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Consolidated Fuel Reprocessing Program

DESIGN CONCEPTS AND ADVANCED MANIPULATOR DEVELOPMENT FOR NUCLEAR FUEL CYCLE FACILITIES

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ABSTRACT

In the Fuel Recycle Division, Consolidated Fuel Reprocessing Program at the Oak Ridge National Laboratory, a comprehensive remote systems development program has existed for the past seven years. The new remote technology under development is expected to significantly improve remote operations by extending the range of tasks accomplished by remote means and increasing the efficiency of remote work undertaken. The application of advanced manipulation is viewed as an essential part of a series of design directions whose sum describes a somewhat unique blend of old and new technology. A design direction based upon the Teletec 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 is feasible through advanced technology.

INTRODUCTION

The emphasis of this paper is the history and development of the bilateral force-reflecting manipulator. The force-reflecting manipulator, successfully applied to a nuclear fuel cycle facility or to any other manipulator environment, is a subsystem of a larger design undertaking. The manipulator technology utilized in a design will affect the design of the facility and will affect the design of the equipment in that facility. For these reasons, it is initially valid to view manipulator development within the context of a broader design effort.

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The effective interplay in the design process of the technical scenario, the equipment to fulfill the technical scenario, and the facility to house the equipment, are an iterative process in the promulgation of an effective design concept. We chose to place the manipulator as a part of the facility design in considering this trilogy of factors shown in Fig. 1. In applications where the technical scenario, the equipment, and the facility or area of operation already exist or are defined, additional emphasis is placed on the attributes and capabilities of the manipulator chosen. The most successful designs result from an equal consideration of these factors.

Five areas that are primary in the Consolidated Fuel Reprocessing Program's (CFRP's) consideration of the design of a facility for remote production work are

1. the single-cell concept,
2. low-flow ventilation concept,
3. television viewing,
4. equipment mounting racks, and
5. force-reflecting manipulation.

The Single-Cell Concept

What is really represented in the single-cell concept is a significant decision by the designers and by the eventual operators of the facility regarding the maintenance philosophy to be practiced in the operation of the facility. The core issue in arriving at a maintenance philosophy is the definition of an acceptable radiation exposure for operating personnel. That core issue is represented by a determination of those pieces or areas of equipment that are to be remotely maintained and those that are to be maintained by direct contact. An early and popular design concept for reprocessing used a series of smaller hot cells, each separated by a shielding wall and each housing a specific piece of the process. This design provided a capability to decontaminate a malfunctioning segment of the process and to introduce personnel for maintenance purposes. It had a design disadvantage of requiring duplication of overhead equipment such as cranes and electromechanical manipulators, but the major disadvantage occurred in operation. While the concept of decontamination and contact maintenance is a valid one, the actual operation of the concept has often been flawed. The time required to decontaminate to a level to ensure minimal or reasonable exposure of the maintenance personnel is in direct conflict with the urgency to complete the repair and resume operation. This conflict has more often than not resulted in radiation exposure levels that exceed planned levels. For these reasons, we have contended that one of the major design criteria must be a well-defined and rigorously followed design personnel exposure level, and then one must design the maintenance activities to meet those exposure levels.

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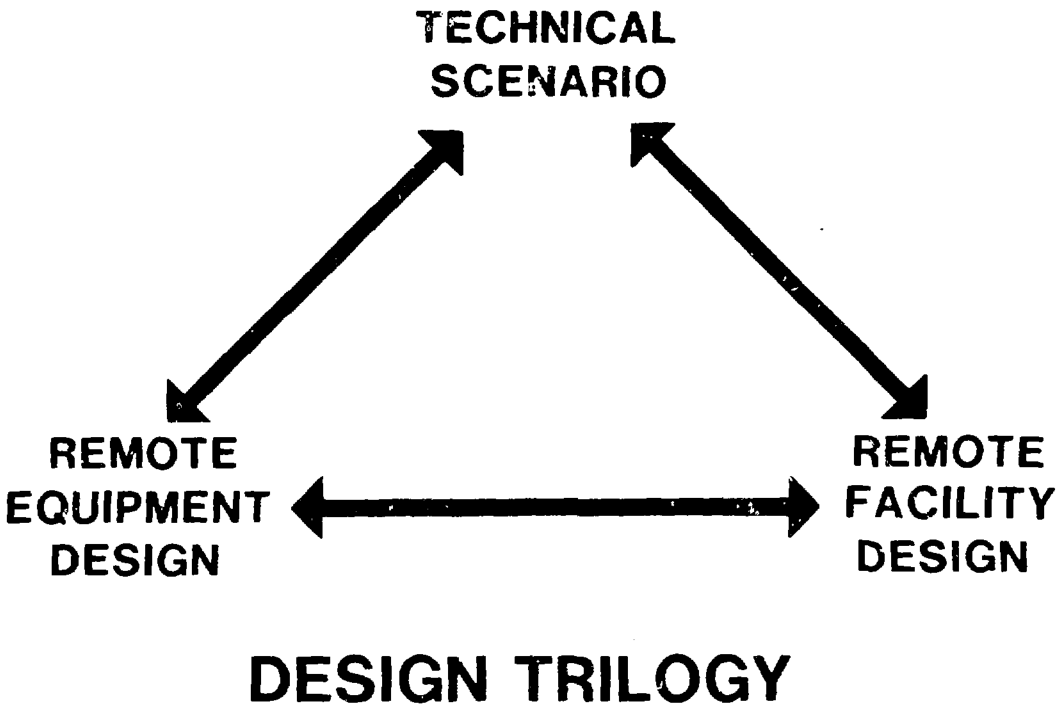

Fig. 1. Trilogy

The requested maintenance is a normal plant activity and must be considered in the design--it is not an abnormal activity.

In our designs, we have tended to push the contact-maintained equipment boundary to cover a relatively small amount of equipment, and this decision reflects the violation of exposure limits we have observed over the years. The exact position of the boundary between contact maintenance and remote maintenance must reflect the management's true position of acceptable personnel exposure.

Low-Flow Ventilation

The concept of a low-flow ventilation system is an evolution of a design concept that favors concentration over dilution. The low-flow ventilation scheme provides for processing of off-gas streams from the head-end equipment, dissolver, and process vessels at minimum concentrated volumes and provides a basis for designing cleanup systems of reasonable size with high decontamination factors.

Construction details for this type of facility design are well known.[1,2] Cells lined with stainless steel are justified for not only their contribution to leak tightness, but also for their contribution to ease of decontamination, and at a later stage, to decontamination and decommissioning. The thick shielding walls required because of the inherent radiation levels associated with fuel reprocessing may themselves provide adequate leak tightness for this purpose. The degree of leak tightness required has an effect on the facility design. In the Argonne National Laboratory-West Facilities, where the operating criteria required control of oxygen and moisture to the 10- to 50-ppm level, the design of all penetrations was carefully controlled. All penetrations were doubly sealed with an inert gas purge between seals to guarantee low inflow of moisture and oxygen. In present designs where oxygen levels of 2 to 4% or higher are controlling criteria, single penetration seals without a gas purge appear adequate. A major factor in low-flow design is the requirement for a double-ended transfer lock large enough to handle any piece of equipment that may require exchange or maintenance. Equipment can be modularized (segmented) to reduce the required lock size. In addition, design care must be exercised to ensure that the required transfers through the lock to and from the production activity do not constitute a restriction to the operational efficiency of the process.

