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Consolidated Fuel Reprocessing Program

REMOTE MAINTENANCE IN NUCLEAR FUEL REPROCESSING

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ABSTRACT

Remote maintenance techniques applied in large-scale nuclear fuel reprocessing plants are reviewed with particular attention to the three major maintenance philosophy groupings: contact, remote crane canyon, and remote/contact. Examples are given, and the relative success of each type is discussed. Probable future directions for large-scale reprocessing plant maintenance are described along with advanced manipulation systems for application in the plants. The remote maintenance development program within the Consolidated Fuel Reprocessing Program at the Oak Ridge National Laboratory is also described.

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INTRODUCTION

Nuclear fuel reprocessing plants are designed and operated for recovery of plutonium and uranium from spent nuclear reactor fuels with most today using the Purex solvent extraction process. Highly radioactive fission products are separated and prepared for disposal. As seen in Table 1, large-scale fuel reprocessing plants have been built and operated in the United States, both for weapons production and for commercial recycle, from the mid-1940s until today. Fuel reprocessing (Figs. 1 and 2) resembles other similar large-scale chemical industry operations with the major difference being that working with large quantities of very highly radioactive materials requires the installation of process equipment within shielded enclosures and the application of remote operating and maintenance techniques.

In a reprocessing plant, as in any facility incorporating operation and maintenance with radioactive materials, the designs of the facility and cell equipment are strongly influenced by the repair philosophy and, if remotely maintained, the remote maintenance equipment capabilities. The facility and all in-cell equipment must be arranged to facilitate repair. This is true whether the maintenance philosophy is contact using man entry or remote using remote manipulation techniques. All in-cell equipment, from very large equipment modules to the smallest tubing jumper or gasket, must incorporate features necessary to allow the maintenance system to accomplish its task. Lack of consideration of these issues during facility design and construction can result in exceedingly long outage times when failures in process equipment occur.

A modern, large reprocessing plant designed for commercial light-water Reactor (LWR), breeder reactor, and/or other advanced reactor fuels would be sized for a throughput in the range 0.5 to 5.0 metric tons of heavy metal

Table 1. Major reprocessing facilities in the United States

Process	Plant location or name	Number of facilities	Date of construction	Type of maintenance
Bismuth phosphate precipitation	Hanford	3[a]	1944	Remote crane canyon[b]
Redox	Hanford	1	1948	Remote crane canyon[b]
Electrochemical and chemical dissolution; TBP and hexone solvent extraction	Idaho Chemical Processing	1	1953	Contact
Purex	Hanford	1	1956	Remote crane canyon[c]
Purex	Savannah River	2	1954	Remote crane canyon[c]
Pyromet	EBR-II Fuel Cycle Facility	1	1963	Total remote
Chop-leach, Purex	Nuclear Fuel Services	1	1966	Remote/contact
Aquafluor	Midwest	1	1974	Remote
Chop-leach, Purex	Barnwell Nuclear Fuel Plant	1	1976	Remote/contact

[a]Only two were operated.
[b]Limited to removal and replacement.
[c]Minimal repair of process equipment, and that only by contact means after decomtamination.

fuel material per day. Based on studies by the Consolidated Fuel Reprocessing Program (CFRP), a totally remotely maintained plant of this throughput would consist of remotely operated process cells about 12 m wide, 15 to 30 m tall with a cell length of more than 300 m. This large volume could be subdivided into three major process functional groupings: the mechanical head-end area, the main process area (chemical separation, purification, and waste processing), and the product conversion area. The mechanical head-end area of a fuel reprocessing plant typically incorporates equipment that (1) cleans residual sodium (when the fuel is from sodium-cooled fast reactors) and partially disassembles the fuel assemblies in preparation for shearing and (2) shears the fuel assemblies into 2.5- to 7.5-cm-long rod sections to expose the fuel for dissolution. The head-end will include very heavy equipment, such as the shear, which requires significant modularization into smaller components. A head-end for other reactor types would have different types of equipment but with similar requirements. Whatever the feed material, this is complex mechanical equipment that is expected to have a significant number of failures during the plant lifetime. Preventive maintenance and mechanical adjustments will be required. The complexity of this equipment, along with the need for regular preventive maintenance and mechanical adjustments, requires dexterous remote manipulation with coverage over large volumes of cell space.

The main process area of a reprocessing plant is, by far, the largest portion from a cell volume standpoint. It is within this area that (1) the spent fuel material is dissolved out of the fuel rod sections; (2) the usable fissile fuel and fission product waste are separated; (3) the fuel is purified and stored as a liquid; (4) the high-level fission product waste is collected, concentrated, and packaged for disposal; and (5) all other solid, liquid, and gaseous wastes are treated as required for recycle or safe disposal. Equipment in the main process area is dominated by various sizes of chemical equipment such as tanks, columns, and evaporators. Large amounts of piping are required to both interconnect this equipment in the cell and to bring utility services from outside the cell. This equipment has demonstrated relatively low failure rates in this type of application. The equipment can be grouped into large racks, or modules, to facilitate handling should a failure occur. Removal of a module for either maintenance or equipment upgrade involves disconnecting a large number of piping and electrical connections, as well as handling very large, heavy equipment. This can result in low plant availability if required often. Although equipment failures are typically considered to be an infrequent occurrence, it should be noted that every major process vessel type was replaced at least once during operation of the Hanford Purex Plant.[1]

Although the main process area equipment is composed predominately of equipment with low failure rates, there are a number of small equipment items with significant probability of failure during the plant lifetime. These can include pumps, valves, tube bundles, in-line instruments and filters. To maintain a reasonably high plant availability, these items should be replaceable without the necessity of removing the large modules.

Finally, the product conversion area of the reprocessing plant involves equipment associated with converting the liquid fissile fuel material solution into a powder and packaging this powder for shipment to the fuel fabrication facility. Product conversion equipment tends to be rather small and lightweight, but it is typically mechanically complex, and a significant number of failures can be expected during the plant lifetime. The complexity of this equipment, along with the need for preventive maintenance and mechanical adjustments, requires the application of rather dexterous remote manipulation, but over a relatively small hot-cell volume.

HISTORY OF U.S. REPROCESSING PLANT MAINTENANCE

Large-scale reprocessing plants that have been built in the United States can generally be grouped into three basic maintenance philosophy categories: (1) contact-maintained cells, (2) remote crane canyon, and (3) combined remote/contact maintained cells. The historical evolution of these basic types of plants in the United States is illustrated in Fig. 3 taken from Ref. 1 and in Table 1. The remote crane canyon plants, evolving from the Bismuth Phosphate Plants (start-up 1944), were the earliest application of remote maintenance in large reprocessing plants. The Savannah River Purex Plant, started up in 1954 and operating today, and the Hanford Purex Plant, started up in 1956 and currently back in service after shutdown in 1972, are examples of the remote crane canyon maintenance concept. A cross section of the Savannah River Purex Plant can be seen in Fig. 4, while Fig. 5 illustrates the warm canyon in-cell equipment arrangement. A cross section of the Hanford Purex plant is shown in Fig. 6 and an exterior view in Fig. 7. Figures 8, 9, and 10 illustrate the in-cell equipment arrangement of the Hanford Purex Plant. Equipment removal and replacement in these plants are accomplished principally by simple overhead cranes. An impact wrench carried by a crane hook is used to loosen fasteners on equipment and piping connectors. The crane then provides the equipment removal, transportation, and replacement capability. This maintenance technology has been successfully demonstrated in these and other government reprocessing facilities for almost 40 years.[1,2,3,4] The Savannah River Purex Plant certainly earns recognition as the U.S. reprocessing plant with the greatest longevity. The availability of this plant during the first 25 years of operation is reported to have been over 80%.[2] It does not appear, however, that production demand was very close to capacity. The average annual occupational radiation dose of workers ranged from 0.70 to 0.32 rem between 1965 and 1979.[2] Note that the government remote crane canyon facilities have not required the large and complex mechanical systems associated with the head-end of commercial reprocessing plants.

The Idaho Chemical Processing Plant (ICPP) is typical of a reprocessing plant designed for contact maintenance. The ICPP was started up in 1953 and remains in operation today. The ICPP was designed based on the successful experiences at the Oak Ridge Pilot Plant. Since the ICPP had much smaller throughput and more complex head-end processes than the remote crane canyon plants, a more conservative approach which would minimize risk was followed.[5] The radioactive process equipment is contained in a large number of separate small cells with a small number of equipment items in each cell. These cells are provided with equipment to effect decontamination of both the process equipment and cell walls prior to entry for maintenance. To keep plant availability high, installed equipment redundancy is provided, and high-failure-rate components are located out of cell. Although little information is available regarding the efficiency of operation of the ICPP, it should be noted that a new facility, the Fuel Processing Restoration Facility (FPR), is being designed to replace the solvent extraction and denitration portions of the present ICPP. One of the reasons for this new facility is increasing failure rates due to age of the present equipment. The FPR will group all failure-prone equipment into common areas that will be designed for remote operation and maintenance to reduce personnel radiation exposure and improve contamination control.

The Nuclear Fuel Services (NFS) plant and the Barnwell Nuclear Fuels Plant (BNFP) are examples of the combined remote/contact plant design philosophy. The NFS plant, the first large-scale plant for reprocessing of commercial LWR fuels, began operation in 1966 and shut down in 1972. Construction of the BNFP was completed in 1976, but the plant was never started up. These plants were designed for recycle of commercial spent LWR fuels. The mechanical complexity of the required head-end operations increases significantly when processing commercial LWR fuels. The mechanical head-end portions and high-radiation chemical process portions of these plants were designed for maintenance using a combination of cranes, power manipulators, and mechanical master/slave manipulators. The downstream chemical process portions of these plants were judged to have high inherent reliability and were designed for contact maintenance.

The average on-stream operating efficiency over the NFS plant life was apparently less than 60% of plant design capacity, although fuel availability may have influenced this to some extent. It appears that the occupational radiation dose to workers was significantly higher than that experienced at the remote crane canyon plants.

