices that require man-in-the-loop. A robot, therefore, must have the ability to operate automatically on its own via built-in intelligence, a programmable memory, or simply an arrangement of adjustable mechanisms that command the manipulation. The robot then performs the programmed steps without deviation until it is reprogrammed or reconfigured.

Industrial robots can be used to automate tasks in structured nuclear applications. Routine process operations are the easiest to recognize. These are production tasks, which include handling fuel slugs, performing radiation assays on parts, and preparing samples. These nuclear operations share many similarities with standard industrial robot applications.

The advances in both mechanisms and electronics will most likely increase employing robotic systems. The inherently limited versatility of industrial robots is being enhanced by adopting sensor technologies, artificial intelligence, and supervisory man-in-the-loop control schemes evolving into the new field of telerobotics. Using these enhancements, robotic systems may offer viable, cost-effective alternatives for repetitive or programmable remote handling applications. Robots, as defined and presently exist, do not appear to be easily adaptable to the unstructured use and maneuverability required during maintenance of equipment existing within a large remote shielded cell. However, application to repetitious tasks appears unlimited.

2.2.3 Telerobotic Manipulators

A new generation of systems is in the developmental stage. It is proposed for these manipulators to operate either with a man-in-the-loop or with autonomous control. These telerobots would consist of either an industrial robot with improved sensors/artificial intelligence or a teleoperator with autonomous capability. Further discussion of this classification of future manipulator systems is provided in Sect. 4.

3. EXISTING EQUIPMENT AND TECHNOLOGY ASSOCIATED WITH ROBOTIC, REMOTE HANDLING, AND MAINTENANCE SYSTEMS

3.1 COMMERCIALLY AVAILABLE EQUIPMENT

The *Manipulator Type Book* authored by Gerhard W. Kohler and published by Karl Thiemig, Munich, Germany, 1981, is the encyclopedia of remote equipment for hostile environments available until 1980. Information provided in this report is intended to augment the information available in the book. For detailed information, equipment photographs, and specifications, the reader is referred to this excellent reference.

3.1.1 Cranes

Two companies have been active internationally providing overhead handling systems for remote nuclear facilities, GCA (formerly PaR) in the United States and ACB in France. Many domestic companies make overhead handling systems that could be modified to operate in a radioactive environment.

Many applications result in modifications of standard products. Box beam construction used in the majority of these systems makes design modifications easy to accomplish. Advances occurring in the robotics industry has led to improved crane controllers with attributes such as path following, teach playback, or direct operator control. Such controls are available from GCA and others.

3.1.2 Electromechanical Manipulators

The U.S. market has been dominated by GCA for this type of manipulator. GCA produces a family of EMMs with multiple degree-of-freedom articulations, switch-box control, and high arm lift capacities up to 270 kg (600 lbs). TOS manufactures a power manipulator, the AP4450, with a 184-kg (400-lb) capacity.

3.1.3 Mechanical Master/Slave Manipulators

Central Research Laboratories (CRL) has been the world's leading producer of mechanical MSMs since they received the fabrication rights to these systems developed under the direction of Ray Goertz at ANL in the 1950s. Several foreign companies also produce MSMs: Toshiba (Japan), Vickers (England), Walischmiller (Germany), and LaCalhene (France).

CRL produces a line of mechanical master/slave manipulators for use in hot cells, hospitals, and waste handling facilities. The 14 models presently available range in capacity from 4.5 kg (10 lb) to 45 kg (100 lb) and are adaptable to various environments up to and including inert sealed systems.

3.1.4 Servomanipulators

Presently, two U.S. companies manufacture force-reflecting servomanipulator systems: TOS, the model SM-229; and CRL, the model M-2. A non-force-reflecting servomanipulator, the RM-10, has been developed by Remote Technology Corporation. Several other companies, MB Associates, Western Space and Marine, and Remotion Co., make hydraulic manipulators, but these are considered unsuitable for radioactive environments due to the problems associated with radiation damage to seals and degradation of the hydraulic fluid. Internationally, several companies make servomanipulation equipment, including LaCalhene (France), Blocker and Walischmiller (Germany), Selenia (Italy), and Mediensha (Japan). The designs of most of the servomanipulators are based on the original work performed at ANL.

The manipulator program at ORNL has developed an advanced servomanipulator (ASM). This servomanipulator uses gears and torque tubes to translate motions, is force-reflecting, and is remotely maintainable. The commercial potential of this new technology is being pursued with interested industrial participants.

3.2 STATE-OF-THE-ART TECHNOLOGY APPLICATIONS

A few applications of remote handling capabilities in the nuclear industry will be discussed to calibrate the state of the technology. In teleoperations for nuclear installations, the leading domestic effort has been at ORNL for the Department of Energy (DOE).

Teleoperation applications at ORNL have concentrated on the development of maintenance equipment for process equipment in fuel reprocessing facilities. Three facilities, the Remote Systems Development Facility (RSDF), the Remote Operations and Maintenance Demonstration (ROMD) Facility, and the Advanced Integrated Maintenance System (AIMS), have been used as test facilities during the past five years.

The RSDF was operated from 1982 to 1985 to become familiar with manipulator capabilities and to evaluate various human factor issues in order to gain an understanding of the interdependence of the human operator and the machine. Principal equipment included a three axis transporter, a pair of camera positioning arms, a pair of wall-mounted cameras, and a dual arm force-reflecting manipulator system. The servomanipulators, SM-229s, were manufactured by TOS and had 7 D.F. with a 10-kg (22-lb) capacity. The arms were connected to a computer system for collection of operational data, for demonstration of robotic teach/playback control, and to provide automatic camera tracking.[17] The overhead handling system was also integrated into the computer[18] to perform teach/playback and position mapping.[19] At the completion of the testing program, the SM-229 manipulator controls were converted from analog to digital with marked performance improvement.[20]

The ROMD facility is pictured in Fig. 7. The control room is shown in Fig. 8. This facility includes one bridge with two crane trolleys and a second bridge with a Par power manipulator, a number of closed circuit TV cameras, and the CRL model M-2 force-reflecting servomanipulator system. The facility is used to carry out some process operations required in a fuel reprocessing plant, but the primary objective is the remote maintenance demonstration of various in-cell process equipment.

The pair of CRL model M-2 force-reflecting servomanipulators, shown in Fig. 9, are used for performing in-cell dextrous manipulative tasks.[21] Each arm has a 23-kg (50-lb) continuous capacity and a 45-kg (100-lb) time-limited (peak) capacity. A 225-kg (500-lb) auxiliary hoist is located between the two arms to perform the heavier lifts. An azimuth drive provides 540° of rotation for orientation of the manipulator-hoist system at the task site.

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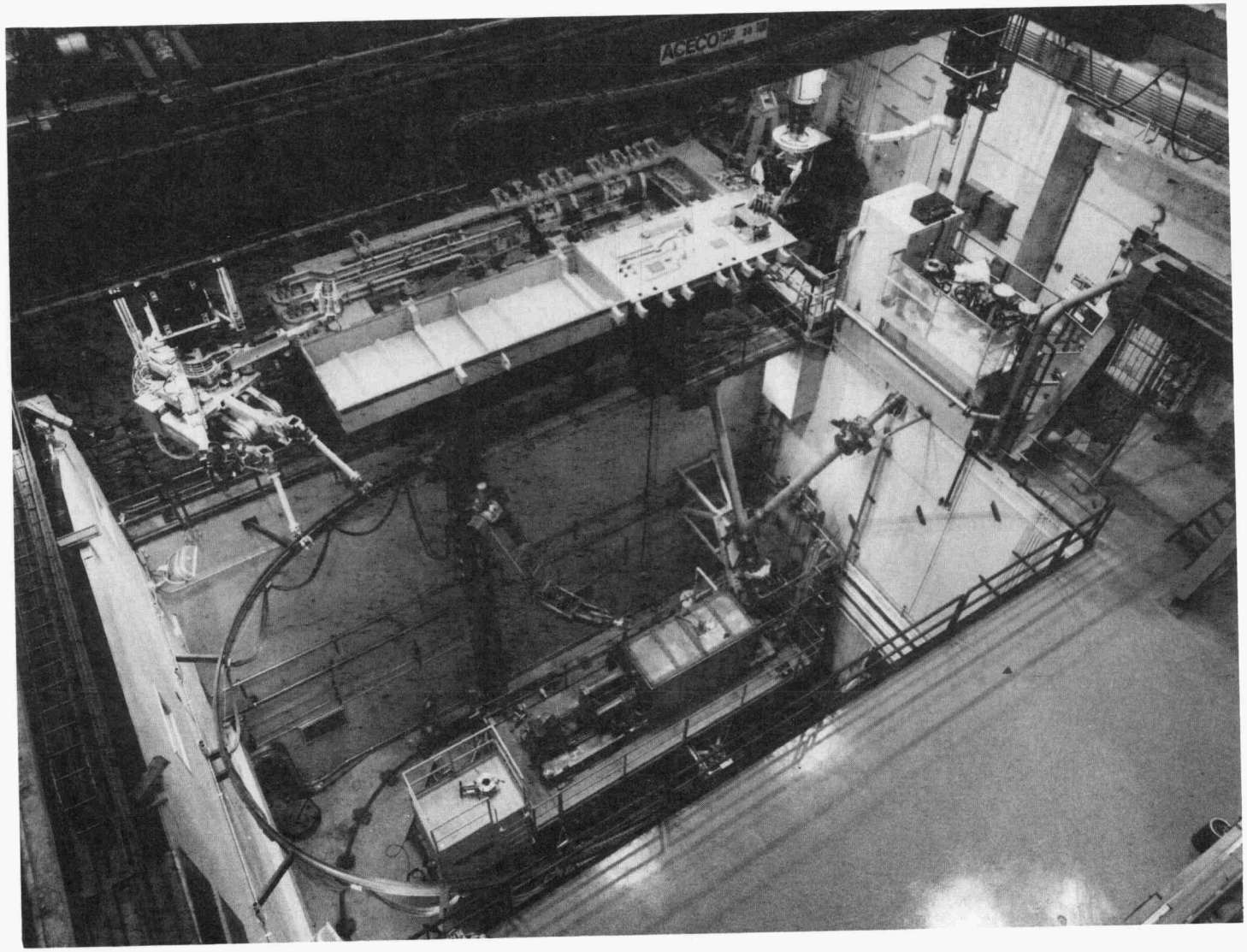

Fig. 7. ROMD facility.

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Fig. 8. ROMD control room.

ORNL-PHOTO 3549-83B

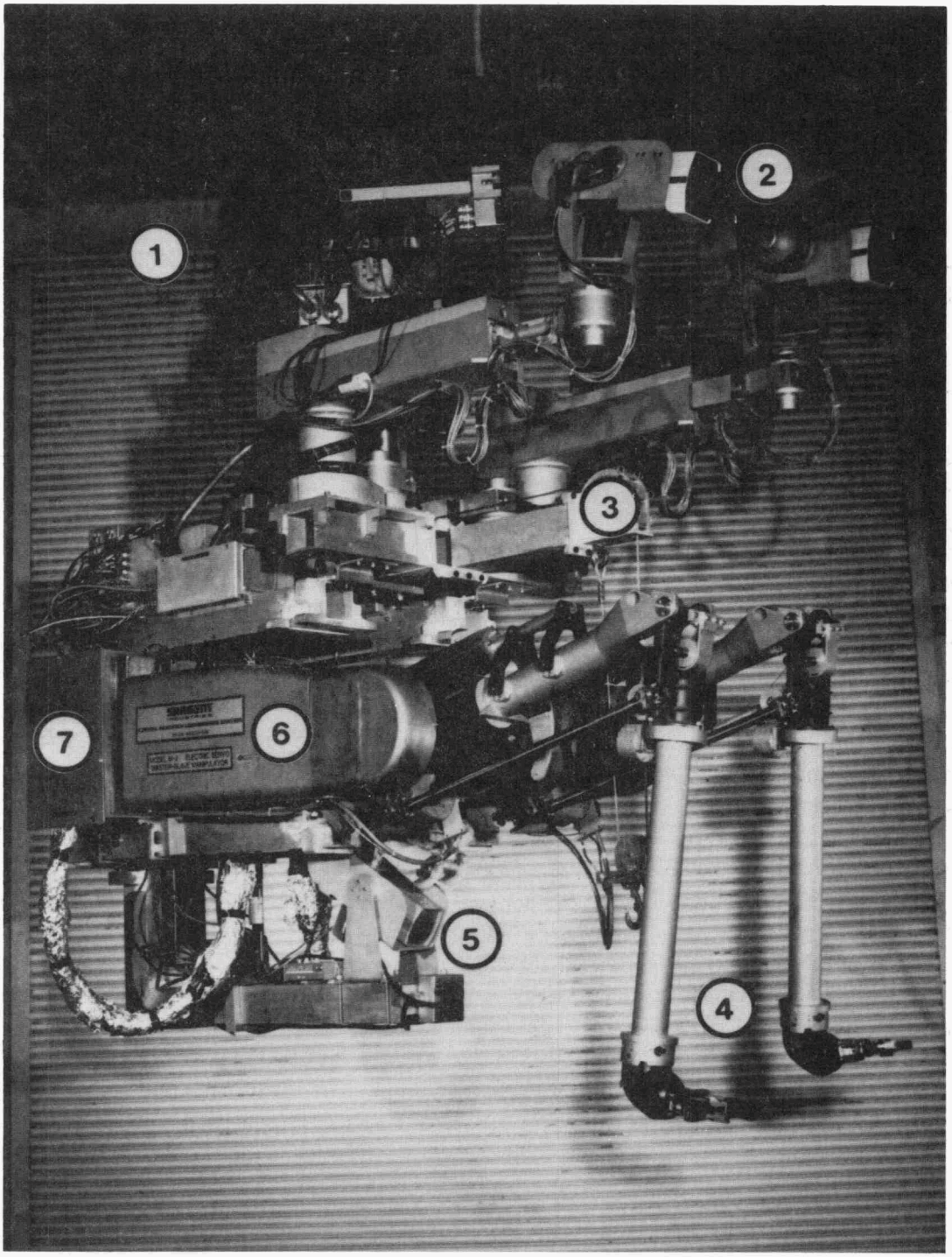

Fig. 9. Model M-2 manipulator.