We believe that the low-flow ventilation concept provides a mechanism and a capability in meeting today's gaseous effluent criteria and, in addition, has an inherent capability to be expanded to accommodate changes in the regulations that may be imposed in the future.

Television

The utilization of television as the primary viewing medium has taken a relatively long time to become established in remote control technology. In windowed facilities, television is used to provide viewing in areas where in-line viewing is blocked or is difficult. In windowless facilities, it is beginning to replace the periscope viewing used in the past.

For large volume installations being concepted or in design, the trade-off studies between television viewing and adequate window coverage are indicating an economic preference for television viewing. Development work still needs to be accomplished to make the use of television in high-radiation fields a working reality. The work to date in a number of countries indicates that a serious effort is under way to establish the choices, trade-offs, and optimizations so that a reliable television viewing system can be incorporated into reprocessing facilities or into other high-radiation-field operations.

The work to date has been pursued in two distinct avenues. The first has been the utilization of relatively standard video cameras in what would be considered a throwaway mode. Minimum electronic modification and the use of nonbrowning lenses are options that are part of the throwaway decision. The costs for this mode are initially relatively low and the application successful if applied correctly.

The second avenue is one in which developing technology or the innovative utilization of existing technology modified for use in high-radiation fields is applied to television viewing. We know that certain classes of electronic components have higher radiation life expectancies and that circuit designs can reflect this advantage. We are also aware that electronic components within the circuit design can be selected so that higher radiation exposure levels can be successfully reached. We know that separation and shielding of some of the electronics of a video camera can be achieved, and we are aware that fiber optics can be used to transmit an image to a shielded video camera. Within this broad range of feasible technical avenues lies a series of solutions to the use of television in remote facilities. The options are being evaluated in a number of countries, and the progress to date indicates that solutions will be available that provide acceptable operation at total exposures between 10^8 and 10^9 R.

The use of television to provide viewing for manipulation has additional attributes that we have evaluated experimentally. For detailed viewing, our experimental evidence indicates[3] that the operator efficiency is about equal when color and black and white screens are compared. We are also conducting experiments with high-resolution television systems having about five times the pixel density of commercial U.S. systems, and we continue to test stereo television for both efficiency and continuous operator compatibility.

Equipment Racks

The use of racks for housing a multitude of equipment types and configurations, particularly in the chemical processing areas, offers a series of advantages to both the designer and the operator. Paramount to the design approach in using the rack as the common structure for housing equipment is the availability of a four-sided approach for maintenance activities. Equipment designs that have four sides accessible for maintenance ease some of the restrictions imposed on equipment design.

For fuel reprocessing facilities, the availability of racks with a standard height and of a repeatable configuration provided a simplification in the placement of penetrations and an efficiency in the design of interrack piping.[4] It also provided an envelope used in sizing the entry and exit locks and was a base on which a robotic sample bottle collection system could be designed.

Of major importance to our design philosophy is that the rack is fundamental to our three-tiered maintenance approach. The first tier provides for the option to move the entire rack to an internal maintenance area or to decontaminate the total unit and service the rack by direct human contact. The second tier exercises an option to remove major pieces of equipment from the rack for transfer to a hot repair area or to decontaminate the removed unit to a controlled level and use contact means for maintenance. The first two tiers also provide a path for volume reduction and disposal as contaminated waste for equipment that is not repairable.

The third tier [and the tier that is innovated in the Teletec (Remotex) design concept][5] is the repair in place of defective equipment, in situ maintenance. There is no simple statement that can be made about the number of components that will require maintenance in an identifiable equipment item or the number of maintainable items on a total equipment rack.

A leaking tank, which may be the sole item on a rack, is a single-component system; a tank with removable cooling coils is a two- or more-component system. A centrifugal contactor has two major components--the motor and rotor--but a bank of contactors as we are currently designing units may come in banks of 8 or 16, and with the necessary valves, off-gas lines and instrumentation, can be treated as a 20- to 40-component system. A vitrification furnace, whether housed on a rack with other equipment or as the sole piece of equipment on a rack, has in various designs a high number of maintainable components.

The third tier of maintenance capabilities recognizes that in a multicomponent system, it is only one of the components whose failure will shut down that machine. The higher the number of components on a rack, the more valuable to the plant operating efficiency is the capability to make in situ repairs. The analysis of the value of in situ repair must include each maintainable component of a piece of equipment, the instrumentation that controls the equipment, and the auxiliaries, such as pumps and valves, that support the equipment.

Let us extend the concept of in situ maintenance to an additional area that experience has indicated to be of vital importance in operating remote facilities. The area is that of unplanned events.

In normal practice, we design into either the piece of equipment or into the manipulator system the capability to respond to malfunctions. We carefully outline a maintenance or replacement path for those items our design analysis indicates will require response. Experience has shown that no matter how detailed the failure analysis is, the actual operating experience will produce events that have not been planned. The availability of manipulation that closely parallels human capabilities is of major importance in responding to these unplanned events.

Our designers design equipment based on manned maintenance. There is no other model--except man--for them to follow. The force-reflecting servomanipulator and its capability to execute operations with a manlike sense of feel provides an insurance policy to the continuing operation of a remote process under nearly all circumstances.

Typical racks for use in the design of a nuclear reprocessing facility are shown in Figs. 2 and 3.

Bilateral Force-Reflecting Servomanipulators

If one were to summarize the historical progress in remote technology, that histograph can be represented by Fig. 4. An early period that preceded significant development activities is followed by an era which includes the work done by Goertz and his co-workers at Argonne National Laboratory. The Argonne work was followed by a significant period in which the concepts developed during the 1950s were applied and refined. A detailed accounting of the history and development in remote technology is described in an earlier paper.[6]

The work at the CFRP at Oak Ridge National Laboratory (ORNL) was begun by dividing the development effort into seven subsystems as shown in Fig. 5. The work had as its starting point five fairly similar force-reflecting servomanipulator systems that existed in the late 1970s. Three of these were foreign developments. The Italian Mascot was developed in the 1960s, and in a modified form is the basic tool planned for use in maintenance of the Joint European Torus (JET) Fusion Project.[7] The Germans under Köhler[8] at Karlsruhe have a working servomanipulator that was developed about the same time. The most advanced European program has been in France where the work under the late Jean Vertut has produced the MA-22 and MA-23 servomanipulators.[9] In the United States, two independent developments occurred. Carl Flatau at Brookhaven National Laboratory developed the Brookhaven arm, a forerunner of the TOS SM-229, and he later set up an independent company to market manipulators. Central Research Laboratories (CRL), who produced, marketed, and elaborated on the basic mechanical master-slave developed by Ray Goertz at Argonne National Laboratory, also marketed a servomanipulator tailored after a series of Argonne electric master-slave development arms, E1, E2, and E3, that were produced by Goertz. The set of arms currently available from CRL, descended from the E4A, is designated as Model M-2.[10,11] All of these arms, while successful in a mechanical sense, had continuing control circuit problems. It is important to note that the recent explosion in electronic development had not yet occurred when these five units were developed.