Techniques for total remote maintenance of a fuel reprocessing installation were successfully applied in the Fuel Cycle Facility (FCF)[6] operated by Argonne National Laboratory. The FCF used pyrochemical reprocessing techniques to recycle fuel from the Experimental Breeder Reactor-II from 1964 to 1969. The FCF successfully demonstrated remote maintenance of both process as well as remote handling equipment.

FUTURE DIRECTIONS IN REPROCESSING PLANT MAINTENANCE

Today's efforts in the area of defense fuel reprocessing in the United States are aimed primarily at upgrading and improving the present facilities.

The Savannah River Purex Plant continues to function in an outstanding manner. There are efforts to improve the efficiency of the overhead maintenance cranes and to improve overall viewing with television systems. The Defense Waste Processing Facility (DWPF) is a major new addition to the Savannah River Plant (SRP) facilities for the vitrification of high-level waste. The DWPF will incorporate the remote crane canyon maintenance concept with a remote-controlled crane and television viewing.[7] The Hanford Purex Plant remote crane canyon plant has been refurbished and is returning to full operation.

At the ICPP, the New Waste Calcining Facility (NWCF) began operation in 1982 to process ICPP high-level wastes. The NWCF utilizes a combination of total remote maintenance for equipment expected to have high failure rates and contact maintenance for equipment with lower expected failure rates.[8] The remote maintenance capabilities of the NWCF have already demonstrated much improved plant availability and reduced personnel radiation exposure during unscheduled maintenance activities compared to the previous contact-maintained Waste Calcining Facility (WCF) In addition, the FPR project with construction scheduled for completion in 1991, will add significant remote maintenance capabilities to the ICPP.

The BNFP was to be the next step in the evolution of commercial reprocessing of LWR fuels in the United States. Commercial operation of this plant was indefinitely postponed in 1977 due to the Carter Administration's deferral of commercial fuel reprocessing in the United States. The BNFP was finally shutdown totally in 1983 and the plant personnel have been released. With shutdown of the BNFP efforts, the likelihood of processing commercial fuels in the United States within the next decade is nil.[10]

The CFRP at the Oak Ridge National Laboratory (ORNL) is responsible for U.S. research and development of all facets of advanced nuclear fuel reprocessing applicable to the commercial nuclear power fuel cycle. The primary emphasis of the CFRP is on breeder reprocessing development. A major aspect of the CFRP is the development of improved facility concepts that reduce personnel radiation exposure, reduce environmental impact, and increase operational availability over the entire design life cycle. New plant concepts developed by the CFRP are also giving full consideration to provisions that are essential for the decontamination and decommissioning at the end of useful plant life.

To meet the new challenges presented by increased facility performance objectives and the general increase in remote operations complexity associated with many of the advanced process systems (e.g., rotary dissolvers, centrifugal solvent extraction contactors), the CFRP has committed to the Teletec concept (formerly called Remotex).[5] Teletec is based on the use of force-reflecting bilateral servomanipulators and closed-circuit television viewing (in addition to conventional cranes) as principal remote maintenance tools. The historical perspective, underlying philosophy, and supporting research behind the CFRP commitment to Teletec are given in Refs. 5 and 11.

The initial application of the Teletec maintenance concept by the CFRP was in the conceptual design of a 0.5 metric ton per day breeder fuel reprocessing facility called the Hot Experimental Facility (HEF).[12] The HEF concept called for a large, single barn-like cell for the major reprocessing steps with equipment mounted in remotely removable equipment modules on the cell side walls as shown in Fig. 11. The center-aisle of the process cell was utilized for access to process equipment by a force-reflecting servomanipulator-based remote maintenance system to be used for rapid in situ process component replacement. Although the HEF was not funded for construction, the basic validity and benefits of this design concept have been recognized worldwide. The German WA 350 LWR reprocessing plant, with a very similar cell layout and maintenance approach to the HEF concept though using power manipulators, is planned with construction to begin this year.[13] In addition, the Japanese FBR Fuel Recycling Pilot Plant for breeder fuels, taking into consideration experiences at the Tokai LWR Reprocessing Plant, will utilize a HEF-type cell arrangement with force-reflecting servomanipulators.[14] Construction of this facility will begin in 1989. The CFRP has carried forward this plant design concept in the United States in the Breeder Reprocessing Engineering Test (BRET) Facility design. The BRET was a 0.1 metric ton per day breeder reprocessing pilot plant designed to handle spent fuel from FFTF and CRBR and to be installed at Hanford, Washington.[15] The project has now been deferred. A cross section of the BRET reprocessing cell is given in Fig. 12.

REMOTE MAINTENANCE DEVELOPMENTS AT ORNL

For the past six years, the Remote Control Engineering (RCE) Task within the CFRP at ORNL has been developing techniques, equipment, and guidelines to improve the efficiency of remote maintenance operations. This work is based on the use of force-reflecting servomanipulators for dexterous manipulation over large cell volumes, television viewing of the task site, and man-in-the-loop teleoperation for nonrepetitive tasks in unstructured environments. The increased dexterity of force-reflecting servomanipulators will unquestionably increase the range of accomplishable work tasks. This will in turn reduce capital costs by decreasing remote design provisions in process equipment, increase plant operating efficiency by decreasing mean time to repair, and enhance the remote maintenance system's inherent ability to respond to unexpected failure events.

The CFRP is developing reprocessing plant concepts, such as HEF and BRET, which utilize the benefits of servomanipulator-based maintenance throughout the remote process cell areas. Future commercial plants may adopt this method or may use servomanipulator-based maintenance for the head-end areas with one of the other maintenance scenarios described earlier in the balance of the plant. This, of course, will be guided by future trade-offs of complexity, reliability, and plant cost.

The RCE development program covers all aspects of an advanced remote maintenance system that will reliably meet the requirements of future reprocessing. The key elements of the new system are an improved servomanipulator concept and the development of electronics and video technology that is compatible with the harsh reprocessing environment. The new servomanipulator, the Advanced Servomanipulator (ASM) shown in Figs. 13 and 14, will use an all-gear drive force transmission system to increase reliability, and modularization will make remote maintenance of the manipulator itself possible.[16] A new light-duty master controller, shown in Fig. 15, is being designed for use with the ASM.[17] A state-of-the-art microprocessor-based control system (Fig. 16) is being developed to allow advanced servocontrol algorithms, on-line self diagnosis, and more reliable, maintenance-free operation.[18] The ASMs will be positioned in-cell using a four-degree-of-freedom overhead transporter based on stacker-crane technology as shown in Fig. 17. The operator control station, shown in Fig. 18, is designed for improved operator efficiency through flexible graphic displays and proper attention to human factors.[19] These components, along with an advanced microwave-based signal transmission system and improved radiation-resistant television cameras, are being assembled at ORNL into a mockup maintenance demonstration system call the Advanced Integrated Maintenance System (AIMS) shown in Fig. 19. The AIMS is scheduled to go into full maintenance demonstration operation in 1986.

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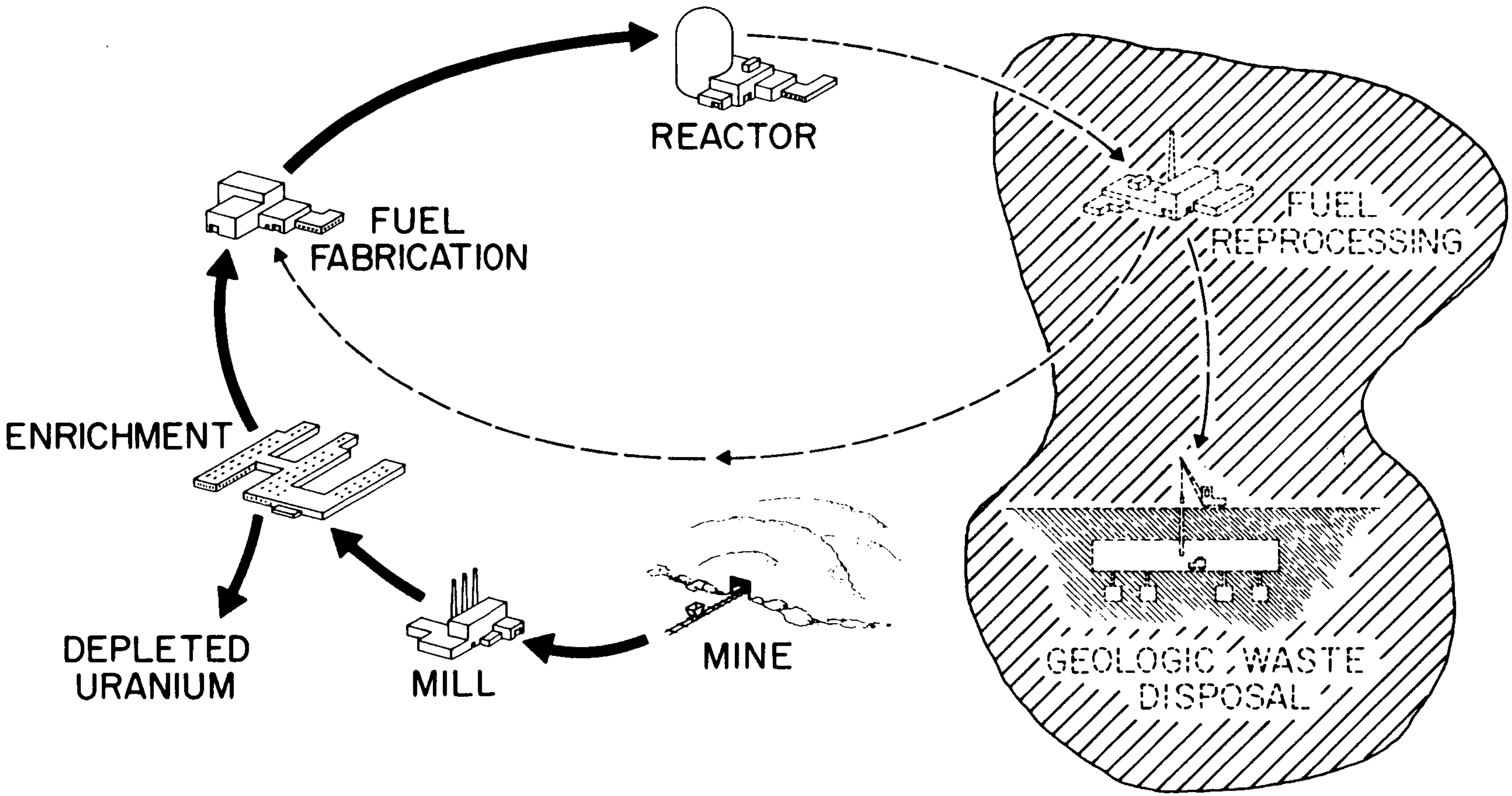


Fig. 1. Commerical LWR fuel cycle today.

