Project 30103
GA/NRC-337-02

GENERAL ATOMICS

U.S. Nuclear Regulatory Commission
Attn: Ms Raji Tripathi
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6 August 2002

Subject: GT-MHR Conceptual Design Description Report

Reference: NRC Project No. 716

Dear Ms. Tripathi:

As we discussed in our telephone conversation of last week, I am enclosing a copy of the document *GT-MHR Conceptual Design Description Report*, 910720, Dated July 1996. This document provides a summary of the plant concept at the time and includes results of cost, safety, constructability, operability, maintainability, and availability assessments. The work was prepared as part of the GT-MHR project funded at the time by DOE. Subsequently, work under this project has been terminated but the GT-MHR design has continued and progressed significantly as part of the NNSA's Material Disposition program.

In view of the evolution that has occurred in the design since the time of publication, we remind you that details described in the report may be out of date. Nevertheless, the major process parameters and design concept remain unchanged. Therefore, we feel that the report gives a good overview of the plant and is the best description of our plans for the balance of plant and site arrangement currently available.

Should you have any questions on this document, please feel free to contact Laurence Parme at 858 443-2518.

Sincerely,

Laurence L Parme
Manager: GT-MHR Safety & Licensing

Enclosures: (1)
Cc: (w/out encl.)

Leslie Fields	Office of Nuclear Reactor Regulation
Tom Miller	Department of Energy

910720
Revision 1

GAS TURBINE-MODULAR HELIUM REACTOR (GT-MHR)

CONCEPTUAL DESIGN DESCRIPTION REPORT

JULY 1996

GENERAL ATOMICS

910720
Revision 1

GAS TURBINE-MODULAR HELIUM REACTOR (GT-MHR)

CONCEPTUAL DESIGN DESCRIPTION REPORT

Issued by General Atomics
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GA 1485 (REV 9/89)

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GT-MHR CONCEPTUAL DESIGN DESCRIPTION REPORT

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CONTINUE ON GA FORM 1485–1

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NEXT INDENTURED DOCUMENT(S)

DOE-GT-MHR-100001

☐ GA PROPRIETARY INFORMATION

☒ NO GA PROPRIETARY INFORMATION

LIST OF EFFECTIVE PAGES

PREFACE

This report provides a summary description of the 600 MWt Gas Turbine Modular Helium Reactor concept and the results of assessments of cost, safety, constructibility, operability, maintainability, and availability. The design of this concept was initiated in the latter half of fiscal year 1993. Participating organizations are ABB Combustion Engineering Nuclear Systems, AlliedSignal Aerospace Company, Bechtel National, Inc., General Atomics, Oak Ridge National Laboratory, and Stone & Webster Engineering Corporation. Utility requirements and design review are provided by Gas-Cooled Reactor Associates. The design work was funded by the United States Department of Energy.

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ABBREVIATIONS AND ACRONYMS

ALWR	Advanced Light Water Reactor
ASME	American Society of Mechanical Engineers
BOEC	Beginning of equilibrium cycle
BOP	Balance of plant
CWW	Circulating Water System
DOE	U.S. Department of Energy
EFOH	Equivalent forced outage hours
EFPD	Equivalent full power day
EOEC	End of equilibrium cycle
FBP	Fixed burnable poison
FHS	Fuel Handling System
FHSS	Fuel Handling and Storage System
FSV	Fort St. Vrain
GCRA	Gas-Cooled Reactor Associates
GT	Gas turbine
GTCC	Gas turbine combined-cycle
GT-MHR	Gas Turbine-Modular Helium Reactor
HPS	Helium Purification System
HSS	Helium Service System
HTGR	High Temperature Gas-cooled Reactor
IPS	Investment Protection System
LBP	Lumped burnable poison
LEU	Low enriched uranium
LWR	Light Water Reactor
MHR	Modular helium reactor
MHTGR	Modular High Temperature Gas-cooled Reactor
MHTGR-SC	Modular High Temperature Gas-cooled Reactor-Steam Cycle
MOEC	Middle of equilibrium cycle
NI	Nuclear island

NPR	New Production Reactor
NRC	Nuclear Regulatory Commission
NU	Natural uranium
O&M	Operation and maintenance
PAG	Protective action guideline
PCCWS	Power Conversion Cooling Water System
PCDIS	Plant Control, Data and Instrumentation System
PCS	Power Conversion System
PRA	Probabilistic risk assessment
PSER	Preapplication Safety Evaluation Report
QA	Quality Assurance
QC	Quality control
RCCS	Reactor Cavity Cooling System
RPS	Reactor Protection System
RSC	Reserve shutdown control
RV	Reactor vessel
SC	Shutdown circulator
SCS	Shutdown Cooling System
SG	Steam generator
SHE	Shutdown heat exchanger
TBD	To be determined
VS	Vessel System

1. SUMMARY

1.1. PURPOSE

This report provides a conceptual design description of the GT-MHR. Technical data as currently developed by the GT-MHR program is presented. In addition, in those areas where limited funding has been expended on the GT-MHR concept, technical descriptions from prior HTGR programs are included where it is expected that it will, in due course, be included in the GT-MHR design.

1.2. PROGRAM OBJECTIVE

The objective of the Gas Turbine-Modular Helium Reactor (GT-MHR) program is the development of a passively safe, economic nuclear power option for commercial power generation. The reference concept selected to meet this objective is the GT-MHR which consists of four identical modules each comprised of a reactor core coupled to a gas turbine power conversion unit. The current reference plant size is 550 MWt per module with a goal of achieving 600 MWt per module. All systems, structures and components are being designed for 600 MWt providing a potential total electrical output of approximately 1145 MW(e) for power generation applications.

1.3. DESIGN STATUS

The conceptual design of the GT-MHR plant is described in the next section. This gas-turbine plant design has evolved over the last 10 years (as described in Section 2.1) from the steam cycle. The current design is based on a highly recuperated and intercooled Brayton cycle. The design description reflects the design status as of October 1995. However, the GT-MHR is an evolving design, and current parameters and details may differ from those shown in this report.

The engineering team working on the plant design consists of General Atomics for the reactor core and system design and integration, AlliedSignal for the turbomachine and recuperator, and Asea Brown Boveri-Combustion Engineering (ABB CENSYS) for the vessels and other

heat exchangers. Utility/user requirements and design review are provided by Gas-Cooled Reactor Associates (GCRA) and system integration is provided by the Plant Design Control Office (PDCO). Technical support, primarily in the areas of fuel and materials, is provided by Oak Ridge National Laboratory (ORNL). Architect Engineer technical input to the design is provided by Bechtel National, Inc. (BNI) and Stone & Webster Engineering Corp. (SWEC), and fuel manufacturing is provided by GA with support from Babcock & Wilcox. The overall effort is funded by the United States Department of Energy (DOE). The following sections present an assessment of the present design and a summary of the plans for development in the near term.

1.3.1. GT-MHR Concept Assessment

The high temperature capability of the GT-MHR ceramic core is very effectively utilized by directly coupling the helium cooled MHR core with a helium turbomachine in a closed loop. Independent estimates of the net plant efficiency by General Atomics, Oak Ridge National Laboratory, and the Massachusetts Institute of Technology agree that the high efficiency value is achievable. The high efficiency (nominally 47.7%) provides a significant improvement in plant economics over the 38% efficiency of the steam cycle MHTGR and over the 32% efficiencies of the light water cooled nuclear power plants. Preliminary economic assessments indicate the U.S. operating cost is about 36 mills per kWhe for the 4x550 MW(t) plant and 32 mills per kWhe for the 4x600 MW(t) plant (Ref. 1.2-1) for startup in the year 2016 of an equilibrium target four module GT-MHR. The busbar costs including capital, operation and maintenance, fuel cycle, and decommissioning and based on a plant capacity factor of 85% for the target 4x550 MW(t) and 87% for the equilibrium target 4x600 MW(t) GT-MHR are significantly lower than other advanced nuclear alternatives.

The basic design characteristics of the GT-MHR plant provide a significant reduction in the required plant equipment due to the simplified and reduced number of safety systems and due to the elimination of a large amount of steam power conversion equipment (i.e., steam lines, valves, the condenser, the deaerator, feedwater heaters, etc.). This reduction in equipment results in a significant reduction in the number of operating personnel required to operate and maintain the plant. The plant simplification, reduction in required systems/equipment, modularization, and reduction in equipment requiring regulatory oversight all contribute to an increased capacity factor relative to other nuclear concepts.

1.3.2. Development Plans

The GT-MHR was recommended by the U.S. gas reactor program participants, endorsed by utility program representatives, and adopted by the DOE as the reference concept for the U.S. program (Ref. 1.2-2).

The higher operating temperatures of the GT-MHR and the incorporation of the complete power conversion system within the primary coolant boundary leads to specific technical issues and technical information needs that must be addressed through follow-on studies and appropriate development activities. The key areas are:

1. Fuel Design Confirmation and Qualification

   The GT-MHR passive safety performance relies in large part on the performance of the ceramic fuel under normal and accident conditions. Recent changes in the design and manufacture of particle fuel which significantly increased the quality of as manufactured fuel relative to Fort St. Vrain fuel did not meet the requirements during irradiation testing. Subsequent post-irradiation examinations confirmed the adverse impact of those changes and identified fixes based on existing US and German technology in the fuel design. The design and manufacturing process is being modified to implement that technology. QC examination techniques are also being improved. The resulting fuel will be irradiated and tested under GT-MHR normal operating and accident conditions to confirm compliance with performance requirements.

2. Power Conversion Equipment Design and Demonstration

   Although the feasibility of the concept has been shown, additional system and component design, and prototype component testing of the Power Conversion System is required.

   An integrated test of the entire power conversion vessel and equipment is planned to demonstrate performance. Although generally based on existing technology,

individual equipment items require reconfiguration and significant engineering and testing for GT-MHR application.

1.3.3. Licensing Interactions

A safety and licensing review by the U.S. NRC was initiated on the 350 MW(t) steam cycle plant in late 1986 which led to issuance of a Draft Preapplication Safety Evaluation Report (PSER) in March 1989. While this report provided a substantial confirmation of the MHTGR's enhanced safety, key policy/criteria issues, many of which were applicable to all advanced reactor types, were identified that require resolution. The NRC is preparing a final PSER that will review the application of these key issues to the MHTGR design and report the results of NRC's consideration of recent safety analyses by the design team.

Since the safety approach of the GT-MHR is expected to be similar to that of the MHTGR, most of the conclusions of the PSER are expected to be applicable to the GT-MHR design. However, when licensing resumes, it will be necessary to introduce the GT-MHR concept to the NRC staff.

1.4. CONCEPT DESCRIPTION

1.4.1. Plant Description

The GT-MHR module arrangement is shown in Fig. 1.3-1. Each GT-MHR plant consists of four reactor modules. The primary components for each module are contained within a steel vessel system, which includes a reactor vessel and a power conversion vessel, connected by a cross vessel. The vessel system is located inside an underground concrete silo 25.9 m (85 feet) in diameter by 42.7 m (140 feet) deep, which serves as the containment structure. The reactor vessel is made of high strength 9Cr-1Mo-V alloy steel and is approximately 8.4 m (27.5 ft) in diameter and about 31.2 m (102 ft) high. It contains the reactor core, the reactor internals, control rod drives, refueling access penetrations, and the Shutdown Cooling System. The reactor vessel is surrounded by a Reactor Cavity Cooling System which provides totally passive safety-related decay heat removal by natural draft air circulation. The Shutdown Cooling System located at the bottom of the reactor vessel provides forced helium circulators for decay heat removal for refueling and maintenance activities.

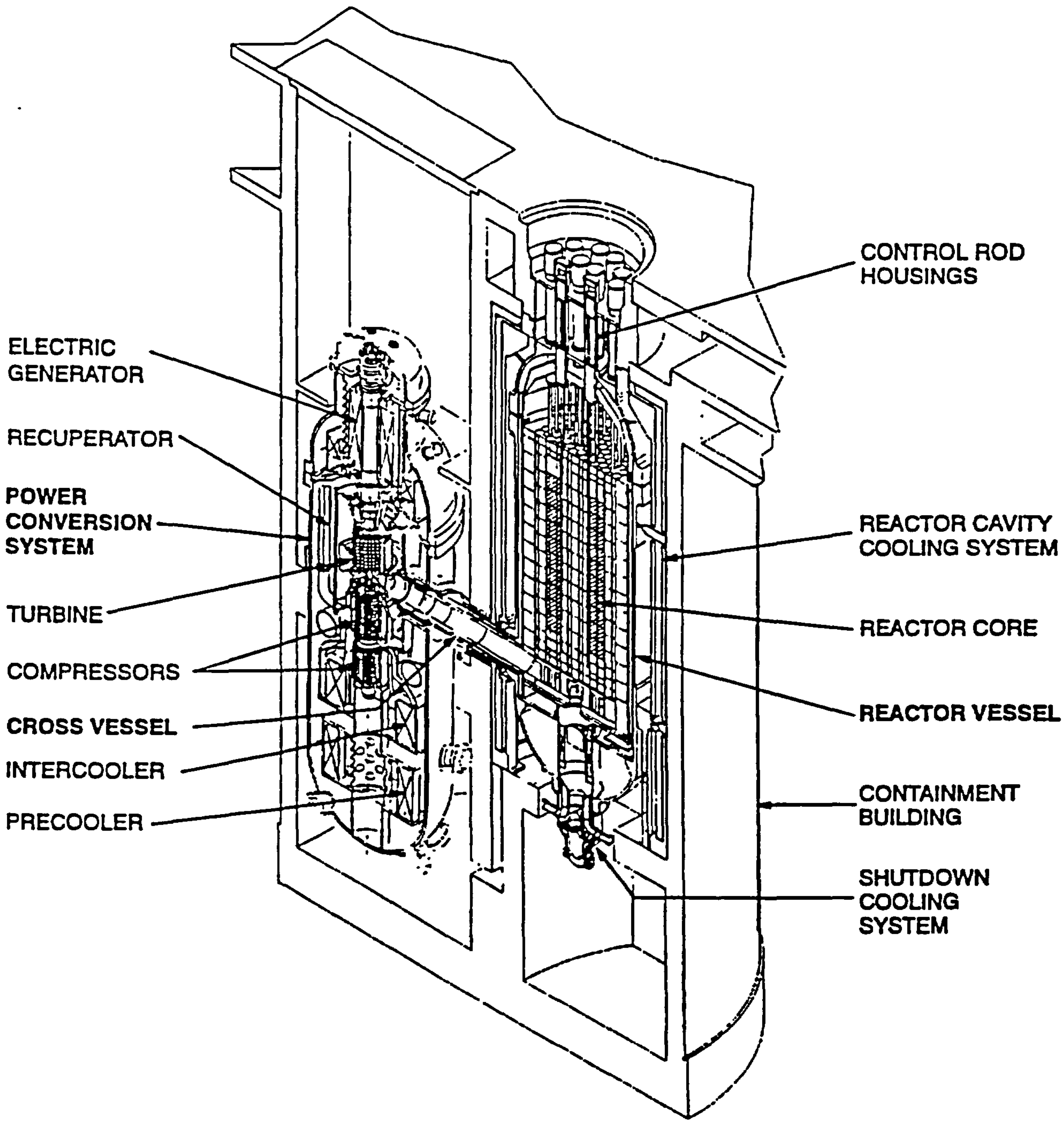


Fig. 1.3-1. GT-MHR module arrangement

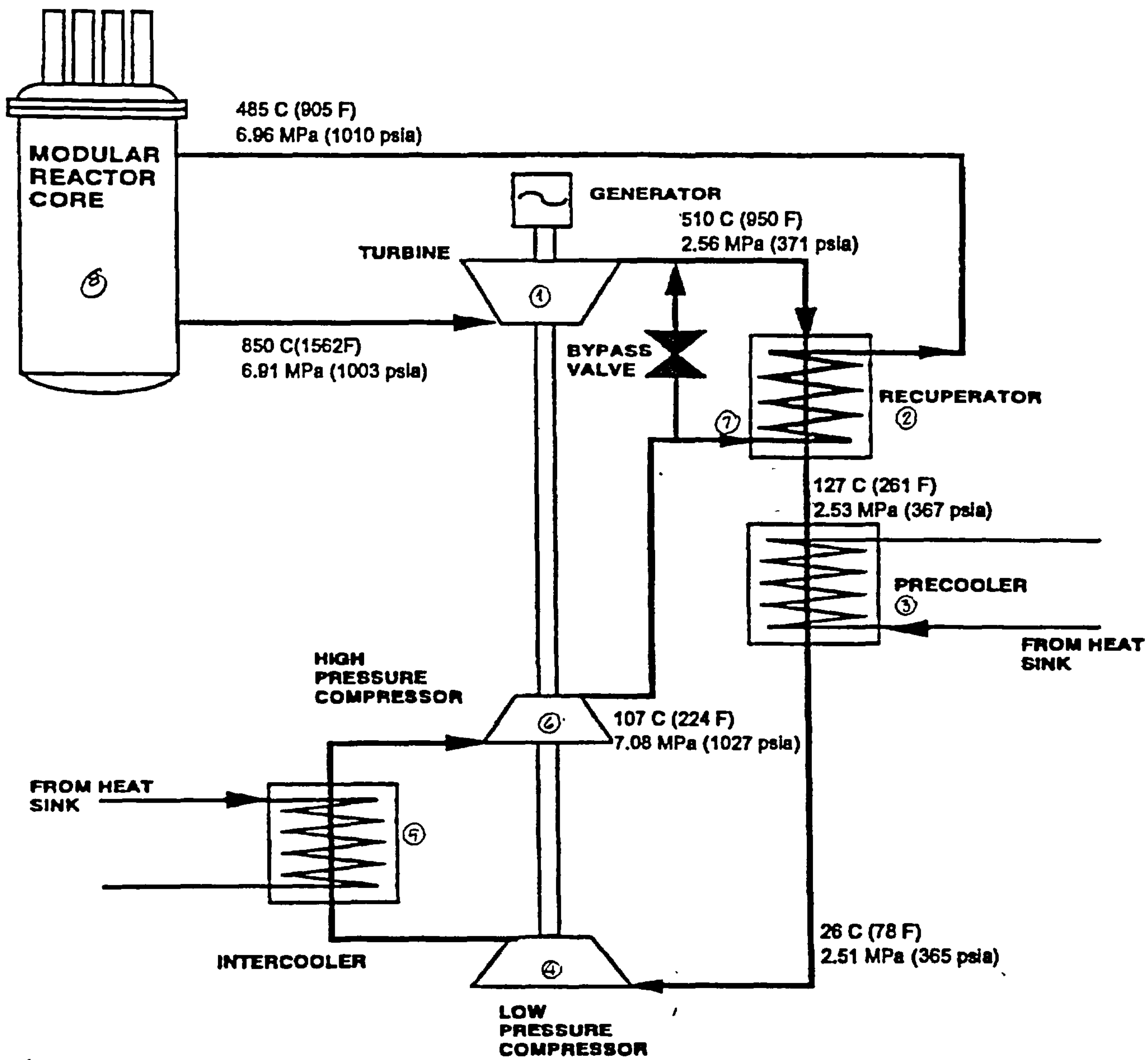
The power conversion vessel is also made of modified 9Cr-1Mo-V alloy steel and is approximately 8.5 m (27ft-11.0 in.) flange outside diameter and about 35.4 m (116 ft) high. This vessel houses the turbomachine, a plate-fin recuperator, and a helical tube water-cooled inter-cooler and precooler. The turbomachine includes a generator, a turbine, and two compressor sections all mounted on a single shaft supported by magnetic bearings.

The GT-MHR process flow diagram is shown in Fig. 1.3-2. The helium coolant exits the reactor core at 850°C (1562°F) and 6.91 MPa (1003 psia), flows through the center hot duct within the cross vessel, and is expanded through the turbine. The turbine directly drives the electrical generator and the high pressure and low pressure compressors. The helium exits the turbine at 510°C (950°F) and 2.56 MPa (371 psia) and flows through the high efficiency plate-fin recuperator, to return as much energy as possible to the cycle, then finally through the precooler to reject heat to the ultimate heat sink. Cold helium at 26°C (78°F) enters the intercooled compressor where it is compressed to 7.08 MPa (1027 psia) at 107°C (224°F), then passes through the recuperator. Helium at 488°C (910°F) and 7.00 MPa (1015 psia) flows from the recuperator exit, through the outer annulus within the cross vessel, up the core inlet riser channels located between the reactor vessel inside wall and the core lateral restraint, and finally down through the core to complete the loop.

1.4.2. Plant Safety

In the design of the GT-MHR, the desirable inherent characteristics of the inert helium coolant, graphite core, and coated fuel particles are supplemented with specific design features to ensure passive safety. The release of large quantities of radionuclides is essentially precluded by the fuel particle ceramic coatings, which are designed to remain essentially intact during normal operation and off normal events. The integrity of the particle coatings as a barrier is maintained by limiting heat generation, assuring means of heat removal and by limiting the potential effect of air and water ingress on the particles under accident conditions.

The GT-MHR is designed to meet the same stringent safety goals and standards as the steam cycle MHTGR plant (Ref. 13-1). Gas-cooled steam cycle plants that have previously been licensed include the Peach Bottom and Fort St. Vrain plants in the United States. Both the steam cycle and gas turbine MHR plants have the unique feature of passive decay heat removal. This feature was made possible by design selections that include the core power density and annular



* Note flow conditions shown correspond to 600 MW(t) case

Fig. 1.3-2. GT-MHR process flow diagram

core configuration, the high heat capacity of the graphite core, and the uninsulated reactor vessel that allows heat transmission to the Reactor Cavity Cooling System. The capability for the GT-MHR to reject core afterheat passively by conduction through the reactor vessel wall and by radiation/convection to the air-cooled panels in the Reactor Cavity Cooling System has been confirmed by preliminary safety analyses of cases with the primary coolant pressurized or depressurized.

The safety assessment of this design was based on the examination of important accident families which had been identified in previous PRA assessments for HTGR concepts. These accident families were primary coolant leak events and water ingress events both with and without forced cooling. In addition, accident categories specific to the rotating equipment in the gas-turbine design were also assessed.

The results of the qualitative safety assessment of the gas turbine design as compared to the MHTGR steam cycle are:

- The risk of water ingress into the primary coolant during power operation is much less for the GT-MHR due to the absence of a high-pressure water source, i.e., steam generator, but the risk of water ingress during plant shutdown or low-load operation with reduced pressure is comparable.

- The frequency of primary coolant leaks in the vessel system was judged to be slightly higher for the GT-MHR as compared to the steam cycle due to the increased number of vessel system penetrations.

- The frequency of successful cooling with Power Conversion System following a primary coolant leak was judged to be better for the GT-MHR due to the simpler design of this cooling circuit.

- The potential radionuclide release from the core to the primary coolant after a primary coolant leak with loss of forced cooling is higher for the GT-MHR plant due to the higher initial core operating temperatures.

- The consequences of the turbine overspeed and turbine deblading events are unique for the GT-MHR. Based on previous experience and limited analysis, these events are judged to cause no significant radiological releases.

The first item above has the most significant effect on safety risk. The overall qualitative conclusion on the safety of the GT-MHR, based on differences in the dominant accident families affecting cumulative risk, is that the GT-MHR has a lower risk than an equivalent steam cycle plant and meets the same safety requirements as the steam cycle plant.

1.4.3. Plant Economics

The economic performance of the GT-MHR has been evaluated on the Cost Estimate Guidelines or Advanced Nuclear Power Technologies developed by Oak Ridge National Laboratory (ORNL) and reviewed by supportive utilities. The purpose of these guidelines is to provide a consistent and comparable basis for advanced reactor cost estimates. The guidelines establish the reference site, field labor wage and productivity rates, bulk site material prices, financial parameters, common definitions for cost estimate scopes plus the approach for applying learning and contingencies. Table 1.1-1 provides a summary of the financial parameters from the guidelines for a conventional investor owned utility (IOU) as well as a nominal set of parameters for an independent power product (IPP).

The GT-MHR Program has adapted the ORNL guidelines to a MHR Cost Estimating Groundrules and Procedures document to further guide and control the cost estimating effort. Several GT-MHR plants are evaluated over the deployment sequence that reflect progressive cost reductions expected from learning, high throughput in dedicated manufacturing facilities plus achieving full performance and stretch capacity output from the plant. For this ~~paper~~ report, a mature "Target" plant is evaluated that is projected for the 2010 to 2020 time frame and is assumed to be the fifth 4-module plant from a first series of commercial plants. It is noted that further cost reductions for later plants are projected through achieving higher power levels, capacity factors and operating temperatures as well as from volume manufacturing experience.

TABLE 1.1-1
FINANCIAL PARAMETERS

	IOU	IPP
Capitalization, %		
Debt	50	70
Preferred stock	10	–
Common equity	40	30
Return on capitalization, %/year		
Debt interest	9.7	12.0
Preferred dividend	9.0	–
Common equity return	14.0	18.0
Average cost of money, %/year	11.35	13.8
Inflation rate, %/year	5.0	5.0
Real (inflation adjusted) average cost of money, $/year	6.05	8.38
Book/analysis life, years	30	30
Levelizing period, years	30	20

Capital Costs

The capital costs for the Target GT-MHR plant is summarized for the major cost accounts in Table 1.1-2. These estimates were developed by the team of program participants, with input based on the respective programmatic scopes. Supportive utilities have maintained a review role of the respective cost inputs and have been active in the cost integration and comparison efforts. While the GT-MHR cost estimates are based on a conceptual level of design with high uncertainties in some areas, appropriate contingencies have been included with the intent to reflect the 50% confidence estimate. Detailed contingency inputs ranged from 40% to 15% with an overall contingency in the range of 20%.

O&M Costs

Plant staffing and overall O&M costs have grown with the current generation of nuclear plants to represent a major cost and risk issue. A key GT-MHR incentive for the owner/operator is the potential for major reduction in such costs and risks.

GT-MHR O&M costs have been estimated based on the cumulative judgment of utility personnel that have O&M experience with past HTGR plants. LWR plants and fossil plants, plus are familiar with the GT-MHR plant design and O&M requirements. For the Target Plant with the expected reductions in operational licensing requirements, a plant staff level of 241 is projected, which accounts for approximately one-third of the total annual O&M cost of $35M.

Fuel Cycle Costs

The nuclear and fossil fuel cost parameters used in the economic evaluations are given in Table 1.1-3. No real escalation of the nuclear fuel unit costs are projected, but real escalation is forecast for both natural gas and coal. Comparisons of the natural gas and coal cost projections with recent forecasts from the Energy Information Administration indicate that the values are appropriately conservative.

TABLE 1.1-2
GT-MHR CAPITAL COST ('94 M$)

Summary Categories	Target Plant
Land and Land Rights	2.1
Structures & Improvements	155
Reactor Equipment	352
Power Conversion Equipment	267
Electric Equipment	69
Miscellaneous Equipment	33
Heat Rejection Equipment	35
Construction Services	110
Home Office Engineering & Services	72
Field Office Engineering & Services	53
Owners Cost	145
Contingency	314
Total Overnight Cost	**1607**
AFUDC	198
Total Capital Cost	**1805**
Unit Capital Cost, $/kWe	**1719**

TABLE 1.1-3
FUEL COST PARAMETERS

	1994 Price	Real Escalation
Nuclear Fuel		
Uranium ore price	$25/lb	0
Uranium conversion price	$10/kg U	0
Enrichment price		
Up to 10.5% enrichment	$125/kg SWU	0
Incremental enrichment >10.5%	$925/kg SWU	0
Spent fuel disposal	1 mill/kWh	0
Fossil Fuel		
Delivered coal	$1.54/MBtu	1%/yr
Delivered natural gas	$2.48/MBtu	2.2%/yr

The GT-MHR fuel cycle is a once-through cycle that combines a 19.9% enriched fissile particle with a natural uranium fertile particle to yield an average enrichment of 15.5%. The average design burnup is 121,000 MWt-days/metric ton of heavy metal. At full power operation, half the core is reloaded on approximately a 18 month interval. GT-MHR fuel fabrication estimates build on past experience an assume a new, dedicated fabrication facility, whereby modular fabrication lines are expanded as the market dictates.

Decommissioning Costs

Estimates and actuals for nuclear plant decommissioning costs have varied widely due to different criteria and recent rampant increases in low-level waste disposal costs. An initial program estimate for decommissioning was done in 1993 that addressed two alternatives: a return to green field conditions and onsite entombment of the low-level wastes in the silo concrete structures. The two estimates ranged from $260 million to $120 million, respectively. For this paper, a nominal value of $200 million has been applied. Consistent with the groundrules, funds for decommissioning are collected over the economic life of the plant and invested in an external sinking fund of high grade investments.

Generation Cost Comparison

Costs for alternative power generation plants presented herein are based on the latest U.S. Council for Energy Awareness (now Nuclear Energy Institute) report. In addition to the IGCC and the CCCT plants discussed earlier, two ALWR plants are included -- the 1200 MWe evolutionary plant and for the sake of normalized output, a two unit version of the 600 MWe passive plant. Appropriate adjustments for consistency have been made for financing charges or allowance for funds used during construction (AFUDC), escalation to 1994 dollars and fuel cost assumptions.

Summary results are presented in Table 1.1-4 and 1.1-5 for an IOU owner entity and an IPP owner entity, respectively. A 2015 startup date has been applied for estimating the impact of real escalation with the fossil plants. The following points are noted:

TABLE 1.1-4
POWER GENERATION COST COMPARISONS FOR IOU OWNER TARGET AND EQUILIBRIUM GT-MHR PLANTS VERSUS ALTERNATIVE GENERATION OPTIONS
(2015 STARTUP, '94$)

	GT-MHR	Fossil Plants		ALWR Plants	
	4Target Plant	ITGCC	CCCT	Evolutionary	Passive
Plant Parameters					
- Thermal Rating (MWt)	4 x 550	4 x 650	4 x 550	1 x 3587	2 x 1829
- Net Efficiency (%)	47.7	38.1	45.4	33.5	32.8
- Net Rating (MWe)	1050	1000	1000	1200	1200
- Net Heat Rate (Btu/kWh)	7155	8950	7514	10200	10400
- Capacity Factor (%)	85	85	85	80	85
Cost Summary					
- Total Capital ($M)	1805	1709	563	1973	2157
- Unit Capital Cost ($/kWe)	1719	1709	563	1644	1798
- Annual O&M (M$/yr)	35	51	12	58	70
- Fuel Cycle Cost ($/MBtu)	1.30	1.54	2.47	0.77	0.77
- Fuel Real Escalation (%/yr)	0.0	1.0	2.2	0.0	0.0
Generation Costs (mills/kWh)					
- Capital	22.0	22.5	7.4	22.5	23.2
- O&M	4.5	6.9	1.6	6.9	7.8
- Fuel Cycle	9.3	19.2	39.0	7.9	8.0
- Decommissioning	0.7	0.1	0.0	0.9	0.8
Generation Cost	36	49	48	38	40

TABLE 1.1-5
POWER GENERATION COST COMPARISONS FOR IPP OWNER TARGET GT-MHR PLANTS VERSUS ALTERNATIVE GENERATION OPTIONS
(2015 STARTUP, '94$)

	GT-MHR	Fossil Plants		ALWR Plants	
	4Target Plant	ITGCC	CCCT	Evolutionary	Passive
Plant Parameters					
- Thermal Rating (MWt)	4 x 550	4 x 650	4 x 550	1 x 3587	2 x 1829
- Net Efficiency (%)	47.7	38.1	45.4	33.5	32.8
- Net Rating (MWe)	1050	1000	1000	1200	1200
- Net Heat Rate (Btu/kWh)	7155	8950	7514	10200	10400
- Capacity Factor (%)	85	85	85	80	85
Cost Summary					
- Total Capital ($M)	1892	1770	576	2072	2274
- Unit Capital Cost ($/kWe)	1803	1770	576	1726	1895
- Annual O&M (M$/yr)	35	51	12	58	70
- Fuel Cycle Cost ($/MBtu)	1.33	1.54	2.47	0.79	0.79
- Fuel Real Escalation (%/yr)	0.0	1.0	2.2	0.0	0.0
Generation Costs (mills/kWh)					
- Capital	30.1	30.2	79.8	30.8	31.9
- O&M	4.5	6.9	1.6	6.9	7.8
- Fuel Cycle	9.5	18.6	35.9	8.0	8.2
- Decommissioning	0.7	0.1	0.0	0.9	0.8
Generation Cost	45	56	47	47	49

- Compared to the reference clean coal IGCC plant, the GT-MHR Target Plant projects a reduction of about 25% and 20% in generation costs for IOU and IPP owners, respectively. Therefore, within the guidelines and assumptions of the overall cost evaluation effort, the mature GT-MHR plant meets the Program's economic goal of at least a 20% generation cost advantage over comparably sized clean coal alternatives.

- Compared to CCCT plant, the GT-MHR Target Plant projects about a 25% reduction in generation costs for an IOU owner, but is only slightly less for the IPP owner. Note that for IOU owners, the CCCT and IGCC generation costs are on par for the 2015 startup and projected fuel prices. However, for an IPP owner, the CCCT plant maintains an advantage of greater than 15% over the IGCC plant.

- The evaluated generation costs for the Target GT-MHR Plant compares favorably with the ALWR plants where there is no impact due to startup date, i.e., real escalation. The GT-MHR Plant's total capital outlay is on par with the ALWRs but offers greater flexibility in cash flow commitment due to the smaller increments of capacity.

1.5. REFERENCES

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1.3-2 "Technical and Economic Prospects for the Gas-Turbine MHTGR," by L. Mears and S. Penfield, Jr., IAEA Technical Committee and Workshop on High Temperature Applications of Nuclear Energy, October 19-20, 1992.

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2. INTRODUCTION

2.1. BACKGROUND

Helium cooled nuclear reactors have evolved both in the U.S. and internationally for more than 35 years. Over 50 gas cooled reactors (largely CO_2 reactors) have operated worldwide. The first demonstration of large steam cycle helium cooled nuclear power generating stations occurred in the 1970s in the U.S. (Fort St. Vrain) and in Germany (THTR). Although these plants are no longer operational, they provided operational experience on the helium cooled reactor design with the inherent characteristics of inert, single phase coolant; refractory coated nuclear fuel which retains fission products at temperatures up to 1600°C (2912°F); and high heat capacity with long thermal response times and high temperature stability. In the late 1970s, economic and institutional barriers caused a halt in the new construction of any type of nuclear power plants in the U.S. It was recognized that new and innovative reactor designs would be necessary to meet these challenges and retain the capability of nuclear power to meet future U.S. energy needs.

In the 1980s, under the sponsorship of the U.S. Department of Energy, the nuclear industry, national laboratories, and utilities undertook a cooperative program to develop a new, simple, modular helium cooled power reactor design with inherent safety features. This design utilized existing proven technology, successfully demonstrated components, and the proven safety characteristics of helium cooled reactors. In September 1985, the 350 MW(t) steam cycle version of the modular helium reactor was adopted as the reference design for the national HTGR program. A Preliminary Safety Information Document was submitted in late 1986 to the Nuclear Regulatory Commission to begin the preapplication licensing review. This design incorporated many new and unique features, including a standardized modular design which could generally be factory fabricated and then shipped to the site for installation in an underground silo. The most important capability of this new design was that it could meet all safety goals using only the inherent passive characteristics of the modular helium reactor, without relying on active safety systems or operator actions.

In 1989, as part of DOE's New Production Reactor Program (NPR), the MHR was selected as one of two reactor types to replace existing defense program reactors. The design of

the NP-MHR was well advanced when the NPR program was deferred in late 1992 due to planned reductions in nuclear weapon inventories. In the interim extensive design engineering and component testing of the concept had been completed. Much of that development work is supportive of the GT-MHR concept.

The next step in the evolution of the modular helium reactor occurred in 1990, when an effort was completed to improve the economic competitiveness of the design to complement the unparalleled level of safety and flexibility of the modular design. At this time, a 450 MW(t) version of the steam cycle modular helium reactor was developed that retained the impressive passive safety characteristics and reduced the busbar power costs to a level that was comparable with modern coal plants and other advanced nuclear power options. But about this time the utility industry became more interested in advanced open cycle gas turbines burning natural gas, which when operated in a combined cycle mode, had very high thermal efficiencies and very low busbar power costs. In order to better compete within this market, substantially improved power generation economics were necessary.

The helium cooled reactor has the unique capability to be coupled directly to a closed cycle helium turbine using the Brayton cycle, with its associated high thermal efficiency. No other existing or proposed advanced nuclear power system can offer that capability. In the 1970s, designs of direct cycle gas turbine versions of the helium cooled reactor were evaluated. It was found that available gas turbine sizes did not match the large (2000 to 3000 MWt) reactor power outputs of the time, oil lubricated bearings for a turbomachine submerged in helium were troublesome, large size heat exchangers were required for recuperation, and the large reactor designs required active forced shutdown cooling to meet safety goals.

By 1992, advances in technologies encouraged reconsideration of the direct cycle gas turbine. The small passively safe modular helium reactor size now matched available gas turbine sizes. Magnetic bearings were being used in commercial applications. Forced cooling was not required for safety; therefore, interruption in the power conversion, e.g., a turbine deblading event, posed little or no nuclear safety consequences. Highly effective, compact plate-fin recuperator designs were commercially available. Based on the favorable results of this new evaluation, the modular helium reactor design evolved from the 38% efficient steam cycle design to the 46% efficient Gas Turbine-Modular Helium Reactor. This clearly was a potential quantum leap forward for competitive economics of nuclear power generation, especially compared to the

32% plant net efficiencies exhibited by the current generation of light water cooled nuclear power plants. The busbar power costs were now below other nuclear and coal options, and were competitive with costs for combined cycle gas turbines.

The remaining question is whether the GT-MHR busbar power costs could be reduced even further. Previous cost reduction efforts showed that increasing the net power output within the standard MHR design envelope was the most effective means of reducing the busbar power costs. Therefore, developing a power "stretch" version of the GT-MHR by starting with the reference 450 MW(t) GT-MHR design and increasing the power output to as much as 600 MW(t), decreases busbar cost significantly while retaining the reactor vessel size and most importantly, retaining the unparalleled level of inherent safety.

2.2. DESIGN APPROACH

As described above, the reactor system for the GT-MHR module is a direct adaptation of the 450 MW(t) reactor configuration selected for the steam cycle MHR. The thermal power was increased to 600 MW(t) with a reoptimized reactor core configuration to reduce busbar costs. The power conversion system was optimized and the recuperator, intercooler, and precooler were sized to provide high effectiveness and low pressure drop.

Manufacturing and maintenance were considered in the design to allow for factory fabrication of individual components in modules, access to components after installation, remote handling of potentially radioactive components, and external maintenance access for activities such as tube plugging and in-service inspection.

The GT-MHR offers significant economic improvements by taking advantage of state-of-the-art technologies. To confirm the design approach and to resolve any uncertainties, a rigorous program of design, development, and testing is planned. In the near term, more extensive analysis is planned to confirm the conceptual design. As the design progresses, a thorough technology development program and component testing will be completed. Prior to deployment of the first GT-MHR module, a non-nuclear integrated test of the full-scale, first module power conversion loop will be performed. This test will be performed either at a fossil fired test facility or will be performed in situ at the first plant site using fossil fired or electric helium heaters. Separately, the nuclear fuel and reactor components will undergo exhaustive testing to confirm

that performance requirements under normal and accident conditions are satisfied. Finally, the first GT-MHR module will be subjected to extensive hot flow testing prior to first nuclear powered operation.

2.3. SCOPE

This report provides a description of the 600 MW(t) GT-MHR conceptual design, including configuration descriptions of the major systems and a summary of the nominal and transient operation of the GT-MHR module. Also included are the results of assessments of the important aspects of this design such as maintenance and availability, safety and investment risk, and plant economics. A construction schedule is briefly discussed.

The system configuration descriptions contained herein may include systems descriptions that have been developed under other MHR programs. In such cases the description included herein represents the latest design for such systems which are expected to be included as part of the 600 MW(t) GT-MHR design.

Appendix A provides a list of the standard MHR terminology that is used in this report.

3. OVERALL PLANT DESCRIPTION

3.1. PLANT SITE

The detailed reference site parameters for the GT-MHR are included in the Overall Plant Design Specification document (Ref. 3.1-1). The site characteristics in this document envelope a majority of prospective U.S. sites. The plant is designed for a site adjacent to a source of cooling water such as a river or a lake with an assumed elevation range of 30.5 m (100 ft) to 1830 m (6000 ft) above mean sea level. Based on an assumed exclusion area boundary of 425 m (1390 ft), a minimum of 181 hectares (200 acres) is required for the site.

3.2. PLANT ARRANGEMENT

The plant arrangement, as shown in Fig. 3.2-1, consists of four reactor modules with several common support buildings and facilities. Systems containing radionuclides and safety-related systems are located in the Nuclear Island (NI) area which is separated physically and functionally from the remainder of the plant facility.

Each reactor module is housed in adjacent, but separate, reinforced-concrete structures located below ground level as shown in Fig. 1.3-1. This below-grade location provides significant design benefits, which include grade level access for refueling, reduction of seismic effects, missile protection and improved site visual activities.

For the GT design, the length and diameter of the power conversion vessel control the dimensions of the silo portion of the building. Based on the 8.51 m (27 ft-11 in.) outside diameter of the power conversion vessel flange, the silo diameter (measured at the center of the walls is 25.91 m (85 ft). The position and thickness of the power conversion vessel cavity walls must accommodate the larger vessel diameter and allow for the embedment of heavy support beams.

The silo must accommodate the length of the power conversion vessel below the cross vessel centerline, and must also accommodate the machinery used to service the shutdown

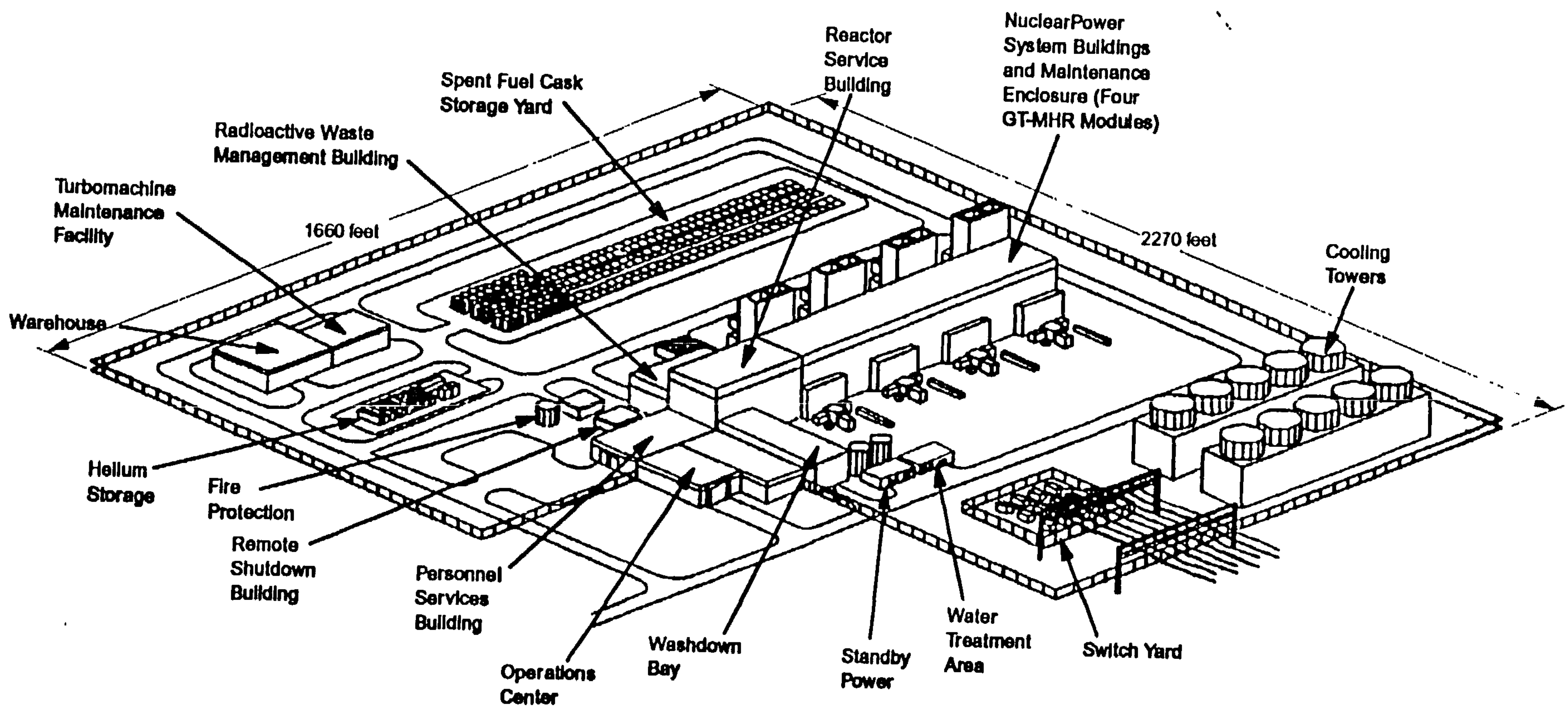

Fig. 3.2-1. Isometric of four-module GT-MHR plant

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circulator and heat exchanger under the reactor vessel. The silo depth required to create space below the Shutdown Cooling System, which is greater than that required for the power conversion vessel, is approximately 39 m (129 ft).

3.2.1. Module Description

The standard reactor module, which is the basic building block of the reference GT-MHR, consists of a reactor core and power conversion equipment.

The reactor core and power conversion equipment are housed in separate welded steel vessels that are connected by a cross vessel. The same helium that flows through the reactor is the working fluid in the power conversion portion of the module.

A simplified schematic flow diagram of one reactor module is shown in Fig. 3.2-2. The single standard reactor module, which is the building block of the MHR, contains the nuclear heat source and all the power conversion equipment required to generate electricity within the primary pressure boundary. This equipment includes the turbocompressor-generator set, plate-fin recuperator modules, precooler, intercooler and the interconnecting flow ducting.

Pressurized helium enters the reactor core from a plenum located above the graphite core. After flowing downwards through the cooling channels, the heated helium is collected in an outlet plenum and guided to the power conversion vessel through the inner hot duct of the concentric cross vessel. The helium enters the turbine at a temperature and pressure of 848°C (1559°F) and 7.01 MPa (1016 psia), respectively. Upon expanding through the turbine, helium at 511°C (952°F) and 2.62 MPa (380 psia) flows through the hot side of the six parallel recuperator modules, recovering turbine exhaust heat to the helium returning to the core on the cold side of the recuperator modules. Cooled to 125°C (258°F), the helium then flows down through the precooler where it is further cooled to approximately 26°C (78°F).

The cooling of the helium from 511°C (952°F) at the turbine outlet to 26°C (78°F) at the precooler outlet reduces the work required to compress the helium from 2.57 MPa (373 psia) at the compressor inlet to the high pressure level of 7.24 MPa (1049 psia) at the compressor outlet. However, 73% of the turbine exhaust heat is recovered in the recuperator prior to precooling and, hence, is not lost from the power cycle.

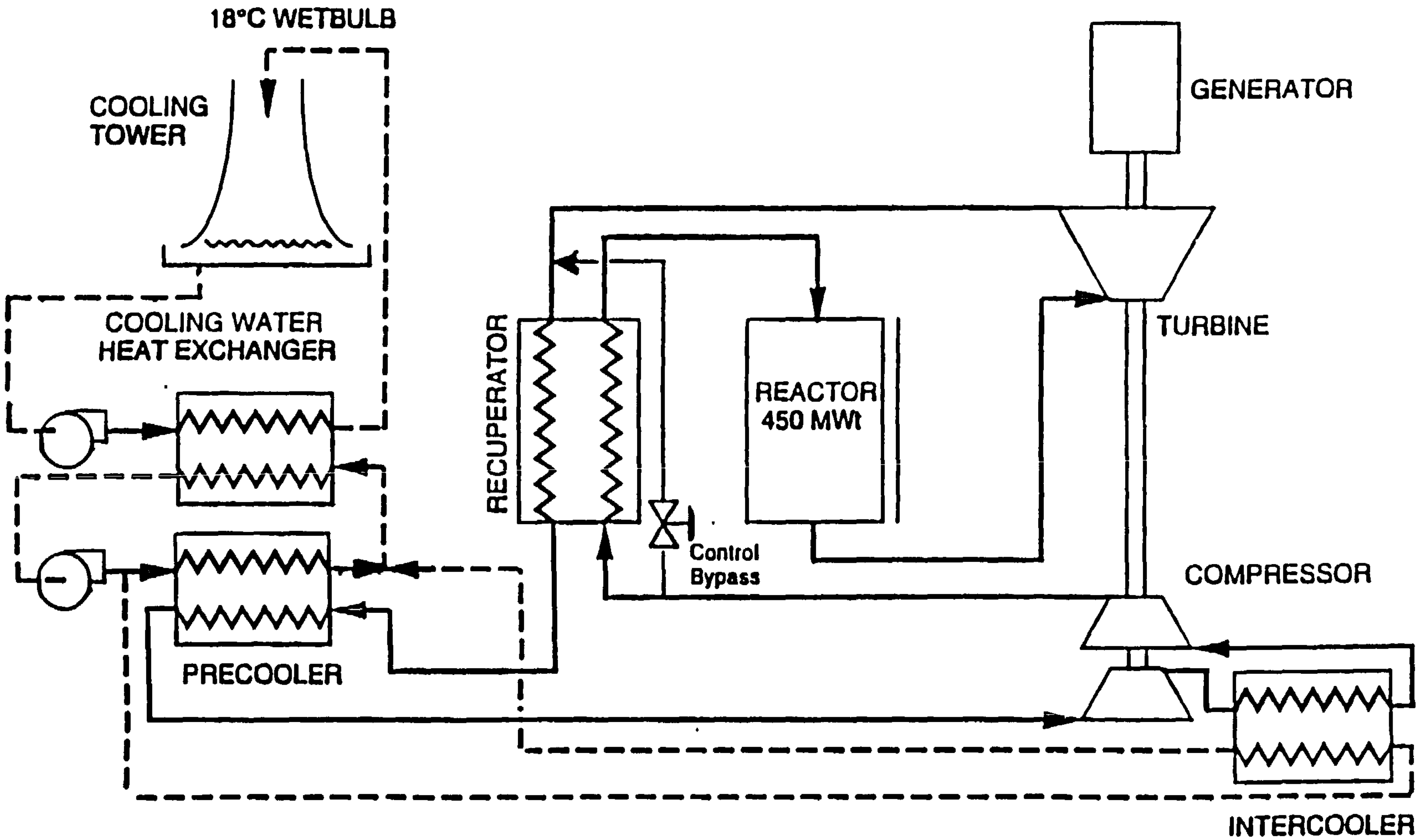

Fig. 3.2-2. GT-MHR simplified schematic flow diagram

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The cold helium is compressed in two steps in the low- and high-pressure compressors. In the low-pressure compressor, the helium is compressed from 2.57 MPa (373 psia) to 4.31 MPa (625 psia). The helium then flows through an intercooler where it is cooled to 26°C (78°F) to further optimize the compressor work in the high-pressure compressor. There, the helium is compressed from 4.29 MPa (622 psia) to 7.24 MPa (1049 psia) and heated by compression work to 105°C (222°F). Upon leaving the compressor section, the helium is channeled through the cold high-pressure side of the recuperator modules. To achieve 95% recuperator heat-transfer effectiveness, the cold side helium flows in a U-shaped flow-pattern through this component. Consequently, cold side inlet and outlet manifolds are both located at the bottom of the recuperator modules. The helium is heated to 491°C (915°F) at the recuperator outlet. Here, the helium is collected in a ring-shaped outlet plenum from which it is guided through the outer annular portion of the concentric cross vessel back to the reactor vessel. The helium then flows upwards in riser channels that are attached to the outside of the core barrel to the plenum located above the reactor core.

Figure 3.2-3 presents the power conversion layout that depicts the helium flow path functionally described above. The ducting, headering and annular flow paths necessary to implement the described cycle may be observed. The figure also illustrates the compactness of the power conversion loop, which is entirely contained in a vessel somewhat larger than the reactor vessel.

3.2.2. Plant Systems

The gas turbine plant includes the following key systems:

- Reactor System, which includes the reactor core, core supports, internal structures, reactivity control assemblies, and hot duct.

- Vessel System, which includes the reactor vessel, power conversion vessel, cross vessel, vessel supports, and lateral restraints.

- Power Conversion System, which includes the turbomachine, recuperator modules, precooler, intercooler, internal supports, shrouds, and seals. This system also includes the equipment and handling casks necessary for the removal and replacement of PCS components.