Our recent development activities at ORNL in the area of servomanipulators have been conducted in three distinct stages that are identified with three different servomanipulators. Our first experience with servomanipulators and with total television viewing was conducted in an unused hot-cell facility at Oak Ridge. We installed the control station 150 cable feet from the manipulator and the hot cell. A set of

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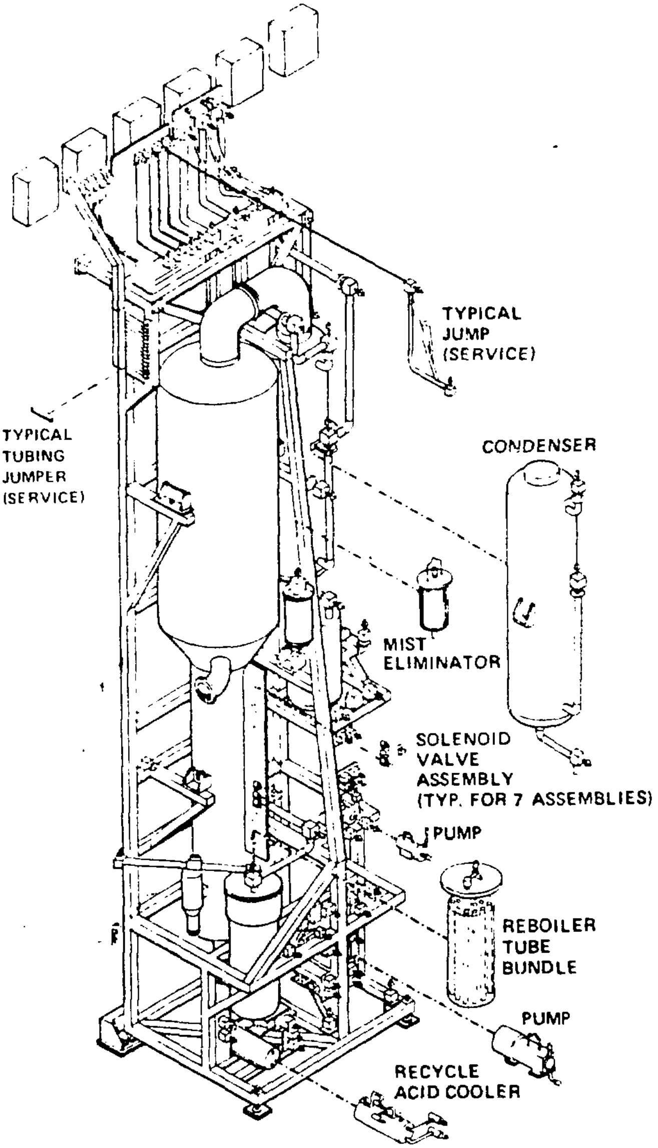

