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REMOTEX – A NEW CONCEPT FOR EFFICIENT REMOTE OPERATIONS AND MAINTENANCE IN NUCLEAR FUEL REPROCESSING

M. J. Feldman and J. R. White
Chemical Technology Division

Consolidated Fuel Reprocessing Program
Oak Ridge National Laboratory*
Oak Ridge, Tennessee 37830

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ABSTRACT

Remotex is a concept of remote operation and maintenance that utilizes advanced manipulator design to improve plant operating efficiency, reduce personnel exposure, and improve safeguards and diversion resistance. It is a concept developed over the past two years in the conceptual design of the Hot Experimental Facility (HEF), a mechanically intense pilot plant facility designed to demonstrate reprocessing technology for early U.S. breeder demonstration reactors. The Remotex concept is directly applicable to all segments of nuclear and non-nuclear industries where work tasks or conditions exist that are hazardous to the health of man.

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INTRODUCTION

The application of remote maintenance concepts to the field of nuclear fuel reprocessing has had a spotty, if not inconsistent, history. That history is partially understandable if viewed via three vistas. The first represents the fact that initially fuel reprocessing was fundamentally a non-mechanical, liquid-phase chemical system whose components has long expected lifetimes. The second vista represents a chronology which shows that the initiation of reprocessing preceded the development of the tools, techniques, and designs which make remote maintenance possible. The third is an awareness that the lack of continuous effort in the development of reprocessing technology did not provide for a paced absorption of remote handling capabilities as they became proven and available.

The underdeployment of remote technology in fuel reprocessing today is interfacing with a series of developing directions that govern the impact of reprocessing on the environment and on the population. The response to greater emphasis on environmental impact requires that existing and proposed capabilities for remote maintenance now be employed.

The conceptual design of the liquid-metal fast breeder reactor (LMFBR) fuel reprocessing hot pilot plant, called the Hot Experimental Facility (HEF), is being performed at the Oak Ridge National Laboratory (ORNL) for the Department of Energy (DOE).[1] This plant, scheduled for hot startup in the 1990's, will be capable of storing and reprocessing spent fuel from the Fast-Flux Test Facility (FFTF), the Clinch River Breeder Reactor (CRBR), Gas-Cooled Fast Reactor (GCFR), future breeder reactors, and light-water reactors. Demonstrating that spent fast reactor fuel can be safely and economically reprocessed is essential to verify that the breeder reactor is a viable energy source.[2,3]

In addition to the initial mission of the HEF, that of demonstrating the existence of a publicly acceptable reprocessing system, a longer range mission for the facility is incorporated in its design. That charter is to provide a facility with the flexibility for demonstrating positive developments in the reprocessing field. This capability serves not only as a demonstration of improvements in economy and efficiency, but also as a capability to respond by demonstration to changes in regulations that may take place. This flexibility in facility design is a normal function of the pilot plant concept and tends to overcome one of today's obvious problems in attempting to cast concrete around a moving target.

Response to these goals has resulted in the establishment of design criteria for the HEF which include the following:

1. Maintaining an on-line availability of 60% at rated capacity and demonstrating, by extrapolation of operating experience, that a 5-t/d commercial reprocessing plant could achieve an on-line availability of 80%;
2. Providing the capability to replace the initially installed reprocessing equipment with advanced equipment as it is developed;
3. Meeting federal regulations (circa 1980's) for the licensing of nuclear fuel reprocessing plants;
4. Limiting the average radiation exposure of plant personnel to 500 mR/person/year (a design objective not yet formalized as a criteria);
5. Demonstrating fission-product retention factors which, if applied to a 5-t/d commercial reprocessing plant, would yield a site boundary whole-body dose ≤1 mR/year;
6. Meeting federal regulations for shipping fuel from reactors and for waste to repositories.

In reviewing the designs and maintenance philosophies employed at other reprocessing plants, it was apparent that none was capable of meeting all of the HEF design criteria. A new approach called Remotex, was therefore selected as the basis for the HEF design.

DEFINITION OF REMOTEX

Remotex is a concept of remote operation and maintenance that utilizes advanced manipulator design to improve plant operating efficiency, reduce personnel exposure, and improve safeguards and diversion resistance. It is a concept developed over the past two years in the conceptual design of the HEF, a mechanically intense pilot plant facility designed to demonstrate reprocessing technology for early U.S. breeder demonstration reactors.

In this concept, man-enhanced manipulation totally replaces directed manned contact with the radioactive product, the radioactive equipment, and the radioactive work place. Remotex is an improvement in the efficiency and capabilities of the types of remote operation that have been successfully employed over the past 30 years. It is the next logical step toward improving remote operation and maintenance while, at the same time, utilizing developments of the past decade.

In a remotely operated and maintained facility, the equipment and facility designs are strongly affected by the maintenance and repair scheme. In turn, that scheme and the ability to attain the design mission are strongly affected by the type of manipulation selected to accomplish remote operations capabilities. The key system in the Remotex concept is the bilateral force-reflecting electronic manipulator, which has been developed as a natural sequence in the master/slave manipulator family.

In 1978, the Hot Experimental Facility conceptual design effort had reached an intermediate review and decision point. A review of the facility concept indicated that more recent developments in manipulation and viewing technology could be utilized to improve the design and to provide additional benefits in ease of operation and maintenance. Thus, the Remotex concept grew out of an analysis of the status of the conceptual design of the HEF.

The primary changes in the new design were in adopting bilateral force-reflecting manipulators in place of electromechanical manipulators and in increasing reliance on television viewing in place of shielding windows. These features appeared to offer distinct advantages in the areas of improved plant availability, reduced environmental impact, safeguards, recovery from unplanned events, and plant decommissioning. At the same time, these changes did not call for drastic alterations to the previous concept.

MANIPULATOR SELECTION

Various types of remote manipulation devices have been used in nuclear facilities since the birth of the industry in the 1940's. Currently, the most accepted or conventional manipulator systems are a crane, power manipulator, mechanical master/slave manipulators, and suited personnel as shown in Fig. 1. The crane, coupled with a portable impact wrench, can be used for some remote maintenance work as was demonstrated at the Hanford and Savannah River fuel reprocessing plants for many years. Since the crane can only exert upward forces and has no tong for gripping, there are serious limitations on the amount of work that it can accomplish.

Power manipulators became commercially available in the early 1960's. These are single-arm manipulators with a parallel-jaw tong that can squeeze and rotate continuously. When mounted on a telescoping-tube trolley and bridge system, the manipulator's working volume is limited only by the vertical travel of the telescoping tube. These manipulators are a significant improvement over the crane-impact wrench approach in doing remote work. They have been applied extensively in hot cells throughout the world. However, their use in reprocessing plants has been limited to cells containing mechanically intensive fuel shearing equipment. The power manipulators are unilateral, that is, they are not force-reflecting. As a result, they can easily damage equipment components during maintenance.

Mechanical master/slave (M/S) manipulators are the work-horses for performing remote maintenance tasks in hot cells throughout the world. They are force-reflecting and, therefore, provide the operator with a sense of feel. Viewing is normally through a shielded window when doing work with these manipulators. Generally speaking, almost any type of task can be performed with mechanical M/S manipulators. This includes the disassembly or reassembly of equipment components using screwdrivers, wrenches and even hammers. Commercially available tube fittings, electrical connectors, valves, and pumps can all be used in a remote cell when M/S's are available for maintenance. The authors have witnessed an M/S operator replacing balls in a ball bearing. The major disadvantage of the mechanical M/S's is the limited coverage that is obtainable. In some facilities, this is overcome by using a crane-impact wrench or power manipulator system to remove a failed component. The component is then placed in front of a window work station where detailed repairs can be made with M/S manipulators.

A suited person is shown in Fig. 1 as a conventional manipulator-maintenance system because of its extensive use in reprocessing plants. Man is certainly the best of all currently available manipulator systems; however, he does encounter complications when working within a radioactively contaminated environment. First, the interior of the shielded enclosure and its contained equipment must be decontaminated to a level that will allow man to enter and do work. This operation must usually be done remotely, takes a considerable amount of time, and results in large quantities of contaminated liquid waste.

