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APPLICATION OF SHUTTLE REMOTE MANIPULATOR SYSTEM TECHNOLOGY TO THE REPLACEMENT OF FUEL CHANNELS IN THE PICKERING CANDU REACTOR

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Abstract

Spar Aerospace Limited of Toronto was the prime contractor to the National Research Council of Canada for the design and development of the Shuttle Remote Manipulator (SRMS). Spar is presently under contract to Ontario Hydro to design and build a Remote Manipulation Control System to replace the fuel channels in the Pickering A Nuclear Generating Station. The equipment may be used to replace the fuel channels in six other early generation CANDU

SRMS Background

The first SRMS was delivered to NASA February, 1981 as a gift of the Canadian Government. It was integrated onto the orbiter Columbia in June 1981 and has been flown on STS-2 and STS-3. Spar Aerospace Limited is under contract to NASA to build 3 more SRMS systems for delivery in 1982, 1983 and 1985.

The SRMS is a dedicated man-in-the-loop manipulator designed to meet the requirements of the space environment (see Figure 1). The SRMS as a major subsystem of the Payload Deployment and Retrieval System, will provide the shuttle orbiter with the capability for the deployment and retrieval of payloads weighing up to 65,000 lbs. and measuring up to 15 feet diameter by 60 feet long. The system is designed for a 10 year, 100 mission life.

The RMS is comprised of four major subsystems:

(a) Mechanical Arm Subsystem,
(b) Display and Control Subsystem,
(c) Electrical Subsystem,
(d) Software Subsystem.

(a) Mechanical Arm Subsystem

The mechanical arm subsystem consists of the manipulator arm, the payload interface, the thermal protection system and the CCTV and lighting assembly (see Figure 2).

The manipulator is a 6 degree of freedom arm comprising six electro-mechanical rotary joints connected by structural members.

The sequence of joints starting from the orbiter interface are, shoulder yaw and pitch, elbow pitch, wrist pitch, yaw and roll. The arm booms are made of graphite/epoxy thin-walled tubular sections with internal stabilization rings. The End Effector is bolted onto the wrist roll section.

The space environment and weight considerations favoured the selection of an electro-mechanical drive system. Housed within the joint structure, each joint contains a brushless dc servo-motor and high efficiency, high ratio gearbox. The drive systems are similar for all joints with the gear trains designed for both forward and backdrive capability (see Figures 3, 4 and 5).

The standard RMS/Payload interface is the snare type end effector which mates with a grapple fixture attached to the payload. The grapple fixture carries a target for visual alignment.

(b) <u>Display and Control Subsystems</u>

The Display and Control Subsystem (see Figures 6 and 7) provides the following capabilities:

i) <u>Operating Mode Selection</u>

- o Manual Augmented Modes (4 hand controller modes),
- o Automatic Mode (4 of 20 automatic programs),
- o Single Joint (computer supported joint by joint mode),
- o Direct Drive (hardwire joint by joint control),
- o Back-Up Drive (a separate hardwire joint by joint control).

ii) <u>End Effector Control</u>

- o Capture and Release (prime mode),
- o Release (separate back-up release).

iii) <u>Status and System Health Data</u>

- o Mode and Operating Tellbacks, Failure Warnings,
- o Joint Angle Rate and Position,
- o End Effector Rate and Position,
- o Temperature Data.

The prime means of operating the arm is via two hand controllers; one providing translational (X,Y,Z) rate command of the end point and one providing (P,Y,R) rate command of the end point. The end point of control can be selected to be with respect to the orbiter, the end effector or a point within a payload.

Further detail data is provided to the operator on 2 CRT pages selected on the shuttle CRT's i.e. detail failure warning indications which support malfunction diagnosis. The operator can also access the RMS software program via a keyboard.

Control of the television monitors to select cameras located on the arm (elbow and wrist) and the orbiter (forward and aft cargo bay) is provided to the operator on a panel adjacent to the D&C panel.

(c) <u>Electrical Subsystem</u>

The electrical subsystem comprises the Manipulator Control Interface Unit (MCIU) and the Arm Based Electronics (ABE) distributed along the arm. The MCIU utilizes a microprocessor to receive and distribute commands and data between the GPC, D&C panel, hand controllers and ABE. The MCIU communicates via asynchronous serial digital data buses (to GPC at 12.5 Hz, to D&C panel at 50 Hz and ABE at 25 Hz).

The ABE comprises power conditioning and signal processing to control the 6 arm joints.

Both the MCIU and ABE contain built-in-test-equipment (BITE) to monitor for malfunctions. In addition to the computer augmented commands sent from the GPC via the MCIU and ABE data bus, the joints are hardwired to the D&C panel for joint by joint control in prime power (direct drive) and back-up power (back-up drive) modes.

The end effector status and BITE data are also accessed through the ABE-MCIU data bus. The end effector is commanded via hardwires from the Display and Control panel.

(d) Software Subsystem

The RMS software is located in one of the 5 orbiter GPC's. The software provides the following functions (see Figure 8):

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i) Executive mode control,
ii) Rate transformation and processing to create joint commands,
iii) Joint rate and torque limiting,
iv) Automatic trajectory data storage (20 sets of up to 200 points each),
v) Payload characteristics storage (5 data sets),
vi) End effector characteristic storage (5 data sets),
vii) System health monitoring.

The GPC interfaces with the orbiter CRT's and keyboards and the MCIU; which in turn, provides access to the D&C panel, ABE and end effector. The SRMS software is operated at 12.5 Hz.

Remote Manipulation and Control System for Ontario Hydro

Background

The unique capability developed at Spar during the Shuttle Remote Manipulator System (SRMS) program came to the attention of Ontario Hydro in the spring of 1979. At that time, Ontario Hydro was investigating various methods of performing a large scale fuel channel replacement at their Pickering 'A' Nuclear Generating Station. Spar was contracted to perform a feasibility study with the object of establishing the potential saving in replacement critical path time and work crew radiation exposure using a remote system during a full scale retube. This study predicted a potential 42% exposure saving during fuel channel removal and reassembly, with a potential 32% saving in critical path time. These early estimates resulted in a further conceptual design study phase (Phase A) which was completed in the fall of 1980. The preliminary design phase (Phase B) will be complete April 1982 and will be followed by:

Phase 'C' - Engineering prototype detailed design, build and test.

Phase 'D' - Full system build and test.

Phase 'E' - Post delivery (i.e. support of the installation and operation of the equipment in the reactor).

The CANDU reactor contains its fuel bundles in a system of horizontal calandria and pressure tubes that span the reactor volume (Figure 9 and 10). Heavy water coolant at approximately 1400 psia and 560°F (293°C) is circulated through the space between the pressure tube and fuel bundles. The heated heavy water passes through boilers which convert light water to steam to run the turbine-generators.

As anticipated, the fast neutron flux generated during reactor operation causes the Zirconium alloy tubes to creep axially. Experience in the operation of four reactors at Pickering and three at Bruce, all representing an early generation of CANDU reactors, shows that this

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creep is occurring faster than design estimates predicted. Thus, the creep phenomenon limits the "tube life" to about 15 years or half the design life. As the pressure tubes creep, the end fittings are pushed outwards and eventually drop off their supporting bearing sleeves (Figures 11 and 12).

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 a Pickering 'A' reactor with 390 fuel channels would take approximately one year to retube and expose work crews to a minimum of 4000 man rem for tube disassembly and replacement excluding the exposure encountered during preparation activities. Safety regulations limit the allowable exposure to 5 rems per man, per year and 3 rems per man per quarter.

A System Concept

Inherent in any manual approach are the problems associated with:

(a) recruitment and training,
(b) cumulative job experience,
(c) task efficiency,
(d) multiple reactor retubes.

The scope of the full retube task obliged Ontario Hydro to consider retube procedures that would significantly reduce work crew exposure and the associated cost and critical path time.

Ontario Hydro established the following program objectives:

(a) Rehabilitate the subject reactors and meet quality standards that would minimize unscheduled outage.

(b) Minimize personnel radiation exposure.

(c) Complete the retube mission within an acceptable time limit.

(d) Perform the retube task in a cost effective manner.

Design Principles

The system design concept configured to meet these objectives was based upon the following design principles:

(a) The proposed system should represent an appropriate trade-off between man and machine, allocating to the latter those tasks that are "man-rem" intensive, that require only modest dexterity and that yield predictable results.

(b) The proposed system should be designed to maximize reliability and minimize maintenance.

This principle applies especially to items of equipment which are located permanently in the reactor vaults during the retube operations.

(c) Multiple remote work stations equipped with complementary tool suites should be considered in order to improve flexibility in task scheduling and/or reduce total elapsed time.

(d) The system configuration at each side of the reactor face should be similar in order to permit the responsibility for tasks to be shifted from face to face as required.

(e) The system should use the facilities and services already available within the reactor vault without causing these facilities or services to be overloaded, to experience excessive wear or to affect their expected life span.

(f) Scheduled human intervention should comprise tasks that require minimal training and permit maximum preparation in a radiation-free environment away from the reactor face. Such tasks should be grouped together and executed at regular intervals.

(g) The design should permit the manual use of the system's tools and equipment in the event that unscheduled human intervention is required.

(h) Visual observation of the functioning of the system using CCTV should be the primary means of feedback to the operator.

(i) The use of an electronic event prompter and log should be considered to eliminate inadvertent duplication or deletion of operations or tasks.

(j) Multiple operator stations with appropriate interlocking to eliminate mutual interference should be considered to permit work to be conducted at more than one fuel channel at a time.

Operations Analysis and Planning

In conjunction with the system design activity, detailed operations analysis and process planning has been performed to:

(a) Define the sequence of operations and steps which must be executed.

(b) Deduce the facilities required to implement the operations.

(c) Estimate total execution time and man-rem exposure.

System Description

The Remote Manipulation and Control System (RMCS) is a system of the Ontario Hydro Reactor Component Replacement Equipment (RCRE) used during the operational process of replacing fuel channels in a Pickering "A" type reactor. The RMCS comprises:

(a) Some of the equipment, tools and auxiliary devices designed to carry out this replacement task either remotely or locally within the fuelling machine vault.

(b) The devices to control, display, monitor, prompt and record activities of men and equipment inside the fuelling machine vault.

The RMCS is subdivided into the following major subsystems (see Figures 13 and 14):

(a) the Remote Work Station (RWS) Subsystem,
(b) the Remote Manipulator Subsystem (RMS),
(c) the Vault Observation Subsystem (VOS),

(d) the Data Transmission Subsystem (DTS),
(e) the Remote Operation Centre (ROC),

Additionally, there is:

(f) the Tool Subsystem (TLS), (Spar portion),
(g) the Equipment Transport Subsystem (ETS), (Spar portion).

Remote Work Station (RWS)

The Shielding Cabinet System (SCS) is a structure provided by CGE mounted on the Fuelling Machine (F/M) vault bridge to provide shielded worker access to the face of the reactor. The RWS translates back and forth inside the SCS parallel to the reactor face to align tools with the fuel channels during the replacement process.

Four remote work stations, two in each shielding cabinet function as holding and positioning beds for tools (see Figure 15).

The RWS contains the turret assembly which provides the structure to mount up to four tools. A turret lifting fixture is used in conjunction with the shielding cabinet crane to facilitate the loading of turrets on and off the RWS.

The RWS also provides a compatible interface for directly mounted tools which do not require mounting within a turret assembly. The RWS provides standard electrical and pneumatic services and common data and command links to the tools. The RWS can be operated either remotely from the ROC or locally via a local control panel.

Remote Manipulator Subsystem (RMS)

The Remote Manipulator Subsystem is used to manoeuvre containers and stores in the Fuelling Machine (F/M) vault and to transport new and discarded fuel channel components between the vault floor and the F/M bridge (see Figure 16).

The RMCS is a multi-joint dextrous arm controlled either from hand controllers at the RMS Operator's Station in the ROC, locally using the RMS Local Control Panel (a joint-by-joint command mode) or automatically from the Operation Instruction Set resident in the ROC software.

A Manipulator Control Unit (MCU) located outside the vault houses the RMS Joint Control Algorithms and signal processing. It responds to ROC commands and provides status information to the ROC for operator displays, fault monitoring and to the instruction set for automatic program sequencing.

Vault Observation Subsystem (VOS)

The VOS comprises the CCTV cameras, camera mounting assemblies, monitors, audio/video recorders, microphones, lights, pan, tilt and elevation units, operator control panels, and support electronics required to provide the visual and audio coverage of the remote RWS, TLS and RMS operations in the F/M vault. The VOS is used as a means of audio/visual feedback for the RMCS in both the east and west vaults. The control panel monitors, recorders and video switching units are installed into the operator stations as part of the ROC (Remote Operations Center).