Fig. 2. HEF Module

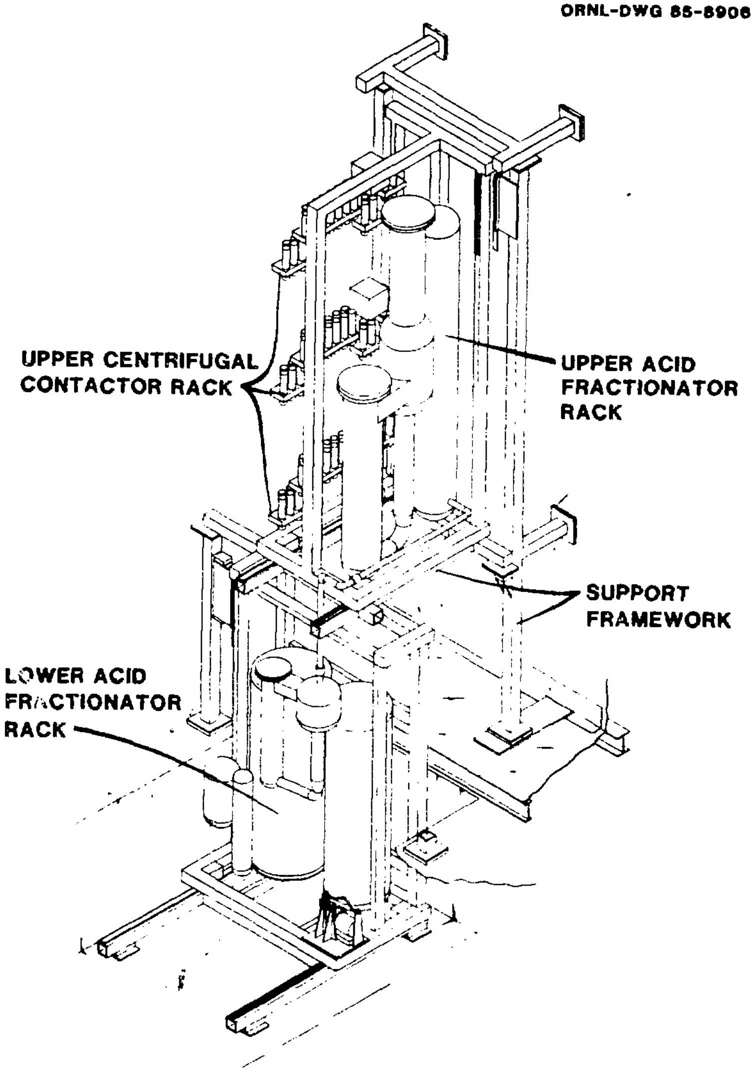

Fig. 3. BRET Module

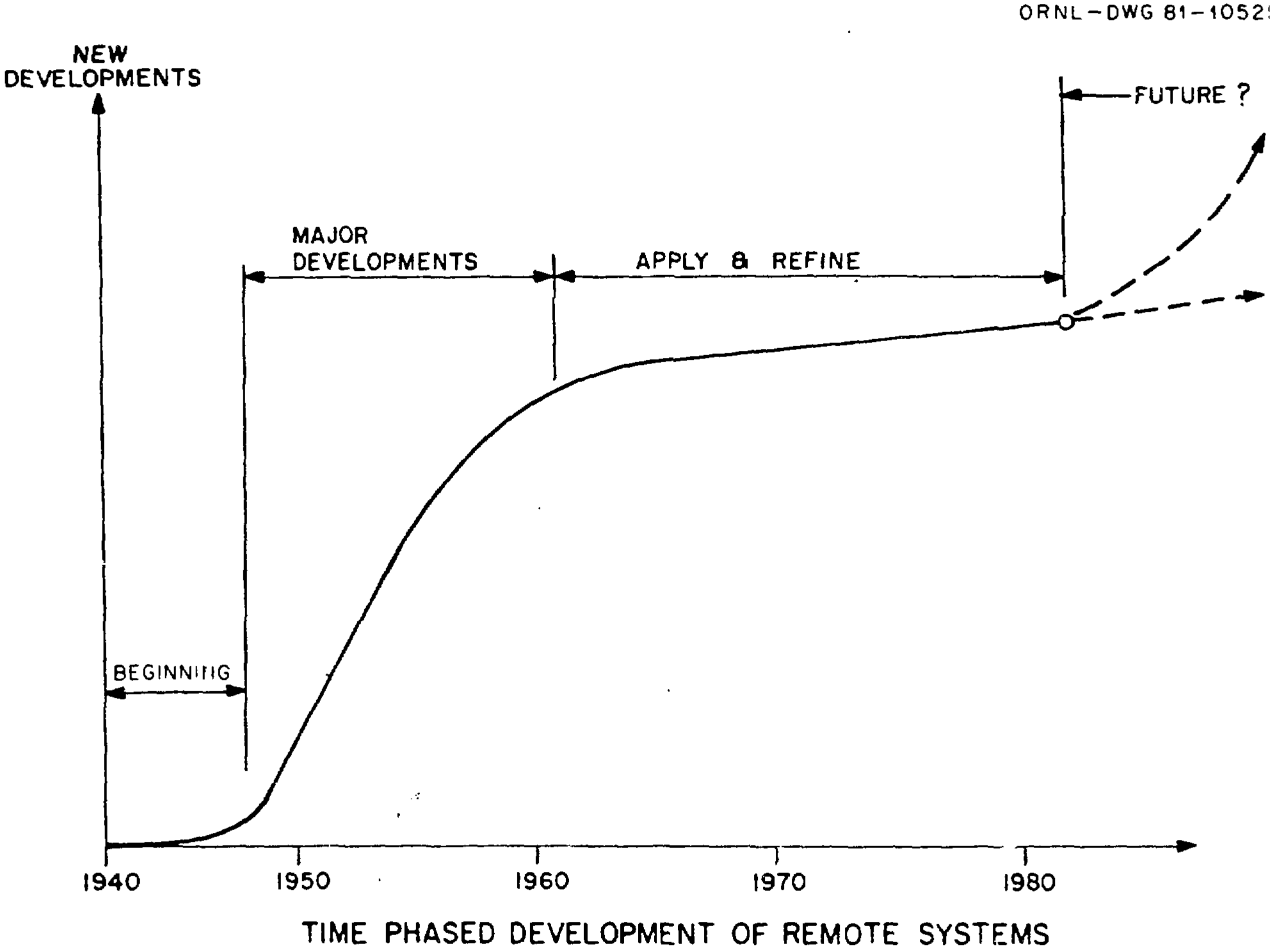

Fig. 4. Historical Development Curve

TOS SM-229 servomanipulators were loaned to us by a sister laboratory. We incorporated these servomanipulator arms into a facility for remote systems development. Starting in 1981, we did our initial investigations in two areas. The first was the investigation of control circuitry for the transporter and manipulator systems, which was an early forerunner to the development of the digital control system now in use, and the second was a detailed study of the man-machine interface. A series of studies was conducted which attempted to optimize the relationship between man, the television camera, and the servomanipulator. The studies have been documented in the literature.[12]

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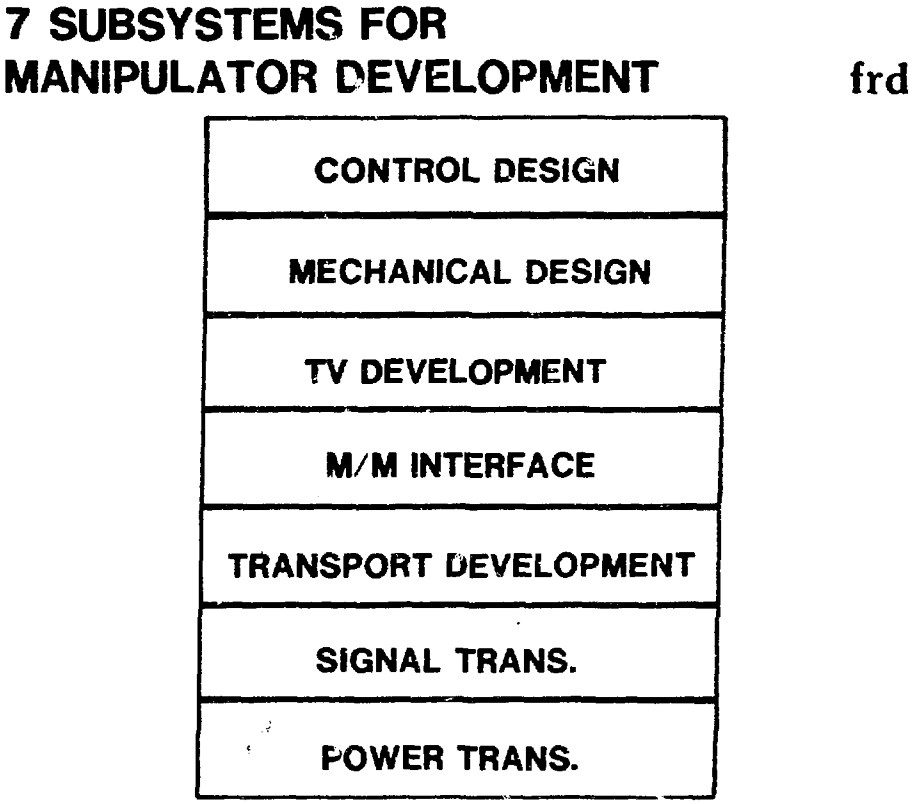

7 SUBSYSTEMS FOR MANIPULATOR DEVELOPMENT

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- CONTROL DESIGN
- MECHANICAL DESIGN
- TV DEVELOPMENT
- M/M INTERFACE
- TRANSPORT DEVELOPMENT
- SIGNAL TRANS.
- POWER TRANS.

Fig. 5. Seven Subsystems

We also used the facility to evaluate voice control of television cameras and introduce the necessary software for automatic camera tracking. Figs. 6 and 7 depict the manipulator and its control station.

At about the same time, we undertook a contract to upgrade an existing commercial servomanipulator system by designing and integrating to it a digital control system. We worked with Sargent Industries, CRL, and the cooperative effort produced the Model M-2 which we strongly feel is one of the better manipulator systems available today. We have been using the unit to perform remote maintenance routines on various pieces of reprocessing equipment in our nonradioactive mock-up test area. The M-2 slave system, as we employ it, consists of the slave arms, two television cameras with pan, tilt, and zoom mounted on two-degrees-of-freedom positioning arms, and a fixed camera mounted at a belly position. A 500-lb hoist positioned between the arms is also a part of