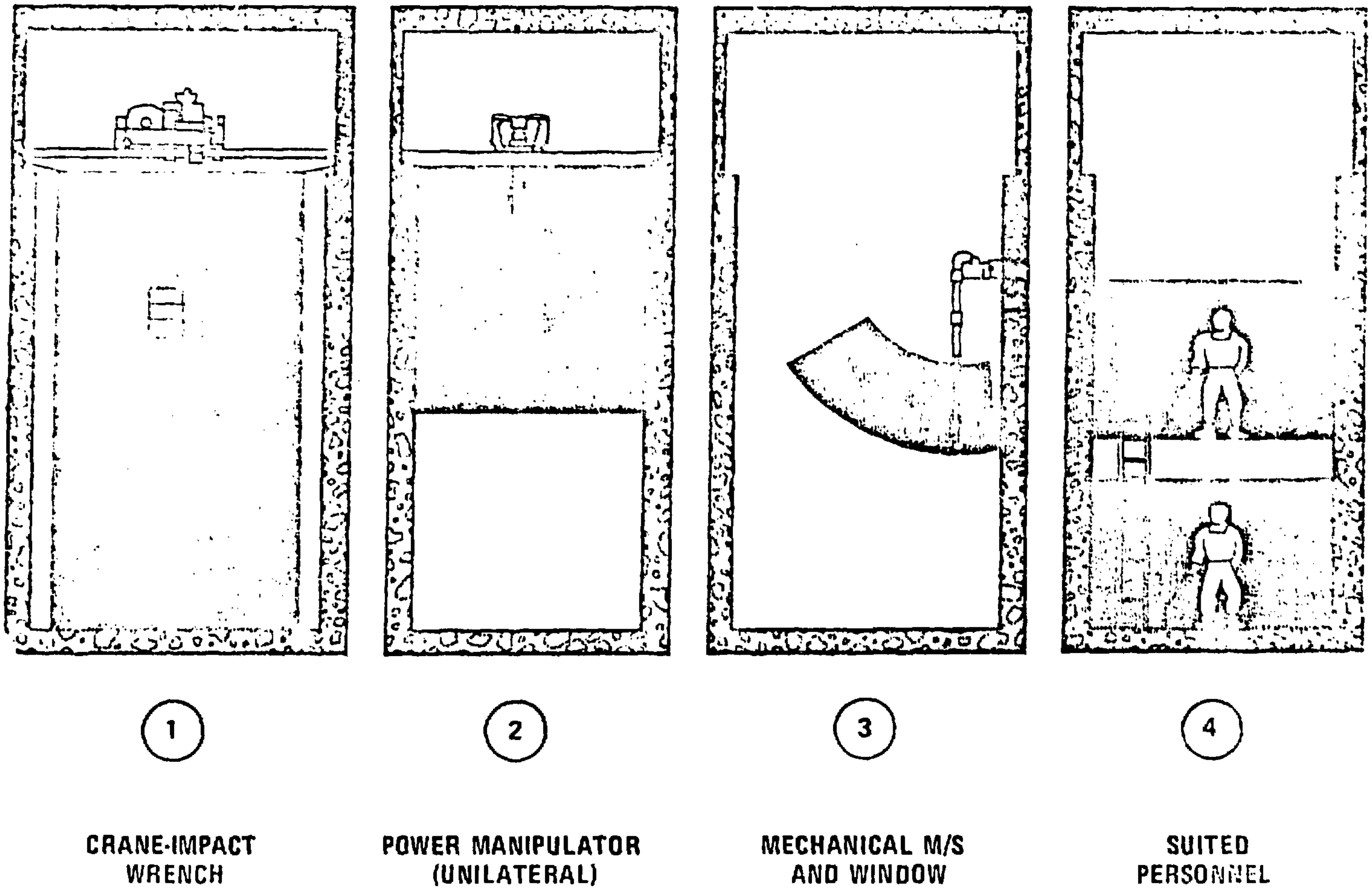


Fig. 1. Conventional manipulator-maintenance systems.

A number of studies and tests have been performed and documented[4-8] to determine the time required to perform a set of work tasks using different types of remote manipulators. The general results of these studies are shown in Fig. 2. In each case, an unsuited man (assumed with two arms) was selected as the reference and assigned a value of 1 when performing a specific task. The same task was then performed by different types of manipulation systems, and the increased time required was determined. The numbers shown are multiplying factors, that is, it takes eight times longer to do a task using mechanical master/slave manipulators than it does using human hands. Further, it takes 60 to 100 times longer to do the same task using electromechanical manipulators (EMM). The results of these studies clearly show that manipulators with force-reflection (the ability to feel) can perform tasks in far less time than nonforce-reflecting manipulators. It is also obvious that none of the manipulators available to date are comparable to man.

The use of personnel in future reprocessing plants to maintain equipment by contact means will be significantly less than has been allowed in the past. The Remotex concept is designed to minimize contact maintenance and to seek a replacement for man in the radioactive environment. The closest, currently existing substitute for man is the electric master/slave manipulator shown in Fig. 3. This system has the same capabilities as the mechanical master/slave except that the master and slave arms can be physically separated. Hence, full-volume coverage of the interior of a cell is possible with a single manipulator system. The electric manipulator was developed during the early 1950's and is commercially available from four sources. Widespread application has not occurred because of the relatively high cost, the concern for reliability of these units, and the fact that mechanical master/slave manipulators, coupled with windows and overhead nonforce-reflecting manipulators, could be used to do the required work. The experiences at three facilities[9-11] where electric master/slave manipulators are used have been favorable.

MANIPULATOR INSTALLATION

The electric master/slave is ideal for a large barn-type cell, such as the HEF, because of its dexterity and large-volume coverage. This is, however, only one part of the total solution. The other equally important parts are the transporter system that positions the manipulation within the cell and the design of the in-cell equipment so that it can be maintained by the manipulators.

The HEF is a chemical fuel reprocessing plant that requires a multitude of large tanks, pumps, and piping. This equipment is mounted within large structures or frames which are attached to the cell walls as shown in Figs. 4 and 5. There are approximately 100 of these modules located within an H-shaped cell. Each module is about 10-ft by 12-ft by 50-ft-tall and can be remotely removed as a unit. The primary maintenance mode, however, is to replace failed components in situ, that is, without removing the module from its installed position. Replaceable components will be located essentially anywhere within the modules as depicted in Fig. 6. Hence, it is necessary for the electric M/S manipulator to have full-volume coverage of the cell interior and be able to reach into the confines of the modules.

	LASL	MIT	NASA	MBA	CEA
TWO ARMED MAN (UNSUITED)	1	1	1	1	1
TWO ARMED MAN (SUITED)	–	–	–	8	–
TWO ARM MECHANICAL M/S	8	8-10	8	8	2-8
ONE ARM MECHANICAL M/S	16	–	16	–	–
ONE ARM EMM (POSITION CONTROL)	80	40-50	64	55	10-30
ONE ARM EMM (SWITCH CONTROL)	480	80-100	640	–	50-100
CRANE (IMPACT WRENCH)	>500	>100	>600	>500	>100

Fig. 2. Time comparison to perform remote tasks.

