Robotics Systems for Reactor Servicing and Repair

P. Pickerill
Manager, Industrial Sales
Remote Manipulator Systems Division
SPAR Aerospace Limited

ROBOTIC SYSTEMS FOR REACTOR SERVICING AND REPAIR

P. Pickerill
Marketing Manager
Industrial Systems
Spar Aerospace Limited
Weston, Ontario

June 1986

ABSTRACT

The "Canadarm", the robotic arm which is an integral part of NASA's space shuttle missions, is familiar to audiences all over the world as a result of media coverage of the space shuttle program during the past five years.

Technology developed in the "Canadarm" is finding increasing applications in hostile environments on earth. The nuclear industry is an early beneficiary of this technology in the form of a Remote Manipulation and Control System to assist in a large scale fuel channel replacement program at Ontario Hydro's Pickering Nuclear Generating Station.

Elements of the system include precision tooling, a laser based alignment mechanism, a manipulator or robotic arm known as the Spar 2500, an audio-visual feedback system, and a remote operations centre.

The concepts applied in the development of this comprehensive system and certain major components of the system such as the Spar 2500 robot arm are expected to find further application in nuclear plant servicing, repair, equipment replacement and decommissioning.

INTRODUCTION

The world's best known and most recognizable robot is undoubtedly the Shuttle Remote Manipulator System (Figure 1).

This robotic arm, known also as the "Canadarm" or the "Space Arm" has played an integral role in NASA's Space Shuttle missions for the past five years. Used routinely for the release and retrieval of satellites, the versatility of the Space Arm has been demonstrated in other diverse operations, as a work platform for astronauts, to hold and position satellites while repair operations are carried out in space, and even to repair a frozen water drain on the shuttle itself.

The arm is a six degree of freedom anthropomorphic robot which can perform preprogrammed operations in the same manner as a conventional industrial robot. It can also be controlled by an astronaut from within the Shuttle using two proportional hand controllers.

Measuring more than 50 ft. in length and with an approximate weight of only 900 lbs., the arm is unable to lift its own weight in earth's gravity yet handles payloads in excess of 60,000 lbs. in space. It operates in an environment which is untenable to humans and extremely hostile to equipment by virtue of vacuum conditions and extreme temperature gradients.

Following the success of the "Canadarm", its designer and builder, Spar Aerospace Limited, decided to pursue the business of robotics in other applications where the environment was hostile to man and posed challenges in the design of the equipment.

The nuclear industry was an obvious choice, and provided Spar with the opportunity to transfer the technology from the world's most famous robot into the world's largest robot.

Nuclear Application - The Pickering Re-Tubing Program

Over 30% of Ontario Hydro's total production capability is through the generation of nuclear power using the CANDU-PHW (CANada Deuterium Uranium-Pressurized Heavy Water) system developed by a consortium of Ontario Hydro, the Province of Ontario's electric utility, Atomic Energy of Canada Limited (AECL) and Canadian General Electric (CGE). The CANDU reactor contains its fuel bundles in a matrix of horizontal calandria and pressure tubes that span the reactor volume. The basic design did account for the axial creep of the Zirconium alloy tubes which results from the neutron bombardment encountered during reactor operation and the high temperature and pressure of the heavy water coolant. However, experience in the operation of the four reactors at Pickering, all representing early versions of the CANDU design, shows that this creep occurs at a higher rate than design estimates predicted. This creep and associated problems could ultimately lead to operational difficulties for the reactor system. Ontario Hydro was obliged to consider a large scale fuel channel replacement to extend the life of the reactor.

Objectives

Major repairs on equipment in a hazardous environment present a unique set of problems. These problems are further magnified if these repairs must be repeated numerous times. When should the repairs be performed manually; when should they be performed using remotely controlled equipment? How do you trade off man versus machine? What level of involvement should each have? What level of involvement should the operator have in the control and monitoring of the equipment? These and numerous other questions faced Ontario Hydro, when it became apparent that major repairs tantamount to decommissioning of the reactor core and in-situ rebuild might have to be performed on a number of its nuclear reactors.

As with any repair activity, the prime objective of the Large Scale Fuel Channel Replacement Program is to rehabilitate the reactors for the minimum overall cost. The three main contributing factors to this cost are:

(a) the total outage or downtime of the reactor,
(b) the radiation exposure to personnel,
(c) the design and development of the repair tooling.

Although these are not all the factors that affect the overall cost, they represent the most significant variables in any comparison of manual versus remotely controlled tooling.