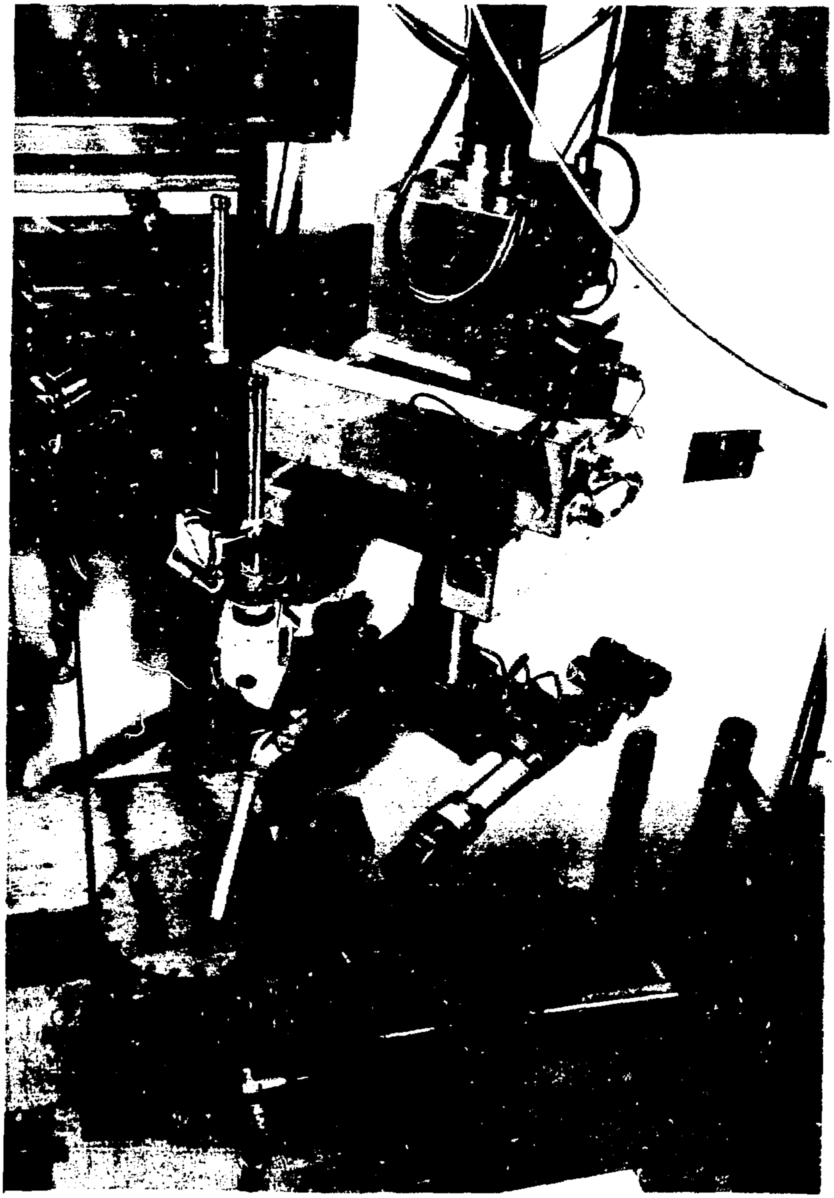

Fig. 6. Remote System Demcnstration Facility Slave

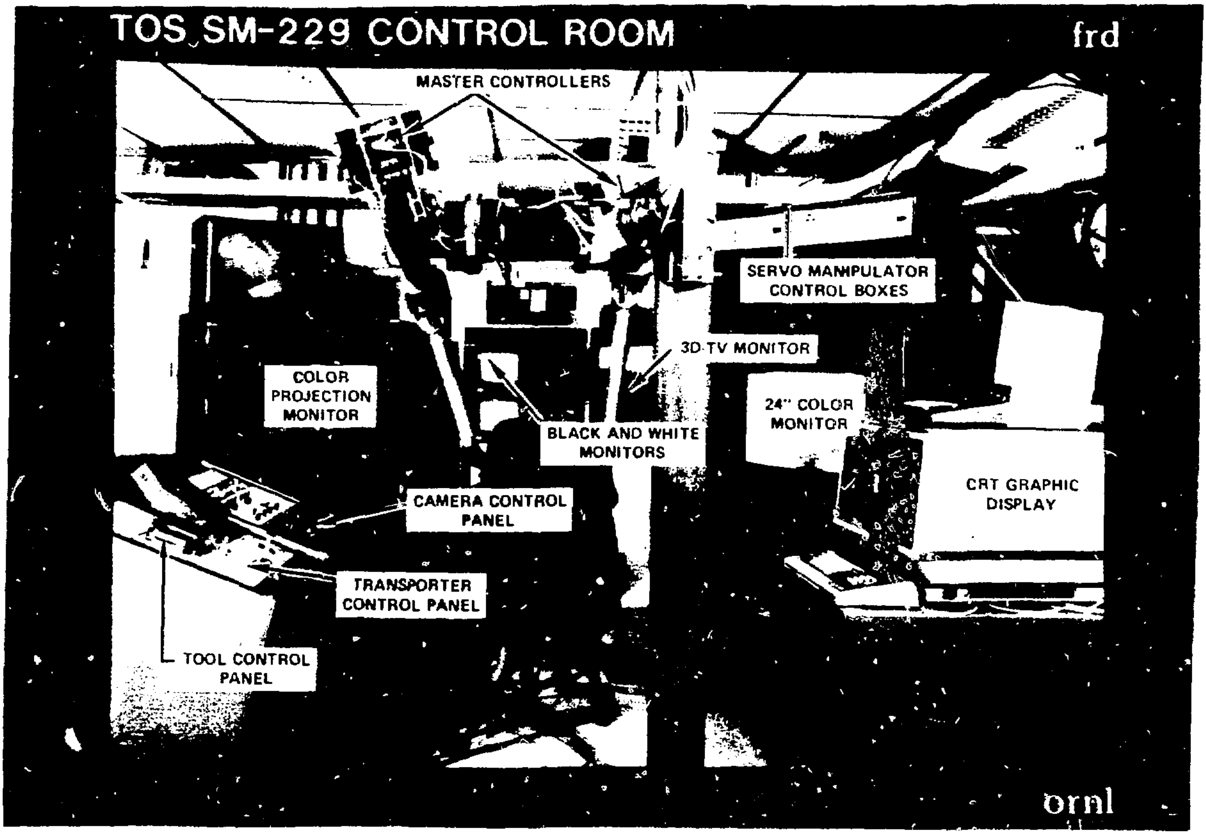

Fig. 7. Remote System Demonstration Facility Master

the operating package. The system has been operating with a standard cable connection to the bridge and manipulators.

The digital control system allowed us to demonstrate a series of operational modes that indicate the versatility of the manipulator and its control system.[10,11] We utilize a "dead man" master system which provides "free wheeling" of the master when the operator's hand is removed from the grip—while the slave is locked in position. The master and slave can also be easily indexed to provide an optimum operator position. Currently the force feedback ratio can be varied from 1:1 to 1:8 and could be varied in reverse ratios if the need arises. All of these controls are menu driven, and the selection process is either by a touch screen or through a selection switch mounted on the master control handle. We have implemented a routine that brings the master and slave into synchronous position at a controlled slow speed. The digital control system is also utilized for a diagnostic system that indicates to the operator the condition of the system in use. The diagnostic system provides valuable information in attaining optimal system performance. Figs. 8 and 9 show the M-2 manipulator and its control station.

