SPECIAL PRESENTATION

L. Jones, Chairman

The Advancement of Remote Systems Technology: Past Perspectives and Future Plans

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THE ADVANCEMENT OF REMOTE SYSTEMS TECHNOLOGY:

PAST PERSPECTIVES AND FUTURE PLANS*

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ABSTRACT

In the Consolidated Fuel Reprocessing Program at the Oak Ridge National Laboratory, a comprehensive remote systems development program has existed for the past five years. The new remote technology under development is expected to significantly improve remote operations by extending the range of admissible remote tasks and increasing remote work efficiency. The motivation and justification for the program are discussed by surveying the 40 years of remote operating experience which exists and considering the essential features of various old and new philosophies which have been, or are being, used in remote engineering. A future direction based upon the Remotex concept is explained, and recent progress in the development of an advanced servomanipulator-based maintenance concept is summarized to show that a new generation of remote systems capability is feasible through advanced technology.

INTRODUCTION

In the Consolidated Fuel Reprocessing Program (CFRP) at the Oak Ridge National Laboratory (ORNL), a comprehensive remote system technology development effort has existed for the past five years. This effort was established to respond to the requirements of advanced nuclear fuel reprocessing. The Remote Control Engineering and Special Remote Systems tasks are major CFRP development activities and represent a major commitment to the realization of a new generation of remote handling technology. This new technology is expected to significantly improve remote operations by extending the range of admissible remote tasks and increasing remote work efficiency.

This research is believed to represent the largest dedicated effort in the United States since the intensive program at Argonne National Laboratory in the 1950s and 1960s. The ORNL work encompasses a full range of activities from manipulators and television viewing through radiation-hardened electronics and remote tooling. The especially rapid advances of the 1970s and 1980s in the microelectronics and materials technologies provide the foundation for new remote systems. Although the ORNL work is driven by the special requirements of fuel reprocessing, most of the results are in fact generically applicable to remote operations in hazardous environments. The purpose of this paper is to discuss the ORNL advanced development program in regard to the history of remote technology, the basic philosophies that have been adopted, and its implications for future remote operations.

HISTORICAL REVIEW

The goal of the remote technologist has always been to supply effective manlike capabilities inside hostile environments. Accomplishing remote operations involves two basic elements, or perspectives. First, the capabilities of the remote handling system restrict the range of admissible work tasks. Handling capabilities also constitute a design constraint which the second element must accommodate. The second element is the conditioning or design provisions that are incorporated into the facilities and equipment to be operated. The synergism between these two elements is the essence of remote engineering.

Plants and Facilities

In the 40-year period that encompasses nuclear history, remote technology improvements have progressed along a discernible path, although there have also been times of sideward diversion. This is especially apparent when this history is viewed in terms of facilities and operations. Over the years, one can observe a wide range of facility concepts which represent large investments, display differences in

* Research sponsored by the office of Spent Fuel Management and Reprocessing Systems, U.S. Department of Energy, under contract No. W-7405-eng-26 with Union Carbide Corporation.

technical complexity, and reflect varying dependence on human radiation exposure.

Two classes of facilities evolved which are so different that they led to very different remote concepts. The Manhattan Project required that basic research and the construction of production facilities for weapons materials occur simultaneously. Hot laboratory systems were developed to support bench-scale research in radiochemistry, metallurgy, and other disciplined research. Larger facilities like the Idaho Chemical Processing Plant and the defense production plants (i.e., Purex) were designed to meet production requirements.

The hot laboratory problem led to remote concepts based upon small, dedicated work spaces (of the type researchers usually require). Memory and the stories of our colleagues tell of the first remote manipulators which were, in effect, "reach rods." Primitive beginnings with grocery tong devices initiated a progression of developments which had the goal of replicating, to the best of our mechanical and sometimes electrical engineering abilities, man's dexterity. Hot lab needs resulted in the ultimate development of two basic remote operations capabilities. Glove box systems were designed to provide low radiation containment while permitting direct human contact/manipulation through gloves. The other capability was the basic shielded hot cell with an approximate 3 m x 3 m x 3 m working volume. This basic building block was used to develop integrated facilities by connecting them in various schemes and intercell transfer systems. An entire class of remote handling and viewing equipment was developed to meet the needs of the "small" work space.[1] Over the years, an endless list of complex research has been successfully performed using the basic hot cell concept. Many consider the demonstrated dexterity and capabilities of remote hot cell techniques as a sound example for all remote systems.

The limited work volume of the basic hot cell module is economically and technically incompatible with the equipment scale-up normally associated with production. This incompatibility explains the early commitment to the canyon concept used in the defense production plants. White and Harvey[2] describe this general class of remote operations by reviewing the evolutionary history of nuclear processing facilities. Fig. 1, reproduced from their paper, clearly depicts the paths that have been followed in large-scale remote operations. Three basic plant forms have been built: (1) remote canyons, (2) remote cells, and (3) contact cells. The fully remote concepts attempt to minimize human radiation exposure through greater dependence on sophistication of handling equipment. This approach is essentially an extrapolation of the hot lab cell to larger working volumes. The contact cell philosophy embodied in the Idaho Chemical Processing Plant, the West Valley Nuclear Fuel Services Plant, and the main process cells of the Allied Gulf Nuclear Services (AGNS) Barnwell Plant is based upon the iterative use of decontamination and air-suit human entrance. The contact cell philosophy represents a conservative approach in terms of its dependence on remote handling equipment. The tacit assumption underlying this approach is that carefully designed and fabricated remote equipment will have low failure rates making contact repairs infrequent. It further assumes that radiological characteristics of the cell are predictable and controllable (e.g., contamination and particulate buildup). Some remote technologists consider the contact approach nonconservative because of its dependence on nondeterministic factors like failure characteristics.