Over the past few years, a number of fuel channels have been replaced using work crews and specially developed manual tooling. Based upon this experience, it is estimated that it would take approximately two years to retube a 390 channel reactor and would expose work crews to a minimum of 4000 man-rem for channel disassembly and replacement, excluding the exposure during preparation activities. Canadian Atomic Energy Control Board regulations, based on the International Commission on Radiological Protection recommendations, limit the allowable exposure to 5 rem per man per year or 3 rem per man per quarter-year.

Constrained by these exposure limits, the recruitment and training of personnel become serious problems. Task efficiency is also greatly reduced due to the non-productive time spent suiting up in the protective clothing, monitoring radiation levels after each step of an operation and decontaminating equipment used in the reactor repair. At the same time, cumulative job experience is minimal since the actual time spent working on the reactor by each individual would be relatively short and separated by many months of non-related activity. These problems are further compounded when the same repairs must be performed on a number of reactors. Faced with the obvious shortcomings of a manual retube, Ontario Hydro had to consider a fuel channel replacement system that would significantly reduce work crew exposure. Under contract to Ontario Hydro, Spar Aerospace Limited has produced a remote manipulation and control system and specialized tooling which contribute to potential savings in excess of 42% on radiation exposure and 32% in critical path time. The significantly higher design and development cost of remotely controlled tooling, as compared to the manual tooling, is offset by the exposure and critical path savings based on four reactors, to produce an overall reduction in repair cost.

Design Guidelines

The system produced by Spar is not totally remotely controlled. Early operations planning, and preliminary design layouts of tool concepts, indicated that many operations could not justify the development expense of the sophisticated remotely controlled tooling necessary to perform the tasks. A simple set of design principles were developed to determine the appropriate allocation of operational tasks between manual and remotely controlled tooling. Operations which are man-rem intensive, require modest dexterity and yield predictable results are remotely controlled. Conversely, operations which require a dexterity level which is extremely to reproduce using a machine, and for which operational results are not fully predictable, are performed manually. At the same time, these operations require minimal training, allow maximum preparation in a non-hazardous environment and permit regular scheduling.

To ensure that an overall minimum radiation exposure level is maintained for the remote tooling, a primary design goal was to minimize the amount of maintenance in the radiation environment by maximizing tool reliability. In addition, each tool design is required to accept manual intervention to allow operators to continue the operation of the tool manually to a point where the failed tool can be safely removed from the environment for repair.

Operations Planning

The operational process of replacing fuel channels using the Remote Manipulation and Control System is performed by equipment placed in the fuelling machine vaults on either side of the reactor. The fuelling machine bridge, which normally supports the fuelling machine used to move fuel bundles in and out of the reactor, provides the base for the equipment which actually works on the fuel channels. Replacement of fuel channel components is performed on a row-by-row basis starting at the bottom of the reactor. At the completion of a row, the fuelling machine bridge is raised to permit operation on the next row.

The Remote Manipulation and Control System

The remote Manipulator and Control System (Figure 2) is subdivided into the following major subsystems:

- The Remote Work Stations
- The Remote Manipulator (Spar 2500) Arm
- The Vault Observation Subsystem

Additionally, there is a Tool Subsystem and an Equipment Transport Subsystem.

Operation and control of the several parts of the remote manipulation and control system are supported by a Data Transmission Subsystem. A Remote Operations Centre located more than 1500 feet from the reactor houses a host computer and the operator and supervisor work stations.

Remote Work Stations

The tools are aligned in front of a fuel channel by a mobile tool bed designated the Remote Work Station subsystem, (Figure 3) which provides the universal interface for mounting the tool mechanisms. In general, four tool mechanisms are mounted in a cylindrical frame to form a turret assembly. Each quadrant can be removed from the turret without disturbing the remaining three. This allows for the grouping of any combination of tools. Detailed process analysis has shown that the interchangeable multi-tool turret approach allows the greatest operational flexibility. Thus, the tooling or tooling sequence can be changed, as necessary, based on actual operating experience without modifying the system design.

At specific points during the fuel channel replacement sequence, the operating turret contains an alignment tool. Using feedback from this tool, the operator positions the remote work station to null the alignment errors in the tool so that the remote work station becomes oriented relative to the fuel channel axis. The stored position values permit the remote work station to be returned to the fuel channel in the proper orientation such that subsequent tools are also aligned.

To achieve this alignment, the remote work station provides two translational and three rotational degrees of freedom to the turret, including turret indexing about the turret's long axis.

Each degree of freedom is electro-mechanically driven by stepper motors while the actual position is indicated by encoders. A repeatable accuracy of eight-tenths of a thousandth of an inch has been achieved in this part of the system.