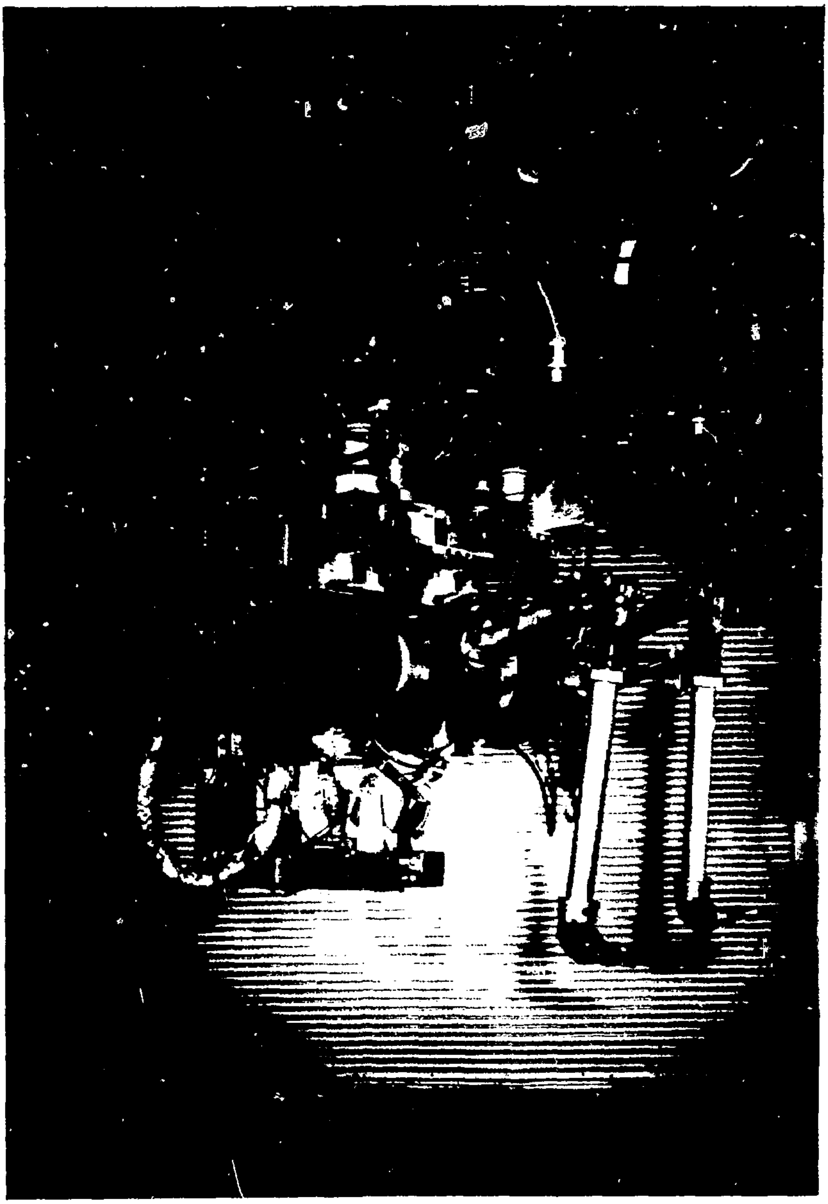

Fig. 8. M-2 Slave

Fig. 9. M-2 Master

The third stage in our present development program is one in which we have a great deal of pride. For the application of reprocessing, and for other applications where reliability and repairability are major considerations, we felt that improvement in these two attributes of the servomanipulator were necessary. To that end, we have developed and manufactured a gear and torque tube driven servomanipulator.[13]

Replacing the tape and cable tendon drives with gears and drive shafts provided us with a solution to our goal of increased reliability and improved maintainability. These mechanisms are inherently more reliable, and the gear and spline interfaces provide a manipulator that is separable into removable and replaceable modules. The manipulator modules were designed to be within the weight capacity and dexterity of another manipulator arm.

In addition to designing the manipulator for greater reliability and for ease of repair, we accomplished an additional and needed design change. All of the existing servomanipulator designs paralleled the through-the-wall master-slave design in configuration. The "elbows up" configuration is best suited for tabletop work. The "elbows down" (anthropomorphic) is manlike and more suitable for work on equipment housed in racks or for the vertical face of equipment. Designing a manipulator in the anthropomorphic (manlike--elbows down) configuration required that we solve a different design problem--that of the four-degree-of-freedom wrist. We have successfully met that design challenge.

To expedite our development program, we produced the two slave arms on a fast-track schedule that paralleled the design and fabrication activities. While we are completing the design and fabrication of the master arms, we are using one of the slaves as a master. We are currently checking out the digital control system--hardware and software--with this "pseudo" master-slave pair. Recognizing that we have twice the friction and backlash of the final system, the tests to date indicate we have been successful. Following the operation with the pseudo master-slave, we will add the master arms now in construction and begin operation of a pair of advanced servomanipulators in about September of this year.

The digital control system used on the Advanced Servomanipulator (ASM) is a staged advance over the control system described for the M-2 manipulator. It is, in fact, a system with greater capabilities that are generated by the use of state-of-the-art microcomputer technology. The advanced control system and the pseudo master-slave arm have been used to generate a series of software programs that are responsible for improving the operating characteristics of the units. To date, we have completed initial phases of programs for electronic counterbalancing, inertia compensation, friction compensation, cross-coupling compensation, camera tracking, and robotic operation. The innovations are the beginning of what we feel are an almost infinite series of beneficial paths that can be applied to manipulator design and control--many of which will be tested in pursuing the goal of manipulation that applies manlike qualities to hostile environments.

Fig. 10 shows the ASM in its conceptual form. Fig. 11 shows the pseudo master-slave as it is now being tested. Fig. 12 shows the configuration of the master arms that are being manufactured, and Fig. 13 shows the ASM slaves as they will be deployed on a newly configured transporter. The ASM control room currently under construction is shown in Fig. 14.

Our present demonstration schedule indicates that during 1986 we will have adequate test and development information to produce through