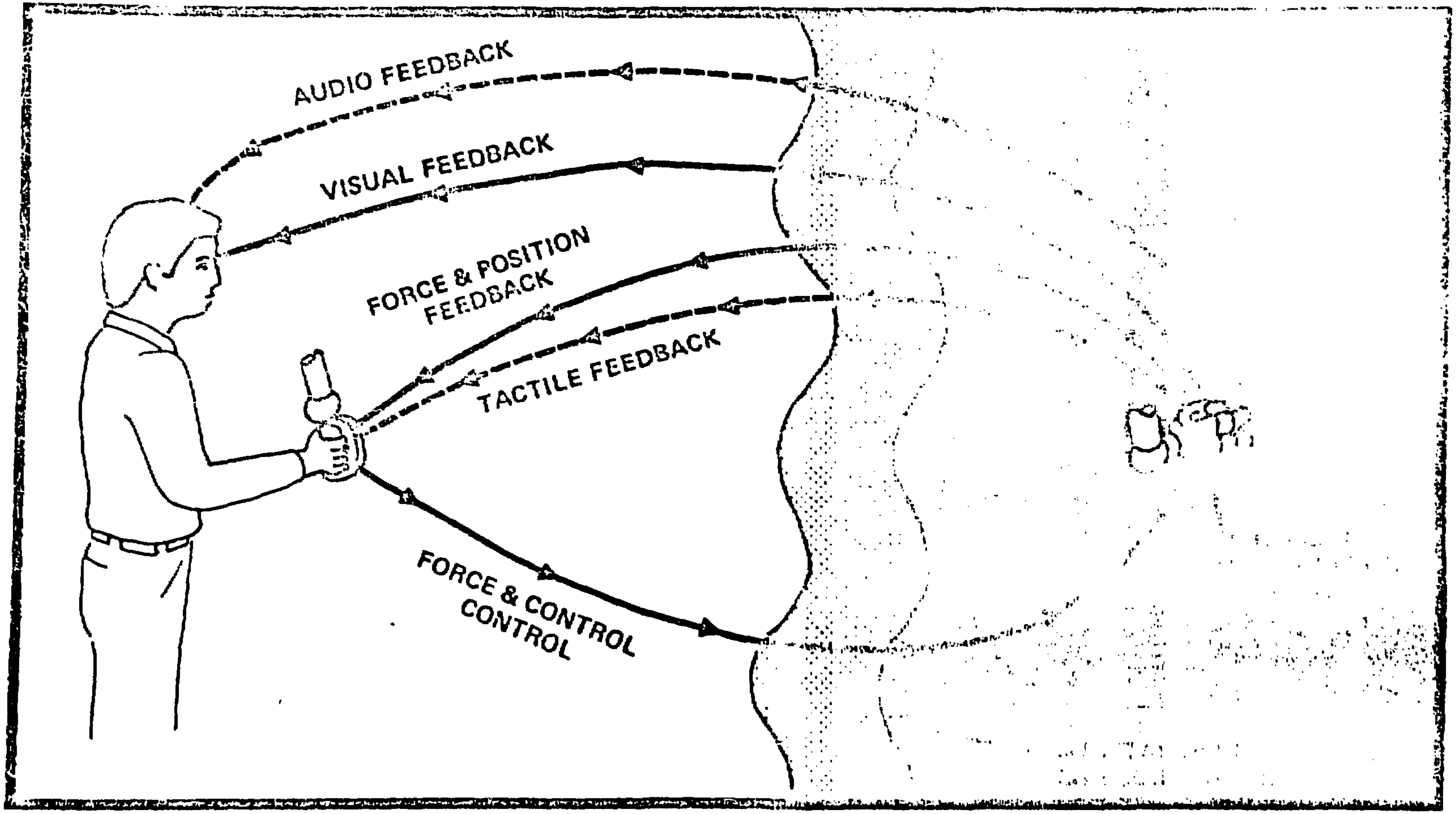


Fig. 3. Electric manipulator.

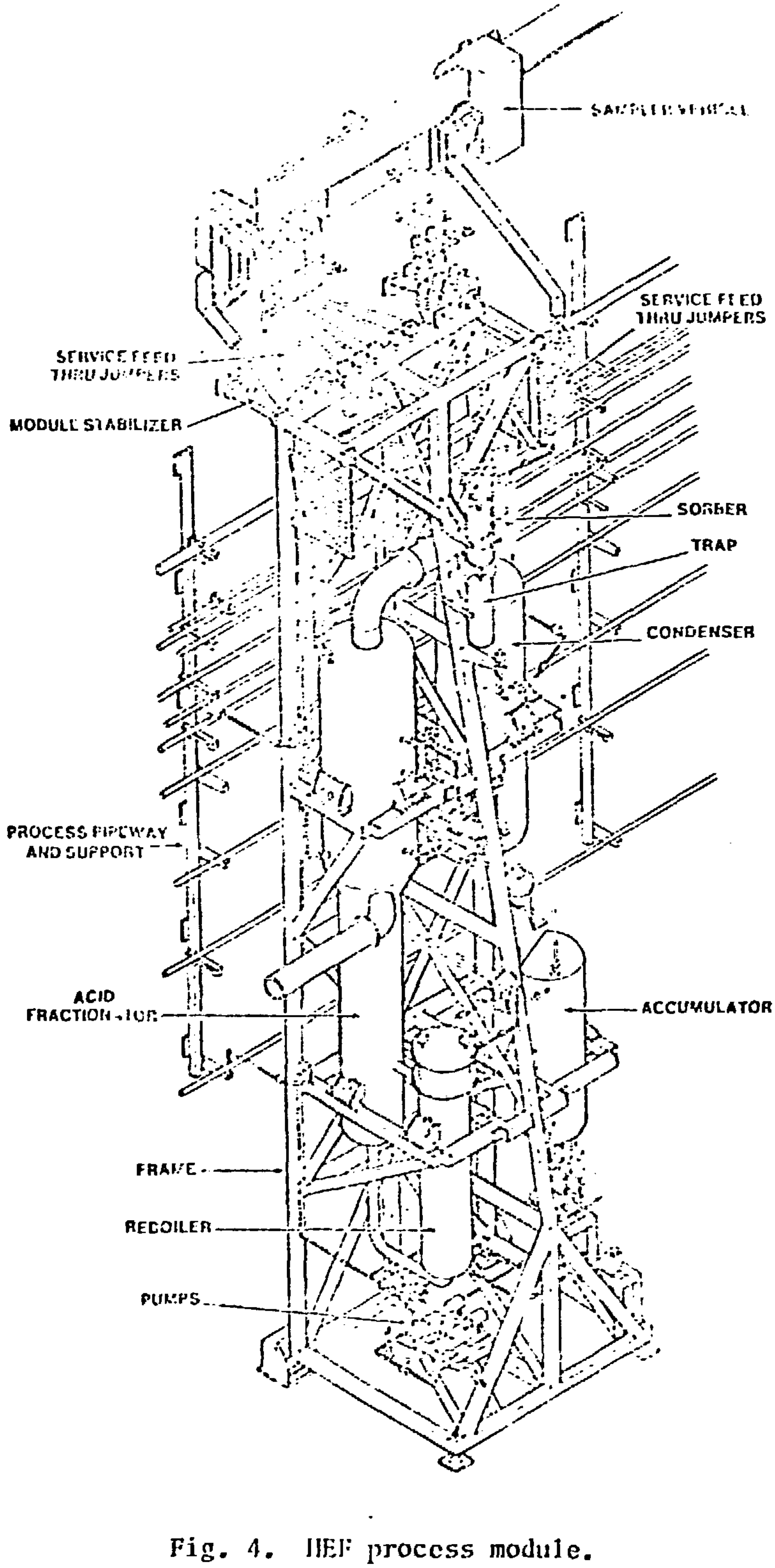


Fig. 4. HEF process module.