Data Transmission Subsystem (DTS)

The DTS provides the following services to the vault resident equipment.

(a) control and status links between the ROC and the vault equipment,
(b) power distribution and conditioning,
(c) local control equipment for RWS, TLS and RMS.

The DTS provides for communication between the ROC and the in-vault equipment via a synchronous data bus and handles commands and status signals utilizing 2 microprocessors each serving 2 RWS/TLS locations and 2 Shielding Cabinet interfaces. Each RWS/TLS and Shielding Cabinet interface communicates with the microprocessor via a separate serial data bus.

The DTS was configured to ensure the simplest and minimum amount of electronic circuitry is housed within the F/M Vault to reduce radiation susceptibility design considerations to a minimum.

In addition, the DTS was configured to ensure that no single failure can cause loss of both RWSs at either the East or West side of the vault.

Remote Operations Center (ROC)

The ROC subsystem consists of trailer housed equipment remote from the reactor building (R/B) to control and monitor the outage operations comprising (see Figure 17):

(a) display and control panels for the operators, (RWS, RMS, Supervisor and System Engineer Control Station),

(b) the equipment for operations control of the RMCS (General Purpose Computer, peripherals and software),

(c) the trailer to house the equipment and operators,

The ROC GPC controls communication (commands and status) between the Operator Remote Control Stations and the in-vault equipment via the DTS. The ROC contains the necessary software for:

(a) direct communications between operator stations, control panels and in-vault equipment which they control,

(b) system health monitoring (safety through equipment status and fault detection),

(c) implementation of the outage operation, instruction set, (operator displays and data, automatically and manually initialized equipment command sequence routines and associated interlocking).

Tool Subsystem (TLS)

The tool subsystem (TLS) encompasses all the tools designed as part of the RCRE to be used during the operational process of replacing fuel channels in the Pickering "A" type reactor.

The tools that interface directly with the RMCS are classified as follows:

Class I — Tool mechanisms installed as tool modules into a turret.

Class II — Specifically designed tools operated with the support of the RWS, replacing the turret configuration, which use the RWS services and alignment capability.

Class III Specifically designed tools operated with or without the support of the RWS which do not use the RWS services or alignment capability.

Class III tools meet the same interface requirements as Class II tools.

Spar's portion of the TLS encompasses the following Class I and Class II tools:

(a) the alignment tools,
(b) the shield plug installation and removal tools,
(c) the shield plugs, and
(d) the insertion fixture adaptor.

The alignment tool is a Class I tool mechanism mounted as a module in a turret assembly (see Figure 18). Using feedback from the alignment tool, a Remote Work Station (RWS) operator positions the RWS to null the alignment errors in the tool so that the RWS becomes oriented relative to the fuel channel axis. The stored values of the RWS position permit the RWS to be returned to a lattice site in the proper orientation such that subsequent tool modules are aligned with the fuel channel.

The shield plug installation and removal tool is a Class I tool mechanism mounted as a module in a turret assembly. Every lattice position must contain a shield plug to eliminate radiation beams which would pose a hazard to personnel during scheduled or unscheduled worker intervention.

The insertion fixture adaptor (IFA) is a Class II tool designed to mount directly on the RWS, replacing the turret configuration (see Figure 19). The IFA uses the RWS services and alignment capability while supporting the end fitting pressure tube subassembly insertion fixture. The IFA contains a shield plug installation and removal tool to remove the shield plug from the lattice site before the subassembly is installed. After installation, the shield plug tool inserts a shield plug back into the end fitting.

<u>Equipment Transport Subsystem (ETS)</u>

The ETS consists of the means to achieve the movement of RCRE equipment and supplies in the F/M vault.

The ETS assemblies are used to transport new and discarded fuel channel components and all tools (manual and remote) to and from the required work sites on the vault floor.

<u>System Control and Operation</u>

The system utilizes a prime channel which provides an operational capability during normal and contingency operations. In the event of a prime channel failure during a critical operation, a back-up channel provides an operational capability which will permit the termination of the operation to an uncritical (low radiation) condition.

The retube operations will be controlled by a comprehensive retubing instruction set which will be implemented on a scheduled or unscheduled basis as process planning and operational circumstances dictate (see Figure 20). A subset of the instruction set will be stored as part of the RMCS data base; a separate subset will be on hard-copy. The retubing instruction set along with control options within the RMCS control system will govern the operation of the RMCS equipment by the operators.

The RMCS will operate under either of two basic forms of control:

(a) On-line instruction control under which operations take place as dictated by and within constraints imposed by the instruction set stored in the system data base, and

(b) Off-line instruction control under which the aforementioned on-line instruction control is suspended, and operations are performed as dictated by the instruction set stored on hard-copy.

On-line instruction control is the normal means of operation and provides the following operator benefits:

(a) overall guidance in operations, based on a well-tested and previously proven on-line instructions,

(b) sequential execution of instructions by an operator (i.e. execution of a current instruction only if the previous instruction has been successfully executed),

(c) operational coordination between various operators and their control inputs (i.e. execution of a current instruction only if certain instructions applicable to other operators have been successfully executed),

(d) acceptance of the operator control input only if it is valid for the current instruction,

(e) automatic execution of instructions.

Under off-line instruction control, none of the above advantages exist. Operators are under minimal automated supervision and validation, and assume full responsibility for their actions.

The roles of the instruction set, operators, and the RMCS are summarized as follows:

(a) <u>Instruction Set Role</u>

i) to define the content and sequence of all step-by-step remote operator procedures,

ii) to prompt and direct the remote operator to perform various supporting activities on an as-required basis.

iii) to allocate procedures and responsibilities to appropriate individual operators,

iv) to define coordination requirements between procedures allocated to different operators,

v) to ensure that only commands compatible with the current instruction are accepted,

vi) to define under what conditions an operational instruction is considered to be completed before advancing to the next instruction,

vii) to provide flexibility for automation,

viii) to plan collision avoidance.

(b) Operator Role

i) to monitor operations and provide control inputs as dictated by the instruction set,

ii) to decide whether or not each instruction has been completed (for instructions over which the computer has partial or no control),

iii) to decide whether or not the preconditions for the next instruction have been met and when to proceed to the next instruction,

iv) to decide whether or not to deviate from the instruction set,

v) to decide whether or not to take advantage of automatic instruction execution.

(c) RMCS Role

i) to provide remote equipment control in order to protect operators from radiation hazards,

ii) to simplify equipment control procedures so that operators can concentrate on reactor repair,

iii) to implement the instruction set including coordination between operators.

iv) to perform a supervisory function and monitoring of system status and health,

v) to perform archival recording of all major events in the system for off-line analysis.

Conclusion

Although the RMCS is an order of magnitude larger than the SRMS and operates in earth gravity and a high radiation environment as opposed to a zero gravity space environment, there are many similarities which have enabled Spar to use the design experience and technology gained on the SRMS program. The major points are as follows:

(a) both systems are man-in-the-loop,

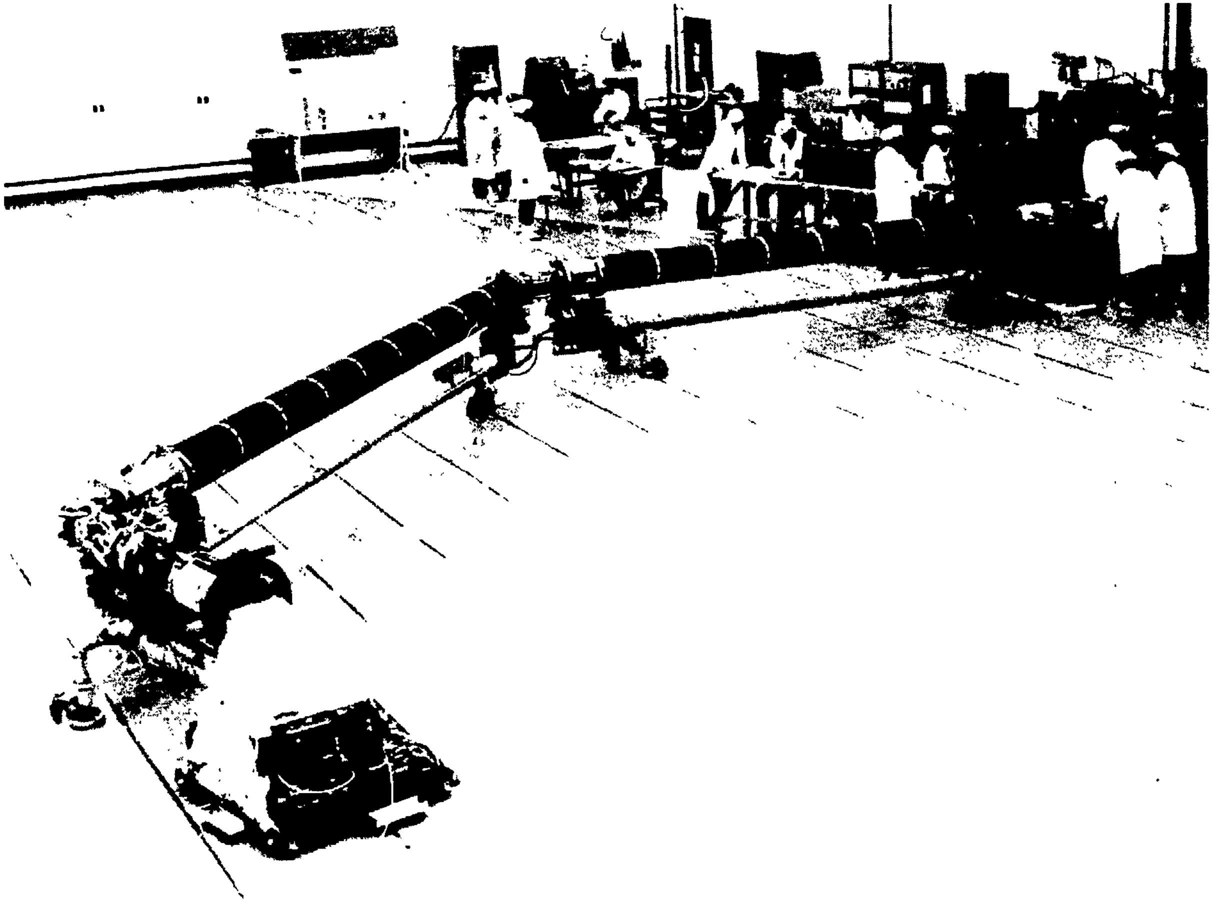
(b) both systems are required to provide the operator(s) with displays of status and diagnostic data to facilitate executive control,

(c) both the systems utilize fully dextrous remote manipulator controls,

(d) there is a similarity between the approach to planning operations and the need for visual cues, etc.,

(e) the systems have common requirements for safety and contingency operation.

The RMCS program has provided Spar with an excellent opportunity to apply the experience and knowledge gained in the development, design and operations support of the SRMS.