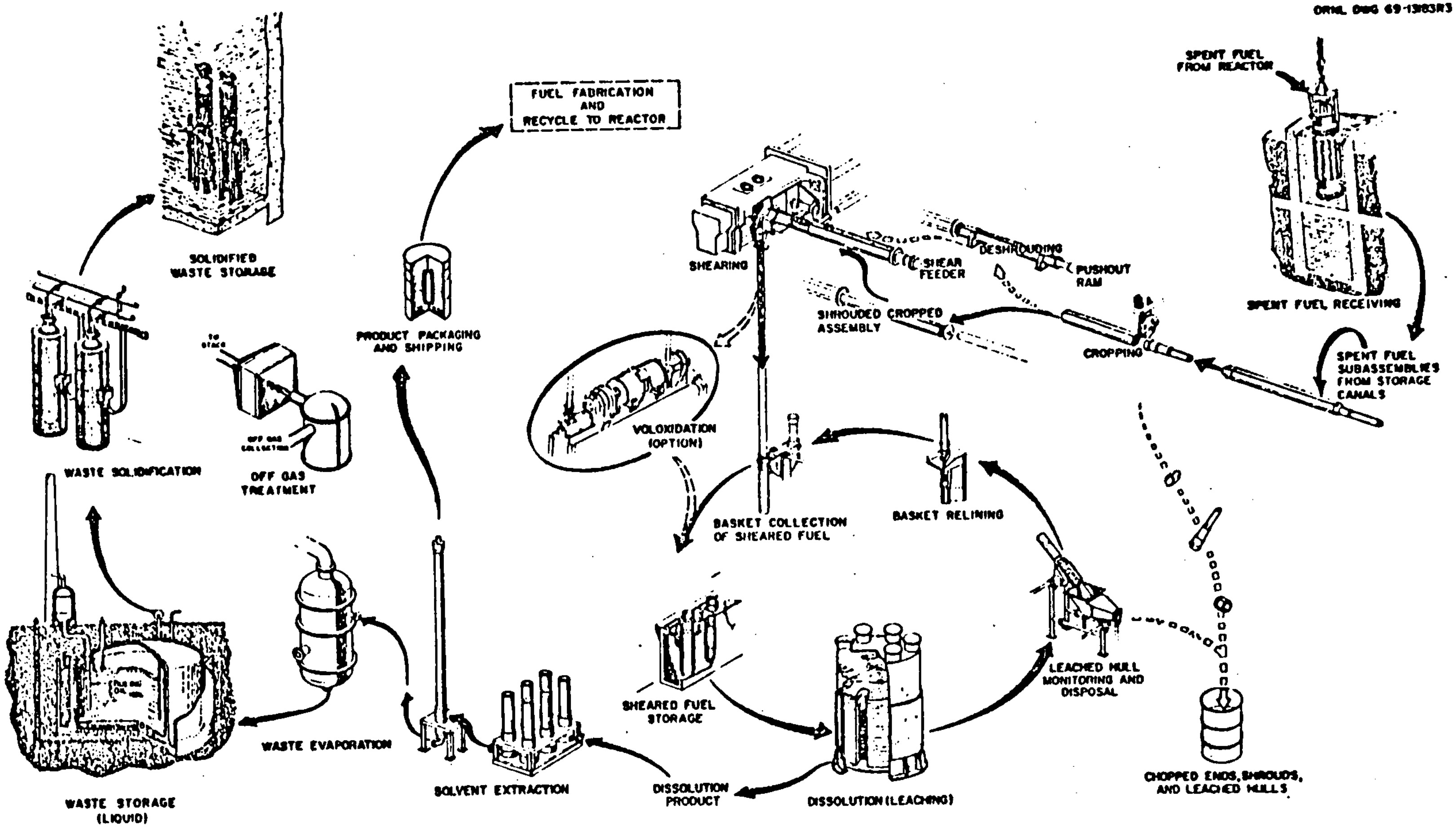


Fig. 2. Typical reprocessing of power reactor spent fuel.

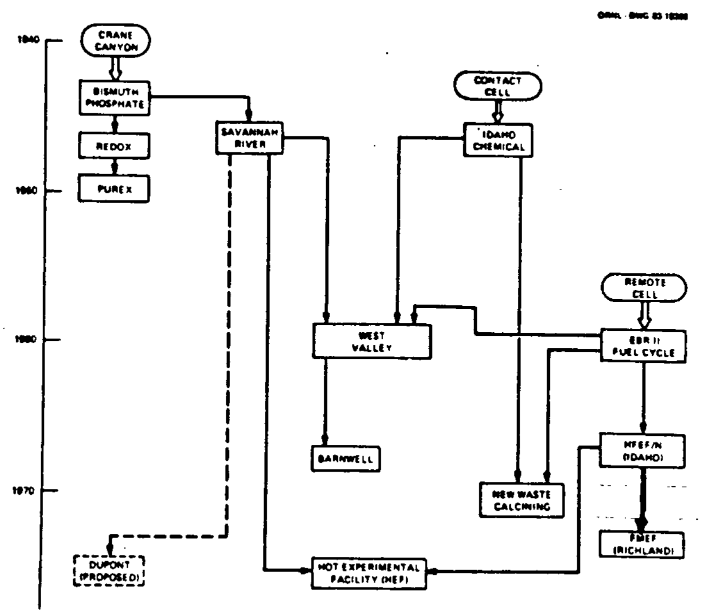


Fig. 3. Historical evolution of fuel reprocessing plant maintenance (from Ref. 1)

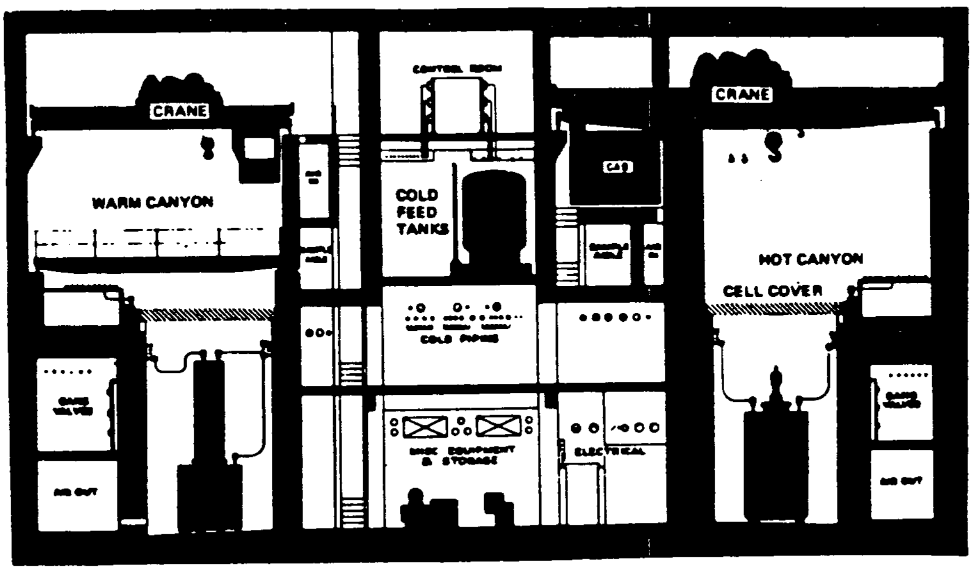


Fig. 4. Typical cross section of Savannah River Plant.

Fig. 5. Interior of the Savannah River Plant.

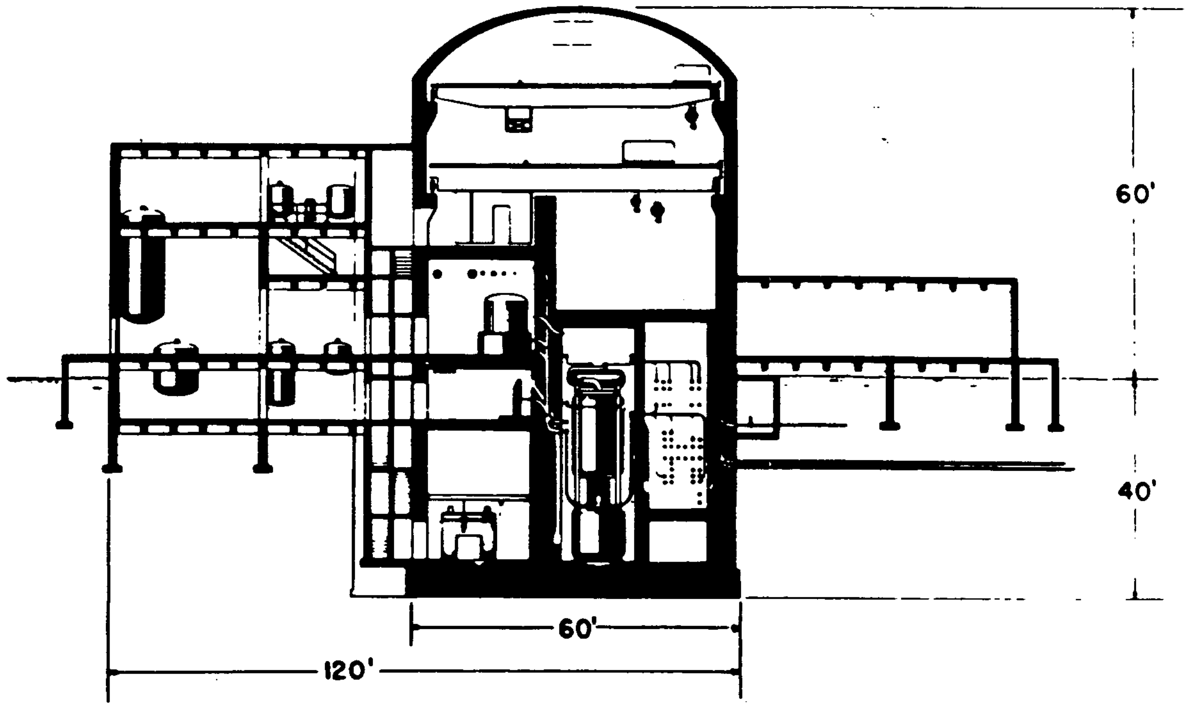


Fig. 6. Typical cross section of the Hanford Purex Plant.