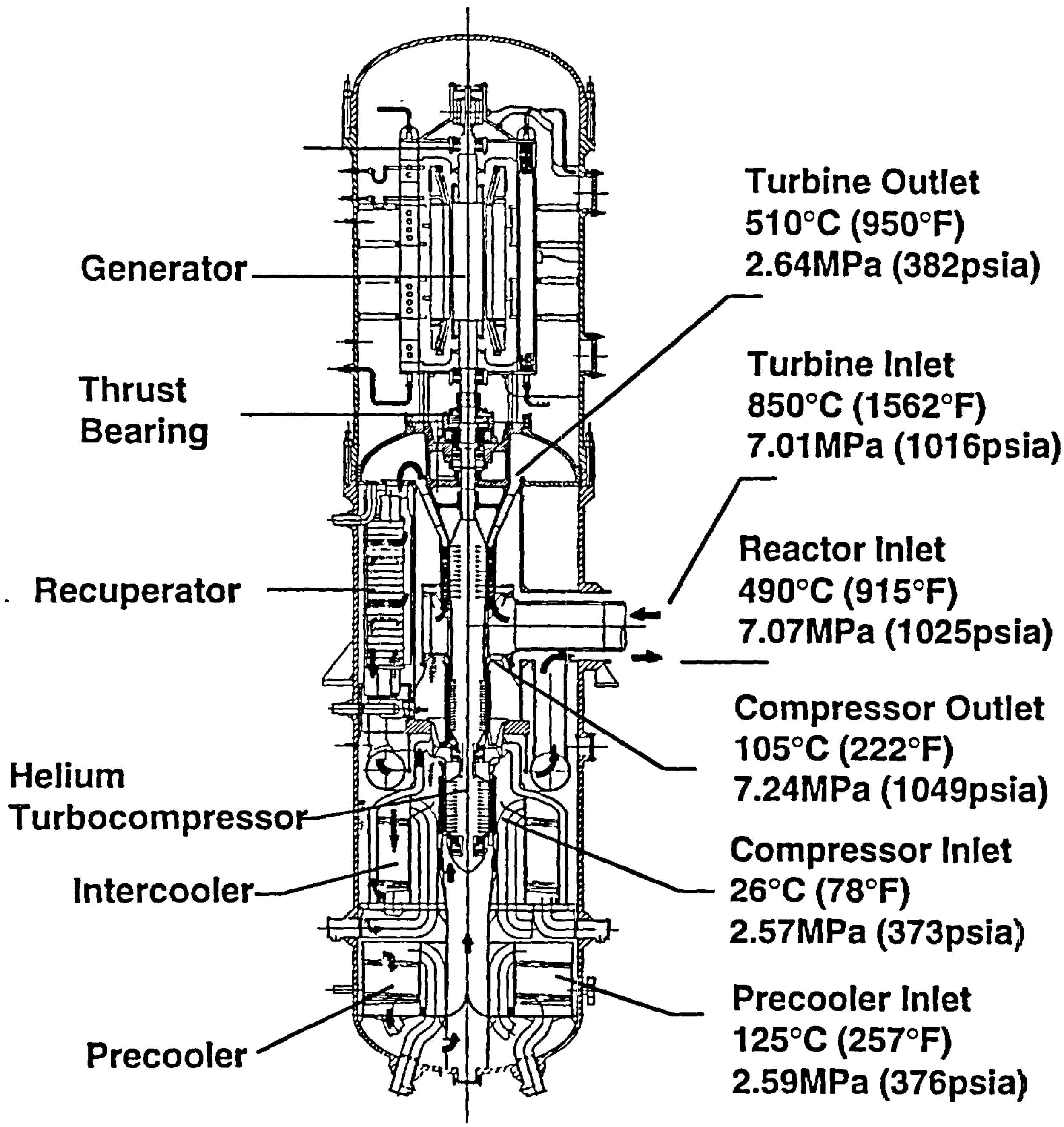


Fig. 3.2-3. Helium flow path in power conversion module

- Shutdown Cooling System, an independent forced convection cooling system for backup decay heat removal, which includes the shutdown circulator, shutdown heat exchanger, and shutdown cooling control.

- Reactor Cavity Cooling System, a safety-related passive air cooling system for backup decay heat removal, which includes structures for inlet/outlet of atmospheric air, a set of cooling panels surrounding the reactor vessel, and the hot/cold duct work for transporting the air.

- Fuel Handling System, which handles fuel and reflector elements, and transports them between the receiving facility, the reactor core, and the fuel packaging and shipping facility.

- Helium Services System, which includes the helium purification system and the helium transfer and storage system.

- Reactor Protection System, which performs automatic safety-related plant protection functions.

- Investment Protection System, which performs automatic nonsafety intersystem investment-related protection functions.

- Plant Control, Data, and Instrumentation System, which monitors plant parameters, automatically regulates plant conditions, provides information to the operator, and accepts and executes manual control commands from the operator.

The Power Conversion System in the gas turbine GT-MHR replaces the Heat Transport System and associated steam and feedwater systems of the steam cycle MHTGR.

3.2.3 Nominal Plant Performance

Table 3.2-1 provides the design parameters for the conceptual design of the GT-MHR. Several of these parameters can have a significant effect on the plant performance, component

size, and integration of the system within the power conversion vessel. The current design is based on the selection of a set of parameters that provides for optimum plant economics, considering the limits imposed by the current and expected state-of-the-art in key technologies. When combined, these parameters give a net plant efficiency of 47.7%.

The parameters that provided some degree of freedom for optimization of thermal efficiency within the envelope of hardware limits were:

- Core outlet temperature/turbine inlet temperature
- Compressor pressure ratio
- Recuperator effectiveness

The basis for selecting these key parameters is discussed briefly below.

Core outlet temperatures are constrained by the metallic temperatures of the hot duct and the core support structure. Also, increasing the core outlet temperature results in increased peak fuel temperatures. A core outlet temperature of 850°C (1562°F) was selected for the GT-MHR. This value reflects a prudent choice with respect to the current state-of-the-art in high-temperature materials and demonstrated experience in high-temperature gas-cooled reactors.

The turbine expansion ratio (and compressor pressure ratio) was selected to lower the turbine exit temperature and core inlet temperature. This was necessary to achieve an acceptable reactor inlet temperature of 491°C (915°F), thus accommodating the steel reactor vessel temperature material limits.

At the low turbine inlet temperature (relative to open-cycle gas turbines) of the GT-MHR, the net plant efficiency is relatively sensitive to recuperator effectiveness. An evaluation

TABLE 3.2-1
DESIGN PARAMETERS — CONCEPTUAL DESIGN

REACTOR	
Core power, MW(t)	600
Core inlet/outlet temperatures, °C/°C (°F/°F)	491/850 (915/1562)
Core upper plenum inlet pressure, MPa (psia)	7.07 (1025)
Helium mass flow rate, kg/s (1000 lb/h)	320 (2531)
Active core pressure drop, MPa (psid)	0.051 (7.4)
TURBOMACHINE	
Turbine mass flow rate, kg/s (1000 lb/h)	320 (2531)
Turbine inlet/outlet temperatures, °C/°C (°F/°F)	848/511 (1559/952)
Turbine inlet/outlet pressures, MPa/MPa (psi/psi)	7.01/2.64 (1016/382)
Compressor inlet/outlet temperatures, °C/°C (°F/°F)	26/105 (78/222)
Compressor inlet/outlet pressures, MPa/MPa (psi/psi)	2.57/7.24 (373/1049)
RECUPERATOR	
Mass flow rate, kg/s (1000 lb/h)	321 (2542)
Hot side inlet/outlet temperatures, °C/°C (°F/°F)	511/125 (952/258)
Hot side inlet/outlet pressures, MPa/MPa (psi/psi)	2.62/2.59 (380/376)
Cold side inlet/outlet temperatures, °C/°C (°F/°F)	105/491 (222/915)
Cold side inlet/outlet pressures, MPa/MPa (psi/psi)	7.18/7.11 (1041/1030)
PRECOOLER	
Mass flow rate, kg/s (1000 lb/h)	323 (2559)
Inlet/outlet temperatures, °C/°C (°F/°F)	125/26 (257/78)
Inlet/outlet pressures, MPa/MPa (psi/psi)	2.59/2.57 (376/373)
INTERCOOLER	
Mass flow rate, kg/s (1000 lb/h)	323 (2559)
Inlet/outlet temperatures, °C/°C (°F/°F)	104/26 (219/78)
Inlet/outlet pressures, MPa/MPa (psi/psi)	4.31/4.29 (625/622)
POWER PLANT	
Net electrical output, MW(e)	286

determined that an effectiveness of 95% could be achieved while maintaining pressure drop and volume within reasonable limits.

3.2.4 Normal Plant Operation

This section describes the operation of the GT-MHR plant under normal operating conditions. The normal operating modes are summarized and an overview of control functions and protection is presented.

Philosophy of Plant Operational Control

The GT-MHR plant is designed for separate and independent control and operation of each of the four reactor modules by the operators from a central control room. The plant control and protection systems are designed with a high level of automation. The operator will supervise all automatic control and protection actions and will have the means to intervene manually during normal, off-normal, and emergency events. Since the GT-MHR uses inherent characteristics in a configuration which provides assured, simple, and passive safety features, (1) neither operator actions nor active engineered safeguards equipment are needed to protect public health and safety, and (2) operator errors cannot negate these safety features and capabilities.

The Reactor Protection System (RPS), the Investment Protection System (IPS), and the Plant Control, Data, and Instrumentation System (PCDIS) are functionally, physically, and electrically independent, except for information that flows unidirectionally from the protection systems to the PCDIS and IPS through appropriate isolation so that control adjustments can be made in the portions of the plant that remain in operation following a protection trip and so that protection information is available to the operator at all times. All protective actions are fully automated, do not depend on actions by the PCDIS or operator to maintain plant protection goals, and cannot be circumvented by the PCDIS or the operator. The PCDIS architecture is based on modern distributed control systems. The PCDIS controls are designed to accommodate transients resulting from the loss of major plant components, and to keep the plant in operation with the equipment that remains functional.

Helium Bypass and Inventory Control

Power output is controlled in the near term (0 to 20 min) of transient events by varying the position of the bypass valves, and making a simultaneous slower adjustment in reactor helium inventory. Opening the bypass valves diverts helium from the reactor and turbine, which causes an immediate reduction in turbine output, an increase in core temperature, and a decrease in reactor power due to the negative temperature coefficient of reactivity. Since thermal effects in the reactor core are slow, control rods are used to achieve a faster core power response. Closing the bypass valves causes the reverse: a turbine output increase, a core temperature decrease, and a reactor power increase.

When the bypass valves are opened, helium flow bypassing the core and the turbine requires pumping power, does not contribute to plant power output, and, therefore, creates inefficiencies. In order to restore a high level of efficiency following an opening of the bypass valve, helium inventory is decreased. As inventory decreases, the bypass valves are reclosed to maintain constant mass flow through the core and restore high efficiency. This is a longer term process (0 to 60 min).

Inventory control is achieved by transferring helium between the primary coolant circuit and the helium storage tanks: helium is transferred from the high pressure compressor outlet to the tanks of the Helium Services System (HSS) via the helium purification system (to remove fission products). In the opposite direction, helium is transferred from the tanks (which contain purified helium) directly into the low pressure compressor inlet. In this manner, the turbocompressor does most of the pumping work for the transfer of helium with only minimal helium pumping being required in the HSS. Load modulation is performed with the bypass valves as stated above. The helium transfer process is strictly an efficiency optimization function that does not require modulation and is performed by a simple on-off controller that opens the helium transfer valves.

Operating Modes

Four specific operating modes are defined:

Energy Production. This mode covers the reactor power operating range from approximately 15% to 100% power, which is the load-following range of the plant. Also, the energy production mode covers the reactor power range from the power where the generator is synchronized to the grid, self-sustaining and ready for power ascension to 15% power. This includes the range of house load (approximately 3% power) to 100% power.

Startup/Shutdown. This mode represents the transition between the shutdown and production modes. It covers the power range from reactor subcritical to approximately 3% power where the plant is self-sustaining and synchronized to the grid. In this mode, all plant service and supporting systems are made functional and ready to operate the module up to the minimum production level. This mode includes bringing the reactor power to low power condition, raising the system temperature, bringing the turbomachine to a self-sustaining speed (by using variable frequency power supply to motor the generator), and coordinating a rise in reactor power and turbomachine operating level to the production range.

Shutdown. This mode is defined when the reactor is subcritical by the required shutdown margin. Decay heat removal in this mode may be by operation of the Power Conversion System through motoring of the generator, or by the operation of the Shutdown Cooling System (SCS).

Refueling. This mode is an extension of the shutdown mode, with the reactor subcritical and depressurized to allow refueling operations. In addition to the reactivity requirement, low primary system pressure and core temperatures are maintained to allow core refueling.

3.2.5. Transient Operation and Control

The GT-MHR plant is designed to be base loaded to meet electric load requirements and also to follow electric load demand automatically at up to ±5%/min in the range of 15% to 100%

reactor power. During the energy production mode, the GT-MHR can also operate stably at house load conditions or at 15% electrical production. These top-level plant control requirements are satisfied by two simple control loops:

- Turbine inlet temperature is controlled by varying reactor power using the built-in reactor negative temperature coefficient and the reactor control rods.

- The helium flow rate through the core and turbine is controlled by adjusting bypass flow and by adjusting helium inventory.

In the 15% to 100% power range, electrical power output is adjusted to match the electrical load demand. Power output is adjusted by varying the position of the helium bypass valves over the short-term and by varying inventory over the long-term as described in Section 3.2-4. Temperature is maintained constant throughout these operations due to the inherent effects of the negative temperature coefficient of reactivity and by small adjustments of the control rod position.

These same control loops are used during startup, shutdown and standby operations, except that in these cases the core outlet helium temperature (turbine inlet temperature) is controlled at a lower level due to the much lower power output requirements. Plant output is automatically run back to house load in the event the electrical grid is lost. In the event of a reactor trip, the turbomachine is automatically disconnected from the grid and run back to a lower speed where it is switched to the generator motoring mode using the frequency converter to provide shutdown cooling.

Two separate and independent protection systems are provided to perform protective functions. Both systems sense process variables in order to detect abnormal plant conditions and to actuate equipment to maintain plant parameters within acceptable limits. The safety-related RPS protection function is reactor trip. The major IPS protection functions are turbomachine overspeed protection, isolation of leaks in the primary coolant heat exchangers and initiation of Shutdown Cooling System operation.

3.3. BALANCE OF PLANT

The major balance of plant buildings and facilities are shown in Fig. 3.2-1. These include the following:

- The operations center is located in a position adjacent to the NI personnel services building. Future layout developments will be needed to create appropriate indoor connections between the two buildings.
- The double plant security boundary uses part of the operations center as part of the security boundary. Persons entering the plant must pass through the single outer security boundary, and will be able to have access to parking, the switchyard, the cooling towers, and parts of the operations center. Pedestrians (plant personnel and visitors) needing to enter the high security zone will do so through the security control facilities in the operations center. Vehicular traffic needing to enter the security area will be inspected before passing through a double gate in the boundary.
- The standby power supply facility, fire protection facility, and water treatment facility are located near the reactor service building.
- The NI warehouse and turbomachine maintenance facility are combined and located on the northeast part of the site. Onsite maintenance of the turbomachinery equipment will be performed in the combined facility. To minimize plant downtime, a spare turbomachine will be kept at the plant site. Large access space is required for transportation of the turbine-compressor unit in a shielded cask. It is expected that a vehicle similar to the carrier for onsite spent fuel storage casks will be used to move the turbine-compressor units.

3.4. REFERENCE

3.1-1. "Overall Plant Design Specification [600 MW(t)] GT-MHR," DOE GT-MHR-100001/0, December 1, 1994.

4. PLANT TECHNICAL DESCRIPTION

4.1. REACTOR SYSTEM

4.1.1. Reactor Core

The reactor core consists of hexagonal graphite fuel and reflector elements, plenum elements, startup neutron sources, and reactivity control material, all located inside a reactor pressure vessel. The core is designed to provide 600 MW(t) at a power density of 6.6 MW/m^3. A core elevation view is shown in Fig. 4.1-1 and the plan view is shown in Fig. 4.1-2. The left side of the core in Fig. 4.1-1 is a cut from the center of the core through the corners of the elements, and the right side of the core in Fig. 4.1-1 is a cut from the center of the core through the flats of the elements.

The active core consists of an assembly of hexagonal graphite fuel elements (blocks) containing blind holes for fuel compacts and full length channels for helium coolant flow. The active fuel region of the core consists of 102-fuel columns by 10 blocks high, arranged in three annular rings as shown in Fig. 4.1-3. The fuel elements are stacked in the core to form columns (10 fuel elements per column) that rest on support structures as shown in Fig. 4.1-1. The active core columns form a three row annulus, with columns of hexagonal graphite reflector elements in the inner and outer regions (see Fig. 4.1-2). Twelve core columns and 36 outer reflector columns contain channels for control rods. Eighteen columns in the core also contain channels for reserve shutdown material.

The annular core configuration was adopted to achieve maximum power rating and still permit passive core heat removal while maintaining the fuel temperature at less than 1600°C (2912°F) during a conduction cooldown event. An active core effective outer diameter of 4.93 m (194.1 in.) permits a minimum reflector thickness of 0.64 m (25.2 in.) within the 7.23 m (284.5 in.) inner diameter reactor vessel and allows for a lateral restraint structure between the reflector and vessel. The height of the core with 10 fuel elements in each column is 7.9 m (312 in.). The core is designed to preclude exceeding the maximum stress design limits of graphite and metal in the core.

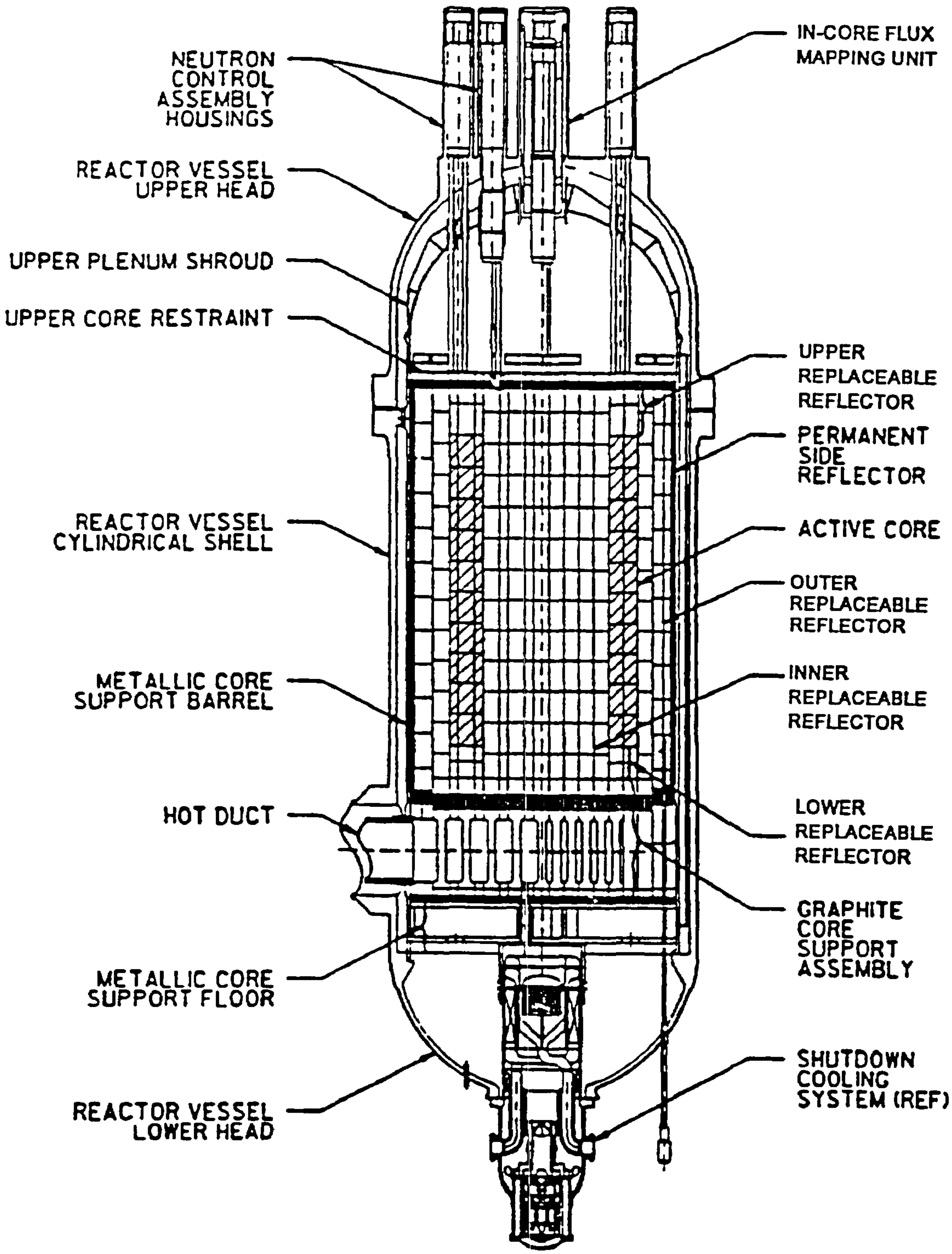


Fig. 4.1-1. Reactor elevation view

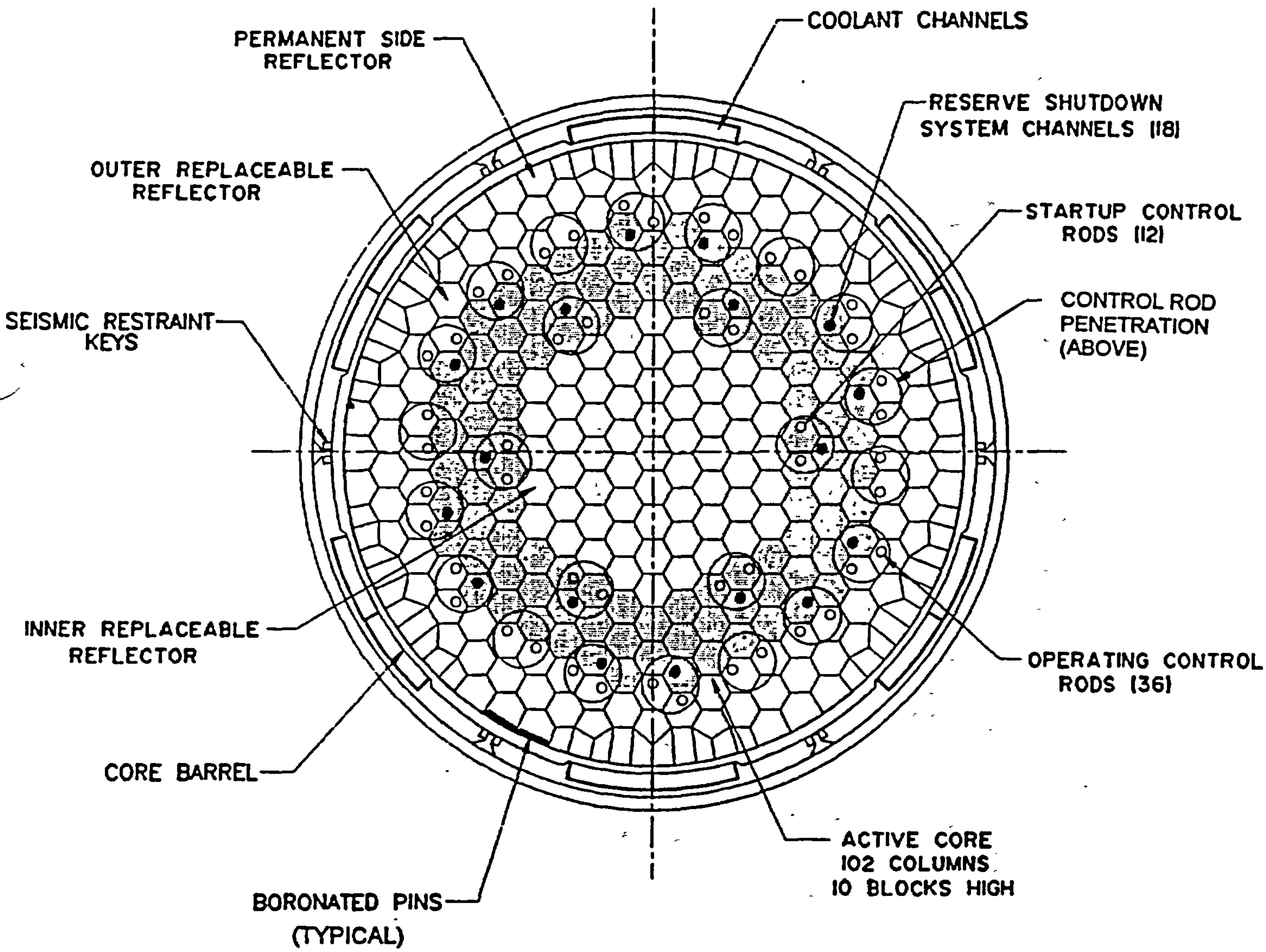


Fig. 4.1-2. GT-MHR core arrangement

10 Axial Fuel Layers
Top and Bottom Reflectors Not Shown

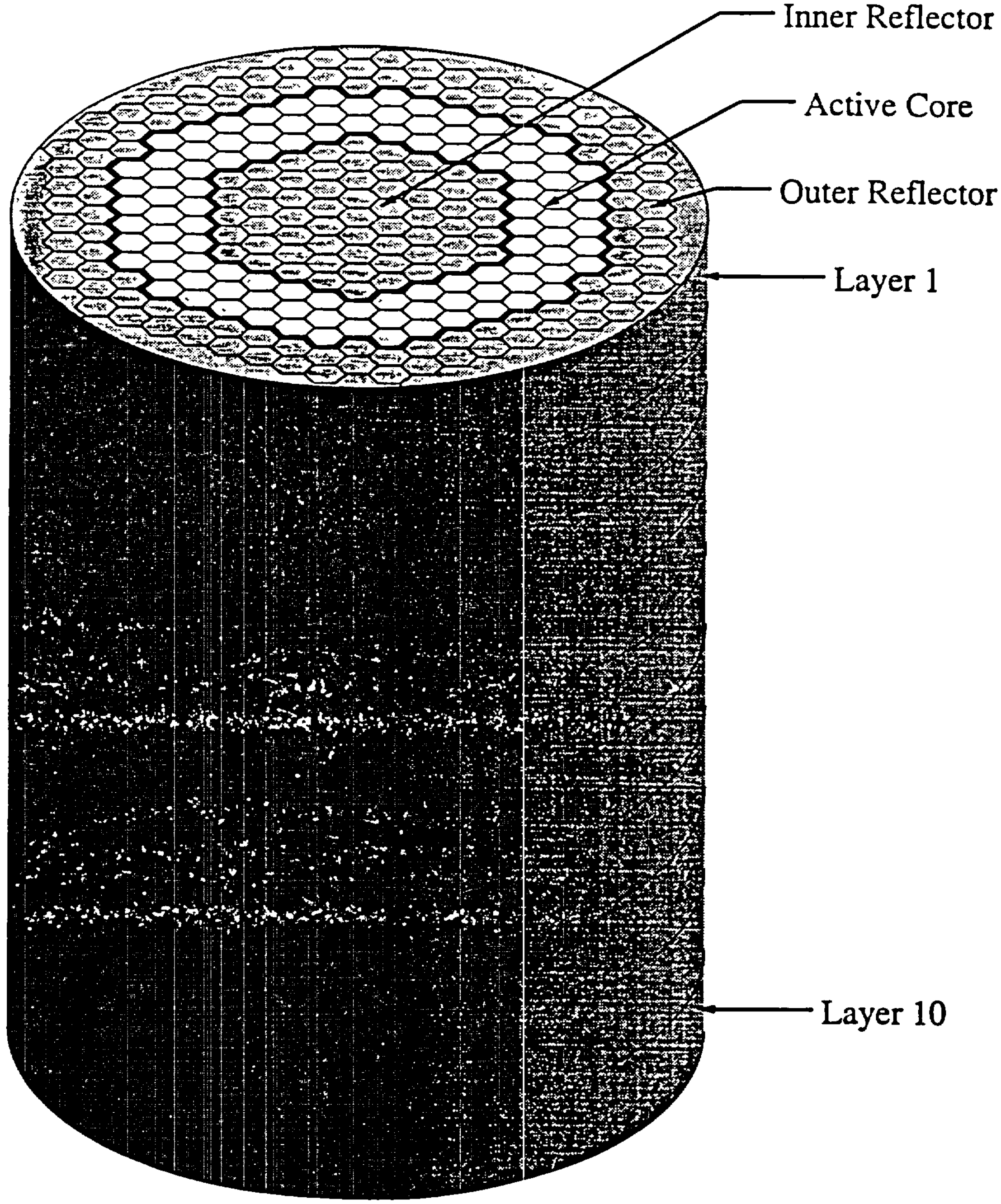


Fig. 4.1-3. 102-column core layout

The core reactivity is controlled by a combination of lumped burnable poison (LBP), movable poison and a negative temperature coefficient. The movable poison is in the form of control rods. Should the control rods become inoperable, independent reserve shutdown control is provided in the form of boronated pellets that may be released into channels in the active core.

The control rods are fabricated from boron in annular graphite compacts suspended in a carbon/carbon composite assembly for structural support. The 36 operating control rods are located in the outer reflector. The 12 startup control rods are located in the core and are withdrawn before the reactor reaches criticality. With the startup and operating rods inserted, a 1% $\Delta\rho$ shutdown margin can be indefinitely maintained under cold conditions.

All the Reactor System components are based on similar components and technology successfully demonstrated at Fort St. Vrain. While all components are the same for the 600 MW(t) GT-MHR as were designed for the 450 MW(t) steam cycle MHTGR, they are configured differently to form the larger annular core.

Key core nuclear design parameters are summarized in Table 4.1-1.

4.1.1.1. Fuel Element Design. There are three types of elements that contain fuel: standard fuel elements, reserve shutdown elements that contain a channel for reserve shutdown control, and control elements that also contain a control rod channel. The principal fuel element structural material is H-451 graphite (1.74 Mg/m^3) in the form of a right hexagonal prism, 793 mm (31.22 in.) high and 360 mm (14.17 in.) across the flats. Fuel and coolant holes run parallel through the length of each prism in a regular triangular pattern of two fuel holes per coolant hole. The standard fuel element, shown in Fig. 4.1-4, contains an essentially continuous pattern of fuel interrupted by the central handling hole, which is surrounded by smaller coolant holes. The reserve shutdown and control fuel elements differ from the standard fuel elements in that they contain 95.3 mm (3.75 in.) and 101.6 mm (4.0 in.) diameter channels, respectively (see Fig. 4.1-5). Those channels replace 24 fuel and 11 coolant holes. The pitch of the coolant and fuel hole array is 18.8 mm (0.74 in.). The minimum web thickness between a 15.9 mm (0.63 in.) coolant hole and a 12.7 mm (0.5 in.) fuel hole is 4.5 mm (0.18 in.).

TABLE 4.1-1
CORE NUCLEAR DESIGN PARAMETERS

Core power, MW(t)	600
Core columns	102
Power density, MW/m^3	6.6
Hexagonal fuel element dimensions, m (in.)	
Flat-to-flat dimension	0.36 (14.2)
Height	0.79 (31.2)
Effective active core diameter, m (in.)	
Outer	4.83 (190.5)
Inner	2.96 (116.6)
Active core height, m (in.) 7.93 (312)	
Number of fuel elements (10/column)	
Standard	720
Control	120
Reserve shutdown	180
Number of control rods	
Inner reflector	0
In-core	12
Outer reflector	36
Number of reserve shutdown control channels in core	18
Fissile material in kernel (19.8% enriched U)	$UC_{0.5}O_{1.5}$
Fertile material in kernel (natural U)	$UC_{0.5}O_{1.5}$
Refueling interval, months	15.8
Columns refueled each cycle	51
Time to refuel, days	14
Module capacity factor	84%
Equilibrium cycle length, EFPD	417.0
Fuel loading, kg (lb)	
Initial core LEU	2354 (5190)
Initial core NU	2327 (5130)
Each reload LEU	1748 (3854)
Each reload NU	514 (1133)

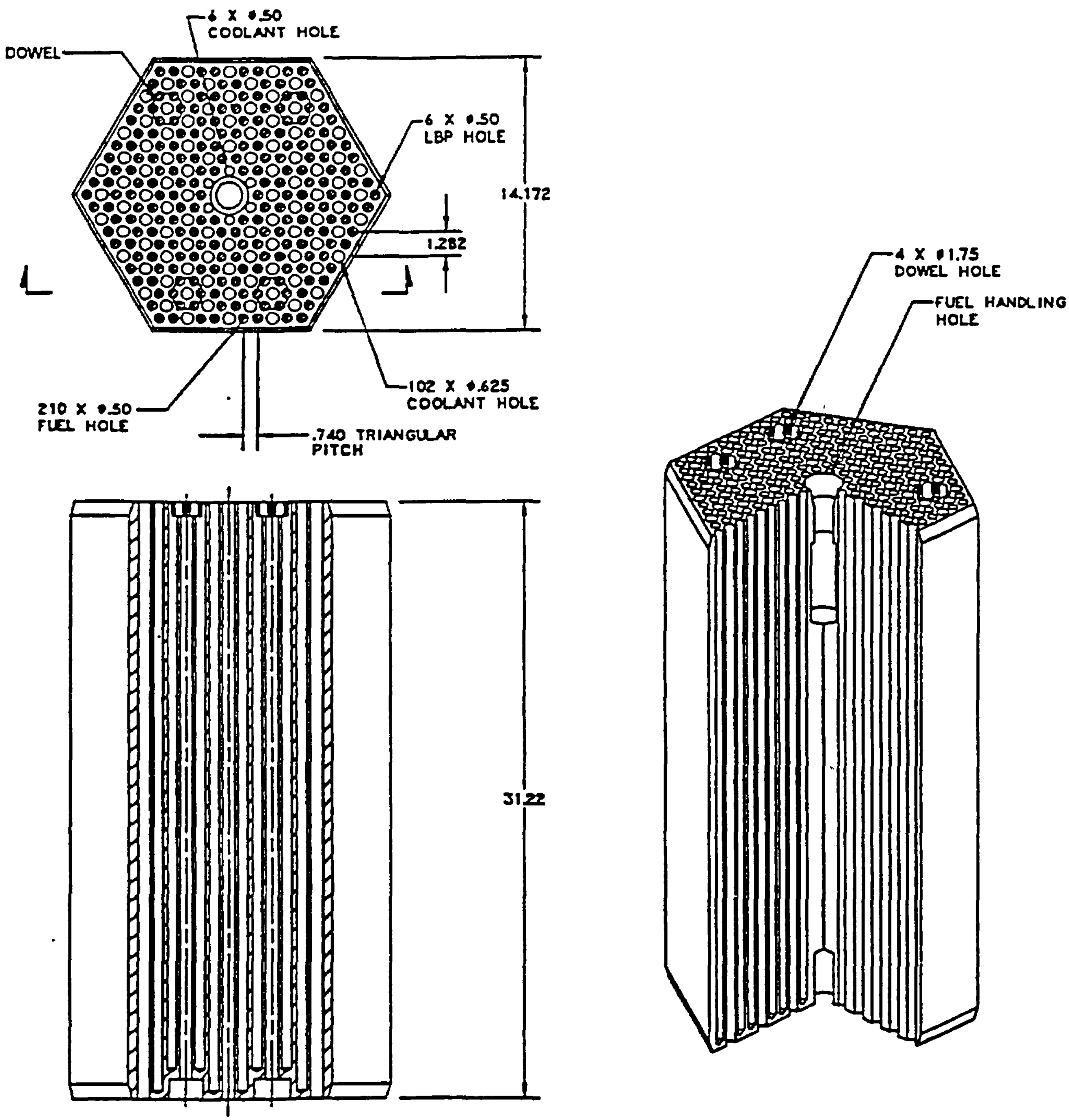


Fig. 4.1-4. Standard fuel element

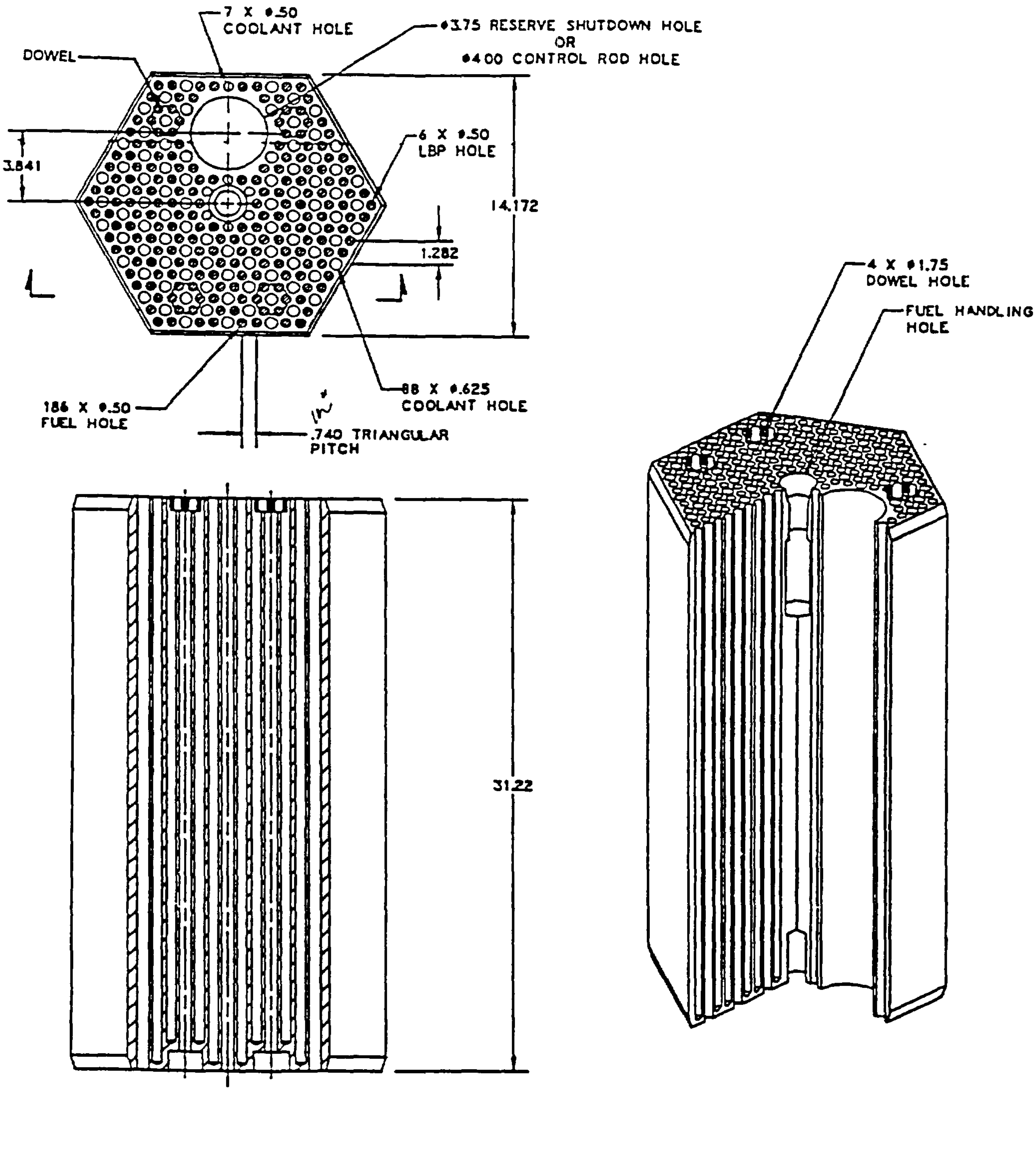


Fig. 4.1-5. Control or reserve shutdown fuel element

At each axial element-to-element interface in a column, four dowel/socket connections provide alignment for refueling and coolant channels, and transfer of seismic loads from fuel elements. A 35.0 mm (1.38 in.) diameter handling hole located at the center of the element extends down about one-third of the height. The hole has a ledge where the grapple of the fuel handling machine engages. There is also a tooling hole at the bottom of the element along the centerline that is needed during element manufacturing. It has a diameter of 25.4 mm (1.0 in.) and a length of about 50.8 mm (2.0 in.). The top and bottom edges of the element are beveled to assist insertion of the elements into the core. The design of the fuel elements is summarized in Table 4.1-2.

4.1.1.2. Fuel Compact Design. The fuel compacts contained in the fuel holes have a 12.45 mm (0.49 in.) diameter with a length of 49.3 mm (1.94 in.). Each fuel compact is a mixture of fissile, fertile, and graphite shim particles bonded by a carbonaceous matrix. These compacts are stacked in the fuel holes. The six stacks under each of the four dowels contain 14 fuel compacts; all other stacks contain 15 fuel compacts. Graphite plugs cemented into the tops of the fuel holes enclose the fuel compact stacks.

A nominal radial gap of 0.127 mm (0.005 in.) between the fuel compact and the fuel hole allows for fuel element assembly and precludes interference between the fuel compact and the graphite block during operation. Graphite plugs cemented into the tops of the fuel holes enclose the fuel compact stacks. A gap between the top of the fuel compact stack and the graphite plug also precludes interference during operation.

4.1.1.3. Fuel Specification. The reference fuel cycle employs low-enriched uranium and natural uranium. The fissile fuel is a two-phase mixture of 19.8% enriched UO_2 and UC_2, usually referred to as UCO, having an oxygen-to-uranium ratio of about 1.5 in fresh fuel, and a carbon-to-uranium ratio of about 0.5. The UCO kernel composition consists of distinct UC_2 and UO_2 phases. Introduction of just enough UC_2 into a UO_2 kernel acts as a getter for oxygen and prevents CO gas formation during irradiation. In this way, the rare earth fission products are retained as oxides in the kernel, while at the same time kernel migration of UO_2 is minimized because of the very low CO pressure. The fertile fuel composition is the same as the fissile fuel, except that natural uranium is used rather than enriched uranium.

TABLE 4.1-2
FUEL ELEMENT DESIGN DATA

Distance across flats, m (in.)	
Not including gaps	0.3600 (14.172)
Including gaps between elements	0.3610 (14.212)
Element height, m (in.)	0.7930 (31.22)
Control rod hole diameter, mm (in.)	101.6 (4.0)
RSC hole diameter, mm (in.)	95.25 (3.75)
Coolant holes per element, small/large	
Standard element	6/102
Control and RSC element	7/88
Coolant hole diameter, mm (in.)	
Small	12.70 (0.50)
Large	15.88 (0.625)
FBP holes per element	6
FBP hole diameter, mm (in.)	12.70 (0.50)
Length, m (in.)	0.7815 (30.77)
FBP rods per element	5
FBP rod diameter, mm (in.)	11.43 (0.45)
Length, m (in.)	0.7214 (28.40)
Fuel holes, under dowels/not under dowels	
Standard element	24/186
Control and RSC elements	24/162
Fuel hole diameter, mm (in.)	12.70 (0.50)
Fuel hole length, m (in.)	
Under dowels	0.7526 (29.63)
Not under dowels	0.7815 (30.77)
Fuel compacts in fuel hole	
Under dowel	14
Not under dowel	15
Fuel compacts per element	
Standard element	3,126
Control and RSC element	2,766
Compacts in core	3,102,120
Fuel compact diameter, mm (in.)	12.45 (0.49)
Length, mm (in.)	49.28 (1.94)
Block graphite density, Mg/m^3	1.74

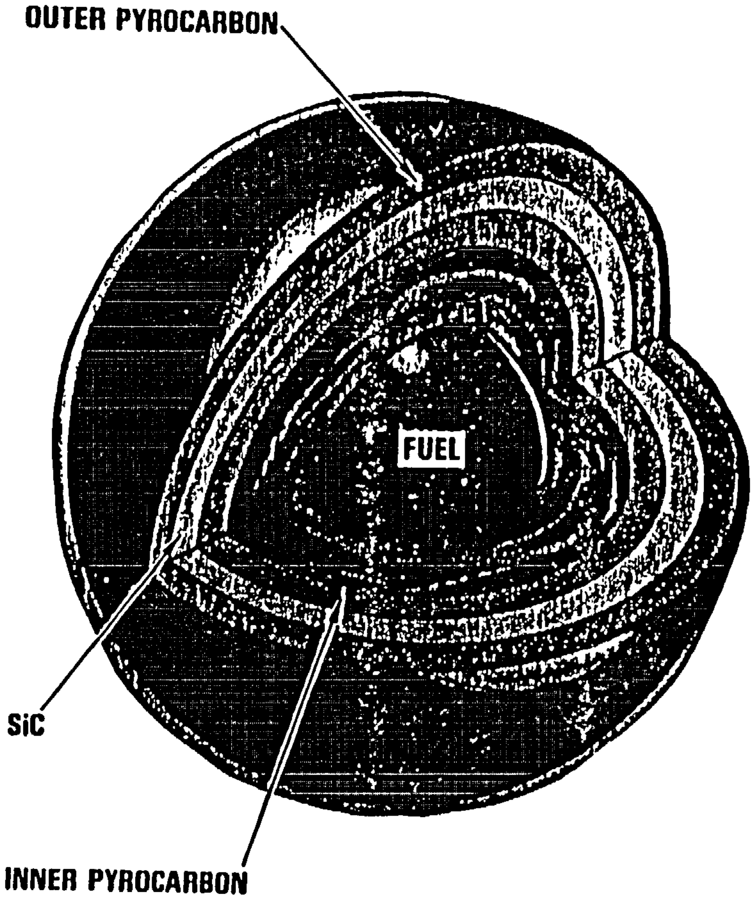
4.1.1.4. Fuel Particle Design. Both fertile and fissile fuels are dense micro spheres coated in a fluidized bed with TRISO coatings, the primary purpose of which is to retain fission products. The TRISO coating contains three types of material: a low density pyrolytic carbon (PyC), SiC, and a high-density isotropic PyC. The low-density coating is provided to protect the dense PyC from fission recoil damage and to provide void volume to limit the fission gas pressure. The PyC of both coatings is deposited under conditions which produce isotropic properties. With this design, the dense PyC has good irradiation stability and capability to remain intact to perform the function of fission product retention under much more severe exposure conditions.

Sandwiched between the two dense PyC coating layers, the third material, SiC, provides metallic fission product retention and mechanical strength. The identification and purpose of each particle component in the TRISO particle design is shown in Fig. 4.1-6.

The coated fissile and fertile particles are blended and bonded together with a carbonaceous binder into a fuel compact. Figure 4.1-7 illustrates the TRISO coating concept and how the fuel is packaged in the fuel element. Details of the TRISO particle design are given in Table 4.1-1-3. Bonding the TRISO particles into fuel compacts (Table 4.1-4) prevents mechanical interaction between the fuel particles and moderator graphite by maintaining the fuel as a free standing nonstructural component of the fuel element. It also maximizes the thermal conductivity in the fuel, and provides a secondary barrier to metallic fission product release through absorption mechanisms.

4.1.1.5. Fuel Quality. The fuel quality and performance limits are given in Table 4.1-5. The quality of the coated particle fuel has evolved significantly along with the design. The allowable exposed heavy metal fraction in fuel compacts is restricted. The coating defect level has also been reduced through improved fabrication processes, however, further testing under GT-MHR normal and accident conditions is required. The total heavy metal contamination and SiC defect fraction is specified at $\leq 6 \times 10^{-5}$.

The performance of TRISO coated particle fuel under normal conditions which can be influenced by reactor design and fuel cycle times have been engineered to avoid coating failure in particles. High temperature tests on particles show that significant failure does not take place except under time and temperature conditions far in excess of anticipated accident conditions.



COMPONENT/PURPOSE

- FUEL KERNEL
  - PROVIDE FISSION ENERGY
  - RETAIN SHORT LIVED FISSION PRODUCTS
- BUFFER LAYER (POROUS CARBON LAYER)
  - ATTENUATE FISSION RECOILS
  - VOID VOLUME FOR FISSION GASES
- INNER PYROCARBON (IPyC)
  - PROVIDE SUBSTRATE FOR SiC DURING MANUFACTURE
- SILICON CARBIDE (SiC)
  - RETAIN GAS AND METAL FISSION PRODUCTS
- OUTER PYROCARBON (OPyC)
  - PROVIDE BONDING SURFACE
  - PROVIDE FISSION PRODUCT BARRIER IN PARTICLES WITH DEFECTIVE SiC

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Fig. 4.1-6. TRISO-coated particle components

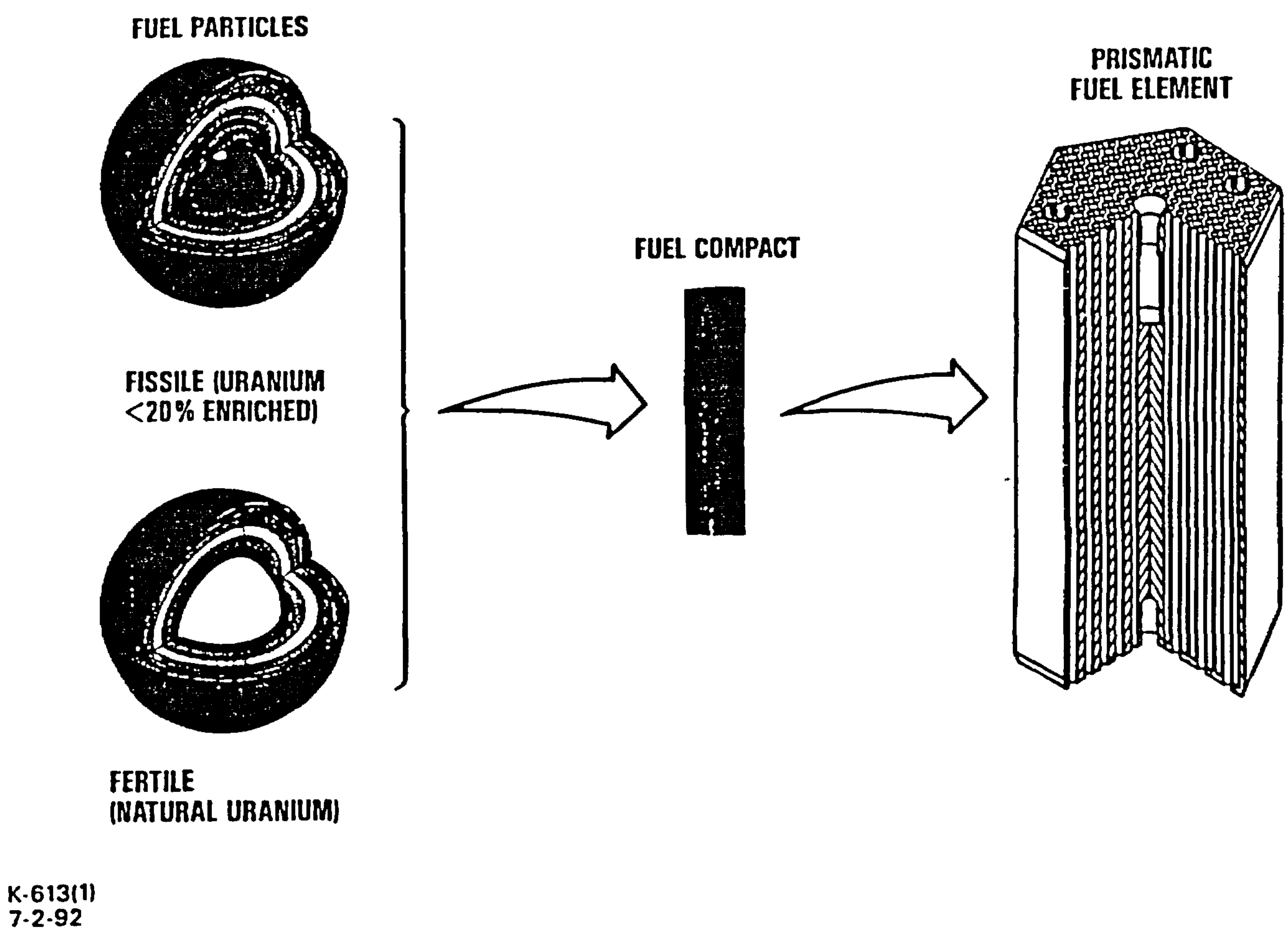

Fig. 4.1-7. Fuel element components

TABLE 4.1-3
COATED PARTICLE DESIGN

	Fissile Particle	Fertile Particle
Composition	$UC_{0.5}O_{1.5}$	$UC_{0.5}O_{1.5}$
Uranium enrichment, %	19.8	Natural U
Kernel diameter, μm	350	500
Coating thickness, μm		
Buffer	100	65
Buffer seal	--	--
Inner pyrocarbon[a]	35	35
Silicon carbide	35	35
Outer pyrocarbon	40	40
Particle diameter, μm	770	850
Mean densities, Mg/m^3		
Kernel	10.5	10.5
Buffer	1.00	1.00
Buffer seal	1.95	1.95
Inner pyrocarbon	1.87	1.87
Silicon carbide	3.20	3.20
Outer pyrocarbon	1.83	1.83
Weights per particle, g		
Carbon	3.057-04	3.799-04
Oxygen	2.566-05	6.162-05
Silicon	1.045-04	1.332-04
Uranium	2.541-04	6.102-04
Total	6.900-04	1.185-03

[a]Includes thickness of buffer seal.

TABLE 4.1-4
CHARACTERISTICS OF FUEL COMPACTS

Diameter, mm (in.)	12.45 (0.49)
Length, mm (in.)	49.3 (1.94)
Shim	Graphite particles
Density of shim particles, Mg/m^3	1.74
Binder type	Petroleum pitch
Filler	Petroleum derived graphite flour
Matrix density, Mg/m^3	Range is 0.8 to 1.2
Volume fraction of fissile, fertile and shim particles	~0.61

TABLE 4.1-5
FUEL QUALITY AND PERFORMANCE LIMITS

Parameter	Segment Mean 95% Value	Upper Bound Value
As-manufactured fuel quality		
Heavy metal contamination fraction	$\leq 1.0 \times 10^{-5}$	$\leq 2.0 \times 10^{-5}$
Missing buffer fraction	$\leq 1.0 \times 10^{-5}$	$\leq 2.0 \times 10^{-5}$
Missing or permeable inner pyrocarbon	$\leq 4.0 \times 10^{-5}$	$\leq 1.0 \times 10^{-4}$
SiC coating defect fraction	$\leq 5.0 \times 10^{-5}$	$\leq 1.0 \times 10^{-4}$
Missing or defective OPyC	$\leq 1.0 \times 10^{-4}$	$\leq 1.0 \times 10^{-3}$
Fuel performance (allowable core average)		
In-service failure fraction (normal)	$\leq 5.0 \times 10^{-5}$	$\leq 2.0 \times 10^{-4}$
Incremental failure during accident	$\leq 1.5 \times 10^{-4}$	$\leq 6.0 \times 10^{-4}$

The results are not dependent upon kernel type but are an intrinsic property of the TRISO coating. Tests on TRISO particles have shown the ability to retain integrity after 500 hours in a 1600°C temperature field. Fission gas release at temperatures above 1600°C is a function of time at temperature. However, SiC coating failure and loss of fission products become rapid when temperatures exceed 2000°C, which is well beyond accident temperatures of the GT-MHR.

4.1.1.6. Fixed Burnable Poison Design. A typical fuel element contains up to six fixed or lumped burnable poison (LBP) locations in the six corners of the block as shown in Figs. 4.1-4 and 4.1-5. The poison rods consist of B_4C granules dispersed in graphite compacts. The amount of burnable poison is determined by reactivity control requirements, which may vary with each core reload. The diameter of the LBP rods are specified according to self shielding requirements of the absorber material to control the burnout rate relative to the fissile fuel burnout rate. The GT-MHR core contains an average of five fixed burnable poison rods per element in each cycle. Details of the fixed burnable poison design are given in Table 4.1-6, assuming that each fixed burnable poison rod contains 14 compacts.