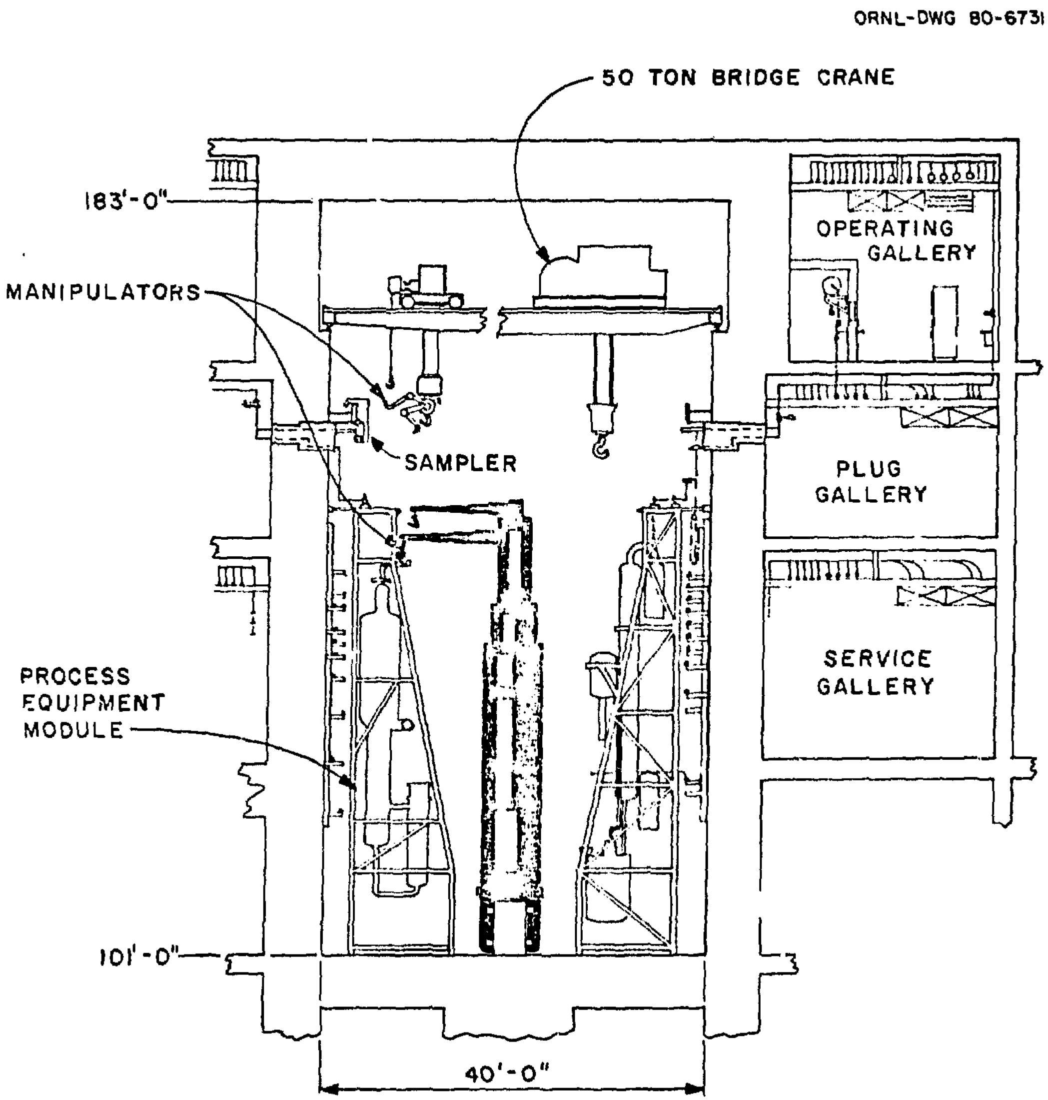
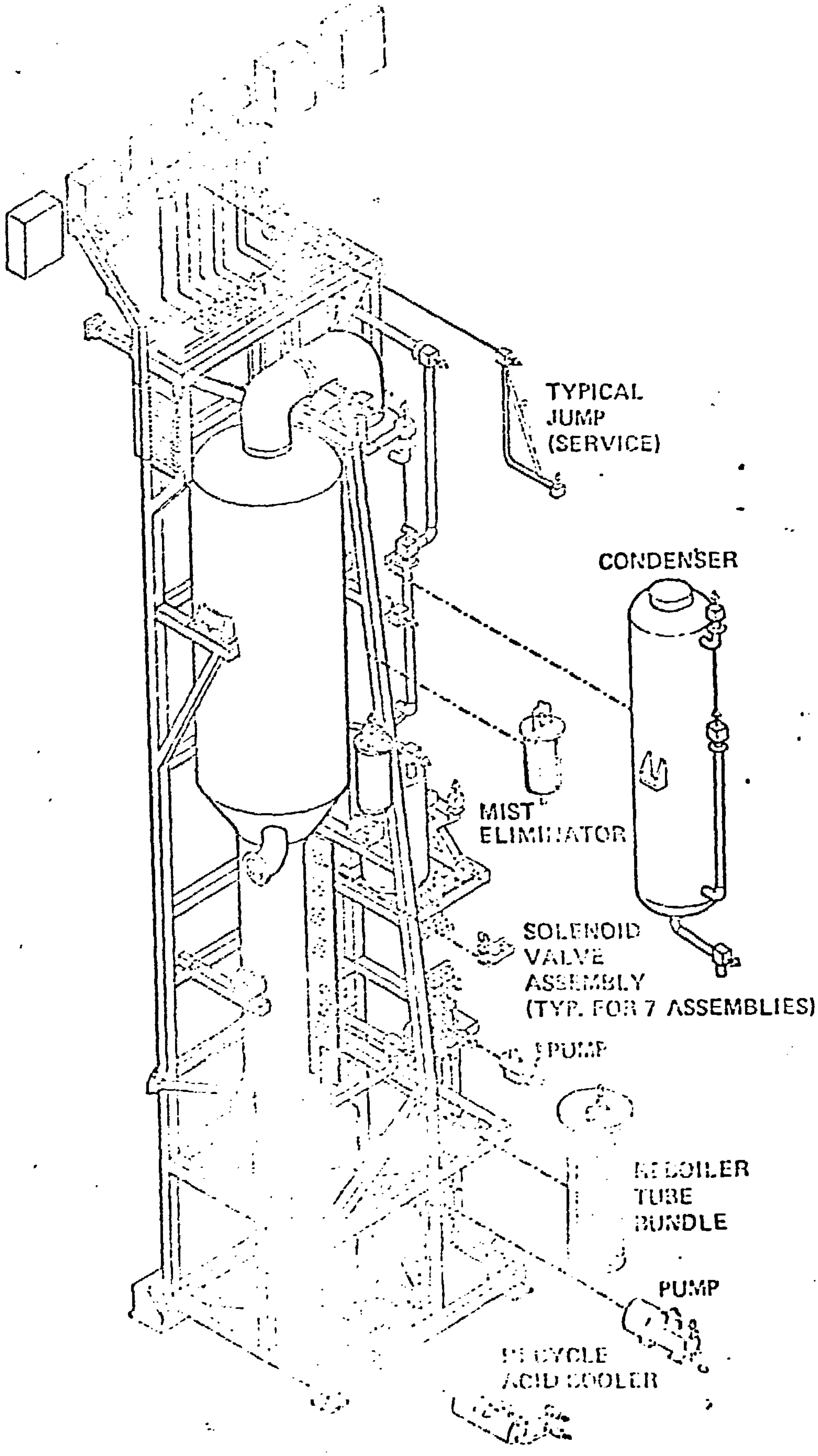


Fig. 5. Process cell section.


TYPICAL
JUMP
(SERVICE)
CONDENSER
MIST
ELIMINATOR
SOLENOID
VALVE
ASSEMBLY
(TYP. FOR 7 ASSEMBLIES)
PUMP
TUBE
BUNDLE
PUMP

A number of alternative approaches were considered for the manipulator transporter system. The preferred choice was a rail-mounted transporter that has the manipulators attached to a horizontal telescoping tube as shown in Figs. 7 and 8 This tube is attached to a structure that elevates and rotates. The combined effect of these motions (X, Y, Z and rotation) is to provide full-volume coverage in the process cells to about 60 ft above the floor. A separate horizontal telescoping tube is located above the manipulator tube on the transporter. A 0.5-t hoist is attached to the end of this upper tube, which permits the removal of relatively heavy components that are located within a module and not accessible to the overhead bridge crane.

An overhead bridge crane is located within each wing of the H-shaped cell complex. These cranes have separate 50- and 5-t hoists that are used to lift heavy equipment, including an entire process module or the floor transporter. One reason that a floor-mounted manipulator transporter was selected is to provide independent operations of the overhead cranes and manipulators. In this way, the manipulators can operate much like a maintenance man. They would replace failed equipment items without using a hoist if possible. If the item is beyond their capacity, they can attach rigging, such as cable lifting slings, to the crane and steady or position the item as it is being raised or lowered by the crane hoist. It is possible to deploy two floor-mounted manipulators to a work task and still use the overhead crane.

Electric master/slave manipulators are also transported by overhead bridge/trolley systems in the HEF (Fig. 5). The vertical travel on the telescoping tube is 35 ft. This provides an overlap of manipulator coverage, between the floor- and bridge-mounted units, of about 15 ft. The top of the process modules can then be serviced by either system. In some of the subcells, it is not possible to use a floor-mounted manipulator, and only an overhead system is used.