Operator viewing is provided at the remote task site by one center and two outboard television cameras equipped with auxiliary lighting. Motorized camera and lens positioning allows the operator to optimize viewing perspective and enhance depth cues.

The master station incorporates a pair of servomanipulator master arms to control the motions. Switches on these arms also activate the brakes, indexing, and tool controls of the remote slave arms. The operator accesses the control system through a CRT and touch-screen system to provide operating mode selection, force ratio selection, camera/lighting control, and system status diagnostics. The model M-2 was the first successful implementation of complete digital control technology to force-reflecting servomanipulator control.[22,23]

The AIMS, shown in Fig. 10, is the third generation complete manipulation system developed or installed at ORNL. The AIMS not only incorporates all the subsystems required for large-volume remote reprocessing applications but also incorporates many of the developments and improvements resulting from the work started in 1978.

A key feature of AIMS is the use of the force-reflecting ASM slave arms. The gear and torque tube sections that transmit the forces and motions were designed for modular remote maintainability.

The ASM also incorporates kinematic improvements by operating in the anthropomorphic (man-like) stance. This elbows-down configuration required development of unique wrist mechanisms to provide yaw, pitch, roll, and grip actuation while avoiding mechanical singularities. The anthropomorphic stance reduces manipulator obstruction of viewing the work site, increases horizontal reach dexterity, and potentially decreases the number of mental transformations required of the operator. The ASM is attached to a transporter by means of an interface package which also supports a 450-kg (1000-lb) hoist, three adjustable TV cameras, and lighting. The operator control station is state of the art in optimizing the man-machine interface. Based on experience from RSDF and ROMD, plus application of human engineering, a two person team is utilized with the primary operator handling the master manipulator controller and the secondary operator handling the television system, transporter, and crane controls. The operators are close enough for normal conversation and have a clear view of each other without obstructing their respective views of the monitors. Both operators have access to system information and control of remote views. Manipulation feedback is provided through a human-engineered master station, which is shown in Fig. 11.

A complete description of the various components of AIMS is found in the literature.[24] Details of the controls,[25] slave manipulator,[26] master manipulator,[27] operator control station,[28] and philosophy of the approach[29] are found in available publications.

Robotic applications to remote environments have been developed recently at ORNL, SRP, GA Technologies, Inc., and HEDL. These applications are, respectively, automated process sampling,* material bag-out handling in hot cells,[30] decommissioning of chemical weapons demonstration,[31] and nuclear waste cask remote handling system demonstration.[32] These systems demonstrate that robotic systems can be very useful in remote environments. The application of a structured machine, a robot, requires cognizance of the rapid development of improved components such as fixturing, controls, computers, and the emerging area of artificial intelligence.

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*This work is sponsored by the Department of Energy through the Consolidated Fuel Reprocessing Program, and publication and foreign disclosure of some of this information is restricted by law. Interested parties may contact the authors concerning additional information.

ORNL-PHOTO 1312-86

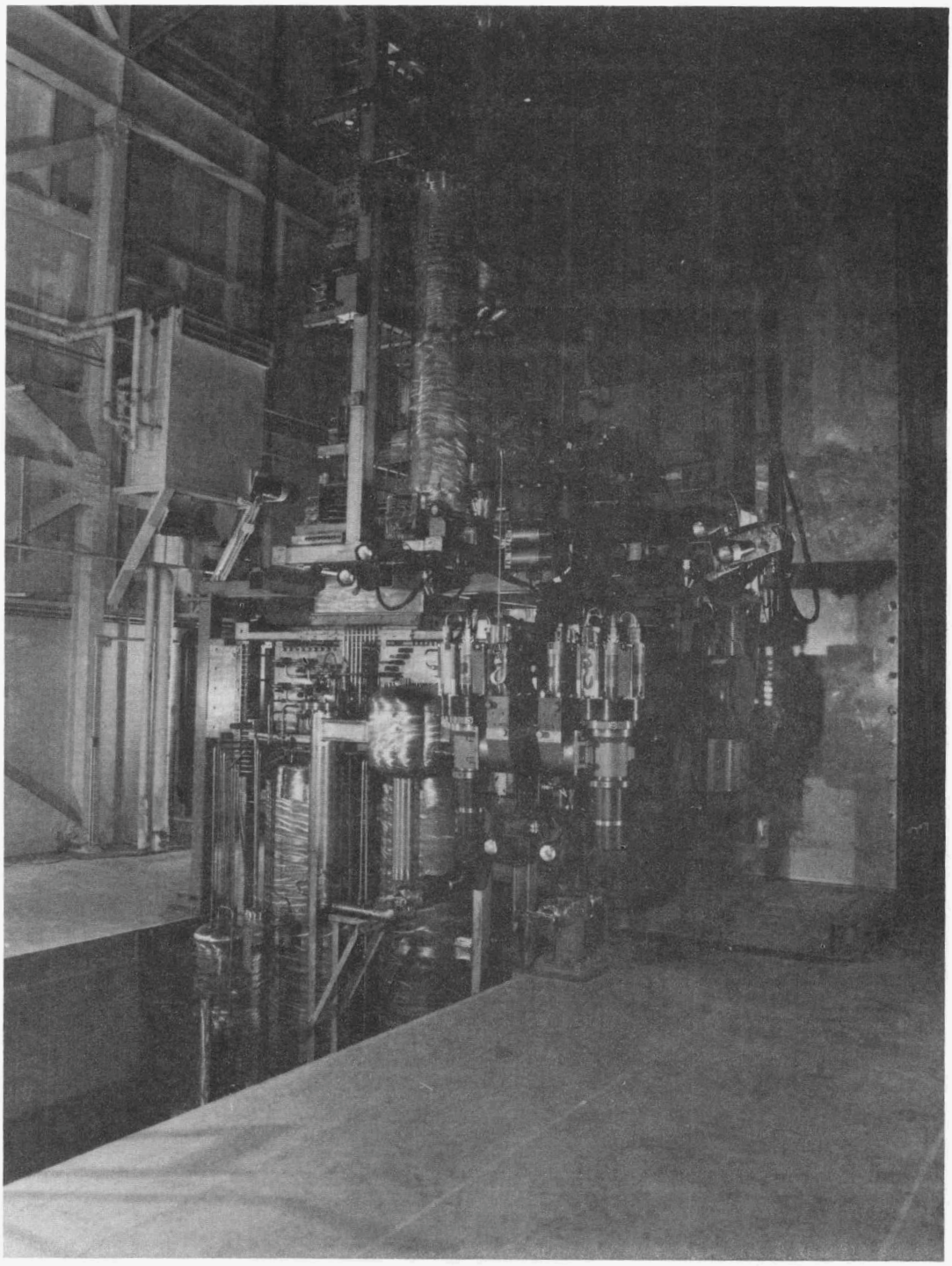

Fig. 10. AIMS advanced servomanipulator near test equipment racks.

ORNL-PHOTO 0378-86

Fig. 11. Advanced Integrated Maintenance System control room.

Improvements have evolved that allow the operator to receive a complete understanding of the robotic operations at the work site. These include graphic displays of work progress, adjustable velocity control of the manipulator, status displays, and force information. Telerobotics, where supervisory control capabilities of preprogrammed operating periods are interspersed with man-in-the-loop initialization, are also under development at ORNL. These are not yet directed at a specific application that could be cited as an example for FWMS systems.

3.3 SUMMARY OF ACTIVE ORGANIZATIONS

Growth in R/RH systems research and development parallels the advancements in microelectronics and computer technology. Many educational institutions now offer courses relating to R/RH, and many have established research centers for the integration of computer science, mechanical engineering, and electrical engineering into R/RH systems.

Continuing research at national laboratories has resulted in an advanced state of development of master/slave systems and dexterous end effectors. Several spin-off companies are focusing this experience on R/RH systems, especially mobile surveillance systems. Specific problems (e.g., steam tube generator repair) have resulted in very specialized systems, now available from the nuclear service vendors.

A summary of many of the current R/RH research and development programs that are under way, including government agencies/laboratories, universities, private companies, and foreign programs, is tabulated in Appendix A. Although not complete, it does serve to indicate the very wide range of activities that exist today. Significant advancements are leading to increased practical applications on virtually a daily basis.

While one of the major objectives of this assessment was the potential application of in-cell remote handling and remote maintenance systems, the RAC reviewed the current state of the R/RH technology from a broader viewpoint. The information presented in Appendix B identifies specific R/RH systems developed for various tasks where independent mobility is also a major objective of the device. These systems were not considered in the current evaluation due to the recognized need for full volume coverage by the in-cell maintenance system. It is believed that these systems have potential applications in both in-cell and ex-cell environments, which have not been defined in sufficient detail to allow adequate assessment. Future activities should consider these devices as applications are identified. The information is presented in order to make the reader aware of the very broad spectrum of technology that exists today and is offered as a starting point for any ensuing endeavor.

4. FUTURE RESEARCH DEVELOPMENTS

The ultimate technological goal of advanced R/RH is to provide a system that is both autonomous and adaptable to the work environment. This goal typifies systems that are capable of doing increasing numbers of different tasks with decreasing dependence on human intervention. Two systems discussed earlier, industrial robots and teleoperators, are approaching this goal by different evolutionary pathways. Today's industrial robots are highly automated and can be perceived as quite autonomous, since once programmed, further human intervention is not normally required. Because of sensory limitations such as vision and their simple control programs, these systems have limited flexibility in adapting to work environment changes. The teleoperator is very adaptable because it is essentially a manually controlled system with the human operator performing sensing and decision making. Figure 12 depicts the qualitative relationship of these systems to the ultimate goal. This relationship was first proposed by Jean Vertut of the Commissariat A L'Energie Atomique, Saclay, France. Achievement of the goal leads to a hybrid system whose functionality suggests the concept of a telerobot. Telerobotic systems research is striving for adaptability through enhanced sensory feedback and artificial intelligence concepts, thereby making task decisions from input data. The key objective of telerobotics is to improve overall remote work efficiency by allowing the man and the machine to each do that for which they are best suited. Research in supervisory control and man-machine interface methods to reduce operator burden are intended to improve operator efficiency. Many research activities are aimed toward reducing cost and expanding applications. These include improved data communications methods, advanced digital control techniques, basic sensor development (force, tactile, vision, etc.), mobility, modularity, and subsystem components (actuators, amplifiers, materials, etc.). Appendix B, Sects. B.1.2 and B.1.3, describe technology in the areas of artificial intelligence and machine vision currently under development at leading laboratories. Several current research activities that directly support the emergence of telerobotics systems are discussed below.

The Jet Propulsion Laboratory has been studying kinematically dissimilar manipulator controllers for many years and has developed a universal manipulator controller.[33] The fundamental concept is to develop a master arm that can be used to operate any slave/manipulator system by means of real-time computer transformation of the kinematic dissimilarities. This method may be applied as a future programming device for industrial robots. One would use a single controller and different transformation software to teach the desired motions to different commercial robot configurations. The master controller kinematics can be selected to minimize operating space and to maximize human compatibility. This concept would also facilitate single-operator supervision of several robots.

Distributed digital control techniques have recently been applied to teleoperator systems to improve their operational flexibility.[34] Reprogrammable microprocessor-based control systems have resulted in improved diagnostic methods, basic servo control performance, and reliability in teleoperator systems. Digital controls have made it possible to incorporate compensation

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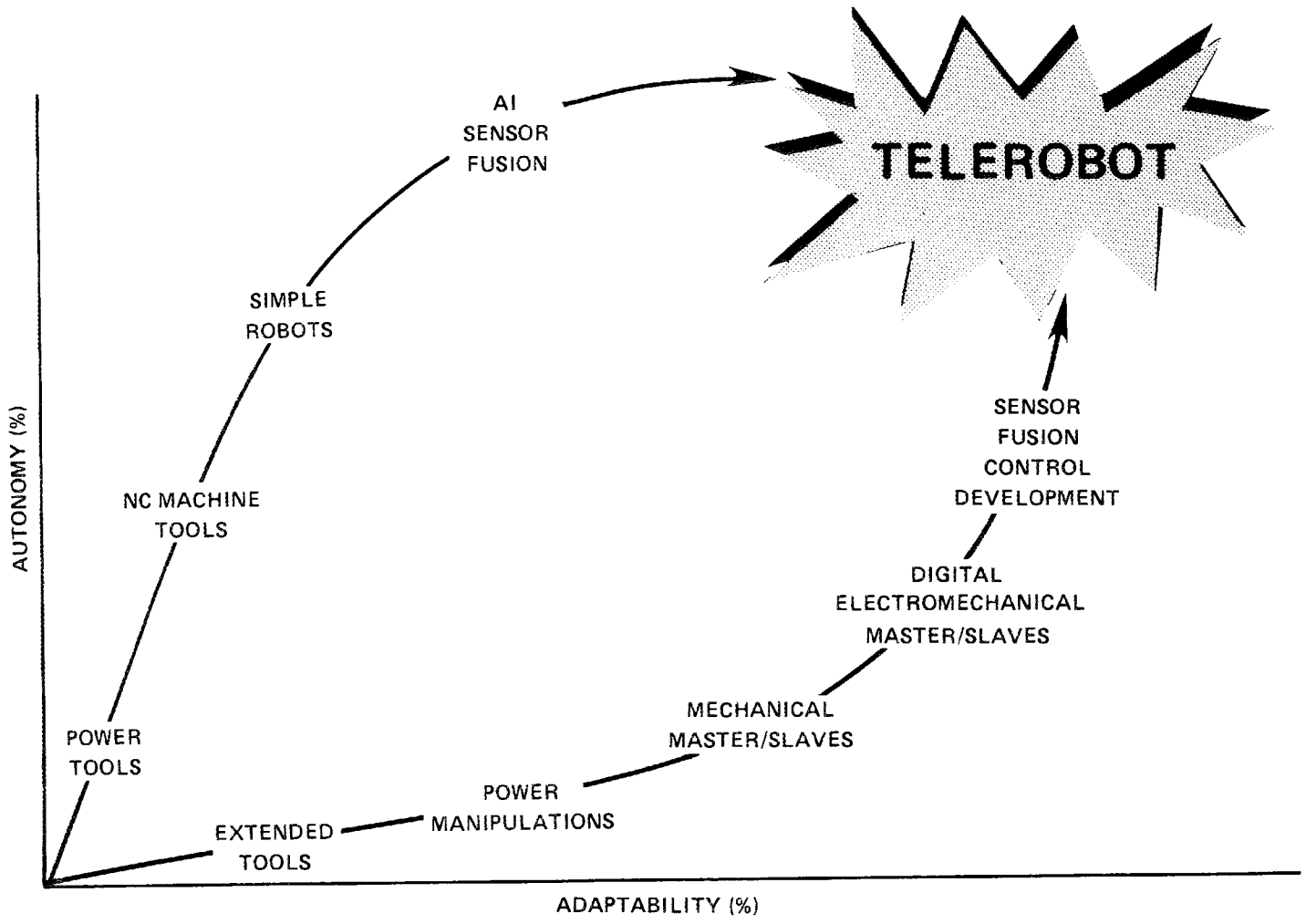

Fig. 12. Teleoperations and robotics converge to the telerobot.

algorithms for inertia, friction, static weight counterbalancing, and other nonlinear effects that were difficult or impossible to accomplish with analog circuitry. Servomanipulators tend to be mechanically flexible due to the emphasis on low inertia (small structure) and centralized actuators (long force transmission path). Current digital systems will allow such flexibility to be corrected by control adjustments and will improve the positional accuracy of slave[35] manipulators during robotic control.