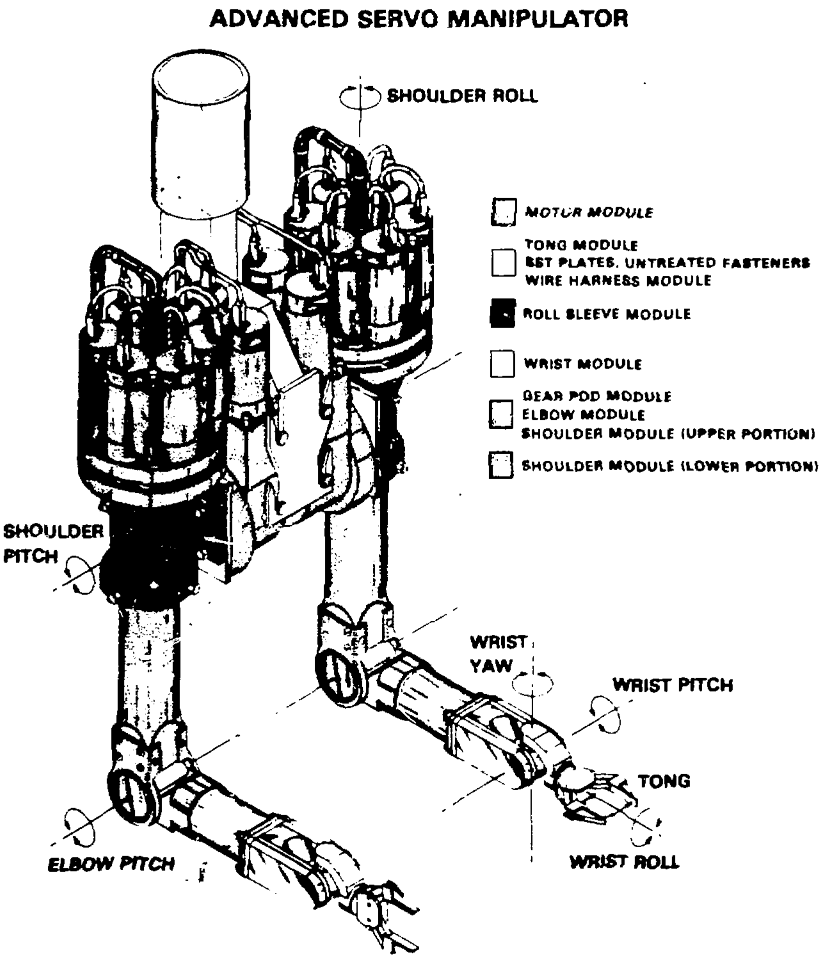

Fig. 10. ASM Slave Isometric

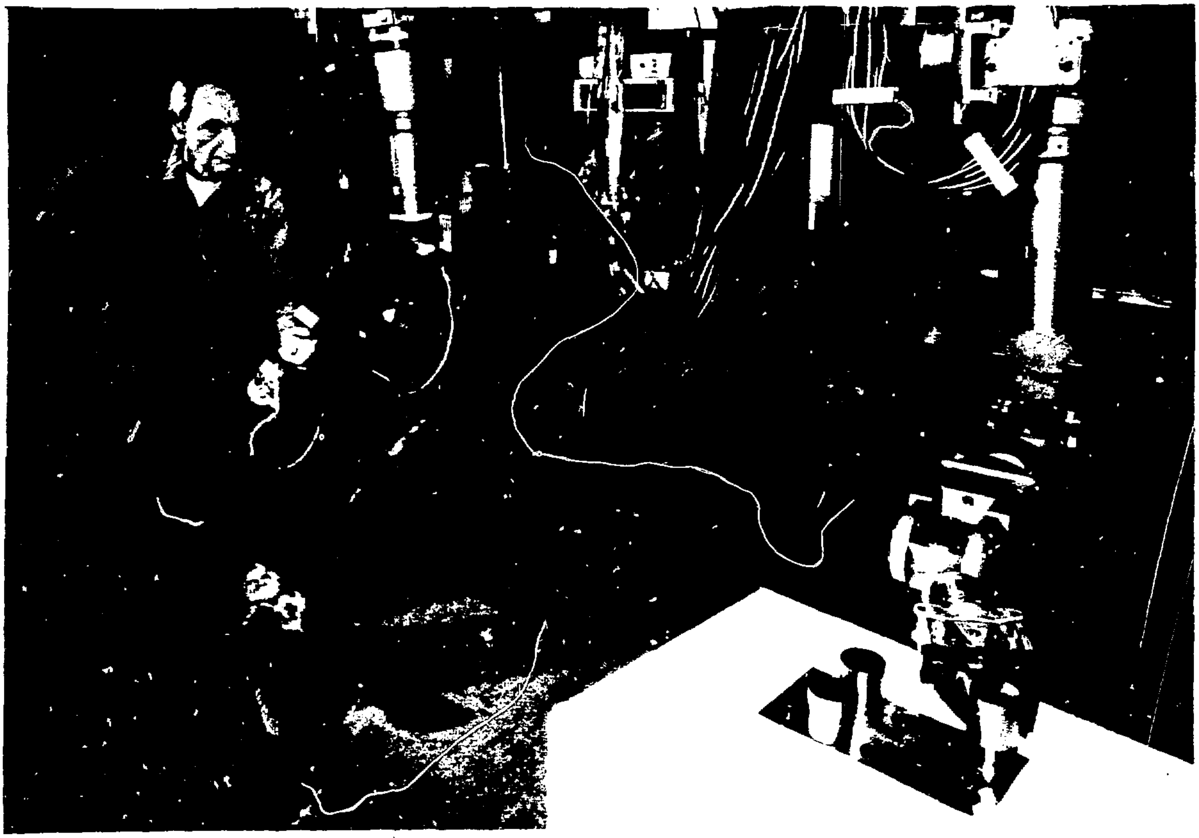

Fig. 11. ASM Pseudo Master-Slave Setup

industry a marketable system that can be available in 1988. That schedule could be expedited if a need were shown.

Technical details of the material presented in this paper are contained in a series of ten papers presented at the American Nuclear Society Topical Meeting on Robotics and Remote Handling in Hostile Environments held in Gatlinburg, Tennessee, in April 1984.[14]

We have reached a stage in remote operations where we can assure the capability to successfully operate and maintain complex equipment and attain reasonable plant output over long periods of time. We view the present levels of development as additions to existing remote operations systems. These additions are capable of increasing the productive capability of a facility, reducing the exposure to facility personnel, providing means to modify and upgrade complete operations, and serving as a major tool in the decontamination and decommissioning of facilities at the end of plant life.