The primary purpose of the LBPs is to control excess reactivity during the fuel cycle depletion. A secondary consideration relates to the reduction in power peaking. The placement of LBP rods is varied axially to reduce axial power peaking where appropriate. Power distribution peaking needs to be controlled to limit peak fuel temperatures which limits fuel element stress, and to assure axial power stability. The principal means of power distribution control is the axial and radial zoning with different concentrations of fissile and fertile fuel. For instance, three radial zones may correspond to the three annular rings of fuel elements. Each zone may have a different relative fissile uranium loading (all of the same enrichment) but may also have a varying fertile (natural uranium) loading, so that the overall effective enrichment may vary by zone.

4.1.1.7. Core Neutronic Modeling. Both the two-dimensional and three-dimensional diffusion code models for the GT-MHR utilize hexagonal geometry in the x-y plane. For annular cores such as the GT-MHR, which has an effective width of less than 1 m, large thermal flux gradients occur at the inner and outer core/reflector interfaces. Experience has shown that mesh spacing corresponding to only one hexagonal region per fuel or reflector element results in an underestimation of the relative power and burnup in the regions of fuel/reflector interface. To obtain better resolution, the hexagonal elements (fuel and reflector) are divided into seven hexagonal-

TABLE 4.1-6
CHARACTERISTICS OF FIXED BURNABLE POISON

FBP rods/element, average	5
FBP compacts/FBP rod	14
Compact diameter, mm (in.)	11.43 (0.45)
Compact length, mm (in.)	51.5 (2.03)
Rod length, mm (in.)	721.4 (28.4)
Volume fraction of B_4C particles + shim particles	0.61

FBP Component	Composition	Diameter (mm)	Thickness (mm)	Density Mg/m^3
B_4C particle				
Kernel	B_4C	200	—	2.47
Buffer coating	C	—	18	1.00
Pyrocarbon coating	C	—	23	1.87
Shim particle	C	—	—	1.74
Matrix	C	—	—	0.94

shaped subregions as shown in Fig. 4.1-8 for a fuel element. The "subhex" model slightly changes the perimeter outline but conserves the total volume of each fuel and reflector element. Material is homogeneously distributed within each of the seven subhexes, thereby producing seven relative power factors per element. In reflector or fuel elements containing control rods, the material of the control rod is similarly homogenized over one of the seven subhexes with appropriate shielding factors derived from transport cell calculations.

4.1.1.8. Hexagonal Reflector Elements. The hexagonal reflector elements are H-451 graphite. Their size, shape, and handling hole are similar to the fuel elements, except that some of the reflector elements are half-height or three-quarter height.

The reflector above the active core is composed of two layers of H-451 graphite: one layer of full-height elements above a layer of half-height elements (see Fig. 4.1-1), for total reflector height of 1.2 m (46.8 in.). The top reflector elements channel coolant flow to the active core and provide for the insertion of reserve shutdown material into the active core. They have the same array of coolant holes as the fuel element and the same holes for the insertion of reactivity control devices.

The reflector below the active core has a total height of 1.6 m (62.4 in.). It consists of two layers: one layer of two half-height reflector elements above a layer of two half-height flow distribution and support elements (see Fig. 4.1-1). The bottom two elements provide for the passage of coolant from the active core into the core support area. This is accomplished by directing the coolant channel flow to the outside of the core support pedestal. The channels for the control rods and reserve shutdown material are blind and stop in the lower reflector.

The outer side reflector includes a row of permanent side reflector blocks and two rows of hexagonal reflector columns as shown in Fig. 4.1-2. The permanent side reflector blocks are solid except for the inclusion of boronated steel pins which act as neutron absorbent poison. The outer row of hexagonal elements is solid, with the exception of the handling holes. Thirty-six of the elements in the inner row have a control rod channel in the reflector control element as shown in Fig. 4.1-9. The control rod channel has a diameter of 102 mm (4 in.) and stops at an elevation just below the active core. Crushable graphite matrix at the lower end of each control rod channel will limit the load between the control rod assembly and reflector element in the event that the neutron control assembly support fails. The control rod channel is centered on the flat

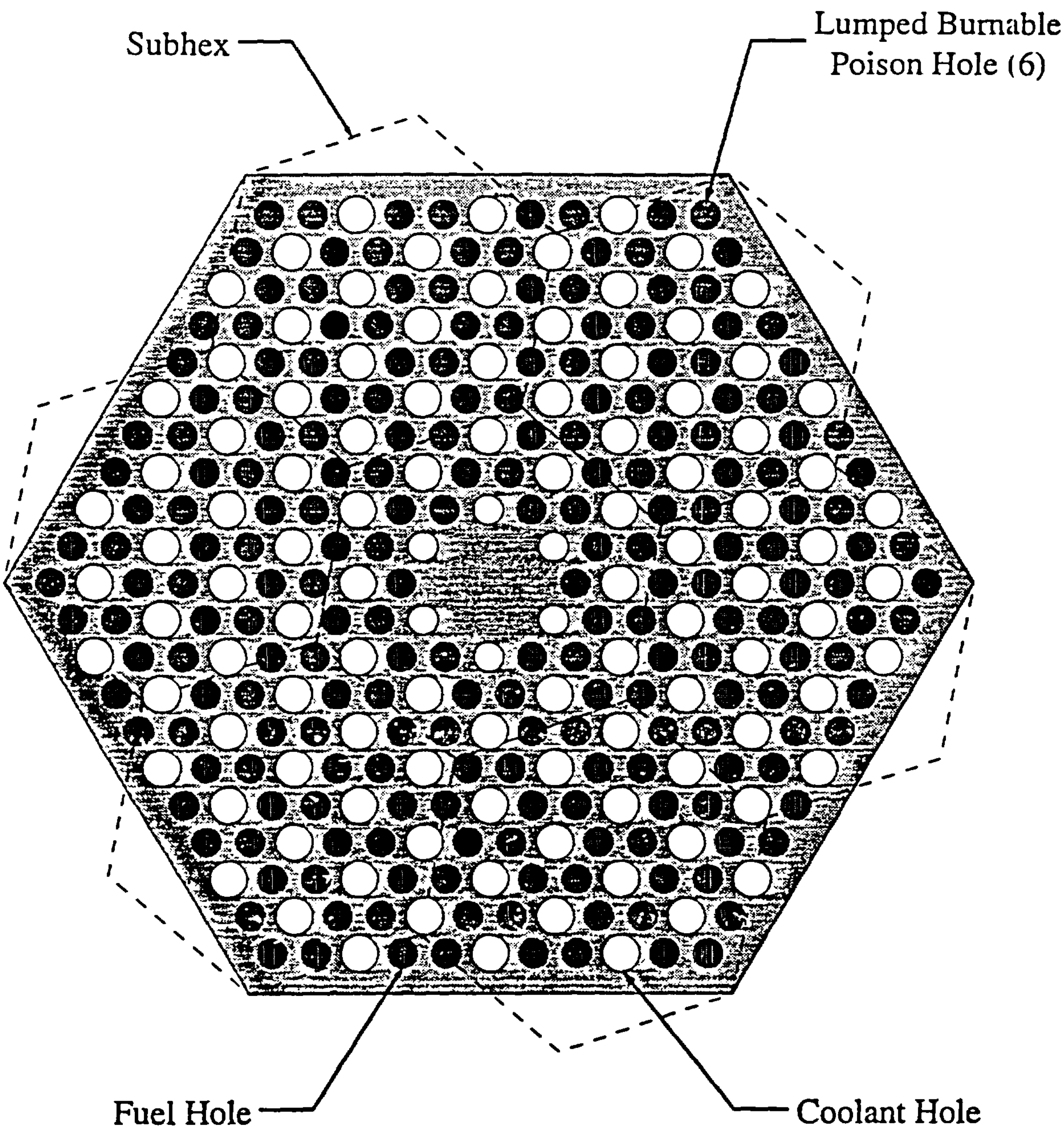

Fig. 4.1-8. Subhex model of fuel element

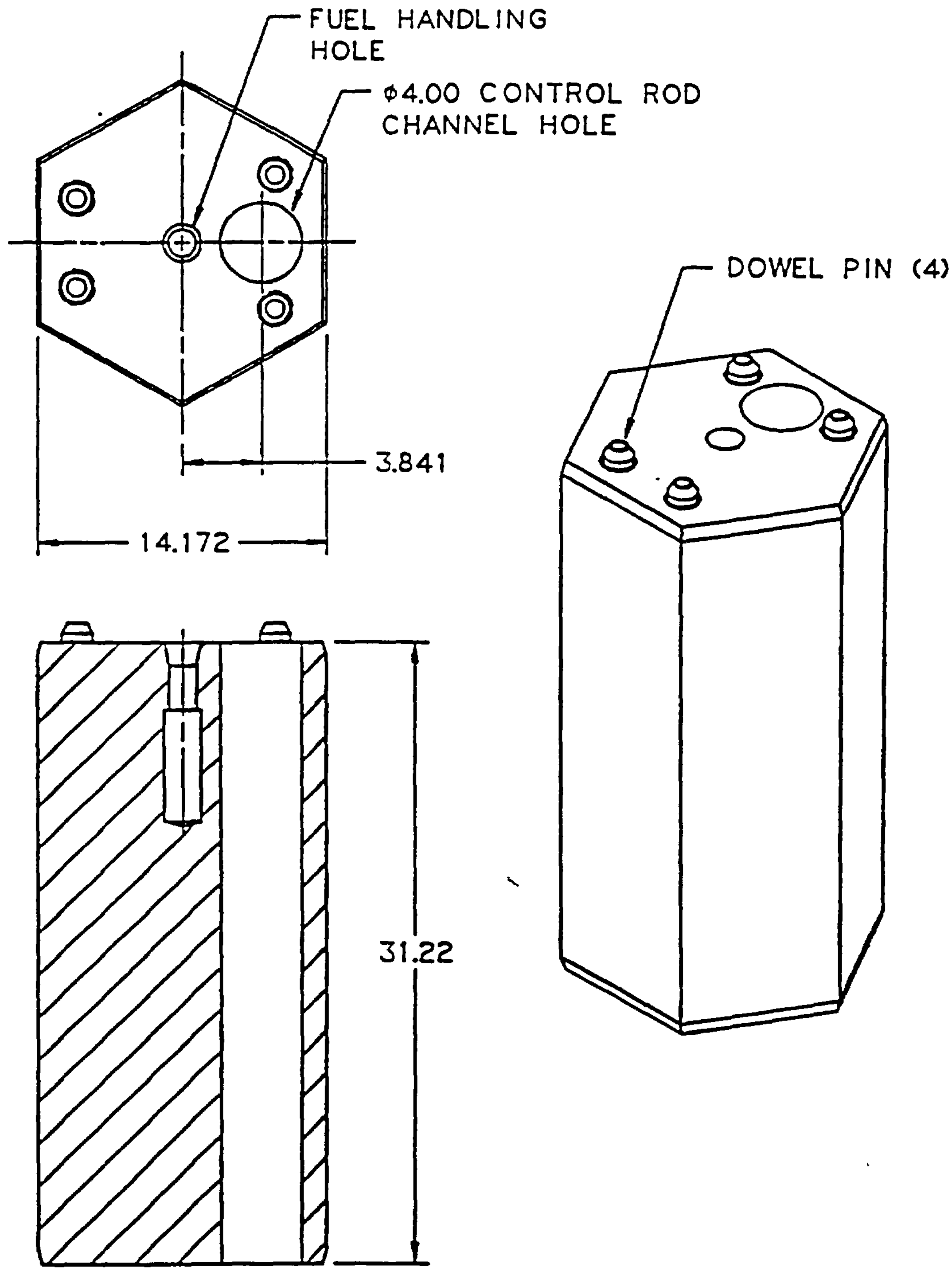

Fig. 4.1-9. Reflector control element

nearest to the active core 102 mm (4.028 in.) from the center of the reflector element. The distance from the flat of the reflector block to the edge of the control rod channel is 27 mm (1.06 in.).

The inner (central) reflector includes 61 columns of hexagonal elements. The central and side reflector columns consist of, from top down, one three-quarter height element, eleven full-height elements, one three-quarter height element, and two half-height elements, above the core support pedestal. These are shown in Fig. 4.1-1. The total reflector height for the equivalent 13.5 elements above the top of the core support pedestal is 10.7 m (421.5 in.). The four dowel/socket connections at each axial element-to-element interface provide alignment for refueling and control rod channels, and transfer seismic loads from reflector elements.

4.1.1.8. Control Rods and Reserve Shutdown Control. The control rod neutron absorber material consists of 40% wt enriched boron (90% B_{10}), contained in B_4C granules uniformly dispersed in a graphite matrix and formed into annular compacts. The annular compacts have an inner diameter of 52.8 mm (2.08 in.) and an outer diameter of 82.6 mm (3.25 in.). These compacts are enclosed in carbon-fiber reinforced carbon (C-C) composite canisters for structural support; the canisters are vented to minimize the pressure differential across the canister wall, although the venting is such that oxidation of the boron carbide is restricted. Small tabs on the outside of the canisters center the control assembly string in the control rod channel. Coolant flows down the annulus between the control rod, its channel, and through the central hole, to remove heat generated in the annular compacts. The string of 18 canisters is designed with mechanical flexibility to accommodate any postulated offset between elements, even during a seismic event. Thus, full control rod insertion is ensured from any normal or abnormal operating condition. Each startup and operating control rod assembly is attached to a cable and is supported by its corresponding inner and outer neutron control assembly, respectively. The carbon-fiber reinforced carbon composite design for the canisters is a new concept that will require some development testing before being approved for the design.

The startup control rods are only inserted during the startup/shutdown and refueling operating modes. They are fully withdrawn whenever the core is critical and fully inserted when subcritical.

The operating control rods are inserted to varying heights for control during operation for control and fully inserted for protection. For a pressurized conduction cooldown, the peak temperature for the inserted operating control rods is 1093°C (2000°F). For a depressurized conduction cooldown, the peak

temperature is 1281°C (2338°F). Since the stress levels in the control rod structure are very low (basically deadweight plus pressure drop), the control rods can survive all the above events without damage.

The reserve shutdown control material consists of 40% wt natural boron in B_4C granules dispersed in graphite matrix and formed into pellets. The reserve shutdown pellets are cylindrical, with rounded ends, and are 14 mm (0.55 in.) in diameter. The B_4C granules are coated with dense pyrolytic carbon (PyC) to minimize oxidation and boron loss from the system during high temperature, high moisture off-normal events. The coated B_4C granules are 400 to 600 μm in diameter. When released into the reserve shutdown channels in the active core, the pellets have a minimum packing fraction of 0.55. The pellets are normally housed in storage hoppers located above the reactor core in both the startup and operating rod neutron control assemblies.

4.1.2 Reactor Internals and Hot Duct

Reactor Internals. The reactor internals components include the permanent side reflector, the graphite core support assembly, the metallic core support, the upper core restraint and the upper plenum shroud. Metallic core support is provided around the outside of the core assembly for lateral support (metallic core support barrel) and below the core assembly for vertical support (metallic core support floor). The location of these components is shown in Figs. 4.1-1 and 4.1-2.

The graphite internals include the ring-shaped permanent side reflector which surrounds and provides lateral support to the core array. The permanent side reflector consists of columns of graphite elements that match the irregular outline of the outer replaceable reflector on the inside, and the cylindrical wall of the core barrel on the outside. The graphite core support assembly, shown in Fig. 4.1-1, supports the weight of the core array. A single graphite pedestal supports the individual core columns and replaceable reflector columns, except at the hot duct entrance where, in order to increase flow area, two pedestals support three reflector columns. The graphite core support assembly also collects and channels the coolant out of the active core and into the hot duct, which carries it to the power conversion vessel. From top down, the graphite core support assembly consists of: two layers of hexagonal elements, which match the bottom of the core array; graphite core support pedestals and side reflector support elements, which together form the core outlet plenum; and the lower plenum floor, which consists of a layer

of graphite elements and two layers of ceramic insulation elements that protects the metallic core support floor from the hot core outlet gas. The permanent side reflector and the graphite core support assembly are both made of H-451 graphite, except for a few large core support assembly elements at the entrance to the hot duct, which are made of purified HLM graphite.

The metallic internals are also shown in Figs. 4.1-1 and 4.1-2. The upper core restraint rests on top of the graphite core and permanent side reflector assemblies. The upper core restraint is an array of box-like welded elements, half as high as the standard core element, with the same cross sections as the graphite elements on which they rest. Each hexagonal upper core restraint element has the same central handling hole as the graphite core elements. The upper core restraint elements are doweled to the graphite elements below, and they are keyed to one another and to the core barrel. The main functions of the upper core restraint are to provide core stability during refueling and to prevent thermal fluctuations in the core array during reactor operation by maintaining relatively uniform and limited gaps between core columns.

The metallic core support is a single weldment, composed of a floor section and a core barrel section. It supports and surrounds the core, the graphite internals, the upper core restraint, and the upper plenum shroud. The metallic core support, in turn, is supported both vertically and laterally by the reactor vessel.

The upper plenum shroud is a welded, continuous dome resting on top of the core barrel, with which it forms the core inlet plenum. The upper plenum shroud contains neutron shielding. It is provided with vertical penetrations for inserting the control rods and the reserve shutdown material, for refueling, and for core component replacement.

The metallic core support and the upper plenum shroud route the "cold" gas returning from the power conversion vessel back to the top of the core, so that it cools the metallic internals and the reactor vessel nearly to core inlet temperature. The metallic internals are made of welded, high-temperature alloy 800H. To facilitate heat removal from the core during conduction cooldown event, they are not thermally insulated.

Hot Duct Assembly. The hot duct assembly, shown in Fig. 4.1-10, extends and channels the primary coolant from the core outlet plenum to the bellows section at the inlet of the turbomachine involute. The hot duct is centrally located within the cross vessel. Core outlet gas

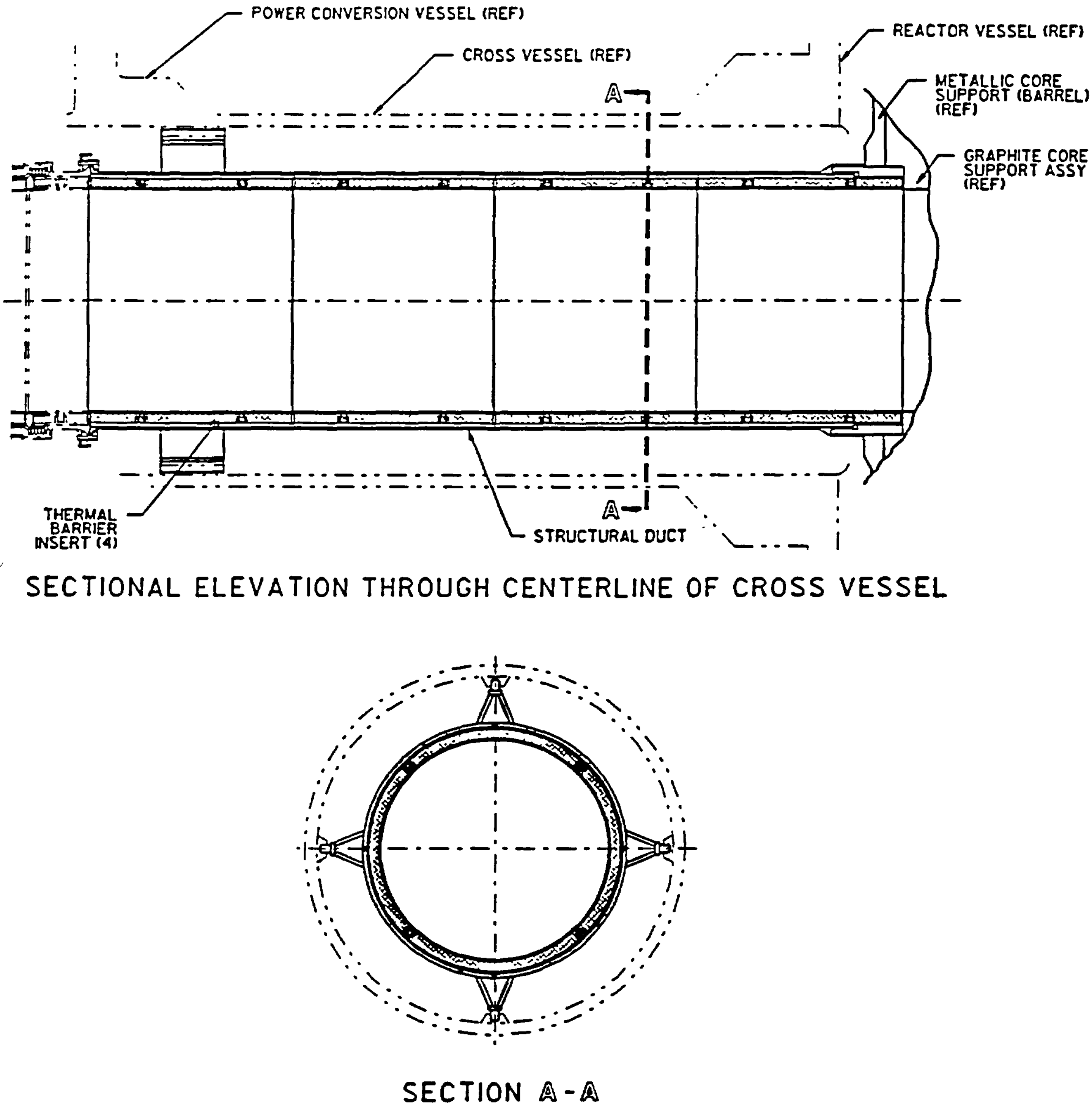

Fig. 4.1-10. Hot duct assembly

flows through the central duct to the Power Conversion System, and the return gas (905°F) flow through the annulus. The hot duct also provides an insulation layer between the core inlet and outlet gasses to minimize the heat transfer from the core outlet gas to the core inlet gas.

The hot duct assembly is comprised of the straight structural duct made of Alloy 800H, welded to the core barrel of the Reactor System and internally protected by a self-contained and separately removable thermal barrier inserts, which contain thermal insulation. The insulation is a ceramic fiber material blanket.

4.1.3. Neutron Control

Neutron control components include equipment for positioning of neutron control material and nuclear instrumentation. The components consist of inner and outer neutron control assemblies, source range detector assemblies, ex-vessel neutron detector assemblies, and in-core flux mapping units.

4.1.3.1. Neutron Control Assembly Drives and Structural Equipment. The arrangement of neutron control assemblies in the reactor core is shown in plan view in Fig. 4.1-11. These assemblies contain a total of 48 control rods, 36 in the outer reflector blocks, and 12 in the core region. Each rod has its own independent drive.

The neutron control assemblies are installed into the reactor vessel as shown in Fig. 4.1-12. Three different types of neutron control assemblies are used:

Type	Quantity
In-core Neutron Control Assemblies	6
Outer Neutron Control Assemblies - Type 1	12
Outer Neutron Control Assemblies - Type 2	6

All neutron control assemblies are equipped with two independent control rod drive units. Each in-core neutron control assembly and outer neutron control assemblies type 1 has two control rods and drives and one reserve shutdown unit. Each outer neutron control assembly type 2 has only the two control rods and drives. These assemblies are interchangeable in any of

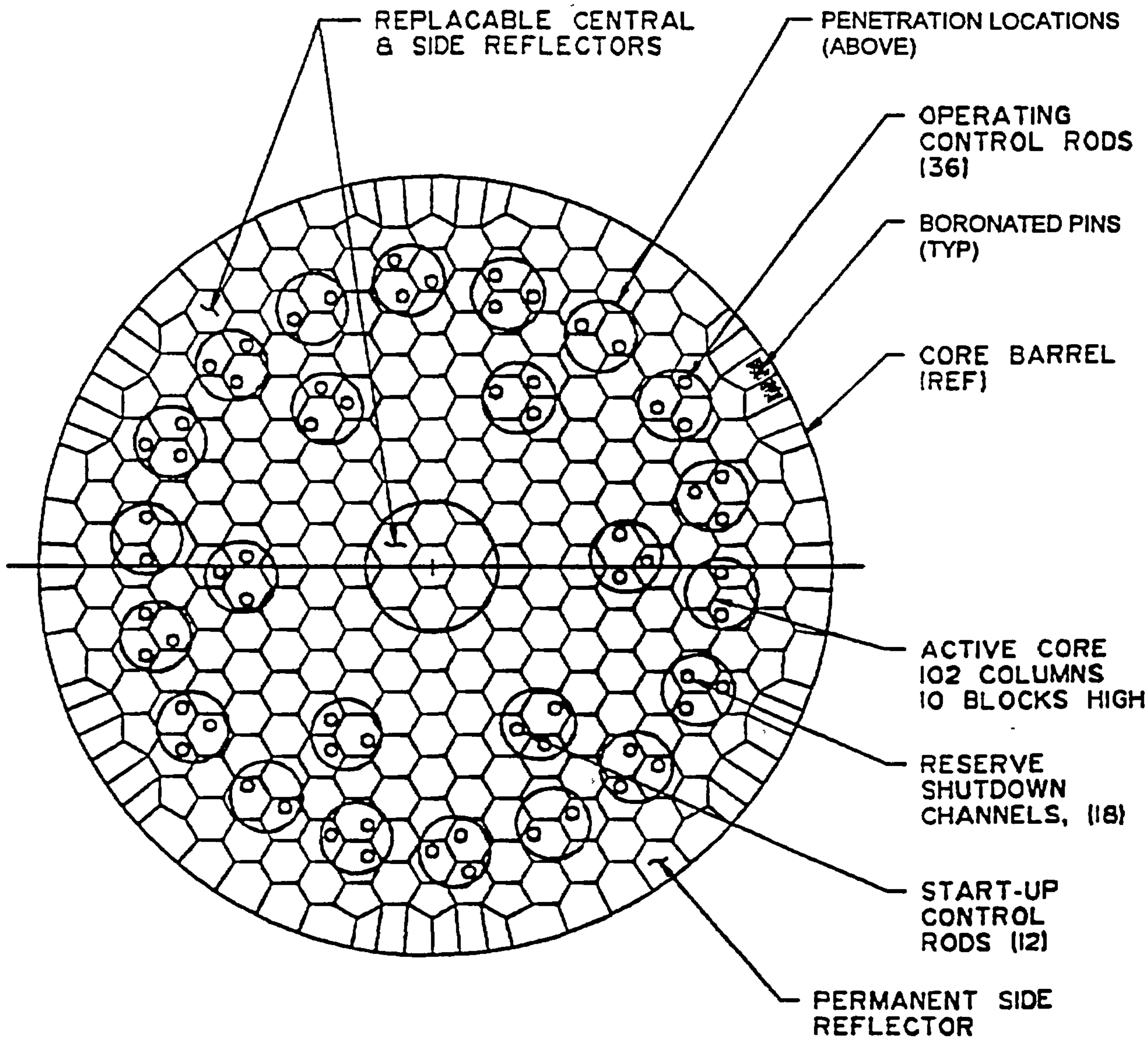

Fig. 4.1-11. Arrangement of neutron control assemblies in the reactor core

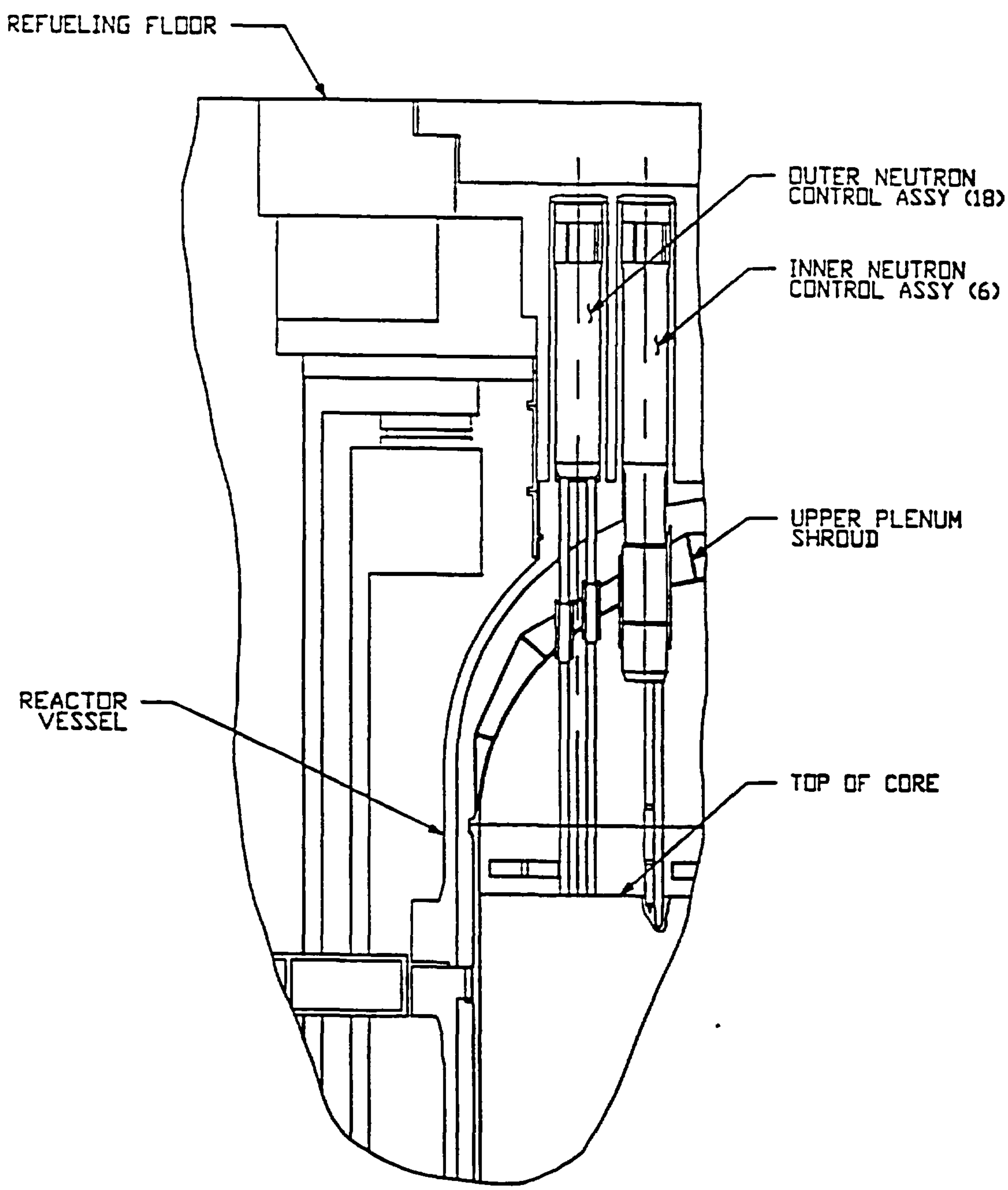

Fig. 4.1-12. Neutron control assembly installation

the assigned penetrations for that type of neutron control assembly. Figure 4.1-13 shows and overall view of an outer neutron control assembly type 2.

Neutron Control Assembly Structural Equipment. The structural equipment consists of an upper structural frame, gamma shielding, neutron shielding, thermal barrier, upper and lower guide tubes, and seals. This equipment, which is illustrated in Fig. 4.1-13, provides the mechanical support of the assembly. The major components of the structure are described as follows.

The upper structure consists of vertical corrosion resistant structural angles welded to a top lifting ring and a lower horizontal plate. This horizontal plate mates with a support ledge in the surrounding penetration and transfers the weight to the reactor vessel. The upper structure provides support for the mechanisms in the upper part of the refueling penetration, where the environment is relatively mild with low radiation and moderate temperature. A circular elastomer seal attached to the horizontal plate is normally in contact with the inner diameter of the surrounding penetration to restrict flow into or out of the upper neutron control assembly region.

The gamma shield is a corrosion resistant plug that fits across the neutron control assembly structure. It protects maintenance crew against gamma radiation from the core and the activated control rods. It provides vertical passages for the control rod support cables. The gamma shield also provides structural attachments for the fixed guide tubes.

The neutron shielding consists of four cylindrical graphite elements containing 1.9 cm (0.75 in.) diameter boron steel pins. A corrosion resistant container positions the shield just below the reactor vessel top head to prevent activation of the upper portion of the vessel. The thermal barrier is positioned above the neutron shielding inside the same container as the neutron shielding. It is used to maintain the temperature of the upper portion of the neutron control assembly within acceptable limits.

The guide tubes for the control rods extend from the gamma shield downward through the top head of the reactor vessel and upper plenum shroud to the interface with the upper core restraint elements on top of the core. The purpose of the guide tubes is to provide guidance for the control rods during reactor operation and assure a clear passage for these components as they are inserted into and withdrawn from the core.

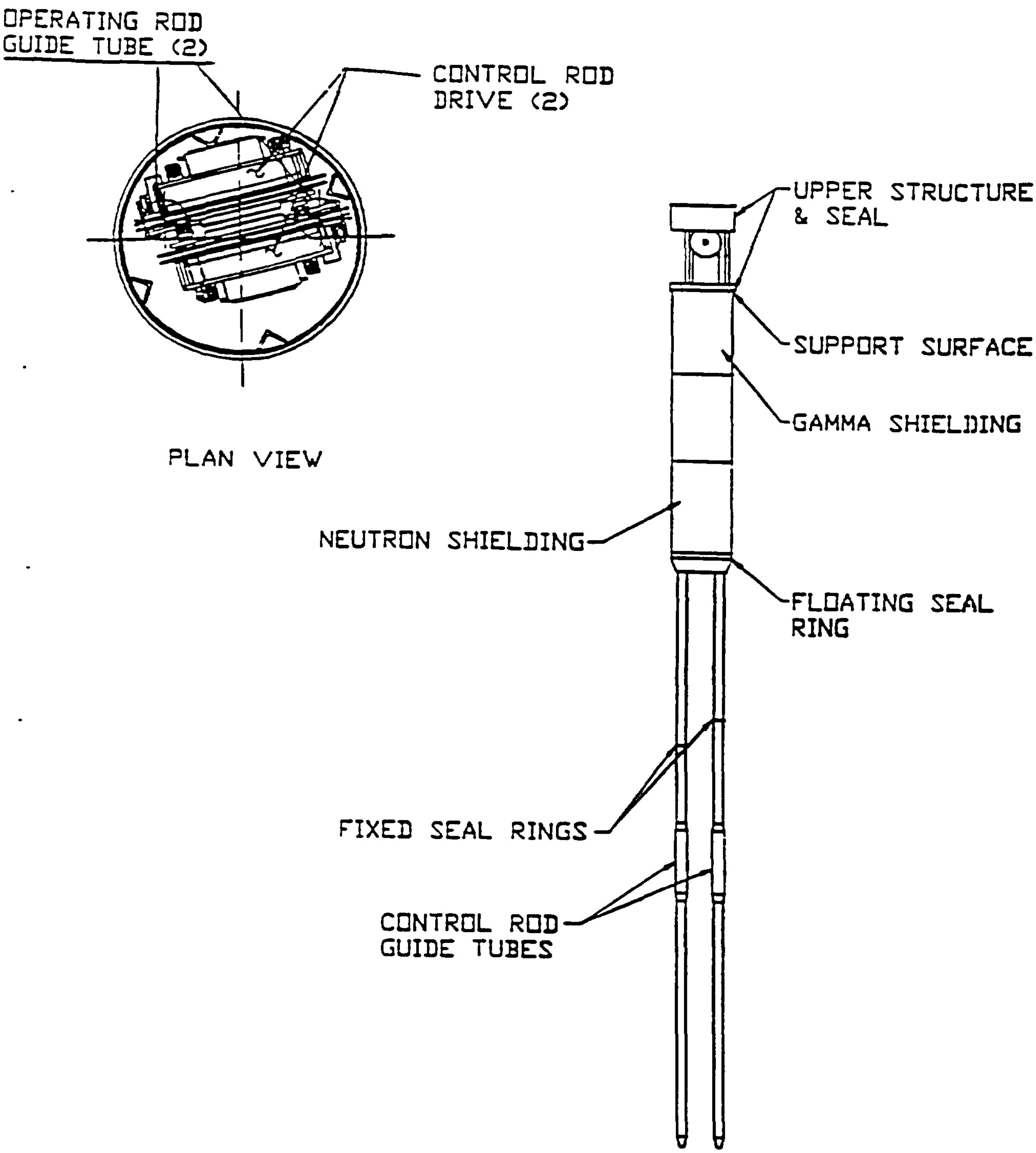

Fig. 4.1-13. Overall view of outer neutron control assembly

Control Rod Drive Equipment. The control rod drive equipment is located in the upper part of the neutron control assembly as shown in the inset in Fig. 4.1-13. It consists of a dc torque motor, which drives the cable storage drum through a harmonic drive unit which provides a 60:1 speed reduction. The control rod is lowered and raised with a flexible high nickel alloy cable which is taken up on the cable storage drum. Small cable guide rollers locate the cable in the proper position above the gamma shield penetration.

The motor, speed reducer, and storage drum are mounted on a metal frame. The frame is attached to the upper support structure by means of a pivoting support shaft. The rotation of the mechanism is resisted by redundant load cells, which are used to monitor cable load, i.e., the weight of the control rod plus friction. These devices are used to detect a control rod or a broken control rod cable. This information is confirmed by the motor current instrumentation.

The drive motor is a brushless dc torque motor, rated for continuous duty. Motor winding insulation is capable of minimum service life of 60 years in the reactor helium atmosphere. Three load resistors are provided to limit control rod velocity in case of power failure or reactor trip. In this case, the motor acts as a generator and the resistors absorb the energy.

4.1.3.2. Reserve Shutdown System. The arrangement of the reserve shutdown system is shown in plan view in Fig. 4.1-11. There are a total of 18 reserve shutdown control equipment units, 12 in the outer core region and six in the central core region. The reserve shutdown control equipment is assembled into neutron control assemblies for installation into the reactor. Figure 4.1-14 shows an inner neutron control assembly with two control rods and drives and one reserve shutdown control equipment unit.

Reserve Shutdown Control Equipment. Each reserve shutdown control unit consists of a reserve shutdown hopper containing boronated graphite shutdown material and a fuse link mechanism which opens the hopper gate by means of an actuation rod. The reserve shutdown guide tube and structural equipment, guides the reserve shutdown material into a channel in the core. Figure 4.1-15 shows the arrangement of reserve shutdown control equipment within the in-core neutron control assembly package.

4.1.3.3. Nuclear Instrumentation. The nuclear instrumentation consists of ex-vessel neutron detectors, source range detectors, and in-core flux mapping units. During power operation the

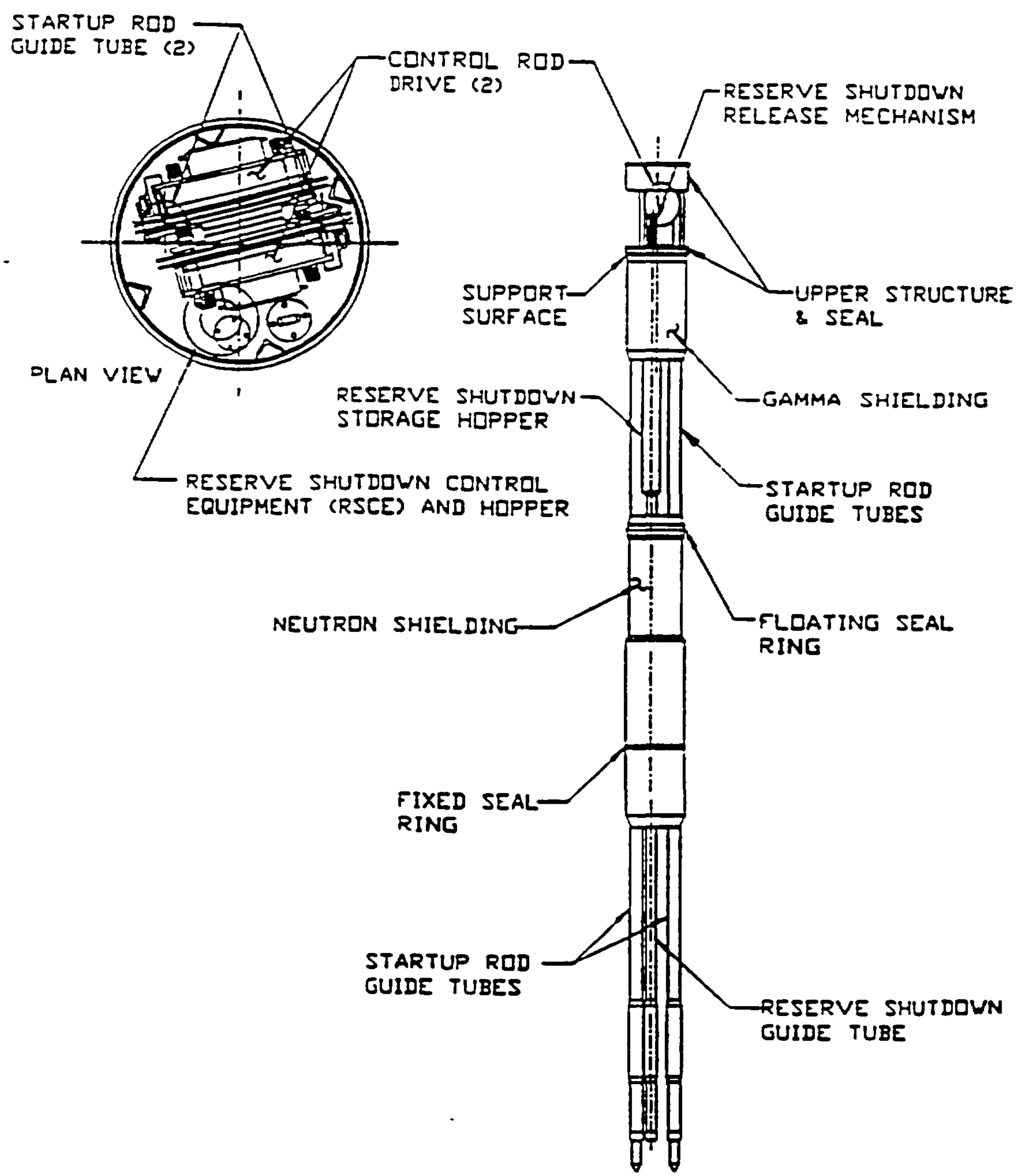

Fig. 4.1-14. Inner neutron control assembly

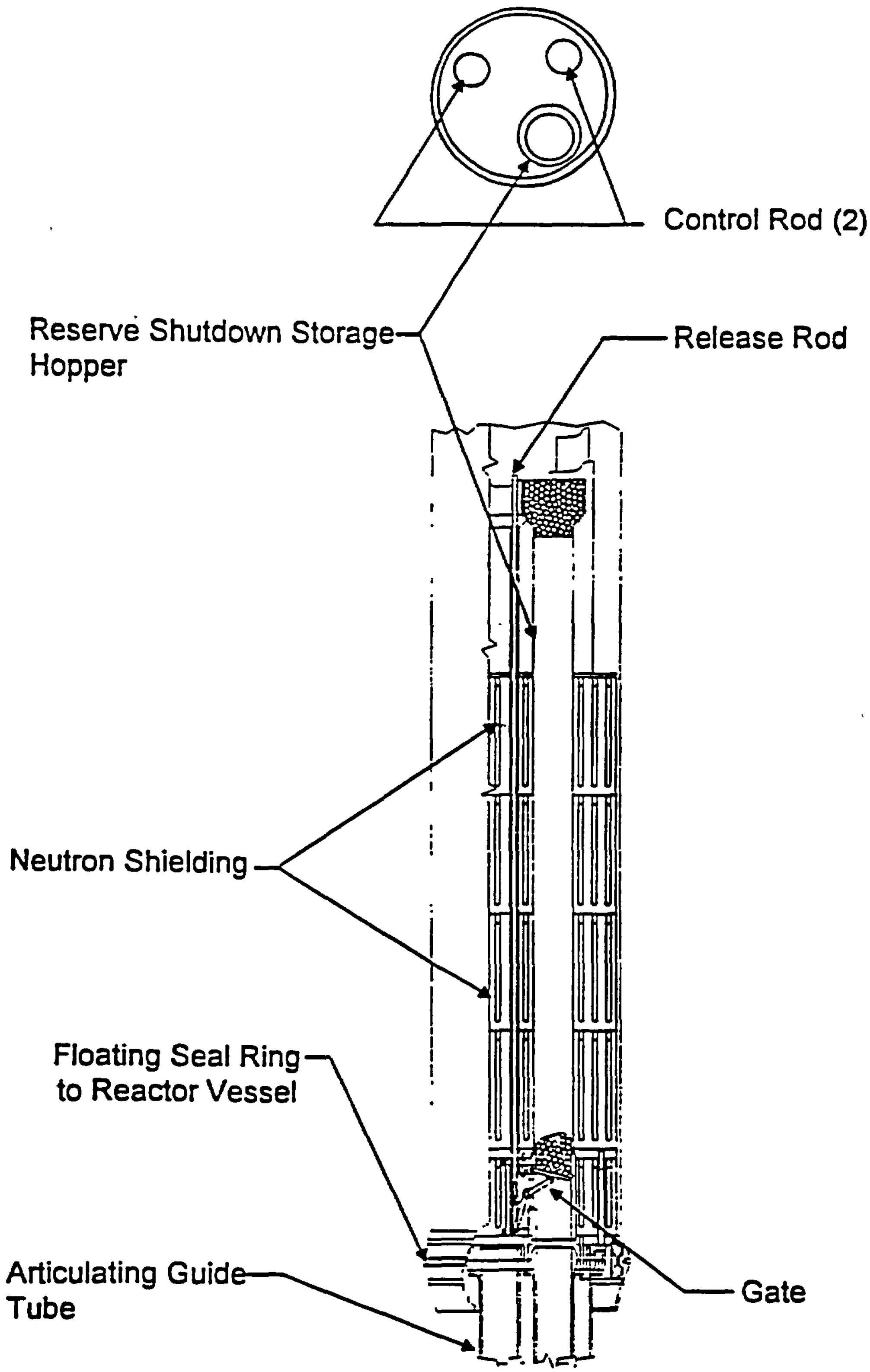

Fig. 4.1-15. Arrangement of reserve shutdown control equipment

neutron flux levels are monitored by the ex-vessel neutron detectors, whose operational range overlaps the range of the source-range detectors. During startup and shutdown, the neutron flux levels are monitored by source-range detectors. The in-core flux mapping units are used to confirm axial power stability.

The ex-vessel neutron detector assemblies consist of fission chamber thermal neutron detectors mounted in six symmetrical vertical wells located outside the reactor vessel. The signals from these detectors are supplied to the automatic control and protection systems to operate the control rod drives or the reserve shutdown control equipment and thereby change the neutron flux levels within the reactor core.

The need for source range detectors in-vessel is dictated by the low neutron flux at the ex-vessel detector location during startup and shutdown conditions. Three source range detector assemblies are installed in order to ensure adequate neutron flux measurements during these low power operations. The source range detectors are fission chambers with appropriate cabling, support structures, and reentrant penetrations. The source range detectors are contained at the bottom head of the reactor vessel in three equally spaced reentrant penetrations. The reentrant penetrations extend into vertical channels in the reflector elements near the bottom of the core.

The in-core flux mapping unit consists of movable detectors in the central column of the inner reflector and in the outer permanent reflectors. The vertically traversing unit, containing two independent fission chambers and a single thermocouple, enters from the housing above the reactor vessel to the top of the core and traverses down through the reflectors.

4.2. VESSEL SYSTEM

The principal functions of the Vessel System (VS) are to contain the primary coolant inventory and to maintain primary coolant boundary integrity. In addition, the VS provides structural support and alignment for the Reactor System components and Shutdown Cooling System components that are housed within the reactor vessel and all Power Conversion System components that are housed within the power conversion vessel.

The radionuclide control functions of the VS are to transfer decay heat from the reactor core to the reactor cavity cooling system (RCCS) during conduction cooldown events, to maintain

the geometry of the reactor core with respect to the neutron control assemblies (NCAs) to control heat generation, and to prevent air ingress and consequent core oxidation.

The Vessel System consists of a reactor vessel, a power conversion vessel, a cross vessel connecting the reactor vessel and the power conversion vessel, primary pressure relief components, vessel support and lateral restraint components, and associated penetrations and closures. The vessel components are arranged as shown in Fig. 4.2-1. The vessel components are fabricated from 9Cr-1Mo-V ferritic steel forgings per SA 336, Gr F91 and plates per SA 387, Gr 91, Cl 2. The principal operating and design parameters for the Vessel System components are listed in Table 4.2-1. The Vessel System and components are designed and fabricated per the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Division 1, to ensure high reliability throughout the 60-year plant life. The in-service inspection program for the Vessel System will comply with the ASME Code, Section XI requirements.

The Vessel System is located below grade, enclosed and supported in a reinforced concrete silo. The reactor vessel and power conversion vessel are placed side-by-side as shown in Fig. 4.2-1 with the power conversion vessel at a lower elevation than the reactor vessel. This arrangement provides for thermal isolation and protection of the power conversion components from the high temperature core during conduction cooldown events.

4.2.1. Reactor Vessel

The reactor, reactor internals, and reactor support structure are housed in the reactor vessel, which is composed of a main cylindrical section with hemispherical upper and lower heads as shown in Fig. 4.2-2. The upper head, which is bolted to the cylindrical section, incorporates penetration housings for the outer neutron control assemblies, the inner neutron control assemblies, and the in-vessel flux monitoring unit. Each of these housings is sealed with a blind flange. The lower head, which is welded to the cylindrical section, has penetrations for the Shutdown Cooling System, the In-Service Inspection access, and source range neutron detectors. The shutdown heat exchanger housing and shutdown circulator housing are considered to be included in the reactor vessel design since they are part of the primary pressure boundary and are mounted on the reactor vessel. The upper portion of the lower head incorporates a ring forging which provides support to the core through the core support structure. Lateral seismic restraint is provided to the core by six lugs welded to the interior surface of the vessel, near the top of the

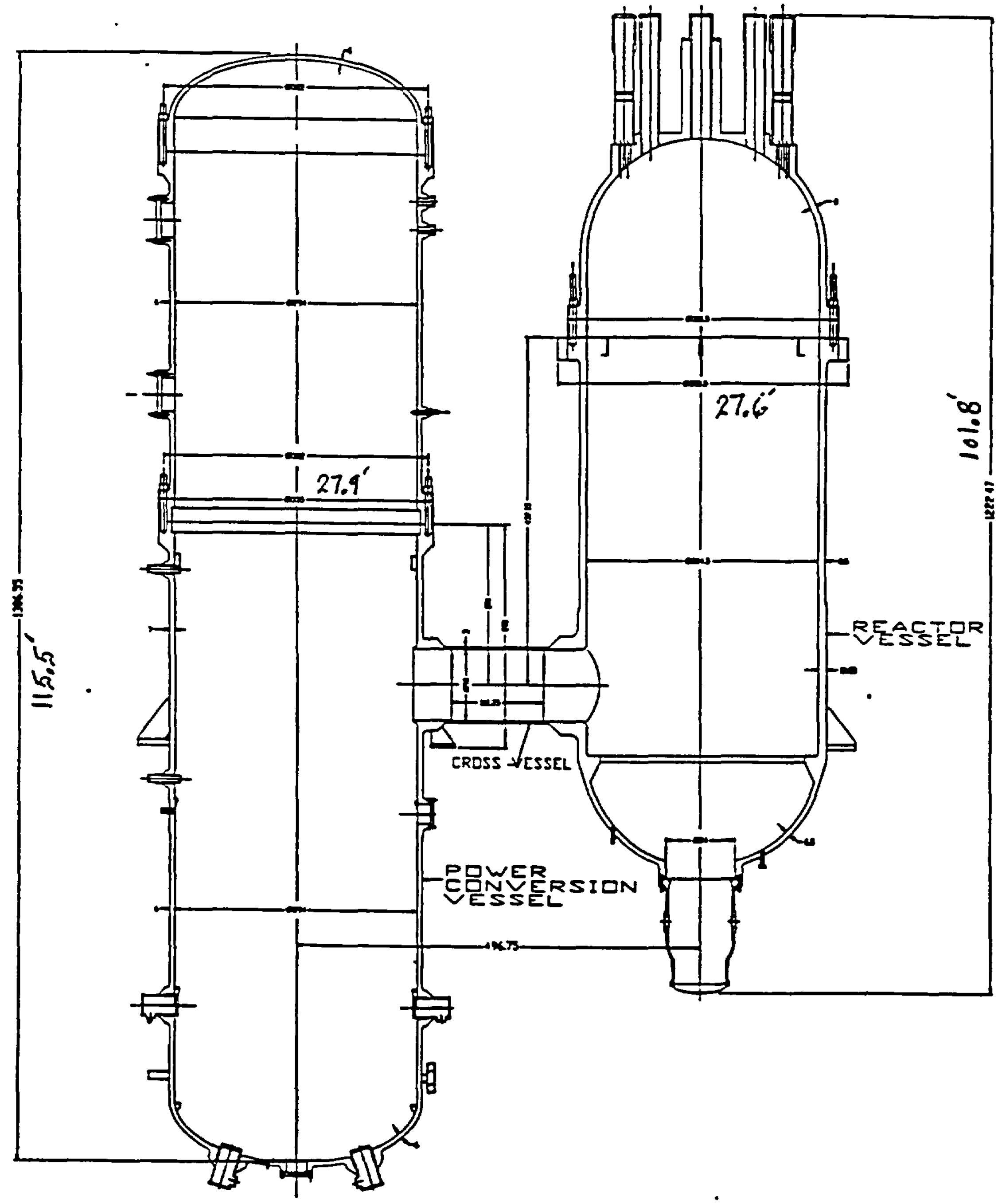

Fig. 4.2-1. GT-MHR Vessel System general arrangement

TABLE 4.2-1
VESSEL SYSTEM PRINCIPAL DESIGN PARAMETERS
(60 year life)

Vessel	Region of Vessel	Design Pressure	Design Temperature/Duration
Power Conversion Vessel	Above flange	845 psia (5.82 MPa)	71°C (160°F)
	Below flange	845 psi (5.82 MPa)	204°C (400°F)
Reactor Vessel	Entire vessel	1160 psia (8.00 MPa)	495°C (923°F) for 4.6 x 10^5 h
			538°C (1000°F) for 1 x 10^3 h

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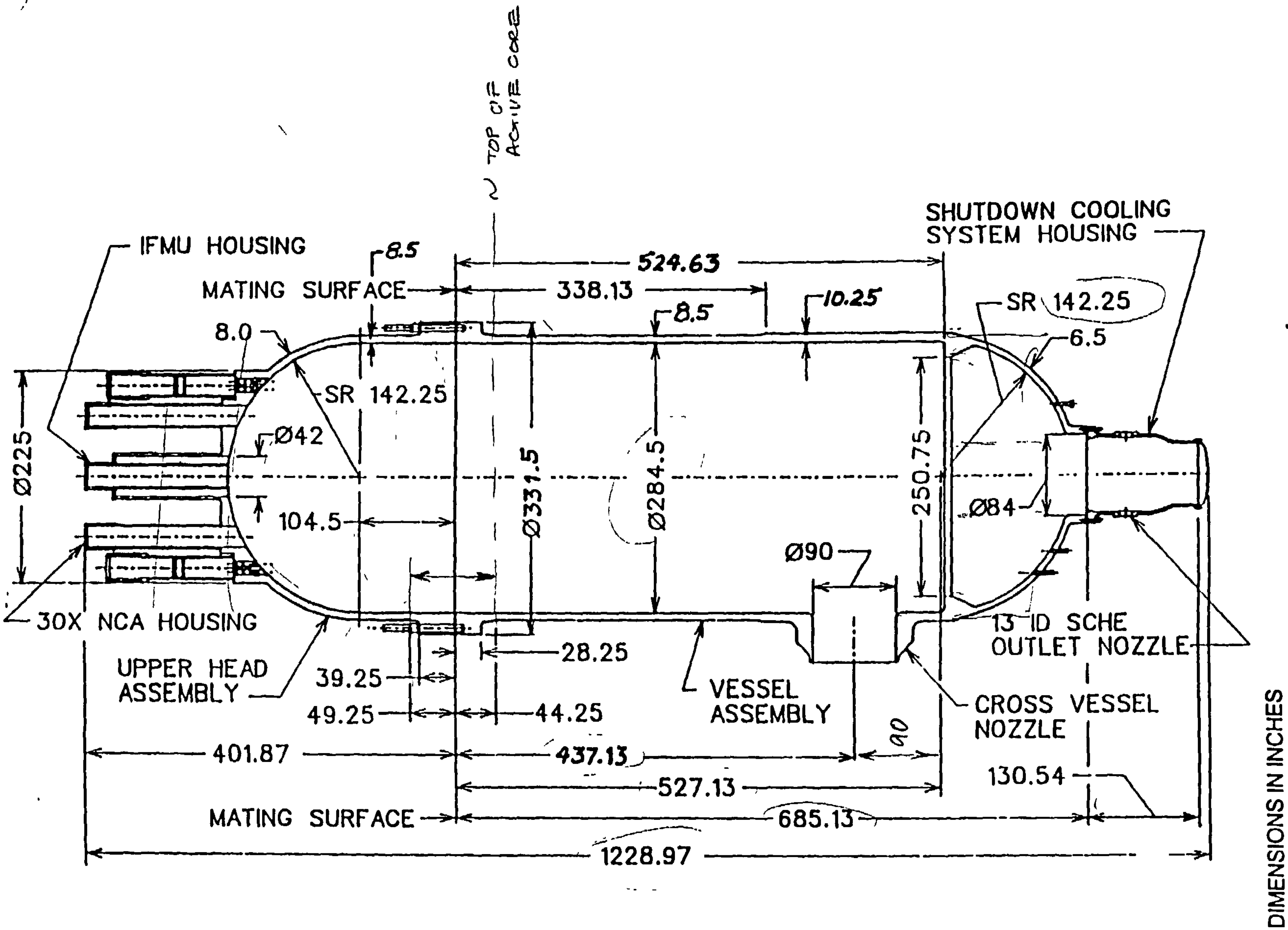

Fig. 4.2-2. GT-MHR reactor vessel

cylindrical section. The cylindrical section also incorporates a nozzle forging for the attachment of the cross vessel, reactor vessel support lugs, and lateral restraint keys. Details of the reactor vessel are given on Table 4.2-2.