Traffic flow of the manipulator system within the H-shaped cell (Fig. 9) is another concern. The approach taken is to install an overhead bridge crane and a telescoping manipulator bridge in each of the four cell wings and the center (decon maintenance) section. The bridge units in the cell wings are restricted to performing work only in their respective wing. They can be interchanged using the bridge crane in the center cell section, however, this is not a routine operation. The floor manipulators are treated as a roving maintenance crew. The current plan is to install five separate floor manipulators. Turntables are installed at the intersection of the cell wings and the center cell section. There is a double rail in the center section, which permits the floor manipulators to pass each other; thus, each manipulator is capable of working within any sector of the H-shaped cell. It is possible to assign a floor manipulator to a long-term remote maintenance task in the center cell section without interference. The floor manipulators will also be used to transport component assemblies between the inlet transfer ports and the process modules.

Remote recovery from all potential failures within the process cells is a basic requirement of the HEF This includes failures of the manipulator systems and the bridge cranes. A "buddy system" is used to recover from manipulator/crane failures. It is possible in all cell wings, subcells, and enclosures to install an overhead bridge and trolley to release loads and tow a failed unit to a position where it can be repaired or replaced. Modular construction is also employed to locate high-potential failure components such as motors, synchros, and bearings in a remotely replaceable assembly. In many cases, this will permit in-situ repairs to be made. A concept for modularization of the electric manipulator is shown in Fig. 10. Another possible aid is a recovery trolley that can be placed on any overhead bridge and perform repairs in the upper volume of the cells using electric manipulators.

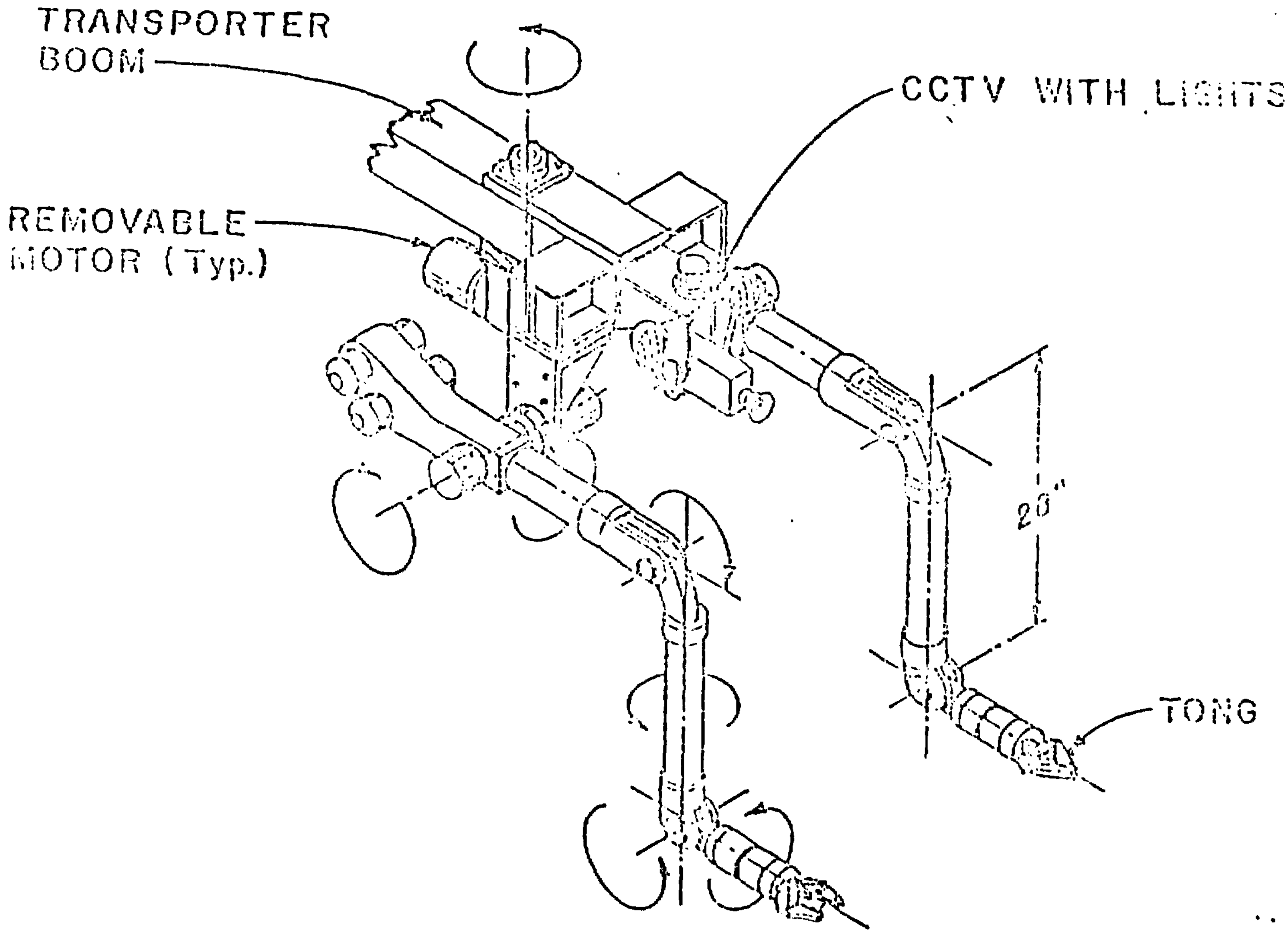


Fig. 7. Electric master/slave manipulator concept.

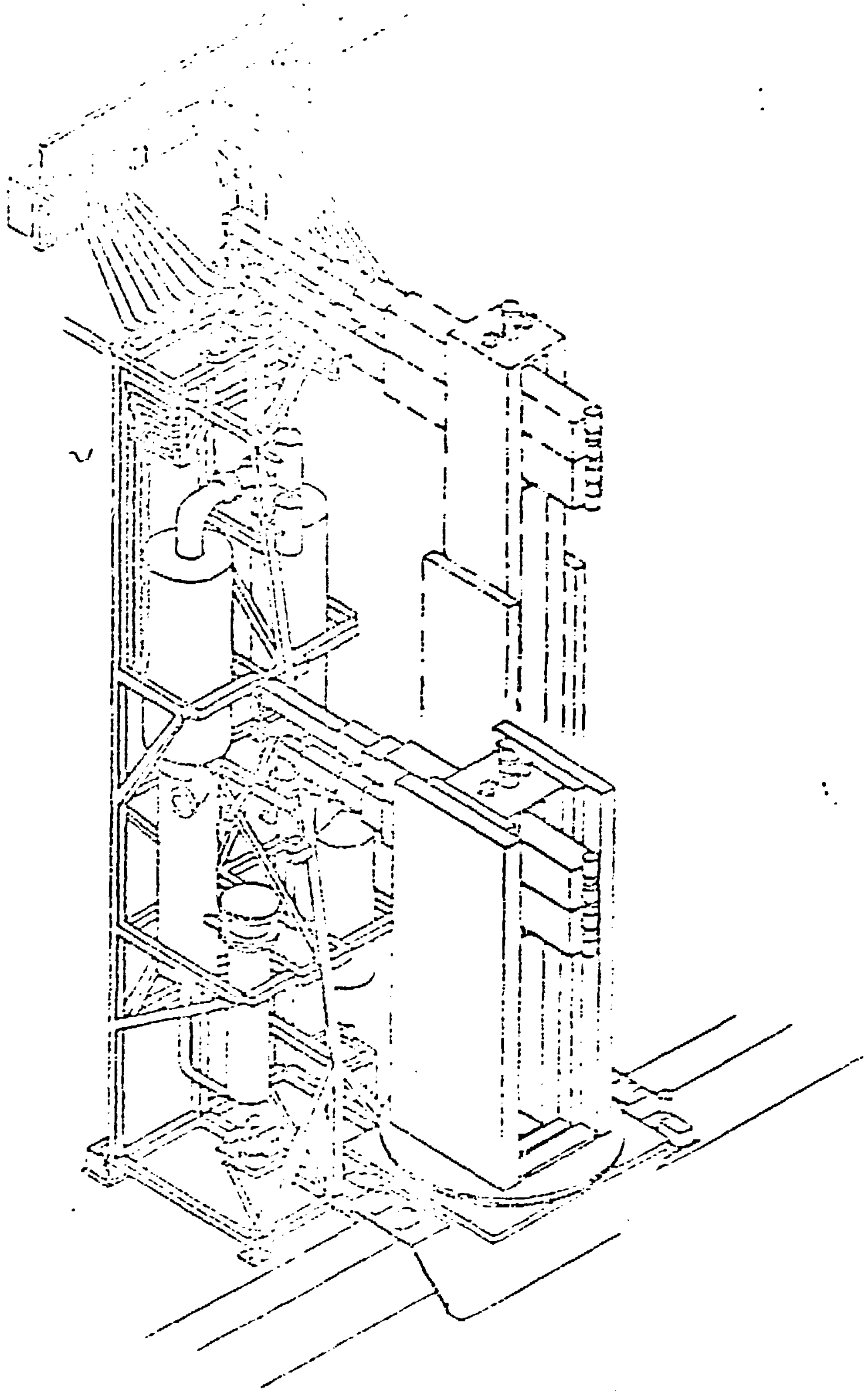


Fig. 8. Manipulator transporter.