Contact cells have been used principally to reduce capital cost and to reduce the complexity of remote equipment. Cost is reduced by eliminating expensive handling equipment and decreasing cell volume; complexity of the equipment is reduced since humans are more dexterous than manipulators. The best plant operating performance has been achieved with the supposedly more complex remote cell design approach.[2] In addition, the remote cell-type plants have, on the average, operated at lower occupational radiation exposure than the contact type. A very important difference between the two approaches is their inherent ability to accommodate unexpected or unplanned equipment failures which fall outside of the realm of the original design provisions. The Experimental Breeder Reactor (EBR-II) Fuel Cycle Facility and the Hot Fuel Examination Facility/North (HFEF/N) also incorporated remote maintainability into the remote handling equipment to improve overall plant availability. The authors agree with Harvey and White[2] in summarizing that the 30 years of remote operating plant experience clearly shows that the more successful facilities have been those based upon fully remote operations. When total plant life is considered, it appears that the increased capital cost of mechanized remote handling capability is justified and radiation exposure is minimized.

<u>Remote Handling Technology</u>

A discussion of remote operations from the perspective of remote handling equipment development is appropriate because many of the decisions made to use contact operations have been heavily influenced by judgments of the high complexity and likely unreliability of sophisticated electromechanical equipment (e.g., manipulators, cranes).

The initial work to remove man from radioactive exposure began with simple mechanical tong handling devices, periscopic devices, and shielding walls. Increasing radioactivity levels led to the ANL program[3] whose greatest achievement is generally recognized as the mechanical master/slave manipulator (MSM).[1] These devices, like the Model 8 shown in Fig. 2, are 7 degrees-of-freedom manipulators. The master and slave arms are mechanically coupled through a low friction and low inertia metal tape/pulley force transmission system which provides an incredibly useful dexterity and sense of feel. When used in concert with shielded window viewing, MSMs project the human operator's two most important senses - sight and feel - into the remote environment with a fidelity that allows him to perform a very

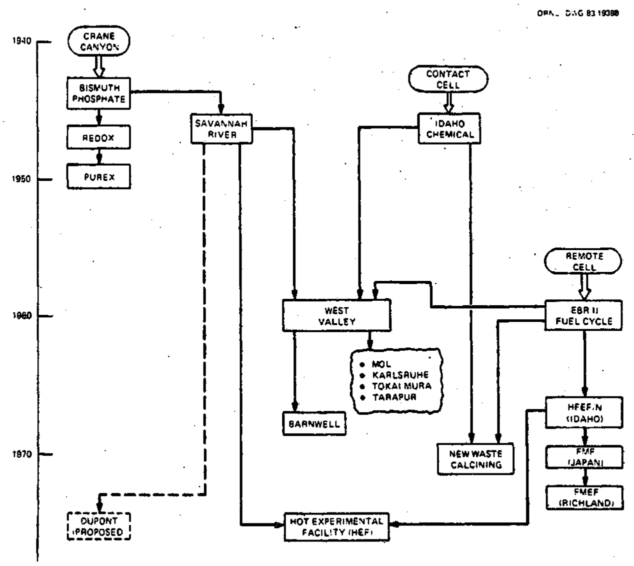

Fig. 1. Family tree of process plants.

large fraction of the tasks he is able to do directly with his hands.

Because of the mechanical tape coupling, the distance and configuration between the master and slave of an MSM is limited to the hot cell work environment topography. The defense production plants, from the outset, dealt with a larger engineering scale that

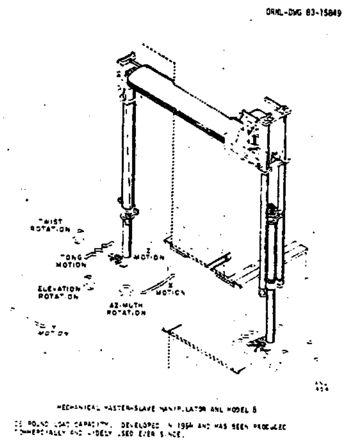

Fig. 2. Mechanical master-slave manipulator ANL Model 8.

dictated an entirely different approach.[4] 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 mounted on a crane hook. The crane hook is manipulated through the overhead bridge crane system piloted by an operator in a shielded cab. The flexible-cable handling mechanism requires that many special design provisions be incorporated into the facility and the equipment to be maintained. All equipment and components are designed for vertical access, and the canyon cells must have sufficient height for vertical clearance of 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, which is certainly noteworthy, represents a tribute to innovation and the inherent adaptability of teleoperation.

While the crane-impact wrench system was being developed for the canyon approach, the remote cell approach (refer to Fig. 1) fostered the development of more sophisticated electromechanical systems. These developments progressed through various steps intended to improve the limitations of flexible crane cables and culminated in the unilateral electromechanical manipulator (EMM), which has been marketed in various configurations ad capacities. EMMs are sometimes called power manipulators. Their designs emphasize mechanical simplicity and large load capacity.

Because of these criteria, EMMs operate at slow speeds (e.g., high gear ratios provide torque amplification) and do not provide force reflection (e.g., power transmissions are nonbackdriveable). EMMs typically have 6 to 8 degrees of freedom and, when mounted on overhead telescoping-tube transporters, provide a reasonably universal lift capacity in the range of 100 to 200 kg. The most recent version of EMM development is summarized by Vertut.[5] Although EMMs have been installed in remote operations all over the world with both success and failure, it is generally recognized that EMMs with the correct type of operator controls are an improvement over the crane-impact wrench approach. It is also generally recognized that EMMs are much more difficult to use than MSMs because of their slow operating speed and high load capacity. The large load capacity of EMMs is very difficult to reliably modulate without force reflection. The only feedback presented to the operator is visual such that his only perception of force interaction is by virtue of relative clearances and deflections. Since the operator cannot control the EMM load output, all process equipment must be designed to withstand the manipulator's full capacity, or risk being overloaded.