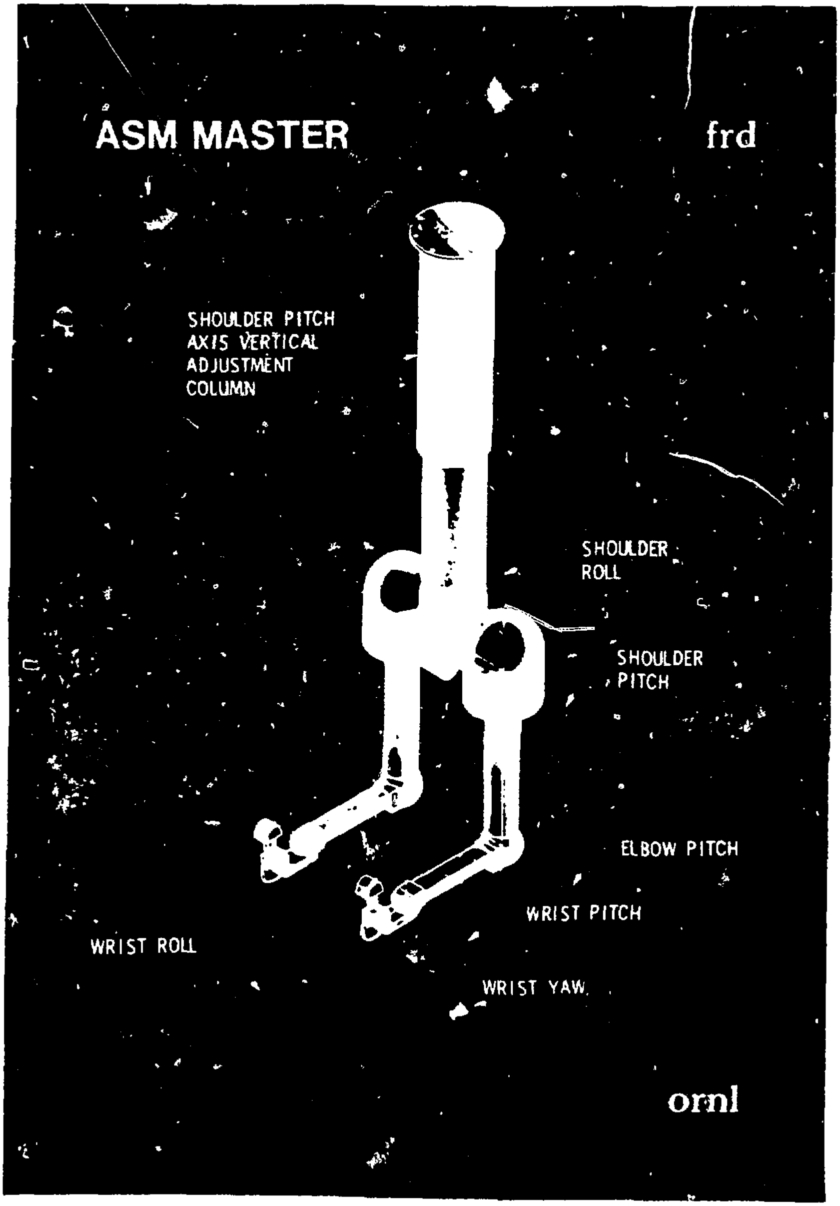

Fig. 12. Master Controllers

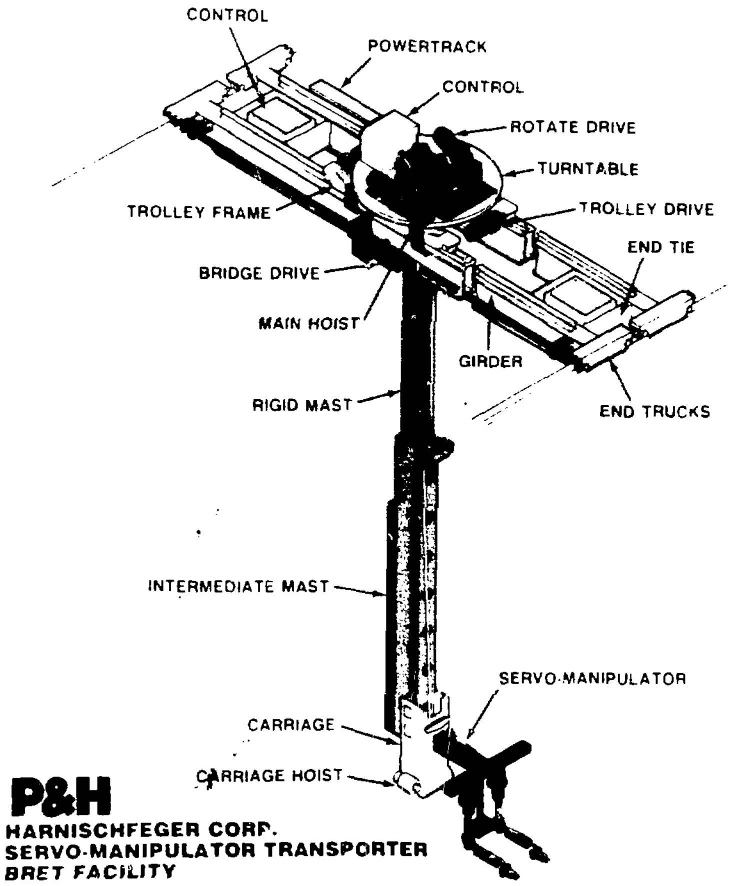

Fig. 13. Transporter with ASM Slave Arms

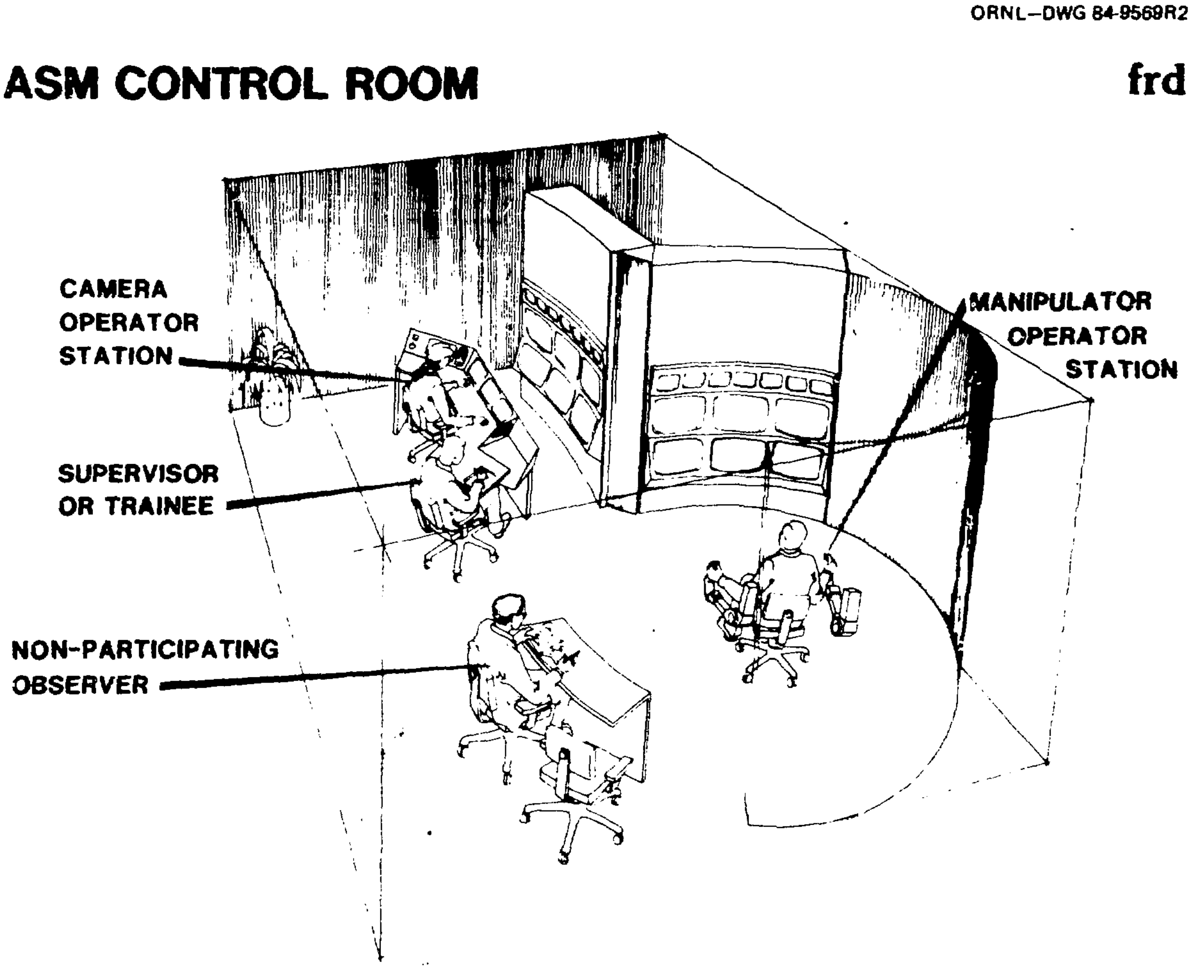

Fig. 14. Control Room for ASM System

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