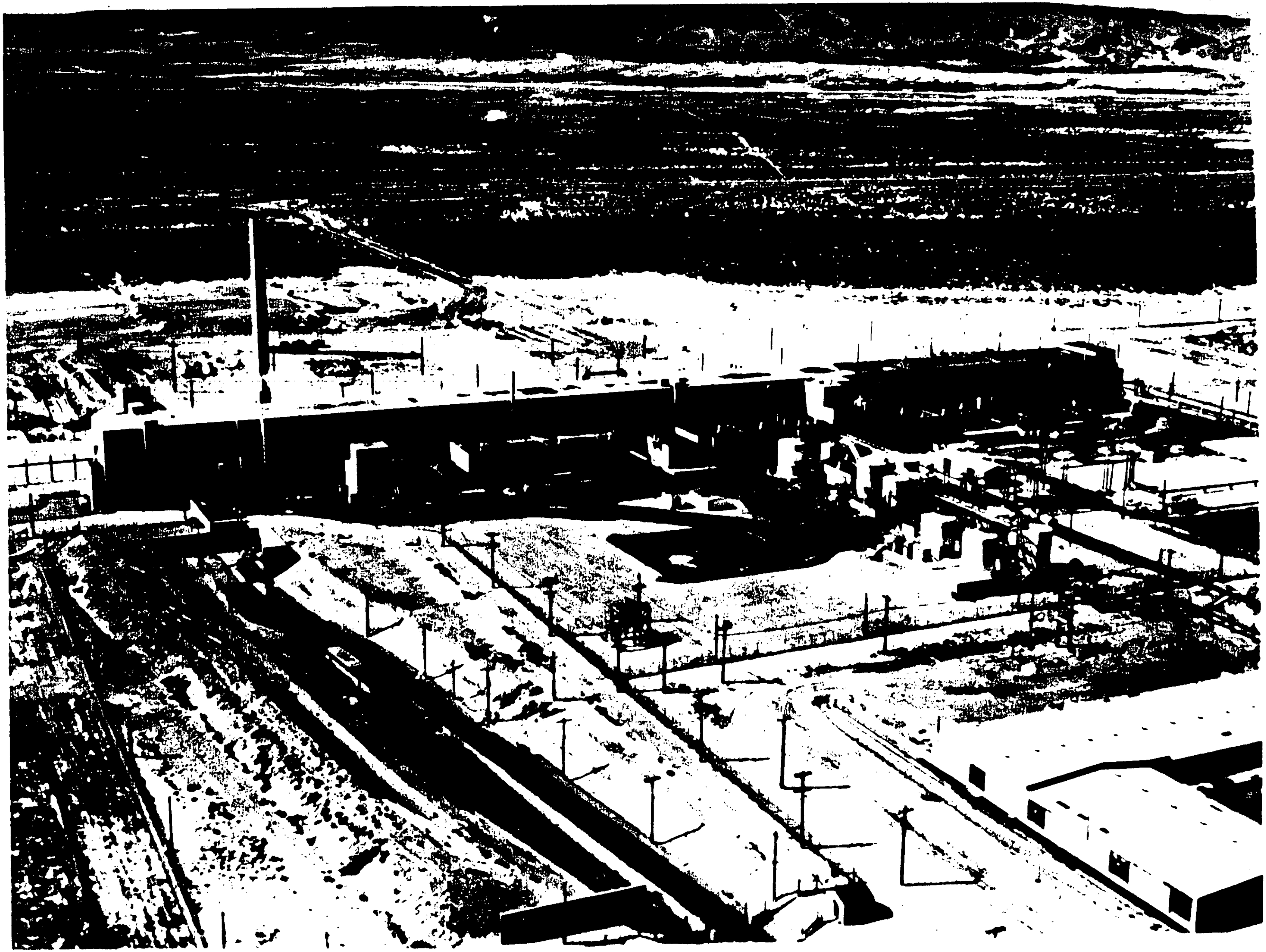


Fig. 7. Hanford Purex Plant.

Fig. 8. Interior of the Hanford Purex Plant.

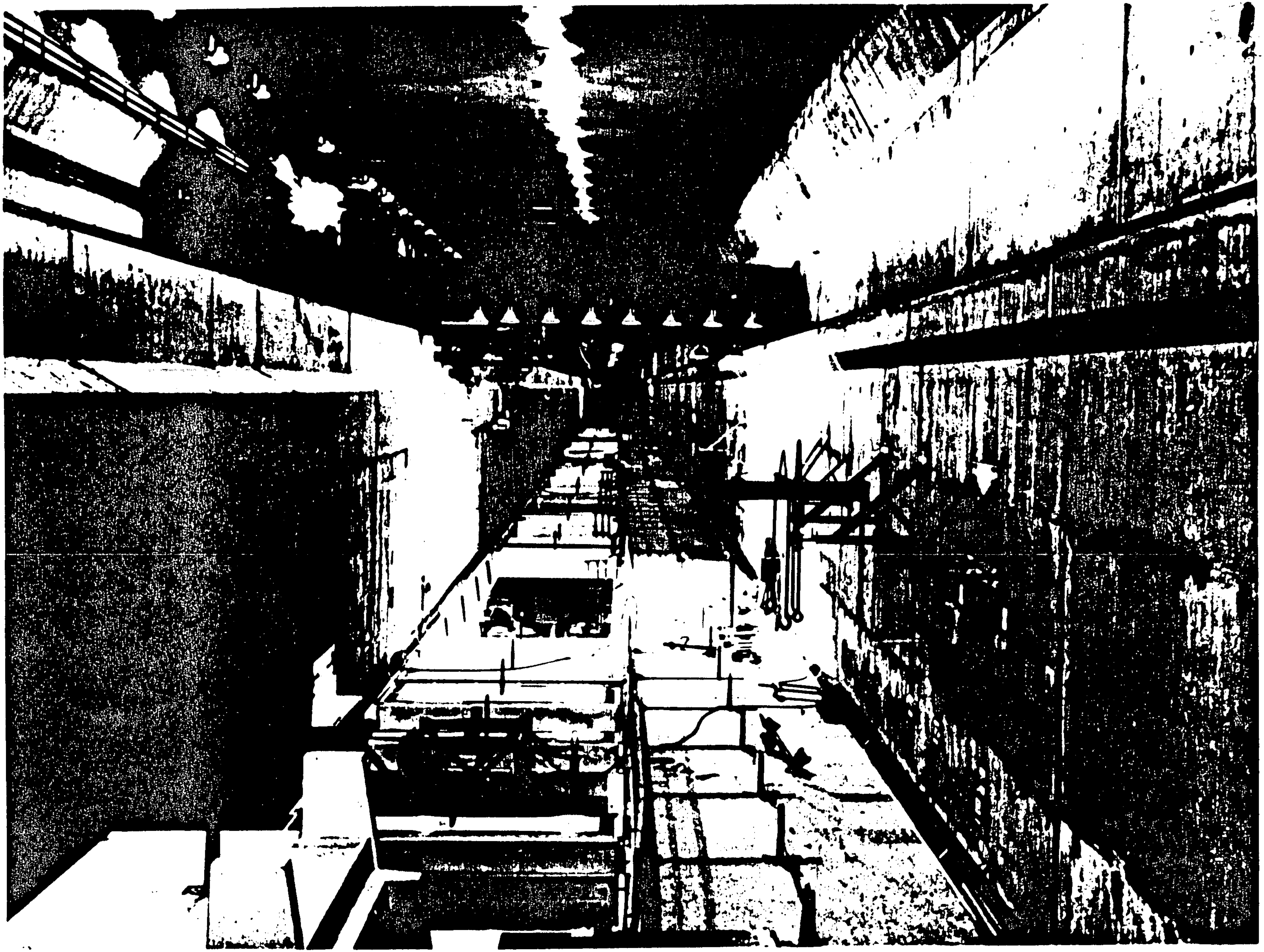
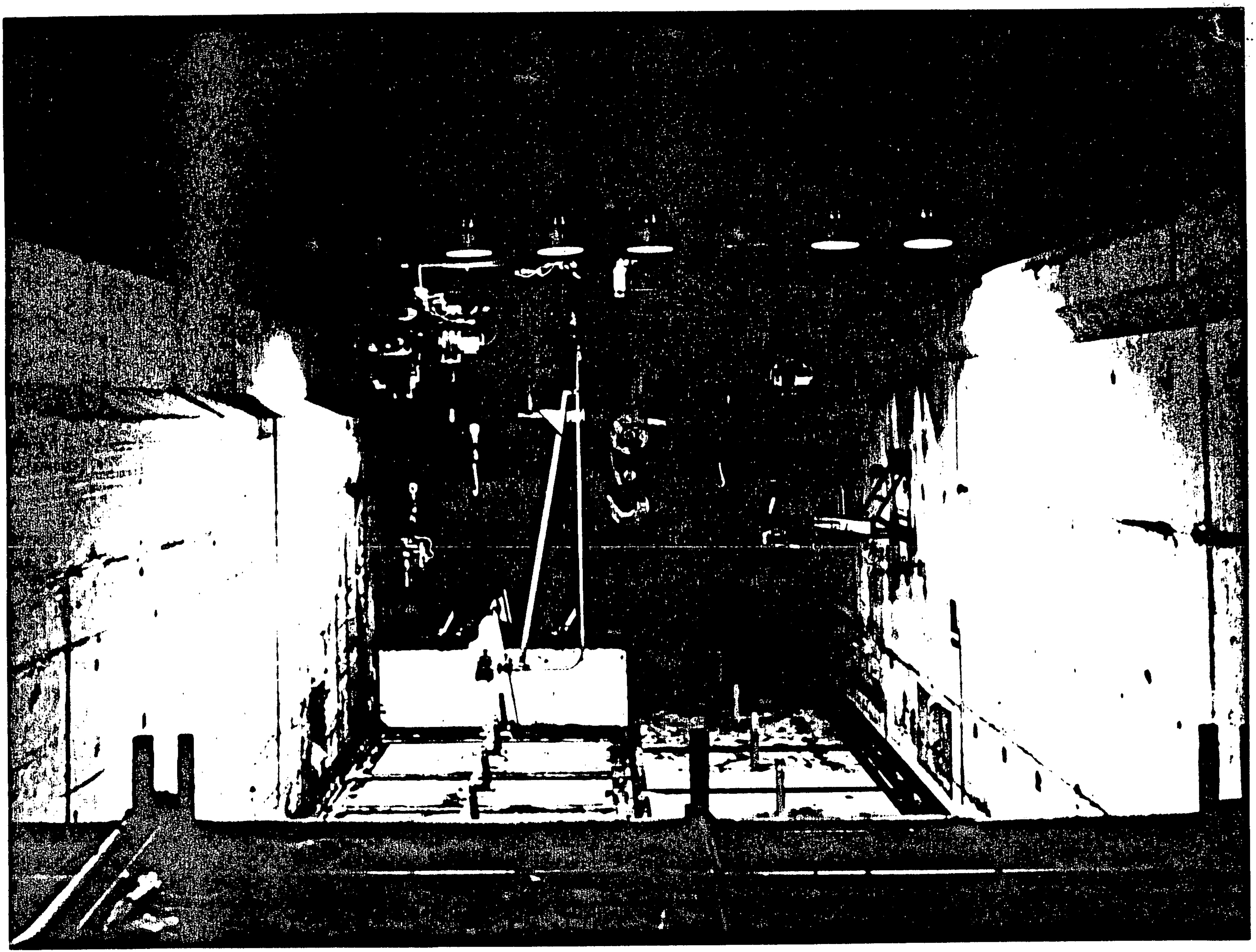