With the success of the MSM development, an ANL program was directed in 1954 toward the development of an electrical equivalent which could be used in larger work volumes. Electrical servomechanisms that could feasibly reproduce the force reflection quality achieved in the MSMs were developed and used in the Model E1 electric master/slave manipulator. This design was improved through several models to the Model E4. The Model E4 used ac servos and had a 25-kg capacity with force reflection and speed of operation comparable to MSMs. The Model E3 was used by the Italians as a basis for development of the MASCOT servomanipulator.[6] The E4 and other important development activities in television viewing came at a time when such designs were seriously stretching the limits of available electronic technology. Cabling systems requiring hundreds of conductors and state-of-the-art electronics were required. The application of such things in harsh radioactive environments was generally considered premature and did not attract much interest among facility designers.

In spite of limited applications, the development of electric master/slave manipulators continued through the tenacity of specific individuals. Jean Vertut was able to proceed with the development of the MA-22 and finally the MA-23,[7] which is now being applied in operating plants. Carl Flatau formed TeleOperator Systems Corporation and now markets the SM-229 servomanipulator,[8] which is used at ORNL in nonradioactive development work and at the Los Alamos Scientific Laboratory for particle accelerator remote maintenance. Kohler, et al., developed an interesting 8 degrees-of-freedom servomanipulator for use in hot cells and on emergency vehicles.[9] This class of manipulators is generally called servomanipulators. They are mechanically very similar to MSMs in that metal tapes or cables are used to transmit torque from the centralized motor actuators to the arm joints. Servomanipulators use dc permanent magnet servomotors which provide more favorable power density and dynamic response than the ac servos used in the ANL E-series. The MA-23 and SM-229 are shown in Figs. 3 and 4. Note that kinematically these manipulators are similar to MSMs (Fig. 2) although MSMs usually have a prismatic (sliding) lower arm joint to increase coverage. The elbow-above-the-wrist configuration derives from over-the-wall shielded window design requirements and fortuitously led to one of the most compact yet dexterous lower arm mechanical designs possible. The development reflected in the MA-23 and SM-229 was essentially completed in the early 1970s. Vertut has since studied other peripheral problems associated with the practical application of servomanipulators and has given particular emphasis to improving reliability and maintainability.[10] Servomanipulators are certainly a functional success in that they are able to reproduce MSM-type dexterity and performance in a system which can be interconnected with electrical wiring. It is fair to say that they have yet to be proven in actual applications of the magnitude of the Purex plants. They have been used successfully in accelerator maintenance, which involves a lesser contamination environment.[11]

The state of the art in advanced remote handling systems left some serious technical barriers in the way of practical application, especially in very harsh reprocessing-type applications. 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, the achievement of such performance with the equivalent resulted in a proportional increase in electrical complexity. The technology was at an early stage of development and because of suspect reliability it was not incorporated into ongoing facility designs. Consequently, until recently force-reflecting servomanipulators had not been considered for use in nuclear facilities as the principle handling tool. The major change in the availability of supporting technology has been the introduction and rapid progress of solid-state electronics.

PHILOSOPHY AND REMOTE ENGINEERING

The history of remote operations is confusing if one tries to place in chronological order the developments that have occurred and the lessons that have, or should have, been learned. The historical record as shown in Fig. 1 reflects the fact that the evidence available was subjectively interpreted, and variables of compromise and expediency played a large part in the decisions made.

General Discussion

The canyon-type defense plants and the ICPP, both developed about 30 years ago, are based on different concepts, yet these different remote philosophies are used throughout the world today. Let's discuss some of the underlying factors that may be involved. As

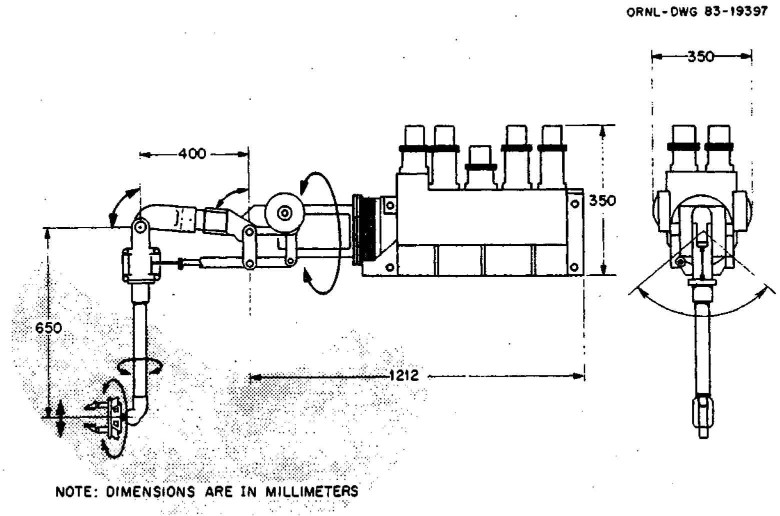

Fig. 3. Schematics of MA-23 bilateral servomanipulator.