Mechanical modularity, which enhances manufacturability and maintainability, is another area in which both teleoperator and robot manipulators can be improved. A modularly constructed robot can be reconfigured for heavier loads, greater reach, or different kinematic constraints. American Robot Corporation describes its latest system as a Modular Expandable Robot Line (Merlin).[36] Modular construction should also provide increased availability by facilitating faster in situ repair of failed systems. Modularity may also enhance mobility in that the ability to reduce a manipulator to small easily assembled parts should improve its transportability to various work sites.

Man-machine interface advancements are aimed at increasing operator efficiency and compatibility. Computer graphics display techniques are effective for the concise presentation of complex information concerning operating modes, fault conditions, equipment locations, etc. These display systems are programmable, which permits them to be easily adapted and structured into menu-driven tree architectures that are much easier for human assimilation. The ergonomics of the man-machine interface of teleoperators is a very sensitive performance factor also. Human factors engineering associated with master controllers, remote viewing, controls and displays, physical layout, and operator team structures is a basic research area receiving much attention. Remote viewing is an area where future advancements in stereo vision and high resolution wide angle optics may be major improvements.

The National Bureau of Standards, Industrial Automation Division, has spent many years studying the issues of complex manufacturing automation involving integrated control and information management. Their work has gone far toward the development of a discipline for structuring such systems into effective hierarchies. They have shown that underlying the operation of successful multifunctional systems is the ability to partition tasks into a series of defined acts. Such partitioning produces a structured organization of system hardware and software. Such hierarchical systems concepts apply equally well to both teleoperator and robot systems. Both systems can be decomposed into similar subsystems (servo control, sensor data acquisition, kinematic transformation determination, etc.) with congruent goals (manipulate, orient, enunciate, etc.).[37]

The computer technology available to implement these control system hierarchies is constantly improving and will certainly affect the potential capabilities of future telerobotic systems. Today's 32-bit microprocessors provide the computational power of VAX super minicomputers at the chip level of physical size and cost. Consequently, the hardware cost of deploying extremely powerful advanced computer architectures, both parallel and multiprocessor, will be insignificant. Software costs will be more of an issue, but research in software languages and intelligent software development aids may help.

The advances will effectively integrate symbolic and numerical processing such that high-density sensory data input (computer vision), advanced controls (manipulator force control), and logical decision processing (path/task planning) can be handled much more easily.

Remote viewing research for teleoperation has emphasized human interface issues: multiple camera views, optimal perspective, stereo versus monocular, color versus black and

white, and optimal lighting. Telerobotic concept evolution introduces the subject of computer vision. Computer vision is probably the single most important sensor necessary for intelligent robotic systems (refer to Appendix B). Unfortunately, it is also one of the most complex and difficult. The amount of data processing required increases exponentially with image size, resolution, and contrast. A simple image can contain megabytes of digital information. The crux of computer vision is how to process the massive data sets into useful results such as the location and orientation of objects of interest in the field of view. Because of the advances being made in high performance microprocessors, many of the necessary vision processing phases (image acquisition and segmentation) can be accomplished in real-time. The ability to recognize objects in an image with respect to a given knowledge data base (which humans accomplish readily) is in the practical sense unsolved. Consequently, it will be some time before the telerobotic system can both see and understand in a functional way. Teleoperation development has included research into environmental coloring to aid operator recognition and multiple viewing to improve depth perception. These enhancements may also find application in advanced computer vision.

Research activities in teleoperators and robotics are strongly complementary. The major motivation in robotic research is economics, but the different perspective offered by teleoperator development could open new areas useful to both. As industrial robotics systems and applications move toward more complex and unstructured task environments, it is expected that these two related technologies will continue to converge.

5. ASSESSMENT OF REMOTE HANDLING AND REMOTE MAINTENANCE OPTIONS

5.1 REPOSITORY AND MRS REQUIREMENTS

The design concepts for the Repository and the MRS facilities could best be characterized as very large material handling facilities. The primary mission is to prepare nuclear reactor fuel assemblies and other nuclear wastes for storage. In addition to the systems in the various processing steps, systems are required to move various waste forms from one processing station to the next. Most of the materials handled (other than decon solutions) remain in solid form, necessitating the use of mechanical handling systems. The efficiency and reliability of these systems will be critical to the overall performance of the facility. These complex mechanical systems will require scheduled maintenance, require adjustments, and be subject to failure during the plant lifetime. The mission of a remote maintenance system will be to allow the plant operators to respond in a manner that minimizes personnel exposure and is time efficient. Time efficiency is, of course, important due to the fact that facility downtime for repair has a significant impact on plant availability/productivity and operating costs.

In the conceptual design for the MRS facility[38] reviewed during this assessment, the capability has been provided for personnel access into the processing cells if required. The conceptual design stipulates that all radioactive sources would be decontaminated or remotely removed. Although this last resort answer to equipment failures gives some designers a "comfortable feeling" during the plant design phase, previous experience, ALARA considerations, and the existing level of remote handling technology should be weighed against sending personnel into high radiation areas. Reviewing the forty plus years of reprocessing experience, it is readily apparent that the remotely maintained facilities have experienced significantly higher levels of operating efficiency and lower personnel exposure to radiation compared to contact-maintained plants. Decontamination prior to personnel entry for repairs has historically required significantly lengthy downtimes and high personnel exposure. It is recommended that no consideration be given to contact maintenance within the large facility processing and storage cells. Contact maintenance should be reserved for equipment that has been previously removed from the main cell areas and decontaminated prior to human contact.

Repository and MRS remote handling requirements will probably fall into two major categories. The first is movement or removal of very large and very heavy equipment items in the range of 1 to 35 tons. This operation will be very frequent in the case of entry port shield plugs, plugs for the canister lag storage area, storage canisters, and exit port shield plugs. Movement or removal of actual process equipment in this weight category should be fairly low. Implementation of large rigid mast overhead transporters with a level of automation for the standard process operation and with necessary end-effector compliance should be an acceptable solution for this set of operations. The second, and more challenging category, is handling equipment items in the 1 to 2000-lb range. Much of the Repository and MRS process equipment

is complex mechanical equipment, which can be expected to require preventive maintenance and mechanical adjustments and have significant numbers of component failures during the plant lifetime. The complexity of much of this equipment, primarily in the fuel disassembly and rod consolidation, canister handling and sealing, and Repository overpack handling and sealing areas, will require dexterous remote manipulation with coverage over large volumes of cell space.

The preceding discussion of plant maintenance requirements has been based on equipment-related aspects. The following paragraphs include a number of guidelines related to maintenance that are desirable from an overall facility operational viewpoint and are within the state of the art to accomplish in future waste processing plants.

As mentioned earlier, it is important to keep overall radiation exposure levels low by designing for total remote operation and maintenance within the process cells. An important corollary to this philosophy is to minimize the need to perform contact maintenance. Thus, the ability to provide good dexterity for module and component remote repair after removal and replacement is essential. This will minimize the number of items requiring decontamination and transfer to an out-of-cell contact repair area with resulting operating personnel exposure.

In order to reduce construction costs, it is important to reduce the cell volume required to house the process equipment (without severely impacting equipment maintainability) and to reduce the need for specialized design and fabrication of one-of-a-kind equipment features. The ease and speed with which maintenance operations can be performed is important to minimize the damage to adjacent equipment when performing maintenance.

A final general guideline is to provide sufficient remote maintenance system capabilities to support decommissioning the waste processing plant at the end of its useful life. This may require removal, decontamination, and packaging of all in-cell equipment, as well as decontamination of the cell and process building structure. Of course, if the majority of the decommissioning can be accomplished, remotely operating personnel radiation exposure can be minimized.

The maintenance system requirements described earlier in this section relate to maintenance operations that are planned and accommodated in the plant design. These should cover the majority of all maintenance operations during a plant's operating lifetime. Nevertheless, the unplanned failure has been a particularly troublesome event in many of the world's present reprocessing plants, and future waste processing facilities can be expected to experience the same types of problems. Unplanned failures are those that were not considered likely or were overlooked in the original plant design. These types of failures have tended to be located in areas inaccessible to the remote maintenance system or in areas where no remote maintenance capabilities exist.[6] Examples experienced at reprocessing plants include leaks or plugs in permanently installed pipes at the West Valley and LaHague plants and leaks in the permanently installed dissolvers at the Karlsruhe and Tokai-mura plants.[1]

The replacement of a complete unit process step due to changing regulatory requirements or process improvements could also be identified as unplanned maintenance activities. Desirable maintenance system features for unplanned maintenance needs are (1) ability to access and view the equipment throughout the cell areas from many directions; (2) ability to use general maintenance tools such as saws, drills, impact wrenches, and other power tools, as well as special tools; (3) ability to position these tools in any required orientation in space; and (4) most importantly, sufficient adaptability such that an operator can perform complex tasks in a timely manner with little prior training on that particular task.

All the criteria and guidelines described in this section are considered to be features that should be addressed by remote maintenance systems for future waste processing plants. These are summarized in Table 2.

Table 2. Maintenance system requirements and guidelines for future waste processing plants

Maintenance system requirement	Comments
Very heavy lift requirements 1-35 ton range	Particularly true for port shield plugs and waste canisters, also large process equipment removals for maintenance and equipment upgrades including maintaining the maintenance equipment
Rapid in situ process component removal and replacements; 1-2000 lb range	Throughout the plant; primarily to decrease operating costs associated with downtime; particularly important in the canister and overpack handling areas
Dexterous in situ maintenance capabilities in some cell areas	Preventive maintenance and mechanical adjustments
Good in-cell repair dexterity to minimize contact repair.	Reduce overall operating personnel exposures
Allow compact process equipment arrangements	Minimize cell sizes to reduce capital costs
Allow more commercially available types of equipment	Reduce capital equipment design and fabrication costs
Minimize damage to surrounding equipment during maintenance activities	Reduce operating costs related to plant downtime
Allow process equipment removal and complete facility decontamination (preferably remote)	For decommissioning purposes
Capability for handling "unplanned" maintenance: • access equipment throughout cell areas from many directions • use general and special tools • position tools in any orientation in space • adaptable for ease of operation	To reduce facility operating costs related to plant downtime

5.2 EVALUATION OF OPTIONS FOR REPOSITORY AND MRS REMOTE HANDLING SYSTEMS

As described in Sect. 2, the need to maintain radioactive equipment in past nuclear fuel reprocessing plants has previously resulted in the application of three basic approaches: (1) the remotely operated canyon with crane and impact wrench; (2) the remote cells using varying

combinations of cranes, power manipulators, and mechanical master/slaves; and (3) the totally contact-maintained cells. As was described, some plants incorporate a mix of these. Techniques for total remote maintenance have been successfully applied in some of these facilities. However, recent advances in the areas of motor technologies, microprocessor-based control techniques, and industrial robotics applications have resulted in the need to reassess the various options for total remote maintenance available to a plant designer. In addition, specific needs for waste plants should be examined.

In Tables 3 through 6, the basic capabilities of each of the remote maintenance systems described in Sect. 2 are summarized.[39-41] Based on a comparison between these capabilities and plant needs, various combinations of these systems that are meaningful for future waste plant maintenance will be established and rated. The manipulative systems that will be considered are the (1) crane, (2) power manipulator, (3) master/slave manipulator, and (4) servomanipulator. Based on the heavy lift capacity requirements given in Table 2, it can be assumed that a crane is part of any combination. Thus, the possible combinations of these four maintenance systems can be reduced to a total of eight:

1. crane
2. crane plus power manipulator
3. crane plus MSM
4. crane plus servomanipulator
5. crane plus power manipulator plus MSM
6. crane plus power manipulator plus servomanipulator
7. crane plus servomanipulator plus MSM
8. crane plus power manipulator plus servomanipulator plus MSM

Each of these eight systems can accomplish parts or all of the requirements listed in Table 2. Hence, the problem of selection becomes difficult. Attempts have been made in the past to define a figure of merit or dexterity quotient for comparing manipulative system capabilities.[42] Although these studies have generally resulted in good comparisons of many manipulative systems, the results have not been complete enough to allow a plant designer to objectively select, with confidence, the most appropriate maintenance system for application in a plant. Usually, the selection of a remote maintenance system has been reduced to the level of subjective judgment, technical compromise, and expediency.[6]

The difficult part of the evaluation is to compare and rank these eight maintenance system groupings without the decision process becoming too subjective. The best approach appears to be a relative rating of these groupings against the requirements from Table 2. Each system is rated (on a scale of poor-0, fair-1, good-2, and excellent-3) against the requirements from Table 2. These ratings are based on the capabilities of the system as given in Tables 3 through 6. The ratings for each group are totaled to give an overall rating for each grouping. System ratings are somewhat subjective within each requirement, but the overall trends should give a valid conclusion. Weighting factors were not applied to the requirements of Table 2 since all requirements are deemed very important.

The overall ratings are given in Table 7 for the first five maintenance system groupings. The last three groupings: crane plus power manipulator plus servomanipulator, crane plus servomanipulator plus MSM, and crane plus power manipulator plus servomanipulator plus MSM, are combinations that make only minor additions to the in-cell manipulative capabilities contained in the first five groups. Additions to the crane plus servomanipulator grouping does not significantly affect the overall rating. They should be considered as enhancements with use based on specific task needs and economic trade-offs.