4.2.2. Cross Vessel

The cross vessel consists of a one-piece forged cylinder designed and fabricated to ASME Code, Section III, that connects the reactor vessel to the power conversion vessel. This vessel houses a concentric hot duct. The hot core outlet gas passes through the hot duct and the cold core inlet gas passes through the annular gap between the hot duct and the cross vessel.

The cross vessel dimensions are 2.29 m (90 in.) inside diameter by 76.2 mm (3.0 in.) thick and approximately 3 m (10 ft) long and details are given on Table 4.2-2. The actual length of the cross vessel will be determined later, after detailed design of the cross vessel nozzles.

4.2.3. Power Conversion Vessel

The Power Conversion System is housed in the power conversion vessel, which consists of a cylindrical shell with a hemispherical lower head that is welded to the shell and an upper cylindrical closure head that is bolted to the lower vessel shell. The lower cylindrical shell contains the penetrations for the cooling water inlet and outlet of the intercooler modules and the lower hemispherical head contains the penetrations for the cooling water inlet and outlet of the precooler. The upper closure head contains the turbomachine penetration. Details of the PCS vessel are given on Table 4.2-3.

TABLE 4.2-2
REACTOR VESSEL AND CROSS VESSEL DESIGN DESCRIPTIONS

REACTOR VESSEL	Height	31.0 Meters (1222.5 In.)
	Vessel Inner Diameter	7.2 Meters (284.5 In.) 23.7'
	Vessel Outer Diameter	8.4 Meters (331.5 In.) (at Flange)
	Wall Thickness Top Head Shell Thickened Ring Bottom Head	 203 MM (8.0 In.) 216 MM (8.5 In.) 261 MM (10.25 In.) 165 MM (6.5 In.)
	Weights Closure Head Vessel Assembly	 490 Metric Tons (540 Short Tons) 838 Metric Tons (925 Short Tons)
	Material ASME Callouts	9 Cr-1Mo-V SA-387 Grade 91 Class 2 Plates SA-336 Grade F91 Forgings
CROSS VESSEL	Inside Diameter Wall Thickness Length Material	2.29 Meters (90.0 In.) 76.2 MM (3.0 In.) [TBD] (Approx. 2.86 MM, 112.25 In.) 9Cr-1Mo-V, 1-Piece Forged

TABLE 4.2-3
POWER CONVERSION VESSEL DESIGN DESCRIPTION

Height	35.2 Meters (1386.6 In.)
Vessel Inner Diameter	7.5 Meters (294 In.) 24.5'
Vessel Outer Diameter	8.5 Meters (335 In.) (at Flange)
Wall Thicknesses	152 MM (6.0 In.)
Weights Ellipsoidal Head Upper Vessel Assembly Lower Vessel Assembly	 178 Metric Tons (197 Short Tons) 482 Metric Tons (532 Short Tons) 717 Metric Tons (791 Short Tons)
Material ASME Callouts	9Cr-1Mo-V SA-387 Grade 91 Class 2 Plates SA-387 Grade F91 Forgings

4.2.4. Selection of Vessel Materials

The vessels are designed and fabricated from a high temperature ferritic steel, 9Cr-1Mo-V to meet temperature and irradiation requirements. The 9Cr-1Mo steel, used primarily for heat exchanger tubes in the past, has been stabilized and strengthened by the additions of Columbium, Vanadium, Nickel, Aluminum and Nitrogen. The "Modified 9Cr" alloy was developed by Oak Ridge National Laboratory and Combustion Engineering, Inc. during the 1970s and 1980s to extend and optimize its high temperature properties. Although the material has been primarily used as tubing and piping in fossil fueled boiler applications, the developers of the steel envisioned its use in nuclear steam generators and vessels in liquid metal reactor applications. The use of 9Cr-1Mo-V in the construction of heavy-wall vessels for refinery applications has been proposed by the French. Section thicknesses up to 300 mm (12 in.) have been produced.

A significant database has been established characterizing the effects of fast neutron (E > 0.1 MeV) irradiation on the mechanical properties of 9Cr-1Mo-V in support of liquid metal reactor development. Samples were irradiated in the EBR-II, FFTF, and HFIR reactors, and data were obtained on tensile, creep, and fracture toughness, as well as changes in microstructure and swelling. Both the neutron spectra and neutron fluences were far more severe than those which would be encountered in the GT-MHR. Additional data will be required to qualify 9CR-1Mo-V for the specific operating conditions of the GT-MHR. However, every indication is that 9Cr-1Mo-V will be at least as good as SA-533/SA-508 low alloy steel (the material used for LWR and MHTGR-SC vessels) with respect to irradiation properties.

9Cr-1Mo-V ferritic steel has been approved by the ASME Code Committee for use in Section I boilers and in Section VIII, Division 1 unfired pressure vessels. ASME Code Case N-466-1 allows its use in Section III, Division 1, Class 1, 2 and 3 components at temperatures up to 371°C (700°F), and Code Case N-253-6 allows its use up to 649°C (1200°F) for Class 2 and Class 3 components. A Code Inquiry has been submitted and is being pursued by ABB-CE and Oak Ridge National Laboratory for inclusion of 9Cr-1Mo-V alloy in the Section III, high temperature Code Case N-47.

4.2.5. Vessel Support Arrangement

Vertical vessel support is provided at the same building elevation for both the reactor and power conversion vessels. This feature minimizes differential vertical thermal expansion between the two vessels at the cross vessel elevation, thus minimizing shear and bending moment on the cross vessel. The vertical support is provided through sliding pads which allow unrestrained thermal and pressure expansions of the Vessel System in the horizontal plane, minimizing cross vessel axial loads. The vessel support design limits relative motions between the vessels and reactor building during a seismic event.

The reactor vessel supports consist of a lower support structure, a lower lateral support frame, and an upper lateral support frame. The lateral support frames are designed to restrain the vessel against horizontal motion while allowing free radial and axial thermal expansion of the vessel. The vertical support for the reactor vessel is provided by four support feet integral with the reactor vessel below the cross vessel elevation. Each foot has an attached lubricated spherical bearing which mates with the lower support frame. This support frame transmits all vertical loads to the reactor cavity cooling floor. The support feet also mate with keyways on the lower lateral support frames thereby providing horizontal restraint for the reactor vessel. Four upper lateral keyways located on the reactor vessel main flange mate with keys on the upper lateral support frame transmitting tangential loads to the reactor cavity walls. The reactor vessel supports provide vertical support and tangential restraint while allowing unrestrained radial and axial thermal growth.

The power conversion vessel is supported by four sliding pads spaced 180 degrees apart below the cross vessel centerline. The sliding pads allow the power conversion vessel to move freely in line with the cross vessel to accommodate thermal expansion/contraction of the Vessel System. The support lugs on which the sliding pads are mounted also act as lateral restraint keys to prevent motion perpendicular to the cross vessel axis. Two lateral restraint keys are located near the bottom of the power conversion vessel to provide lateral restraint perpendicular to the cross vessel while allowing movement in line with it. Two large-bore hydraulic snubber mechanisms are also located near the bottom of the vessel at different elevations from the partial restraint keys, which allow unrestrained movement of the power conversion vessel in line with the cross vessel to accommodate slow thermal expansions of the vessel system during all design duty

cycle events. However, they prevent any rapid motion of the vessel, mitigating high seismically induced stresses in the cross vessel.

4.3. POWER CONVERSION SYSTEM

The Power Conversion System (PCS) receives about 600 MW of thermal energy from the reactor system and converts it to 286 MW of net usable electrical energy, with an overall efficiency of about 47%.

The major components of the PCS are as follows:

- The turbomachine, which consists of the turbocompressor, the electrical generator, exciter and auxiliaries, bearings, and seals. The turbocompressor includes the turbine and two compressor sections.
- The recuperator.
- A precooler and intercooler.
- Shrouds, ducts, and seals.

The arrangement of these components is shown in Fig. 4.3-1. Each component includes the seals necessary to maintain the integrity of the helium flow path.

The helium flow path within the PCS, is also shown in Fig. 4.3-1. Helium, heated in the reactor, is received by the PCS from the hot duct. The helium then expands through the gas turbine, which is coupled to the electrical generator. From the turbine exhaust, the helium flows through the hot side of the recuperator, transferring heat to the helium on the cold side of the recuperator which is on the return leg to the reactor. Upon leaving the hot side of the recuperator, the helium flows through the precooler where it is further cooled. The helium then passes through the low pressure compressor, the intercooler, and the high pressure compressor. From the compressor, the helium passes through the cold, high pressure, side of the recuperator, where it is heated for return to the reactor system. The generator cavity is maintained free of radioactive contamination at a low 50°C (122°F) maximum temperature by isolating it from the primary coolant flow path using a labyrinth shaft seal, with a helium buffer system.

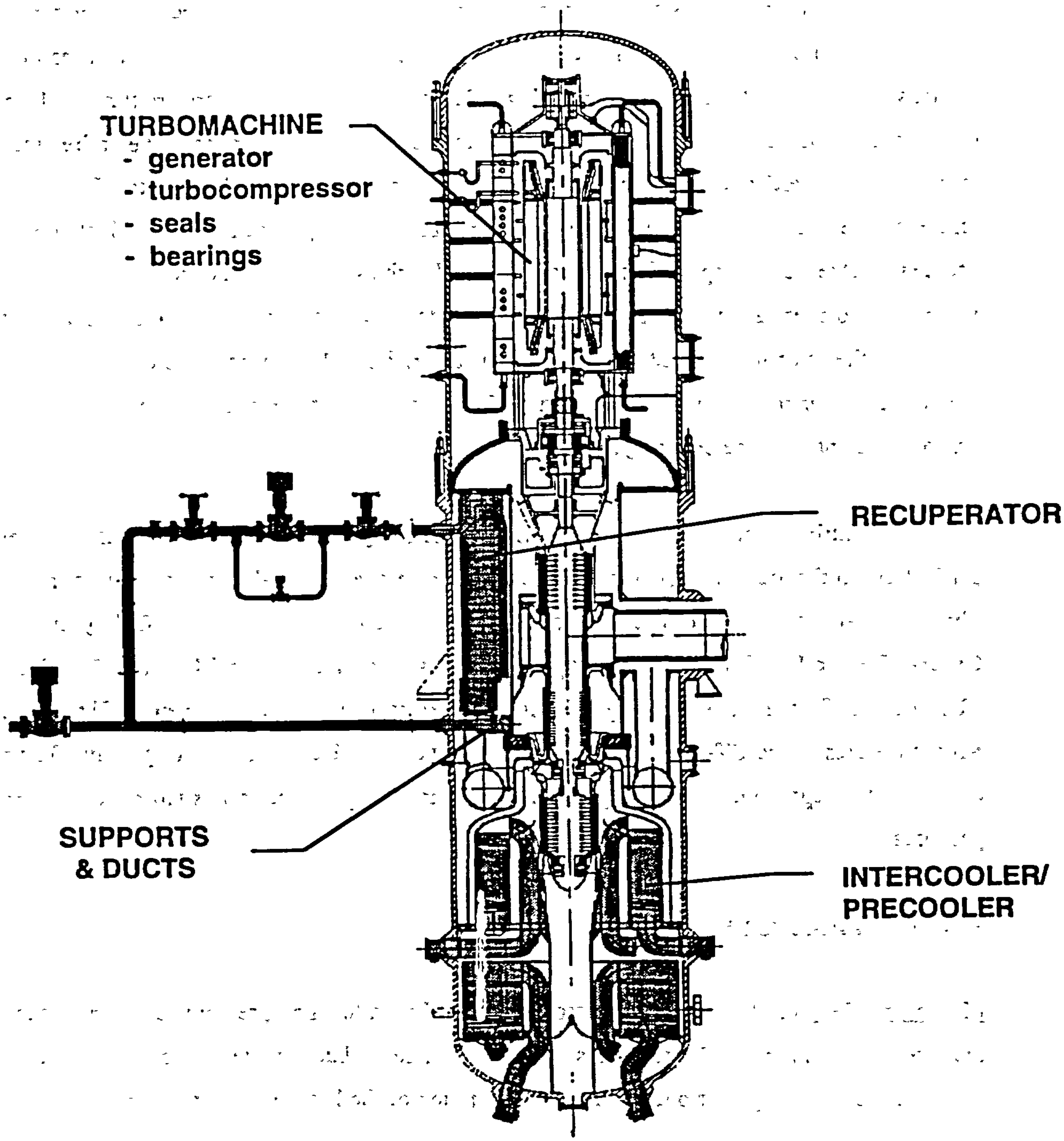

Fig. 4.3-1. Power Conversion System arrangement

4.3.1. Turbomachine

The turbomachine assembly consists of a turbocompressor and an electric generator, as shown in Fig. 4.3-2. The turbocompressor consists of a turbine section and two compressor sections, which are split to allow intercooling. The turbine and compressors are thrust balanced during normal operation. A brushless exciter is included with the generator. The entire assembly is installed in a vertical orientation, and is sealed to interfacing ducts and supports. The turbomachine 3600 rpm rotor includes the turbocompressor and generator shafts, which are coupled together, and supported on active magnetic bearings. A main and backup power supply is provided to energize and control the bearings. Catcher bearings are also included in the design to support the rotor in the event that magnetic fields are lost. The generator is contained within the power conversion vessel to avoid the need for a rotating shaft penetration and seals at the primary coolant pressure boundary.

The turbomachine design is based on the technology available from gas turbine engines, particularly in the areas of design methodology, performance, materials, and fabrication methods. This state-of-the-art technology is derived from both aeroderivatives, as exemplified by the General Electric LM6000, and large industrial engines such as the General Electric MS9001F (Ref. 4.3-1). Dimensional and weight details of the rotating assembly are given on Fig. 4.3-3. Salient features of the GT-MHR turbomachine are given in Table 4.3-1. Corresponding features of these other representative power generation units are also provided in this table for comparison purposes.

4.3.1.1. Turbocompressor.

Mechanical Design. The turbocompressor is designed with the high pressure gas in the center of the assembly. This not only minimizes the number of seals, but provides a near balanced thrust condition during full power operation. With separation of the low and high pressure compressors

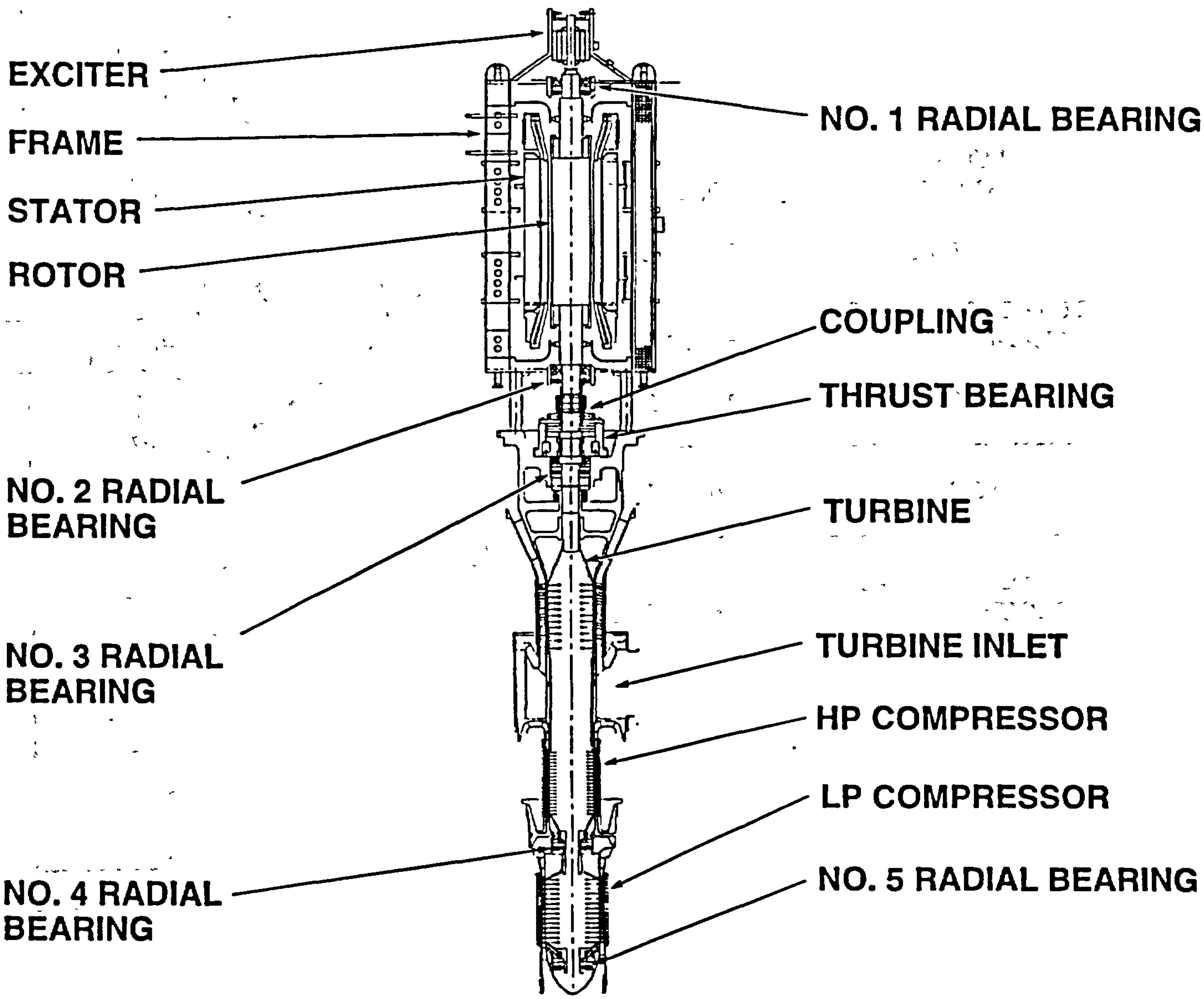

Fig. 4.3-2. Vertical turbomachine view

GENERATOR	
STATOR	600,000 LBS
ROTOR	88,000 LBS
TURBOCOMPRESSOR	
STATIC STRUCTURE	80,000 LBS
ROTOR	28,000 LBS
TOTAL	796,000 LBS
TOTAL ROTATING GROUP	116,000 LBS

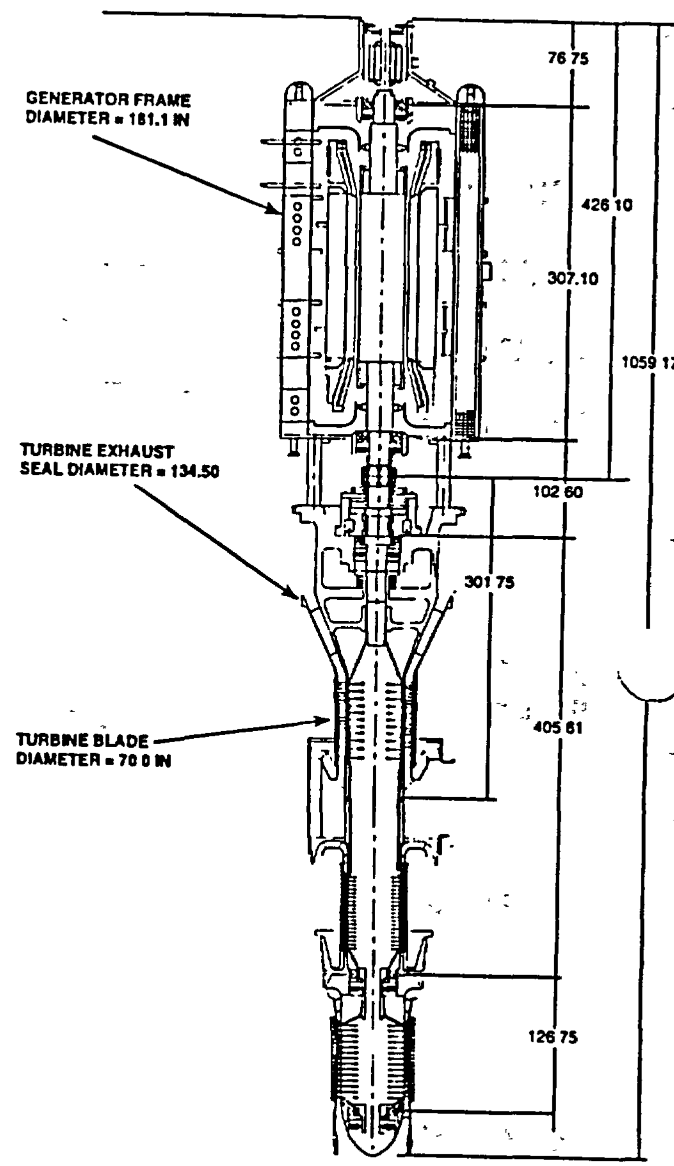

Fig. 4.3-3 Turbomachine Dimensions

TABLE 4.3-1
COMPARISON OF TURBOMACHINE FEATURES

Parameter	Nuclear Gas Turbine	Heavy Duty Industrial GT	Aeroderivative Gas Turbine
Plant	GT-MHR	MS9001F (GE)	LM6000 (GE)
Power, MW(e)	286	226	42
Working fluid	Helium	Air	Air
Thermodynamic Cycle	Recuperated and Intercooled	Simple cycle	Simple cycle
Turbine inlet temperature, °C (°F)	850 (1562)	1288 (2350)	1243 (2270)
Compressor pressure ratio	2.8	15	30
Mass flow rate, kg/sec (lb/sec)	320 (705)	613 (1351)	123 (271)
Specific power, kW(e)/kg/sec	895	370	340
Compressor			
Number of stages	14 LP + 19 HP	18	5 LP + 14 HP
Maximum tip diameter, mm (in.)	1683 (66)	2515 (99)	1372/737 (54/29)
Number of blades, LP comp.	2961	–	–
Number of blades, HP comp.	4366	–	–
Turbine			
Number of stages	11	3	2 HP + 5 LP
Maximum tip diameter, mm (in.)	1778 (70)	3251 (128)	889/1321 (35/52)
Tip speed, m/sec (ft/sec)	335 (1100)	510 (1674)	476/249 (1562/817)
Blade cooling	Uncooled	Cooled	Cooled
Number of blades	1995	–	–
Rotational speed, rpm	3600	3000 (50 Hz)	10.225/3600
Shaft arrangement	Single shaft	Single shaft	Twin shaft
Bearing type	Active magnetic	Oil lubricated	Oil lubricated
Number of journal bearings	4	2	6
Machine orientation	Vertical	Horizontal	Horizontal
Overall length, m (ft)	27 (88.5)	14.5 (47.5)	4.5 (15)
Overall diameter, m (ft)	3.4 (11)	4.8 (15.7)	2.5 (8.2)
Overall turbocompressor weight, kg (tons)	53,000 (58)	3000,000 (330)	5600 (6.2)
Generator			
Installation	Submerged	External	External
Type	Synchronous	Synchronous	Synchronous
Cooling	Helium cooled	Hydrogen cooled	Hydrogen cooled
Year plant entering service	After year 2000	1991	1992

(to facilitate intercooling), and with the mid-plane turbine inlet duct, the single shaft machine is characterized by a long slender rotor. A lightweight and rigid rotor construction, resembling aeroengine practice, was chosen to minimize weight and ease critical speed concerns.

The two compressor assemblies are of welded construction and the turbine discs are bolted together. The weight of the turbocompressor rotor is 12,700 kg (14 tons), and the overall machine rotating assembly including the generator weighs on the order of 53,000 kg (58 tons). The overall turbomachine weight including rotor and stator components is 356,000 kg (398 tons). Burst shields are incorporated in the machine structure around the compressor(s) and turbine. These are located, such that, in the event of a disc or blade failure, the fragments will be contained within the machine casing. The turbocompressor static structure is supported from the semi-elliptical dome located in a plane below the generator. The rotating assembly is supported from the thrust bearing which is located between the generator and turbocompressor (see Fig. 4.3-4).

The turbocompressor utilizes materials that are in current use in industrial and aeroderivative gas turbines. Extensive studies were run on these materials in a helium environment at temperatures about 871°C (1600°F). Surface and microstructure stability after 10,000 hr, and creep rupture properties after 15,000 hr were investigated. Additional testing to confirm the material behavior in the presence of helium impurities may be necessary prior to final material selection.

<u>Compressor Aerodynamics</u>. Since axial compressor aerothermodynamic design techniques have been well documented, it is not the intent to describe detailed analyses in this report, but rather to outline how the fluid properties of helium influence the flow path geometries, and to emphasize that the dynamic procedures used are essentially identical to conventional air-breathing gas turbine practice. Details of the compressor and turbine are given on Fig. 4.3-5.

The choice of working fluid affects the turbocompressor primarily in two ways: (1) the number of stages for the attainment of the required pressure ratio and high efficiency, and (2) the machine size for a high pressure closed system. The specific heat of helium is five times that of air, and since the stage temperature rise varies inversely as the specific heat (for a given limiting blade speed), it follows that the temperature rise available per stage when running with helium will be only one-fifth that of air. This, of course, results in more stages being required for a helium compressor. The low pressure ratio in a highly recuperated closed Brayton cycle results in a

Support structure at top of turbocompressor reacts axial load of complete turbomachine to PCS internal structure

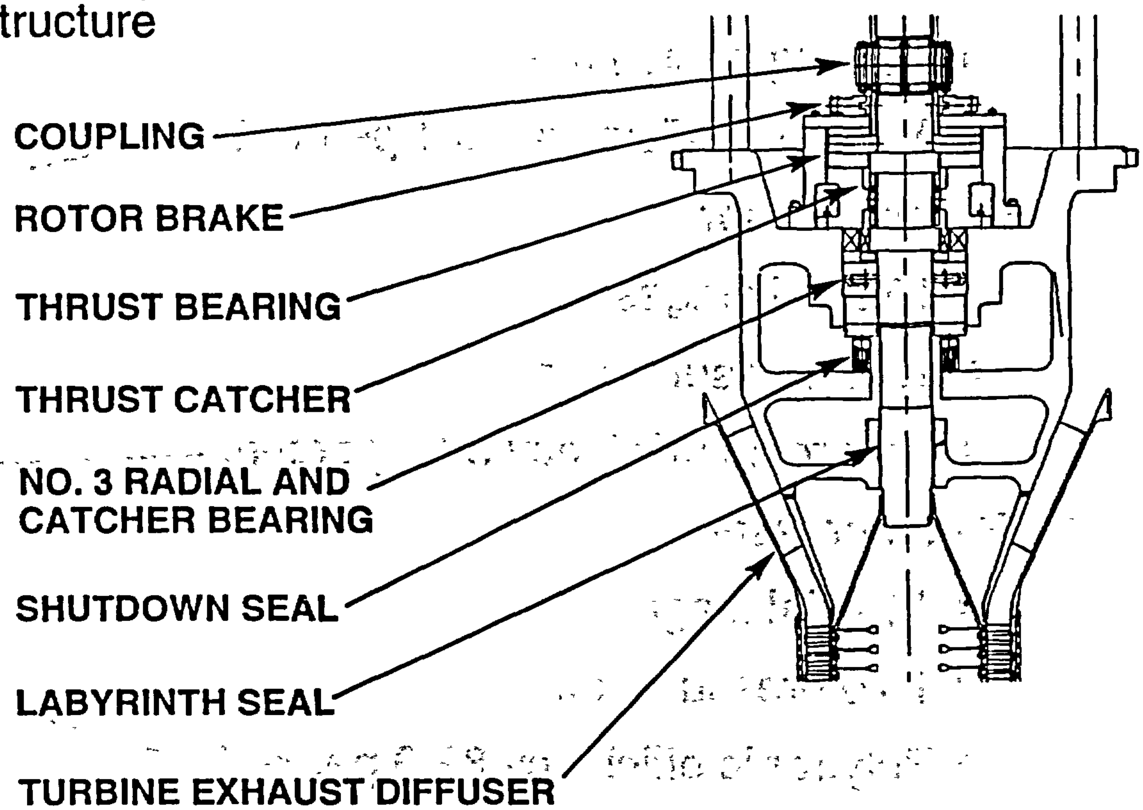

Fig. 4.3-4 Support Structure

- Turbine
  - 11 axial stages
  - 2.64 expansion ratio
  - Adiabatic efficiency 93.1 percent
- HP compressor
  - 19 axial stages
  - 1.70 pressure ratio
  - Polytropic efficiency 89.1 percent
- LP compressor
  - 14 axial stages
  - 1.70 pressure ratio
  - Polytropic efficiency 89.9 percent

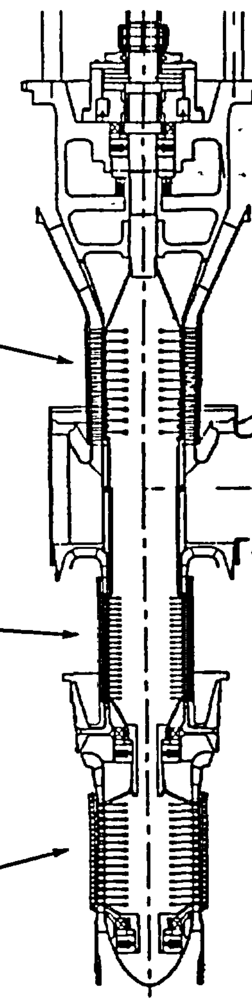

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Fig. 4.3-5 Compressor and turbine design

number of compressor stages that is comparable with existing air-breathing gas turbines and this is illustrated in Table 4.3-2.

Substitution of helium for air greatly modifies aerodynamic requirements by removing Mach number limitations. The problem then becomes that of trying to induce the highest possible velocities that stress-limited blades will allow. For the selected machine configuration (i.e., single shaft with synchronous generator) the compressor rotational speed is, of course, fixed at 3600 rpm. The size of the machine is thus dictated by the choice of blade speed, there being an incentive to use the highest blade speed commensurate with stress limits to reduce the number of stages, since the stage loading factor is inversely proportional to the square of the blade speed.

For the specified thermodynamic conditions, compressor design solutions were established and preliminary results are given in Table 4.3-2. Helium compressors for closed cycle gas turbines are characterized by small blade heights, high hub-to-tip ratios, and low aspect ratios. An important parameter is the rear stage hub-to-tip ratio, and an accepted upper limit for high efficiency compressors is about 0.90. With high pressure helium, the blade heights are small and end-wall losses become significant; thus, careful mechanical design is necessary to minimize tip clearance effects. While the end-wall effects have an adverse effect on efficiency, three factors that will partially offset this are: (1) very high Reynolds number (5×10^6), (2) very low Mach number (<0.40), and (3) close blade tip clearance for a machine not exposed to severe thermal transients. The compressor design given in Table 4.3-2 has high values of polytropic efficiency, acceptable gas dynamic loading factors, and expected surge margins of over 20%.

Turbine Aerodynamics. The properties of helium affect the turbine in very much the same way as they influence the compressor. That is to say for a given expansion ratio, the total number of stages for a helium turbine will be greater than for an air-breathing gas turbine. Because it is desirable to have as high a blade speed as possible in order to reduce the number of stages to a minimum, the most critical stress conditions are those of the first stage since the rotor blade temperature is at the maximum value.

The turbine blade centrifugal stress (for a given blade geometry) is proportional to the $rpm^2 \times$ annulus area, hence for a single shaft, 60 Hz machine, some flexibility is lost to the designer. From Table 4.3-2, it can be seen that an 11 stage turbine with very high adiabatic efficiency was established. With tip speeds conservative by modern gas turbine practice

TABLE 4.3-2
PRELIMINARY AEROTHERMAL DATA FOR TURBOCOMPRESSOR

Parameter	Low Pressure Compressor	High Pressure Compressor	Turbine
Rotational speed, rpm	3600	3600	3600
Number of stages	14	19	11
Efficiency across blading, %	89.9 (polytropic)	89.1 (polytropic)	93.1 (adiabatic)
Inlet and exit losses (Δp/p), %			
Inlet loss	0.10	0.20	0.10
Diffuser loss	0.55	0.55	0.55
Dump loss	0.15	0.15	0.15
Gas flow path data			
First stage			
— Tip diameter, mm (in.)	1684 (66.3)	1372 (54.0)	1707 (67.2)
— Hub diameter, mm (in.)	1466 (57.7)	1242 (48.9)	1367 (53.8)
— Blade height, mm (in.)	109 (4.3)	65 (2.55)	170 (6.7)
— Hub/tip ratio	0.87	0.906	0.80
— Tip speed, m/sec (ft/sec)	317 (1041)	258 (848)	322 (1056)
Last stage			
— Tip diameter, mm (in.)	1661 (65.4)	1372 (54.0)	1783 (70.2)
— Hub diameter, mm (in.)	1466 (57.7)	1242 (48.9)	1367 (53.8)
— Blade height, mm (in.)	97.5 (3.85)	65 (2.55)	208 (8.2)
— Hub/tip ratio	0.88	0.906	0.77
— Tip speed, m/sec (ft/sec)	313 (1027)	258 (848)	336 (1103)
Rotor blade length, mm (in.)	1735 (68.3)	1760 (69.3)	2032 (80.3)

(Table 4.3-1), the helium turbine is characterized by small blade heights (1995 blades). In fact, the diameter of the rear stage of the turbine is substantially smaller than a near equivalent power rated air-breathing industrial gas turbine. The smaller size is attributable to the very high specific power, since the enthalpy drop in the helium gas turbine is much greater than that in an open-cycle gas turbine.

With a turbine inlet temperature of 848°C (1559°F), turbine blade cooling is not necessary, and the turbine blades can be fabricated from a conventional nickel-base alloy. A conservative ground rule established for the turbomachine is that stress levels in the major subcomponents be commensurate with a plant operating life of 60 years. To meet this requirement, cooling of the turbine discs may be necessary. A preliminary analysis showed that the life goal can be met with a purge flow of approximately 1% (bled from the high pressure side recuperator outlet).

Bearings. The entire rotor (generator and turbocompressor together) is supported by an active magnetic bearing system. The initial rotating assembly design is based on the utilization of a five journal bearing system as shown on Fig. 4.3-6. This arrangement has been confirmed for rotor stability, with operation at the design point being between the second and third critical speeds, with adequate margin as shown on Fig. 4.3-7.

The magnetic bearing system incorporates considerable redundancy, the power supply for the primary bearings being backed-up by a second uninterruptible power source. Mechanical antifriction catcher bearings are also incorporated to prevent rotor damage in the unlikely event that both power supplies are lost. Details of the planetary radial catcher system is shown on Fig. 4.3-8.

While the rotor is heavier than in applications to date, the thrust bearing loads and peripheral velocities are bounded by operating experience. In recent years there has been substantial use of magnetic bearings in industrial applications. Today, over eight million hours of operating time have been accumulated on active magnetic bearings. Over 150 large turbomachines (e.g., gas compressors, turbines, turboexpanders) have run for more than 1.5 million hours (Ref. 4.3-2), and the GT-MHR machine will take advantage of this technology base as shown on Fig. 4.3-9.

- Designed to:
  - facilitate assembly
  - limit thermal growth
  - most importantly, obtain acceptable rotordynamics by -
    - * control scheme
    - * limit deflections
- Mechanical catcher bearing at each magnetic location

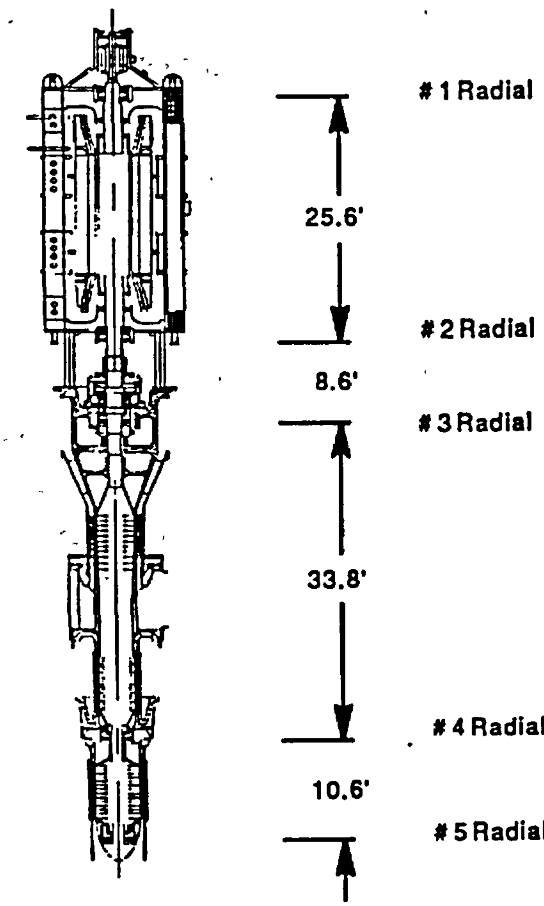


Fig. 4.3-6 Bearing layout

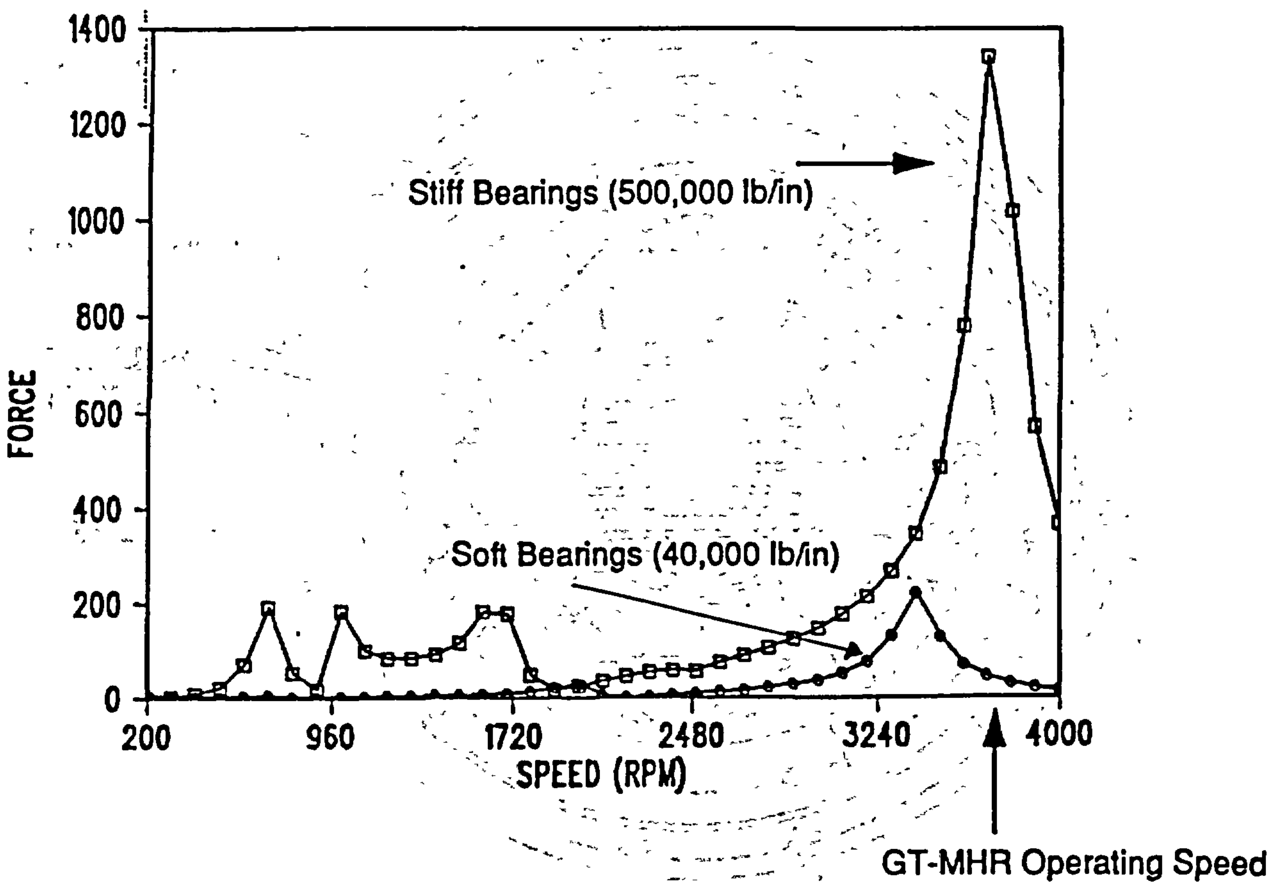


Fig. 4.3-7 Soft bearings with large damping provide acceptable response

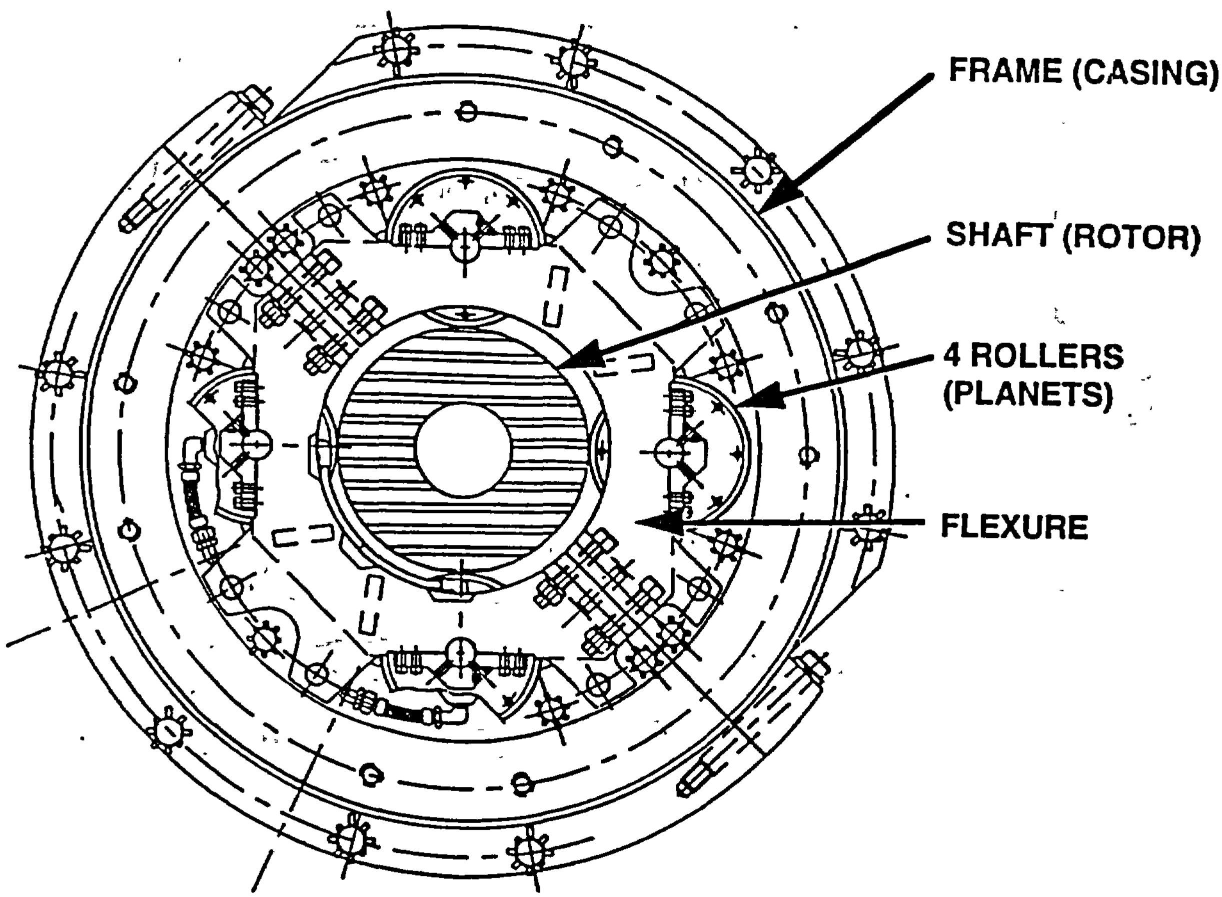
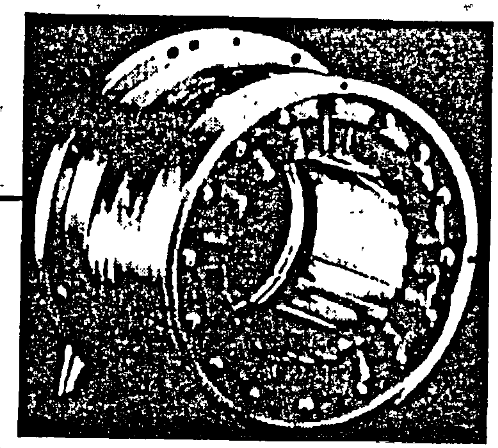


Fig. 4.3-8 MTI planetary radial catcher system

- Over 5500 units with over 8 million hours in operation
- Over 150 large turbomachines (eg. compressors, turbo-expanders) with over 1.5 million hours of operation
- 50 ft long, 10,000 lb vertical rotor on magnetic bearings tested on UF_6 centrifuge



- Operating Parameters

Operating Parameters	Demonstrated	GT-MHR Turbomachine
– Orientation	Vertical	Vertical
– Maximum speed, rpm	20,000	3600
– Shaft size, in.	26	24
– Rotor wight, tons	10	60
– Thrust bearing loading, lb/in^2	75	75
– Number of bearings	3	5

- Full size GT-MHR journal and thrust bearings will be tested before fabrication of prototype machine

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Fig. 4.3-9 Active magnetic bearings - key to high reliability and low maintenance

Seals. A dynamic shaft seal is incorporated between the turbine and the generator to keep the generator cavity free from radioactive contamination. This shaft labyrinth seal is supplied with purified helium and the buffer flow is split in two directions, some clean helium entering both the generator and turbine cavities. The capacity of this system will be sized to cover the full spectrum of plant operating conditions, including startup, shutdown, and transients. The vertical rotor, by using a center high pressure design, minimizes shaft seal requirements and provides balanced thrust conditions during full power operation.

The major helium turbocompressor components are being designed for the 60-year plant life, with scheduled removal (see Section 4.3.1.3) at approximately 7-year intervals for inspection and maintenance as required. The removal frequency is based on the experience from circulators in the gas-cooled plants in the United Kingdom, which are refurbished every 8 years, as well the excellent reliability of industrial turbomachinery used in industry. The 7-year value can be readily adjusted to be in concert with the core access schedule. To minimize plant downtime during refurbishment, a spare machine will be kept at the plant site to replace the machine that is removed. The unit removed would then be decontaminated and refurbished for future use. This maintenance schedule is considered conservative, since less wear is expected for the GT-MHR machine due to the use of magnetic bearings instead of oil bearings and the use of helium gas instead of combustion gases.

The results of a task force identifying seal concepts is given on Fig. 4.3-10. Segmented piston rings of the type shown on Fig. 4.3-11 were selected and their integration in the machine assembly is shown on Fig. 4.3-12.

The turbocompressor has several interfaces with static structures/components within the power conversion vessel. Sliding seals are necessary at these interfaces. The locations, temperatures, and pressure differentials are given in Table 4.3-3. These seals will be designed to (1) minimize leakage, (2) accommodate nonuniformities between the machine and its mating parts, (3) accommodate differential expansion and thermal distortions, and (4) accommodate turbomachine removal and replacement. Initial design work has shown that the requirements (in terms of size, temperature, pressure differential) are bounded by gas turbine industry experience, namely segmented piston ring types (retained by springs).