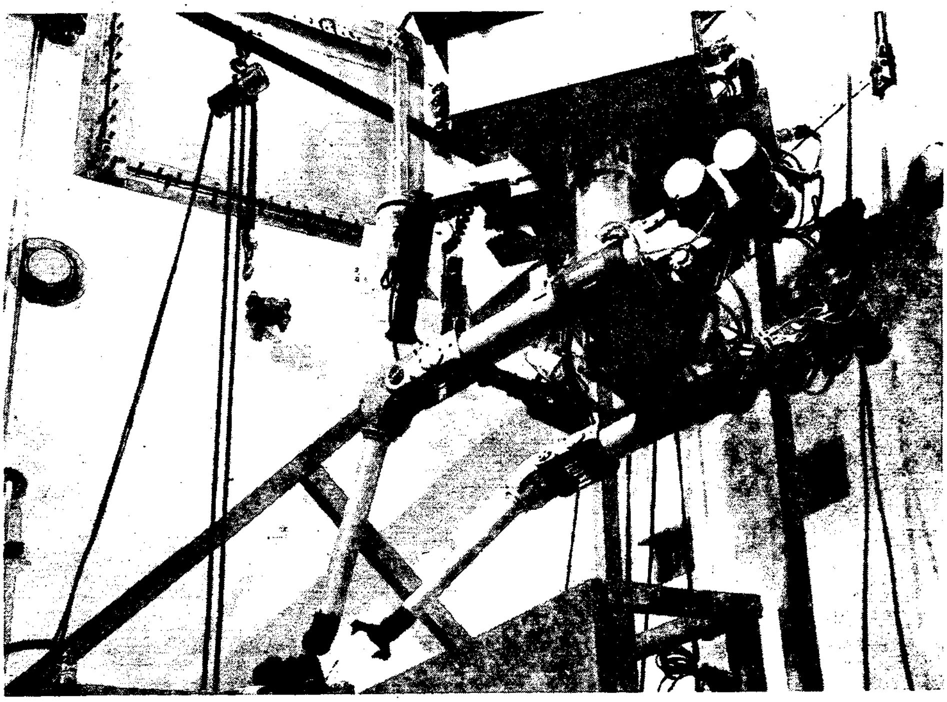

Fig. 4. Teleoperator systems SM-229 servomanipulator.

mentioned earlier, the Purex plants were designed for fully remote operations and maintenance under the most risky and adverse conditions one could envision. The decision to build a remotely repairable facility was an honest and insightful recognition of the probable difficulties to be encountered in a highly radioactive plant that was (1) based on new process technology, (2) being constructed at an incredible pace, and (3) of extreme national importance. The concept required the development of an entirely new technology. The remote handling development included the tooling concept, the shielded-cab operated crane, and the remote viewing system. In addition, basic elements for the remote replacement of process components required the development of the world's first remote fluid and electrical connectors, process component installation schemes, and so on. Recognizing that these plants represented an irrevocable commitment to these undeveloped concepts, one has to be awed by the foresight and "can do" perspective that decision-makers must have had. These men had certain positives in their favor also, such as extreme national priority and presumably unlimited funds.

The ICPP was designed in the late 1940s under the strong influence of the more conservative design practices used in the Oak Ridge Pilot Plant (Building 3019). This design approach was followed to minimize vulnerability to unknown, or unproven, technologies. The ICPP design addressed requirements involving smaller throughput, much more complex head-end processing, and higher radiation levels than the defense plants. The canyon approach was not considered because of the successful operating experience that had been obtained with the contact maintained Oak Ridge Pilot Plant. The essence of the contact approach is to use human entrance prudently to accomplish repairs. Prudence in this connotation essentially means providing facility and process equipment designs which constrain background radiation levels, facilitate decontamination, and provide human access. The ICPP designers apparently were confident (assuming that funding was not a limitation) in their ability to achieve these provisions and saw no reason to use canyon-type remote handling concepts.

Our 40-year history teaches us that the confidence/complexity trade-off should go in the direction of fully remote operations. The canyon and remote cell paths of Fig. 1 have been more successful operationally and environmentally than contact systems. The authors agree with this interpretation of history, but there are a great many options to be considered with respect to fully remote operations. A key trade-off exists between the sophistication of the remote handling system features versus the design provisions that must be incorporated into the equipment to be repaired and operated. This trade-off has been prevalent in all of the remote cell-type facilities and until recently has been constrained by the technical limitations of electromechanical handling systems.

In principle, it should be possible to reduce the number of special design provisions (e.g., cone-head fasteners, access constraints) as the handling equipment capabilities are improved. This simply implies that as the remote manipulators and other handling equipment approach manlike performance, remote operations become similar (in efficiency) to contact operations. In the past, the limitations of the remote handling equipment eroded the human operator's ability to perform useful work.

The trade-off between design provisions and handling sophistication is associated with several parameters that are difficult to evaluate quantitatively. The first is cost impact. The facility and equipment design provisions necessary to accommodate the constraints of a specific handling system concept are expensive and large in number. Also, sophisticated manipulator-based remote systems are costly. Clearly, the use of more dexterous handling systems increases the range of possible work tasks. This in turn increases the probability that the overall facility can operate successfully in the face of unexpected problems. In conflict with this gain, sophisticated handling equipment also inherently increases unreliability, which can degrade plant availability.

A second comparison can be made in the area of design trade-offs. A characteristic of cells designed to permit contact maintenance following rigorous decontamination is the use of intervening shielding walls. This segmentation of the working area provides the option of limiting the decontamination activity to the area immediately surrounding the required work space. The initial trade-off made in implementing the potential for contact maintenance is the cost. The intervening shield walls are costly, as are the transfer capabilities that must be included when barriers are used. In addition, the barriers require duplication of remote handling equipment.

For operations that involve low contamination factors, the segmented cell design is probably preferred. For those operations such as reprocessing, high-level waste handling, and destructive analysis of fuel, a design that allows for both in situ remote repair and an avenue for remote removal, decontamination, and the potential for contact maintenance is probably the most efficient.

A second significant design trade-off - that of the use of television viewing - requires further discussion. As a companion development to the MSM, the high-density glass window was developed for remote viewing. A window and a pair of MSMs became a standard design attribute. Even in these designs, some consideration was being given to the television camera as a secondary viewing mechanism. With the consideration of large-volume operations, adequate viewing over the volume covered by the manipulation system is a major design problem. Shielded windows (at approximately $2 per cubic inch of window) that adequately cover the work volume are questionable economically and also provide a relatively limited field of view. The high initial capital cost of windows for applications requiring, at best, infrequent use provided impetus to utilize the inherent flexibility and mobility of the television camera.

Television viewing introduces important development considerations. The radiation resistance of television electronics, the transmission of signals, and the inherent problems of two-dimensional viewing must be considered in concepts replacing windows. No perfect solution exists, but the optimum decision favors the use of the television camera as the viewing mechanism.