Manipulator Arm

Having established an effective means of performing either manual and/or remote operations on the reactor face, the next major operational obstacle was the transfer of components from the tools on the fuelling machine bridge to the transport carts on the vault floor, and vice versa. No overhead cranes had been installed in the fuelling machine vault when the reactor was built. To best satisfy the reach requirements imposed by operations planning and the spatial constraints of the fuelling vaults, and to minimize the installation time, a multi-joint arm (Figure 4) known as the Spar 2500 Remote Manipulator, has been included in the system. Arm control is achieved through an integrated computer controlled electro-hydraulic system which controls the motion of each joint actuator through a servo system. Simple operator controls which command the speed and direction of the payload in three translational and two rotational degrees of freedom enable manoeuvring of payloads of up to 2500 lbs. without conscious effort by the operator to control the individual joints. The arm has been designed to be "fail operational" so that radioactive components can be transported unshielded from the tools on the bridge to flasks on the vault floor.

The arm, consisting of a series of joints and structural links, is configured as a parallelogram (Figure 5) to maintain the wrist orientation at all boom angles. The arm booms are attached to a carriage which can translate parallel to the reactor face on tracks mounted on a base assembly rigidly secured to the vault floor. During operation, the carriage is locked in one of three positions. A wrist assembly, located at the end of the arm, provides the yaw and pitch movement of the end effector and payload while the arm and carriage assemblies together provide the X, Y and Z translation of the wrist assembly. Payloads are grappled by a two jaw, three claw end effector. Performance and technical data for the Spar 2500 are presented in Table 1.

Further Development

The remote Manipulator and Control System is a complete tele-robotic system incorporating a sophisticated anthromorphic robot, precision machine tools, a laser based alignment device, audio-visual as well as electronic feedback, and a fully remote operations centre. It was developed to perform a major nuclear repair tantamount to decommissioning and rebuilding reactor core in-situ.

The manipulator arm, now designated the Spar 2500, can be applied with little modification to many other nuclear and heavy industrial tasks. It can be configured for mounting on a vehicle and can be readily adapted for payloads up to 5000 lbs.

As the nuclear industry advances into its maturity years, nuclear service activities including repair, maintenance, equipment replacement and decommissioning will become commonplace. After many years of full power operation, radiation fields will be such as to necessitate the use of machines rather than manpower. Where heavy systems are called for, the Spar 2500 or derivative systems will ideally fill the need.

TABLE 1 PERFORMANCE SPECIFICATIONS

Mechanical System

Degrees of Freedom - 4 resolved servo axes
2 unresolved non servo axes

Load Capacity

500 LB-rate range 0-24 in/sec (0/610 mm/sec)
2500 LB-rate range 0-6 in/sec (0/150 mm/sec)

End Effector Clamping Force

- Adjustable from 10 Lbs. to 3000 lbs.

Reach (at Point of Resolution - POR)

Vertical	339" (8.61m)
Horizontal	334" (8.48m)
Rotation	320° (Shoulder and Wrist Yaw)
Carriage Traverse	207" (5.25m)

Speed

Linear Velocity at POR	0-24 in/sec (0-610 mm/sec)
Minimum Rate Resolution	0.05 in/sec (1.25 mm/sec)

POSITIONAL ACCURACIES

DESCRIPTION	LINEAR	ANGULAR
Repeatability	0.050 inches (1.27 mm)	0.02 degrees
Position hold	0.050 inches (1.27 mm)	0.02 degrees
Resolution	0.050 inches (1.27 mm)	0.02 degrees

MASS PROPERTIES

Arm Assembly	15,000
Carriage	8,700
Base Tracks	8,500
TOTAL	32,200 lbs.