Table 3. Typical remote manipulative capabilities of an overhead crane for remote maintenance

Generalized manipulative features	System capabilities	Comments
Capacity/directions	Typically 20 to 100 t; significant force can only be exerted in the lift direction	Capacity is not limiting; the ability to exert significant forces in only one direction requires special design features
Degrees of freedom/kinematics	The lift device can be positioned in any of the three translational degrees of freedom in space; two of the three rotational degrees of freedom are typically not provided unless special end effectors are designed	Limits arrangement of equipment
End-effector speed capability	End-effector speeds slow (about 0.05 to 0.5 m/s)	
Volumetric coverage	The entire cell volume can typically be covered; removable items must be accessible from overhead	Tends to increase cell lengths and heights
Envelope	The envelope for access to equipment tends to be small	The overall equipment envelopes become large due to access only from overhead
Weight/capacity	N/A	
Ease of multijoint operation in real-time (inherent "naturalness" of control motions)	Poor	Typically unilateral, rate controlled from a switch box
Force reflection to sense and control forces	Not provided, load sensors typically difficult for operators to use in real-time maintenance	
Compliance/reversibility to minimize equipment damage	Can be very compliant; rigid mast versions must rely on end-effector compliance	
Index of overall task speed compared to man's hands-on capability	50-500:1	Major equipment replacements typically require 48 h or more

Based on the overall ratings, the crane maintenance system, the mainstay in the U.S. defense production plants, and the crane and power manipulator maintenance system will not be able to meet the requirements of future waste processing plants. This is due to significant amounts of complex mechanical equipment in the plant and the need to minimize contact maintenance of removed equipment. The requirements can be met by either the crane/power manipulator/MSM system or the crane/servomanipulator system.

Table 4. Typical capabilities of an electromechanical manipulator for remote maintenance

Generalized manipulative features	System capabilities	Comments
Capacity/directions	Up to 180 kg, forces can be exerted in all directions (subject to transporter and model constraints). Lift up to 270 kg	
Degrees of freedom/kinematics	6 D.F. plus grip actuation; the grip cannot be positioned in any orientation in space without transporter movement unless a wrist pivot is provided (as in some models of a PaR 3000)	Tends to reduce the ability to perform general work in space and with spatial constraints
End-effector speed capability	0.05 to 0.1 m/s for slower joints	Rather slow compared to man's speed for performing translations
Volumetric coverage	Essentially full cell volume coverage with transporter is feasible	
Envelope	Relatively small	
Weight/capacity	Very good (ranges from 1:0.8 to 1:1.5)	
Ease of multijoint operation in real-time (inherent "naturalness" of motions)	Poor with switch control; better if joystick or master arm control used	Unilateral rate control of individual motions by control switches results in predominantly "one joint at time" motion
Force reflection to sense and control forces	None in most cases. Preselection of grip force available	
Compliance/reversibility to minimize equipment damage	None	Utilizes large gear ratios, typically not backdriveable
Index of overall task speed compared to man's hands-on capability	50-500:1 with switch control; 20-50:1 with joystick or master arm control	

The ratings indicate that the system of choice is the crane/servomanipulator system primarily due to (1) potential increased plant availability with increased ability to perform dexterous repair operations and adjustment in situ throughout the cell volume, (2) much improved ability to respond quickly to unplanned maintenance needs in the plant with flexible and adaptable manipulation at the failure location, and (3) increased capability and flexibility for decommissioning activities at the end of useful plant life.

Table 5. Typical capabilities of a mechanical master/slave manipulator for remote maintenance

Generalized manipulative features	System capabilities	Comments
Capacity/directions	Light duty – up to 9 kg Heavy duty – up to 46 kg Forces can be exerted in all directions	
Degrees of freedom/kinematics	Typically 6 D.F. and grip actuation; provides all six translation and rotation degrees of freedom in space	
End-effector speed capability	Capable of following a man's input motions in real-time	
Volumetric coverage	Limited to a 2.5 by 2.5 by 2.5 m work station adjacent to the shield wall	Limits application in a waste cell to activities that can be reached or brought close to MSM
Envelope	Rather compact	
Weight/capacity	N/A	
Ease of multijoint operation in real-time (inherent "naturalness" of control motions)	Excellent	
Force reflection to sense and control forces	Very good, as long as friction and inertia are kept fairly low	
Compliance/reversibility to minimize equipment damage	Good to fair	Can be abused by operators with resulting increased failure rates
Index of overall task speed compared to man's hands-on capability	8:1	

5.3 MAINTENANCE TASK EXAMPLE FOR THE SELECTED OPTION

The analysis of various manipulator systems for performing remote maintenance indicated that a crane and force-reflecting servomanipulator will most efficiently satisfy the needs identified. An example of the application of this finding may serve to illustrate the benefits of such an approach. The MRS Conceptual Design Report depicts shielded cells with numerous pieces of process equipment that are accessed only by a crane and power manipulator. One such piece of equipment is an ultrasonic tester for checking welds on the fuel storage canisters. Figure 13 includes a series of six computer drawings detailing the steps necessary for the removal for repair or replacement of a transducer from the ultrasonic tester with a force-reflecting servomanipulator.

Table 6. Typical capabilities of a force-reflecting servomanipulator

Generalized manipulative features	System capabilities	Comments
Capacity/directions	Up to 46 kg; forces can be exerted in all directions	
Degrees of freedom/kinematics	Typically 6 D.F. plus grip actuation; provide all six translation and rotation degrees of freedom in space	
End-effector speed capability	0.8-1.5 m/s	This velocity capability allows for following a man's input motion in real-time
Volumetric coverage	Essentially total cell volume when mounted on a transporter	
Envelope	Relatively small	
Weight/capacity	Typically 3:1 to 12:1	
Ease of multijoint operation in real-time (inherent "naturalness" of control motions)	Excellent	
Force reflection to sense and control forces	Very good, as long as friction and inertia are kept fairly low; typical threshold of feel of 0.3 to 0.9 kg	
Compliance/reversibility to minimize equipment damage	Excellent	
Index of overall task speed compared to man's hands-on capability	8:1	

A series of time and motion studies[43] and experience with similar operations have provided an approximation of times necessary for the various steps as indicated below:

Operation	Time to perform (min)
Loosen transducer clamp	0.5
Disconnect electrical connector	0.5
Remove transducer from clamp, discard and insert new on-board transducer	1.5
Tighten transducer clamp	0.5
Plug in electrical connector	2.0
	5 min

Table 7. Comparison of maintenance system capabilities with future waste processing plant needs

Maintenance system requirements and guidelines	Maintenance system rating[a]				
	Crane	Crane + power manipulator	Crane + power manipulator + master/slave	Crane + servomanipulator	Crane + master/slave
1. Large, heavy lift requirements 1-35 t range	2	3	3	3	2
2. Rapid in situ subassembly removal and replacement; typically 10-2000 lb range	0	2	2	3	0
3. Dexterous in situ maintenance capabilities	0	1	1	3	0
4. Dexterous repair capability for removed equipment	0	1	2	3	2
5. Allow compact process equipment arrangements	0	2	2	3	0
6. Allow use of "commercially available" equipment	0	1	2	3	1
7. Minimizes damage to surrounding equipment during maintenance activities	1	1	1	3	1
8. Allows process equipment removal and facility decontamination for decommissioning	1	2	2	3	1

Table 7. continued

Maintenance system requirements and guidelines	Maintenance system rating[a]				
	Crane	Crane + power manipulator	Crane + power manipulator + master/slave	Crane + servomanipulator	Crane + master/slave
9. Capability for handling "unplanned" maintenance					
• Access equipment throughout cell from many directions	1	3	3	3	1
• Use general tools	1	2	2	3	2
• Position tools in any orientation in space	0	2	2	3	0
• Adaptable for ease of operation	1	2	2	3	1
Totals	7	22	24	36	11

[a]Key to ratings: 0 - poor; 1 - fair; 2 - good; 3 - excellent.

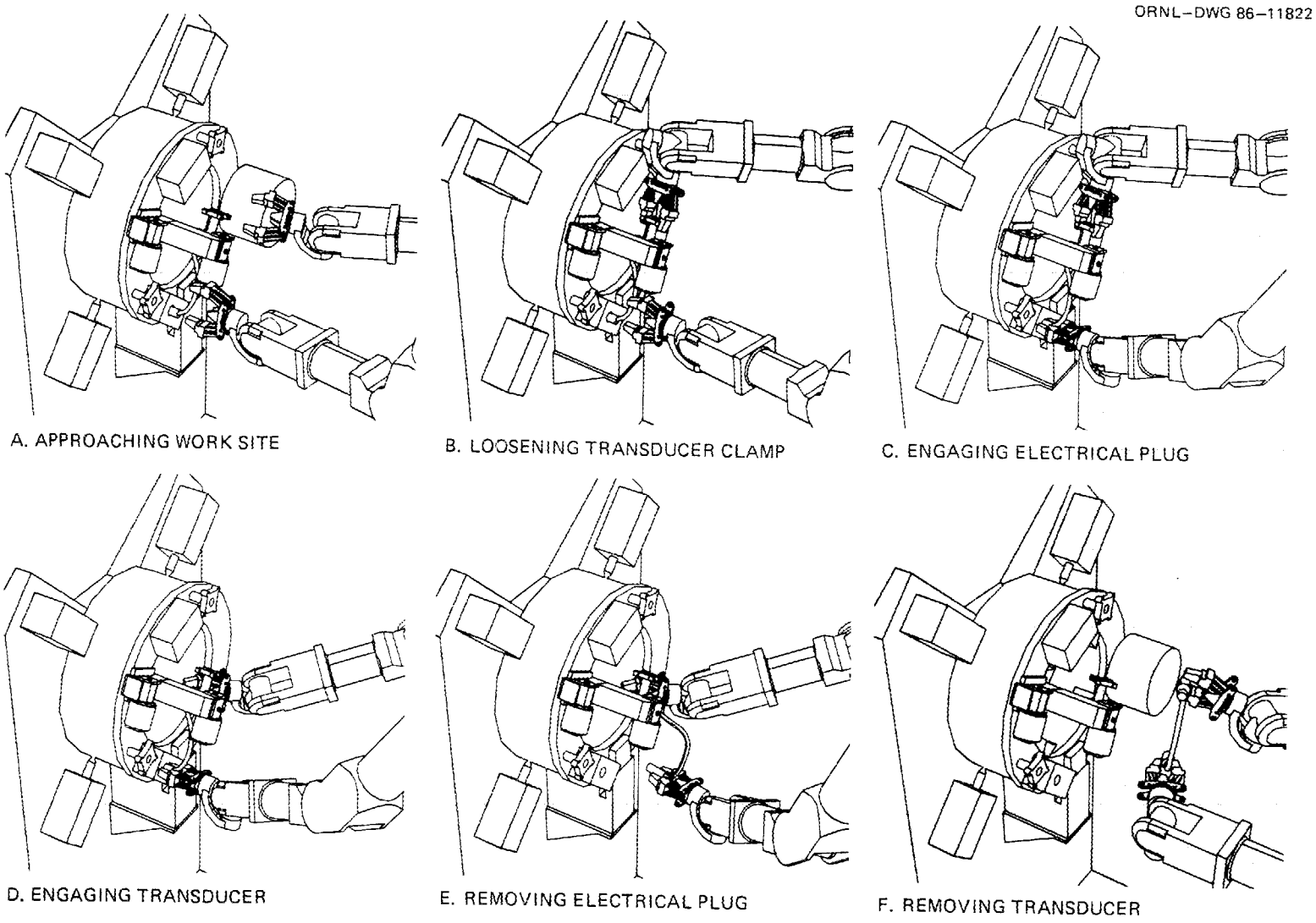

Fig. 13. Replacing an ultrasonic transducer on a welding tester.

From the discussion of relative efficiencies of various manipulator systems included in Sect. 2, the EMM would require a factor of 6 longer to perform similar tasks. Therefore, this simple task, which took about 5 min with a servomanipulator would require about 30 min with the EMM. Extrapolating this data, one can see that a 4-h maintenance task could be elevated to a 24-h plant shutdown.

It should be mentioned that it is very doubtful that an EMM could even perform the task used in the example without destroying the electrical plug or the transducer due to the lack of feel. Most likely EMM would be used to remove the entire ultrasonic tester to an MSM station where the repair could be completed. Obviously, this would take much longer than 30 min.

6. DESIGN CONSIDERATIONS FOR REMOTE OPERATION AND REMOTE MAINTENANCE

6.1 GENERAL GUIDELINES FOR THE DESIGN OF REMOTELY MAINTAINED EQUIPMENT

In any facility incorporating remote operation and remote maintenance, the design of the facility and in-cell equipment is strongly influenced by the repair philosophy and the remote maintenance equipment capabilities. The facility and all in-cell equipment must be arranged to facilitate repair. All in-cell equipment, from very large equipment modules and shielding plugs to the smallest tubing jumper or gasket, must incorporate features necessary to allow the maintenance system to accomplish its task. Lack of consideration of these issues during facility design and construction can result in exceedingly long outage times when failures in process equipment occur.

Therefore, concurrently with the development of the tools for maintenance, the Consolidated Fuel Reprocessing Program at ORNL has developed concepts for the design of in-cell equipment. The critical features of these concepts are formally provided to all design participants, in the form of a Remote Maintenance Design Guide, to assure compatibility between equipment designed by the various participants. Many of these reprocessing plant critical features would be directly adaptable to the highly mechanized equipment of FWMS. Others, specific to FWMS needs, would be generated. The use of a Remote Maintenance Design Guide provides guidance for standardization of the design of the in-cell equipment and establishes the interface between the maintenance tools and the process equipment. A few of the significant points that should be included in a design guide will be addressed in this section.