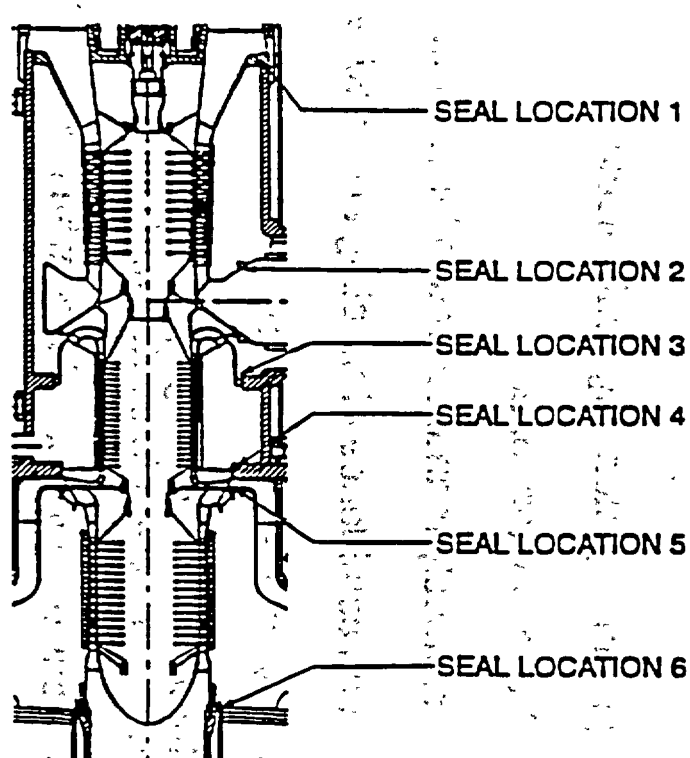
TABLE 4.3-3
SEALS REQUIREMENTS

Technical Data:

Seal Type	Segmented and spring loaded
Turbomachine replacement interval	7 years
Maximum leakage, kg/h (lb/h) (all seals)	5680 (12,500)

Description:

			Operating Pressure (psia)		Operating Temperature (°F)	
Location (see Figure)	Orientation	Diameter (in.)	Side A	Side B	Side A	Side B
1	Horizontal	126	379	1027	956	915
2	Vertical	54	1027	1012	915	1559
3	Horizontal	105	1042	1027	226	915
4	Horizontal	96	1042	624	226	83
5	Horizontal	90	629	624	225	83
6	Horizontal	72	629	371	225	80



- Segmented piston ring seal selected
  - Proven history of use
  - Previously manufactured in large diameters (104 in)
  - High confidence of meeting allocated leakage
  - Several material options
- Material selection is graphite seal on chrome carbide coated mating surface
  - Considerable experience with these materials
  - Wear is on seal that is removed with turbocompressor
- Redundant seal grooves and wearing surface
- Wearing surface can be re-machined if necessary

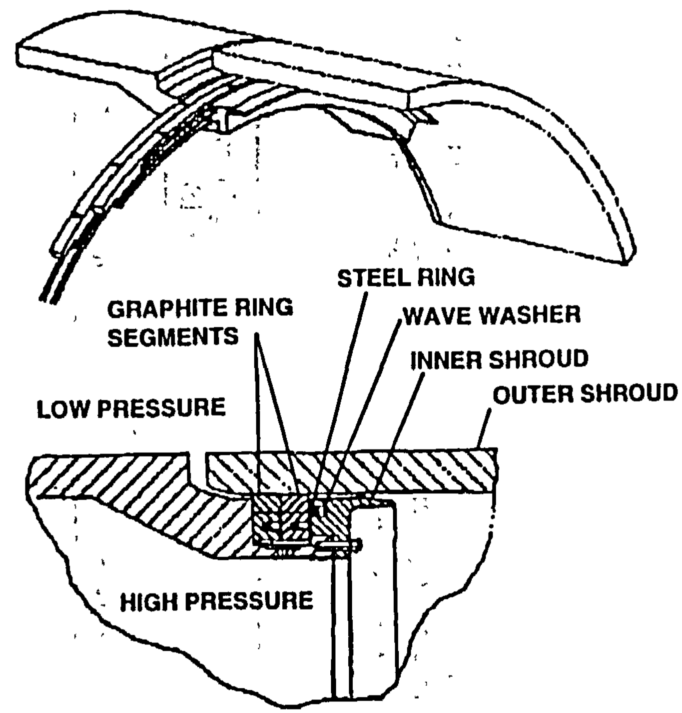


Fig. 4.3-10 Seals must meet and maintain plant efficiency requirements

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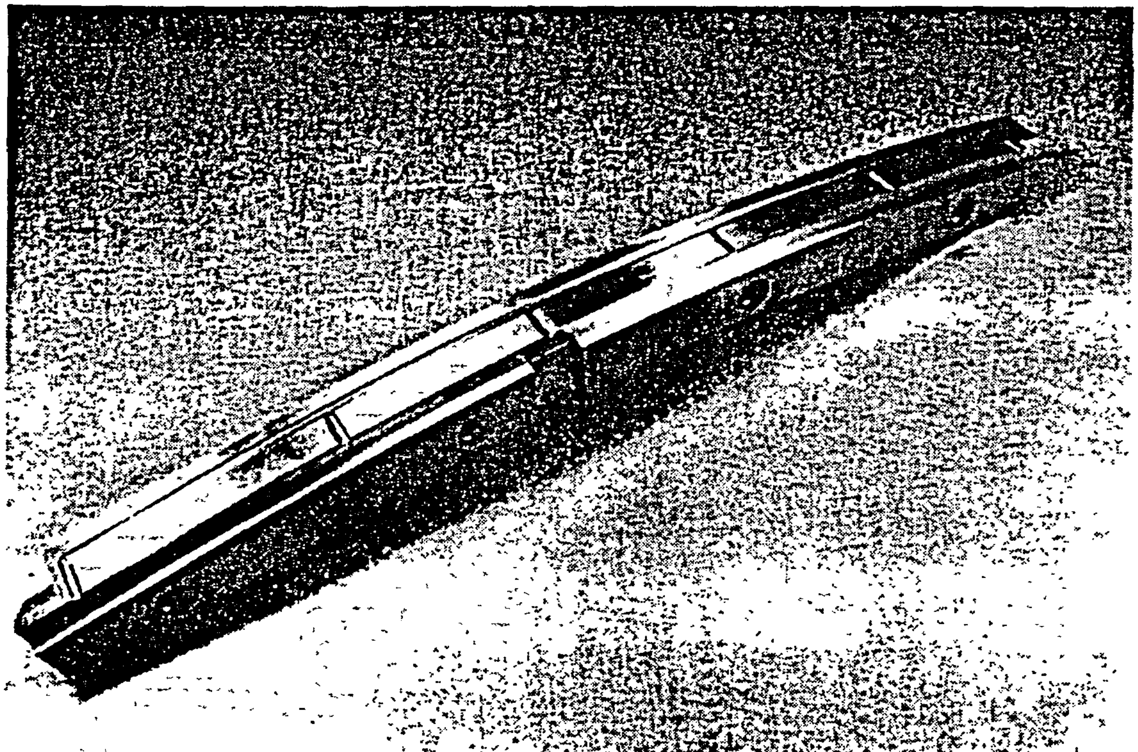

Fig. 4.3-11 Portion of segmented piston ring seal

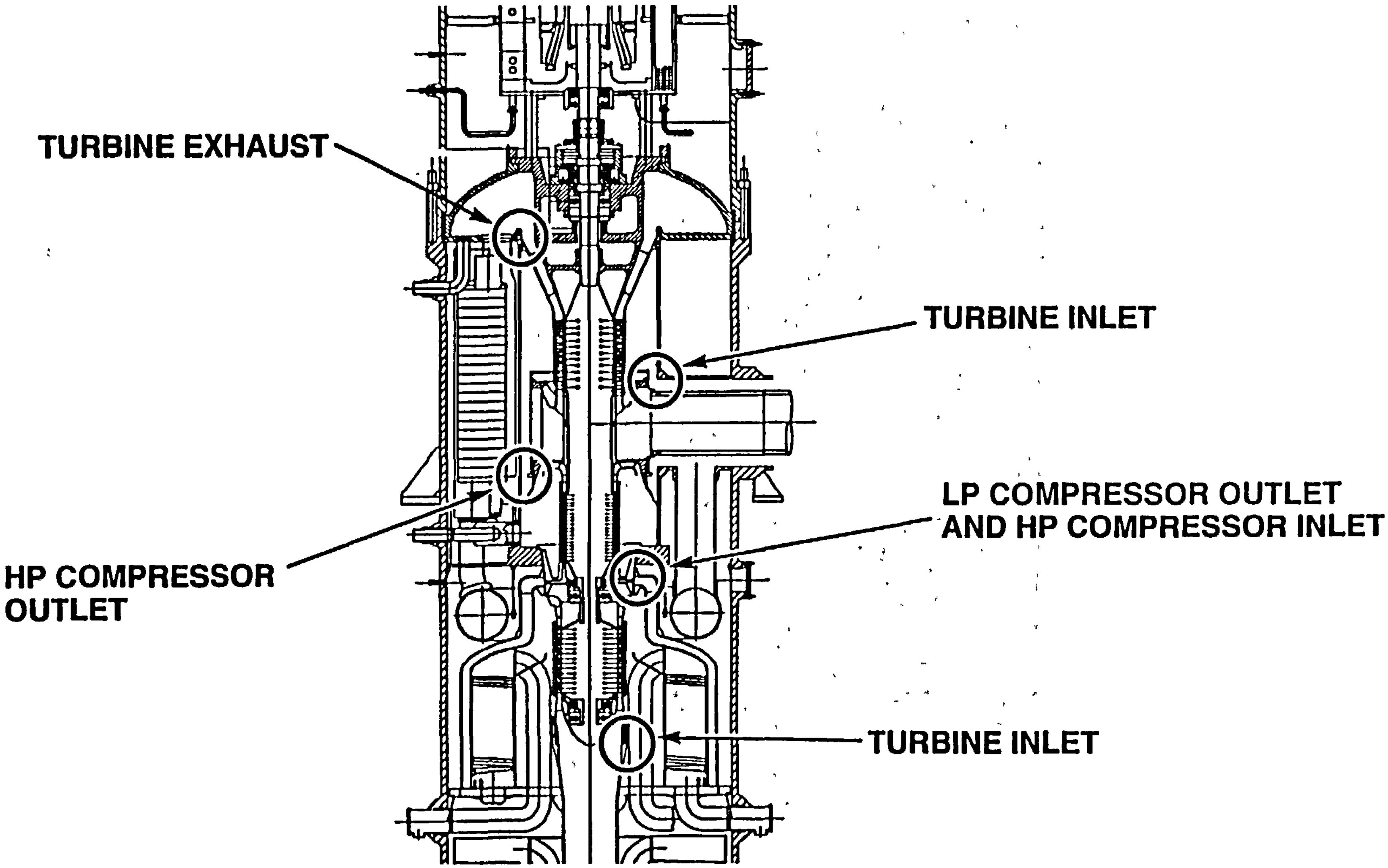

Fig. 4.3-12 Sliding seals control leakage from high pressure to low pressure regions

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The Stein Seal Company has made large seals for sodium applications in diameters comparable to that required for the GT-MHR turbomachine. These seals (typical cross section shown in Fig. 4.3-13) are segmented spring-loaded seals which will be tolerant of motion during assembly and will be able to accommodate some eccentricity. Data supplied by Stein Seal Company indicates that leakage from all six turbocompressor seal locations will be less than 0.5%.

4.3.1.2. Electrical Generator. The generator is a two-pole synchronous unit, and is rated at 333 MVA. To minimize development requirements, a major goal is to use conventional generator technology to the maximum extent possible, recognizing two major differences, namely: (1) vertical installation and (2) operation in a helium environment. The major reason for having a submerged generator is that it obviates having a shaft penetrating the primary pressure boundary.

Preliminary design features for the electrical generator are given in Table 4.3-4. A brushless exciter system with a shaft mounted exciter alternator and shaft mounted diode rectifiers is the most suitable arrangement for supplying and controlling the dc field current in the generator rotor. Details of the exciter are given in Table 4.3-5. A view of the submerged generator is given in Fig. 4.3-14. Initial studies have shown that the following changes to existing units would have to be accommodated for the GT-MHR application: (1) modifications to the stator frame and internal structures for the vertical installation and (2) stator and gap cooling with helium (instead of hydrogen or air). The 333 MVA generator efficiency has been estimated at 98.2%.

An axial flow fan is mounted on the rotor and this circulates helium within the generator cavity. Heat is removed from the electrical equipment (i.e., generator, exciter, upper magnetic bearing) by means of two (100% redundant) helium-to-water heat exchangers installed in the generator cavity. Operational experience from submerged electric motor circulator drives in the AVR and THTR plants has shown acceptable performance and reliability for operation in a helium environment.

The generator must be lifted prior to removal and replacement of the helium turbocompressor which is a scheduled maintenance activity. All of the electrical penetrations are located in the vessel wall surrounding the generator cavity. Major penetrations include: (1) electrical

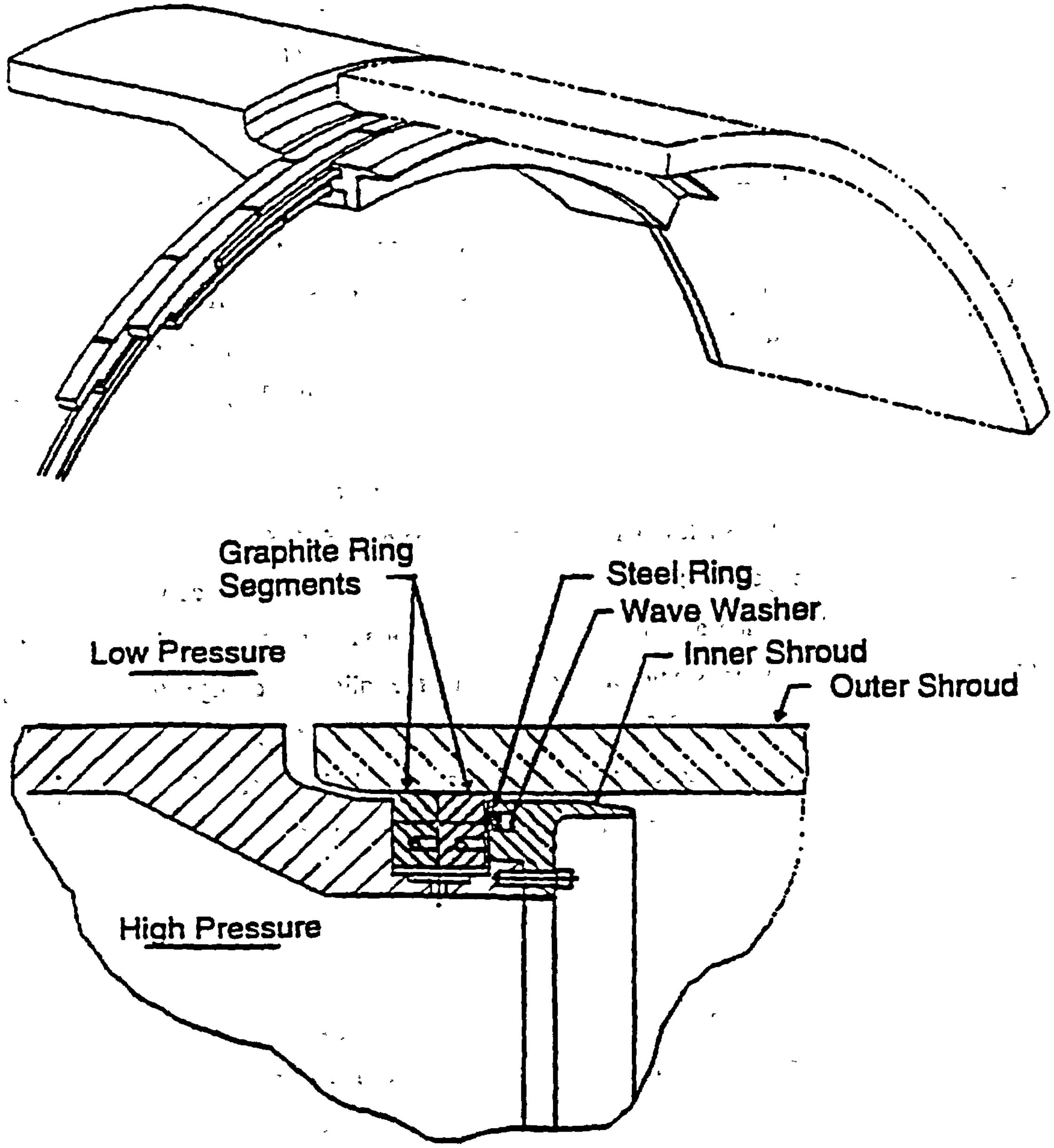


Fig. 4.3-13. Typical segmented piston ring seal

TABLE 4.3-4
GENERATOR GENERAL CHARACTERISTICS

OPTION	60 Hz
Speed	3600 RPM
Actual Design Overspeed	130%
Rated Power	286 MW
Rated Current	10224 A
Rated Voltage	19 KV
Rated Power Factor	0.85
Cold Helium Temperature	40°C (104°F)
Design Helium Pressure (absolute)	26.5 bars (384 psi)
Efficiency	98.2%
MAIN WEIGHTS AND DIMENSIONS	
Frame Diameter	4600 mm
Frame Length	7900 mm
Core Length	3800 mm
Core Diameter	3950 mm
Rotor Diameter	2470 mm
Number of Stator Slots	1000 mm
Rotor Inertia (MR^2)	66
Stator Weight	3800 m^2Kg
Rotor Weight	~162 tons (357600 lbs)
	~34 tons (75050 lbs)
REACTANCES AND TIME CONSTANTS	
Short Circuit Ratio	0.54
Xd	200%
X'd	40.6%
X"d	26.8%
X2	27%
X0	14.4%
T'd	0.7 s
T"d	0.03 s
T'do	3.5 s
Max. Short Circuit Torque	7.7 MmN
Short Circuit Current (peak)	126 kA

TABLE 4.3-5
EXCITER DESIGN PARAMETERS

EXCITATION	
Excitation System	Brushless Multiphase Asynchronous Exciter
Rated Rotor Voltage	350 V
Rated Rotor Current	3255 A
Exc. Current During S.F.C.'s Operation	< 1000 A
COOLING	
Stator	Conventional indirect axial-radial cooling
Rotor	Standard "Contraflow" rotor: direct cooling through axial ducts and radial vents
Expected Operating Temperatures	Stator: ~100 - 100°C (212 - 230°F) Rotor: ~70 - 80°C (158 - 176°F)
Class of Insulation	Class F: 155°C (311°F)
Generator Cooling Helium Flow	~20 m^3/s
Generator Cooling Water Flow	~500 m^3/h

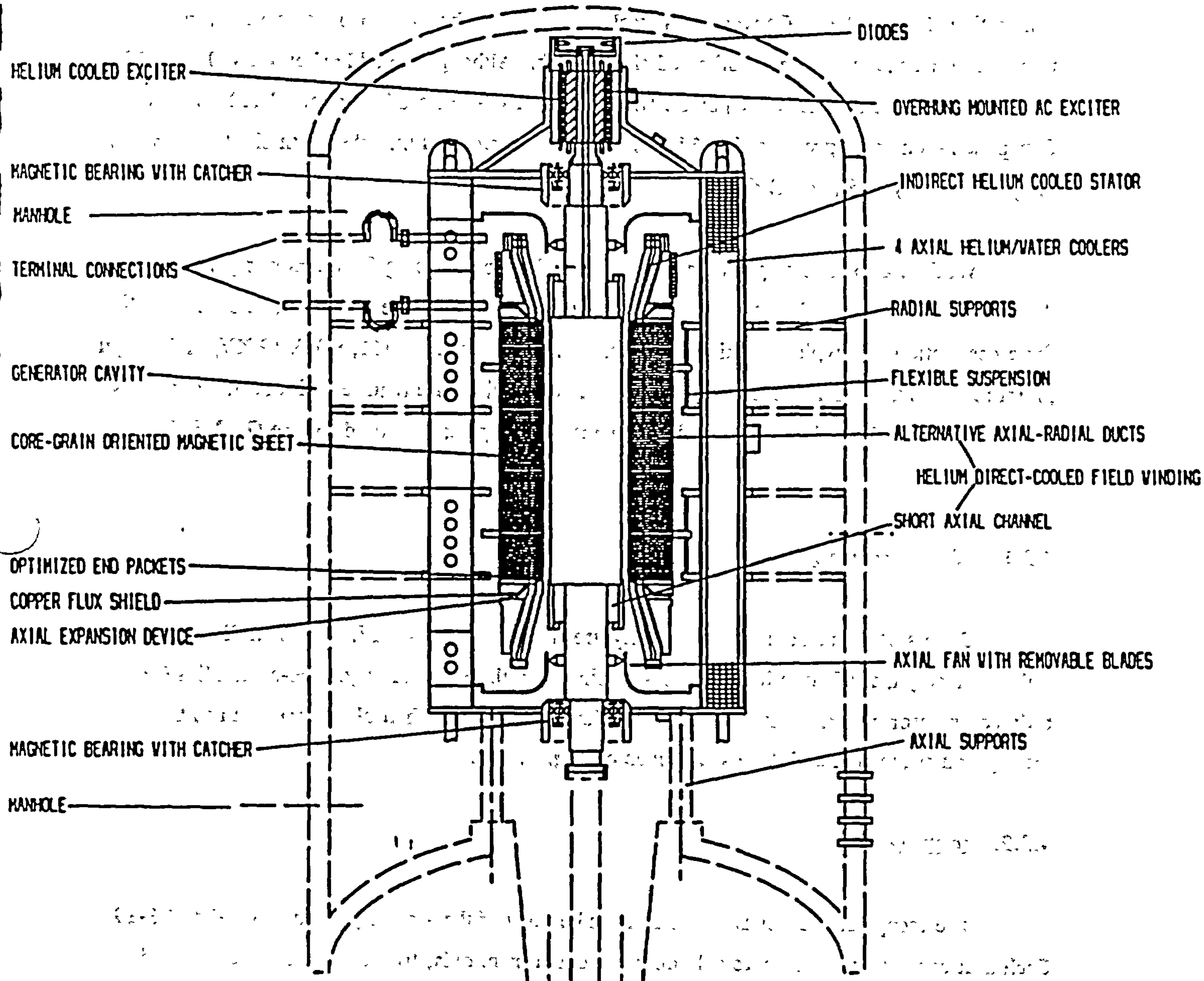


Fig. 4.3-14 Generator Arrangement

power, (2) power supply for the magnetic bearings, (3) water lines for the coolers, (4) instrumentation and diagnostic systems.

4.3.1.3. Power Conversion Vessel Penetrations. Design is currently in progress on the penetrations for the Power Conversion Vessel. Table 4.3-6 shows a list of the expected penetrations including the number and estimated size of each. Although the table shows a 470 mm (18.5 in.) penetration for the generator power, two alternative designs are being considered, one with four penetrations of approximately 254 mm (10 in.) diameter and the other with eight penetrations of approximately 356 (14 in.) diameter.

Work is also underway on the design of an electrical bushing for the power penetrations. Although commercial bushings of the type shown on Fig. 4.3-15 are available (see Fig. 4.3-16 for cross section of a typical bushing), bushings for the power level (11,000 A 19 KV) and design pressure of the GT-MHR are not available. More discussions are required with bushing vendors to assess solid bushing design and to determine the development required for the GT-MHR application.

4.3.1.4 Turbomachine Assembly

Details of the turbomachine assembly are shown on Fig. 4.3-17. The overall construction follows closely that of large industrial gas turbines. With two large major sub-assemblies (i.e., turbocompressor and generator) consideration has been given to their alignment, both in the factory and at the site, and details are given on Fig. 4.3-18.

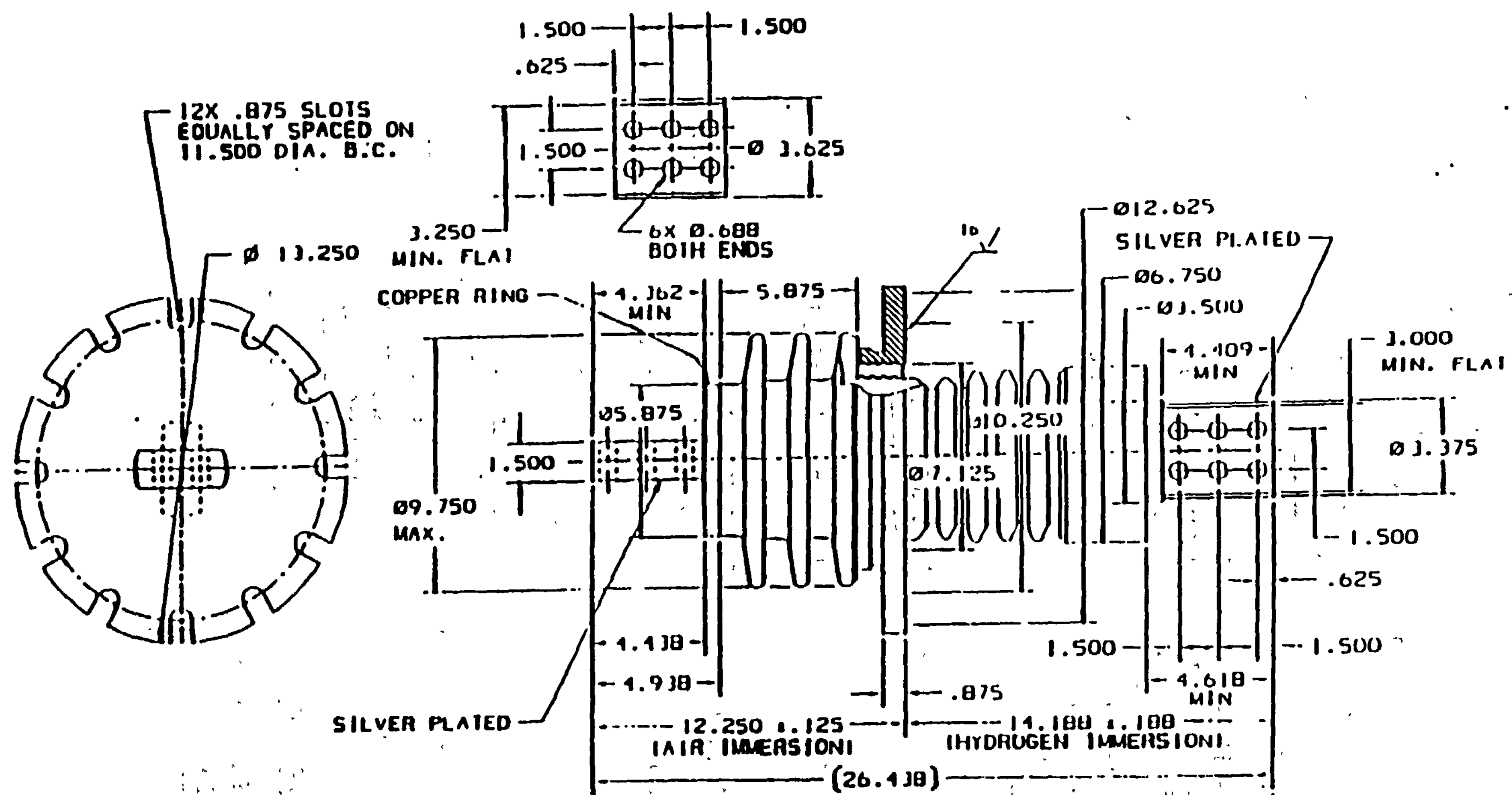
4.3.2. Recuperator

The recuperator consists of six units and a view of the assembly is given on Fig. 4.3-19. Each unit contains high pressure side inlet and outlet manifolds, triangular entry and exit end sections, and a counterflow center core section as shown on Fig. 4.3-20. High pressure helium coolant flow passes horizontally from the inlet to the outlet manifold through the end and center core sections. On the low pressure side, the inlet plenum is formed by the volume between the recuperator units and the adjacent support structure, while the outlet plenum is formed by the volume between the recuperator and power conversion vessel. High pressure helium flows horizontally from manifold to manifold through the end and center core sections. Exchange of

TABLE 4.3-6
GT-MHR ELECTRICAL AND WATER PENETRATIONS IN THE POWER CONVERSION SYSTEM VESSEL, GENERATOR CAVITY
[Penetrations elsewhere in the vessel (precooler water, duct pressure, etc.) not included.
Penetration sizes refer to diameter of hole in the metal.
Center-to-center distances should be at least twice the larger adjacent diameter.]

Number	Description	Size
At the top end of generator: Generator housing dome		
3	Exciter alternator phases, rated at 565 V, 371A	1 in.
3	Exiter neutrals, same ratings as the phases, externally tied	1 in.
2	Thrust bearings, four wires for position sensing[a]	1 in.
2	Thrust bearing, four power wires[a]	1-1/2 in.
2	Journal bearing No. 1, top, eight wires for position sensing[a]	2 in.
2	Journal bearing No. 1, top, eight power wires[a]	2 in.
3	Exciter temperatures, six wires[b]	1 in.
9	Diode surveillance	1/2 in.
At the upper end of the generator stator: Spool		
6	Generator power phases, rated at 18 kV, 11,000 A each	18.5 in.
2	Generator neutrals, same ratings as the phases, externally	18.5 in.
3	Generator temperatures, 18 wires[c]	2 in.
At the belt line of generator stator: Upper part of upper head, immediately below spool lower flange		
4	Water penetrations for (redundant) generator cavity coolers	12 in.
2	Journal bearing No. 2, turbine exit, eight wires for position sensing[a]	2 in.
2	Journal bearing No. 2, turbine exit, eight power wires[a]	2 in.
2	Journal bearing No. 3, turbine bottom, eight wires for position sensing[a]	2 in.
2	Journal bearing No. 3, turbine bottom, eight power wires[a]	2 in.
2	Journal bearing No. 4, mid-compressor, eight wires for position sensing[a]	2 in.
2	Journal bearing No. 4, mid-compressor, eight power wires[a]	2 in.
2	Journal bearing No. 5, bottom, eight wires each for position sensing[a]	2 in.
2	Journal bearing No. 5, bottom, eight power wires[a]	2 in.
3	Six temperature measurements around turbine, 12 wires[d]	2 in.
3	Six temperature measurements around upper compressor, 12 wires[d]	2 in.
3	Six temperature measurements around lower compressor, 12 wires[d]	2 in.
1	Three differential expansion measurements between turbocompressor stator and rotor, six wires	1 in.

[a]The two penetrations are for redundancy.
[b]Three measurements per phase.
[c]Nine measurements per phase.
[d]The three penetrations are for three different vertical levels.



CATALOG	MIN. CREEP DISTANCE (INCHES)	MIN. ARC DISTANCE (INCHES)	AMPS	K.V. CLASS	VENDOR REF. OUTLINE DWG.
181035B8	11.875	5.375	10,000	15	T015J1000SA

MAY BE PURCHASED FROM:
ABB COMPONENT DIVISION
POWER COMPONENT PLANT, ALAMO, IN

THIRD ANGLE PROJECTION

APPLIED PRAC 142A4900

GENERAL ELECTRIC COMPANY
SCHENECTADY N.Y.
HIGH VOLTAGE BUSHING
FIRST MADE FOR 7F/2
SIZE B | CAGE CODE | DWG. NO. 316B3806
SCALE 1/4 | CALC WT LBS | SHEET 1 OF 1

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Fig. 4.3-15 High voltage bushing

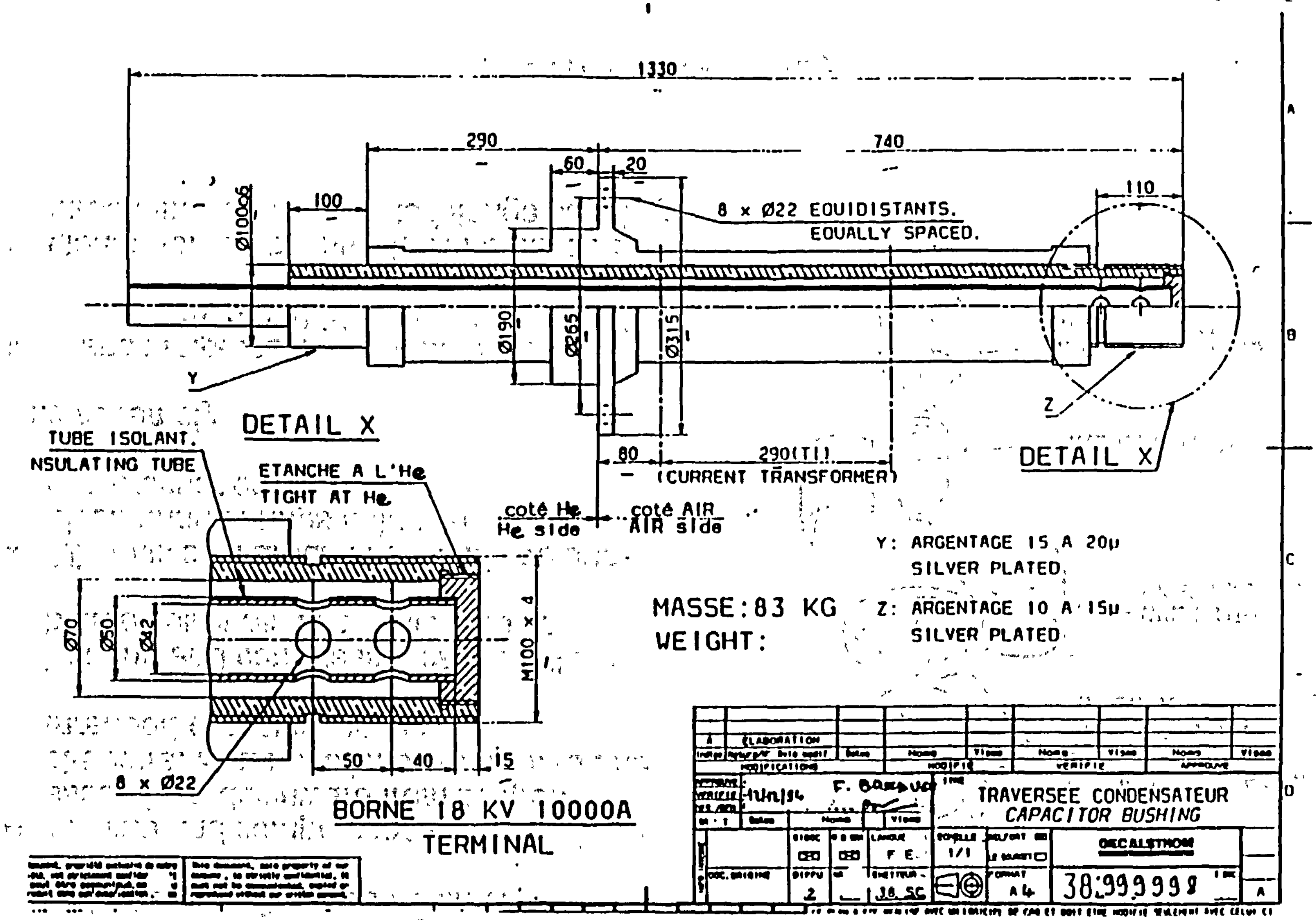

Fig. 4.3-16 Typical high voltage bushing cross section

- Factory assembly
  - Turbocompressor cartridge will be built starting with support structure
  - Turbine and compressor sections will be assembled downward from support structure. Rotor sections are splined and threaded to mating shafts
  - Turbine and compressor cases will have bolted splitlines along axis of rotor
  - All static seal areas of shell will be one-piece annular rings bolted to turbine and compressor cases
- Site assembly
  - Turbocompressor assembly will be installed as a cartridge into PCS vessel
  - Generator will be installed and mated to turbocompressor at bolted flange coupling

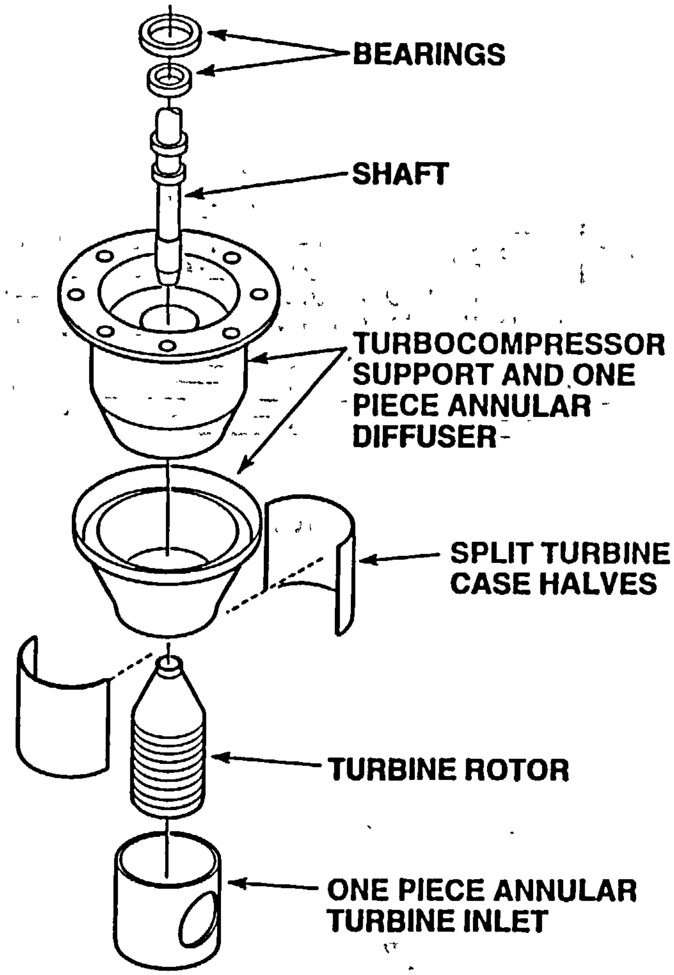

Fig. 4.3-17 Turbomachine assembly

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- Factory alignment
  - Turbocompressor rotor will be aligned in turbocompressor cartridge during assembly
  - Radial catchers and axial fixture will be engaged during shipping
- Site alignment
  - Turbocompressor will be aligned to generator

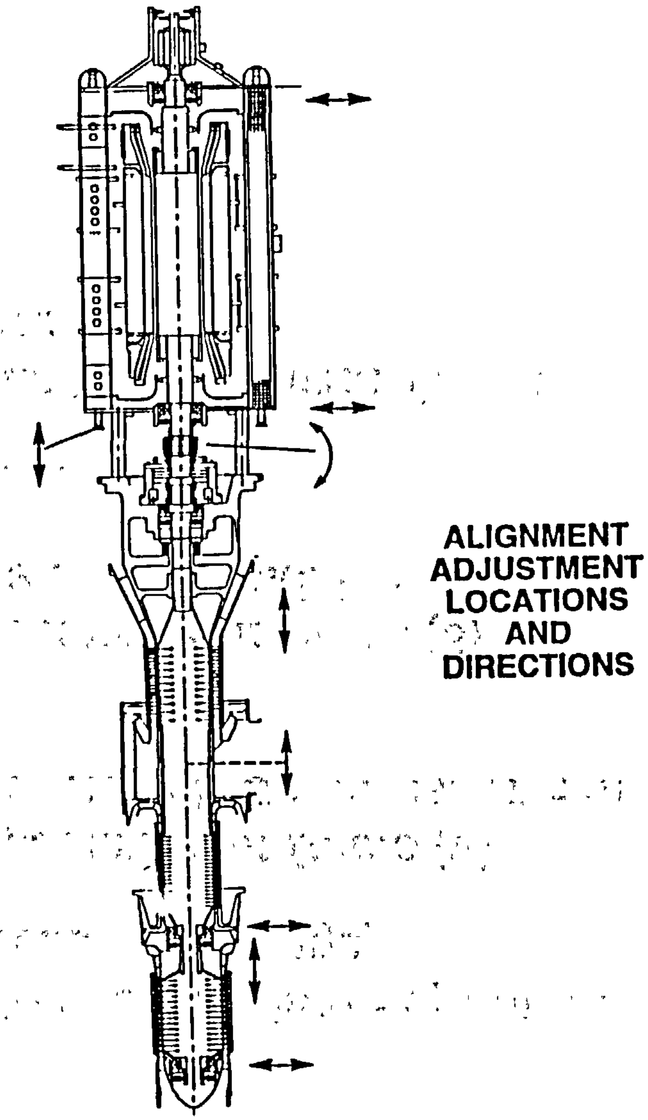

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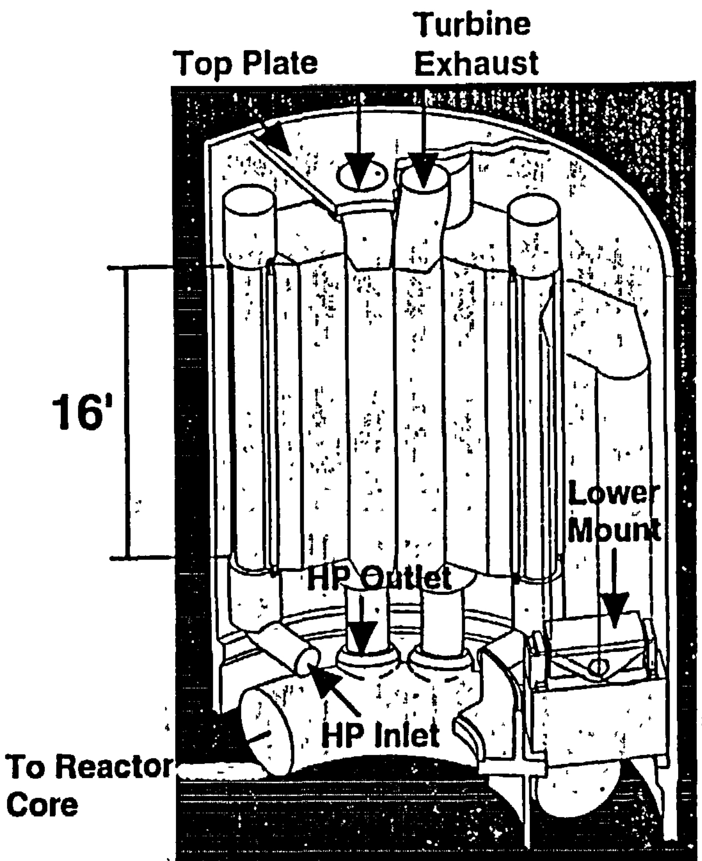
Fig. 4.3-18 Turbomachine alignment



Recuperator Consist of 6 Modules in Parallel (2 shown)

- **6 Modules/Lower Plate Supported from Vessel Wall (Lugs)**
- **High Pressure Inlet Ducts (6) Interface with HP Compressor Exit Diffuser**
- **High Pressure Exit Ducts (6) Interface with Toroidal Manifold**
- **Low Pressure Inlet**
- **Manifolds Interface with Turbine Exit Diffuser**

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Fig. 4.3-19 GT-MHR Recuperator assembly

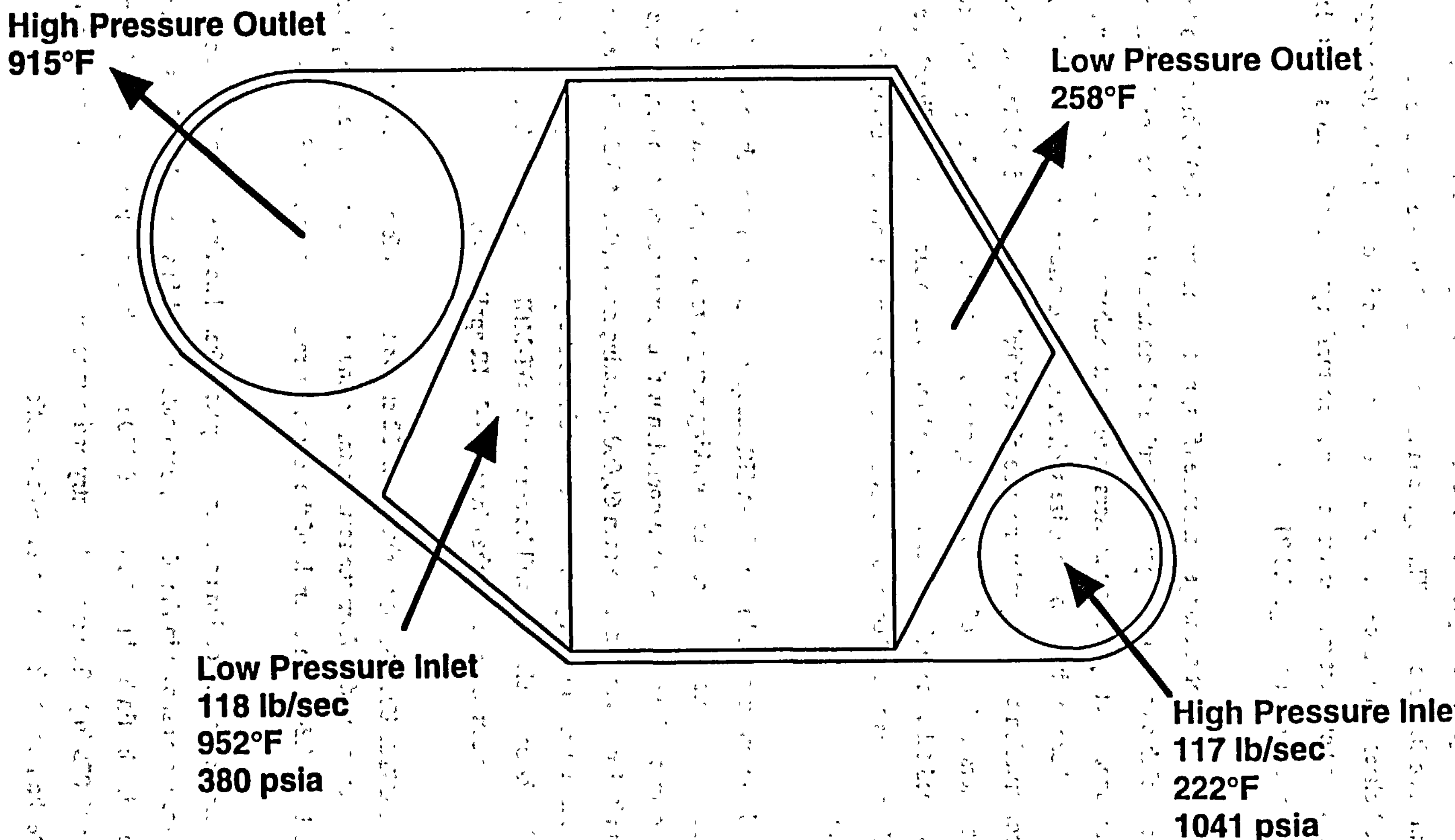

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Fig. 4.3-20 Recuperator module arrangement

heat between high and low pressure helium occurs primarily in the core sections, where flow occurs in opposite directions. The high and low pressure flows are separated from each other by horizontal plates. The space between the horizontal plates is subdivided by closely spaced fins, which provide both heat transfer surfaces and structural support for the plates. Details of the construction are given on Fig. 4.3-21.

The entire heat exchanger structure (fins, plates, and manifolds) is brazed to form a very strong, monolithic unit. The major life-limiting phenomenon in such heat exchangers is low-cycle fatigue brought about by thermal stresses in the heat exchanger. These plate-fin recuperator designs have been produced to minimize such stresses and offer very long life. This is achieved with a construction concept employing tube plates which are contoured to integrally form the sealing barriers at the side of the flow passages and around the manifold rings. This concept, using "formed tube sheets," has been employed for several years by Allied Signal in a variety of applications. This type of construction is essentially immune to acoustic and mechanical vibrations.

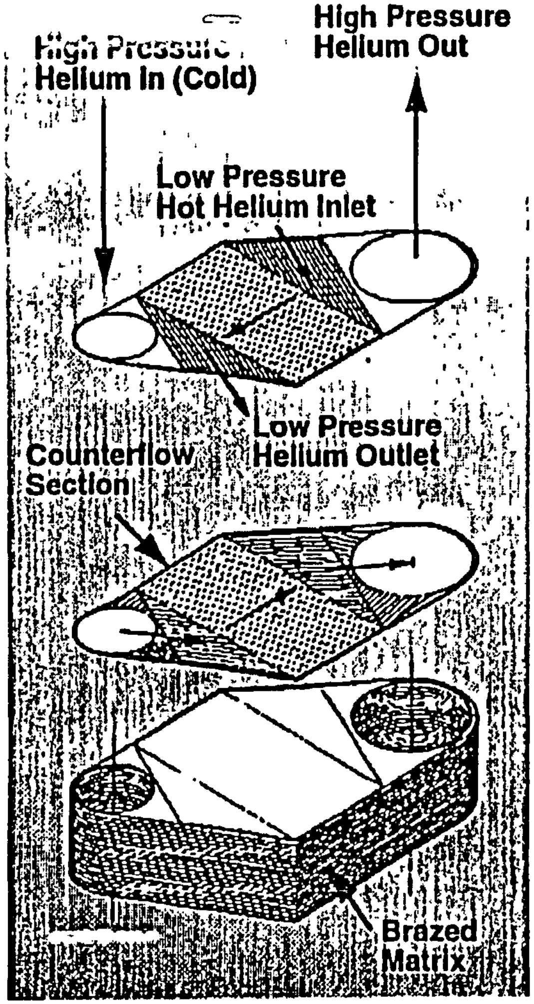
The techniques used in the GT-MHR recuperator design follow those already proven in several programs which have produced working recuperators for propulsion and pipeline gas-turbine engines. Over 60 units are in operation with commercial gas turbines, to date, these gas turbine units have averaged more than 60,000 operating hours (Ref. 4.3-3). In the existing applications (especially with propulsion engines), the recuperators see many more start/stop and low-load/high-load cycles than will be seen in the GT-MHR application. Also, propulsion system transients are much more severe than in the GT-MHR application.

4.3.2.1. Recuperator Structure. Figure 4.3-22 shows the plan form of the recuperator unit. Six of these units are used to form the recuperator assembly. The recuperator design parameters are given in Table 4.3-7. An example of the low pressure seal is shown on Fig. 4.3-23.

The recuperator design uses very compact offset plate-fin surfaces in the counterflow (center) section as shown in Fig. 4.3-24; both sides use 24 fins per inch surfaces. On the high pressure side, the fin height is 1.27 mm (0.050 in.); on the lower pressure side, the fin height is 1.91 mm (0.075 in.). The triangular entry and exit sections employ plain (nonoffset) fins to distribute the flows to/from the counterflow section.