Fig. 9. Hanford Purex Plant maintenance crane.



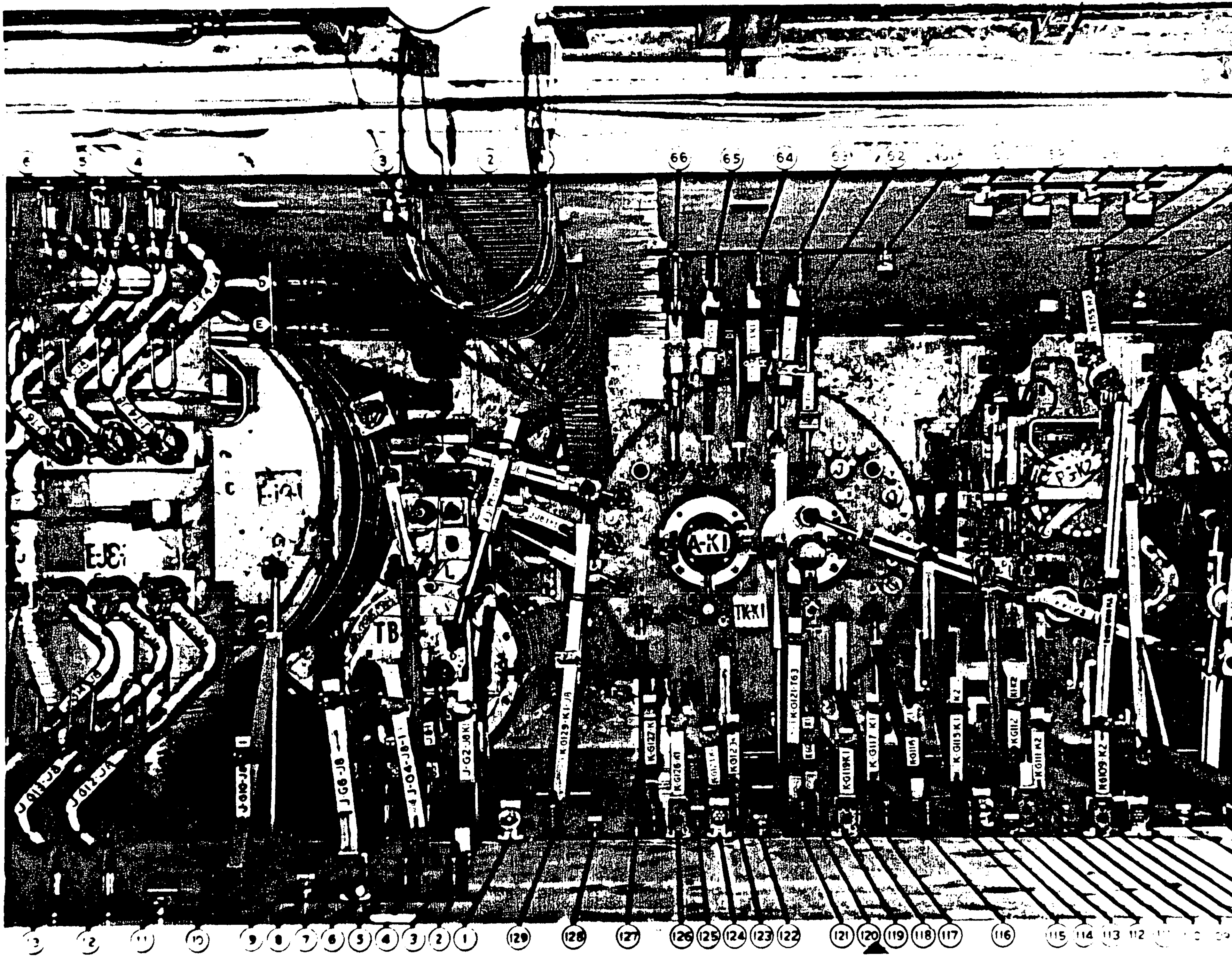


Fig. 10. Hanford Purex Plant typical remote equipment.

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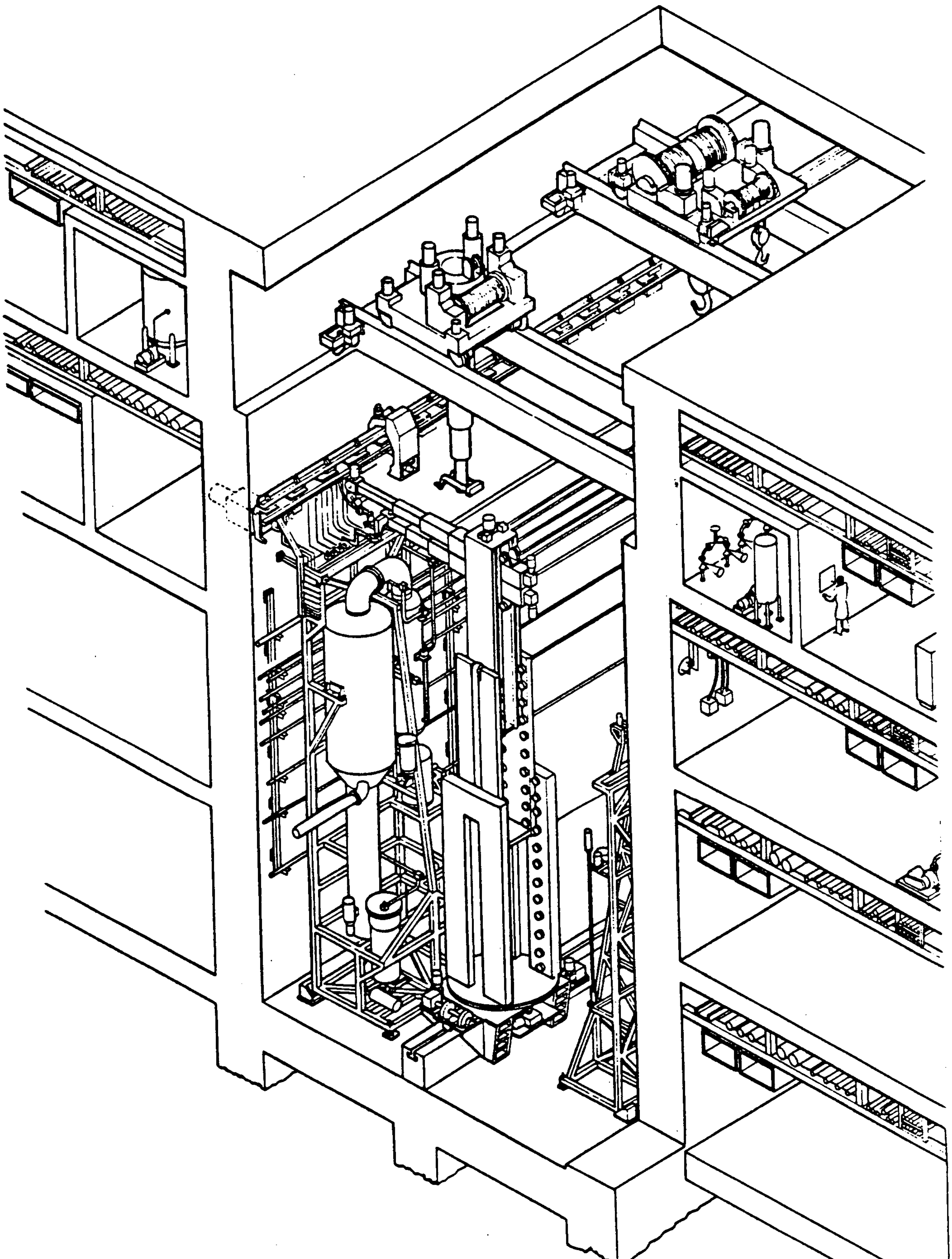

Fig. 11. Hot Experimental Facility Cell arrangement.