In an entirely remotely operated and maintained facility, a determination must be made early in the design of the process equipment as to the possibility and the method for repair of the equipment. An example of this methodology is provided by the Remote Maintenance Schematic, Fig. 14, which outlines the various steps normally followed in a remotely maintained facility. The most frequent occurrence is the replacement of a module, shown on the right side of the figure. Examination of the various steps will determine whether the item in question is to be discarded or repaired. If the former, only the extent of decontamination and the means for disposal must be considered. If it is to be repaired, then the means and tools for remote repair or the decontamination and methods of contact repair to be employed require attention. This latter pathway must consider handling of the assembly and its intricate parts in the restrictions imposed by glove boxes or whether the assembly can be handled in the open. In certain instances, a component is either low in cost or is considered expendable due to its inherent characteristics of nonrepairability. Such items bypass all the steps illustrated directly to disposal. The pertinent issue here is that the application of this methodology be made during the initial design.

In order to ensure the successful remote replacement of all the equipment in the shielded cells initially and throughout the operating life of the facility, an accurate dimensional base line or

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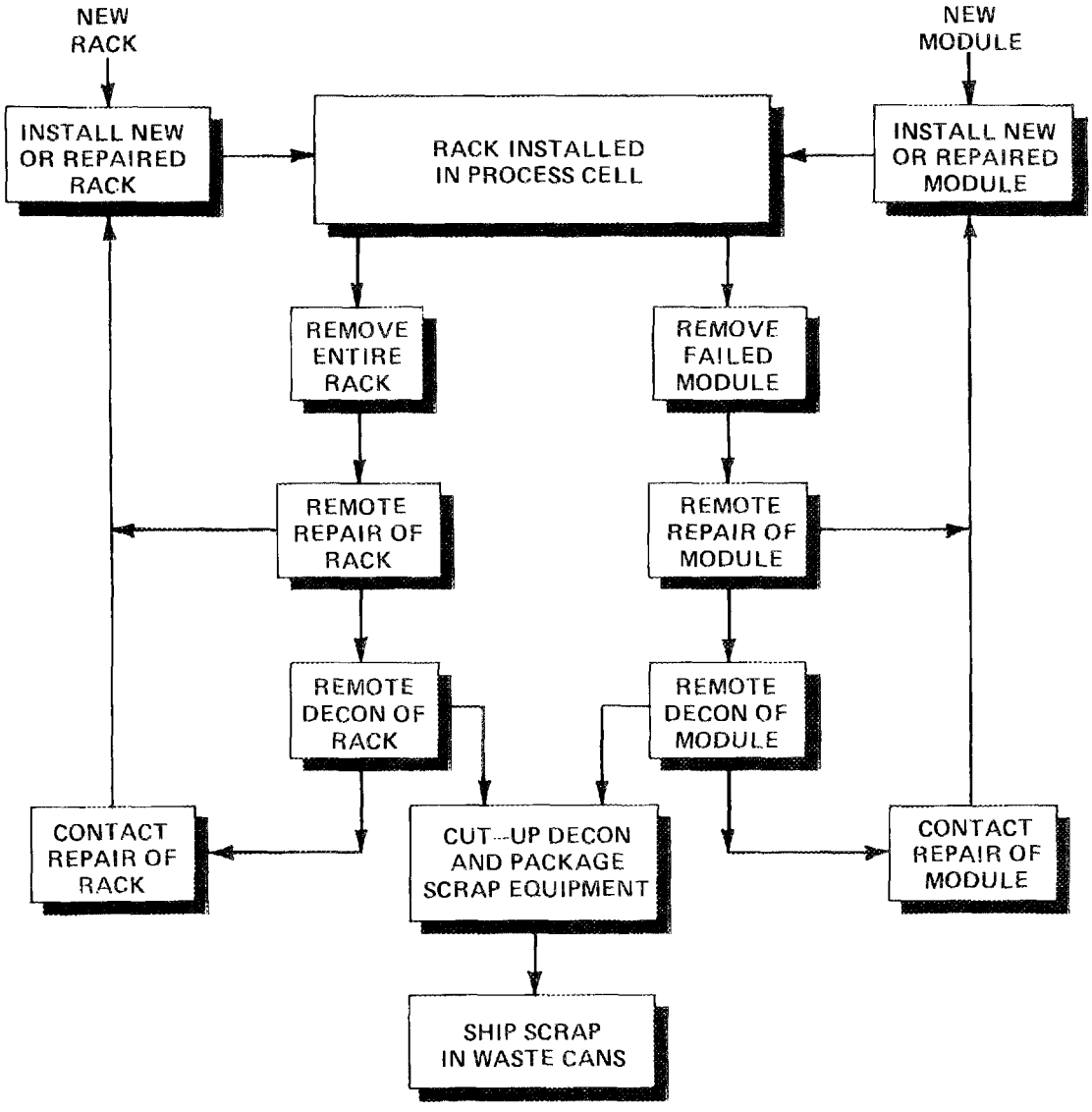

Fig. 14. Remote maintenance schematic.

grid system should be established as a basis for the location of in-cell equipment. The design of all equipment is referenced to this dimensional base line. A mockup of the grid system is maintained during initial fabrication and throughout the operating lifetime of the facility, usually in an on-site shop. Following fabrication, all equipment is verified operationally and dimensionally in this mockup before committing it to the hostile environment. This assures that no adjustments are required following emplacement in the remote cell. Continuing this procedure through the life of the facility assures confident remote replacement of any component in the cell.

Consistent with this philosophy, a machine or unit operation should be subdivided into logical assemblies or parts mounted on a main base frame or equipment rack. The subdivision is determined initially by its operating functions followed by the expected failure frequency, handling ability with the available tools, inherent repair possibilities, and the proposed repair method. Generally, the greater the failure potential, the easier must be the replacement. In order to keep overall plant availability high, small equipment items, such as mechanical activators, electrical switches, in-line instruments, and electrical connectors, are designed to be replaceable in situ. The larger and heavier support racks or other massive machine parts requiring little to no maintenance are removable, but this most likely will not be required except for replacement with advanced technology or until final decommissioning.

In addition to the extensive usage of computers for the manipulator and process equipment control systems, the adaptation of computers to aid in the design of equipment also provides the ability to generate computer models that mimic the movements of a manipulator. This permits checking the interface between the components and the tools that maintain the components during the design phase. An example of this process was shown previously in Fig. 13, a series of six representative frames that depicted the removal of the transducer on the ultrasonic test equipment. The software program CATIA provides the ability to check manipulator/process equipment clearances, thereby confirming the design prior to fabrication. The retention of the data will then provide an operating tool to demonstrate to the maintenance personnel, sometime in the future, how a component is assembled and the means for its replacement.

In summary, the philosophy of how a plant is to be designed to be remotely operated and maintained and the communication of this philosophy early and to all involved will ensure that the plant will maintain a high on-stream availability and be capable of recovering from any unforeseen event.

6.2 APPLICATION OF DESIGN CONCEPTS TO AN FWMS SELECTED OPERATION

The design suggestions and method previously described in this section can best be illustrated by an example of the application of these concepts to a specific area of an FWMS facility. The area to be considered contains the High Activity Liquid Radwaste system, intended for treating liquids generated from operations in the fuel handling areas. This system is described in detail in the MRS Conceptual Design Report.

The system, as concepted, is to be housed in two shielded cells. One of these cells is equipped with a dedicated crane and power manipulator for remote maintenance and removal of equipment for decontamination and contact maintenance in an adjacent cell, and the other is for contact maintenance following in-place decontamination. The remotely maintained cell is also provided with a means of personnel access in the event that the crane and power manipulator cannot cope with the problem. This would entail extensive decontamination prior to entry. The process equipment in the remotely maintained cell was arranged with the equipment in the center of the cell, and adequate space around each equipment item was provided for access. Both cells contained equipment with nonradioactive service functions for the radioactive equipment.

The initial assessment, considering both total system integration and interfacing the remote maintenance and process equipment, indicated changes in the arrangement of the equipment as presented could result in a reduction of building and shielded cell space. Increased efficiency of the chemical operations and the elimination of one bridge mounted maintenance system could also occur. The suggested changes are as follows.

1. The radioactive components of the system can be remotely operated and maintained using the crane-servomanipulator combination described in Sect. 5 and television viewing.

2. The equipment in the cell, other than the evaporator, could be supported on two equipment racks approximately 9 x 9 x 22 ft high incorporating the accurate dimensional grid system. The horizontal evaporator could be mounted on supports attached remotely to these two racks. This arrangement and size will permit both racks to traverse all the identified hatch openings for movement of equipment through the remote cell entry or egress pathway. These components, when grouped and arranged to both function remotely and be maintainable remotely, will require a volume in a shielded cell of 20 x 30 x 25 ft high. This space must be adjacent to a cell wall to accommodate connecting services. Figure 15 illustrates the proposed equipment arrangement. The components on the equipment racks having a high probability for replacement such as motors and similarly vulnerable items will be designed to be maintained with the servomanipulator and its accompanying auxiliary hoist. Tanks, piping, and similar components are considered low probability for failure items for the design life of the plant and are therefore part of the equipment rack.
3. An assessment of cell space requirements, factoring in the total building functions after implementation of item 2, indicated that the equipment can share space in an existing shielded cell. This change could, at the very least, eliminate 3000 ft^2 of existing shielded cells and one complete remote maintenance system as presented in the conceptual design document reviewed. Considering the sources of the liquids treated in this system, the types of other operations performed in an area that might be considered to house the equipment, a potential area designated as the Remote Handled Equipment Maintenance Room in the conceptual design appeared to satisfy the needs. This room, a maintenance area, would provide both the required shielding and remote equipment.
4. The cold chemical equipment and service equipment for the system formerly located in shielded space will require a 12 x 30 x 10 ft high room adjacent to the cell and at an elevation above the equipment in the cell.

This suggested rearrangement would take full advantage of the versatility of the advanced manipulation system and reduce expensive building and cell space. Additional analyses of the MRS Conceptual Design Report could identify other potential applications of these concepts, which would result in similar benefits.

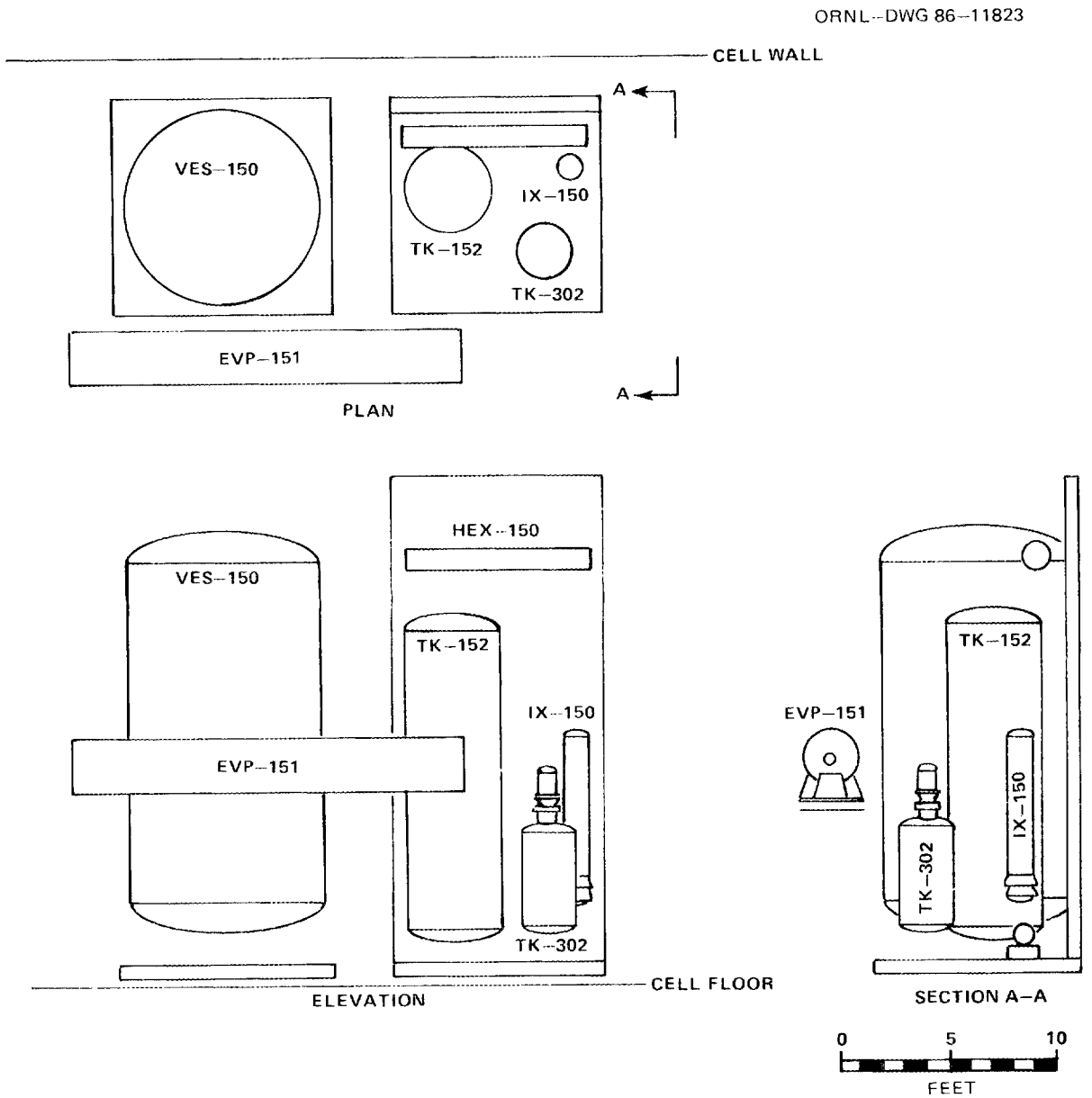

Fig. 15. Reconfigured remote liquid evaporator.

7. RECOMMENDATIONS AND FUTURE EFFORTS FOR THE POTENTIAL APPLICATIONS OF ROBOTIC, REMOTE HANDLING, AND REMOTE MAINTENANCE SYSTEMS

7.1 RECOMMENDATIONS

The uniform evaluation of the potential application of automation, robotics, and remote handling to meet the requirements of FWMS should be a significant activity of OCRWM. Only through the systematic development of the program's needs can the potential worth of this advanced proven technology be established. It is firmly believed by the developers of the technology that the integration of current robotic and teleoperation technology into FWMS will result in major benefits in the following areas:

- improved safety
- reduced personnel exposures
- improved reliability
- increased productivity
- lower costs

A key for the potential incorporation of applicable robotics and remote handling technology is its expeditious transfer to the system designers. It is recommended that this technology be disseminated by conducting workshops, which could consist of R/RH demonstrations and hands-on participation in order for the system designer to gain first-hand knowledge of the capabilities and limitations of various maintenance systems and related facility and equipment design concepts. Facilities, simulating all features except radioactivity, are available at ORNL, which contain the various types of maintenance systems discussed in this report.