It is within the bounds of these issues that the facilities of the future are being considered. Many of the supporting technologies that are fundamental to remote handling systems have expanded at literally explosive rates in the past ten years. Future approaches to remote operations depend on the same judgment issue that has governed decisions in the past. How much confidence should be placed in the increased technical complexity that is required to obtain the additional merits?

Remotex

In 1980, Feldman and White[12] proposed that it was time to improve remote operations in nuclear fuel reprocessing through the use of force-reflecting servomanipulators. This design approach has been called "Remotex" and essentially involves the replacement of EMMs with servomanipulators and a greater reliance on closed-circuit television to accomplish remote viewing. These changes are expected to improve plant availability by reducing the time required to accomplish process repairs. The increased handling capabilities are also expected to substantially enhance recovery from unplanned events. Finally, the servomanipulator-based approach provides many of the basic features that will be required for ultimate facility decommissioning, which is now considered an integral part of the design. The Remotex concept is designed to minimize contact maintenance by seeking a mechanized replacement for man in the radioactive environment. As shown in Fig. 5, humanly compatible speed of operation and sense of feel are very important in teleoperated-manipulator time efficiency.

The Remotex concept is expected to significantly improve the volumetric utilization of hot cell space by allowing MSM-level work task performance throughout canyon-sized cells. This introduces the additional challenge of large-scale mobility in a work environment, which is for the most part within the realm of existing transporter technology. Remotex should substantially increase the adaptability of future remote operations by providing manlike handling capabilities. This, as discussed in Ref. 12, will require the development and refinement of new technologies that have not yet been used in harsh radiation environments. In the next section, the future is discussed within the framework of the extensive development activities which exist at ORNL and are intended to make Remotex a reality.

THE FUTURE

Recent advances in microelectronics, materials, and manufacturing techniques provide the basic ingredients essential for the successful development of the Remotex concept. These new technologies will facilitate the needed advances in remote handling systems. Many major technical hurdles remain, but it is difficult to imagine that they are any larger than those faced in remote development for the defense plants.

For about the last five years, advanced remote systems technology has been one of the largest development activities in the Department of Energy (DOE) CFRP at ORNL. Significant progress has been achieved, especially in the last two years, and early results continue to provide encouragement that Remotex is realistic. In the remainder of this section, the scope and near-term plans for the ORNL work will be summarized. Recent progress in specific areas is highlighted.

Plans for the Next Generation

Remotex constitutes a next generation of remote systems technology built around the force-reflecting bilateral servomanipulator. Fundamental goals have been established to ensure that the requirements necessary for the Remotex concept are achieved. These goals relate to basic manipulator performance, reliability, and the general application of modern technology. As discussed earlier, good force reflection, similar to that achieved in MSMs, is essential for efficient teleoperation. Consequently, the performance of servomanipulators must approach (and hopefully exceed) that of MSMs while not restricting the distance between the master and slave arms. The next manipulators must not only provide improved performance, but must also be substantially more reliable than tape or cable-driven designs. MSMs generally exhibit mean time between failures (MTBFs) of 200 to 500 h. To obtain the plant operating efficiencies desired in the future, it is estimated that remote handling system components (e.g., manipulators) should have MTBFs in the range of thousands of hours. Finally, it is expected that the general application of modern technology, especially computers, will enhance work efficiency. Computer supervision for obstacle avoidance, operator control augmentation (i.e., assistance in tool alignment and control), and the judicious use of automation (i.e., robotic tool changing) are examples.

The scope of the development activities can be viewed effectively in terms of functional breakdown of the remote maintenance system concept. The system has been subdivided into the following seven subsystems:

1. Manipulator Subsystem - An entirely new type of remotely maintainable advanced servomanipulator (ASM) is being developed.

CONVENTIONAL MANIPULATOR - MAINTENANCE SYSTEMS

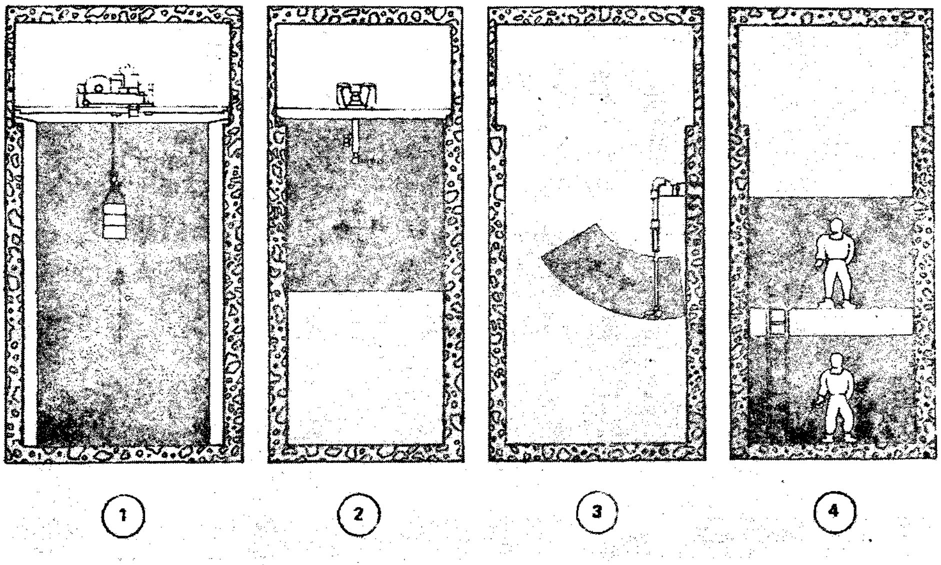

Fig. 5. Time efficiency for remote maintenance systems.

o Mechanical Design - Emphasis is placed upon back driveability and modularity using gear/torque tube power transmission. Refer to Ref. 13 for more detail.

o Control System Design - State-of-the-art distributed digital control concepts are used. The microprocessor-based systems facilitate many advanced features, such as advanced nonlinear servocontrol algorithms, robotic slave operation, on-line self-diagnosis, and automatic camera tracking.

o Position - Position bilateral servoloops are used to produce force reflection. See Ref. 14.