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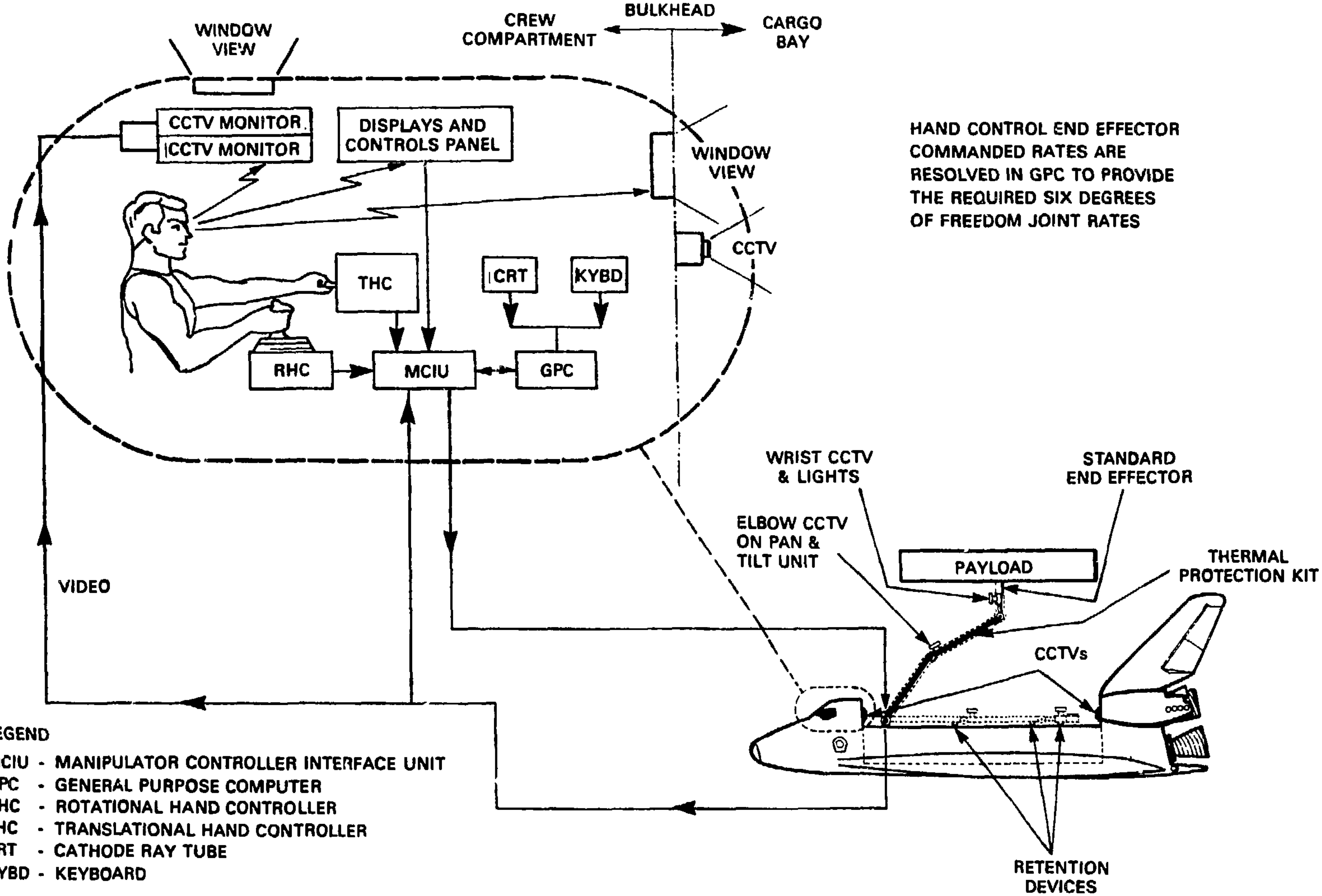

LEGEND

MCIU - MANIPULATOR CONTROLLER INTERFACE UNIT
GPC - GENERAL PURPOSE COMPUTER
RHC - ROTATIONAL HAND CONTROLLER
THC - TRANSLATIONAL HAND CONTROLLER
CRT - CATHODE RAY TUBE
KYBD - KEYBOARD