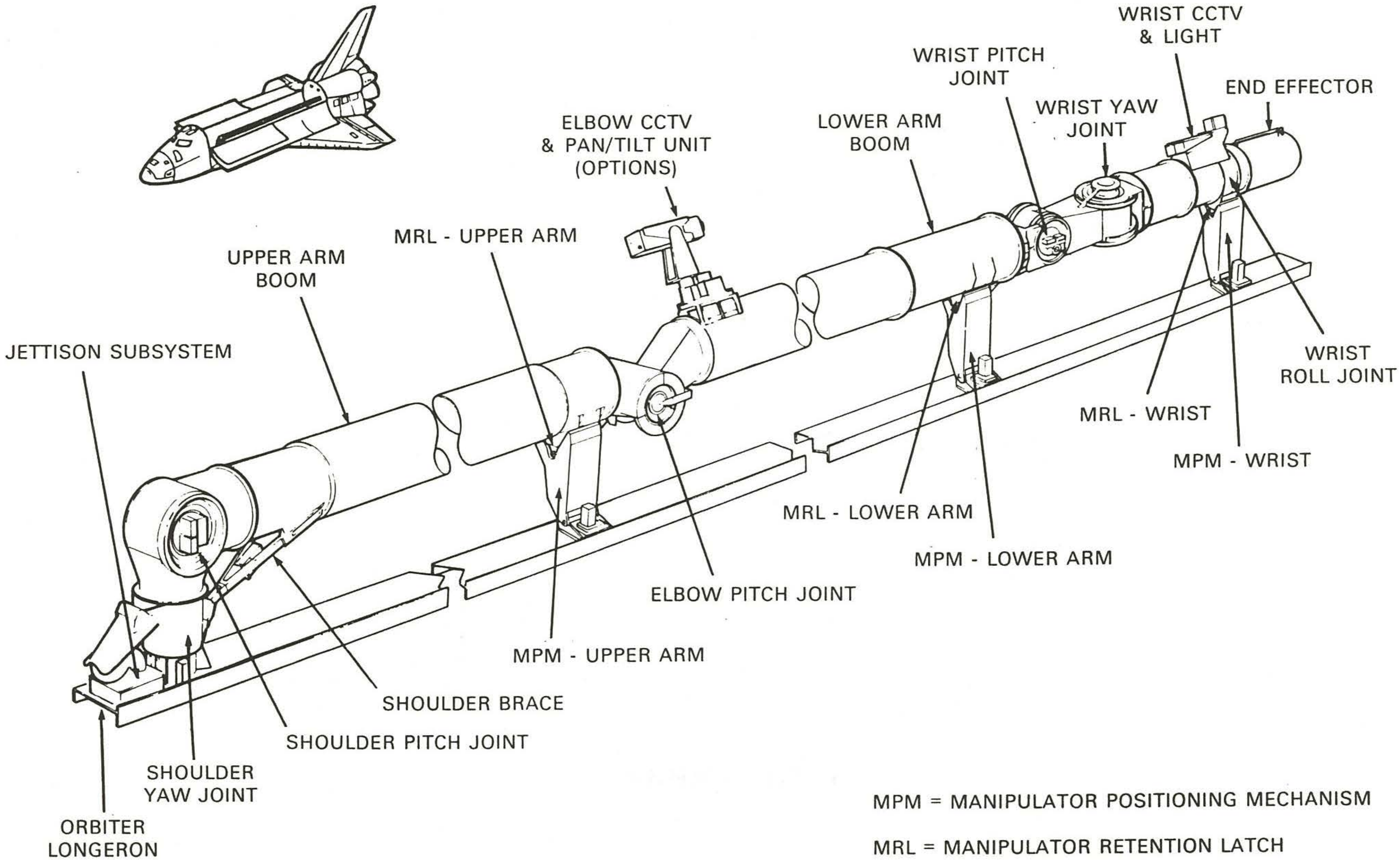

FIGURE 1 THE SHUTTLE REMOTE MANIPULATOR SYSTEM