2. Remote Television Subsystem - Color, black and white normal resolution, high resolution, and 3-D projection systems, along with camera pointing and lighting placement, have been and are being investigated. The performance criteria include ease and speed with which operators can accomplish work tasks.

3. Control Station Subsystem (Man-Machine Interface) - This is a valuable innovation in manipulator system development. The application of the concepts and principles of ergonomics to the design of the master control station and the accomplishment of telepresence at the remote work place are fundamental. See Refs. 15 and 16 for more detail.

4. Transporter Subsystem - This is the mobility system for the manipulator-based work unit. Free-roving, floor-mounted, and suspended transfer systems have been studied. Current development is focusing on rigid and highly reliable overhead telescoping systems.

5. Signal Transmission Subsystem - State-of-the-art electronic systems are signal multiplexing techniques to dramatically reduce cable handling and shielding penetration requirements. Line-of-sight optical, free-space radio frequency, and confined radio frequency techniques have been studied. A digital laser optical system and a noncontact bus bar concept based upon an RF slotted transmission line configuration have been implemented.

6. Power Transmission Subsystem - Conventional solutions have been bus bars, festooned cables, and cable tracks. Onboard power sources have been applied, and a hybrid battery - self-connecting hardware system has been studied. Noncontact inductive coupling for power transmission has been studied elsewhere and has limited potential applications.

7. Machine-Manipulator Interface - The equipment designed for remote operation is in part designed to be compatible with the manipulator capabilities and dexterity which are available. Flexibility and adaptability between the equipment to be maintained and the manipulator system is provided (in part) through the tooling designed for the maintenance operations.

The tooling requires a significant design effort to ensure that it is compatible with the maintenance requirements of the machine and that it also profitably uses the attributes of the manipulator system.

A unique feature of this development program is the balanced attention given to each of the elements of the overall system. Fig. 6 schematically depicts an overall integrated

shown in Fig. 8, incorporates a dual set of TOS SM-229 servomanipulators which are on loan to ORNL-CFRP from the Princeton Plasma Physics Laboratory. The facility has been used to evaluate signal transmission using a slotted transmission line-coupler, computerized obstacle avoidance, automatic TV camera tracking,[17] and limited robotic slave functions. The RSDF has also been used extensively in human factors evaluation of camera-viewing

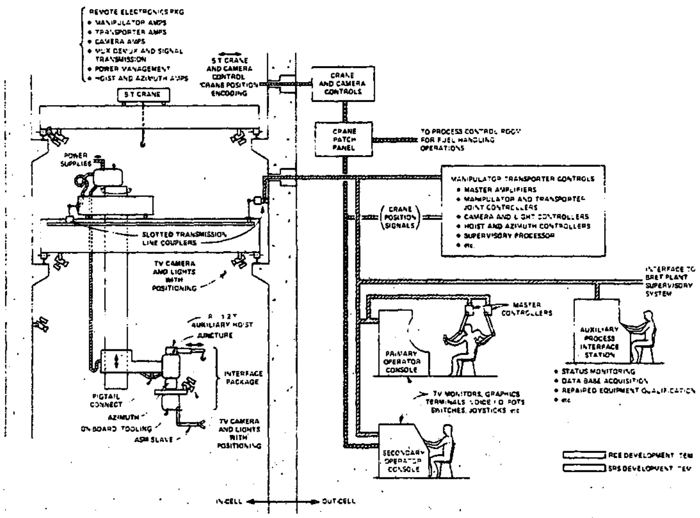

Fig. 6. Breeder Reprocessing Engineering Test maintenance system schematic.

maintenance system arrangement which is being considered in the current Breeder Reprocessing Engineering Test (BRET) project. One should note the incorporation of in-cell electronics to basically reduce cable-handling problems.[14] Specific development activities are addressing electronics radiation hardening and protection. Near-term plans for this development work are shown in Fig. 7. This schedule is based upon requirements of the BRET project which demand extensive development in this fiscal year and early FY 1985 such that an integrated system is completed by the end of FY 1985. Two advanced servomanipulator slave arms were built at ORNL and are currently in initial testing. Prototype units of the ASM have been built to gain experience necessary to accomplish the ultimate BRET procurement. A major effort will be mounted to establish viable commercial sources for the necessary subsystems.

Recent Progress

Important results have been accomplished which fortify the belief that the advantages of servomanipulator-based maintenance are real and can be developed for use in very large hot cells. The Remote Systems Development Facility (RSDF) has been used to evaluate a number of underlying equipment and software concepts, as well as human factors experimentation. The RSDF,

issues. An important off-shoot of these experiments was a systematic quantification of the time efficiency of servomanipulator-based operation with TV viewing.[18] As shown in Table 1, the RSDF system achieved a time

TABLE I.