TABLE 4.3-7
RECUPERATOR DESIGN PARAMETERS

Module rating, MW(t)	600
Recuperator modules minimum inner diameter, m (in.)	3.56 (140)
Recuperator modules maximum outer diameter, m (in.)	7.47 (294)
Recuperator stack height, m (in.)	4.91 (193)
Material	316L
Core weight, kg (lb)	19,500 (42,900)
Unit weight, kg (lb)	27,300 (60,000)
Hot side fin height, mm (in.)	1.91 (0.075)
Cold side fin height, mm (in.)	1.27 (0.050)
Fin thickness, mm (in.)	0.203 (0.008)
Fins per unit length, ($in.^{-1}$)	(24)
Flow rate, kg/s (lbm/s)	322 (708)
Hot side inlet/outlet temperatures, °C/°C (°F/°F)	510/131 (950/268)
Cold side inlet/outlet temperatures, °C/°C (°F/°F)	112/490 (233/915)
Hot side inlet/outlet pressures, MPa/MPa (psia/psia)	2.65/2.62 (384/380)
Cold side inlet/outlet pressures, MPa/MPa (psia/psia)	7.22/7.15 (1047/1036)
Effectiveness, %	≥95
Overall design Δp/p, %	≤2



- Matrix Assembled From Alternating Layers of the Following:
  - Compact Offset Fins in High Pressure Passage
  - Separating Plate (Tube Plate)
  - Compact Offset Fins in Low Pressure Passage
- Low Compactness Fins in the Inlet and Outlet Sections
- Integrally Formed High Pressure Manifolds
- Matrix Assembly Furnace Brazed to Give Basic Recuperator Module Element (Size Determined by Fabrication Considerations)
- Unit Assembled Using Multiple Module Elements to Meet Required Thermal Duty

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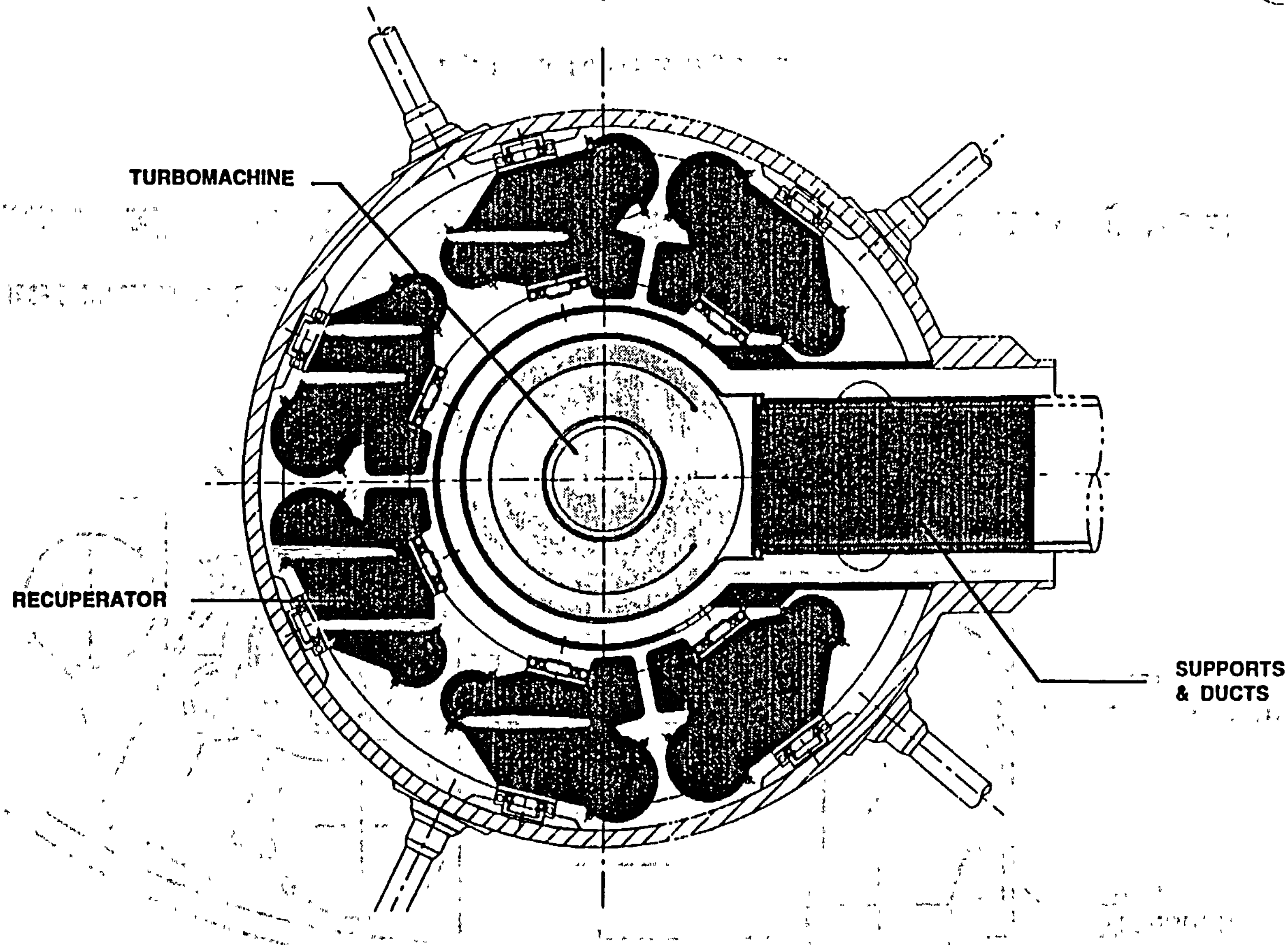
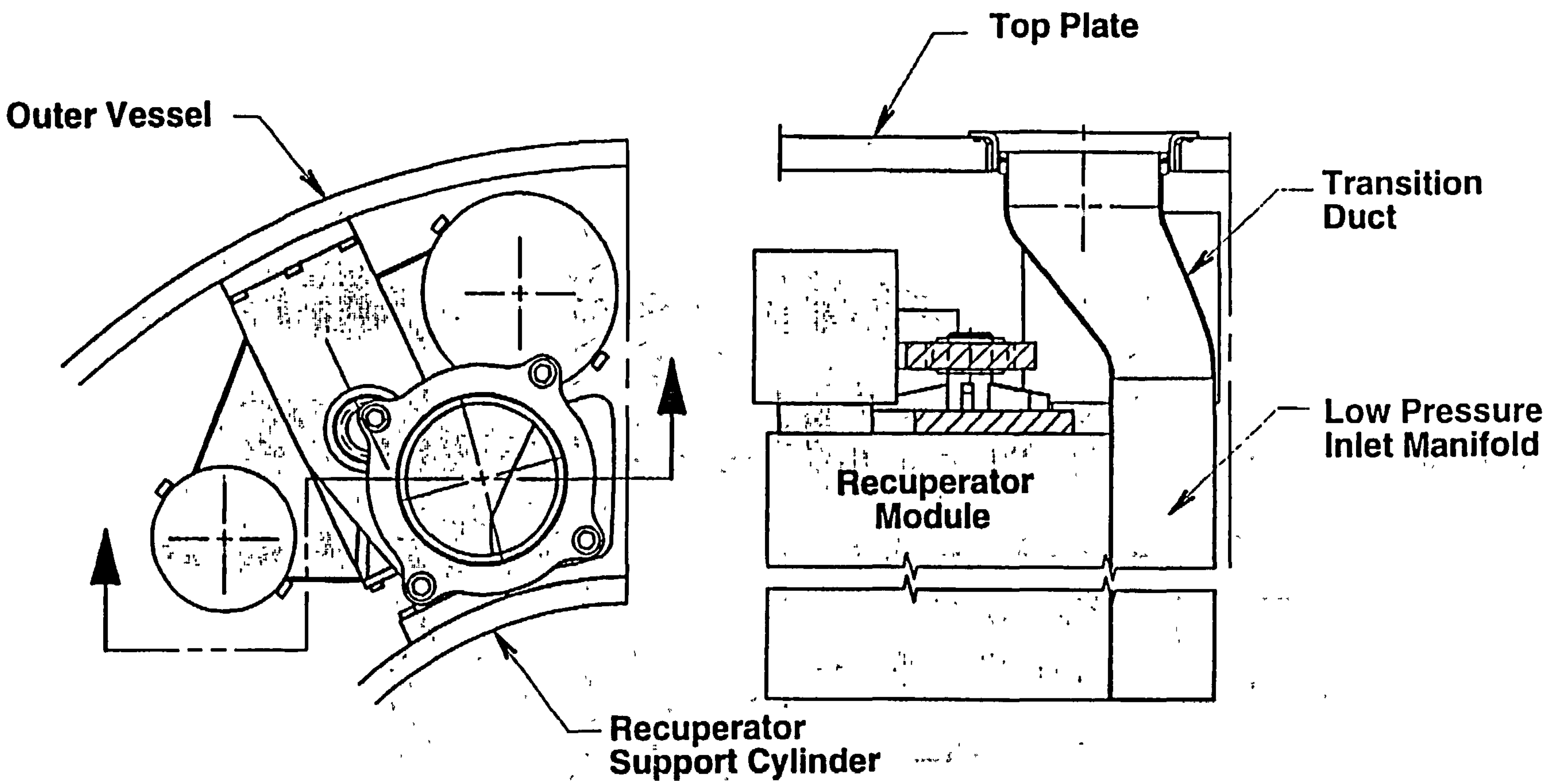
Fig. 4.3-21 Plate-fin recuperator construction



PLAN VIEW AT HOT DUCT ELEVATION

Fig. 4.3-22 Recuperator arrangement within vessel



- **Inlet Manifold Integral with Recuperator Module**
- **Gas Sealing at Top Plate Using Segmented Piston Ring Seal**

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Fig. 4.3-23 Low pressure gas seal

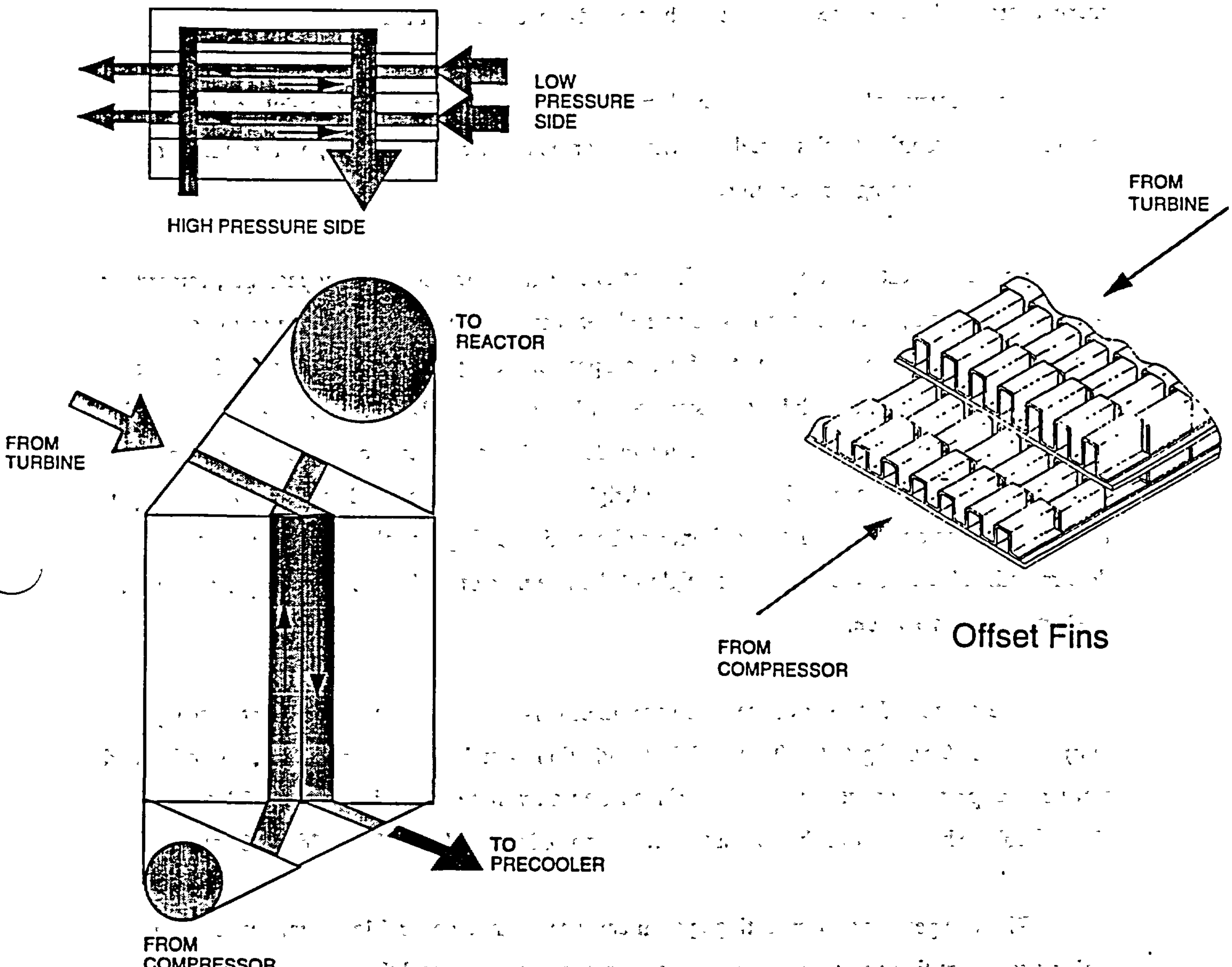

Fig. 4.3-24 Fin configuration in the recuperator

A bellows assembly is provided at each end of every manifold to control the load imparted on the module at the manifold end due to: (1) the pressure differential, (2) the relative thermal growth between the recuperator module the distance between the centerlines of the two manifolds in each module is 175 cm (68.76 in.), and the inlet/outlet ducts, and (3) the relative thermal growth between the module and the tie rods (two per each manifold).

The material of construction for all parts of the recuperator is 316L stainless steel. This low carbon, austenitic stainless steel was chosen for its excellent brazability, and its adequate strength at the operating temperatures.

In the fabrication of most plate-fin heat exchangers, the various flow passages, formed by the contoured tube plates and the fins contained between them, would be stacked one upon another and brazed into a single unit. If the recuperator were produced in one integral unit, the height of the recuperator module (the "stack height") would be 4.91 m (193.3 in.). Because of braze furnace considerations, the recuperator modules will be formed from a number of separately brazed units of approximately 76 cm (30 in.) height which will be welded together with appropriate fittings. The number of individual units to be used in a single stack has not yet been determined. However, the final stack height of the recuperator will not be much larger than the 4.91 m (193.3 in.) value.

The calculated weight of the bare core (thermally active portions of one heat exchanger unit) is about 19,500 kg (42,900 lb). With the addition of end sections, manifolds, mounting and mating duct provisions, etc., the weight of a single unit will be approximately 27,300 kg (60,000 lb). The weight of the six units will be approximately 163,000 kg (360,000 lb).

The recuperator unit mounting system consists of an upper and lower mount, each of which extends radially between the recuperator support structure and the power conversion vessel. The deadweight is supported by the lower mount The lower mount also reacts loads in the horizontal plane. The mount at the top end of the unit reacts loads in the horizontal plane only, but not in the vertical plane. This allows relative thermal growth between the unit and its supports. The mounts have the ability to rotate to accommodate the differential thermal growth across the width of the core.

4.3.2.2. Helium Flow Through Recuperator. The several fin-containing flow channels in the plate-fin recuperator are stacked one upon another, alternating between hot stream and cold stream passages. Helium flow is distributed to these various passages from the connecting ducts by manifolds (sometimes called headers) which are essentially conduits that run perpendicular to the planes of the flow passages, and which deliver helium to, or withdraw helium from the various passages. This flow path is illustrated in Fig. 4.3-21. Based upon the overall flow arrangement of (1) flow into the inlet manifold, (2) flow through the heat exchanger core, and (3) flow out of the outlet manifold, the terms of "Z-flow" manifolds and "U-flow" manifolds are used. In a U-flow configuration, the fluid enters the manifold at the same end of the heat exchanger stack. In Z-flow, the fluid would exit at the other end.

The effectiveness of the recuperator is 0.95 with an overall pressure drop of 2% of the inlet pressures ($\Delta p/p$). In order to attain this high effectiveness, it is necessary that the flow distribution to the various stacked passages be very close to uniform. Any non uniformity in flow distribution reduces the inherent ability of the heat exchanger core in reaching its intended performance. U-flow manifolds have a theoretical advantage over Z-flow manifolds, and are used for the high pressure flow in the GT-MHR.

For the low pressure helium flow from the turbine, the flow enters the annular recuperator envelope at the top of the array of heat exchangers. The hot helium flow is then directed downward in a plenum between the recuperators and support structures. The hot flow enters the recuperator passages, transfers heat to the cold, higher pressure stream, and exits into the relatively large volume between the recuperator ring and the vessel wall. The basic nature of this flow arrangement resembles a Z-flow manifold system. In general, for high effectiveness applications, Z-flow manifold arrangements should be avoided. In this application, the areas available for the distribution and collection of the hot flow are large enough that plenum pressure drops are very small, allowing the attainment of 0.95 effectiveness.

With this recuperator placement, the hot turbine outflow is also contained between the recuperator ring and the turbocompressor shroud. In this manner, hot helium does not touch the power conversion vessel walls. The cooled, lower-pressure helium, which exits the recuperator modules and flows downward in the space between the modules and the power conversion vessel wall, will keep the vessel wall within a relatively low temperature range.

4.3.3. Precooler and Intercooler

The precooler and intercooler designs are very similar. They are both of helical coil, finned tube configuration with the shell-side helium flow downward, counterflow to the tube-side water flow. These helical coil designs make maximum use of the allocated volumes with fewer although longer finned tubes than in straight tube designs. The tube bundles are totally drainable and incorporate individual tube circuits which are continuous from inlet tubesheet to outlet tubesheet. The tube bundles are designed in four interleaved sections and headered at four locations to reduce the header design complexity. The tubes are externally finned and have constant inside diameter and thickness. Therefore, each tube circuit is inspectable and pluggable from outside of the power conversion vessel. The tubes are supported by radially-oriented drilled plates or by built-up scalloped bars supported from the power conversion vessel and the central support cylinder. The material of construction for the tubes, shrouds, and support plates is low chrome-moly ferritic steel (1/2 Cr-1/2 Mo). The general arrangement of the precooler and intercooler is given in Fig. 4.3-25. The pertinent parameters of the bundles are given in Table 4.3-8.

The helium flow from the recuperator is downward through the annulus between the intercooler and the vessel shell. It enters the top of the precooler flows downward through the precooler, and turns upward to the inlet of the low pressure compressor. The helium leaving the low pressure compressor is routed downwards to enter the top of the intercooler where it flows downward through the heat exchanger, then turns upward to the inlet of the high pressure compressor.

The intercooler and precooler assemblies are supported at the vessel wall and inboard by a central support. This support is a cylindrical structure which is designed to transfer the precooler and intercooler loads to the vessel bottom head and to channel the coolant flow from the precooler outlet to the LP compressor inlet. The central support has also the function of providing the mating surfaces for the sliding seal located at the LP compressor inlet structure.

The water flow enters the bottom of the precooler and intercooler through the lead-in tubes and flows helically upward, producing cross-flow/counter-flow in the heat exchangers. The heated water exits the heat exchangers at the top via lead-out tubes. The water enters and exits the tubes through four inlet and four outlet tubesheets for each heat exchanger. The tubesheets

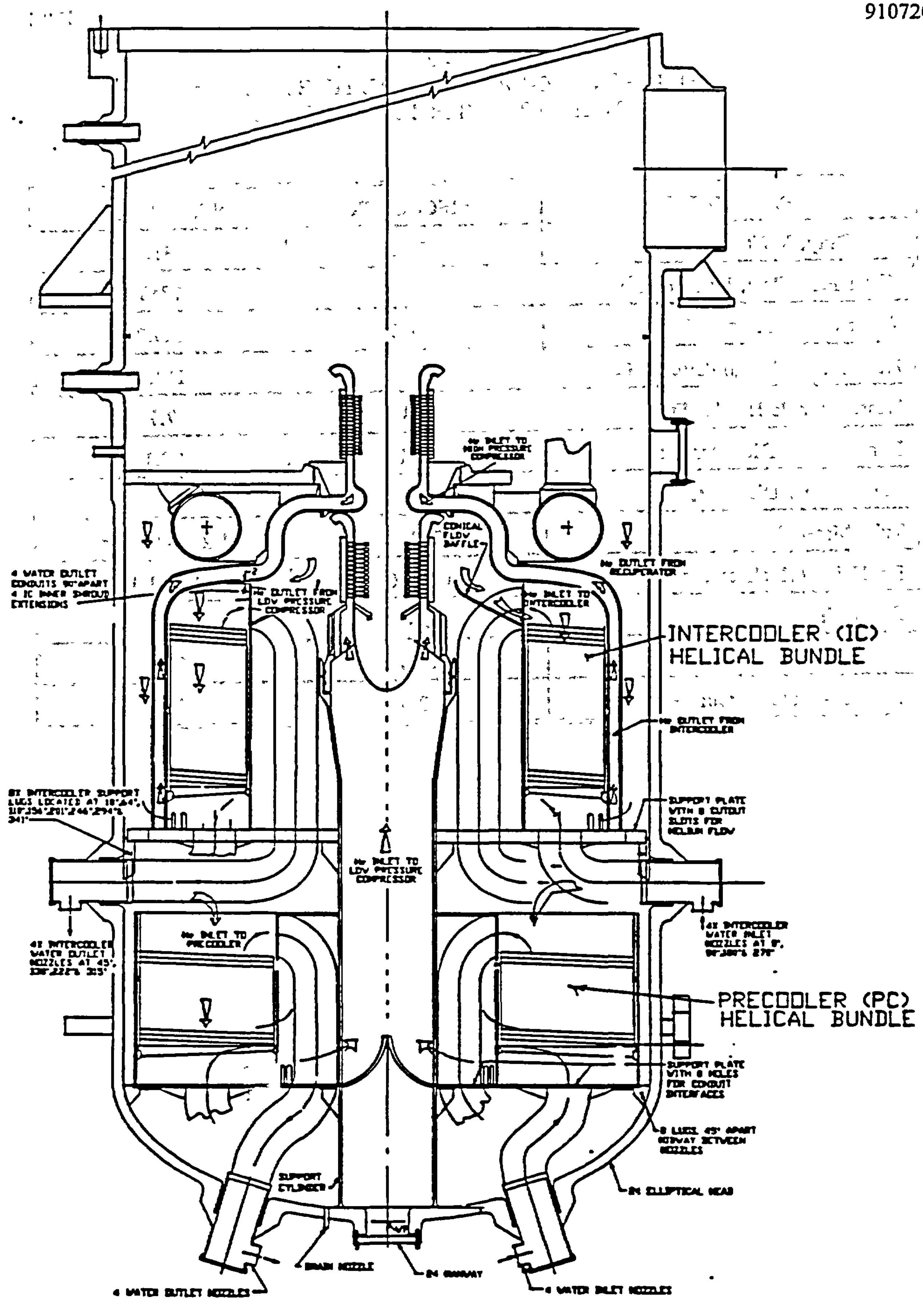

Fig. 4.3-25 600 MWt PC/IC arrangement

TABLE 4.3-8
PRECOOLER/INTERCOOLER HELICAL TUBE BUNDLES
FULL POWER (100%) THERMAL SIZING DATA

PARAMETER	PRECOOLER	INTERCOOLER
Heat Duty, MWt	166.8	131.4
Water Flow Rate, lbs/hr ($x10^3$)	7843	7843
Water Outlet Temp., °F	141.3	125.7
Heated Tube Length/Circuit, Ft	125.3	114.3
Heated Bundle Height, Ft	4.4	7.7
Bundle Outer Diameter, Ft	23.1	20.1
Bundle Inner Diameter, Ft	10.6	13.0
Tube Material	1/2 Cr-1/2 Mo	1/2 Cr-1/2 Mo
Fin Height/Thickness, in.	0.125/0.012	0.125/0.012
Fins/Inch	30	30
Shellside Pressure Drop, psi	1.58	2.34
Total Tubeside Pressure Drop, psi	40.0	35.0

are located at the inlet and outlet nozzles in the power conversion vessel as shown in Fig. 4.3-26 for the precooler. A wet cooling tower, which is isolated by an intermediate cooling water loop, provides the heat sink for the precooler and intercooler service water.

Two possible concepts for supporting the helical tube bundles are shown in Figs. 4.3-27 and 4.3-28. The first concept (Fig. 4.3-27) represents a drilled radial support plate concept where the support plates are equally spaced around the circumference and are radially free to move. Wear protection devices are installed at each tube/support plate interface. These plates are supported at the lower end by means of wagon-wheel type supports. The second concept (Fig. 4.3-28) shows a scalloped bar tube support concept consisting of scalloped vertical strips and wear rings that make up the tube supports. Each vertical support is made up of three strips which fit together to completely capture the helical tubes and wear rings. The arrangement results in tongue-and-groove tube support plates that can be supported from the top through hanger rods.

4.3.4. PCS Component Supports and Ducts

The power conversion system component supports and ducts consist of the following structures:

- Rotor support structure
- Stator support structure
- Recuperator support structure
- Precooler and intercooler support duct
- Bypass ducts within and external to the power conversion vessel

These components are shown in Fig. 4.3-29, and are described below. They are all constructed of low alloy steel (except for the hot duct bellows) for compatibility with the power conversion vessel material.

4.3.4.1. Rotor support structure. The rotor support structure as shown on Fig. 4.3-30 is an elliptical dome that supports the turbomachine (both generator and turbocompressor) rotor and the complete exciter assembly. Loads originating in the rotor, such as rotor dead weight and dynamic

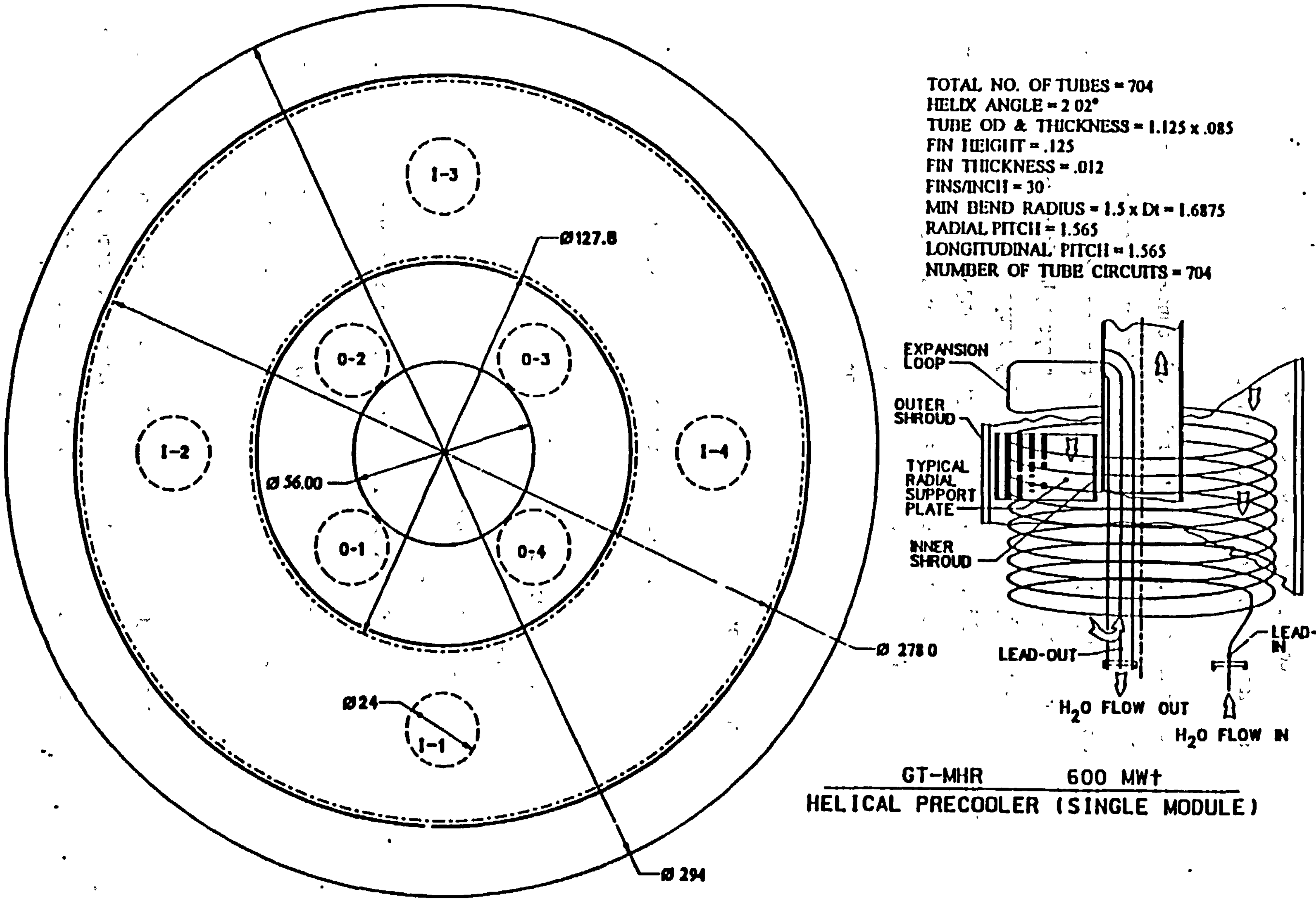

Fig. 4.3-26. Typical precooler tube circuit and flow paths

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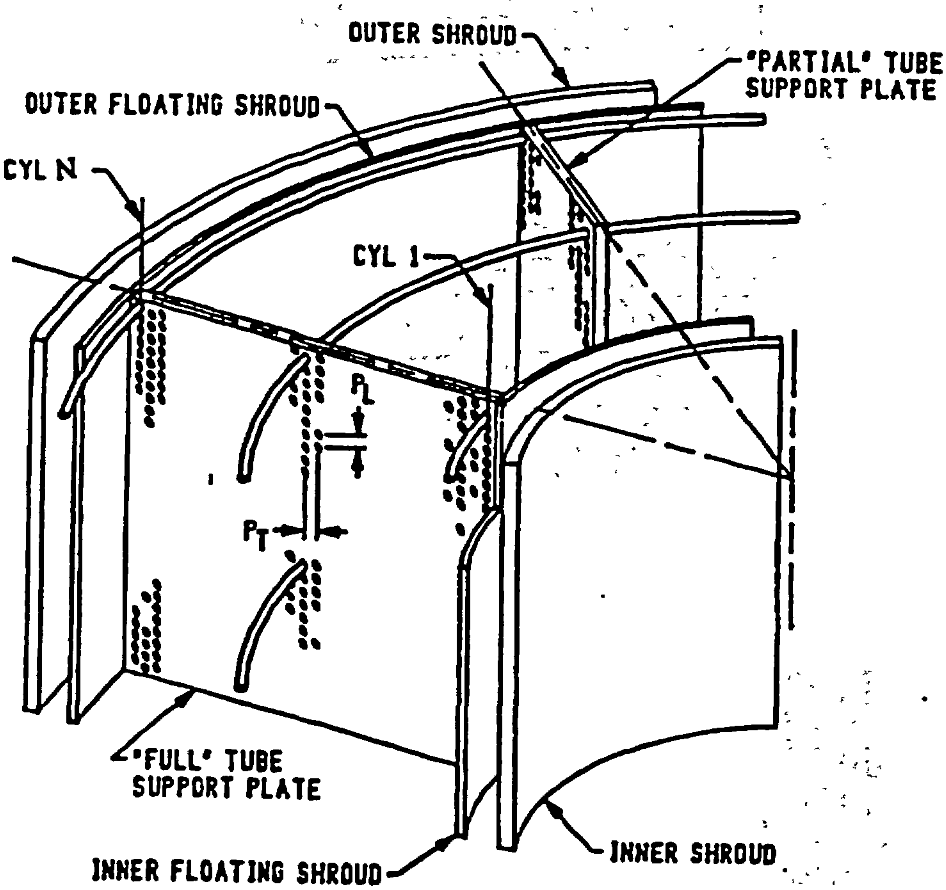

Fig. 4.3-27. Drilled tube support plate concept

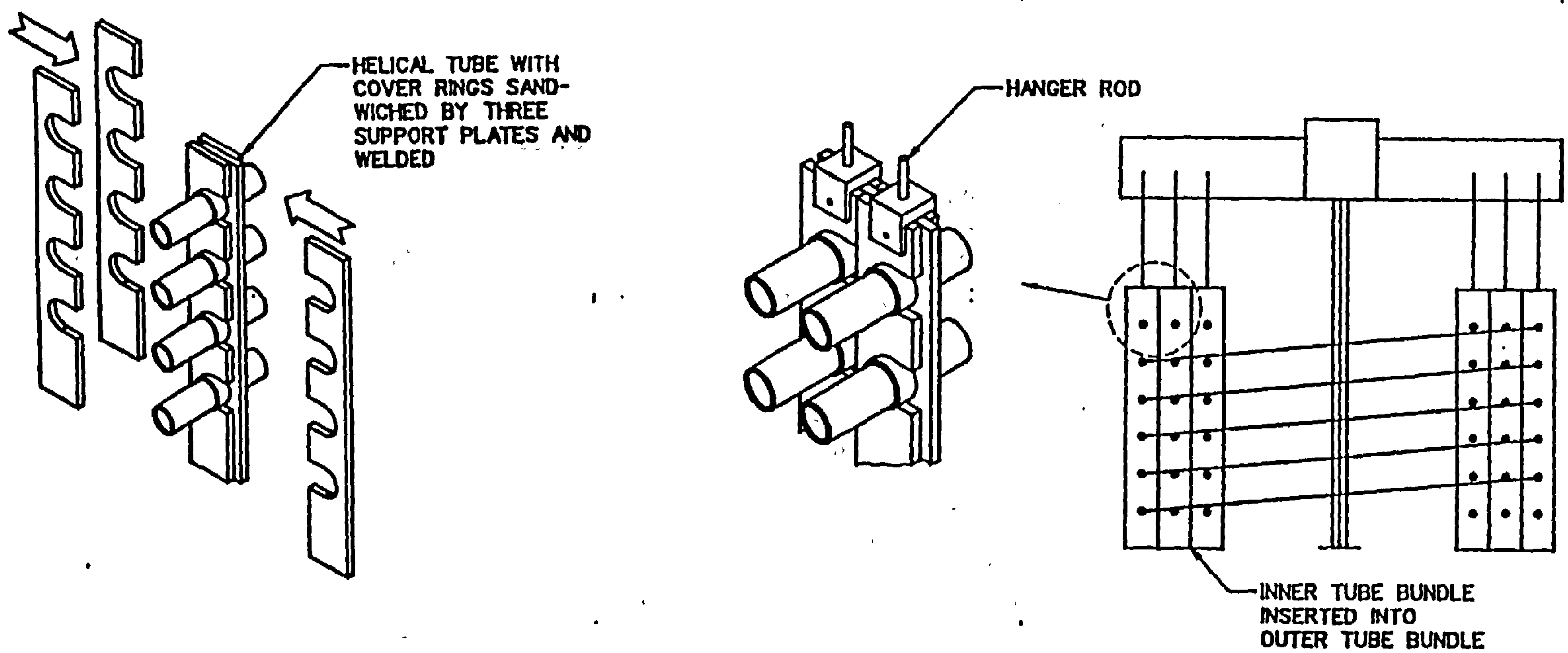

Fig. 4.3-28. Scalloped bar tube support concept

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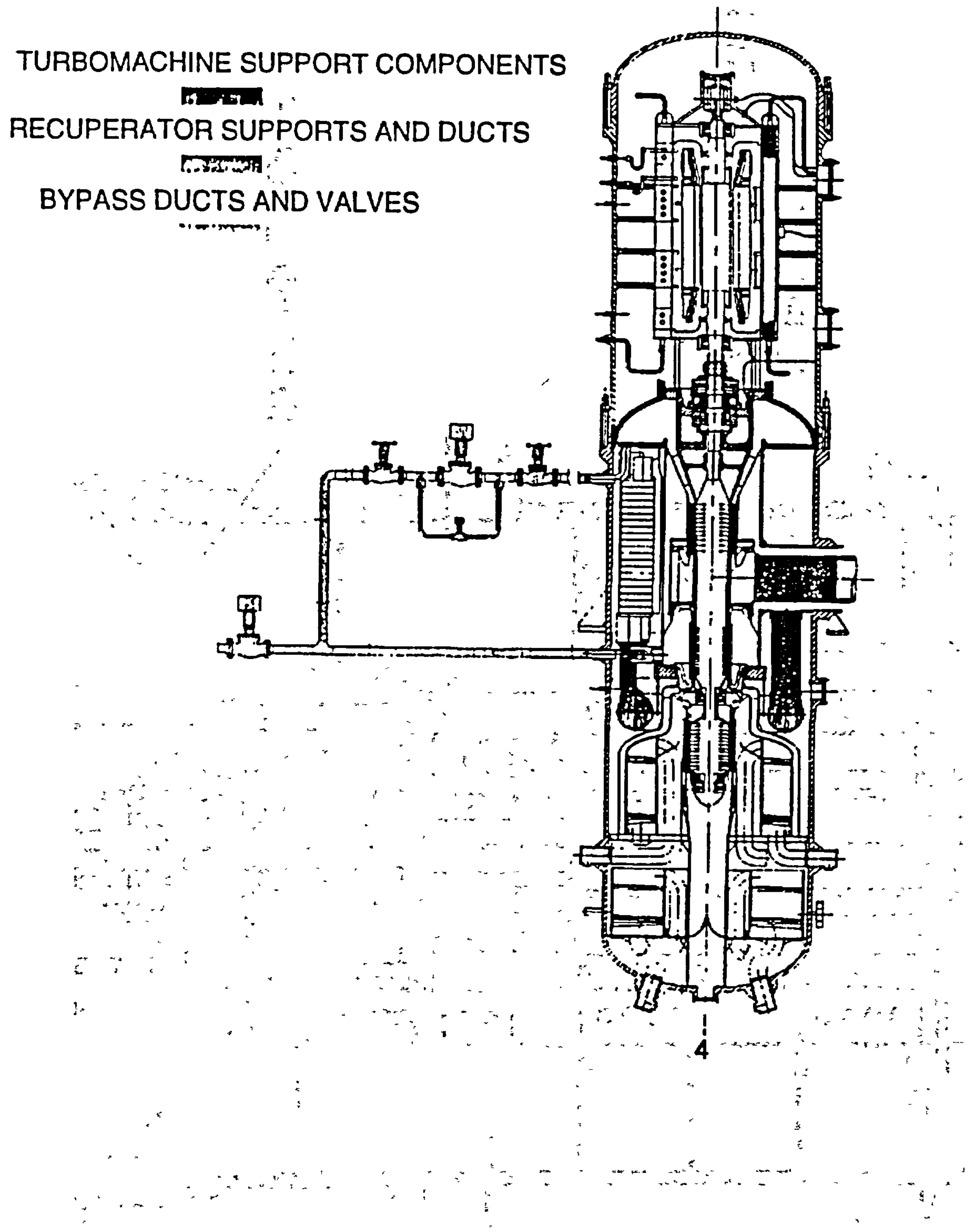

Fig. 4.3-29. PCS supports and ducts

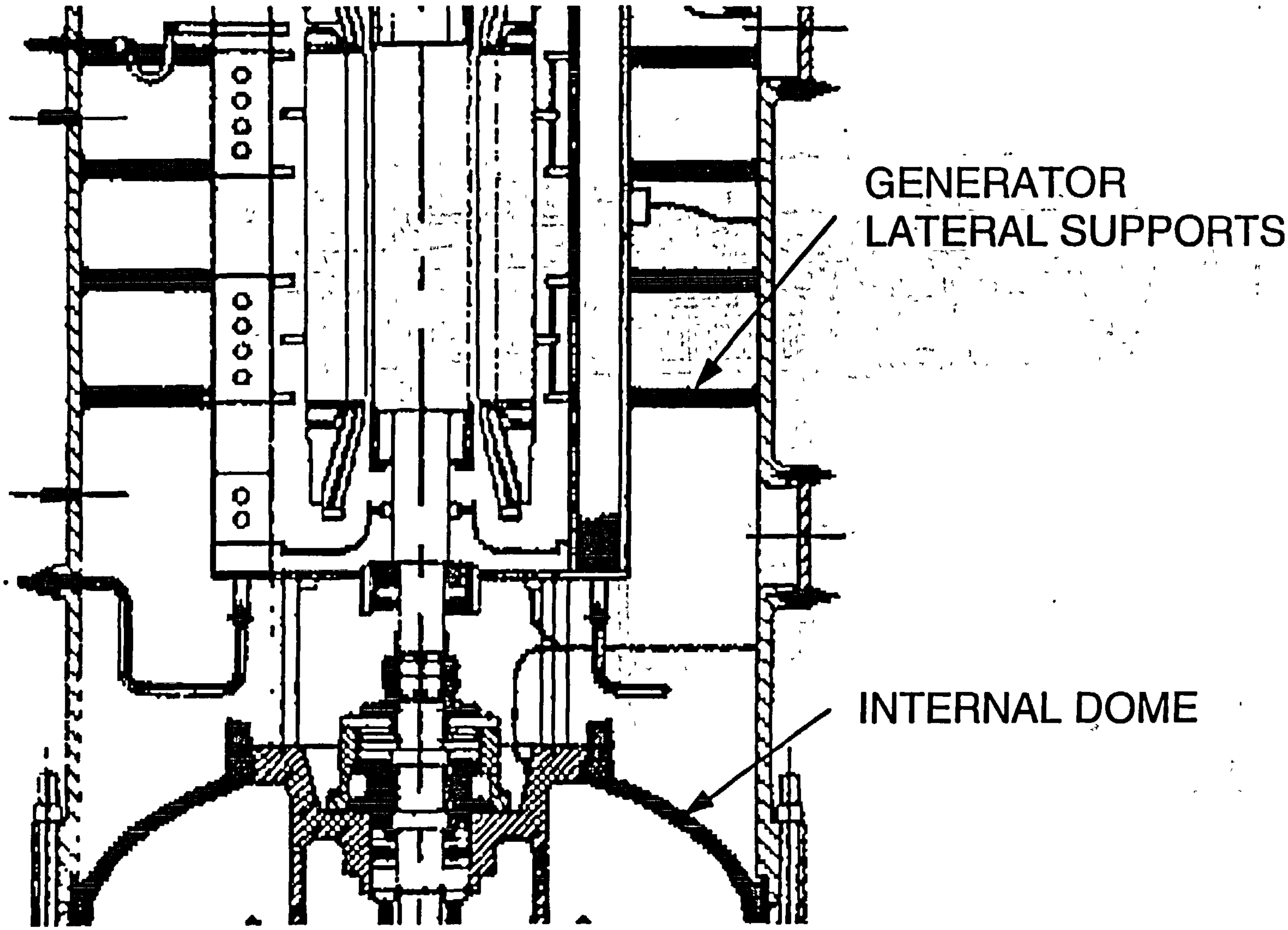

Fig. 4.3-30. Turbomachine support components

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forces resulting from unbalance between the dead weight and the axis of rotation, torque loads from operating generator, are transmitted from the bearing block to the rotor support structure, which then transfers these loads to the power conversion vessel. The bearing block contains the thrust and uppermost journal bearings (both magnetic and backup) and are part of the turbomachine. Lateral forces are transmitted through keyways which resist translation and rotation, but accommodate any radial movement resulting from differential thermal expansion. Holes in the rotor support structure are provided to direct the flow of uncontaminated helium from the generator cavity to and from the exciter.

4.3.4.2. Stator support structure. The stator support structure is also an elliptical dome. This dome directs the primary coolant flow from the turbine exhaust to the recuperator inlet, and provides vertical support to the turbomachine (both generator and turbocompressor) stator, as well as to the generator cooling components. The stator support structure also provides lateral and torsional support to the bottom portion of the generator stator and the upper portion of the turbocompressor stator. (The upper portion of the generator is laterally supported by the power conversion vessel. The lower portion of the turbocompressor stator is laterally supported by the recuperator support structure.) The stator support structure transfers the loads of the turbomachine stator to the power conversion vessel. All lateral and torsional loads are transferred through shear keys which prevent translation and rotation but which allow radial movements resulting from differential thermal expansion.

The stator support structure, in conjunction with the top of the turbocompressor stator, is also used to separate the more benign environment of the generator cavity from the primary coolant flow path exiting from the turbine. Separation is achieved with labyrinth shaft seals (see Section 4.3.1.1) and with static seals at the bearing surfaces where the stator is connected to the stator support structure, and where the stator support structure is connected to the power conversion vessel. These seals are of the same type that are used at the flanges of the power conversion and reactor vessels, and have a low leakage rate. To maintain the temperature difference between the generator cavity and the turbine outlet region, insulation is attached to the stator support structure.

4.3.4.3. Recuperator support structure. The recuperator support structure shown in Figs. 4.3-31 and 32 supports the recuperator vertically and laterally; and also supports the lower portion of the turbocompressor laterally and torsionally. The recuperator support structure also channels the

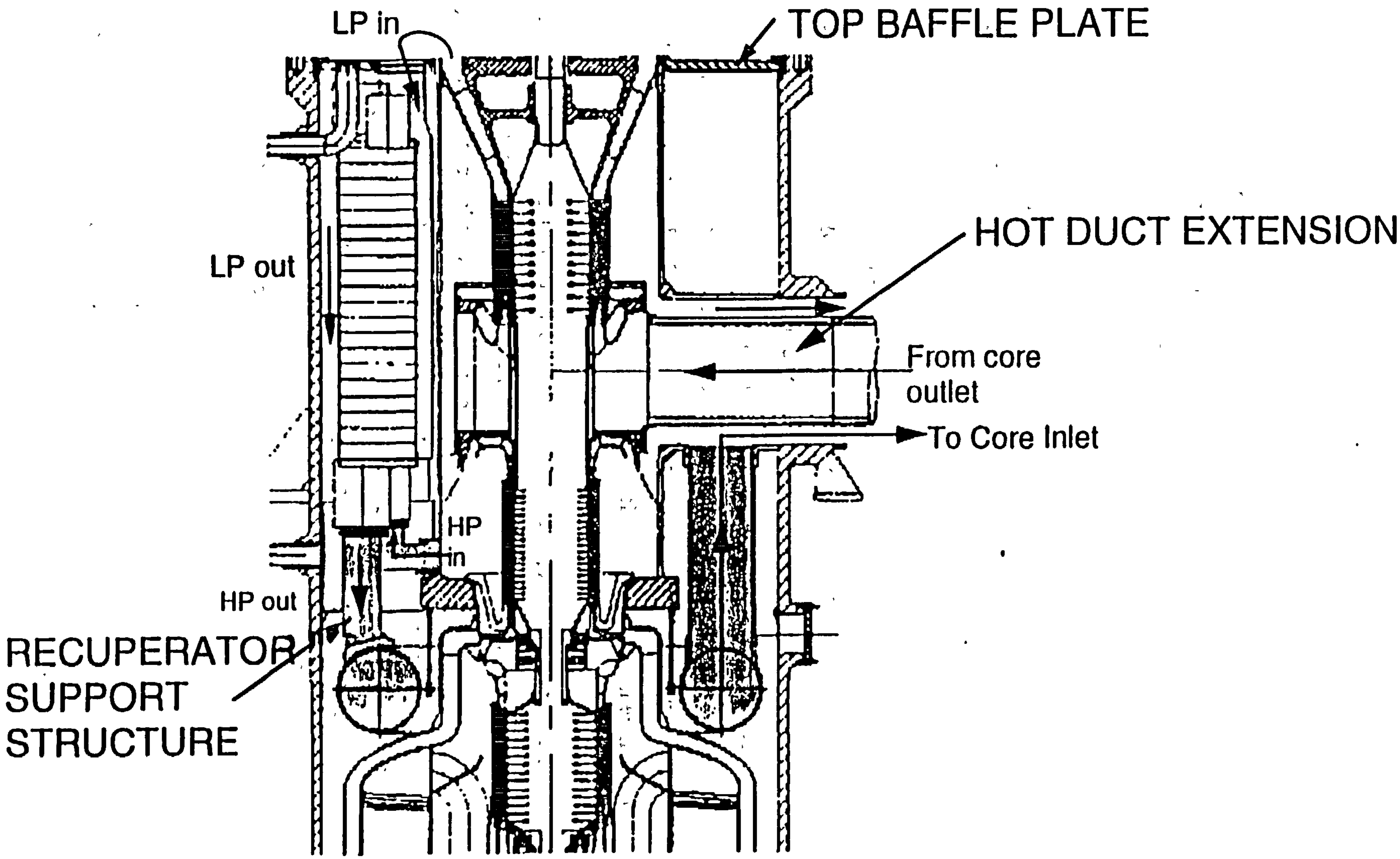

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Fig. 4.3-31. Recuperator support and duct components

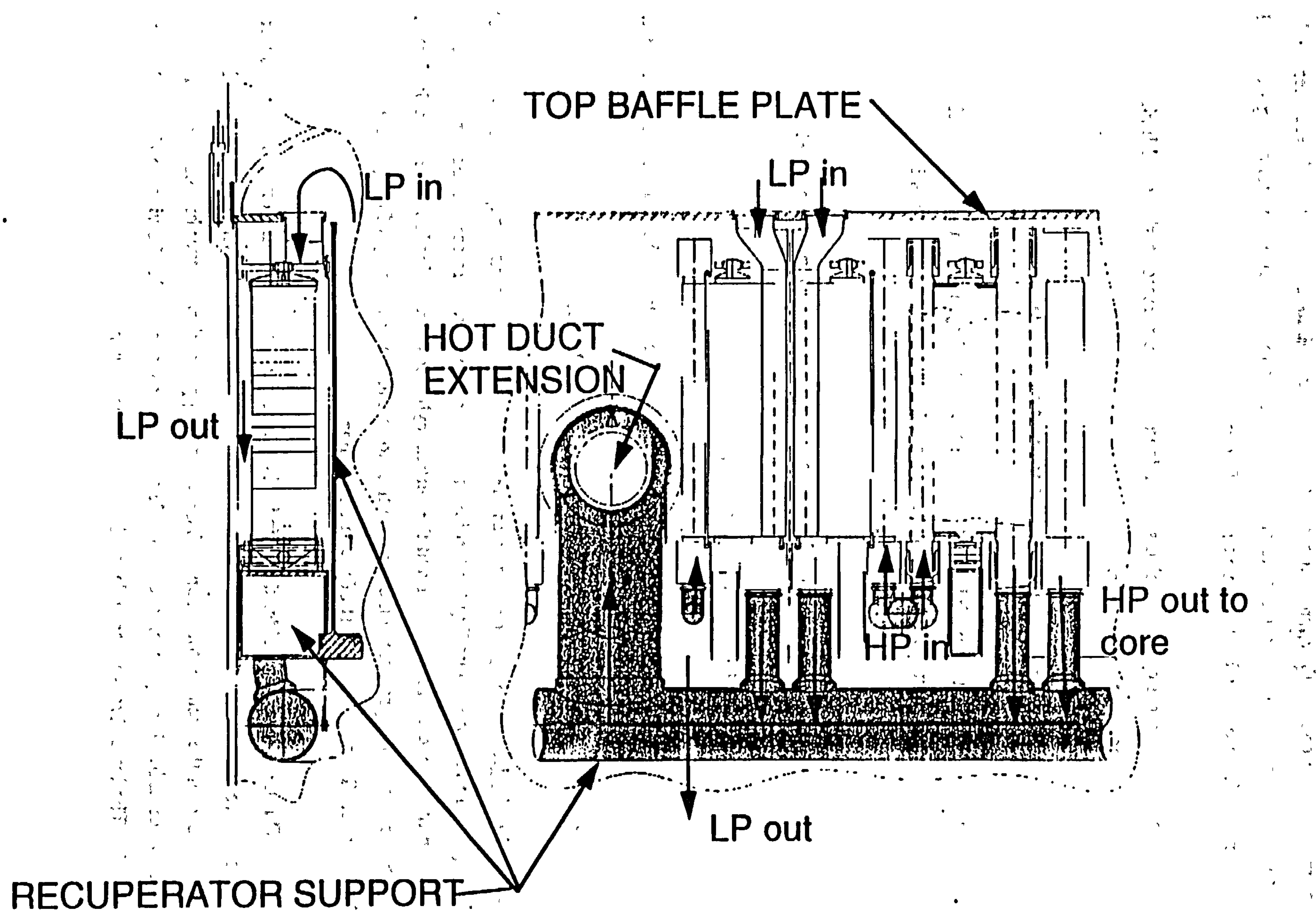

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Fig. 4.3-32. Recuperator support and duct components

primary helium coolant flow into and out of the recuperator, into and out of the intercooler, and into and out of the cross vessel and Reactor System. It is made up from the following structural elements which are assembled as a unit in the factory:

- Vertical cylinder which surrounds the turbocompressor turbine and high pressure compressor.
- Horizontal plate at the base of the vertical cylinder.
- Horizontal core inlet duct between the vertical cylinder and cross vessel nozzle on the power conversion vessel. A turbine inlet bellows is contained within this duct.
- Toroidal manifold which collects the recuperator high pressure outlet flow.
- Recuperator inlet and outlet ducts.
- Two vertical ducts between the toroidal collector manifold and the core inlet duct.
- Intercooler outlet shrouds located below the horizontal plate.

Vertical Cylinder. This cylinder separates the low pressure flow at the recuperator inlet from the high pressure region surrounding the turbine and high pressure compressor. Seals are provided between the turbocompressor stator and the vertical cylinder (or a projection from the cylinder) at the turbine and high pressure compressor outlets to maintain the integrity of the pressure boundaries. These seals are part of the turbomachine.

On the low pressure side, the cylinder is one of the boundaries that forms the recuperator low pressure inlet manifold. Brackets are provided on this face of the cylinder to support the inboard end of the recuperator mounts. There is one upper and one lower bracket for each recuperator unit. The upper brackets provide tangential support while allowing vertical and radial growth. The lower brackets provide vertical and tangential support.

Horizontal Plate. This plate is the element which transfers all loads on the recuperator support structure to the power conversion vessel. It also provides lateral and torsional restraint to the lower half of the turbocompressor stator. The stator is keyed to the plate so that vertical motion is permitted but lateral and torsion motion is not. Sliding seals (part of the turbomachine) are also used at this interface to separate high pressure inlet and outlet flow regions. Adjacent to the power conversion vessel, the plate is deeply scalloped to allow both low pressure recuperator outlet flow, and recuperator outlet ducts to pass through it. The only portions of the plate that extend to the vessel wall are underneath the central core sections of the recuperator units. These portions are approximately 25.4 cm (10 in.) thick to provide adequate strength. Should they need additional stiffness, gussets or other stiffeners can be added. In that event, it may be possible to reduce the plate thickness.

Core inlet duct. This duct extends between the vertical cylinder and the cross vessel nozzle on the power conversion vessel, where it is welded to these two structures. (The weld to the vessel is made during installation). It separates the high pressure Reactor System inlet flow from the low pressure recuperator flow and receives the two vertical ducts which extend upward from the toroidal manifold. It also contains the turbine inlet bellows. This bellows is fabricated from Alloy 800H (or comparable material) for thermal compatibility with the hot duct of the Reactor System and the turbine. One end of the bellows is supported from the hot duct, and the other end from the horizontal duct. The interface between the bellows and the turbine is a sliding sealed joint which permits relative vertical motion, but precludes relative horizontal or rotational motions.

Toroidal Manifold. The manifold is a circular duct which collects the high pressure recuperator outlet coolant from the six recuperator units and delivers it to two vertical ducts which in turn deliver it to the core inlet duct for subsequent delivery to the Reactor System inlet. The toroidal manifold duct is approximately 1.4 m (4.6 ft) diameter and 39 mm (1.5 in.) thick. It is located directly below and supported from the horizontal plate.

Recuperator Inlet and Outlet Ducts. There are six sets of recuperator inlet and outlet ducts (one inlet and outlet duct for each recuperator unit). The inlet ducts transfer coolant from the high pressure compressor outlet to the recuperator inlet. The outlet ducts transfer the coolant from the recuperator to the toroidal manifold.

Vertical Ducts. There are two ducts, each having a diameter of approximately 0.65 m (2.1 ft). As previously indicated, they transfer coolant from the toroidal manifold to the core inlet duct.

Intercooler Outlet Shrouds. There are two shrouds, which together define the flow path from the intercooler outlet to the high pressure compressor inlet. The innermost shroud also defines the flow boundary for the inlet to the intercooler. Each shroud consists of a vertical cylindrical section and a hemispherical section. The base of the hemispherical sections are provided with sliding seals where they interface with the intercooler. The shrouds are supported from the horizontal plate. This outermost shroud is also a pressure barrier between the low pressure flow toward the precooler and the intermediate pressure flow at the intercooler.

4.3.4.4. Bypass Ducts. These 30.5 cm (12 in.) diameter ducts are used for plant control by allowing cold flow from the compressor to bypass the high pressure side of the recuperator and the Reactor System as shown in Fig. 4.3-33. Currently three bypass ducts are planned but provisions for a fourth duct have been made. The ducts extend from the vertical cylinder of the recuperator support structure (which contains the high pressure flow) to the power conversion vessel. The duct exits the vessel, and extends to a valve with a high speed actuator and then returns to the vessel. After returning to the vessel, the duct continues upward within the vessel, crosses over the top of the recuperator, and terminates in a sparger. The sparger then distributes the cold flow uniformly around the circumference of the turbine exhaust, and allows it to mix with this exhaust flow. This cools the flow entering the low pressure side of the recuperator.

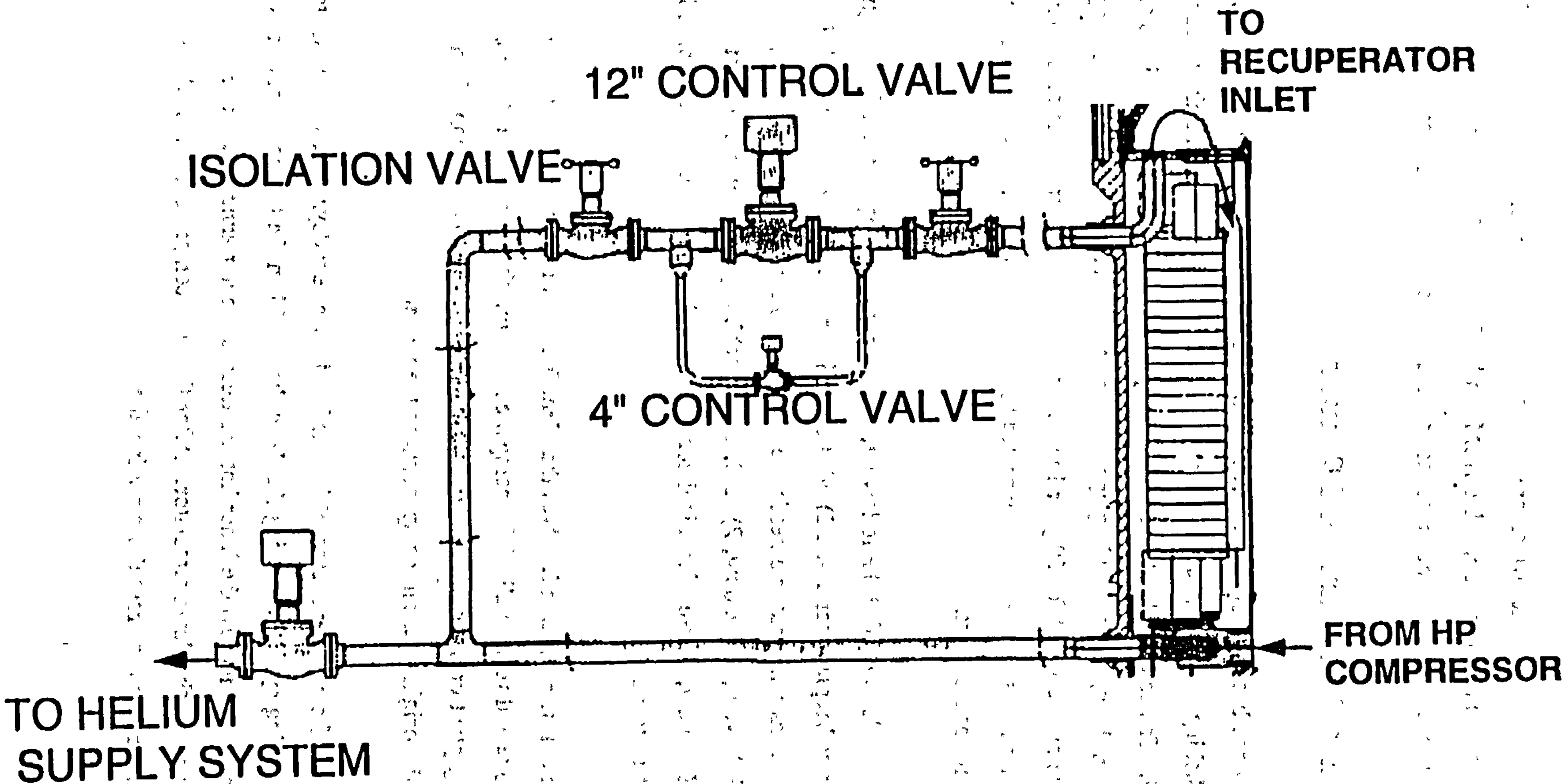

Fig. 4.3-33. Bypass ducts and valves

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The portions of the duct which are outboard of the vessel are included in the Vessel System and are designed to the applicable ASME rules for Class 1 components. The portions of the duct inboard of the welds to the vessel are considered internal structures.