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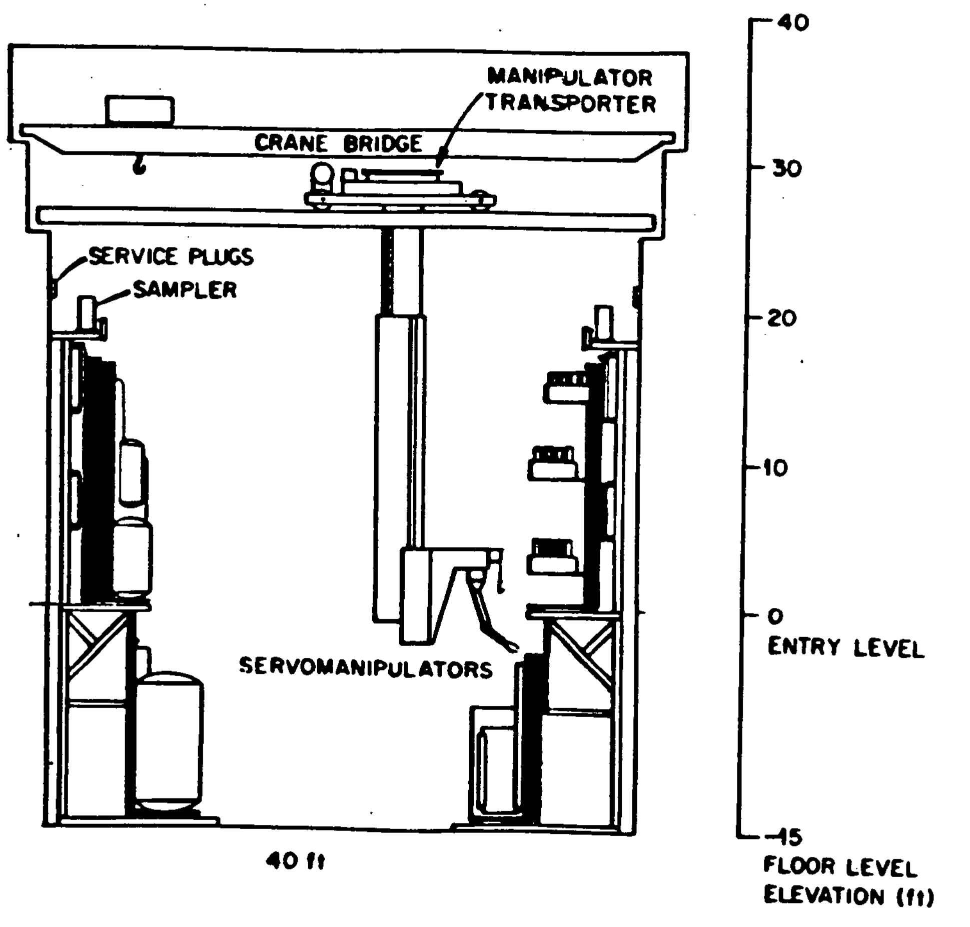


Fig. 12. Cross section of Breeder Reprocessing Engineering Test

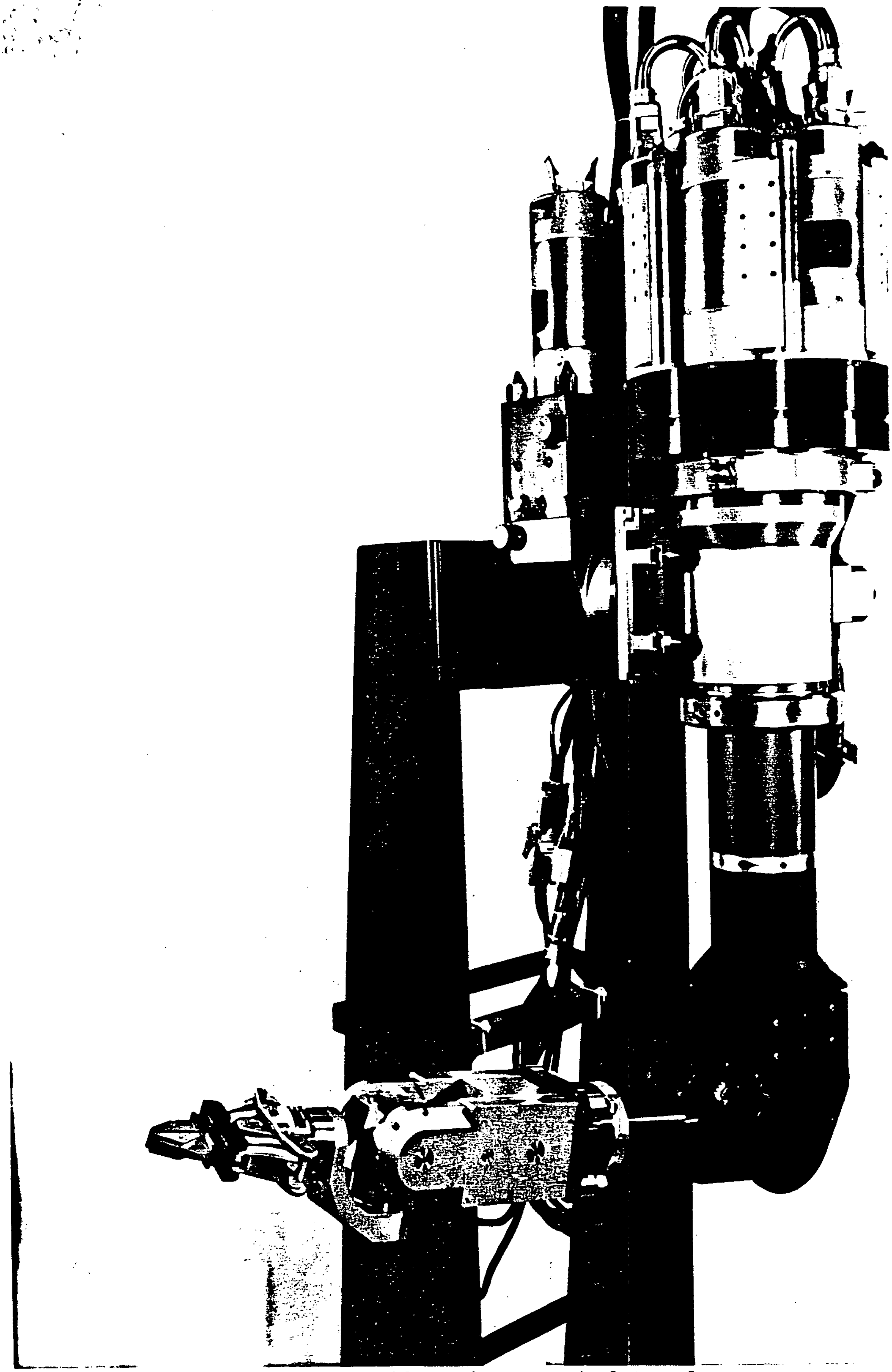


Fig. 13. Advanced servomanipulator slave arm.

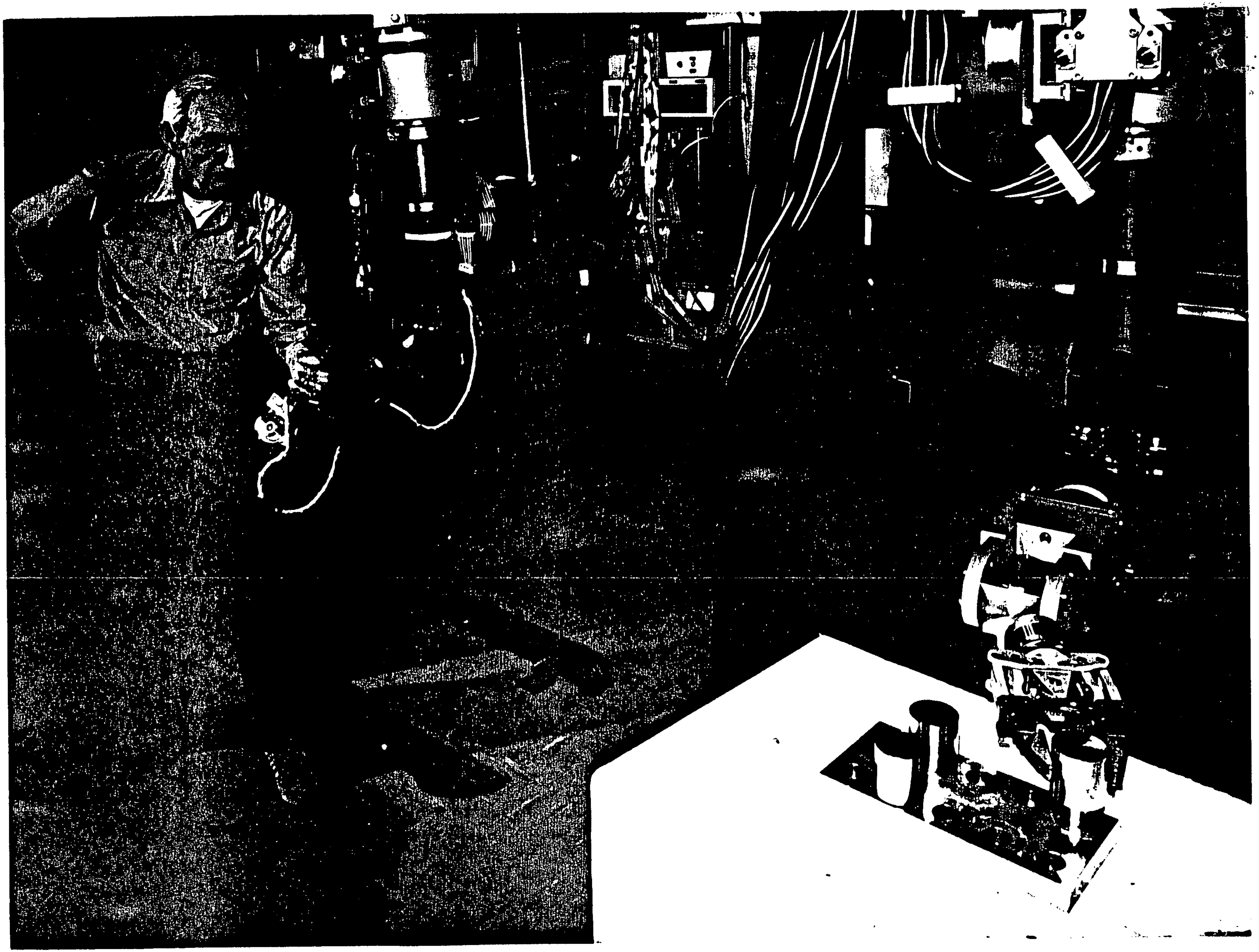


Fig. 14. Advanced servomanipulator master/slave operation.