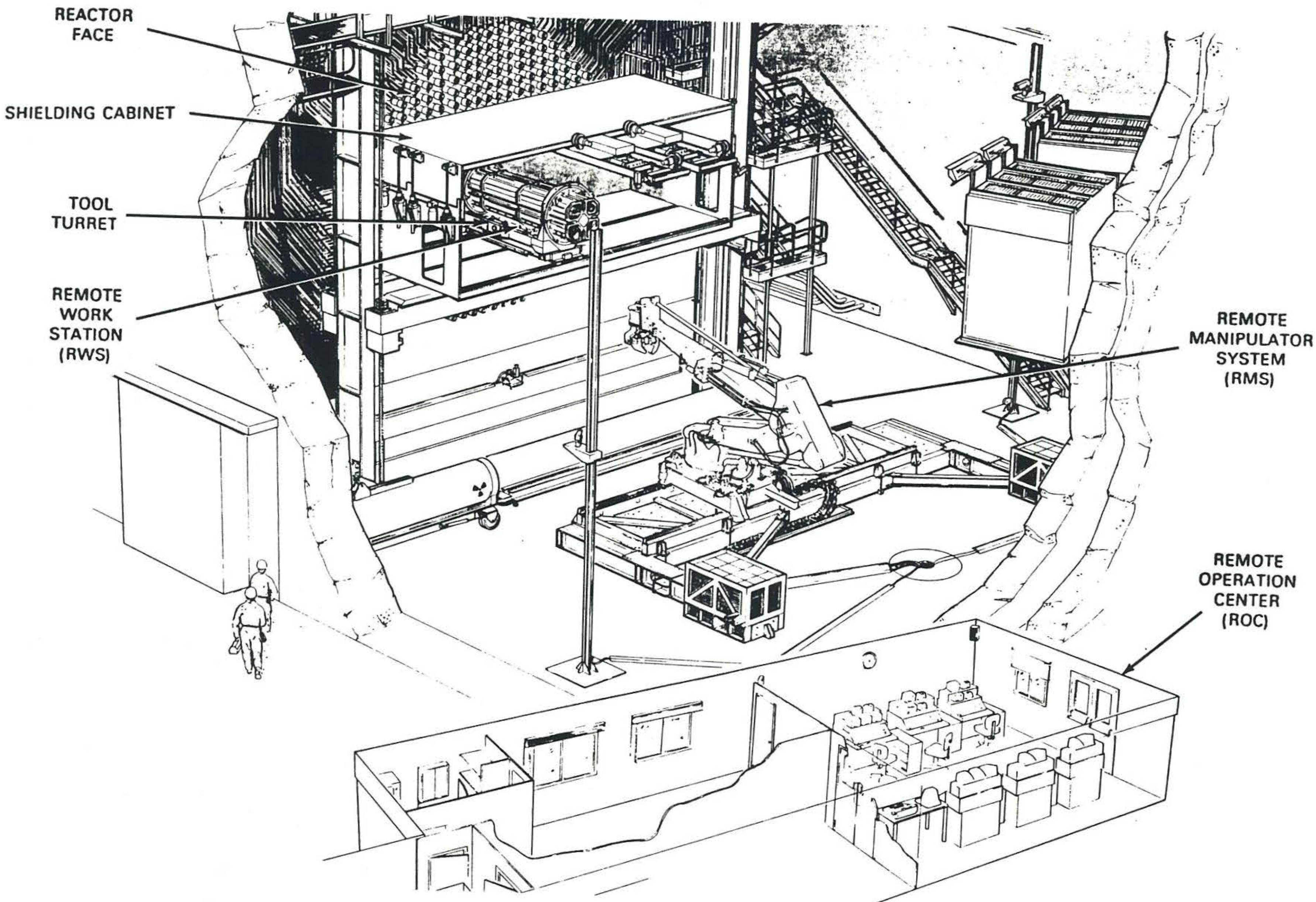

FIGURE 2 REMOTE MANIPULATION AND CONTROL SYSTEM (RMCS) INSTALLED IN WEST FUELLING MACHINE VAULT