4.3.5 Removal and Replacement of PCS Components

A study has been performed involving removal/replacement of the turbocompressor, and involved establishing the sequence of operations to remove/replace the remaining components in the PCS vessel. The study did not address the frequency of component removal/replacement, but rather focused on the operations and equipment necessary to accomplish the various operations. The components are designed for 60 year life, and with the exception of the turbocompressor (where refurbishment is planned), it is expected that the remaining static components will remain in-situ for the life of the plant.

The study also included the following, 1) changes necessary in the PCS design to facilitate component removal/replacement, and 2) what special purpose equipment are needed. Special purpose robotic arms with multiple heads are necessary to remotely perform many operations including the following, 1) welding, 2) cutting, 3) machining, 4) local in-situ post weld heat treatment, 5) X-Raying, 6) use of manipulators for removing/replacing bolted connections, and 7) laser alignment instruments.

This initial investigation involves the identification of activities, and the sequence of events, to remove and replace all of the components within the PCS vessel, these being radioactive following plant operation. This study is in concert with a companion effort involving installation of the original (clean) components in the vessel.

Initiation of component removal is scheduled for a few days after reactor shutdown, with the shutdown cooling system removing the decay heat. When the turbocompressor is lifted upwards (by say a few inches) the inner hot gas duct and outer annulus are open permitting bypass flow from the shutdown circulator. After the turbocompressor removal, the inflatable seals in the inner and outer cross ducts are installed.

All of the component removal/replacement activities are undertaken by utilizing remotely operated equipment, so gas flow in the vessel (and circulation/disturbance of gas borne fission products) is not a factor. A summary of the sequence of operations is given on Table 4.3-9.

4.4. SHUTDOWN COOLING SYSTEM

A Shutdown Cooling System (SCS) provides reactor cooling when the Power Conversion System is nonoperational. The SCS consists of the shutdown circulator and shutoff valve, the shutdown heat exchanger (SHE), and shutdown cooling control. Also included as part of the SCS are the shutdown circulator and shutdown heat exchanger service equipment.

The SCS consists of a single loop (one per reactor module) with the shutdown heat exchanger in series with the shutdown circulator and shutdown loop shutoff valve assembly, all located at the bottom of the reactor vessel. Hot helium from the core outlet plenum flows through multiple parallel openings (pipes) in the center of the core support structure and into the shutdown heat exchanger. Once cooled, the helium continues downward through the shutdown loop shutoff valve to the shutdown circulator where it is compressed and discharged into the reactor vessel bottom head cavity. The cool helium then flows through the internal passage formed by the the core support structure and up the channels attached to the core barrel "risers" to the core inlet plenum. The loop is completed as the helium flows down through the reactor core. There is some helium back flow through the power conversion vessel. The total SCS helium flow must be adequate to cool the core and accommodate the Power Conversion System back flow. Heat is rejected from the shutdown cooling water to the atmosphere through the air-cooled heat exchanger. The shutdown heat exchanger, circulator, and controls are described in more detail in this section.

The shutdown cooling water loop is sized to cool a reactor module following an SCS startup during a pressurized conduction cooldown. The peak heat load during this event is 40 MW(t) per module. In addition, the shutdown circulator and the shutdown heat exchanger are sized to remove 5.8 MW(t) per module under depressurized maintenance conditions 24 hr after reactor shutdown.

For high reliability, the SCS can be powered by either normal or standby electrical power.

TABLE 4.3-9
SEQUENCE OF PCS COMPONENT REMOVAL

COMPONENT	OPERATION NUMBER	COMPONENT OVERALL SIZE/SHAPE	ASSEMBLY WEIGHT	CONNECTIONS (WELDS OR BOLTED JOINTS)	LOCAL DOSE RATE (MR/HR)
PCS vessel after reactor shutdown	0	Access to vessel 24 hours after reactor shutdown and vessel cooldown for initiation of component removal			10
Removal of generator, turbocompressor and all equipment above support plate	1	Removal of all equipment above turbocompressor support plate addressed in previous study. Final activity is placement of temporary cover to block radiation shine through plate aperture			19
Installation of large cask adapter and cask to facilitate removal of PCS components	2	• Cylindrical adapter with built in isolation valve. Approx. 32 ft dia x 80 ft tall x 1" • Cask diameter approx. 32 ft, 130 ft tall x 1" thick	190 tons 300 tons (excluding lifting equipment)	Cask adapter bolted to upper vessel flange	10
Lift and remove domed support structure	3	• Approximately 30 ft diameter structure	70 tons	Remove ring of bolts (cut flange seal welds if appropriate)	20
Recuperator removal a) Disconnect bolted joint, lift and remove recuperator top plate b) Remove and lift out of position the 4 bypass ducts c) Remove and lift out of position individually the 6 modules	4a 4b 4c	Circular Plate - 294" o/d - 138" i/d - 6" thick Circulator Pipe - 8" dia (0.5" thick) -150" long Individual Module - 100" wide - 80" deep - 280" height	47 tons 550 lbs each Each 33 tons (including support structure)	Remove bolts from periphery of plate. Remove seals of cut welds at connection between the four 8" diameter bypass ducts and the plate Cut the 4 pipes adjacent to the vessel (from outside) Through access penetrations in the vessel side wall disconnect the bolts in the 6 HP air inlet ducts (18" dia) and 6 HP air outlet ducts (30" dia)	20

TABLE 4.3 (CONT)

COMPONENT	OPERATION NUMBER	COMPONENT OVERALL SIZE/SHAPE	ASSEMBLY WEIGHT	CONNECTIONS (WELDS OR BOLTED JOINTS)	LOCAL DOSE RATE (MR/HR)
Removal and lift out of position the turbine inlet scroll structure	5	Cylindrical Assembly - 111" diameter - 116" height	15 tons	Remotely remove bolts connecting scroll to backbone structure. Translate horizontally to disconnect from hot gas and lift vertically.	10
Remove and lift out of position the hot gas duct insulation and duct extension	6	Insulation Liner - 102" long - 68" dia Extension of hot gas duct - 102" long - 68" dia - 1" thick	1500 lbs 3 tons	● Cut insulation liner from duct, translate horizontally and lift upwards. ● Cut extension of hot gas duct in plane of vessel wall. Translate horizontally and lift upwards.	10
Removal and lift out of position the backbone structure (horizontal plate is bolted to vessel)	7	Cylindrical assembly with lower toros - 288" diameter - 370" high	215 tons	● Cut outer hot gas duct (97" dia) adjacent to vessel wall. Through vessel side wall penetrations remotely remove bolts in 6 lugs supporting assembly ● Cut the 4 bypass ducts (8" dia) adjacent to vessel wall.	1
Removal and lift out of position the intercooler/ precooler assembly	8	Overall assembly (including manifold to HP compressor inlet) - 279" diameter - 520" height	210 tons	● From penetration in lower vessel head remotely cut cylindrical stanchion (53" dia) ● Using external equipment cut the 16 water pipes outboard of the tubeplates	1
All components removed from PCS vessel	-			- Remove cask	1

Figure 4.4-1 shows the SCS cooling loop and the location of the shutdown heat exchanger and shutdown circulator in the reactor vessel. Table 4.4-1 provides the design parameters for the Shutdown Cooling System components.

The SCS has two different operating modes depending on the condition of the reactor:

1. Standby mode — During normal Power Conversion System operation, a small amount of cold leg helium leaks (back flows) through the closed shutdown valve and flows opposite the normal flow direction through the shutdown circulator and over the shutdown heat exchanger tubes. In this mode the shutdown circulator is not operating, but the Shutdown Cooling Water System supplies a small water flow to the shutdown heat exchanger. This water flow prevents thermal shock when the SCS switches to the cooldown mode. During the standby mode of operation, the water flow in the shutdown heat exchanger removes heat from the primary coolant. This heat transfer is a parasitic heat loss. Therefore, the standby water flow must be set as low as possible without resulting in one of the following adverse conditions: (a) boiling and/or (b) static instability due to the large hydrostatic head in the shutdown heat exchanger.

2. Cooldown modes — When it is desirable or necessary to shutdown the Power Conversion System (PCS) and the reactor is shutdown, the SCS provides reactor cooling in the cooldown mode. The shutdown circulator provides adequate flow to prevent reverse flow in the reactor core and accommodates the PCS back flow.

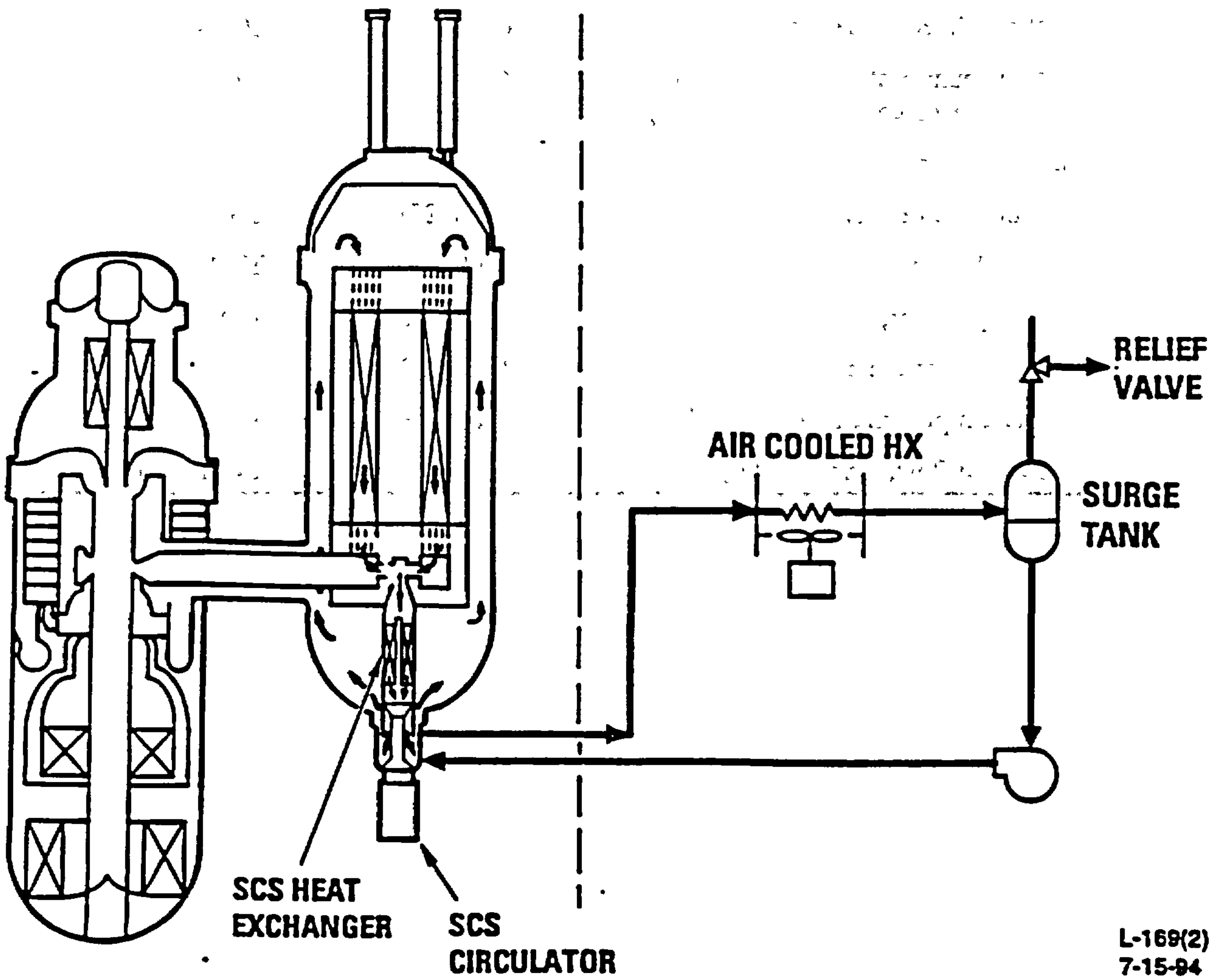

Fig. 4.4-1. Shutdown Cooling System general arrangement

TABLE 4.4-1
SHUTDOWN COOLING SYSTEM DESIGN PARAMETERS

	Depressurized	Pressurized
Shutdown Heat Exchanger		
Heat duty, MW(t)	14.1	35.2
Helium inlet temperature, °C (°F)	1032 (1890)	807 (1485)
Helium outlet temperature, °C (°F)	179 (355)	341 (645)
Helium flow, kg/sec (lb/hr)	3.21 (25,438)	14.51 (115,200)
Water flow, kg/sec (lb/hr)	57.19 (454,000)	57.19 (454,000)
Water inlet temperature, °C (°F)	60 (140)	60 (140)
Maximum heat duty, MW(t) (after pressurized conduction cooldown)	40	40
Shutdown Circulator		
Motor power, kW (hp)	323 (433)	TBD
Speed, rpm	6000	TBD
Exit pressure, kPa (psia)	84.1 (12.2)	TBD
Inlet temperature, °C (°F)	179 (355)	341 (645)
Helium pressure rise, kPa (psid)	6.14 (0.89)	TBD
Helium flow, kg/sec (lb/hr)	3.21 (25,438)	14.51 (115,200)

Backflow through the PCS occurs since the PCS is subjected to the same pressure drop as the core. Depending on the flow resistance of the rotating machinery and the status of the PCS bypass valve, the helium back flow in the PCS will cause the total SCS helium flow to be 10% to 35% greater than that which is required to adequately cool the core (without local reverse flow in the core). The primary coolant can be either pressurized or depressurized. The SCS can also be used in the cooldown mode to provide cooling during refueling. During each of these cooldown modes, the water flow must be large enough to provide an adequate subcooling margin in the shutdown heat exchanger.

The transfer from the standby mode to the cooldown mode, or from the cooldown mode to standby, is a manual operation performed when the operator has evaluated the conditions as acceptable for the transfer.

4.4.1. Shutdown Heat Exchanger

The shutdown heat exchanger is located below the core support floor shield at the bottom centerline of the reactor vessel. The general configuration is shown in Fig. 4.4-2. The shutdown heat exchanger is a vertically oriented, shell-and-tube, cross-counterflow heat exchanger (made of 2-1/4 Cr-1 Mo) for all normal operations except standby mode, for which it is a cross-parallel flow heat exchanger (reverse primary flow). The helical tube bundle has an estimated surface area of 124 m^2 (1334 ft^2) and weighs about 18,100 kg (20 tons). Key parameters for the shutdown heat exchanger are given in Table 4.4-1.

Water inlet and outlet are through the tubesheets located in the lower region (spool piece) of the heat exchanger. The tubes are attached to the inlet tubesheet, routed under circulator conduits to the helical bundle, then spiraled upward through the helical bundle, then to an expansion loop at the top and routed back down where they attach to the outlet tubesheet. Thus, the tubes are continuous from tubesheet to tubesheet and are accessible from both ends for inspection and tube plugging.

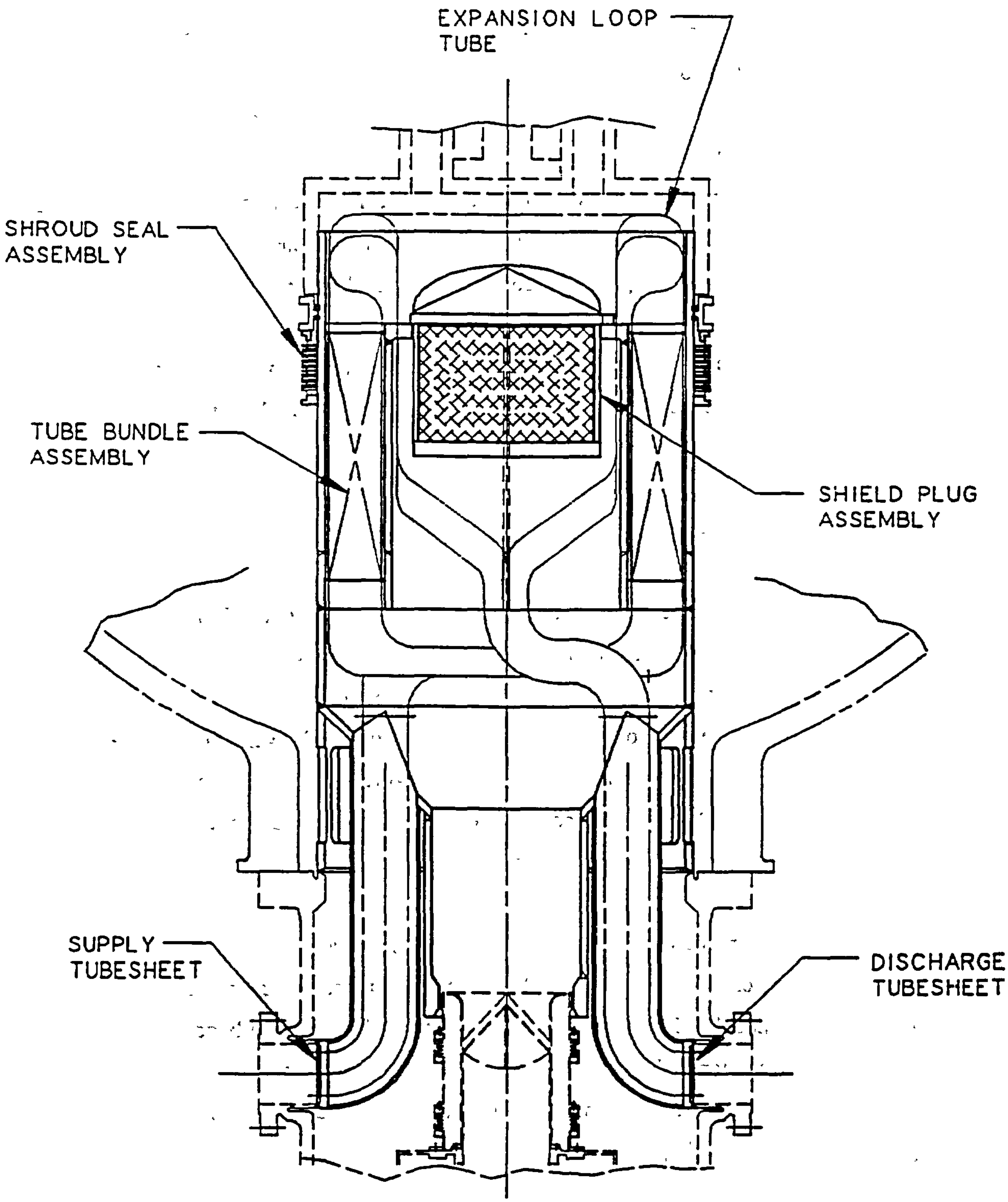

Fig. 4.4-2. Shutdown heat exchanger sectional view

For all normal operations, helium enters the shutdown heat exchanger tube bundle via the core outlet plenum and flows downward over the cross-counterflow helical bundle and through the shutoff valve, and is returned to the lower reactor vessel cavity through the shutdown cooling circulator and the annulus formed between the SHE shroud and vessel wall. During the standby operation mode, the flow is reversed.

The shutdown heat exchanger transfers heat from the helium to the cooling water flowing through the tubes. During full power operation the secondary coolant (water) is at a pressure less than the primary coolant (helium). Thus, any leaks result in a flow of helium into the water side. At lower power operations (approximately $\leq$70% power), the helium pressure in the reactor is decreased to the extent that leakage would be in the reverse direction resulting in water into the primary coolant side.

4.4.2. Shutdown Circulator

The shutdown circulator is a vertically oriented, radial-flow compressor driven by an electric motor. The integral motor/compressor rotor is fully supported on magnetic bearings. Figure 4.4-3 presents a view of the circulator assembly installed in the reactor vessel. The key parameters for the shutdown circulator are presented in Table 4.4-1.

The shutdown loop shutoff valve is installed in the vertical inlet ducting above the compressor. When the SCS loop is in the standby mode, a small coolant leakage flow occurs upward through the closed valve. When the SCS is in a cooldown mode, the loop flow is downward through the open shutoff valve. The shutoff valve is similar in concept to the Fort St. Vrain main loop shutdown valves. Closure of the shutoff valve is effected by counter weights and pressure forces generated by reverse flow from the operating Power Conversion System. The shutoff valve opens automatically when the shutdown cooling loop is operating and sufficient aerodynamic forces are generated by the shutdown circulator. Flow generated by the shutdown circulator will maintain the lightweight valve plates in the open position during all operating conditions. A helium jet override mechanism is included in the design to assist in opening and closing the shutoff valve, if required.

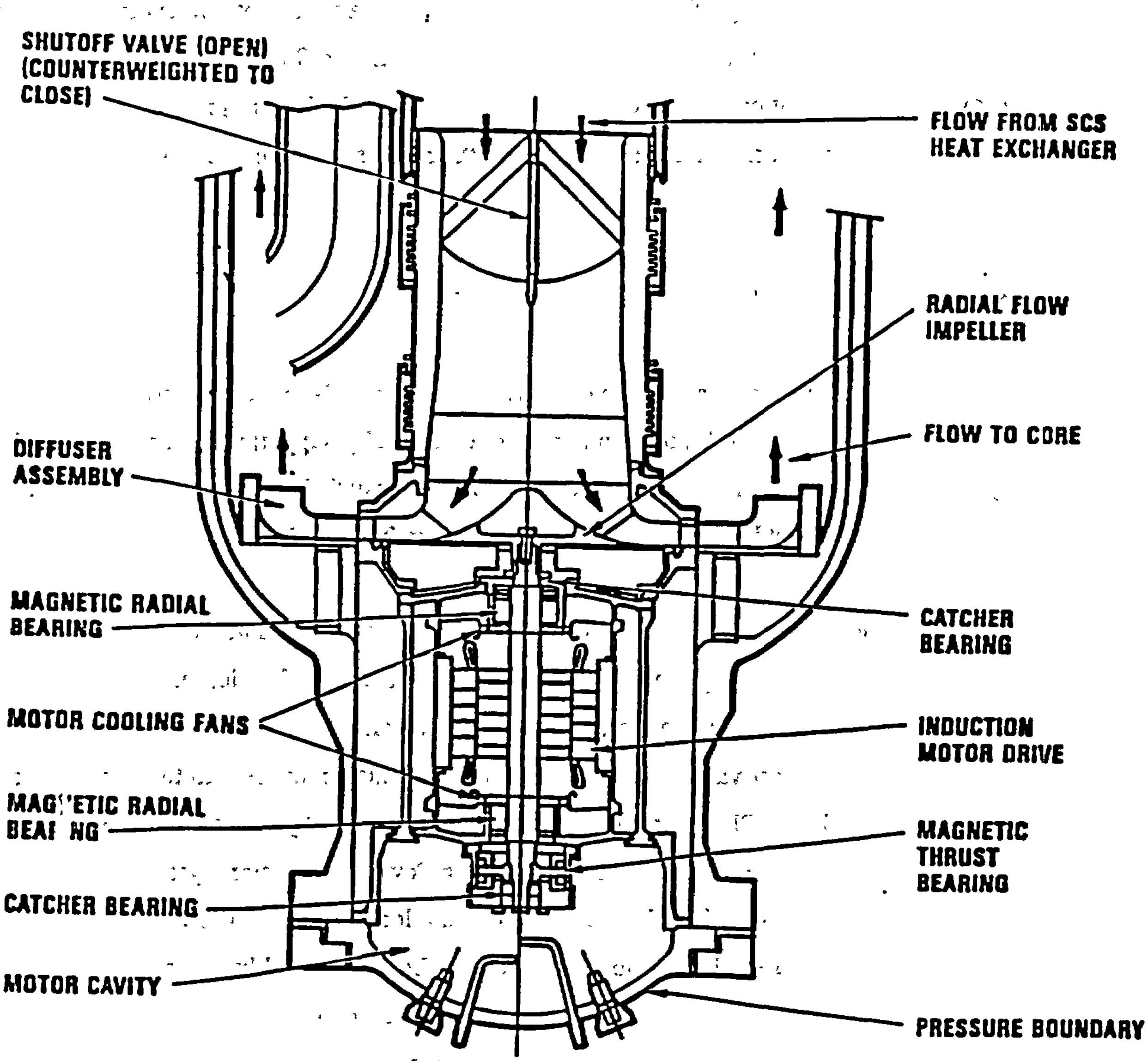

Fig. 4.4-3. Shutdown circulator sectional view

4.4.3. Shutdown Cooling Control

The configuration of shutdown cooling control includes controls for maintaining proper primary and secondary flow and controls for maintaining conditions on the secondary side. The following are the major controls for the SCS:

- Startup or shutdown sequence by coordinating the activation of isolation valves and circulator power supply.
- Shutdown heat exchanger cooling water exit temperature by adjusting the shutdown circulator speed set point (helium flow).
- Shutdown circulator speed by adjusting the output frequency and voltage of the circulator motor power supply.
- Switching between the standby mode water pump and the cooldown mode pump.

With these controls, the required SCS primary and secondary flow are maintained.

The minor SCS controllers include the controls required to maintain level and pressure in the surge tank, a shutdown water pressure control, and a control to maintain circulator speed set point by adjusting motor frequency.

The control system also includes several SCS protection features such as loop isolation upon shutdown heat exchanger leak detection, shutdown circulator overspeed protection, low water flow protection, loss of net positive suction head protection, and shutdown heat exchanger high temperature protection.

During the cooldown mode of operation, the control system controls both helium and water side conditions. During the standby mode, the shutdown circulator is shutdown and the control system controls the water conditions only.

4.5. SHUTDOWN COOLING WATER SYSTEM

The SCS is required to be redundant and diverse from the Power Conversion System, therefore, a dedicated cooling water loop is needed to provide the secondary coolant flow to the shutdown heat exchanger. A separate shutdown cooling water system with the configuration shown in Fig. 4.5-1 is provided for each reactor module. Each shutdown cooling water loop consists of one 100% capacity jockey pump (for standby mode water flow), one 100% capacity cooldown pump, a pressurizer tank, a make-up water storage tank, and one 100% capacity air cooled heat exchanger equipped with two 100% capacity fan banks.

In the standby mode, the cooling water system operates continuously to remove a maximum of 1.3 MW(t) heat resulting from helium back flowing through the shutdown heat exchanger. In the cooldown mode, the SCS provides reactor cooldown to temperatures compatible with maintenance activities and maintains heat removal. The maximum shutdown cooling water heat load occurs when the SCS is started after a pressurized conduction cooldown. The heat load during this cooldown mode is 40 MW(t). At the end of a 24 hour cooldown with the Power Conversion System out of service, the heat load is 5.8 MW(t).

4.6. REACTOR CAVITY COOLING SYSTEM

The Reactor Cavity Cooling System (RCCS) performs two safety functions. It provides a passive means of transporting core residual heat from the reactor cavity when neither the Power Conversion System nor the Shutdown Cooling System is available, thereby preventing the reactor vessel from exceeding design temperature limits. It also protects the concrete walls of the reactor cavity from exceeding design temperature limits for all modes of operation. The RCCS removes heat by conduction through the graphite reflector and by radiation and natural convection from the uninsulated vessel. The system, which receives the heat transferred from the vessel, includes a cooling panel placed around the reactor vessel. Heat is removed from the reactor cavity by natural circulation of outside air through the cooling panel.

The natural draft air cooling concept is shown schematically in Fig. 4.6-1. The design has no pumps, circulators, valves, or any other active components. The surface of the cooling panel serves to separate the outside atmosphere from the reactor cavity atmosphere. This minimizes the site boundary dose due to release of air activated in the cavity. The system has

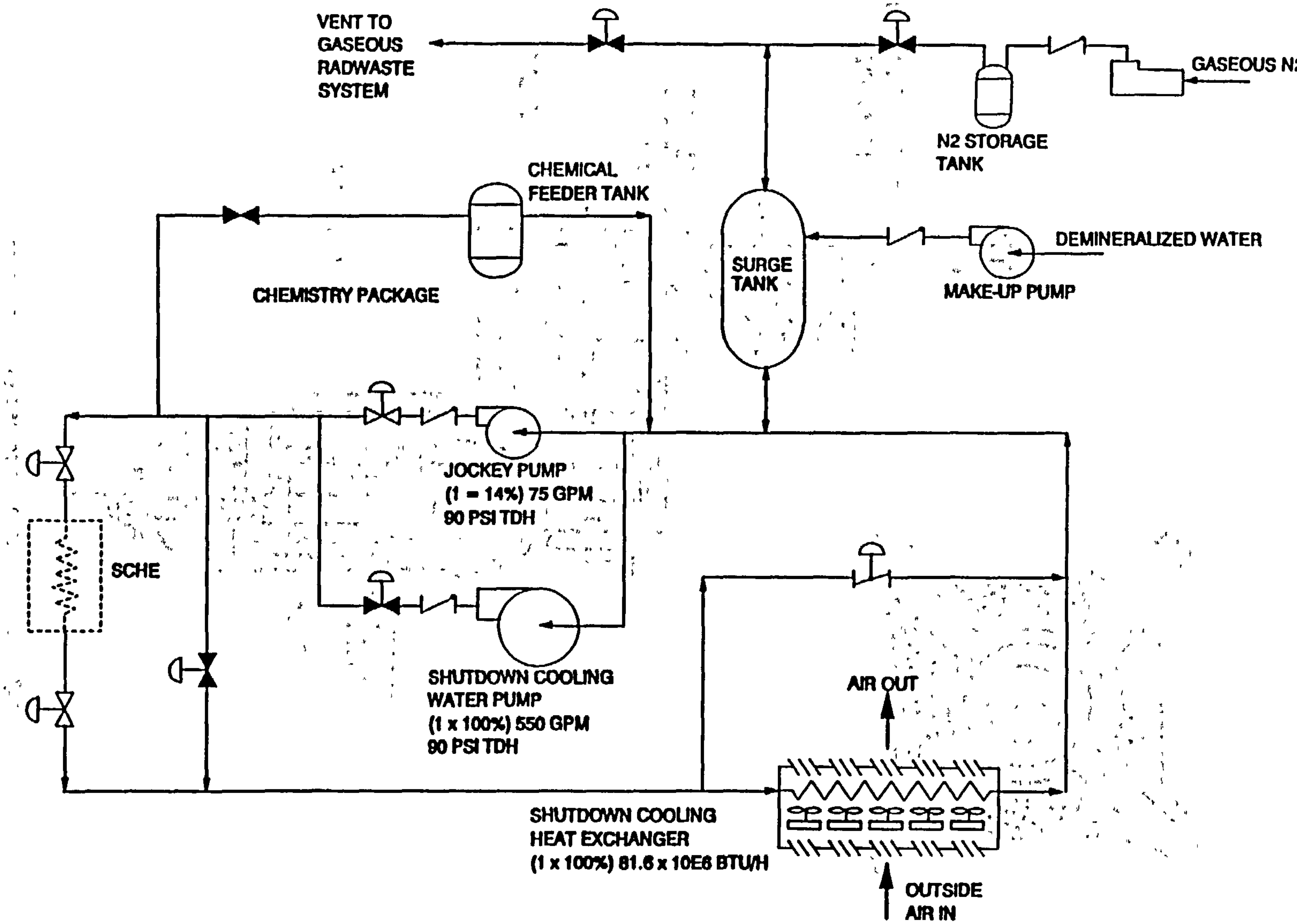

Fig. 4.5-1. Shutdown Cooling Water System flow diagram

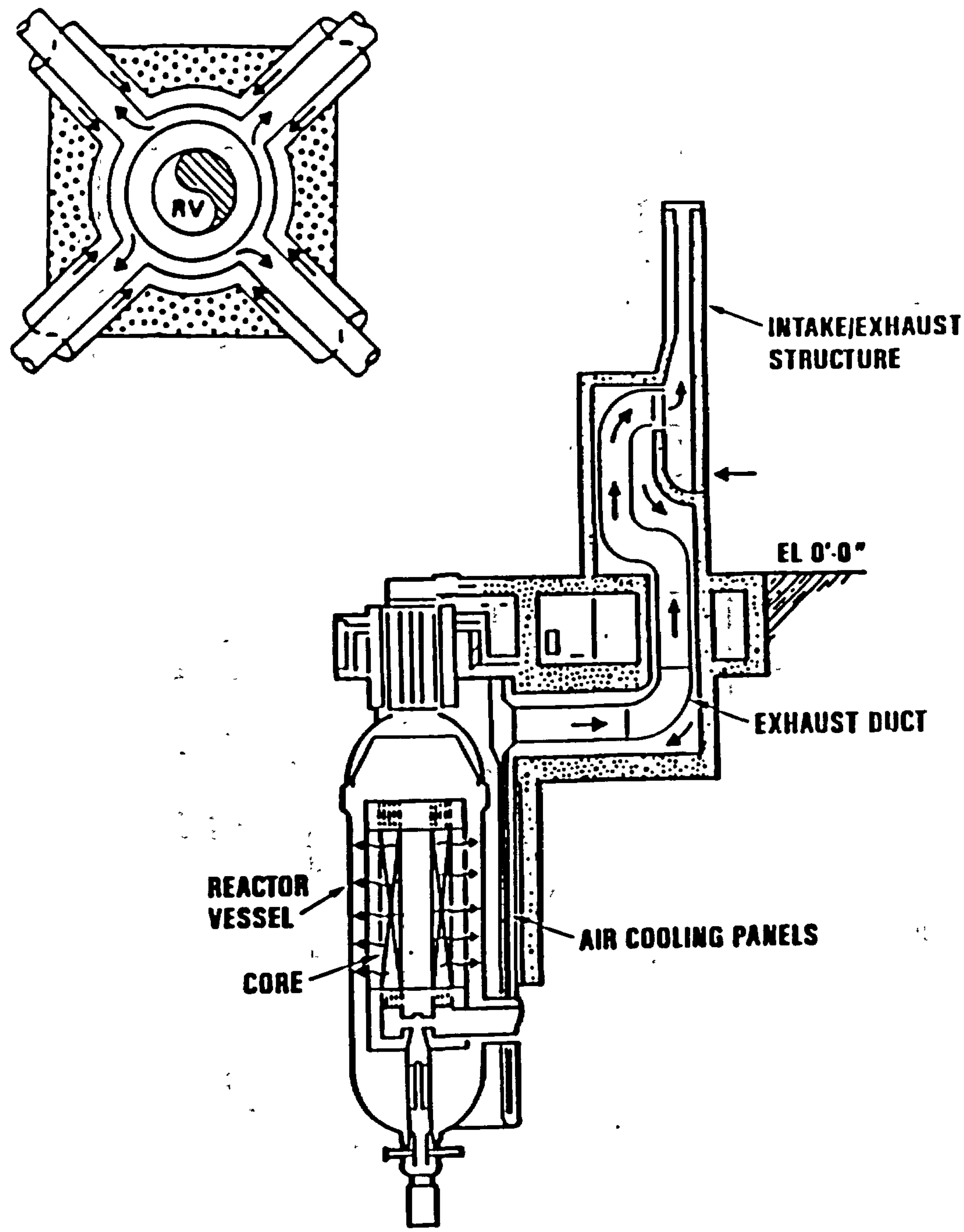

Fig. 4.6-1. Passive air cooled RCCS concept

multiple inlet/outlet ports and interconnected parallel flow paths to ensure continued cooling in the event of blockage of any single duct or opening.

The system is required to operate continuously in all modes of plant operation to support normal operation, and, if forced cooling is lost, it functions to remove decay heat to ensure investment and safety protection. Since the RCCS is relied upon to meet 10CFR100 requirements, the system is classified as "safety-related."

The RCCS consists of a cooling panel which includes cold downcomers and hot risers and is located inside the reactor cavity surrounding the reactor vessel. Connected to the cooling panel are the concentric hot and cold ducts which connect the panel to the inlet/outlet structure.

Cold atmospheric air enters the RCCS through the inlet/outlet structure, which is located above grade on top of the Reactor Buildings.

The cold air flows downward from the inlet/outlet structure to the cooling panel by way of the outer duct of the concentric ducts. The air enters the cooling panel and flows down by gravity to the bottom of the reactor cavity via the outer cold downcomer section of the panel and starts up the inner riser section which faces the reactor vessel. There the air collects the heat radiated and convected from the reactor vessel. The buoyancy imparted to the air due to heatup causes the air to move upward toward the top of the reactor cavity through the riser section of the panel. As the air moves upward, it collects more heat over the full length and circumference of the reactor vessel. The heated air then leaves the cooling panel and reactor cavity, flows through the hot duct to the inlet/outlet structure and finally exhausts to the atmosphere.

4.6.1. RCCS Cooling Panels

The RCCS panel follows the internal contour of the reactor cavity and surrounds the reactor vessel over its full circumference and length. Most of the cold side of the RCCS panel is directly in contact with the concrete wall of the reactor cavity, thus protecting the concrete from reactor vessel heat. The cold side of the RCCS panel consists of four parts: upper cold plenum, downcomer, bottom cold plenum, and drain arrangement. The upper cold plenum receives cold air from the ductwork and distributes the cold air over the full circumference and directs the airflow to the downcomers. It also protects the concrete portion of the cavity ceiling from reactor

vessel heat and serves as a quiescent/damping chamber which attenuates the effects of any atmospheric disturbance in the incoming cold air.

The downcomer part of the cooling panel provides a guided vertical flow path for the cold air to travel to its bottom. The downcomer is formed by two parallel vertical steel plates held 10 in. apart by vertical steel channel diaphragms. The outer plate is anchored to the reactor cavity wall, and the inner plate is bolted to the channels placed at approximately 2 ft intervals along the wall of the cavity. These vertical channels also guide the airflow in the downcomer.

A reflective surface/insulation ("Microtherm" with a metal cover) is provided as a part of the downcomer. This surface is attached to the inner plate and faces the reactor vessel. It serves to reflect the reactor vessel heat back to the cavity, and also protects the cold incoming air from being prematurely heated in its downward journey.

The bottom cold plenum, located at the bottom end of the downcomer, is essentially a box-shaped continuous ring header around the reactor vessel along the cavity wall. It permits change in airflow direction with minimal flow resistance and facilitates proper distribution of airflow to the riser part of the cooling panel. Any atmospheric disturbance and maldistribution that may have propagated down to the bottom of the cooling panel is suppressed in the bottom plenum and proper airflow distribution is restored.

Several drain connections are provided in the bottom cold plenum to drain any water that may be collected from the incoming air. Although the input/output structure is designed to prevent rain water from entering the RCCS, potential sources of water are mist entrained in the air, or some condensation on the cooler surfaces. The drain arrangement consists of four drain connections located at four corners of the bottom cold plenum directly below where the ductwork connects to the upper cold plenum. The drain lines, sized at 4 in. each, are brought down to a sump located at the bottom of the reactor cavity. The drain lines do not have any valves or pumps, and the cooling panel drains to the sump by gravity. The drain lines are oversized to provide flow even if partially obstructed.

The hot side of the RCCS cooling panel consists of two parts: the riser and the hot plenum. The riser part consists of 292 vertical rectangular structural steel tubes arranged around the reactor vessel. The tubes rise from the bottom cold plenum and connect to the hot plenum

located at the top of the reactor cavity. The tubes are vertically supported on the bottom cold plenum and are laterally supported from the downcomer with the help of lateral support plates. Supporting the hot riser tubes on the bottom plenum enables the tubes and the hot plenum to expand as they are heated. The design and configuration of the lateral support plates also accommodate the thermal expansion of the tubes. These high-strength steel plates bend easily as the tubes expand vertically.

A total of 292 tubes are provided. Each tube is a standard structural steel tube of rectangular cross section having external dimensions 2 in. x 10 in. with 0.1875 in. wall thickness. The tubes are arranged with a 2 in. gap between the adjacent tubes. The total number, cross-sectional shape, and configuration of the tubes provide optimal surface area for radiative and convection heat transfer, and optimal cross-sectional area for airflow. In addition, the gap between the tubes allow fractions of thermal radiation from the reactor vessel to reach the reflective surface. The reflected radiation then heats up the back side of the tubes, thus fully utilizing the full tube surface area and enhancing the heat transfer.

The hot plenum is trapezoidal in cross section and is arranged all around the reactor vessel along the cavity wall. The plenum receives hot air from the riser tubes and distributes it to the hot duct at four locations.

The hot plenum is completely supported by the riser tubes and is relatively free to expand. Tandem bellows expansion joints are provided between the hot duct and the hot plenum to accommodate thermal expansion of the riser tube-hot plenum assembly. The entire RCCS cooling panel assembly is a very stable and rigid structure and is designed for all required thermal, seismic, and pressure loading (due to tornado or pipe rupture).

4.6.2. RCCS Operation

RCCS is not required to remove decay heat during normal operation. However, since the system is passive, and due to the difference in the reactor vessel temperature and the outside air temperature, the system removes some parasitic heat during normal power operation, and removes some decay heat during normal shutdown.

During normal power operation, the reactor primary helium cold leg temperature is maintained nearly constant at 485°C (905°F) at 15% and 100% power. Forced circulation results in a uniform vessel temperature. Outside air temperature and, therefore, RCCS inlet temperature is assumed to vary independently over a range of -42°C (-45°F) to 43°C (110°F). These conditions lead to a varying parasitic heat loss to the RCCS cooling panel. The performance of the RCCS under nominal conditions is summarized in Table 4.6-1.

During normal shutdown, decay heat is removed via the Power Conversion System or the Shutdown Cooling System. As a result, a uniform vessel temperature is still maintained. However, the vessel is cooler than at power and becomes colder as the plant continues to cool down. Therefore, the heat rejection to the RCCS diminishes with time after shutdown.

4.7. FUEL HANDLING SYSTEM

4.7.1. System Function

The Fuel Handling and Storage System (FHSS) plays an important role in the GT-MHR as the uninterrupted and accurate movement of new and spent fuel elements in the plant is critical to the goal of achieving high plant availability. The system is used for (1) receiving and inspecting new elements at the receiving and inspection facility, (2) transporting these elements and to local storage facilities, (3) extracting irradiated fuel assemblies out of the reactors and moving them into the local storage facilities, (4) moving and installing new fuel elements back into the reactors, (5) transporting spent fuel elements from the local storage facilities to the packaging and shipping facility, and (6) packaging and shipping spent fuel elements out of the packaging and shipping facility. The system is also used to retrieve and replace spent reflectors and to manipulate special tools for in-service inspection of reactor components.

All the refueling functions are performed under remote automatic control although manual control intervention is allowed at all times. Many functions are performed in parallel to eliminate unnecessary plant down time. For example, new fuel elements are arranged simultaneously in the local storage facilities in preparation for refueling activities. However, refueling operations in a reactor core are intended to be performed in one reactor at a time in order to simplify refueling activities on the refueling floor, particularly the operation of equipment that is used to transport fuel elements between the reactors and the local storage areas. Nevertheless, in every instance,

TABLE 4.6-1
RCCS STEADY-STATE PERFORMANCE
NORMAL PLANT OPERATION
[43°C (110°F) AMBIENT AIR]

Parameter	100% Power
Reactor Vessel	
Heat loss to RCCS, kW	3300
Inside wall temperature, °C (°F)	485 (905)
Average outside wall temperature, °C (°F) (not including flange)	446 (835)
Maximum outside wall temperature, °C (°F)	474 (886)
Cooling Panel (Front)	
Average temperature, °C (°F)	267 (513)
Maximum temperature, °C (°F)	323 (613)
Air inlet temperature, °C (°F)	43 (110)
Air outlet temperature, °C (°F)	274 (515)
Airflow kg/sec (lbm/hr)	14.3 (113,500)
Maximum velocity, m/sec (ft/sec) at exit from panel	11.5 (37.7)
Structure	
Concrete surface temperature, °C (°F)	49 (120)

regardless of whether a function is performed automatically or manually, system computers monitor and electronically log every motion and control action to keep track of all fuel and reflector element transfers. Refueling operations and schedule are described below.

4.7.2. System Design Description

The major fuel handling and storage system components are the fuel handling machine, the fuel transfer cask, the fuel handling equipment support structure, the fuel handling equipment positioner, handling equipment in the local storage facility, and the element handling and accountability system. There is also a fuel sealing and inspection facility which is used for transferring new fuel and reflector elements to the local storage facility. In addition it is used for packaging spent fuel and reflector elements for later on-site dry storage or offsite disposal. The general arrangement of these facilities and equipment is shown in Fig. 4.7-1.

In-core fuel handling is performed by the fuel handling machine and the fuel transfer cask working jointly. They are mounted on the fuel handling equipment support structure, which is mounted on the reactor vessel on a support skirt as shown in Fig. 4.7-2. The fuel handling machine grapples each core element, one at a time, and deposits them on the fuel transfer cask guide sleeve as seen in Fig. 4.7-2. The fuel transfer cask grapples the elements raises them out of the core, and deposits them onto internal sliding storage tables. Once the fuel transfer cask is full (nine elements), it is transported to the to the local storage facility adjacent to the reactor where the elements are unloaded. During unloading, a second fuel transfer cask is placed over the reactor to receive the a load of fuel. When the second cask is filled, it is transported to a second location at the local storage facility where the elements are unloaded. This cycle of alternating fuel transfer cask operations is repeated until a complete core sector has been emptied. Elements are returned to the core in the reverse sequence and finally the foregoing pattern is repeated for the remaining core sectors.

For the two segment GT-MHR fuel cycle, one-half of the fuel during each outage is replaced. The portion of fuel not to be replaced is temporarily stored in the local storage facility for later return to the core. The other half is replaced with new fuel which has been pre-loaded into the local storage facility prior to refueling. The capacity of the local storage facility supports refueling for each of four modules plus the space needed to store one complete core. See Section 4.7.7 for additional discussion of the local storage facilities.

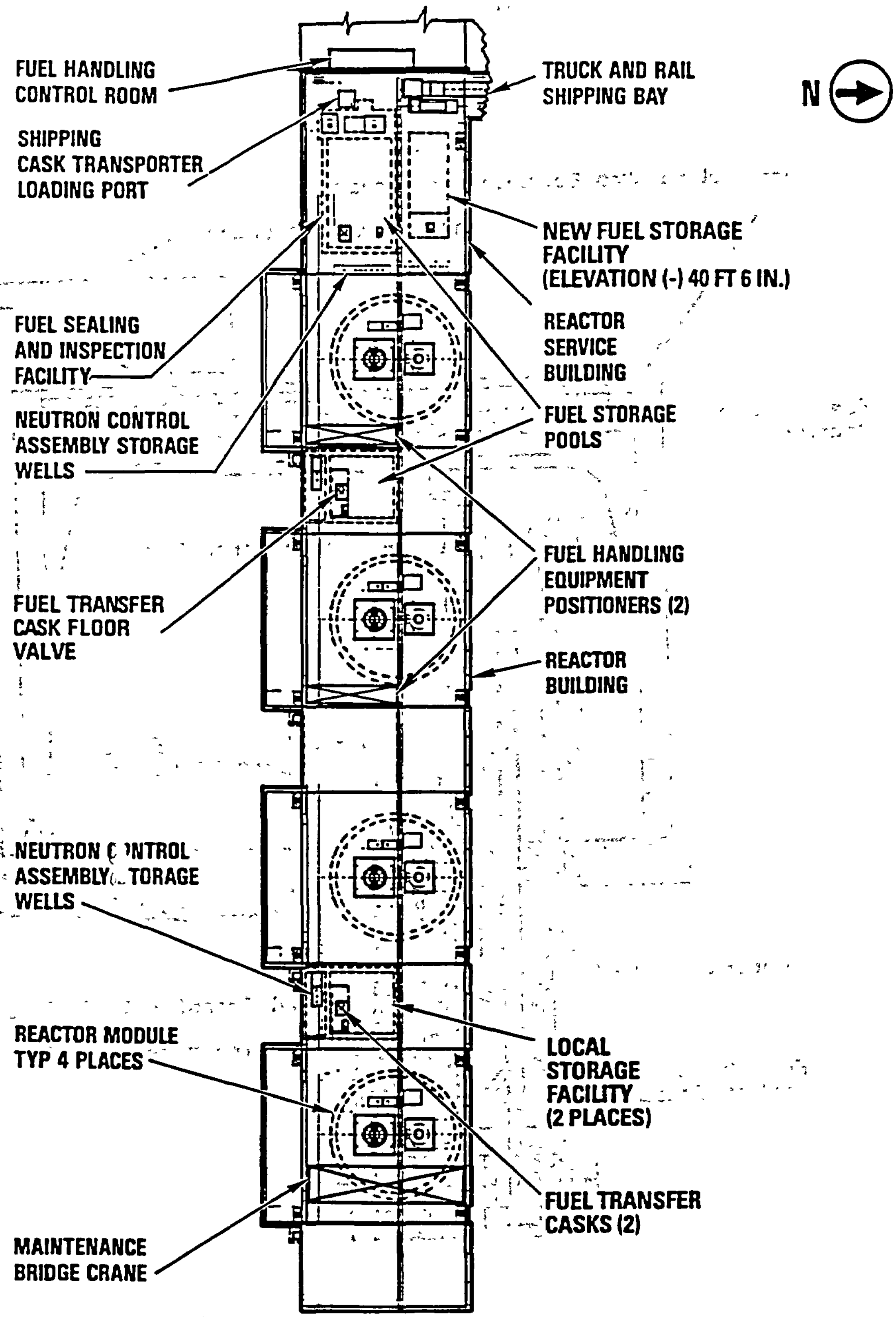

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Fig. 4.7-1. Fuel Handling and Storage System plant arrangement

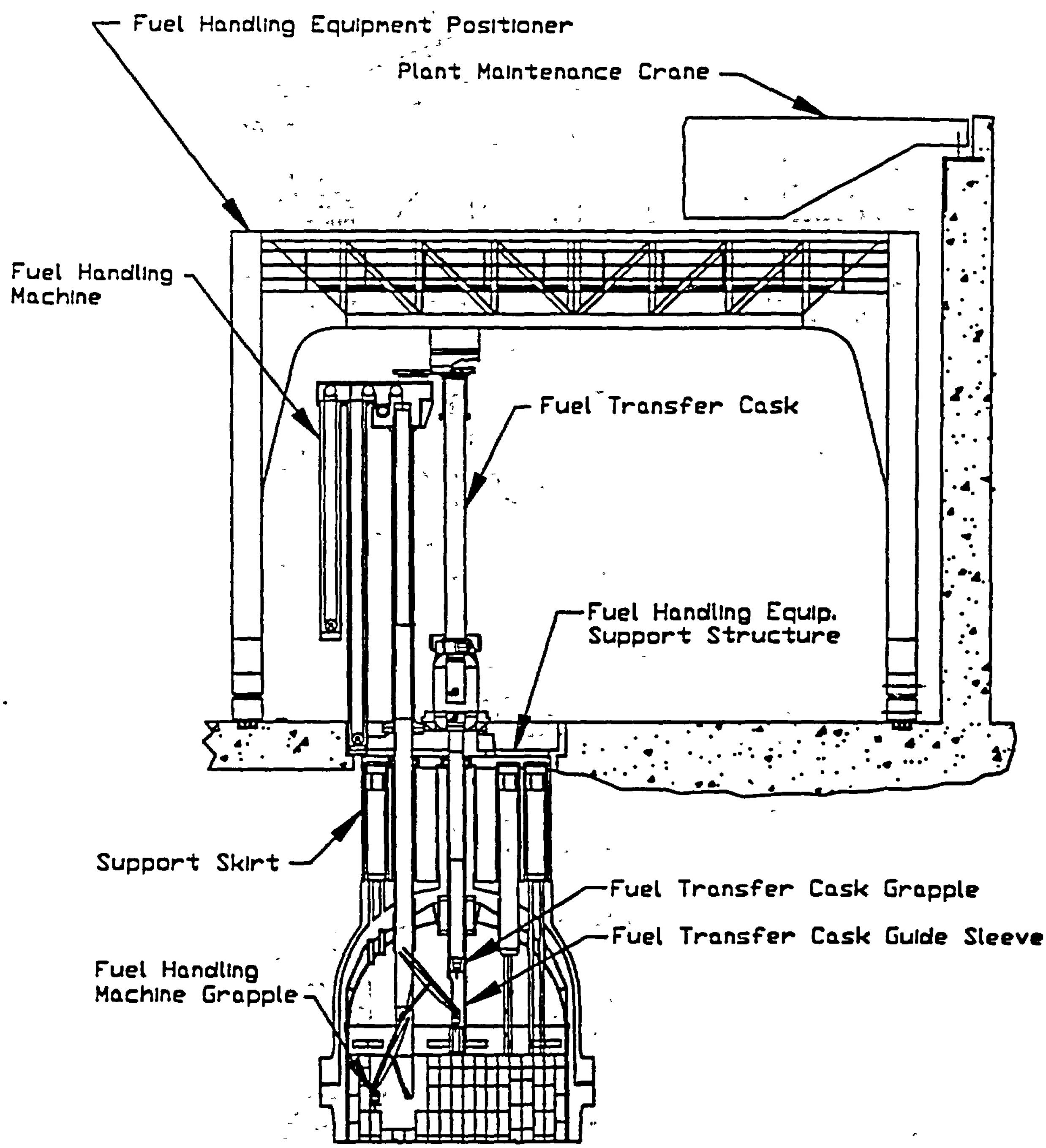

Fig. 4.7-2. Fuel handling equipment arrangement

The fuel transfer casks are transported between the fuel handling equipment support structure and the local storage facilities by the fuel handling equipment positioner, which is also used to position the fuel handling machine on the fuel handling equipment support structure and to position the fuel handling equipment support structure on the reactor vessel skirt before refueling starts. The fuel transfer cask lowers the core elements into the local storage facility and places them on an element turntable. The turntable moves the blocks underneath the element hoist and grapple assembly robot which moves the blocks to fuel storage wells for temporary storage. Once a core sector is emptied, the robot retrieves the blocks from storage and places them on the element turntable one by one. There, the fuel transfer cask picks up the blocks and returns them to the core. Special lanes are provided for the fuel handling equipment positioner so that fuel or other heavy loads are not transported over an operating reactor.