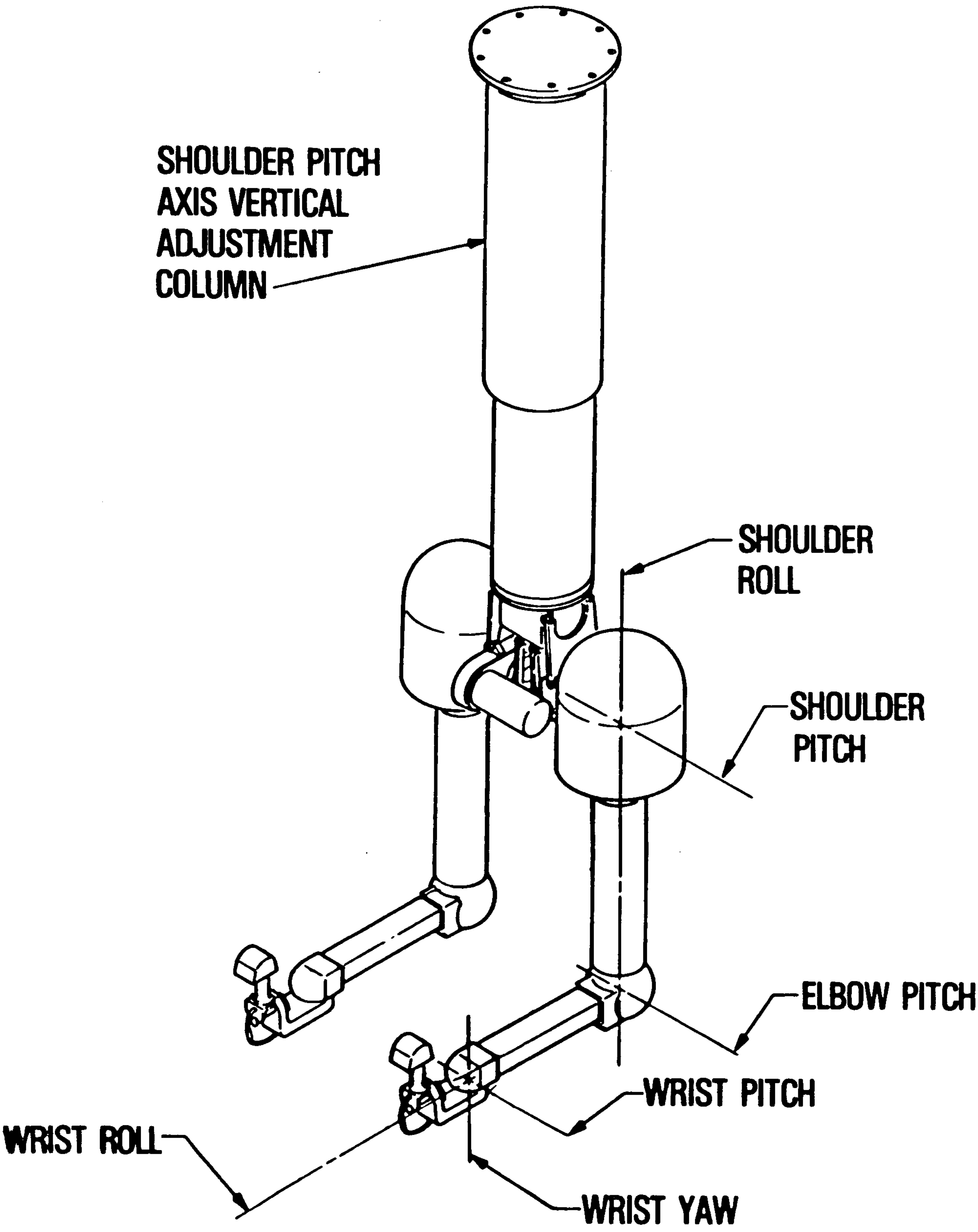


Fig. 15. Advanced servomanipulator master controller.

Fig. 16. Advanced servomanipulator control system.

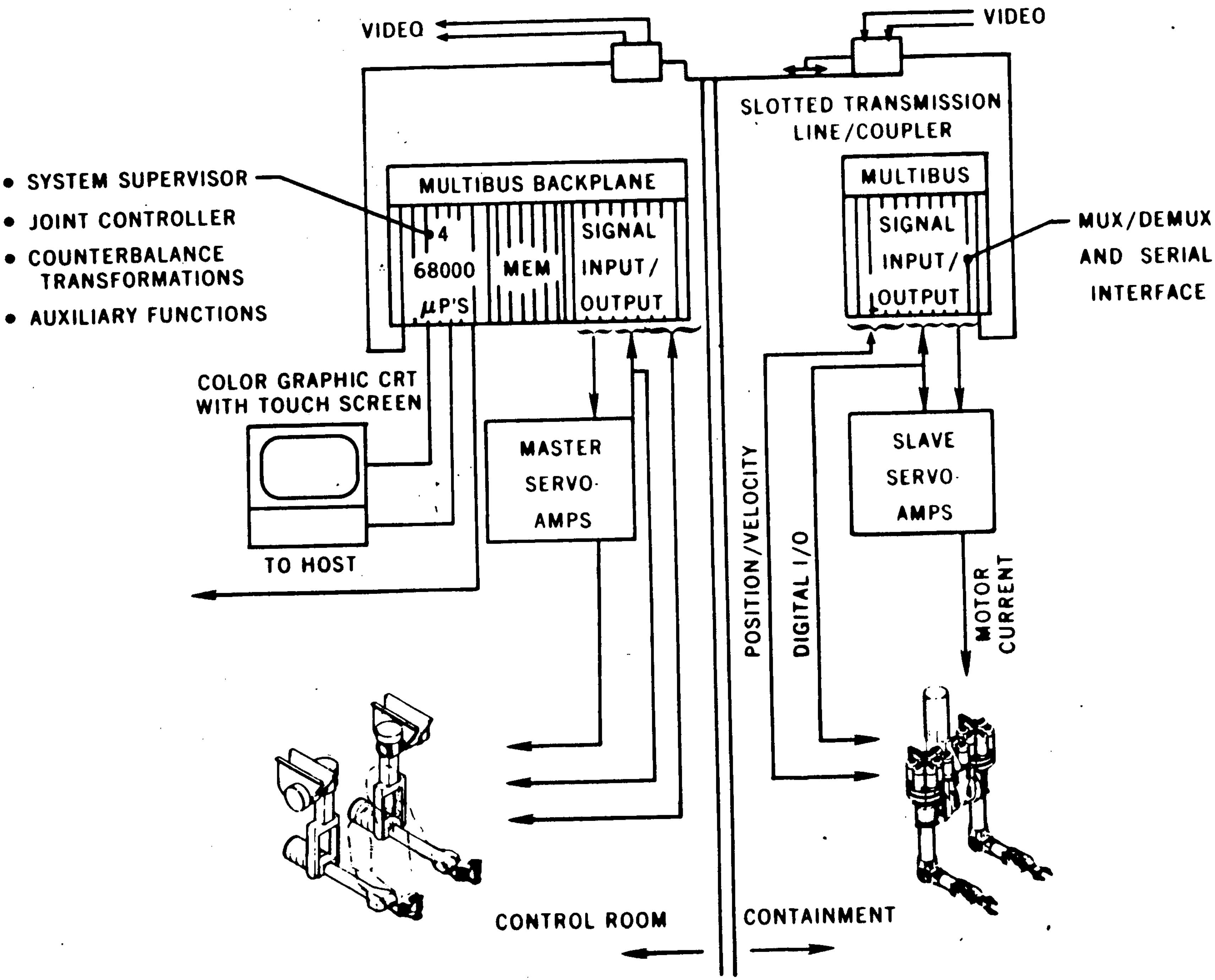
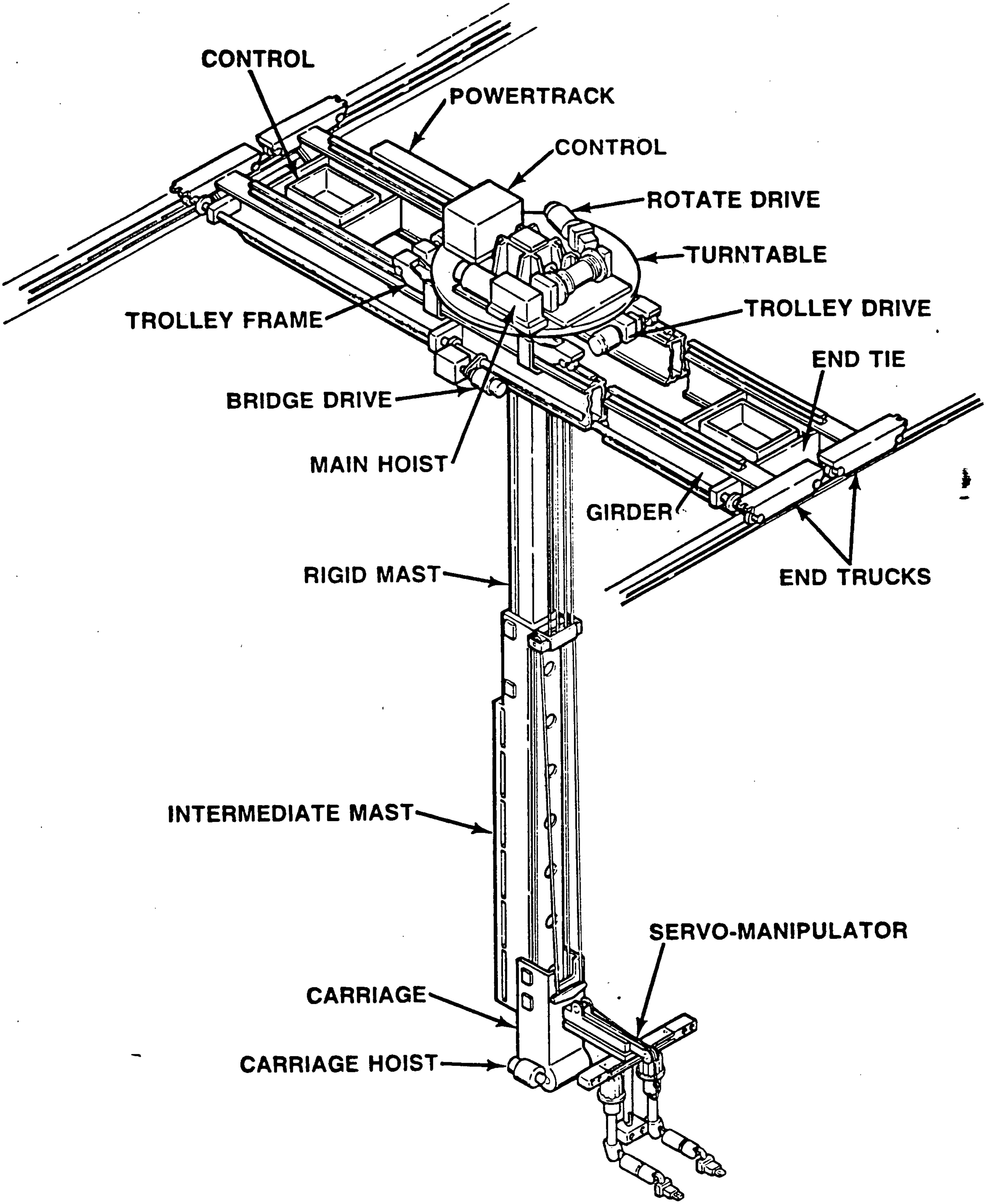