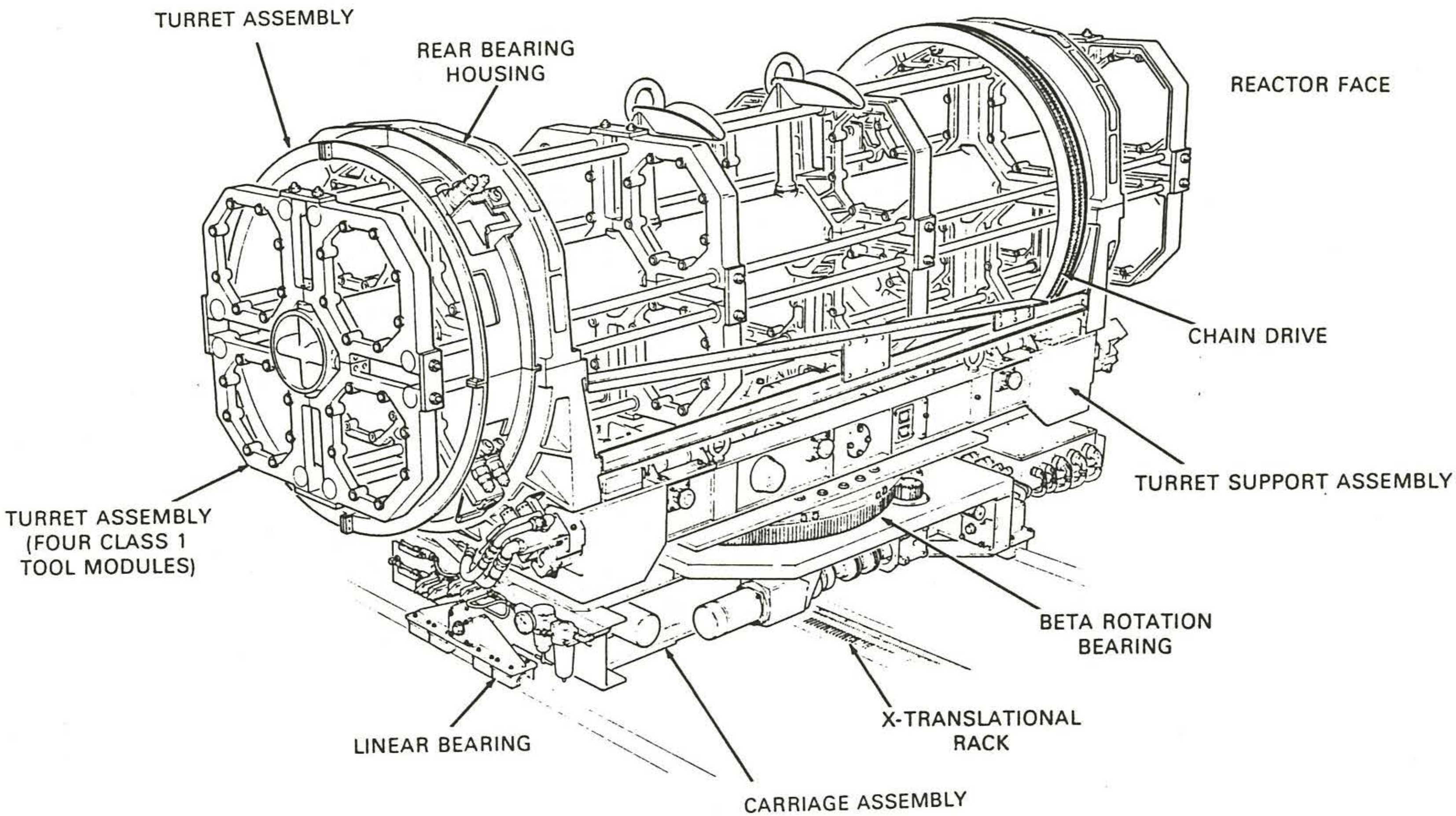

FIGURE 3 REMOTE WORK STATION AND TURRET ASSEMBLY