The following specific recommendations are based on extensive experience by ORNL personnel with remote systems and their application in nuclear fuel reprocessing facilities and recent experience in advanced robotics and intelligent systems. Because of the similarity between equipment and operations in the reprocessing facilities and the FWMS waste processing facilities revealed in this assessment, many guidelines and concepts developed at ORNL for remote systems operations have direct application. The following points summarize key technology issues that were addressed in this assessment and identified as having potential for application to FWMS:

1. Remote handling technology and hardware are available today to incorporate totally remote maintenance into waste handling facilities.
2. Generally it is good practice to designate separate remote handling systems for maintenance and normal process operations. This will assure the availability of equipment when maintenance is required.

3. Various combinations of maintenance system components were compared to the operating system requirements. The crane/force-reflecting servomanipulator system best satisfies these requirements.
4. Servomanipulator systems can be augmented with software and sensory functions to facilitate the automation of repetitive tasks. This will increase overall system work efficiency.
5. In the time frame of FWMS, there will be many opportunities to incorporate advanced robotic and artificial intelligence concepts which can be significant enhancements to FWMS. For example, artificial intelligence techniques could be used to provide sophisticated on-line diagnostic and maintenance management capabilities for the complex remote handling systems. Such methods would also increase safety through fail-safe collision avoidance and motion management control of multiple systems.
6. Process equipment designers must adhere to design constraints represented by the remote maintenance system capabilities to ensure success and to obtain maximum benefits for the appropriate application of this new technology.
7. Equipment design and arrangement concepts that have evolved from years of experience with reprocessing plants have been provided to facility designers in documented form (Remote Maintenance Design Guide). Designers of FWMS facilities should also be provided with a formal design guide directed at these facilities, which includes but is not limited to the following:
   - equipment methodology of repair determined during the design phase
   - equipment location and support dimensional grid system established for design and fabrication control
   - subdivide equipment into logical and maintainable assemblies
   - operationally and dimensionally verify equipment before installation in a remote environment
   - utilize computer aided design for simulation of remote operations to confirm clearances for remote handling and tooling access provisions prior to fabrication
   - provide sufficient description of remote maintenance system capabilities to participants to determine proper interfaces.

7.2 FUTURE EFFORTS

The potential benefits of advanced remote technology are qualitatively clear, and the potential users of the technology are seeking ways to incorporate it within their activities to their long-term advantage. Certainly, the greater challenge is to formulate a more quantitative justification for the incorporation of the technology and to systematically evaluate the long-term potential benefits. Based on this work, it is recommended that OCRWM pursue a systematic and comprehensive evaluation of robotics and remote handling options for FWMS. The major areas of potential application are listed below, and it is recognized that the criteria for the specific functions listed must be developed prior to a detailed evaluation. However, once the evaluation and functional criteria have been established, it is believed that the real value of this technology will be shown.

Transportation

- cask/transport handling
- cask preparation

Surface Facility: Ex-Cell

- cask/cell interface
- cask decontamination
- cask maintenance
- cask recertification

Surface Facility: In-Cell

- fuel unloading
- fuel handling
- fuel processing
- process automation
- canister handling
- canister closure
- canister decontamination
- canister certification
- waste processing
- waste handling
- equipment installation
- equipment removal
- equipment maintenance
- decontamination
- decommissioning

Subsurface Facility

- process automation
- canister handling
- equipment installation
- equipment removal
- equipment maintenance
- decontamination

During the course of the ORNL robotics/remote handling assessment, the Office of Storage and Transportation System (OSTS) of OCRWM implemented the Robotics and Remote Handling Workshop with the following objectives:

1. review facility/component/system design activities
2. review robotic/remote handling technology development activities
3. discuss the areas of:
   - technology applications/benefits
   - level of technology application
   - technology development needs
   - technology transfer needs
   - schedule for future activities
   - prepare the DOE Robotics/Remote Handling Program Plan

The two-day workshop was attended by the developers of the technology and the potential users of the technology. The OSTS presented the diagram shown in Fig. 16 and provided the rationale for an integrated approach to assess the potential application of the technology. It was agreed that a coordinated effort will be required to ensure an overall assessment and, if

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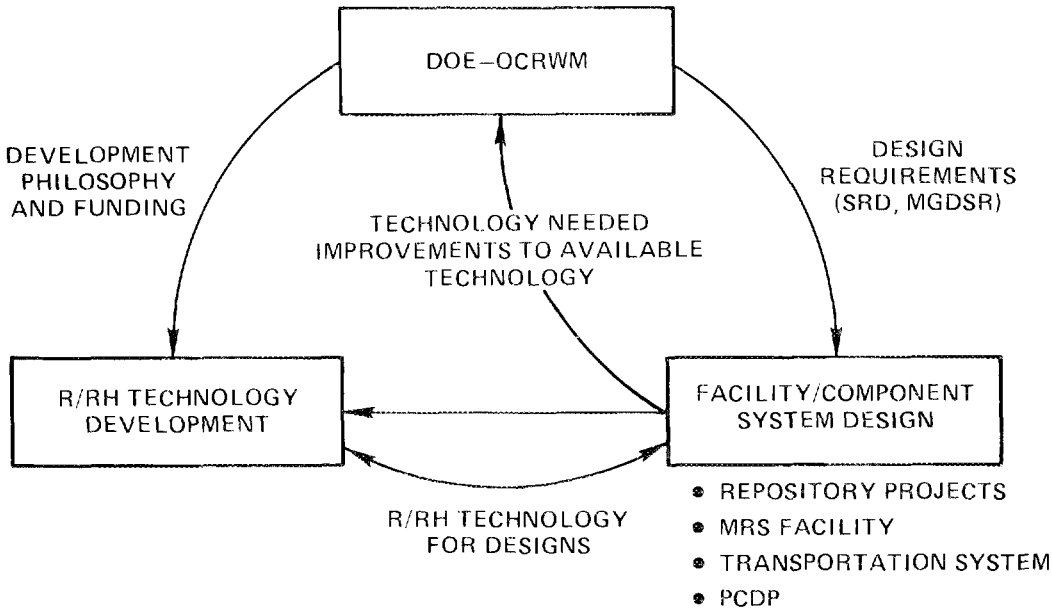

Fig. 16. Interactions between OCRWM system development and robotics/remote handling technology development.

applicable, uniform integration of the technology throughout FWMS. To this end, it was agreed that the DOE Robotics/ Remote Handling Program Plan would be developed by a committee formed from selected participants of the workshop.

As a result of their assignment during the workshop, P. J. Eicker of Sandia National Laboratory and S. A. Meacham of ORNL developed the following logic network for the implementation of such a program plan. It is recognized that for broad acceptance and endorsement, it is critically important that the appropriate organizations are involved in the planning and actual execution of the evaluation. The recommended approach involves a number of elements intended to ensure involvement of government, academia, and industry. This involvement could be through a task force representing technologists from robotics research, remote operations, remote systems development, waste process development, waste facilities design, and appropriate DOE management.

In this context, Fig. 17 illustrates a logic network that provides the rationale for application and implementation of robotics and remote handling systems in FWMS. This logic network provides for the objective assessment and evaluation of robotics and remote handling technology as it best benefits the overall waste system.

The concluding recommendation of this assessment is to proceed with the development of an OCRWM Robotics/Remote Handling Program Plan and implement the plan as soon as possible. A totally organized and integrated effort such as this will not only ensure the uniform evaluation of the potential application of robotics and remote handling technologies within FWMS but sets a benchmark for the rest of the OCRWM program to use for developing integration methodology for various technologies and philosophies.

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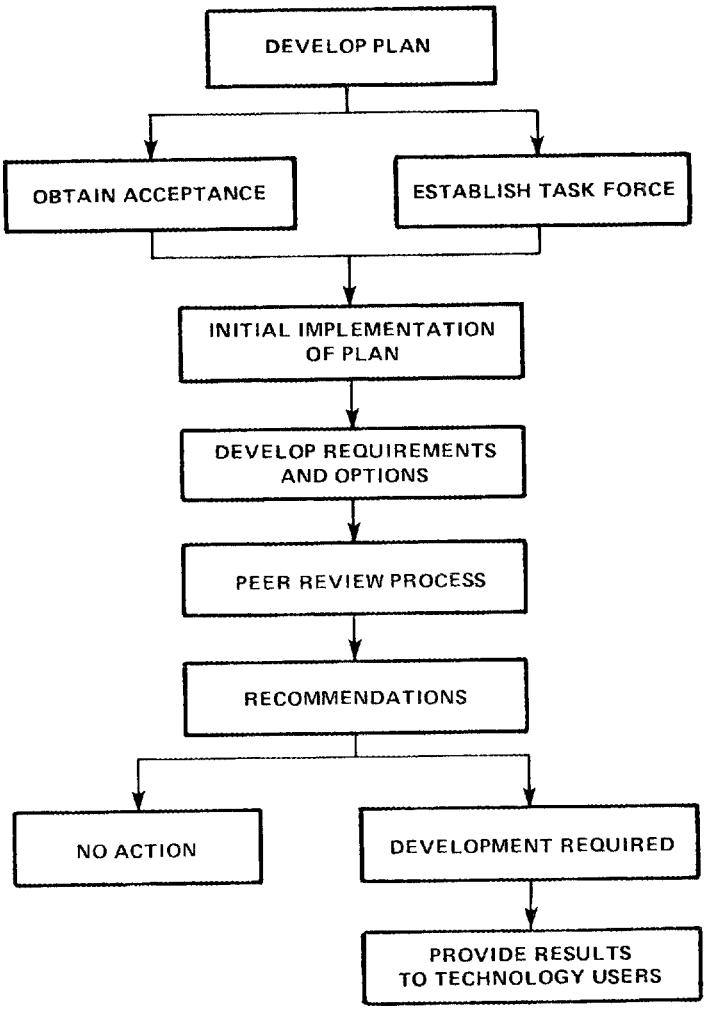

Fig. 17. Logic network for the robotics/remote handling activities.

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APPENDIX A
PARTIAL SUMMARY OF ROBOTICS AND REMOTE HANDLING DEVELOPMENT ACTIVITIES

Table A.1 Partial summary of robotics and remote handling development activities

Organization	Contact	Sponsor	Program Description
Automation Technology Corp.	R. Simmons	EPRI, Gould	Developed and offers the IRIS surveyor system for surveillance
Babcock and Wilcox Contract Research Div.	J. Kerr	Internal	Remote inspection and monitoring systems, including steam generator tube repair inspection system
Battelle Memorial Inst.	Matt Bartilson	Internal	Developed mobile radio-controlled platform (ROCOMP) with manipulator for maintenance in nuclear power plants. Can also be used for gathering smear samples
	John Reidy	Wright Patterson AFB	Design and construction of a robotic engineer repair facility for the Air Force
		ORNL	Design of a remote-weld-repair system concept for radioactive piping
		DARPA	Development of an adaptive suspension system for a rugged terrain vehicle, including hydraulic devices and the machine intelligence system
Brigham-Young University	Dr. Edward Red 801/378-5539	Industry BYU	Developed interdisciplinary systems including vision, CAE, CAD, and robotics for automated manufacturing. Program established a few years ago and is on-going

Table A.1 (continued)

Organization	Contact	Sponsor	Program Description
Brigham-Young (continued)			1. Systems development/implementation • robots • CAE/CAD • vision • digital transmission • software
California Institute of Technol. Jet Propulsion Lab.	Dr. Paul Schenker	DOD NASA Telerobotic Systems Program	NASA's major telerobotics research program encompassing: • Sensor-based manipulator control • Multifingered end effectors • Operating systems • Languages • Supervisory control • Teleoperation • Sensing and perception system • Human factors • Automatic plan generation • Machine intelligence
Canadian General Electric	Barry O'Sullivan 705/748-7183	Self	Monitoring and intervention systems for fuel handling. Underwater robotics system with force sensor feedback
Carnegie-Mellon University Robotics Institute	Dr. Raj Reddy 412/578-2597 Dr. Marc Raibert Dr. Matt Mason Dr. W. Whittaker	Government Industry (30+) DOE, DARPA, EPRI, GRI	Large, interdisciplinary research center studying autonomous systems capable of sensing, thinking, and acting

Table A.1 (continued)

Organization	Contact	Sponsor	Program Description
Carnegie-Mellon (continued)			Robotics Institute was established in 1979 and has more than 200 staff and students. Active in automation computer-integrated manufacturing and robotics for hazardous environments, including nuclear and deep mine shafts. Funding is approximately $9M/year. Direct support to TMI recovery. Advanced computer architectures. Fundamental research in walking machines
CEA France	Jean Loup Rouyer	French Government	Research in computer assisted teleoperations for nuclear applications. Continuing manipulator development activities
Clemson University Engineering Center for Automated Manufacturing	Dr. Frank W. Paul 803/656-3291 Dr. J. Y. Luh	Industrial DOD	Established in November 1981 to support education and research activities in automated machines and robotics, computer-aided design, materials for manufacturing and systems and industrial engineering. The Center works advanced control concepts through its industry members and contactors on problems related to automated manufacturing. The Center is supported by a laboratory having robots, microcomputers, and two VAX 11/780 computers for CAD activities

Table A.1 (continued)

Organization	Contact	Sponsor	Program Description
CMS Technologies, Inc.	C. Stephens	Commercial Market	U.S. representative for systems developed by Blocher in FRG
Defense Advanced Research Projects Agency (DARPA)	Dr. Robert Rosenfeld Dr. William Isler		Supports several university, industry, and military research and development efforts encompassing most aspects of both stationary and mobile systems. Fund the Autonomous Land Vehicle and Advanced Manipulator Systems Program ($50 to $100M/year)
Charles Stark Draper Laboratory, Inc.	Dr. J. Nevins Dr. D. Whitney	DOD NASA USBM Industry	Research in understanding manufacturing processes (assembly,thread mating, grinding, etc.) prior to automating them. Recently rebuilt and delivered special tool-changing robot with 12 tools, computer and sensors for complete documented assembly of precision products. Basic research in impedance control
Drexel University	Dr. Alexander Meystel	U.S. Army	Research in autonomous mobile systems with three distinct levels of intelligence for terrain negotiation
Electric Power Research Institute	Dr. Floyd Gelhaus	U.S. member utilities	Industrial development at mobile systems for surveillance and maintenance work. Support TMI-2 cleanup with specific remote vehicles, in conjunction with CMU
Foster-Miller, Inc.	R. Weisman	U.S. Navy	Developed and manufactured three Ramrod explosive ordinance disposal mobile systems to EOD Center