FIGURE 1 SRMS SYSTEM CONCEPT

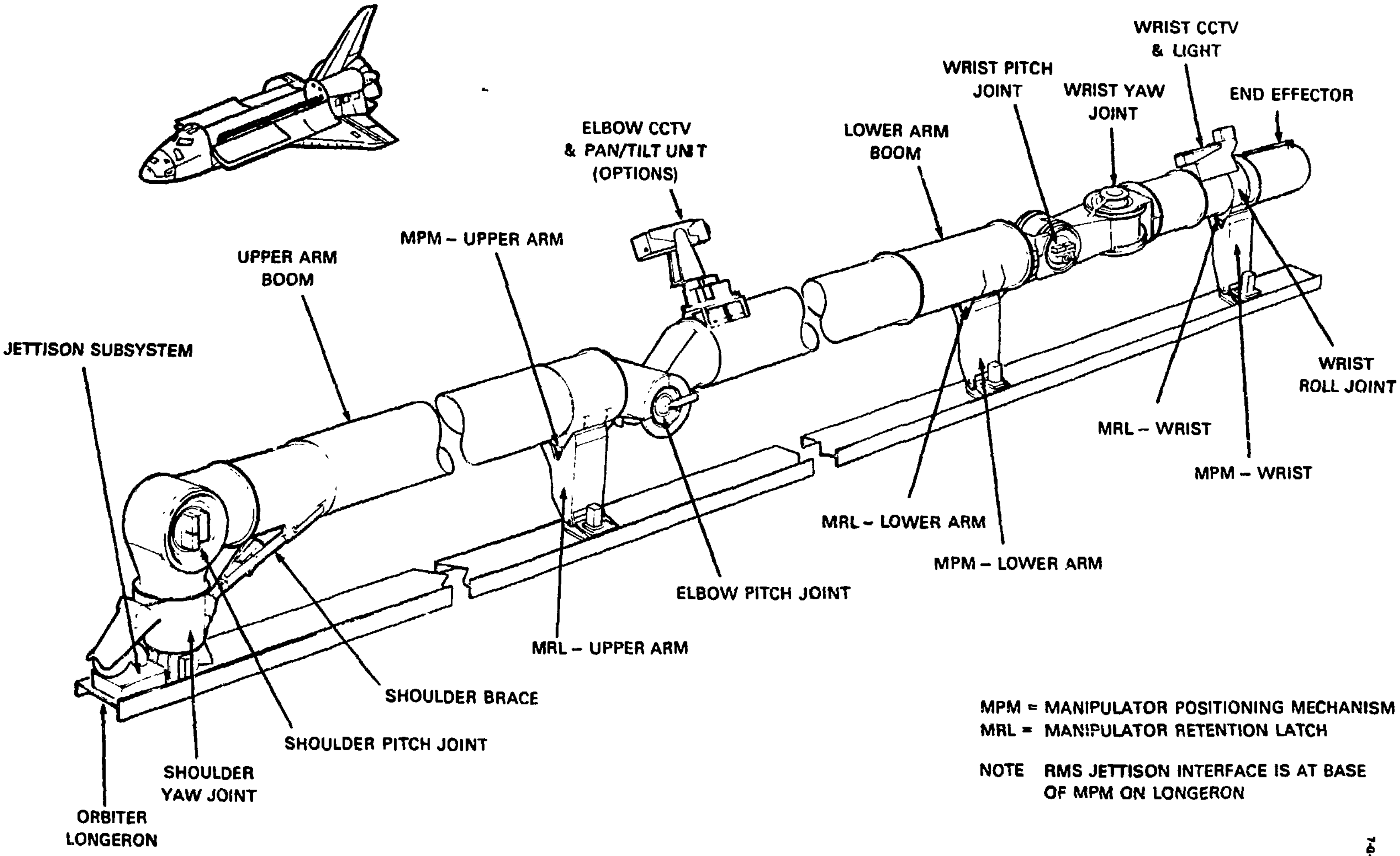

FIGURE 2 SRMS MECHANICAL ARM GENERAL ARRANGEMENT

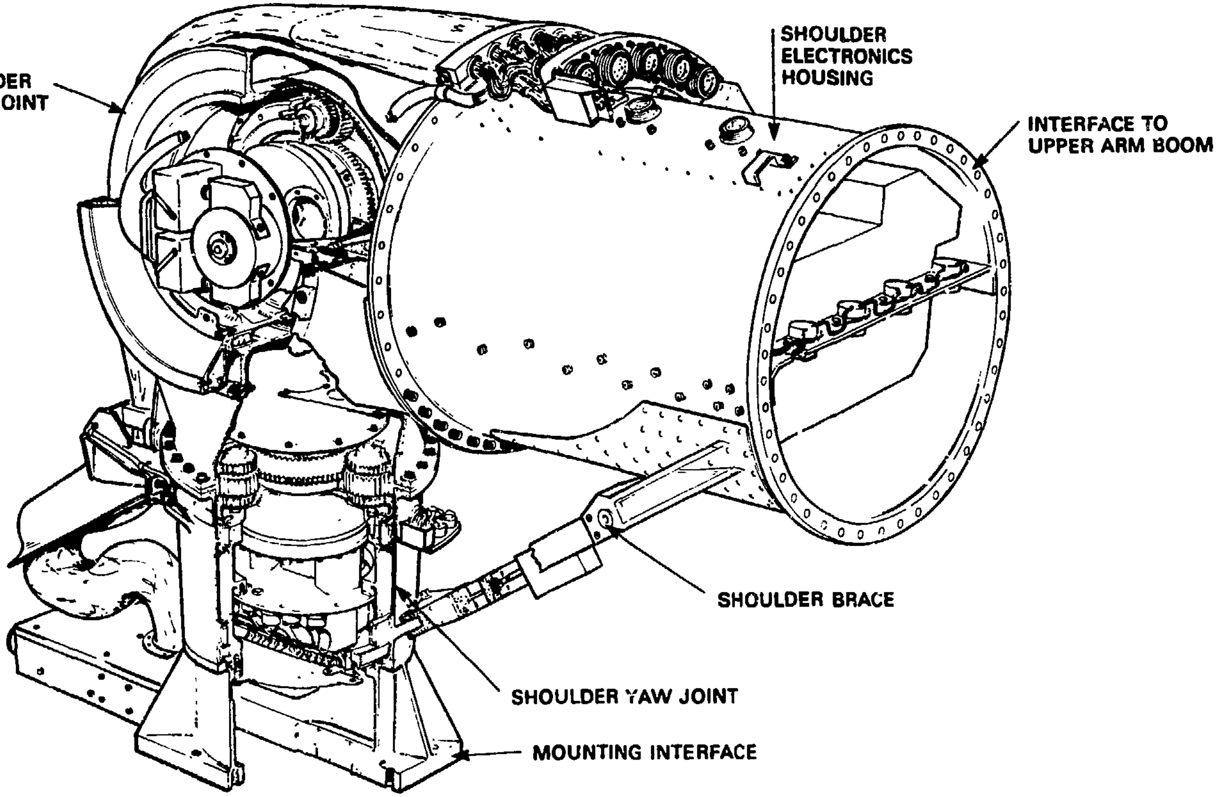

FIGURE 3 SRMS SHOULDER JOINT ASSEMBLY

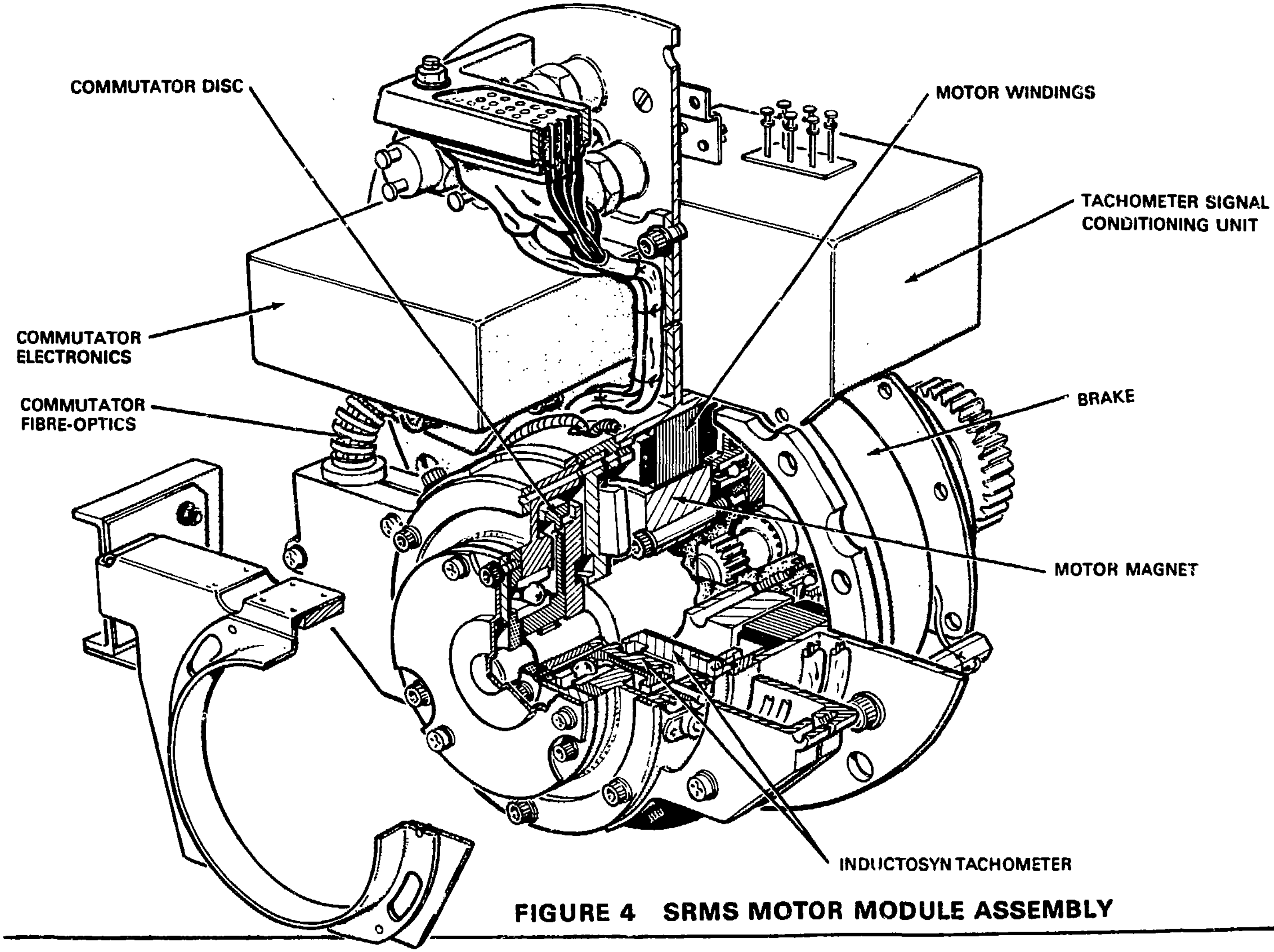

FIGURE 4 SRMS MOTOR MODULE ASSEMBLY

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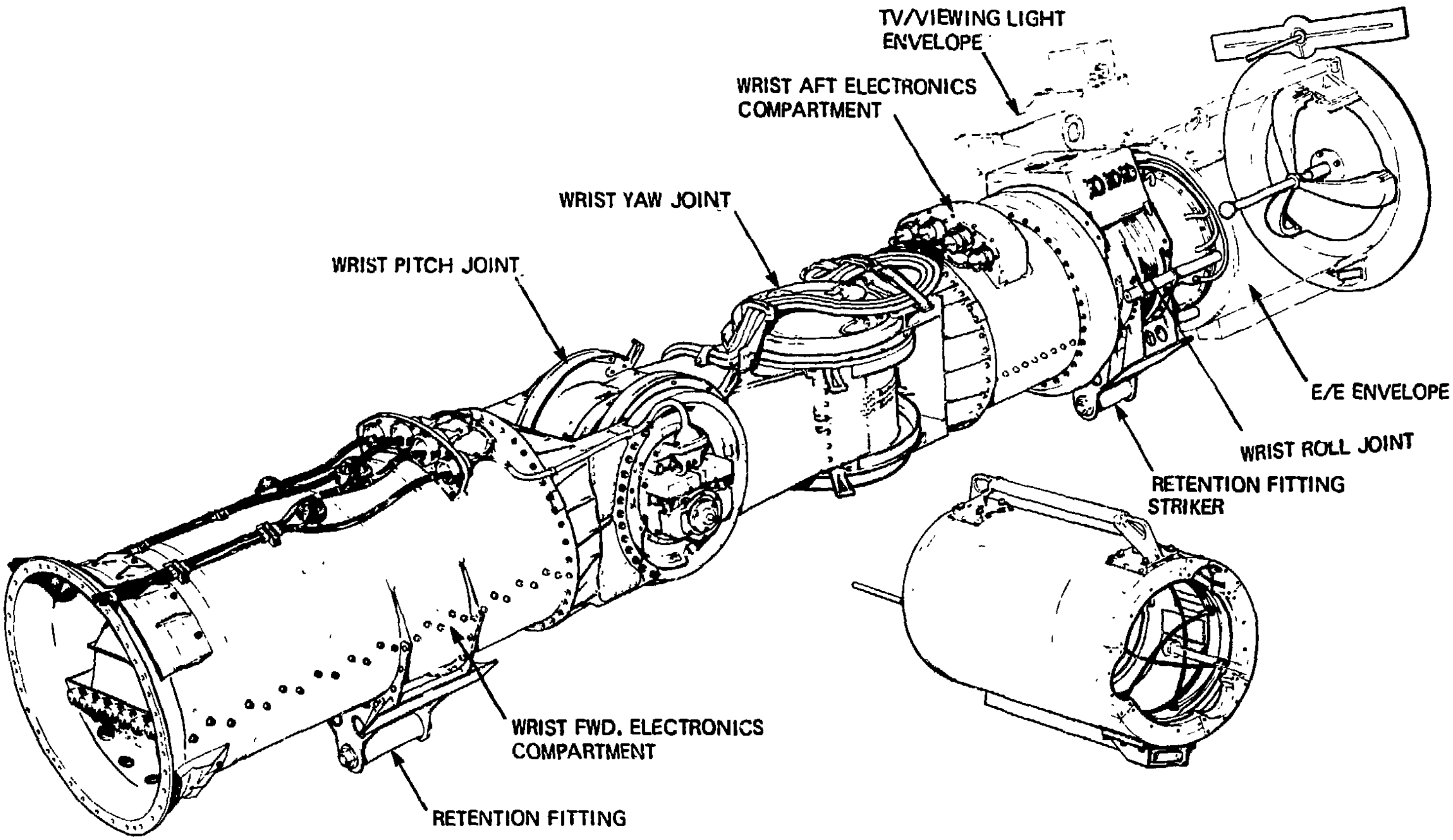