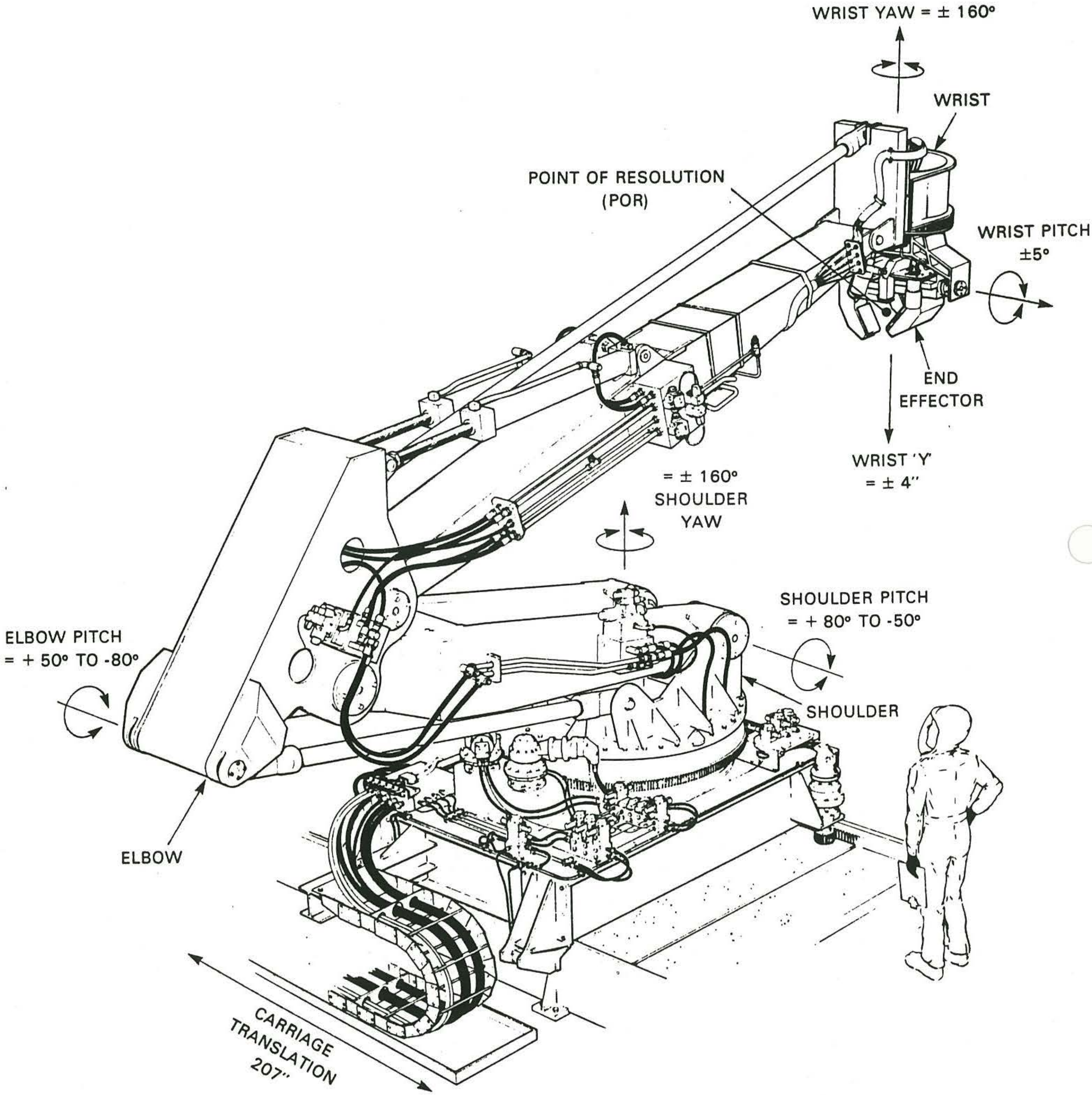

FIGURE 4 THE RMS MECHANISM

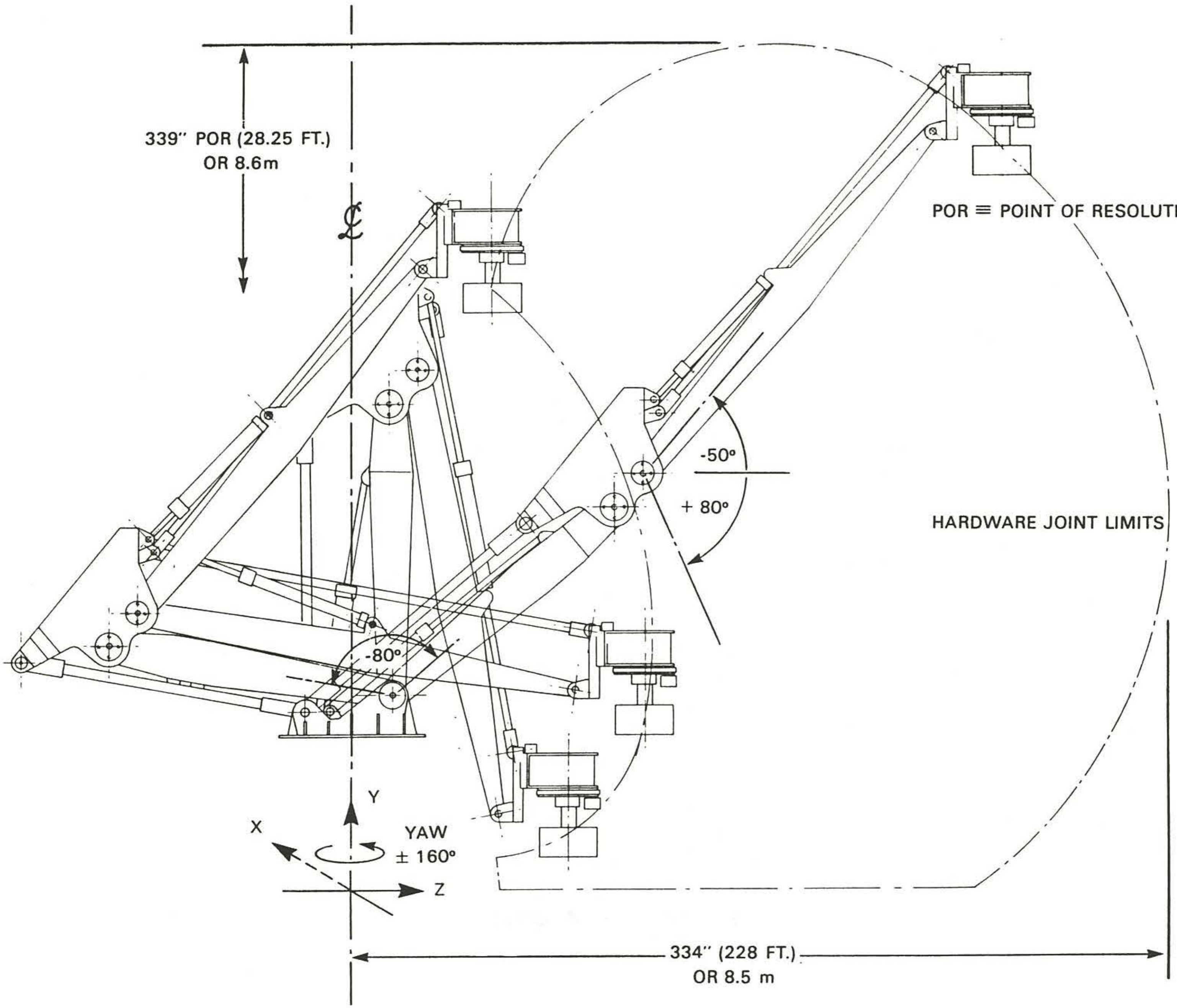