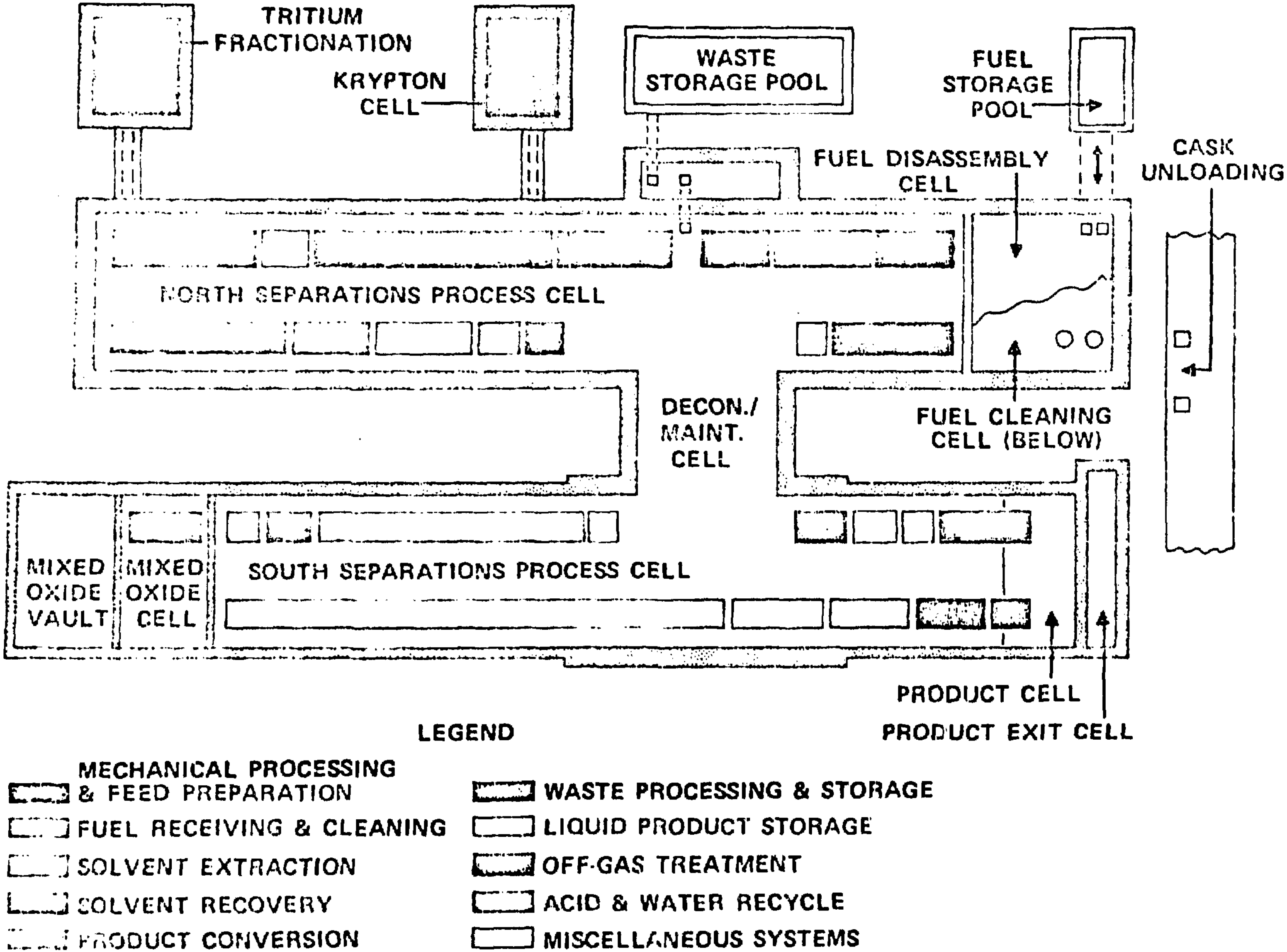


Fig. 9. HEF process equipment placement.

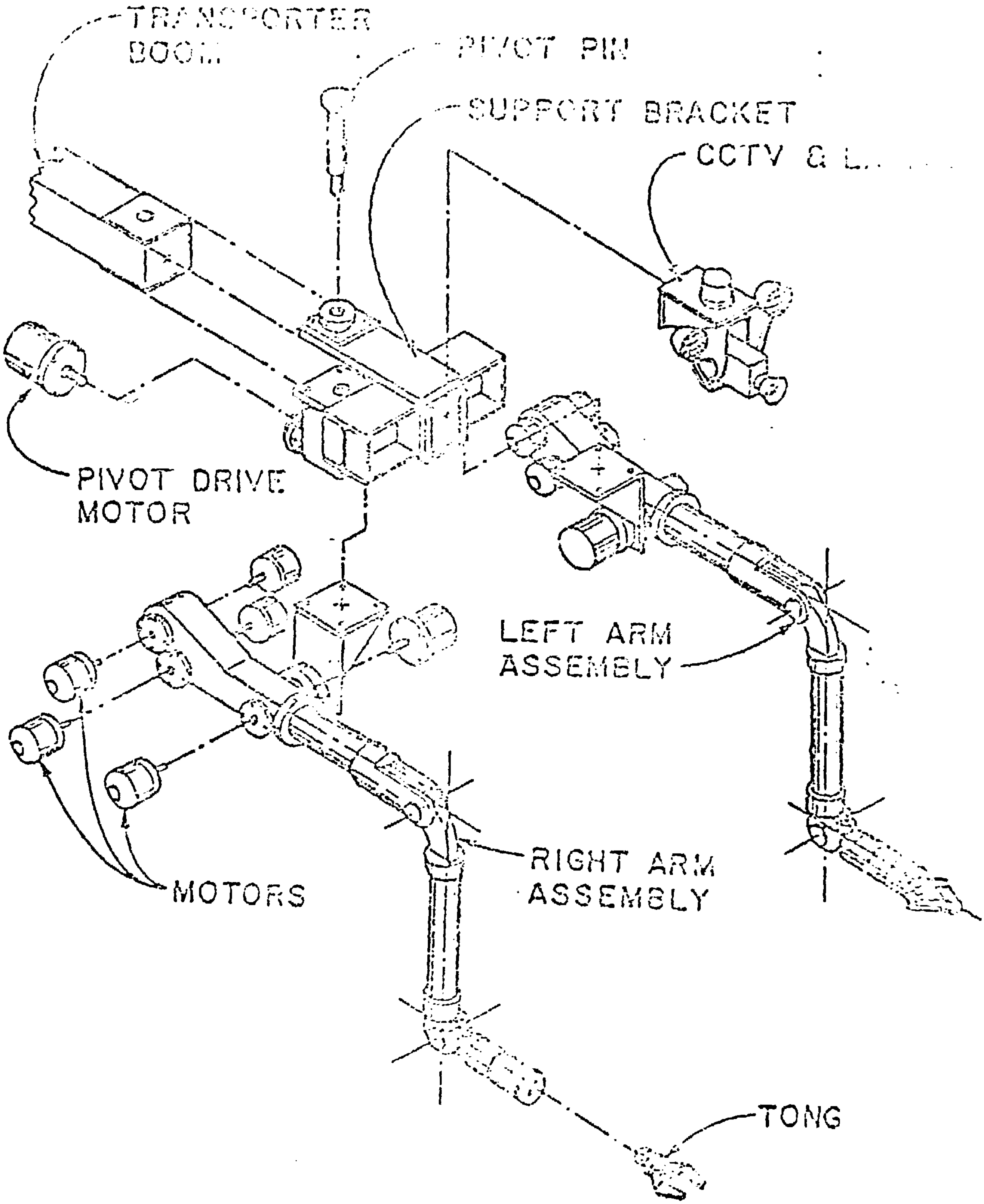


Fig. 10. Modular construction of manipulator.