FIGURE 5 SRMS WRIST ASSEMBLY AND END EFFECTOR

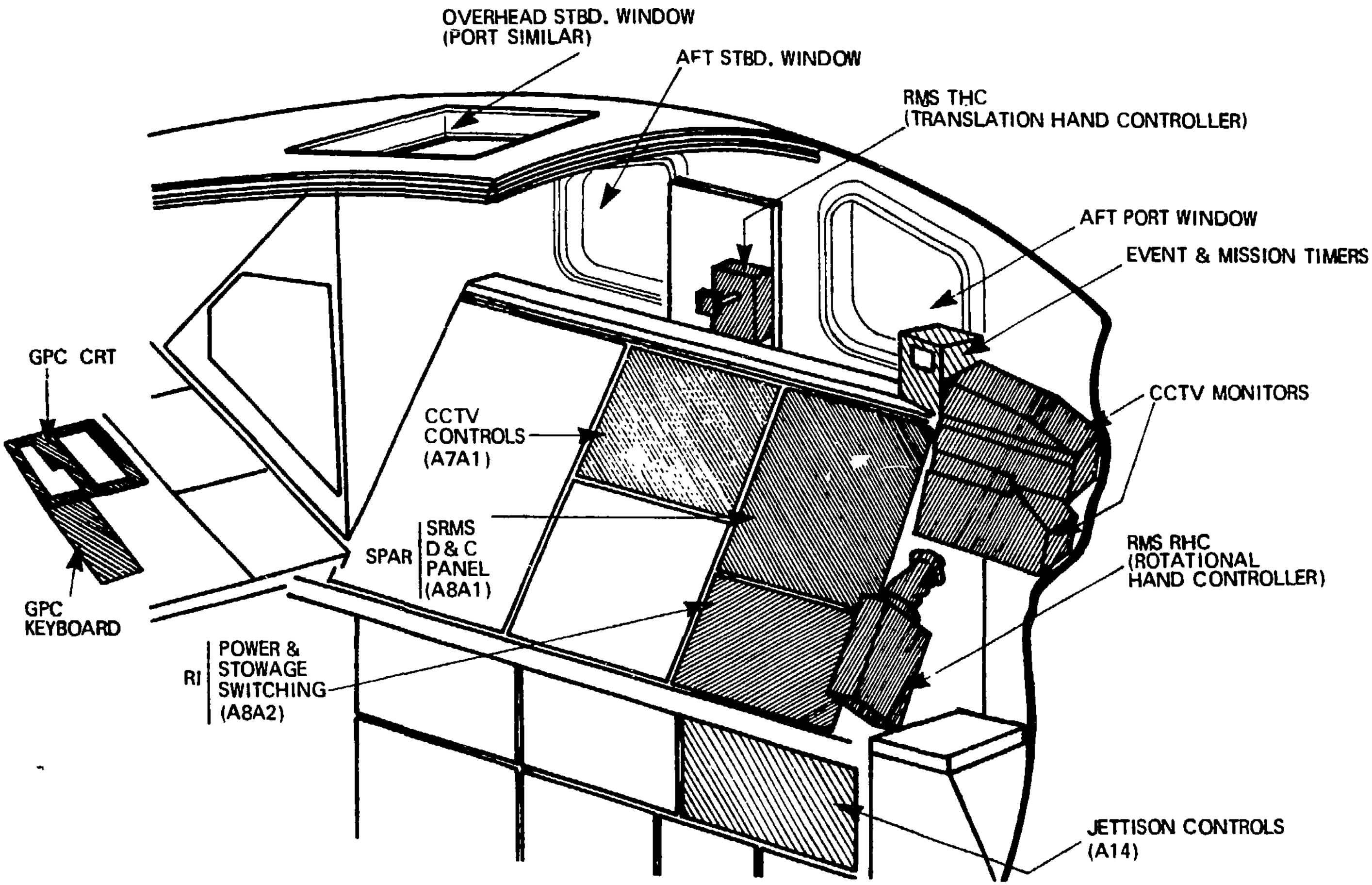

FIGURE 6 ORBITER AFT STATION — LOCATION OF SRMS EQUIPMENT

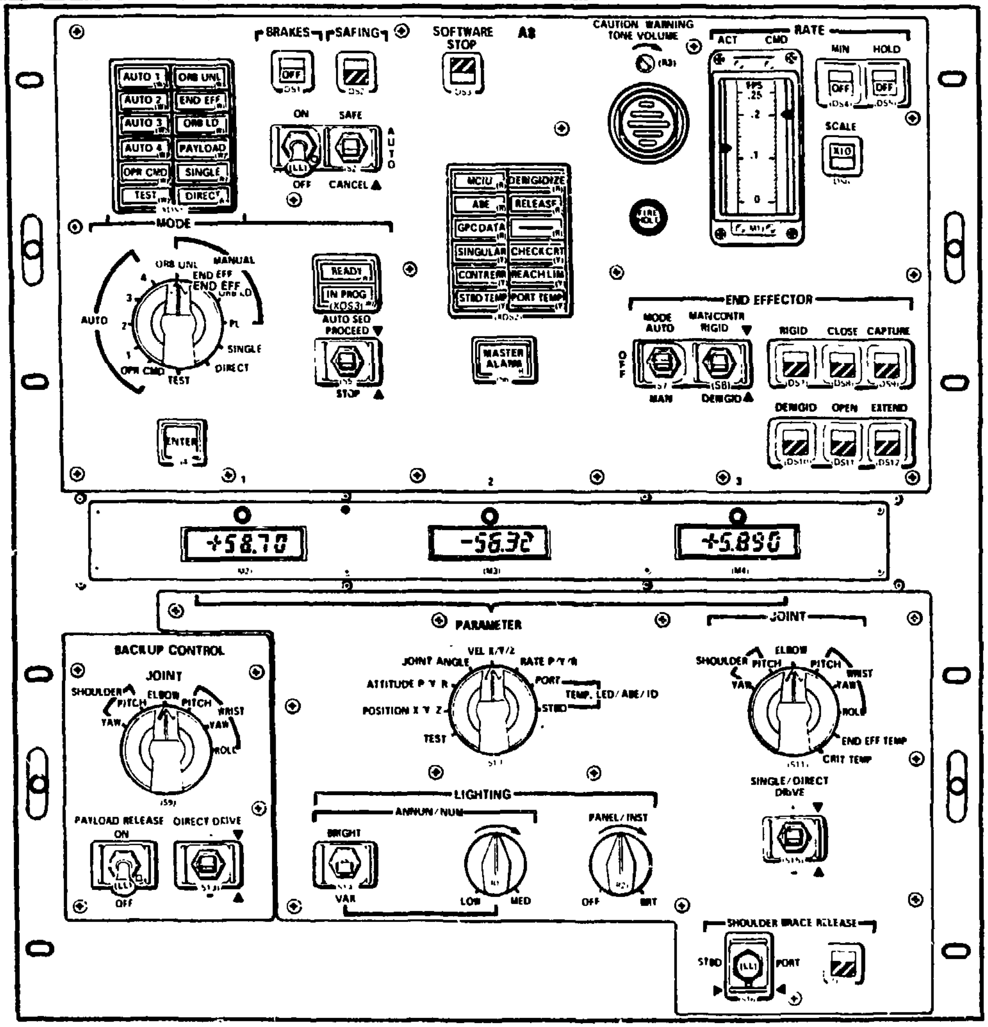

FIGURE 7 SRMS DISPLAY AND CONTROL PANEL

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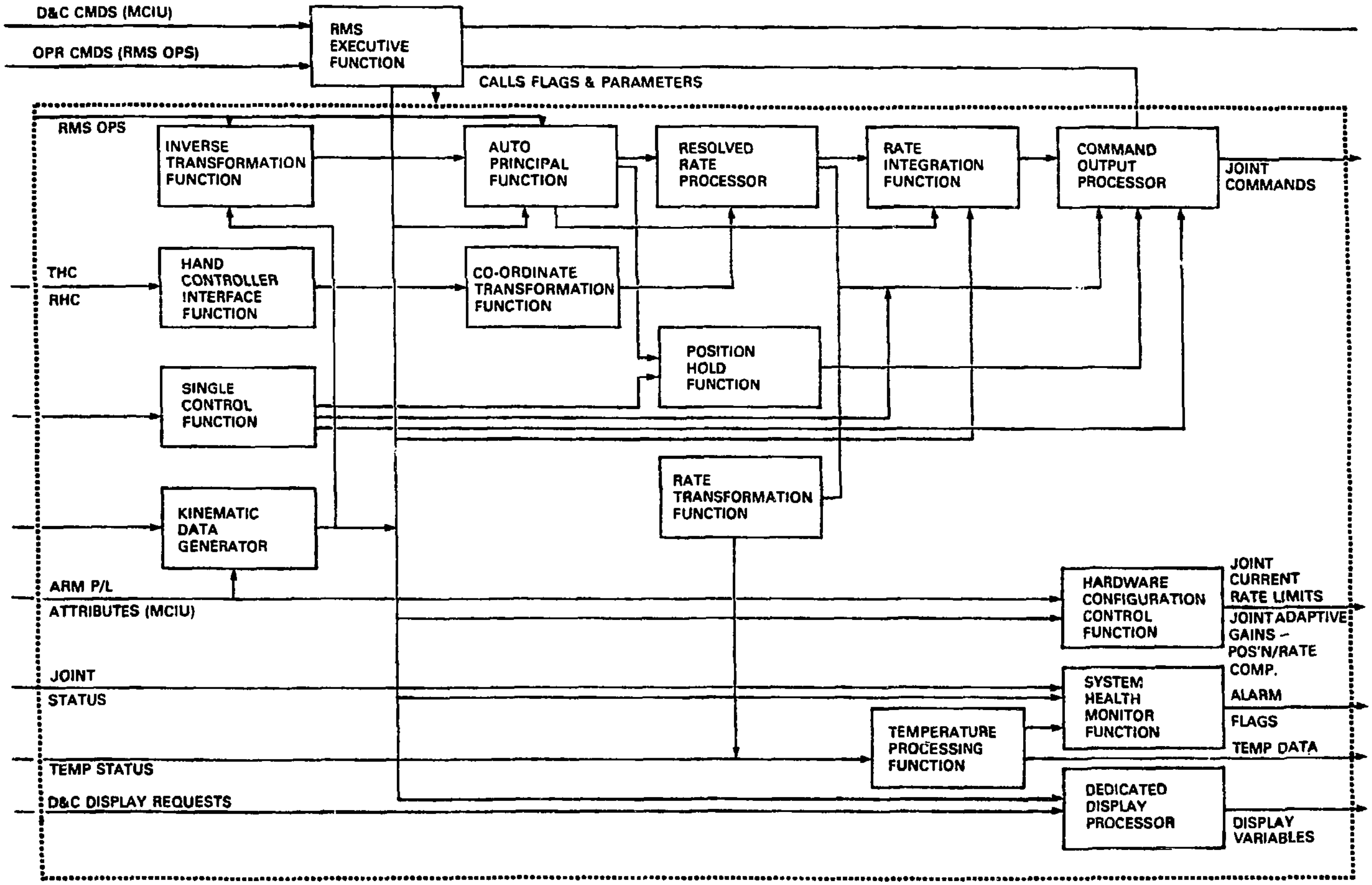

FIGURE 8 SRMS SOFTWARE BLOCK DIAGRAM

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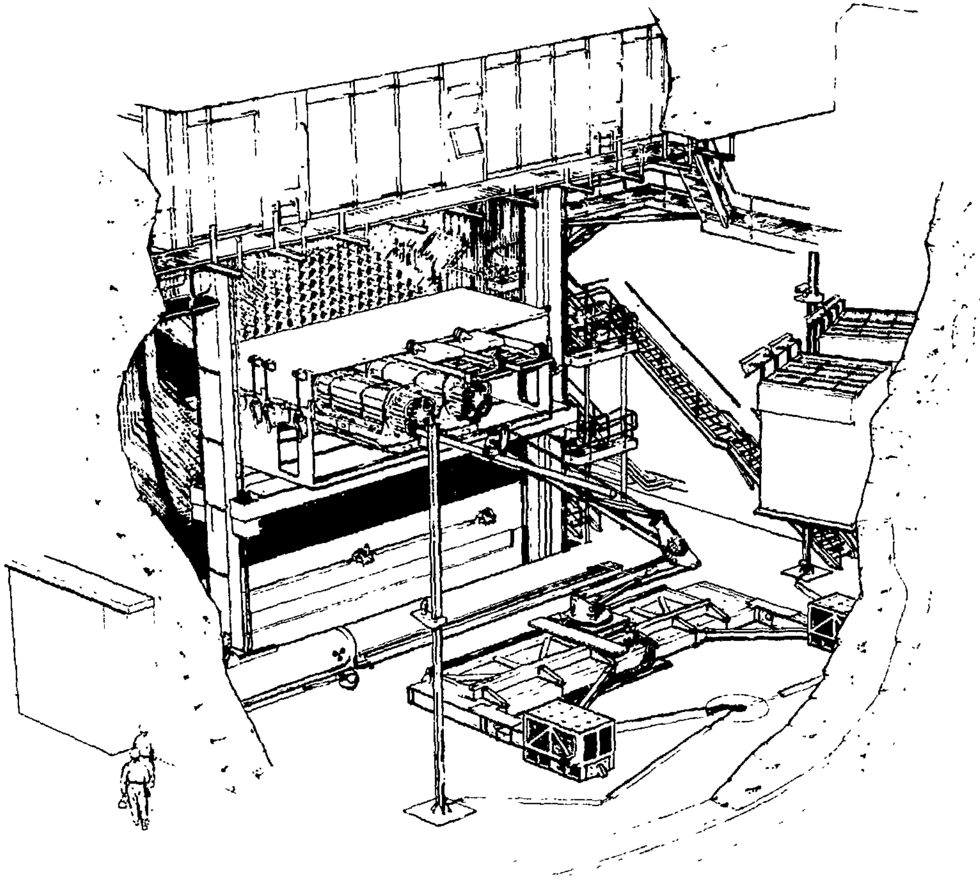

REMOTE MANIPULATION AND CONTROL SYSTEM (RMCS)
IN WEST VAULT OF PICKERING 'A' REACTOR

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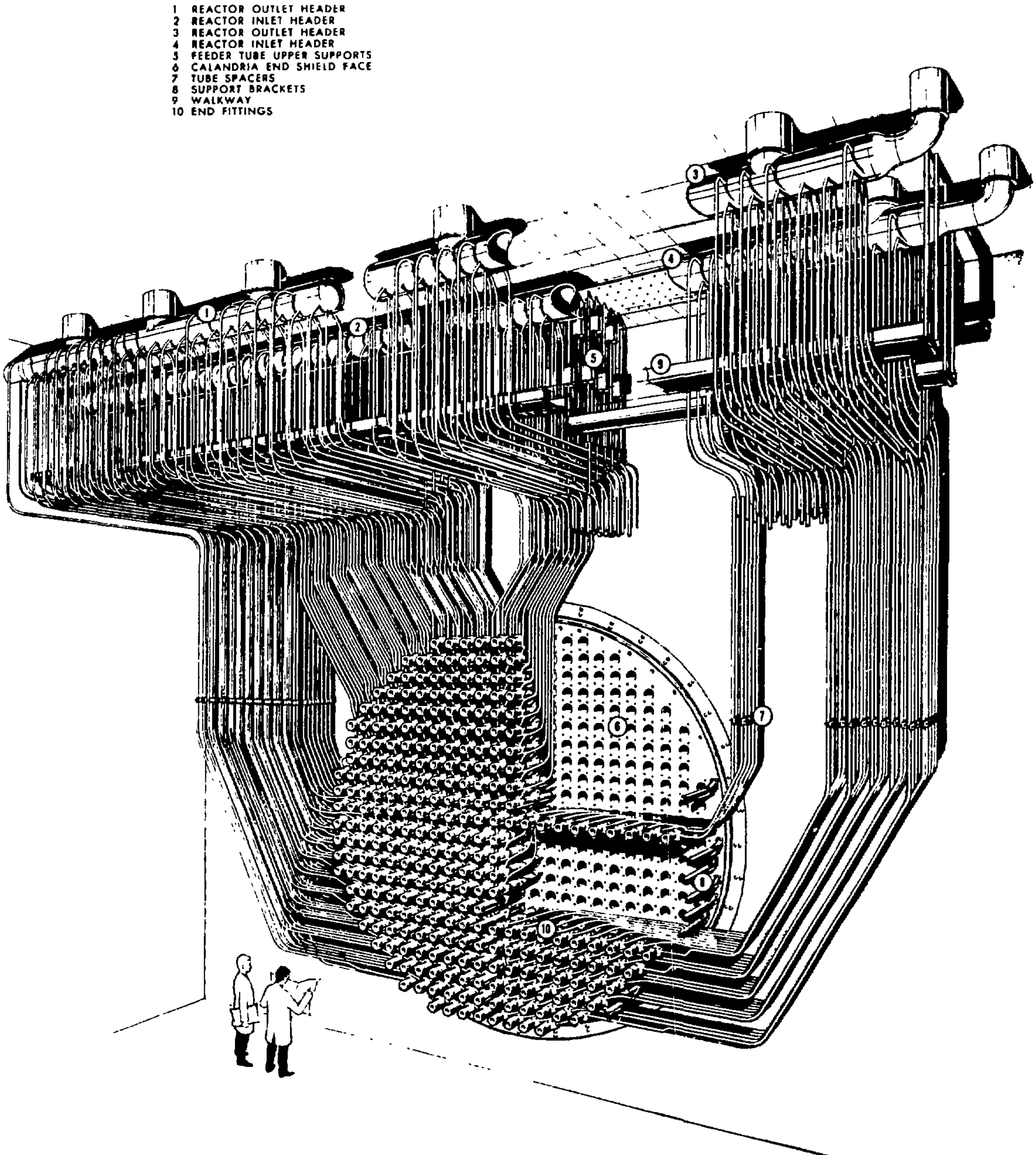
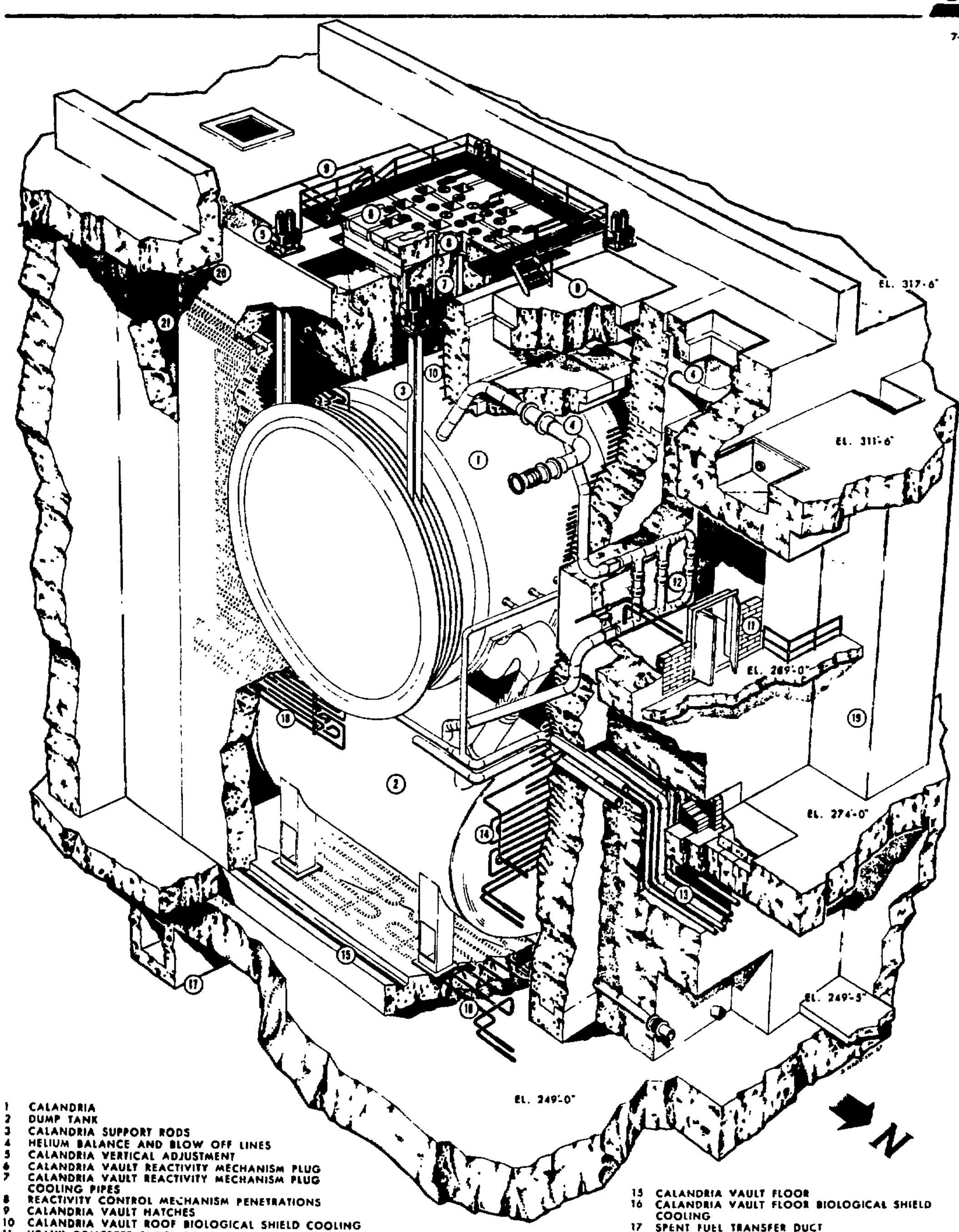