FIGURE 5 SPAR 2500 REACH ENVELOPE

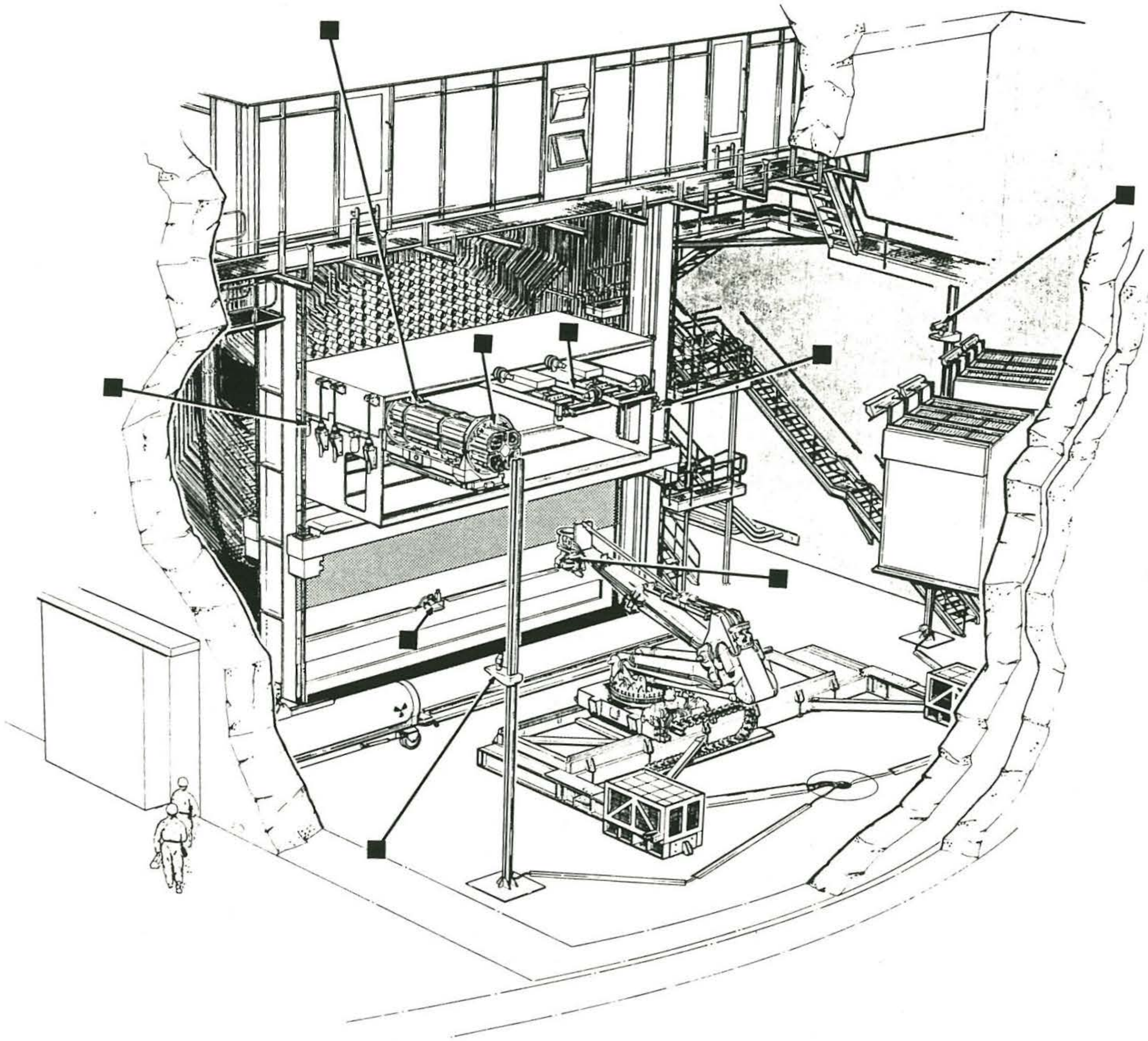

FIGURE 6 REMOTE VIEWING UNIT IN WEST VAULT