Table A.1 (continued)

Organization	Contact	Sponsor	Program Description
FRG Kernforshungszentraum Karlsruhe GmbH	Dr. H. Kolher		Robotic system for fuel handling, mobile vehicles, waste processing, and decommissioning
Georgia Inst. of Tech., Atlanta, GA Center for Material Handling	Dr. Dickerson 404/894-2000	25 industrial sponsors, IBM is the largest	Programs in manufacturing materials handling automation, vehicle guidance, tactile sensing, and high speed/light weight motion system
GCA/PaR Systems	R. Johnston	Commercial market	Offer manipulators, ISI systems, robotic system control for IFA. Manufactured the Herman robot now at ORNL's Y-12 facility
General Electric Company	Mr. Vern Estes 305/889-1401	Self	Extensive robotics hardware/software applications development. "Factory with a Future" program incorporating robots, vision, sensors and manufacturing systems. GE Corporate Research and Development Center Advanced R&D in areas such as computers, languages, assembly robots, CAE/CAD and laser weld tracking via robotics
Hitachi Corporation Energy Research Laboratory	Dr. N. Ozaki		Developed and offers the Hi-Mante remote-operated manipulator vehicle for decommissioning. Research in walking machines and multi degree-of-freedom manipulators
Honeywell, Inc. Technology Strategy Center	R. Mostrom	DOD, NASA	Developed and promotes 3-D TU viewing systems, power-line carrier systems, range finding systems, and various communications systems technologies

Table A.1 (continued)

Organization	Contact	Sponsor	Program Description
Kansai Electric Power Company		Mitsubishi, Fuji Hitachi, Meidensha Electric Mfg. Co.	Robots for operations inside steam generator channel head, valve seal tensioning, manhole cover handling, floor decontamination, and pipe elbow inspection
Los Alamos National Laboratory	Don Grissom	DOE	Remote teleoperation systems used for particle accelerator target area maintenance and refurbishment
Meidensha Electric Co.	T. Amano	Japan Power Reactor and Nuclear Fuel Development Corporation	Bilateral and unilateral servomanipulator development for fuel reprocessing applications
MIT Aeronautics & Astronautics Dept.	Dr. David Aiken 617/253-7107	NASA	Research directed toward structural assembly of space stations. Currently underwater testing two teleoperated vehicles, both master/slave machines
Civil Engr. Dept.	Dr. Gregory Baecher 617/253-7101	U. S. Army	Developing a device to detect leaks in buried water pipes
Mechanical Engr. Dept.	Dr. Steven Dubowsky Dr. Warren Seering Dr. Thomas Sheridan	DOD NASA NSF	Research in human factors, manipulator compliance and dynamic modelling
NASA Langley Research Center	A. Meintel	NASA	Telerobotic systems research for space. Emphasis on AI and man-machine cooperative control

Table A.1 (continued)

Organization	Contact	Sponsor	Program Description
National Bureau of Standards	Dr. James Albus 301/921-1000 H. McCain	NBS, DOD, NASA	Research in advanced manufacturing technology utilizing robotics and AI. Developers of the NBS Real-time Control System. Research in artificial intelligence applied to interactive/autonomous robots
Naval Ocean Systems Center Hawaii	Don Moore	U. S. Marine Corps	Ground-Air Telerobotics Systems Program. Remotely operated jeep-like vehicle for surveillance/attack. Airborne remotely-operated surveillance platform. Development and demonstration of force-reflecting bilateral servo-manipulator for use in reprocessing system operation and maintenance, advanced digital control, man-machine upgrades, and remote TV system. Funded at a multimillion dollar level. Foreign collaboration with Japan and France
Oak Ridge National Laboratory Consolidated Fuel Reprocessing Program	J. N. Herndon 615/574-7152	DOE	
Center for Engineering Systems Advanced Research	Dr. C. R. Weisbin 615/574-6186	DOE DOD/Army, Marine Corps, Air Force, SDI	Basic research in autonomous robot systems for hazardous and unstructured environments. Research in battlefield robotics, advanced computer architectures, concurrent computing software, machine vision, and machine learning

Table A.1 (continued)

Organization	Contact	Sponsor	Program Description
Odetics, Inc.	T. Bartholet	DOD, DOE, NASA	Developed the six-legged robot prototype ODEX. Light weight manipulator systems. Laser range scanners
Public Service Electric Gas of New Jersey	H. Roman	Internal	Utility is assessing needs and for robotic systems in generating stations working with several nearby universities (e.g., NSIT)
Remote Technology Corp.	J. R. White	NRC	Developed the Surbot mobile robot under SBIR funding; other master/slave manipulation systems.
Rensselaer Polytechnic Institute, Manufacturing Technology and Productivity Center, Robotics Research Laboratory	Dr. Leo Hanifin 518/270-6724 Dr. George Saridis	NASA Industry	The Center is currently involved in a broad spectrum of projects, which include the use of interactive computer graphics to create and simulate numerical control tapes to eliminate costly N/C tape verification on the machine-tool; computer graphic simulation of industrial robot arms; the adaptation of microprocessors and computers as controllers to replace manual, hardwires, or CAM controllers; the use of interactive computer graphics to optimize work station layout for robotic assembly. Robotics manipulator advanced controls
Rockwell International Science Center	J. Schoenwald	Internal	Research and development on acoustic ranging systems and robot position control. Intelligent end effectors
SAS R&D Services Ltd. (I)	T. R. Sas	Internal	Developed and commercially offers the Hunter remote controlled EOD vehicle

Table A.1 (continued)

Organization	Contact	Sponsor	Program Description
Savannah River National Laboratory	J. Byrd	DOE	Application of robotics in various operations such as "bag out" of waste cans from a Cf source processing facility; radioactive sample collection; transfer of nuclear sources and evaluation of walking robots
Shimizu Construction Co., Ltd.	T. Yoshino		With Kobe Steel, developed and offers robot for spraying rock wool for the fireproofing of structural steel
Spar Aerospace Limited	Graham Norgate	NASA, AECL	Developer of the Space Shuttle Remote Manipulator System. Manipulator systems for industry and hostile environments
SRI International	D. Nitzan	DOD, DOE, NASA	Research and artificial intelligence and robotic manipulators
Stanford University Inst. for Manufacturing and Automation	Dr. Elliott C. Levinthal 415/497-9037 Dr. Robert Cannon Dr. Thomas Binford	About 25 sponsors including IBM, NSF NASA Mettler AG, SDF, AFOSR,DARPA, DNA, EPRI, and others	Interdisciplinary organization with four major centers whose end products are graduates, research results, and educational activities. Major artificial intelligence research center. Fundamental research in flexible manipulators
Stevens Inst.	Dr. John Crisp	U. S. Army	Work in telematics. Courses offered in microprocessors and one in robotics

Table A.1 (continued)

Organization	Contact	Sponsor	Program Description
TeleOperator System	C. Flatau	DOE, Commercial Market	Developer and manufacturer of TOS SM-229 bilateral force-reflecting servomanipulator. Offer the Telemac, a radio controlled, remote operating vehicle developed in Belgium by ACEC and others
UCLA	Dr. Geo. A. Bekey 213/743-5535	Government Industry	Courses and R&D in artificial intelligence, manufacturing technology, robotics, and automation
United Kingdom Central Electricity Generating Board-Marchwood Eng. Lab.	D. W. Perratt	U.K.	Development of sophisticated, heavy duty manipulators with arm extensions and tools (bolting and welding) for remote repair of Magnox stations
Univ. of California LaJolla California Space Inst.	David R. Criswell 619/452-2047	NASA	Established the Automation and Robotics Panel to provide guidance on the application of advanced automation and robotics to the IOC program
Univ. of Florida Center for Intelligent Machines and Robotics (CIMAR)	Dr. Jack Ohanian 904/392-0464 Dr. Joe Duffy 904/392-0879 Staff about 20 grad students - about 75	DOE, Florida State, Industry	Approximate funding level is $3M/year. Specific - all programs on-going with emphasis toward implementation 1. Real-time man-machine systems • Joystick controllers • 4 D.F. planar controller • 6 D.F. spatial controller • (1 redundant D.F.) controller • Force feedback

Table A.1 (continued)

Organization	Contact	Sponsor	Program Description
Univ. of Florida (continued)			2. Dynamics (Robot Control) • Phase I - correct for inertial loading • Phase II - correct for deflection/flexible loading 3. Graphics - three dimensional 4. Multiple robot systems 5. Kinematics 6. Mathematics
Univ. of Maryland, Systems Research Center	Dr. Yang	DARPA, NSF, ORNL, industry (W-Columbia)	Vision systems and human computer interaction. Have program with EPRI (through GE) on inspection techniques
Univ. of Nevada-Reno	Dr. N. D. Perreria 702/784-6094	DOE	Evaluation of optic sensors for remote maintenance of reprocessing fuel fabrication equipment
Univ. of Rhode Island NSF Center for Robotics	Dr. Morris Driels	Industry	Program directed toward industrial applications that involve fixed-position robots, (e.g., to recognize and remove a part from a bin of parts)
Univ. of Texas Center for Robotics, Manufacturing, and Logistics	Dr. Delbert Tesar 512/471-3039 staff, grad student development under way (expect 200 total)	Air Force State of Texas Industry	Funding is about $1 to $2M for 1985 and is expected to increase to $5 to $7M/year 1. Mobile robots suitable for battlefield operations 2. Manufacturing robots • free-standing/data base controlled

Table A.1 (continued)

Organization	Contact	Sponsor	Program Description
Univ. of Texas (continued)			3. Advanced technology development • new computer architectures • improved man-machine interface • mathematics • dynamic modeling • advanced sensor/vision • manipulators/end effectors/ materials • miniaturized systems/sensors
Viking Energy Corporation	J. Saluja	Commercial Market	Developed the ROD robot for cleanup of radioactive waste at the West Valley Demonstration project
Westinghouse Electric Corporation	C. A. Sadlow, V.P. Adv. Prod. Tech. 412/642-3811	Self	Manufacturers of Unimate robots self-funded development of advanced electric-driven robots, vision systems, laser/MIG automated welding system, artificial intelligence. Supported by Productivity Center and R&D Center. Robotic and remote operated equipment developed for nuclear applications
	J. Gitt Oceancies Division 301/260-5804		Design studies of an autonomous underseas vehicle for DOD

Table A.1 (continued)

Organization	Contact	Sponsor	Program Description
Westinghouse Hanford Co.	Dr. R. E. Dahl 509/376-8724	DOE	Design, development, procurement, installation, and operation of automated, remotely controlled LMR fuel fabrication line. Over 20 robots are utilized
	J. D. Berger	DOE/Sandia	Development of High-Level Waste Shipping container handling during truck loading/unloading. Uses robot and overhead crane
	W. Gajewski 509/376-9586	DOE	Developed the equipment, systems, and facilities for maintenance, in-service inspection, and surveillance of FFTF. Provided SISI and LOUIE mobile robots for TMI-2

APPENDIX B
SUMMARY OF GROUND-BASED MOBILE SYSTEMS

The information presented in this Appendix was extracted from an article that addresses these topics in considerably more detail. Those readers who desire more information should contact Dr. C. R. Weisbin (615-574-6186), Director of the Center for Engineering Systems Advanced Research at the Oak Ridge National Laboratory.

B.1 MOBILE GROUND-BASED ROBOTIC SYSTEMS

While this classification of robotics and remote handling systems is not consistent with the original classifications addressed in this report based on human interaction required, it is a recognized category of remotely controlled devices, and therefore it is worthwhile to consider these systems here. In some applications, the ability to get the manipulation system to the work site is as important and perhaps even more complicated than the task to be performed. The systems considered here were designed for their mobility, as much as their manipulation capabilities.

Mobile remote systems are beginning to make a significant contribution for tasks in hazardous, unstructured environments that require flexible capability in dealing with off-normal events, continuous monitoring and inspection of spatially-distributed systems, and in efficient but variable material transfer, delivery, and process augmentation. We have only to look at TMI or Chernobyl to appreciate the potential value of such systems in dealing with emergency events while minimizing radiation exposure to man. Flexible mobile robotic systems can be used, at least in part, for toxic waste material collection, processing, storage, handling transportation, and disposal site monitoring and characterization, as well as industrial security.

EPRI, DOD, NRC, and DOE are supporting development and testing of systems ranging from those fully controlled remotely (i.e., man-in-the-loop making all cognitive decisions), to supervisory control (i.e., man gives specific implementable directives, e.g., "carry drum A to location B" and monitors system performance), to largely autonomous systems (man gives broad commands such as "find the leak" and the robotic systems decompose the goal statement into executable task sequences that are monitored by the operator). The question of appropriate level of autonomy is a matter of degree and highly problem dependent; man will always be in the loop to some extent. In our judgment, hybrid machines capable of dynamically switching modes between autonomous operation and direct human control may actually be more useful than either of the two systems at both extremes.

The following sections review the availability and status of several mobile robotic systems followed by technology currently available in several of our leading laboratories, which could be deployed in the 1990s time frame to provide added capability to these systems. These areas discussed are diagnosis and planning, advanced computational capability, and machine vision.

B.1.1 Availability and Status of Existing Systems

Many of the tasks of interest are comprised of steps that include navigation to the work site, workpiece recognition and system alignment, tool manipulation including sensor feedback, and disengagement. This generic paradigm applies to numerous application areas which are tabulated below. Mobile systems using legged, tracked, and wheeled locomotion have been developed, which work well in cluttered environments, in traversing sharp inclines, and in moving quickly along relatively flat terrain. These systems include video for teleoperation or for on-line object recognition. Other detectors such as tactile, acoustic, etc., complement the sensor suite. Manipulators for mobile systems of necessity need to be lighter weight than their industrial

counterparts. The emphasis here is on dexterous tool manipulation rather than the ability to deal with massive payloads or rapid movement. For example, the manipulator built at ORNL for the HERMIES mobile robot is designed to lift about 25% of its weight rather than the 5% typical of its industrial counterparts.