FIGURE 9 CALANDRIA FACE FEEDER TUBE ARRANGEMENT



1 CALANDRIA
2 DUMP TANK
3 CALANDRIA SUPPORT RODS
4 HELIUM BALANCE AND BLOW OFF LINES
5 CALANDRIA VERTICAL ADJUSTMENT
6 CALANDRIA VAULT REACTIVITY MECHANISM PLUG
7 CALANDRIA VAULT REACTIVITY MECHANISM PLUG COOLING PIPES
8 REACTIVITY CONTROL MECHANISM PENETRATIONS
9 CALANDRIA VAULT HATCHES
10 CALANDRIA VAULT ROOF BIOLOGICAL SHIELD COOLING
11 HEAVY CONCRETE BLOCK WALL
12 HELIUM VALVE CHAMBER
13 CALANDRIA VAULT PIPING
14 NORTH WALL BIOLOGICAL SHIELD COOLING
15 CALANDRIA VAULT FLOOR
16 CALANDRIA VAULT FLOOR BIOLOGICAL SHIELD COOLING
17 SPENT FUEL TRANSFER DUCT
18 EAST WALL BIOLOGICAL SHIELD COOLING
19 PIPE CHASE
20 FUELLING MACHINE VAULT COOLING
21 CALANDRIA VAULT BOILER ROOM INTER SPACE