Fig. 17. Transporter for future reprocessing plant application.



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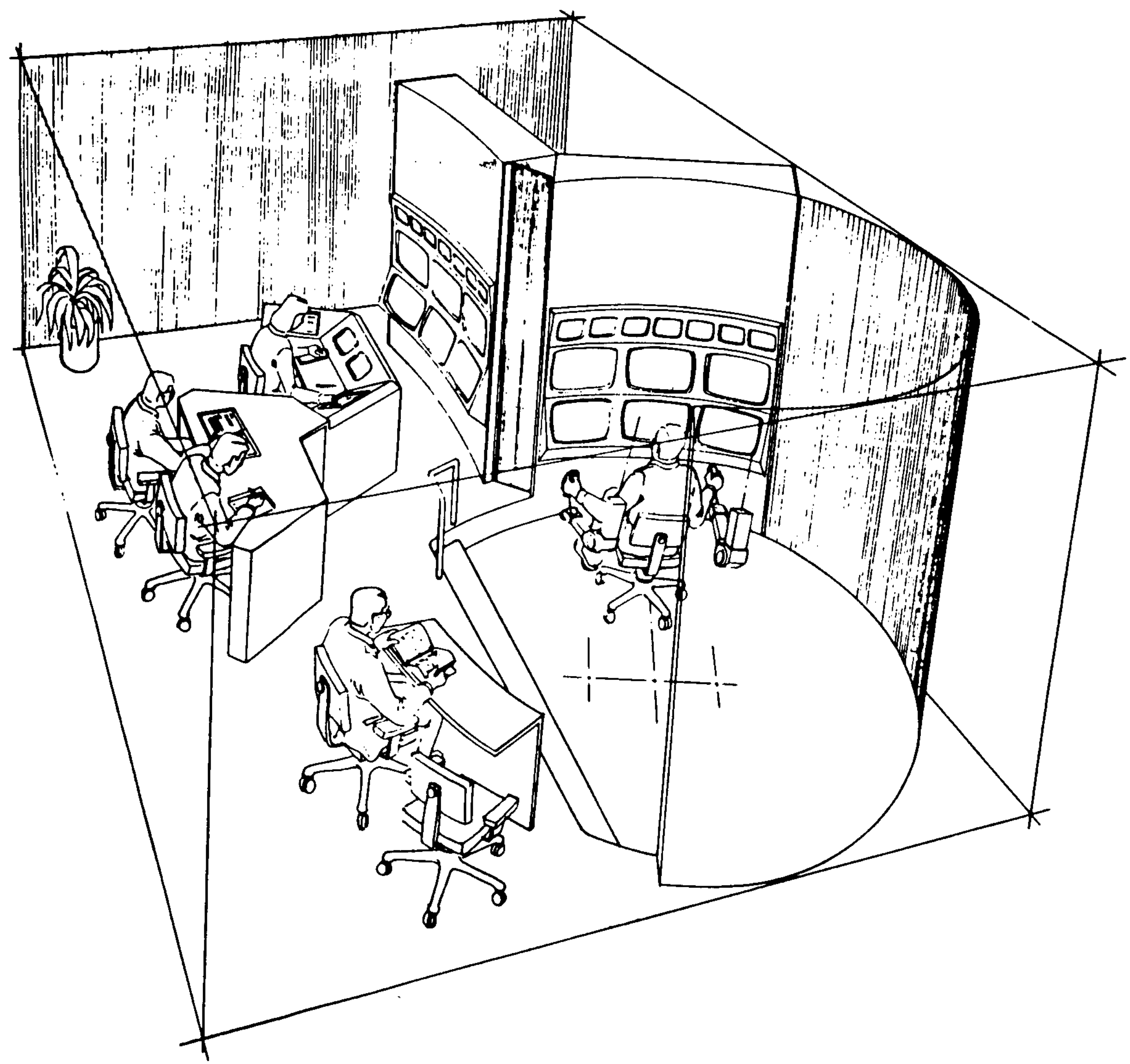

Fig. 18. Operator control station.

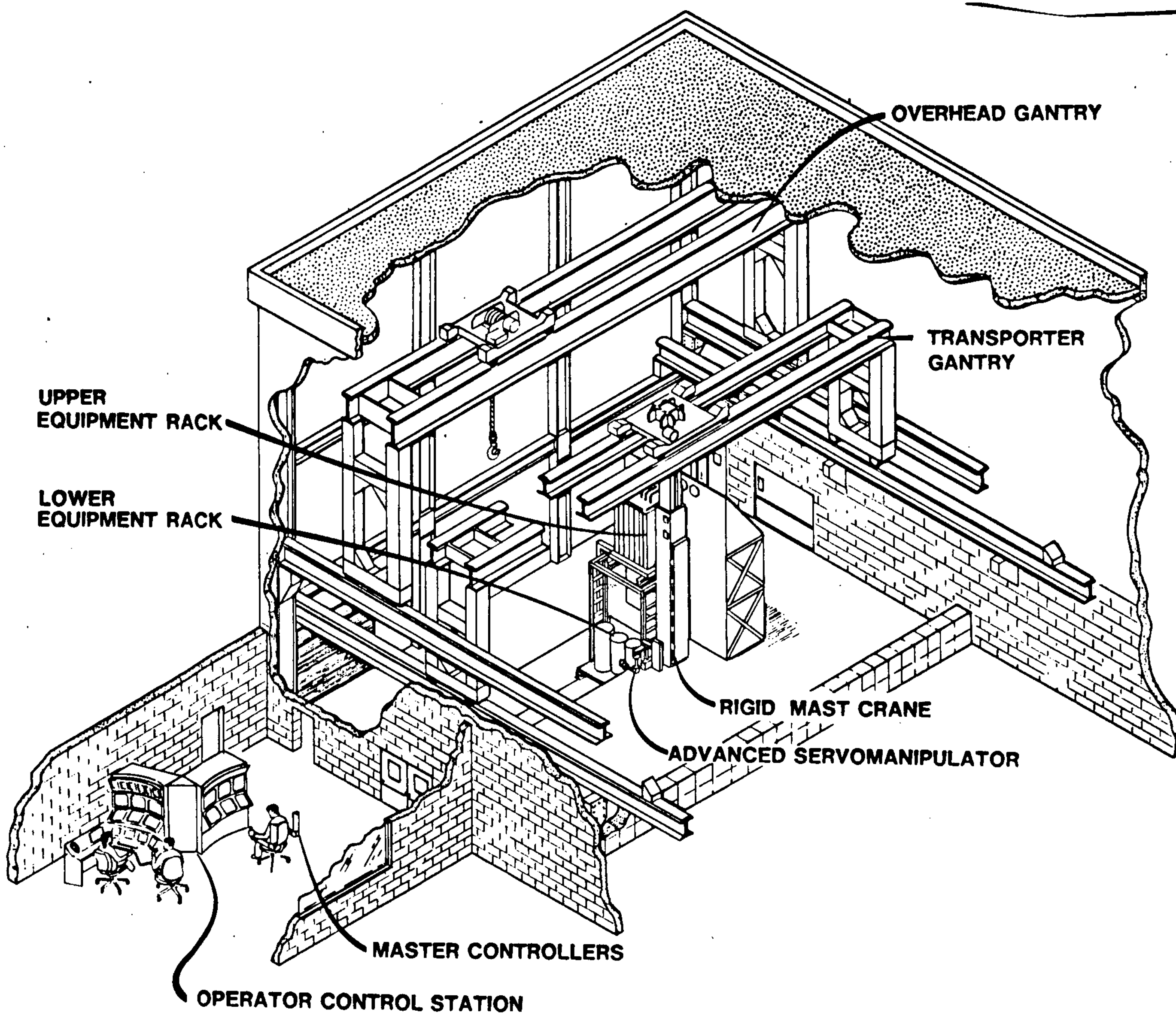

Fig. 19. Advanced Integrated Maintenance System installation at ORNL.