Table B.1 is an update of recent compilations of systems for mobile robotic environments for a number of different applications, including nuclear (N), other hazardous (H), explosive ordinance disposal (E), security (S), firefighting (F), military (M), and miscellaneous (MI). The type of locomotion, i.e., tracked (T), wheeled (W), and legged (L), is indicated along with the name of the specific manufacturer and the country of origin, i.e., Belgium (BL), Canada (CN), France (FR), Federal Republic of Germany (FRG), Great Britain (GB), Holland (H), Ireland (IR), Israel (IS), Japan (JA), and the United States (US). Due to time constraints in this compilation, not all entries are necessarily complete. In addition, judgments of a comparative nature between systems have been reserved for a later report.

B.1.2 Real-Time Expert System Control of an Intelligent Robot

There is technology available today for implementing a far greater degree of autonomy in our robotic systems than one might expect. Described below is an architecture for the near-term implementation of machine intelligence. The HERMIES-II robot at the ORNL's Center for Engineering Systems Advanced Research is a self-powered mobile robot system capable of sensor based navigation in the presence of moving obstacles. This system demonstrates the available capability for real-time sensor-based navigation, the treatment of priorities and interrupts, and the capability for on-line replanning. The use of an expert system for robotic control presents several attractive features: the explicitness and homogeneity of the knowledge representation facilitates explaining, verifying, and modifying the rules that determine the robot's behavior; it also permits the incremental extension of the domain of competence. These extensions to object identification and manipulation tasks are being done today.

In developing software for situation analysis, decision-making, scheduling, control, and other cognitive tasks, the following attributes are considered.

1. flexibility – a diversity of knowledge representation schemes
2. capability to deal with external sensor signals and demonstrate real-time performance
3. nonmonotonic reasoning to withdraw previous inference based upon new information
4. a variety of inference mechanisms
5. incorporation and propagation of uncertainty
6. availability of documentation and source code for modification and update
7. friendly development environment

The following seven general areas of knowledge representation must be considered for intelligent mobile robotic behavior: (1) maps, including the global map and learned information, (2) rules representing search techniques and obstacle avoidance, (3) frames for object identification, (4) scripts for assembly, disassembly, and repair, (5) sensor representation, (6) rules and procedures for scheduling tasks and assigning priorities, and (7) metarules, procedures, and data structures for learning.

The robot must deal with a large array of sensor information coming to it. Effective methods for fusion of independent sensor information and treatment of uncertainty are important elements for success. Forward chaining (inferencing) is necessary for our machine to solve its task; backward chaining must be present so that the robot can explain its activities.

There are a large number of expert systems available today (e.g., PICON, ART, Knowledge Craft, KEE, KES-II, M.1, Rule Master, S.1); only the first two of these appear to have the majority of the characteristics that we desire.

B.1.3 Characteristics and Utilization of Machine Vision

Human vision is an enormously complex sensory capability that can be initiated, but not duplicated, by machine vision. In a machine vision system, the cameras are substitutes for the eyes, and the computers replace the brain. Such a system can be used to interpret an image either to cause some decision to be made during a manipulation (e.g., move a part, reject a part, or avoid a collision) or to build a data base about a series of workpieces so that an analytical model can be developed to describe the expected characteristics of the objects. The system must therefore be able to verify object presence or absence, measure image features, and recognize objects.

Vision technology is new. Recent decreases in computer costs and increases in their capabilities have made them more feasible for use with vision systems. Further, a more sophisticated understanding of natural image processing has led to the development of corresponding algorithms that allow machine vision to more closely simulate that of humans. A third factor is hardware improvement. Among others, the development of solid-state cameras has enhanced the generation of images.

The ultimate goal of an image recognition process is to reduce to a minimum the ambiguities, or the number of ways in which an image can be interpreted, using the least amount of information possible. Whatever the amount of detail required, the machine vision process consists of image formation, image preprocessing, image analysis, and image interpretation.

Table B.1 Summary of ground-based mobile systems

Manufacturer (country) Name of Device	Locomotion/ Primary mission[a]	Comment
ACEC (BL) Telemac (Vampire)	T/N	
Analytical Instruments Ltd. (GB)		
RO-VEH	WT/E	
Automation Technology Corp. (US)		Industrial remote inspection, tetherless, tracked (can handle 45° stairs) supervisory control with articulated arm, stereo vision, sensors
Iris-Surveyor II	T/N	
Babcock and Wilcox (US)		Cable operated. Remotely operated steam generator and repair
Oscar	T	
Roger		
Battelle Columbus (US)		Radio or computer operated mobile platform, teleoperated or autonomous, surveillance function
Rocomp	WT/N	
Beaconsfield		
Hunter		
Blocher-Motor GmbH & Co (FRG) (CMS Technologies, Inc.)		Remotely controlled four-tracked vehicle
MF3	T/N	
MF4	T/E	
Canada		Remotely piloted vehicle for military target acquisition and reconnaissance. Includes TV, laser, radiation detector
CL-227		
Carnegie-Mellon (US)	W/N	Remote reconnaissance vehicle for TMI
RRV		
Remoteborer	W/N	CMU's largest mobile robot gasoline powered for outdoor navigation and road following
RWV	W/N	
Terregator	W/M	
Imp	W/MI	Used for indoor navigation based on a rotating sonar horn.

Table B.1 (continued)

Manufacturer (country) Name of Device	Locomotion/ Primary mission[a]	Comment
Cybermation (US)		
Kluge	W/MI	Surveillance, light work, or parts delivery, teleoperated or, autonomous, zero turning radius
Electricite de France		
Isis		Full-sized mockup of reactor (Chinon A3) used to teach robotic manipulators to carry out repairs
Energy Corp.		
Rod		
Fire and Technical Equipment (US)		
Firecat	W/F	
Foster-Miller (US)		
Ramrod	T/E	
GCA/PAR (US)		
Par-1	T/N	
Par-2	T/N	
Herman	T/N	
Louie	T/N	
GCA/Par-1	T/N	
GMH Security (US)		
Snoopy	T/E	
Hitachi Ltd. (JA)		
RIS	W/N	
PMR	L/N	
Hodges Robotics (US)		
Fred	W/FN	High-pressure water spray for decontamination
Human Engineering Lab. (US)		
TRV	W/M	Tactical Reconnaissance vehicle for surveillance, weapons firing smoke. Teleoperated to build ultimately on ALV

Table B.1 (continued)

Manufacturer (country) Name of Device	Locomotion/ Primary mission[a]	Comment
Hydro Products RCV-150		Tethered swimmer, camera, and arm
Inspectronic (FR)		
Ariane	T/N	
Oreste	N	
Oscar	T/N	
JAMSTEC Homet 5000		Japan Marine Science and Technology Center - fiber optic tethered undersea survey vehicle
Japan Atomic Energy Research (JA) MBS	T/N	
Jet Propulsion Lab (US) RRV		Mars Rover, stereo TV, laser ranging, proximity sensored, tethered
Kentree Ltd. (IR) Hobo	W/E	Extensible arm and gripper with which it can grab suspicious looking objects and take them away for disposal
Lawrence Livermore (US) Atom	T/N	
Martin Marietta (US) ALV	W/M	Darpa funded contract to develop an autonomous land rover as a test-bed for military uses of artificial intelligence, including on-board route planning, terrain analysis, driving aids, etc.
MBA International (US) Roboteer	T/EM	

Table B.1 (continued)

Manufacturer (country) Name of Device	Locomotion/ Primary mission[a]	Comment
Meidensha Electric Manufacturing (JA)		
Meirobo	T/NH	
DCR	W/H	
DIR	W/H	
Ministry of International Trade and Industry (JA)		
CDRV	T/N	
Mitsubishi-Kobe Shipyard (JA)		
CDRM mobile car	W/N	
C/V robot	WL/N	Legs and wheels, manipulators and cameras
Underwater robot	W/N	
Monitor Engineers Ltd. (GB)		
Hadrian	W/EM	
Morfax Ltd. (GB) (Naeco Associates)		
Wheelbarrow MK7	T/EM	Bomb disposal vehicle with video, manipulator, teleoperator controlled, cabled
Marauder	T/E	
Naval Surface Weapons Center (US)		
Robart-I		Test-bed for autonomous mobile sentry.
SCORPEE		Unmanned inspection vehicle used by marine engineers to obtain pictures of the sides of ship hulls
Normed Shipyards		
RM2		
RM3	L/M	Walking robot equipped with three legs and one arm, used to clean the hull of ships using abrasive tools

Table B.1 (continued)

Manufacturer (country) Name of Device	Locomotion/ Primary mission[a]	Comment
NTG Nukleartechnik (FRG)		
MF3	T/N	
Oak Ridge National Lab. (US)		
Herman	W/N	Remote controlled vehicle plus manipulator for emergencies
HERMIES	W/NH	Autonomous navigation and manipulation research
SRIP	W/E	Teleoperated dexterous manipulation
Ohio State University (US)		
Hexapod	L/M	Tethered, six-legged electric vehicle for land navigation
Odetics, Inc. (US)		
Odex-N	L/N	Six-legged walking machine (strength/weight ratio < 5). Can climb stairs, negotiate inclines up to 45°, and step over 30 in. obstacles
Pedsco-Canada (CN)		
RMI-1	W/E	Battery-operated, joystick controlled, with manipulator
Pentek Corp. (US)		
Moose	W/N	Remote scabbler for decontamination
Remote Technology (US)		
Surbot	W/N	Surveillance robot performs visual, audio, and radiation surveillance
Robot Systems International Ltd. (CN)		
Hazcat-M500	W/NH	Designed for safe transportation of hazardous materials
Hazcat-M100	W/NH	Autonomous perimeter patrol robot
Robot Defense Systems		
Prowler		Robotic vehicle for remote weapons firing; RF link to home base, video system, teleoperated
ROBAT	T/M	Remote Obstacle Breaching Assault Tank is designed to enter mine fields and deploy line charges to clear a safe passage. Teleoperated video signal transmission

Table B.1 (continued)

Manufacturer (country) Name of Device	Locomotion/ Primary mission[a]	Comment
Rockwell International (US)		
Worm	T/N	
SAS R&D Services Ltd. (GB)		
Hunter (1 arm)	WT/E	Radio and cable controlled, vision, manipulation
Hunter (2 arm)	WT/E	
Savannah River Lab. (US)		
Adapting Odex		Odex-I plus manipulation and vision system
Standard Manufacturing (US)		
MARS-V	W/MI	Six-wheeled cable powered, mobile base
Stanford Research Inst. (US)		
SHAKEY	W/MI	Application of logic-based problem-solving to a real world navigation task
Stanford University (US)		
Stanford Cart	W/MI	Mobile robot built for low-level perception and control
Subsea (US)		
Pioneer		Remote controlled submersible to detect leaks in oil pipelines and to bring to the surface samples of cement and metal
Sumitomo Electric Mfg. (JA)		
IRS	W/N	
Tokyo University (JA)		
Titan-III		Quadruped walking vehicle
Toshiba University (JA)		
Amooty (LCR-1)		Stair climbing intelligent maintenance robot

Table B.1 (continued)

Manufacturer (country) Name of Device	Locomotion/ Primary mission[a]	Comment
Twenty-First Century Robotics		
Sivan (IS)		
Wasp (TSR-700)	W/EM	
ISR-150	W/EM	
Hornet (TSR-70)	T/EM	Intended for civilian and military ordinance disposal
University of California (US)		Remotely-operated work vehicle to aid in the study of the sea floor
Rum-III		
U.S. Army		Light Helicopter Experimental Rotocraft Technology Integration – designed to automate a helicopter, permitting single-pilot flight
LHX-ARTI		
FMHR		Field Material Handling Robot to reduce the labor intensive functions of handling logistics material in the field
U.S. Navy (US)		
Rover	T/EM	
Firefox	W/F	
Vale Securities (GB)		British unmanned vehicle used for bomb disposal; can navigate to terrorist device and explode it using a shotgun
Scout		
Vermaat Technics (H)		Zero entry steam generator maintenance
Viking Energy Corp. (US)		Remotely operated and driven
Rod	W/N	

Table B.1 (continued)

Manufacturer (country) Name of Device	Locomotion/ Primary mission[a]	Comment
Westinghouse-Hanford (US) Sisi Louie	T/N	System in-service inspection for TMI. Monitor radiation levels
Westinghouse-Nuclear Rosa		Remote controlled tool positioning system for drilling, tube-plugging, and inspection

[a]T = tracked
W = wheeled
E = explosive ordinance disposal
N = nuclear
MI = miscellaneous
F = firefighting
L = legged
H = other hazardous

LIST OF ACRONYMS

AIMS	Advanced Integrated Maintenance System
ALARA	as low as reasonably achievable
ANL	Argonne National Laboratory
ASM	advanced servomanipulator
BNFP	Barnwell Nuclear Fuel Plant
CFRP	Consolidated Fuel Reprocessing Program
CRL	Central Research Laboratory, Division of Sargent Industries
DOE	Department of Energy
DOE-NE	Department of Energy-Nuclear Energy
DWPF	Defense Waste Processing Facility
EMM	electromechanical manipulator
FCF	Fuel Cycle Facility
FPR	Fuel Processing Restoration
FWMS	Federal Waste Management System
GA	General Atomic Technologies, Inc.
HEDL	Hanford Engineering Development Laboratory
HEF	Hot Experimental Facility
ICPP	Idaho Chemical Processing Plant
LWR	light-water reactor
MRS	Monitored Retrievable Storage Facility
MSM	mechanical master/slave manipulator
NFS	Nuclear Fuel Services
NWCF	New Waste Calcining Facility
OCRWM	Office of Civilian Radioactive Waste Management
ORNL	Oak Ridge National Laboratory
R/RH	robotics and remote handling
RAC	Robotics and Automation Council
ROMD	Remote Operations and Maintenance Demonstration
RSDF	Remote Systems Development Facility
SRP	Savannah River Plant
TOS	TeleOperator Systems
TRU	Transuranium Processing Facility
WCFW	Waste Calcining Facility

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