The H-shaped cell complex is essentially a large windowless barn. Maintenance will be performed primarily from the center aisles between process modules by the manipulators using television viewing. Cameras will be located at strategic positions along the cell walls, on the overhead bridges, and on the manipulators. Lighting in the cell will be generally quite low except when a repair or inspection is being performed. Local lighting on the crane or manipulator will be used to illuminate the work area. The operators will be located outside of the process building in a control room. A concept of a typical manipulator control station is shown in Fig. 11.

MANIPULATOR USAGE

The electric master/slave manipulators in the HEF are used primarily to perform maintenance on in-cell equipment. The best way to understand this function is to envision the manipulators as maintenance men mounted on positioning stages or on a platform. This is similar to the approach used by telephone linemen in their work. Each manipulator has a tool box containing both power and hand tools that will be needed for assembly/disassembly tasks. The manipulator operator extends himself to the in-cell work scene through the control console (see Fig. 11). He will be able to see, feel, and hear what the manipulator is doing.

There are many different types of maintenance functions that must be performed in the HEF including:

1. Remote surveillance – the manipulators serve as roving inspectors to look for an indication of impending equipment failures. This inspection includes leaks, cracks in vessels, unusual noises, discoloration, distortion of piping, and perhaps temperature monitoring of vessels.
2. In-situ adjustments on components – tightening bolts on a leaking flange, changing a clutch or brake setting, and tightening bolts that have loosened because of vibration or temperature cycling.
3. Preventative maintenance – relubrication of bearings or replacement of near end-of-life components.
4. Component failure – replacing components that have failed.
5. Cleanup operations – performing clean-up operations following a repair job or a malfunction that spilled material on the cell floor.
6. Improvements or changes – replacing components or entire modules to improve operations or to adapt to operational changes.

In performing these functions, the operator will be assisted by a computerized memory bank. Video tapes of the equipment fabrication drawings, installation and maintenance procedures, cold testing operations, and previous in-cell repair jobs can be recalled and viewed by the operator at the control console.

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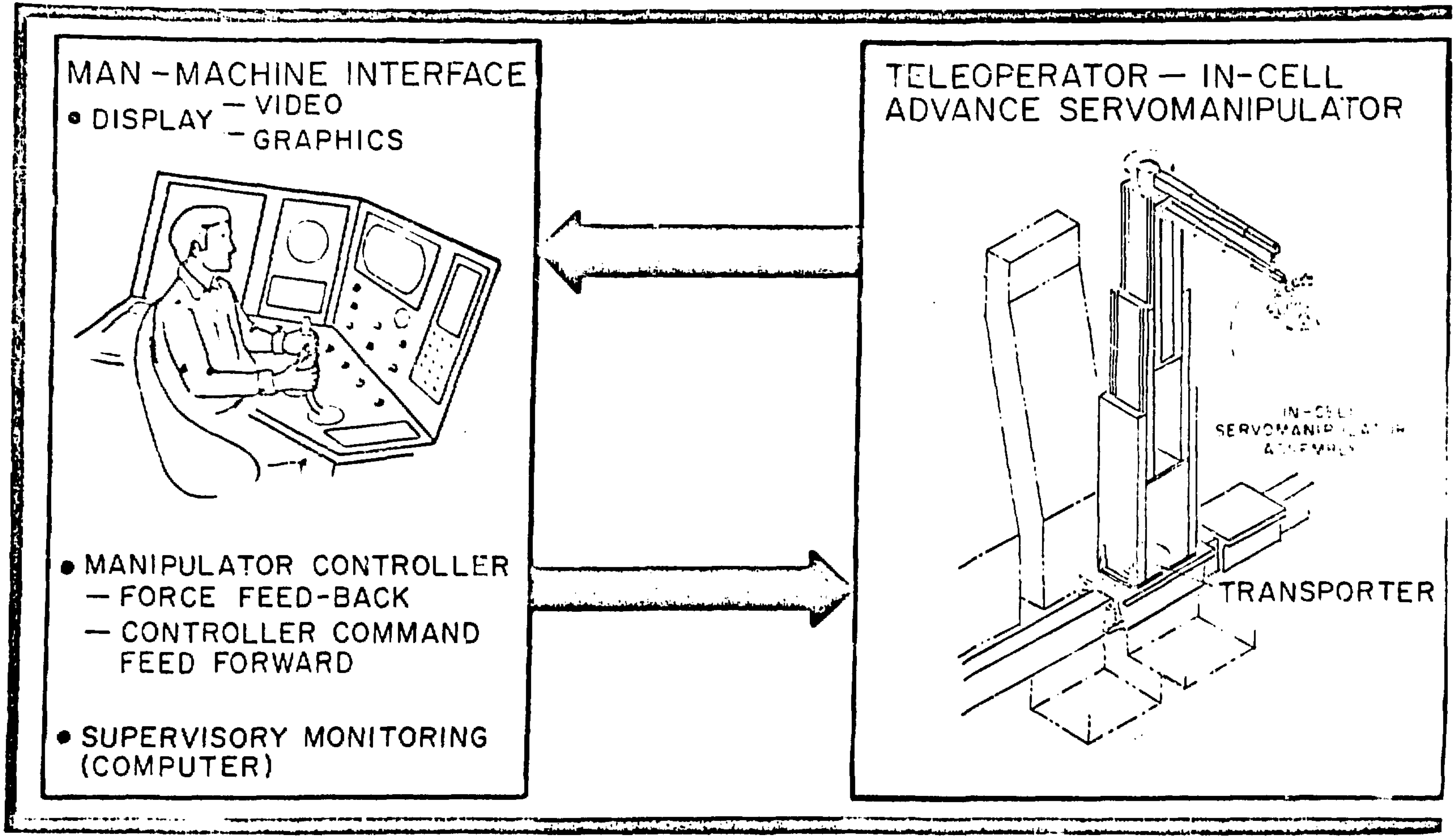
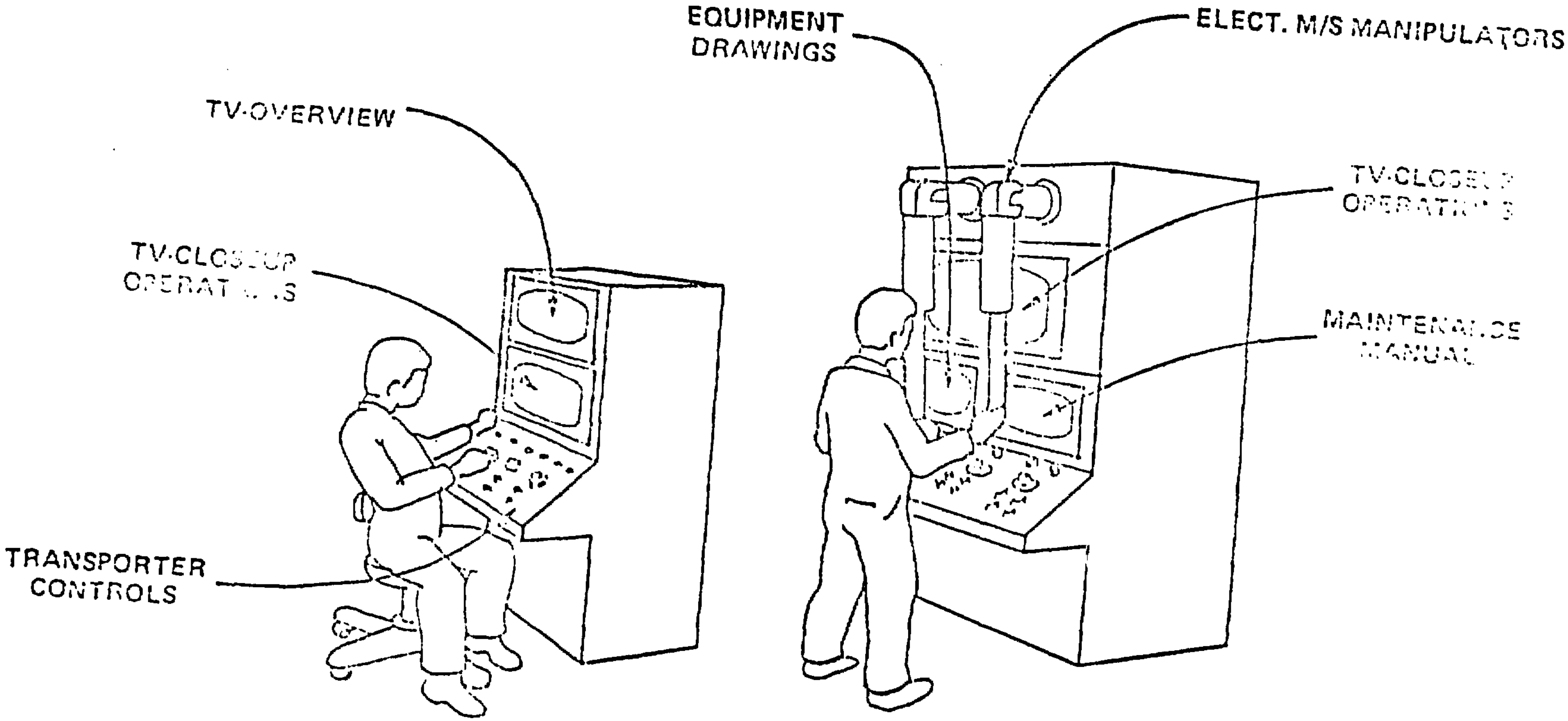