Relative time ratios for manipulator use based on task characteristics and experienced and inexperienced operators

Task Characteristics	Operator Relative Time Ratios Experienced	Inexperienced
Pure manipulator tasks	8.3	12
<90% manipulator use*	13.0	27
<70% manipulator use*	23.0	39

* These involve increasing use of the overhead transporter and other auxiliary equipment

ratio of 8.3:1 for a predominantly manipulator task. This compares amazingly well with 8:1 usually recognized for MSMs with shielded-window viewing. This result verifies (in at

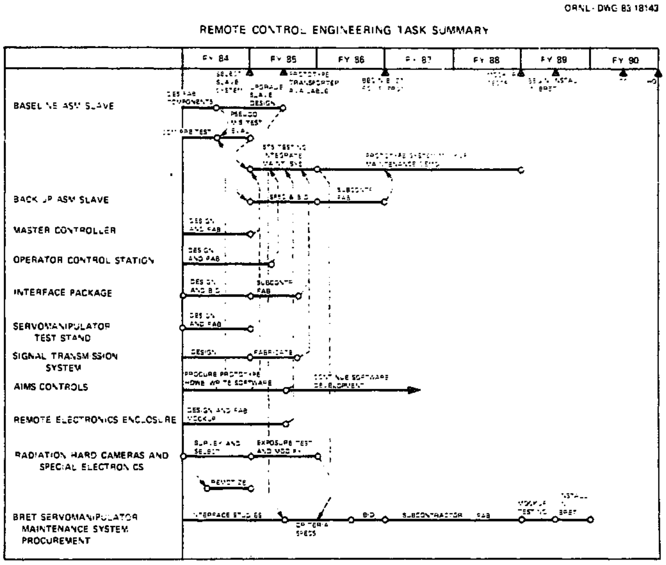

Fig. 7. Remote Control Engineering Task summary.

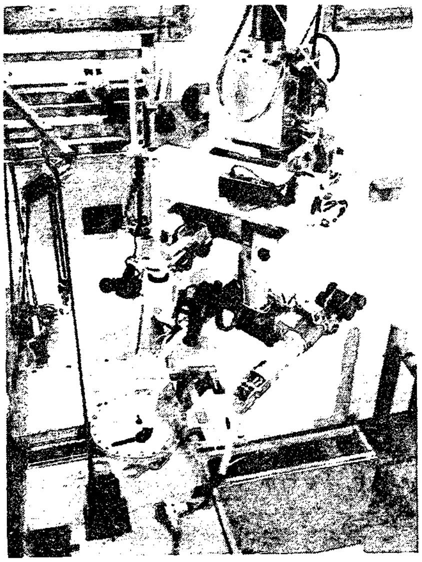

Fig. 8. RSDF: In-cell remote handling/viewing system.

least one case) that servomanipulator performance can match hot lab MSM performance.

The procurement of the Central Research Laboratories (CRL) Model M2 Maintenance System was another very important activity. The M2 has been installed in the CFRP Remote Operations and Maintenance Demonstration Facility (ROMD) where it has been evaluated and used in full-scale mockup testing (see Fig. 9). The M2 was a joint development between CRL and ORNL in which ORNL developed the all-digital control electronics system. The M2 is the first successful demonstration of an all-digital bilateral servomanipulator. The digital controls[19] have significantly improved operating training through the menu-driven touch-screen control interface and have permitted the M2 to be "tuned" to provide friction and force-reflection properties exceeding typical MSMs even though its peak capacity is 45 kg per arm. The overall M2 system is described in Ref. 20.

The remotely maintainable advanced servomanipulator (ASM) is the most technically challenging, yet critical, development activity being pursued. The ASM design[13] is based on the use of gears and torque tubes to replace metal tapes in the drive train. The geared approach facilitates modularity so that the slave arms can be repaired in situ by other ASMs via spare module replacement. The geared approach also increases reliability, but at the expense of increased inertia, friction, and backlash, all of which tend to degrade teleoperation. The first units of the ASM are in fabrication, and the isometric given in Fig. 10 shows how the arm will be modularized. A test stand that simulates the wrist roll axis of the ASM has been used in basic studies of motor characteristics, of gearing nonlinearities, and for control algorithm development. At this time, we remain optimistic that the overall performance of the ASM can be near MSMs in spite of the gear train effects. A new control system architecture based on the Motorola MC68000 16-bit microprocessor has been developed to provide an improved update to the M2 design.[14] The new control system capabilities and an

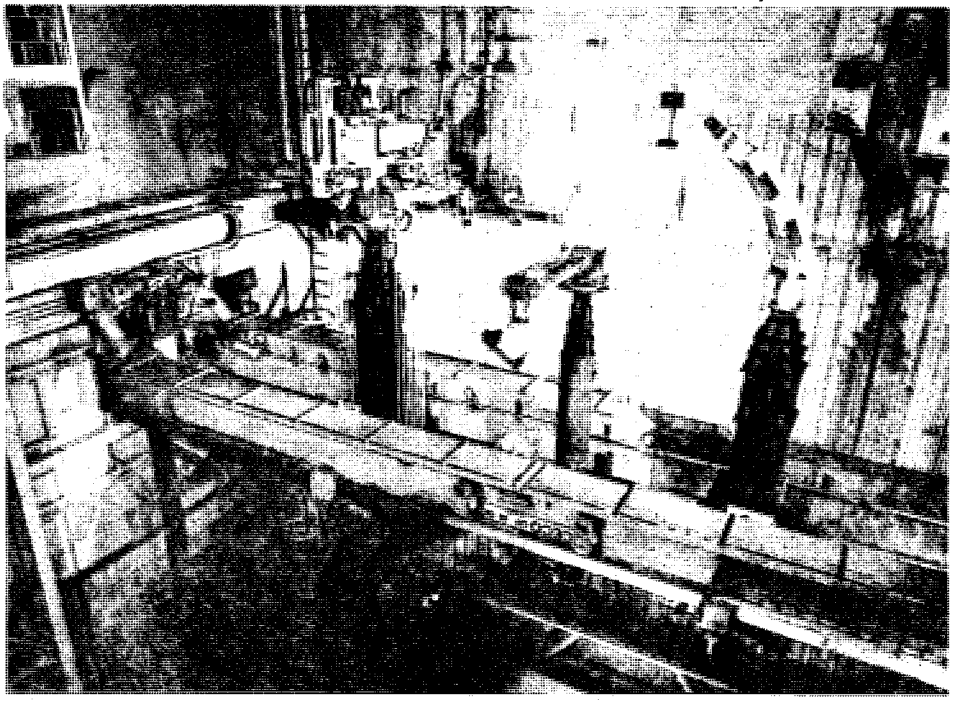

Fig. 9. M2 maintenance system.