FIGURE 10 CALANDRIA VAULT GENERAL ARRANGEMENT

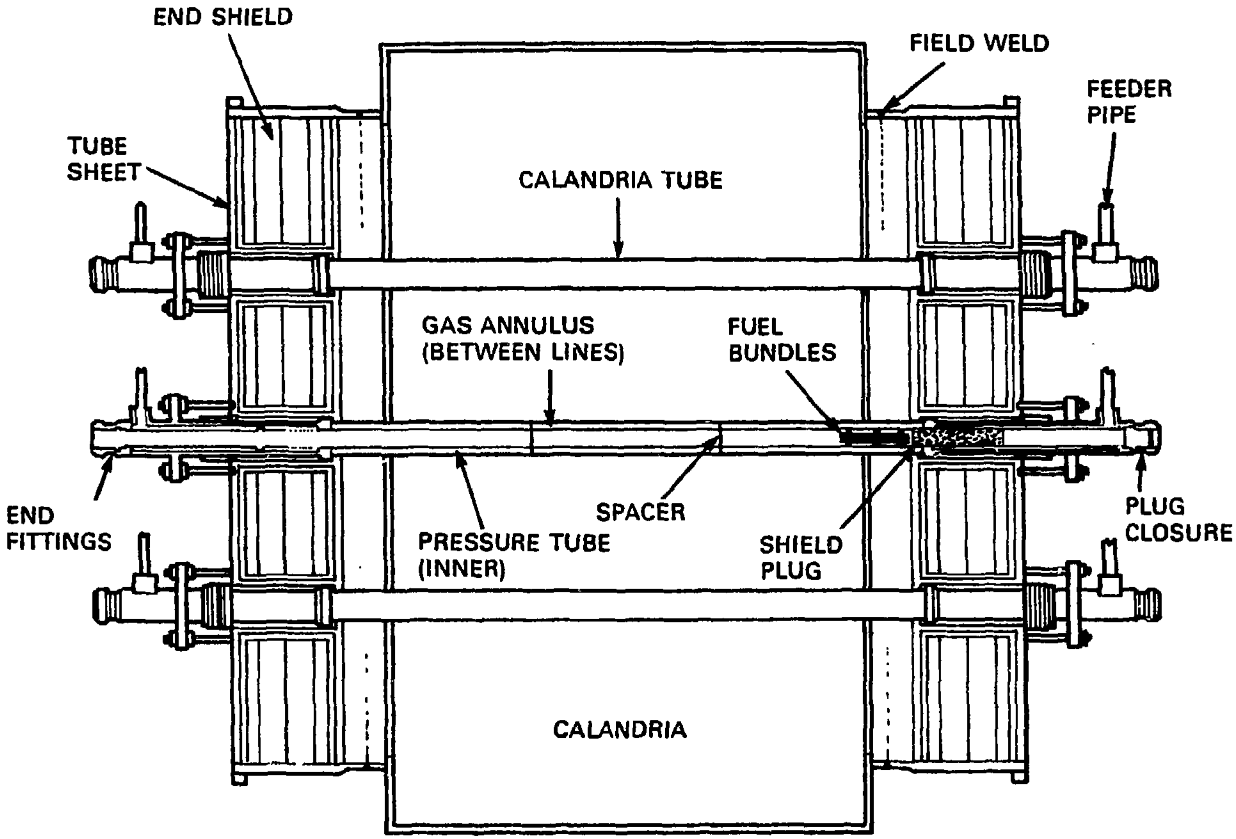


FIGURE 11 THE RETUBE PROBLEM

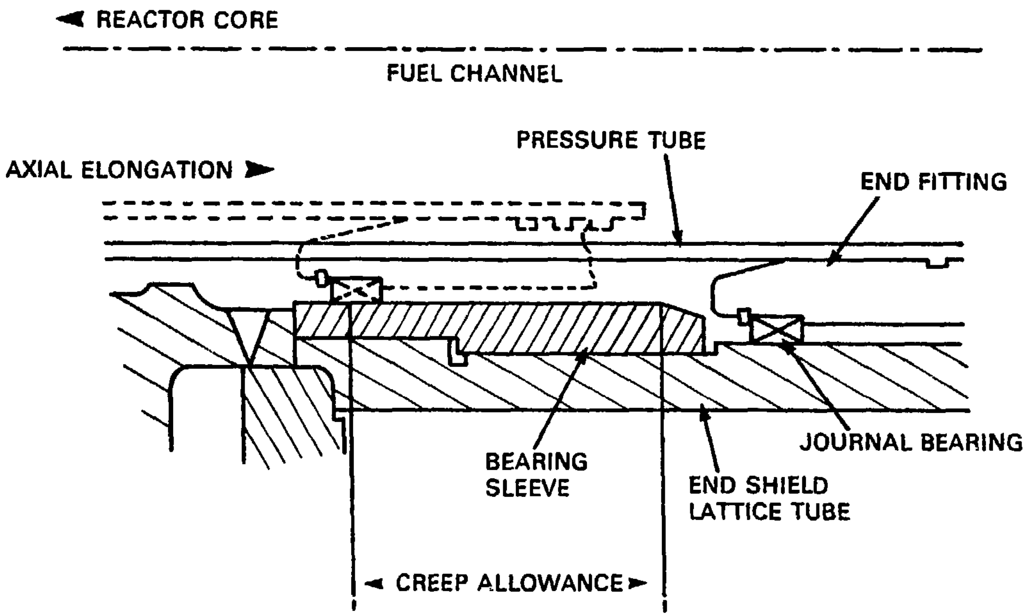


FIGURE 12 FUEL CHANNEL BEARING FALL-OFF DUE TO AXIAL ELONGATION

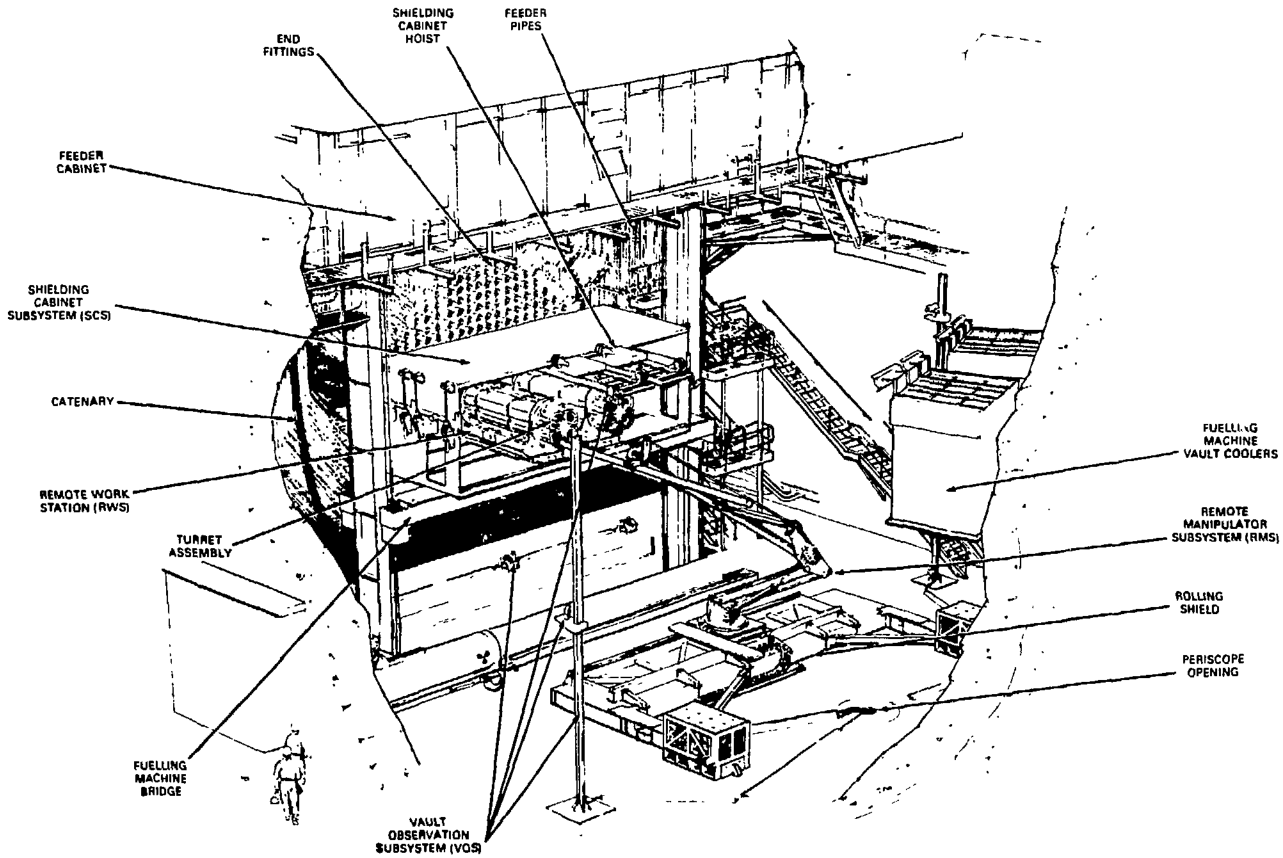


FIGURE 13 REMOTE MANIPULATION AND CONTROL SYSTEM (RMCS) IN WEST VAULT OF PICKERING 'A' REACTOR

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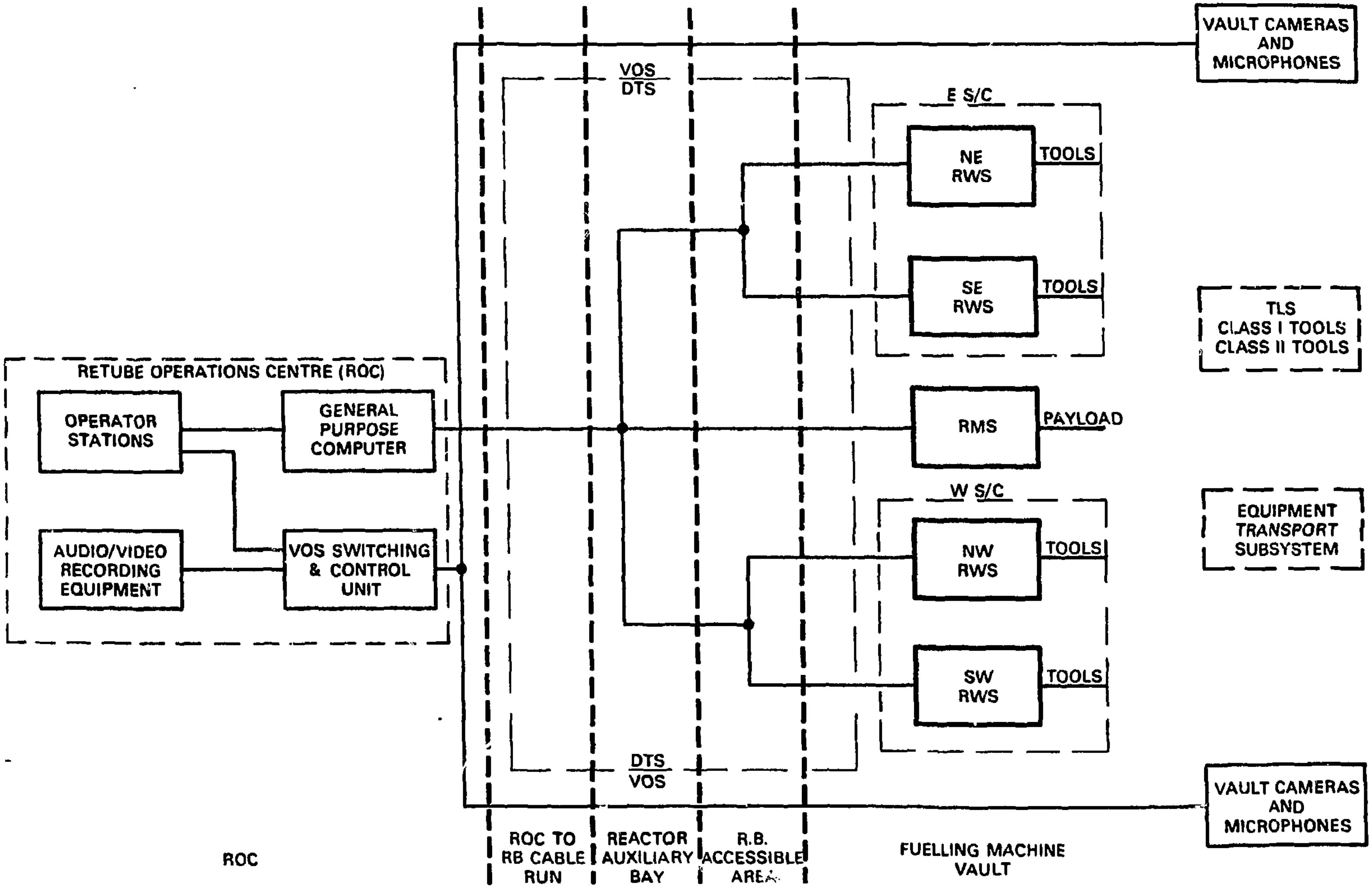

FIGURE 14 RMCS SIMPLIFIED BLOCK DIAGRAM

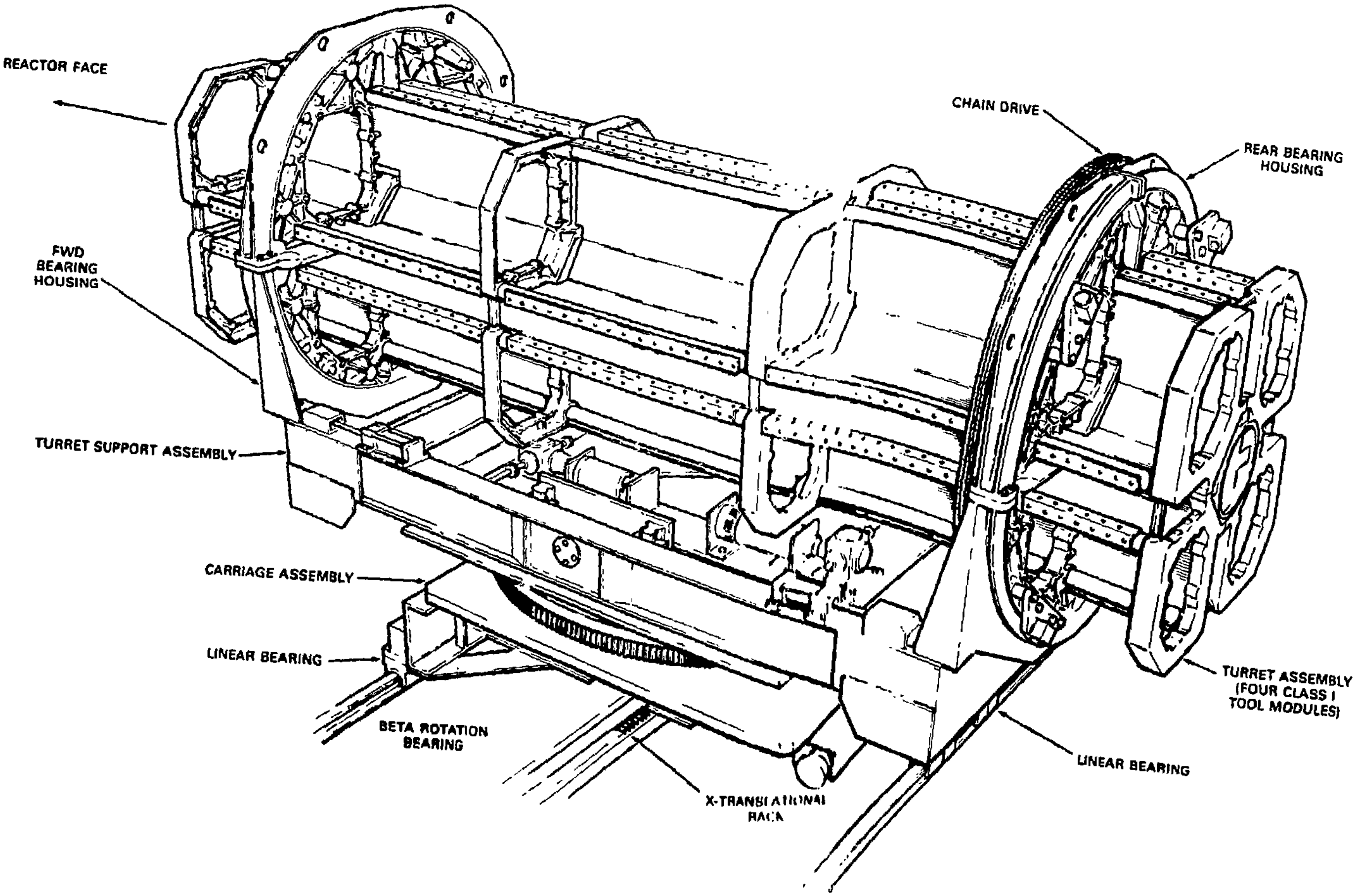

FIGURE 15 REMOTE WORK STATION (RWS)

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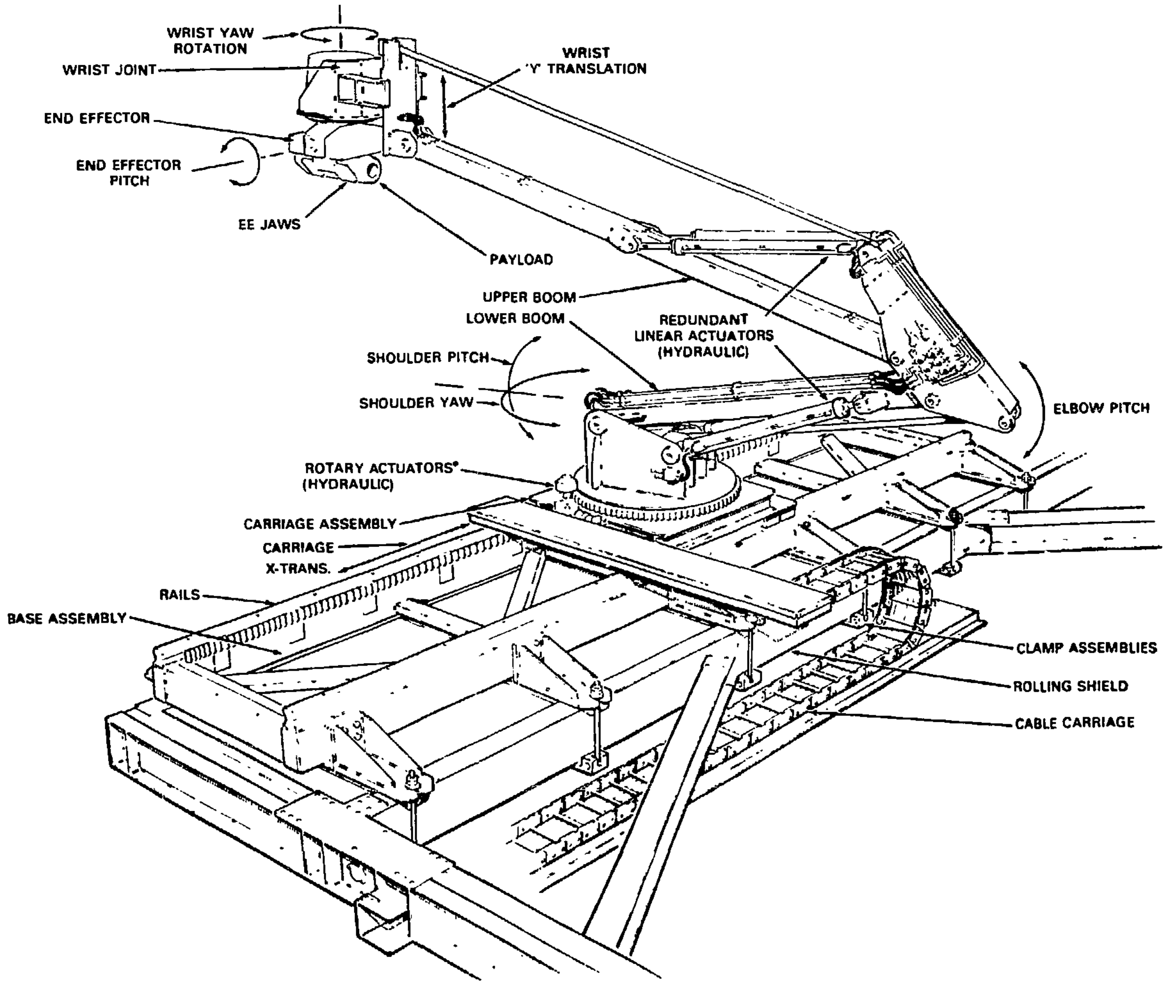

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FIGURE 16 REMOTE MANIPULATOR SYSTEM (RMS)

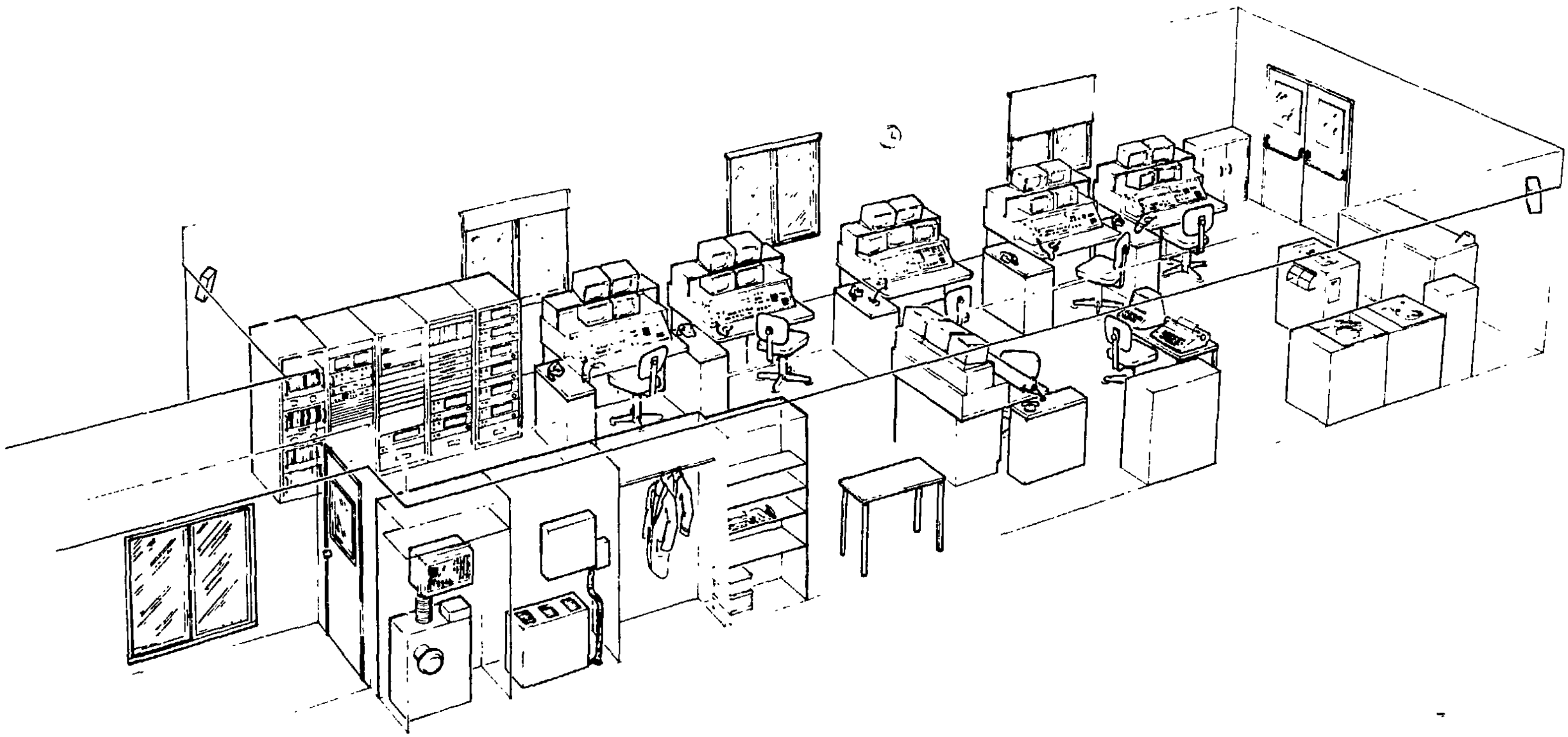

FIGURE 17 RETUBE OPERATIONS CENTRE (ROC)