Fig. 11. Manipulator control station.



NAVIGATOR

- POSITIONS TRANSPORTERS
- PROGRAMS OPERATIONS
- PROCESS INTERFACE
- COLLISION CONTROL
- TV/LIGHTING CONTROL

OPERATOR

- PERFORMS REMOTE REPAIR
- DIAGNOSIS OF FAILURES

Fig. 11. Operating station for an electric master/slave manipulator system

It must be recognized that the master/slave manipulators do not have all the capabilities of man in performing repair tasks. They are versatile enough to permit the extensive use of commercially available components such as pipe connectors, electrical connectors, pumps, filters, etc. It will, however, take longer to make repairs with manipulators as compared to man. In cases where repair time must be minimized to maintain a high plant operating efficiency, the solution employed at HEF, is modular construction. Equipment items expected to have high failure rates will be contained in a remotely replaceable assembly. These component assemblies will be designed to be easily unbolted, removed, and new ones installed by the manipulators.

The process modules in HEF are large, and assemblies that are removable by the manipulators may be located anywhere within the volume of the module. It is necessary, therefore, to assure that the manipulator has access to these assemblies. In cases where an assembly cannot be handled by the manipulators, it will be necessary to use the overhead bridge crane; therefore, these assemblies must be located within the module so that overhead crane access is possible.

DEVELOPMENT REQUIREMENTS

Since 1978, we have investigated the plausibility of the required development activities for implementing Remotex in the HEF and have arrived at the conclusion that the utilization of this manipulation system is feasible and advantageous for nuclear fuel reprocessing. The basic technology exists in two commercially available bilateral force-reflecting manipulation systems: Central Research Laboratory's model M and TeleOperator System's model SM-229. There are, in addition, experimental manipulators being tested by Martin-Marietta Aerospace, Jet Propulsion Laboratory, MBAssociates, General Electric, Stanford Research Laboratories, Massachusetts Institute of Technology, the University of Florida, and Rockwell International.

We have instituted a program to pursue the developmental activities that our feasibility study indicated would need to be done so that advanced manipulator technology could be successfully applied to nuclear fuel reprocessing. These activities and their present status are described below.

Alternate power transmission schemes. The present technology uses cable connections to the slave transporter. The size of reprocessing facilities casts doubt on the fasibility of the use and maintenance of festooned cables. Both bus-bar power (contact and inductive) and battery power are actively being developed.

Wireless signal transmission. The length and number of conductors required for signal transmission of both the manipulator and the viewing systems indicate that wireless signal transmitters have distinct advantages. Inductive loop, laser, radio frequency, and infrared light-emitting-diode systems are commercially available. The adoption of these systems to our application is being pursued.

Manipulator repairability and capacity. The existing commercially available force-reflecting manipulators have an extended reach lift capacity of about 10 kg. An analysis of work tasks indicates that a handling capacity in the range of 20 to 25 kg would be much more useful. A development program for increased capacity, modular repair capability, and ease of decontamination is in progress with commercial vendors.

Transporter development. The concept adapted for the HEF involves center-aisle maintenance on equipment modules that are up to 50-ft high. The conceptual design of transporters capable of transversing a 600-ft-long "H" shaped cell and covering a 60-ft vertical area is being developed.

Television viewing systems. The concepts being developed rely totally on television viewing for all manipulator control. Cameras, lighting systems, and camera and lighting positioning systems that can be incorporated into the overall viewing system are being developed.

Man-Machine Interface. In an attempt to optimize manipulato operator functions, a series of studies has been undertaken to better understand those design areas that would increase operator efficiency and decrease operator fatigue and strain. Light source and camera position, in addition to the mode of visual presentation, are being studied. We are attempting to discern the factors that can maximize the operator's feeling of being at the place of operation – a sense of being "there".

CONCLUSIONS

Remotex is an engineering approach to efficient remote operations and maintenance. This concept has evolved from a decision to utilize developing force-reflecting manipulator technology. It is a summary of technologies developed in the 1970's that are being welded into operating systems in the 1980's and will be applied in the 1990's.

Although emphasis is placed on the design advantages affecting plant operating efficiency, additional advantages are apparent. With the reliance on television viewing (an electronic signal) and the electronic manipulator, all operations can be continuously monitored – an obvious positive safeguards attribute. It is highly probable that the manipulator and its transporter will be positioned by a computer with an obstacle-avoidance program. Whereas the computer will be responsible for directing the position of the manipulator, it can also, in a corollary program, restrict operations in proliferation-sensitive areas. The Remotex concept significantly reduces direct contact by operators with the process and with the product, which is a positive attribute in diversion resistance.

Concentration/Dilution

In its first 30 years of existence, the nuclear industry has, for practical reasons, followed a philosophy of dilution. That practice, although safe and acceptable for an infant industry, it neither wise nor acceptable today. That dilution philosophy was evident in the handling of liquid and gaseous effluents and in the exposure of personnel. The recent increase in public awareness, the changing rules and regulations in handling radioactive effluents (proposed and adopted), and a recognition by the nuclear industry of long-term impacts have precipitated a gradual transition from a philosophy of dilution to one of concentration, capture, and safe isolation of radioactivity. A parallel transition in the chemical industry is evident in today's newspapers. The HEF design approaches this problem in the areas of gaseous and liquid effluents, and the Remotex concept confronts occupational exposure.

Cost Impact

In a 1978 analysis of the cost of reprocessing, Exxon Nuclear Company[12] estimated the design and construction cost of a 1500-ton per year nuclear reprocessing plant at $1 billion. They also estimated the lifetime (20-year) operating cost (including capital cost) of that plant at $150 million per year. At the design capacity, that converts to a cost of $250 per kilogram of heavy metal. The calculation used 192 operating days per year as a base. Therefore, a 1% change in operating efficiency (on-stream efficiency) is equivalent to $3,600,000 per year. We estimate that the ability to operate can be increased by 10% over the 20-year lifetime of the plant with the utilization of advanced manipulation concepts represented by the Remotex concept. Ultimately, we believe that the increase in efficiency may be as high as 25% over the plant lifetime, but at the present development state, that is conjecture.

The Remotex concept is directly applicable to all segments of the nuclear and non-nuclear industries where work tasks or conditions exist that are hazardous to the health of man.

ACKNOWLEDGMENTS

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