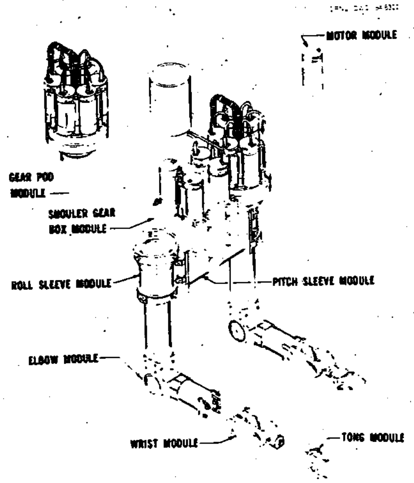

Fig. 10. Advance servomanipulator modularization.

optimized (having minimum inertia) master controller design[16] (being developed by the Jet Propulsion Laboratory for ORNL) will provide important performance gains which are expected to offset the deleterious gearing effects. Work has begun on the advanced integrated operator station,[15] which incorporates ergonomically designed colorgraphics displays and standard remote TV viewing monitors.

SUMMARY

History shows that the design trade-offs associated with remote operations involve as much judgment as rationality. The record for nearly 30 years of operation shows that fully remote designs cost more initially, but in the long run pay off in terms of facility operating efficiency and radiation exposure. The Remotex concept is a recognition of this observation coupled with the goal of applying new technology to remote systems. A major development program has been established in the CFRP at ORNL to accomplish this very thing. Five years of advanced development effort and early results fortify the belief that this is the proper approach for a new generation of remote technology that is practical and achievable.

REFERENCES

1. R. GOERTZ, "Manipulator Systems Development at ANL," *Proc. 12th Conf. Remote Syst. Technol.*, 12 (1964), pp. 117-36.

2. J. R. WHITE and H. W. HARVEY, "The Evolution of Maintenance in Nuclear Processing Facilities," *ANS Winter Meeting*, Washington, D.C., November 1982.

3. R. GOERTZ, "Some Work on Manipulator Systems at ANL, Past, Present, and a Look at the Future," *Proc. of the 1964 Seminars on Remotely Operated Special Equipment*, Germantown, Maryland, May 1964, Vol. 1, pp. 27-69.

4. J. M. McKIBBEN et al., "The Savannah River Purex Plant - 25 Years of Successful Remote Operation," *Proc. of 27th Conf. Remote Syst. Technol.* (1979), pp. 173-77.

5. J. VERTUT, "New Types of Heavy Manipulators," *10th Hot Lab Proceedings*, ANS, Nov. 1962, pp. 185-94.

6. S. BARABASCHI et al., "An Electronically Controlled Servomanipulator," *Proc. of 9th Conf. Remote Syst. Technol.* (1961).

7. J. VERTUT et al., "The MA-23 Bilateral Servomanipulator System," *Proc. of 24th Conf. Remote Syst. Technol.* (1976).

8. C. FLATAU, "SM-229 - A New Compact Servo Master-Slave Manipulator," *Proc. of 25th Conf. Remote Syst. Technol.* (1977).

9. G. KOHLER et al., "Manipulator Vehicles of the Nuclear Emergency Brigade in the Federal Republic of Germany," *Proc. of the 24th Conf. Remote Syst. Technol.* (1976).

10. J. VERTUT et al., "Protection, Transfer, and Maintenance of the MA-23 Bilateral Servomanipulator," *Proc. of the 26th Conf. Remote Syst. Technol.* (1978).

11. D. L. GRISHAM et al., "Monitors 1980: Now There are Two," *Proc. of the 28th Conf. Remote Syst. Technol.* (1980).

12. M. J. FELDMAN and J. R. WHITE, "Remotex - A New Concept for Efficient Remote Operations and Maintenance in Nuclear Fuel Reprocessing," *ANS National Topical Meeting on Fuel Cycles For The '80s*, Gatlinburg, Tenn., October 1980.

13. D. KUBAN and H. MARTIN, "An Advanced Remotely Maintainable Servomanipulator Concept," ANS Topical Meeting on Robotics and Remote Handling in Hazardous Environments, Gatlinburg, Tenn., April 1984.

14. H. L. MARTIN et al., "Control and Electronic Subsystems for the Advanced Servomanipulator," ANS Topical Meeting on Robotics and Remote Handling in Hazardous Environments, Gatlinburg, Tenn, April 1984.

15. M. M. CLARKE and J. KRIEFELDT, "Elements of an Advanced Integrated Operator Control Station," ANS Topical Meeting on Robotics and Remote Handling in Hazardous Environments, Gatlinburg, Tenn., April 1984.

16. D. P. KUBAN and G. S. PERKINS, "Dual Arm Master Controller Concept," ANS Topical Meeting on Robotics and Remote Handling in Hazardous Environments, Gatlinburg, Tenn., April 1984.

17. R. S. STOUGHTON, "Automatic Camera Tracking for Remote Manipulators," ANS Topical Meeting on Robotics and Remote Handling in Hazardous Environments, Gatlinburg, Tenn., April 1984.

18. M. M. CLARKE et al., "Human Factors in Remote Control Engineering Development Activities," *Proc. of 31st Conf. Remote Syst. Technol.*, Vol. 1, Summer 1983, Detroit, Mich. (in press).

19. P. E. SATTERLEE et al., "Control Software Architecture and Operating Modes of the Model M2 Maintenance System," ANS Topical Meeting on Robotics and Remote Handling in Hazardous Environments, Gatlinburg, Tenn., April 1984.

20. J. N. HERNDON et al., "The State-of-the-Art Model M-2 Maintenance System," ANS Topical Meeting on Robotics and Remote Handling in Hazardous Environments, Gatlinburg, Tenn., April 1984.