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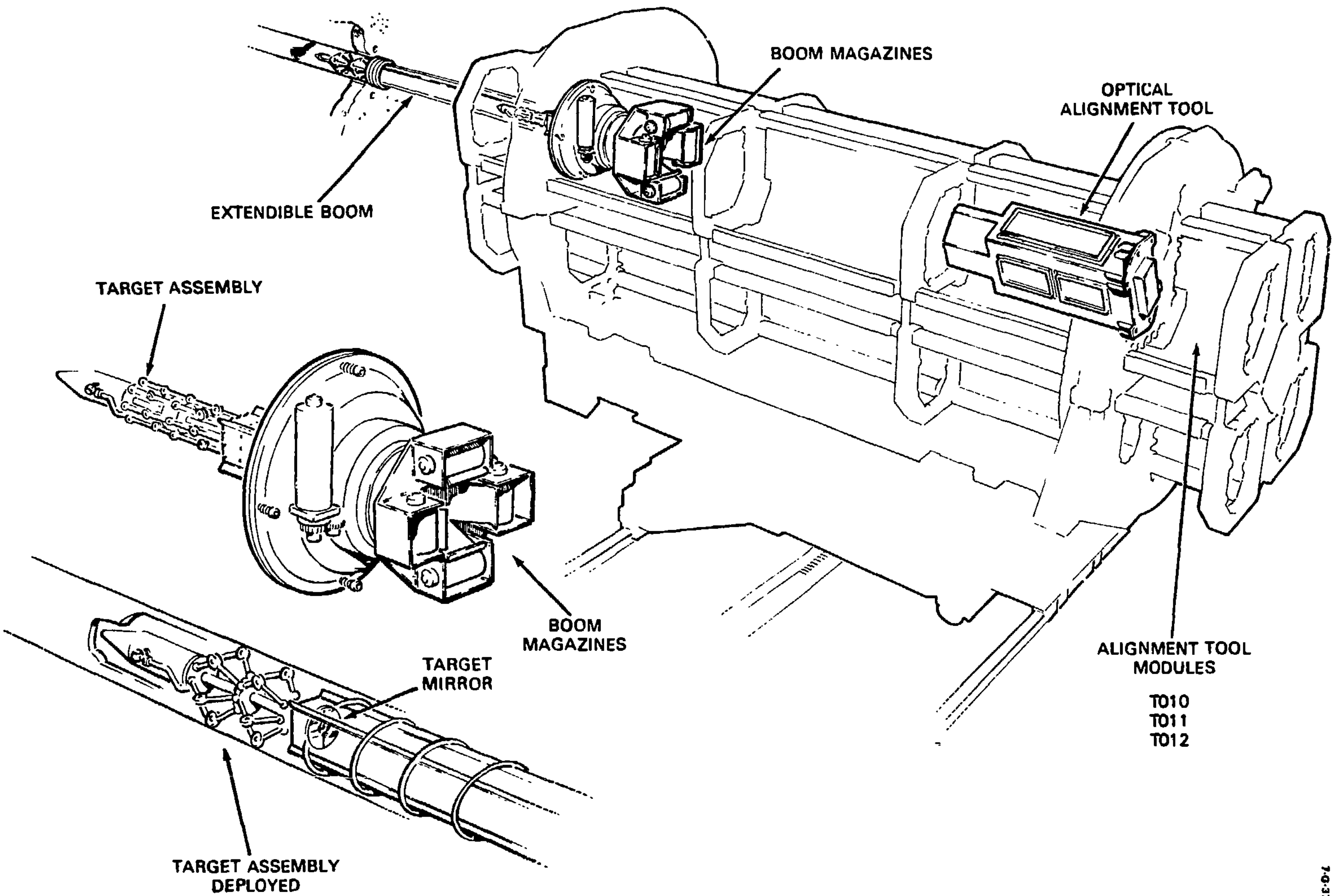

FIGURE 18 OPTICAL ALIGNMENT TOOL ASSEMBLY

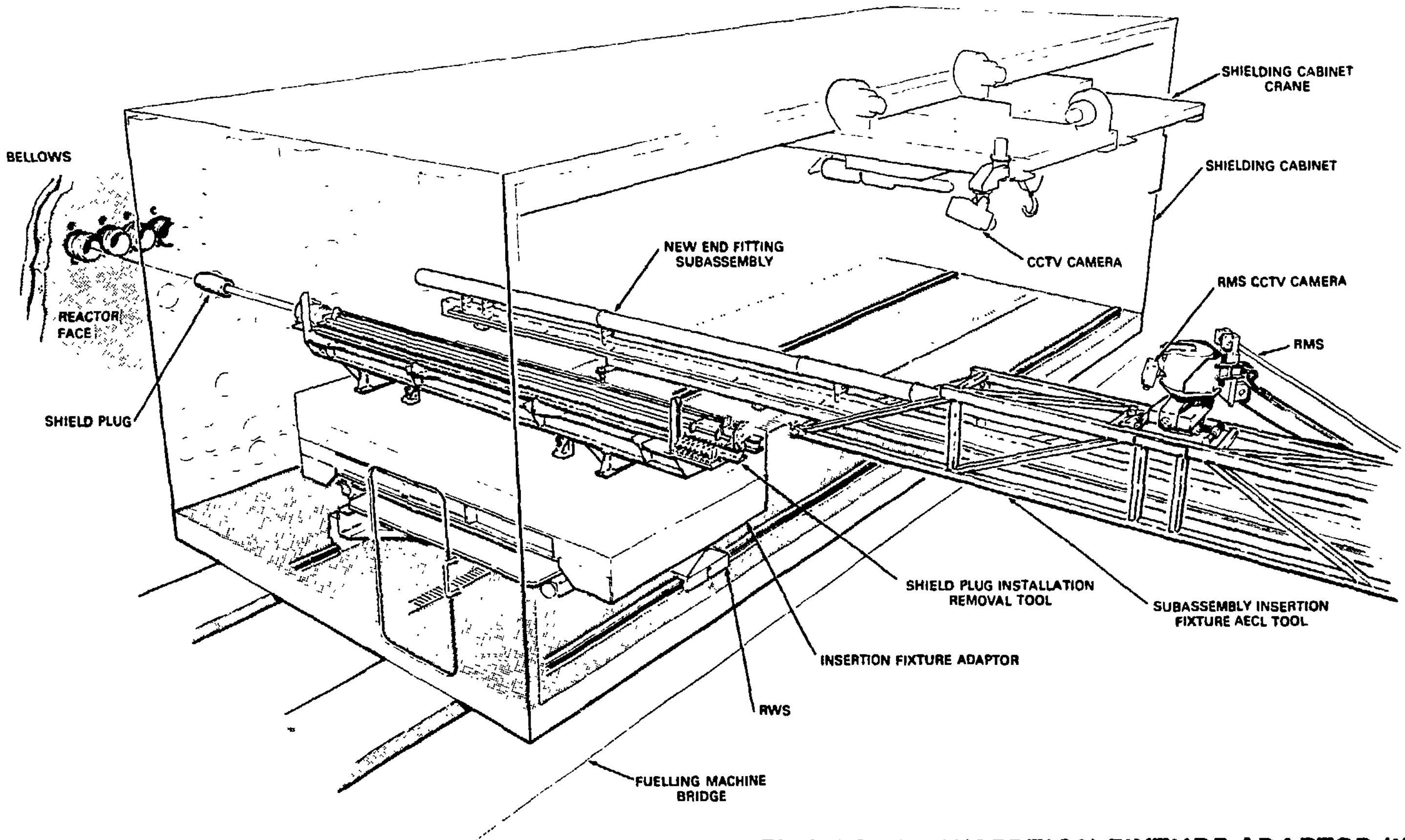

FIGURE 19 INSERTION FIXTURE ADAPTOR (IFA)

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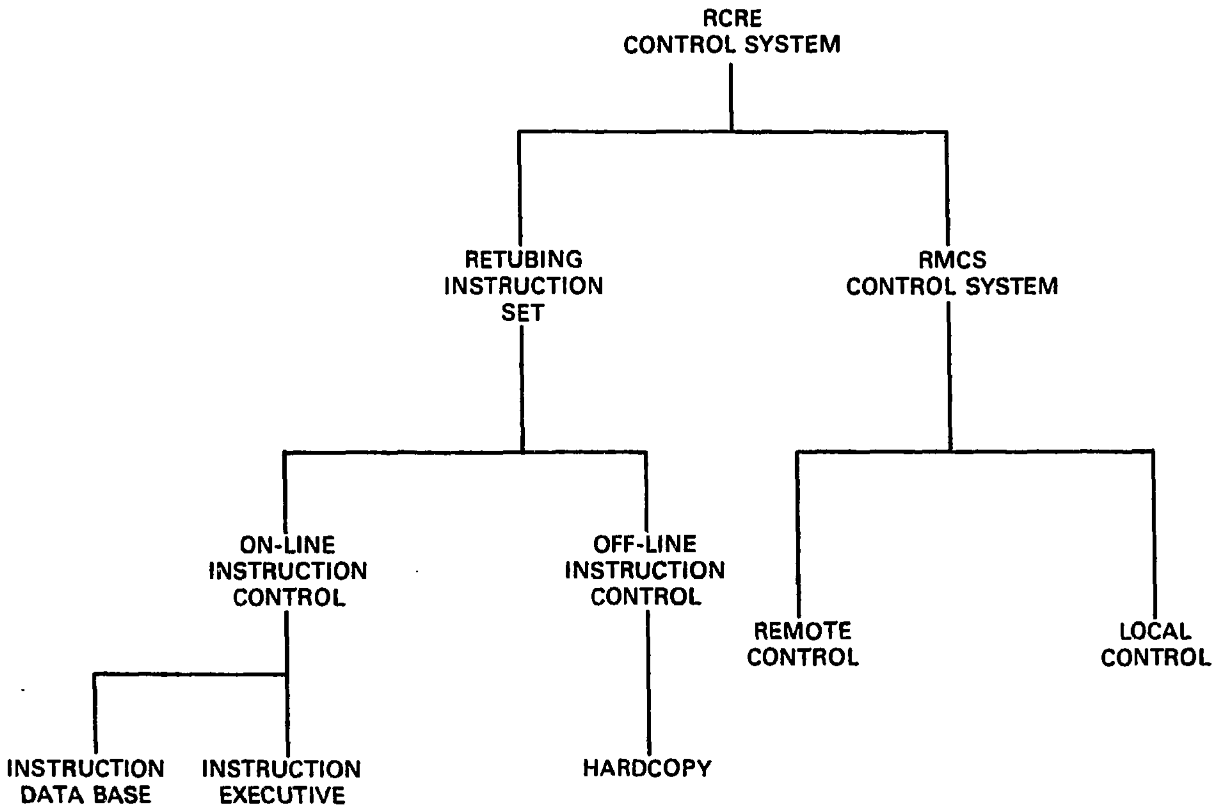

FIGURE 20 CONTROL SYSTEM TREE

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