New fuel elements are transferred from the fuel sealing and inspection facility to the local storage facility in preparation for refueling. Spent fuel elements are transferred to the fuel sealing and inspection facility for packaging and shipping. These operations are accomplished at plant operator convenience between module refueling outages.

All fuel handling functions are planned, executed, and monitored by the element handling and accountability system. This system is a networked multi-computer system used by reactor engineers and refueling operators to plan refueling sequences, to execute the sequences and display the corresponding motion of the refueling system equipment, and to automatically update a data base that contains the location of every element in the plant following every fuel handling equipment move.

All fuel handling equipment use proven technology hardware that has been demonstrated at Fort St. Vrain and off-the-shelf hardware currently in use in industrial material handling applications. The methods used for locating and controlling position, speed and acceleration of elements within the reactor core are based on the Fort St. Vrain methods and techniques.

4.7.2.1 Refueling Operations

The following describes the refueling operations for the GT-MHR. Operations begin by shutting down and depressurizing a reactor module. Decay heat is removed by the Power conversion System or optionally by the Shutdown Cooling System. Helium inventory is trans-

ferred to storage to reduce primary coolant pressure to slightly below atmospheric pressure (6 in. of water).

The containment access plug is removed and stored on the refueling floor. The fuel handling equipment positioner moves the fuel handling equipment support structure over the reactor where it is attached to the vessel support skirt. Refueling crews remove closure plates from the reactor central penetration and the inner and outer neutron control assembly penetrations of the sector to be refueled. The in-core flux mapping unit instrumentation in the central penetration and the control rods in the inner and outer penetrations are retracted to their up position, locked into place, and electrical service lines disconnected.

The in-core flux mapping unit and neutron control assemblies are removed with the auxiliary service cask where they are temporarily stored in near-by equipment storage wells located in the refueling floor. The fuel transfer cask guide sleeve is picked-up by the auxiliary service cask and places it into the reactor central penetration. The guide sleeve is used to guide the grapple head of the fuel transfer cask and provide a shelf in the reactor on which fuel elements are placed by the fuel handling machine. The auxiliary service cask and fuel handling equipment support structure each contain isolation valves to maintain separation of primary coolant and atmospheric air and to provide for direct radiation shielding protection.

Next, the fuel handling equipment positioner places the fuel handling machine onto the fuel handling equipment support structure over the inner neutron control assembly penetration. There are two fuel transfer casks, the first of which is placed onto the fuel handling machine over the reactor central penetration. Fuel elements are picked up in the core by the fuel handling machine and placed on the fuel transfer cask guide sleeve. From their they are picked up and placed on to sliding storage tables within the fuel transfer cask structure. When the transfer cask is filled, it is removed from the reactor and transported to a local storage facility. After the first transfer cask has been removed, the second fuel transfer cask is placed over the reactor where core fuel handling operations continue.

At the local storage facility the first fuel transfer cask places fuel elements onto an element turntable. From there the elements are picked up with the element handling and grapple assembly robot and are placed into fuel storage wells. This operation continues until the fuel transfer cask is empty. After the second fuel transfer cask is filled at the reactor, it is transported

to a second port at the local storage facility where the fuel elements are off-loaded. After the second fuel transfer cask is removed from the reactor core, the first fuel transfer cask is returned for another load of fuel elements. This alternating movement of fuel transfer casks continues until the entire core sector has been removed and all of the fuel elements are placed onto the local storage facility.

Fuel elements are then returned to the core in essentially the reverse sequence of the foregoing description. At the local storage facility, however, pre-stored fresh fuel is placed into the core in addition to the partially irradiated fuel which has not completed the fuel cycle. Fully irradiated spent fuel is thus left in the local storage facility for later transfer to long term storage or disposal.

After the first sector has been refueled the neutron control assemblies are returned to the core. The remaining core sectors are then refueled as described above to complete the refueling. After the final neutron control assemblies and penetration covers are installed, all fuel handling equipment items are removed from the reactor area and the containment access plug is installed. At this point the reactor can be returned to power.

4.7.2.2 Core Refueling Time

The current estimated GT-MHR refueling time is 20.7 days at a 15.7 month interval based on 88% assessed plant capacity factor (see Section 7.2.3). One-half of the 1020 fuel elements and an average of one-fourth of the replaceable reflectors are replaced during the outage. The refueling time estimate includes operations for reactor shutdown and depressurization and reactor repressurization, start-up, and return to power. A 72% refueling inefficiency factor has been included to account for minor equipment and operational delays. The time does not include periods for non-concurrent ISI operations, which include in-core inspections and material sample monitoring activities. Refueling time estimates were developed from a step-by-step breakdown of each core element movement and refueling equipment motion.

4.7.3. Fuel Handling Machine Design Description

An enveloping schematic of the fuel handling machine is shown in Fig. 4.7-3. The machine is similar to other fuel handling machines used in prismatic fuel element gas-cooled

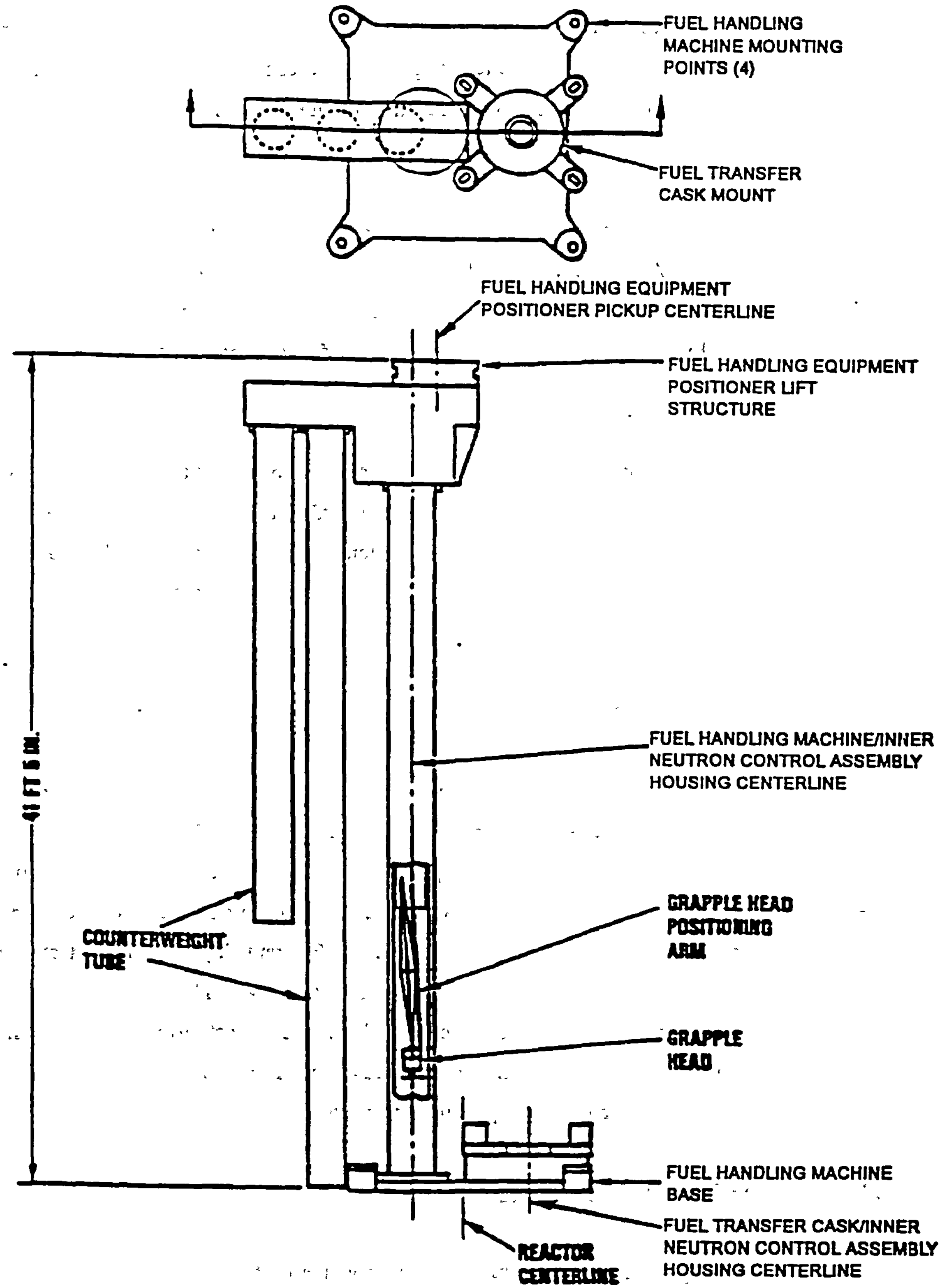

Fig. 4.7-3. Fuel handling machine

reactors. It has increased vertical and radial strokes of 2240 and 173 cm (882 and 68.25 in.), respectively. The weight of the machine is approximately 72.6 metric tons (80 tons), and it is transported by the fuel handling equipment positioner. During refueling, the fuel handling machine is secured to the fuel handling equipment support structure. The fuel handling machine also has the base on which the fuel transfer cask is placed. Together with the fuel handling equipment support structure integral isolation valves, the fuel handling machine provides atmospheric and radiation barriers for the protection of personnel on the refueling floor.

A grapple head supported by a handling mechanism performs the actual coupling of the fuel handling machine to the core elements. The grapple is designed to engage the central handling hole of the elements with a tapered probe and latch arrangement (Fig. 4.7-4). The fuel handling machine provides the capability of moving the grapple head in three coordinates. The vertical motion is accomplished through the extension of a series of telescopic tubes which are lowered into the core with a multistrand support chain and electric drive. Rotary motion of the grapple about the centerline of the telescoping tubes is accomplished with an electrically powered drive system mounted inside the inner telescoping tube. Radial motion of the grapple with respect to the telescoping tubes is accomplished with a mechanical linkage illustrated in Fig. 4.7-2.

The fuel handling machine design is based on the technology and concepts successfully proven at FSV, including the design improvements implemented to facilitate the defueling of the FSV reactor, and a more extensive use of electric drives to replace hydraulic and pneumatic drive systems. The performance of the equipment to defuel core at FSV has been excellent. These elements were used to replace core fuel elements during defueling to maintain integrity of core geometry filling fuel element locations that would have been left empty in the defueling process.

4.7.4 Fuel Transfer Cask Design Description

The fuel transfer cask is similar to the cask developed for earlier steel reactor vessels, and is illustrated in Fig. 4.7-5. Each cask has a capacity of nine full-sized elements and weighs approximately 90.7 metric tons (100 tons). During core refueling operations, the casks are used to transport fuel and reflector elements between the reactor module and adjacent local storage facilities. The fuel transfer casks are also used to transport elements between the local storage facilities and the fuel sealing and inspection facility at other times.

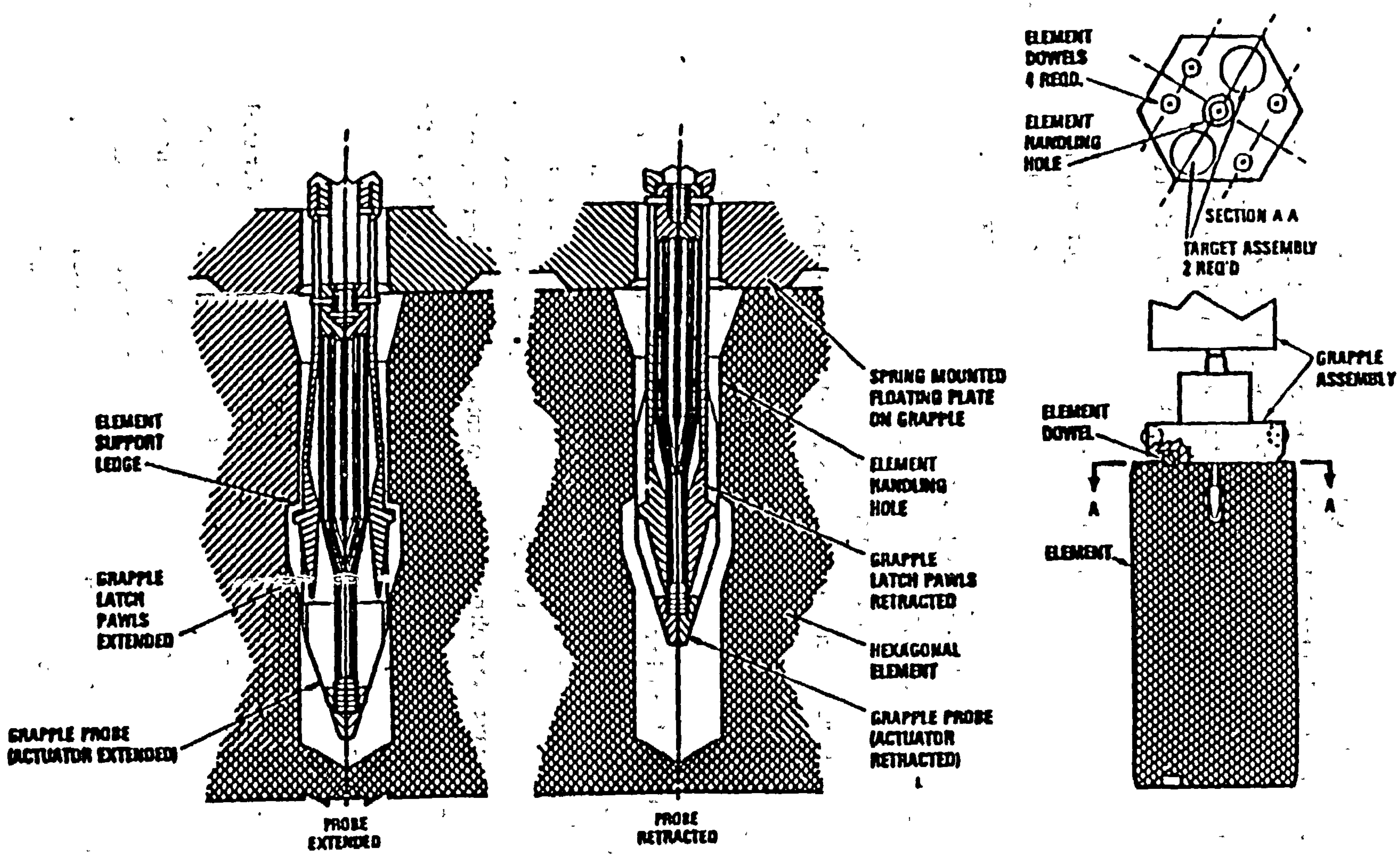

Fig. 4.7-4. Fuel element handling interface

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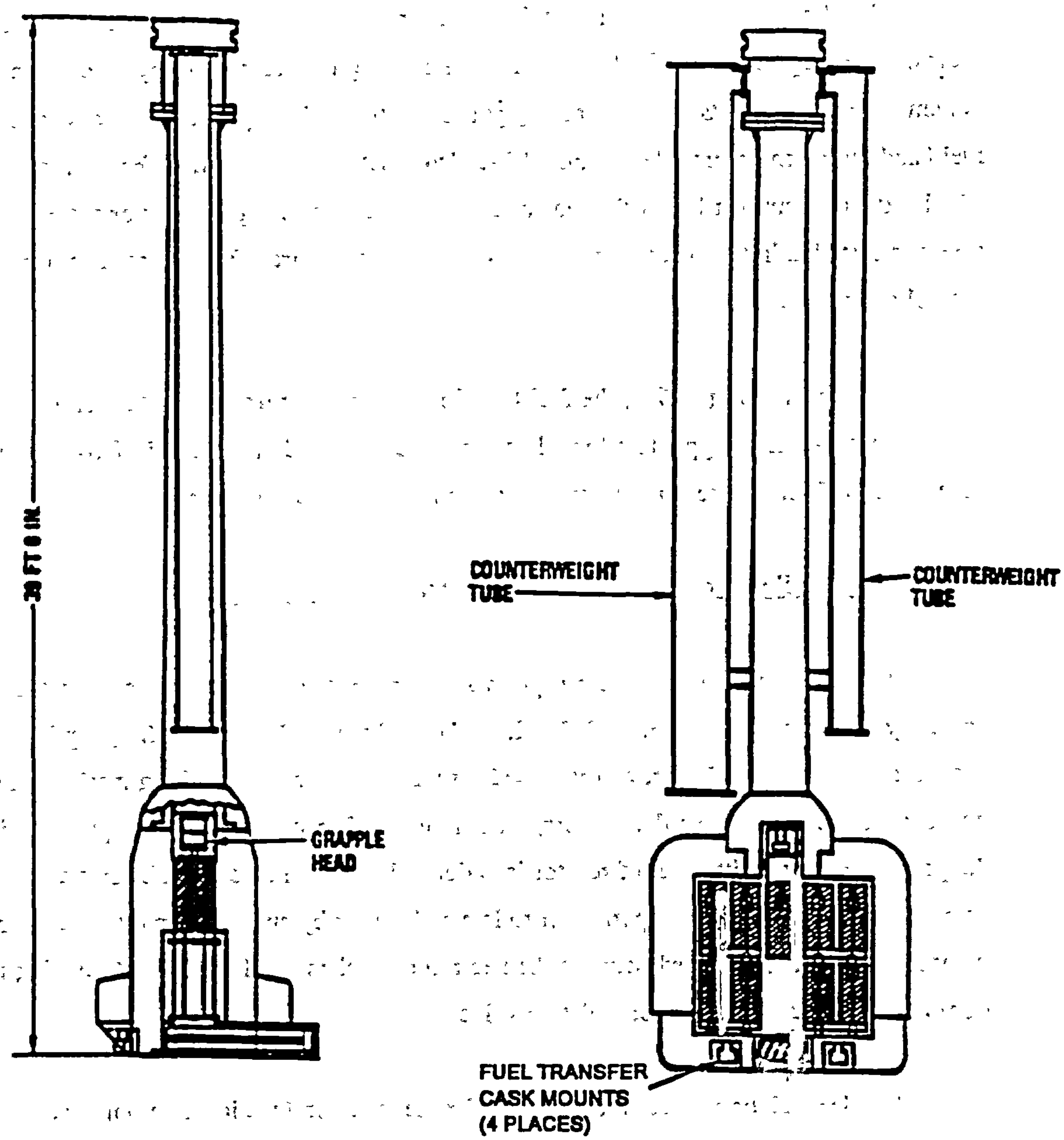


Fig. 4.7-5. Fuel transfer cask

The base of the fuel handling machine supports the fuel transfer cask when the cask is loading or unloading elements at the reactor vessel (Fig. 4.7-2). The thick walls of the fuel transfer cask provide the necessary shielding during the movement of the spent fuel. An automated anchoring system is provided to clamp the fuel transfer cask to the mating fuel handling machine base.

The element grapple within the fuel transfer cask is suspended from a redundant system of chains. The grapple is raised, along with its telescoping tube assembly, by an electric drive and system of counterweights. The grappling portion of the cask grapple assembly is similar to the fuel handling machine grapple. Figure 4.7-2 also illustrates the fuel transfer cask guide sleeve which extends from just below the reactor isolation valve to the upper reactor plenum. The guide sleeve is installed in the access penetration with an auxiliary transfer cask after an inner neutron control assembly is removed.

As shown in Fig. 4.7-5, the fuel transfer cask has four translating tables. They can be positioned under the grapple to allow elements to be deposited or removed. Two elements rest on each table, and one element is suspended from the grapple during transit.

4.7.5 Fuel Handling Equipment Support Structure Design Description

The fuel handling equipment support structure (Fig. 4.7-6) is supported on the reactor vessel by the support skirt (Fig. 4.7-2). It is placed there by the fuel handling equipment positioner utilizing an adapter, and it provides support for the fuel handling machine and the fuel transfer cask directly above the refueling penetrations. The support structure provides isolation of the primary coolant with a set of reactor isolation valves. The reactor isolation valve mechanism consists of a shielded gate supported on rollers and driven by an electric motor and worm gear. An inflatable seal is provided between the neutron control assembly housing (refueling penetration) and the base of the reactor isolation valve.

Similar isolation valves are provided for the isolation function on floor access ports at the local storage facilities and the fuel sealing and inspection facility.

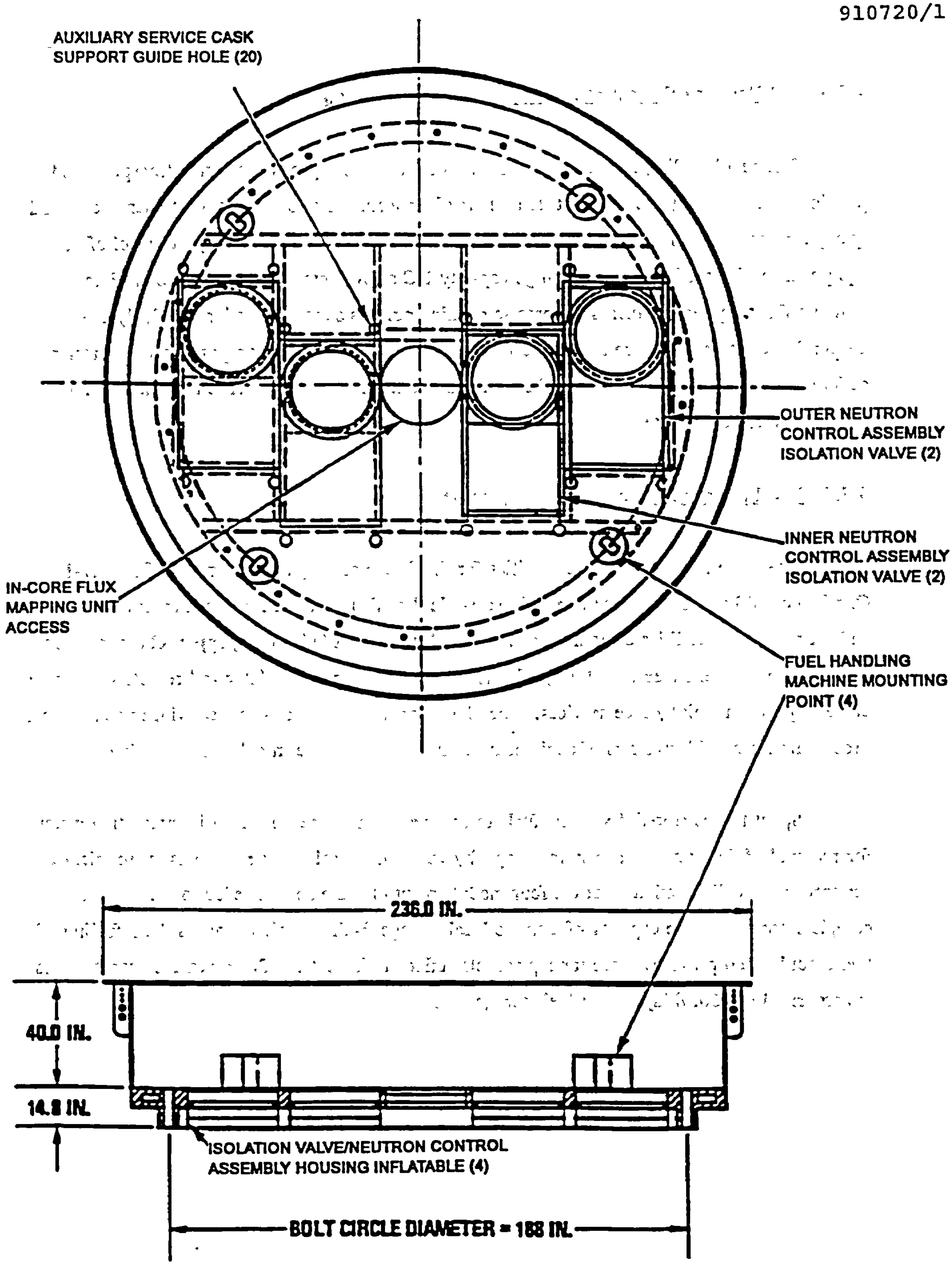


Fig. 4.7-6. Fuel handling equipment support structure

4.7.6 Fuel Handling Equipment Positioner Design Description

The fuel handling equipment positioner is an 100-ton capacity crane that transports and positions fuel handling equipment at its refueling locations. The equipment positioner is essentially a gantry crane, with each leg riding rails on the refueling floor (Fig. 4.7-7). Control of the equipment positioner is provided by high capacity DC servo motors and robotic controllers utilizing fiduciary facility marks for precise positioning. As stated in Section 4.7.2, System Design Description, there are two of these machines. One is used to transport the fuel transfer casks between the reactor vessel and the local storage facilities. The other is maintained in a parked position as a spare.

4.7.7 Local Storage Facility Design Description

There are two local storage facilities for the four module plant as shown in Fig. 4.7-1. One is located between modules one and two while the other is located between modules three and four. These facilities contain element turntables, element hoist and grapple robots, and fuel element storage wells (see Fig. 4.7-8). There is also a service manipulator and remotely operated crane to perform maintenance services. Each local storage facility is arranged with two redundant processing lines, with two sets of equipment items that can operate in either process line.

Spent fuel is stored dry in the fuel storage wells which are immersed in circulating water for removal of decay heat. The storage capacity within the local storage facilities is sufficient to support the refueling activities of the four module plant plus the space needed to store a one complete core. Storage capacity of a single local storage facility, which services the refueling of two modules and provides space for replaceable reflector elements, is 2806 element spaces. This is comprised of 350, 8 layer deep fuel storage wells.

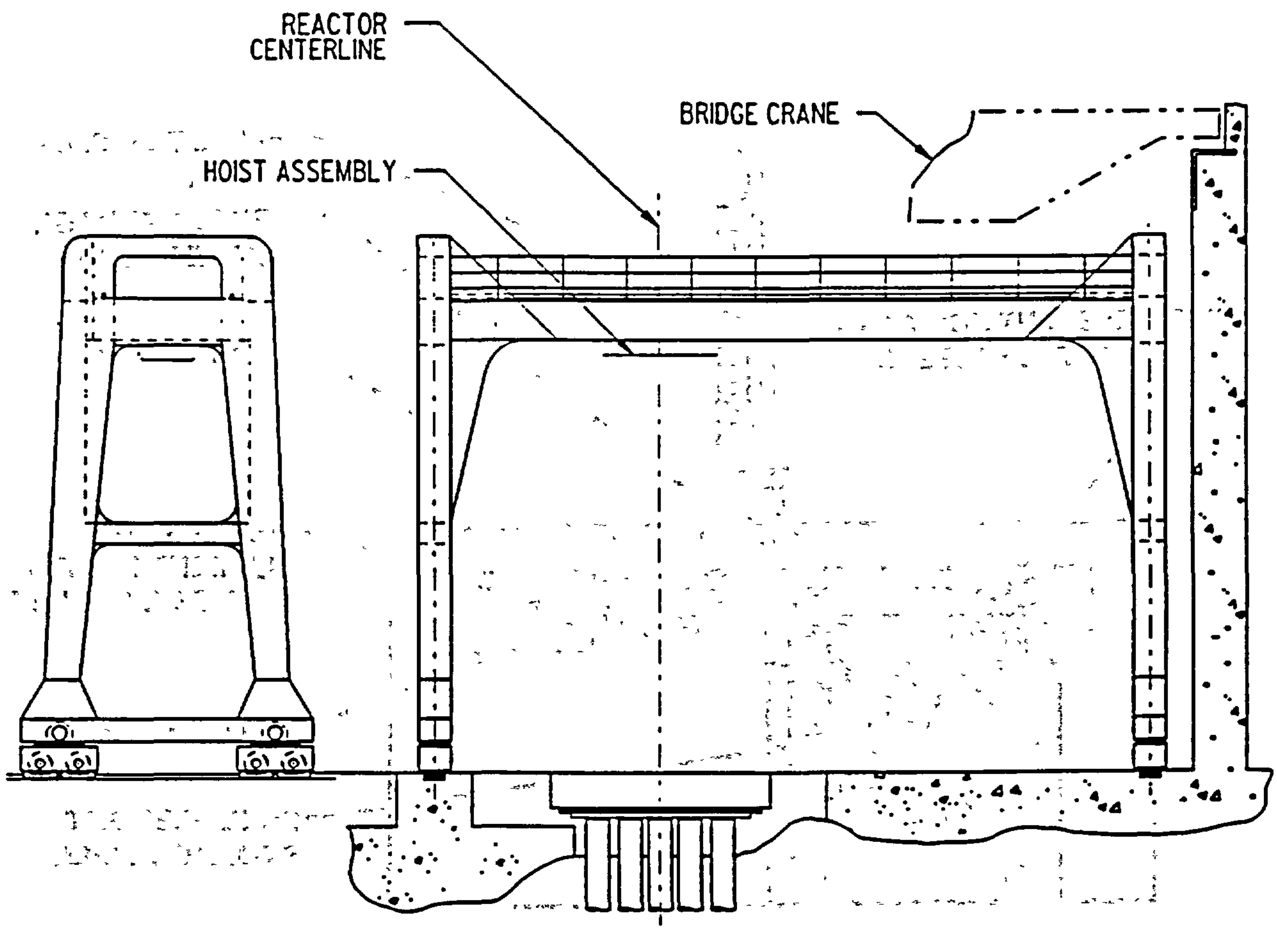


Fig. 4.7-7. Fuel handling eauipment positioner

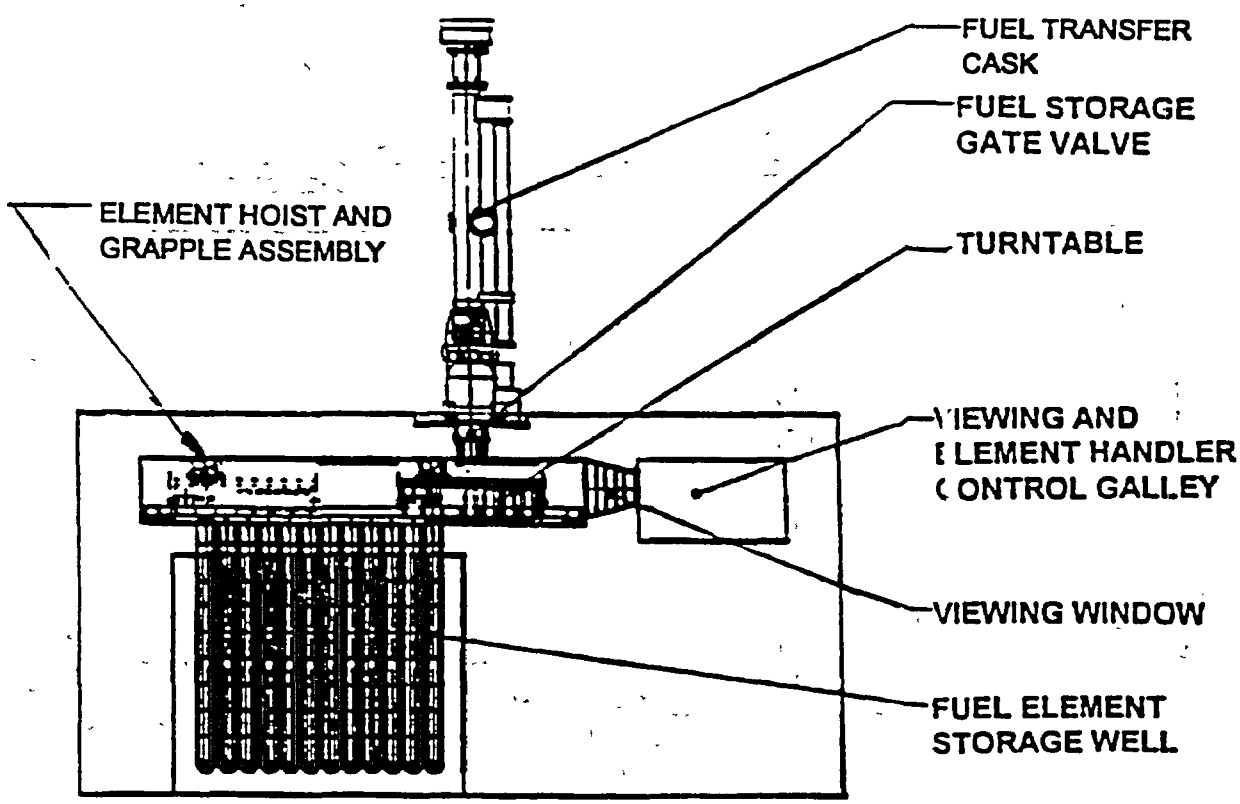


Fig. 4.7-8. Local storage facility

4.7.8 Element Handling and Accountability System Design Description

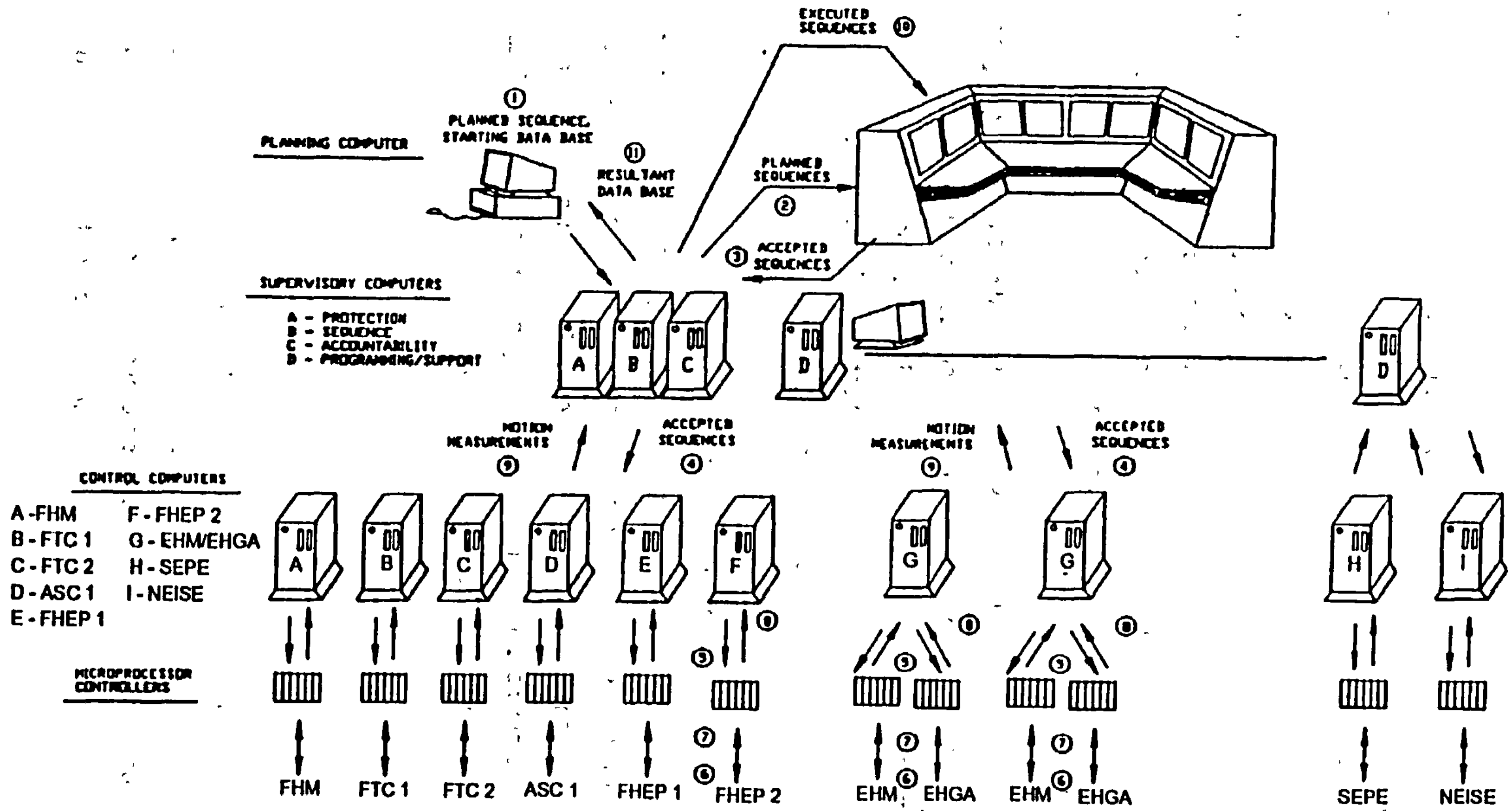
All fuel handling functions are planned, executed, and monitored by the element handling and accountability system. This system is used by reactor engineers to plan refueling sequences using graphic displays of repositories and interactive "point-and-click" motions of a cursor on the display screens. Then, the system is used to simulate the execution of the sequences and to display the simulated motion of the refueling system equipment. This simulation is used by refueling operators to review the planned sequences before they are executed. The system is then used to execute the sequences, automatically controlling the motion components and mechanisms. As the sequences are executed, dynamic displays of all machine motions are displayed to the operator. Manual intervention by the operator is allowed at all times.

The equipment handling and accountability system also tracks the coming and going of every fuel and reflector element in the plant regardless of whether refueling sequences are executed automatically or manually. It does that by monitoring all motion coordinates, by reading element serial numbers at strategic locations for location verification, and by automatically updating a data base of the location of every element after every move.

The equipment handling and accountability system is a networked multi-computer system that consists of four major systems (Fig. 4.7-9): (1) the planning computer, for sequence planing, (2) the supervisory computer system (includes the control console), which generates top-level sequence commands and monitors refueling motions, (3) the control computer system, which generates coordinate control commands for the individual refueling machines, and (4) the local controllers, which regulate and coordinate motion in each machine.

4.8. SPENT FUEL COOLING WATER SYSTEM

The Spent Fuel Cooling Water System is the facility that stores the spent fuel and removes the heat generated by the spent fuel. It consists of dry storage wells immersed in a pool of water. Each spent fuel storage pool has an entirely independent cooling system. The system is designed to function continuously. Cooling water circulating in the storage pool accepts the decay heat generated by the spent fuel and transports it to an air cooled heat exchanger for heat rejection to the atmosphere.



⑤ SETPOINTS AND COMMANDS
⑥ FINAL COMMANDS TO DRIVING DEVICES
⑦ INPUTS FROM SENSORS
⑧ DATA FROM MACHINES

EHM - EQUIPMENT HANDLING MACHINE
FHM - FUEL HANDLING MACHINE
FTC - FUEL TRANSFER CASK
ASC - AUXILIARY SERVICE CASK
FHEP - FUEL HANDLING EQUIPMENT POSITIONER
RIV - REACTOR ISOLATION VALVE
EHGA - ELEMENT HOIST AND GRAPPLE ASSEMBLY ROBOT
SM - SERVICE MANIPULATOR
SEPE - SPENT ELEMENT PACKAGING EQUIPMENT
NEISE - NEW ELEMENT INSPECTION AND SEALING EQUIPMENT

Fig. 4.7-9. Fuel Handling and Accountability System block diagram

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There are two fuel storage pools, one in each local refueling facility. Each storage pool contains 350 dry storage wells which store eight core elements each. Two 100% capacity pumps and one 100% capacity heat exchanger are provided per pool. The pumps are of the horizontal type, located adjacent to the storage pools. The air cooled heat exchangers are of the finned tube type. Each heat exchanger is located at grade, in near proximity to the spent fuel storage pool it is dedicated to cool. One pump is normally operating, with the other one on standby. The water pumped from the storage pool is circulated through the air cooled heat exchanger, where heat is rejected to the atmosphere and the water cooled before returning to the pool.

4.9. NUCLEAR ISLAND COOLING WATER SYSTEM

The Nuclear Island Cooling Water System removes heat from the following systems within each reactor module:

- Shutdown Cooling System.
- Helium Purification System.
- Liquid Nitrogen Recondenser.
- Sampling Systems.
- Helium Transfer and Storage System.

The system consists of four cooling loops - one independent cooling water loop for each reactor module. Each reactor module cooling loop serves cooling loads from potentially radioactive components of the reactor module. Since the Nuclear Island Cooling Water System is a closed system, it provides a barrier to direct transport of radioactivity to the environment.

Each reactor module cooling loop consists of two 100% capacity pumps, five 25% capacity air coolers, a surge tank, and a water chemistry package. The system is also equipped with the required instrumentation and controls. Since the cooling water is not expected to exceed 120°F, the surge tank is maintained at atmospheric pressure. The chemistry package allows for chemical additions to maintain the purity of the water in the system. The heat is rejected to the atmosphere through air-cooled heat exchangers.

The Nuclear Island Cooling Water System operates under all normal and refueling plant conditions, serving each of the four reactor modules. During any of the plant conditions, one pump and one heat exchanger bank in each loop are on standby.

4.10. HELIUM SERVICES SYSTEM

4.10.1. Helium Purification Train

The Helium Purification Train operates to remove helium from the primary coolant loop (helium inventory within the Vessel System), process it to remove chemical and radioactive impurities, and return the purified helium to the primary coolant loop as purge helium for turbomachinery seals, vessel seals, and vessel pressure relief piping. In addition, the Helium Purification Train operates in conjunction with the Helium Transfer and Storage Train to pressurize, depressurize, and control the primary coolant inventory consistent with plant load.

For a typical four-module plant the Helium Purification Train consists of four helium purification sections and two shared regeneration sections. Each helium purification section purifies a side stream of primary coolant helium at a maximum rate of 0.567 kg/sec (4500 lb/hr) and the regeneration section regenerates spent adsorber beds within the helium purification section. One helium purification section is provided for each reactor module, while one regeneration section is shared by two reactor modules.

A block diagram of the helium purification section is shown in Fig. 4.10-1. The system is a helium processing train consisting of filters, dryers, packed beds, and heat exchangers. With the exception of the helium compressors and helium isolation valves, there are no moving parts which assures a system that has high reliability and availability. Also, spares will be maintained for all of the filters, adsorber beds, and compressors to further assure high availability.

During normal plant operation, the helium purification section extracts helium from the primary coolant loop at the high pressure compressor outlet, purifies the helium, and returns the purified helium to the reactor coolant loop at the precooler inlet. The purified helium is also returned to other locations within the Vessel System that require helium flow including the vessel seals, the vessel pressure relief piping, turbomachine seals, shutdown circulator seals, and purges for various other vessel penetrations.

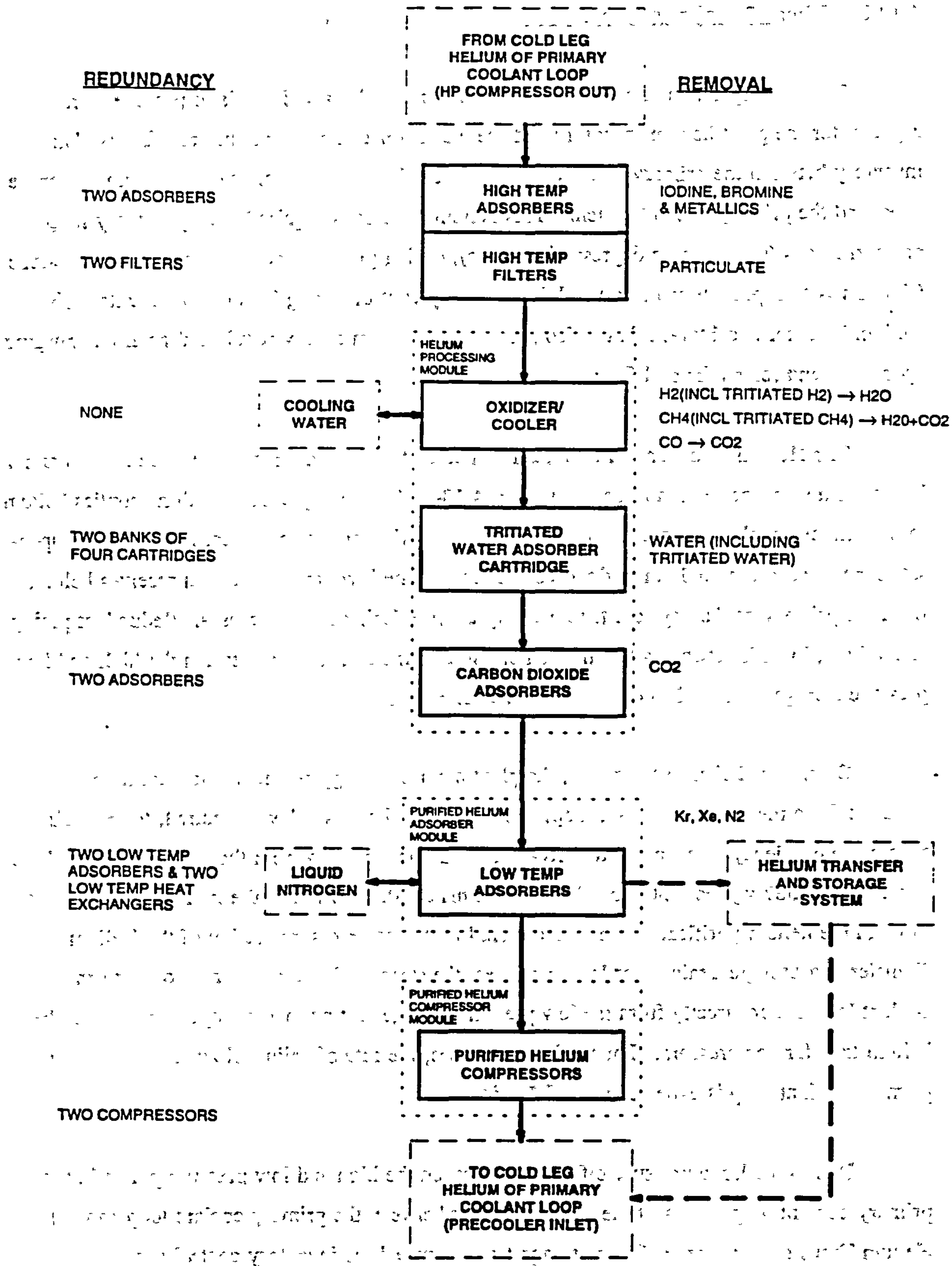

Fig. 4.10-1. Block flow diagram of the Helium Purification Train

4.10.2. Helium Transfer and Storage Train

The primary function of the Helium Transfer and Storage Train is to provide storage capacity for the plant helium inventory and the means for compressing and transferring that inventory between the primary coolant loop and the helium storage tanks or between the storage tanks and the primary coolant system. This helium transfer is required during primary loop pressurizations (startup from depressurized state), during primary coolant loop depressurizations (shutdowns to depressurized state) and for inventory control during load change events. The Helium Transfer and Storage Train also provides the helium supply required for various purging operations and for buffer seal flow.

The Helium Transfer and Storage Train consists of a high pressure storage section and a low pressure storage section as shown in Fig. 4.10-2. The high pressure section supplies helium to the primary coolant system for inventory control during power increases, makeup to compensate for vessel losses, and purge flow requirements. The low pressure section receives helium from the primary coolant system for inventory control during load decreases. Redundant piping and valving in both sections allow the compressors to transfer helium between the high and low pressure storage tanks and in or out of the Vessel System.

During load change transients, the plant control strategy requires that helium be added or removed from the primary coolant loop, depending on the power level required, to maintain a high cycle efficiency. During load decreases, helium is extracted from the primary coolant loop at a rate of 0.567 kg/sec (4500 lb/hr) or approximately 0.75%/min of the inventory, processed through the helium purification train, and stored in the low pressure section of the Helium Transfer and Storage Train. For load increases, the stored helium is returned to the primary coolant loop either directly from the low pressure storage section or is pumped back using the helium transfer compressors. For the load increases, the rate of helium flow returned to the primary coolant loop is expected to be 5%/min.

Due to the large pressure differential between the high and low pressure points in the primary coolant loop, much of the helium transfer between the primary coolant loop and the Helium Transfer and Storage Train storage tanks required for inventory control can be

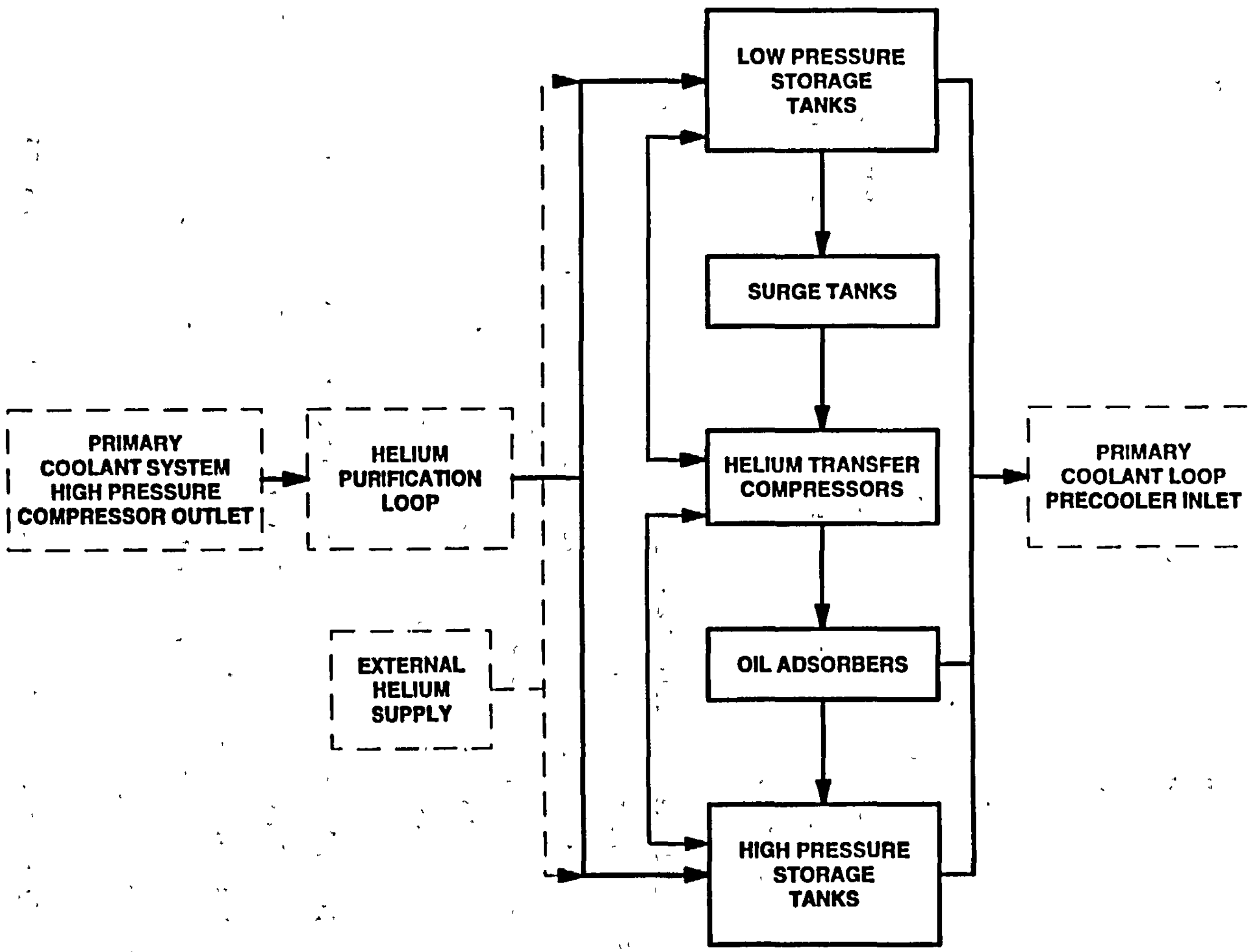

Fig. 4.10-2. Simplified block diagram for the Helium Transfer and Storage Train

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accomplished without requiring the use of the transfer compressors. For load reductions, the helium is transferred by the helium purification train to the low pressure storage section. For load increases from above 50% load, the helium inventory is restored to the primary coolant loop at 5%/min by pressurizing from the low pressure storage tanks. For load increases from below 50% (between house load and 50%), the pressure in the low pressure storage tanks is not sufficient to maintain the 5%/min flowrate. Consequently, the transfer compressor is required either to pressurize the low pressure storage tanks to a higher pressure or to pump helium to the primary coolant loop.

4.11. RADWASTE AND DECONTAMINATION SYSTEM

The radioactive waste management systems segregate, collect, processes, store, and dispose of radioactive liquid, gaseous, and solid wastes originating within the plant site. The liquid, solid, and gaseous radioactive waste management systems are configured to support groups of four reactor modules.

Liquid Radioactive Waste Management System. The Liquid Radioactive Waste Management System is composed of two connected systems which utilize filtration and demineralization to process the liquid radwaste. One system processes high purity (small amounts of containments) waste and the other processes low purity waste. The high purity and low purity waste are each collected in a separate collection tank. The total amount of radioactive liquid waste to be handled by this system is estimated to be 10 m^3 per year per module.

The high purity waste passes through two cartridge filters, a carbon filter and three ion exchangers. Normally a pair of mixed bed demineralizers is sufficient to permit cleanup of waste trains sufficient to produce condensate grade water. Cartridge type filters are provided downstream of each ion exchanger to collect resin fines. Treated and purified liquid wastes are reused in the plant.

The low purity waste is processed through two cartridge filters and a carbon filter to remove suspended solids. This processed waste is intended for discharge to the solid waste system or recycle to the high purity system for further processing.

Each system collects processed waste in monitoring tanks where one may be sampled and processed while the other is being filled. A recirculation pump and blade mixer in each tank assures adequate mixing for representative samples. Wastes from the monitoring tanks can be recycled as necessary to ensure removal of the radioactive species.

Gaseous Radioactive Waste Management System. The Gaseous Radioactive Waste Management System processes waste gases that are potentially radioactive to reduce the activity to a level acceptable for discharge to the atmosphere. The total radioactive gaseous waste for the GT-MHR is estimated to be 3500 m^3 per year per module.

The gaseous wastes are generated and collected in the various buildings in the plant. These wastes are transferred to the Radioactive Waste Building. Most of the gaseous wastes need only to be filtered and monitored before discharge. However, the gaseous wastes generated by the Helium Purification Train and the Pressure Relief System will require a holdup system for decay of short-lived radionuclides, and are routed through charcoal beds before discharge.

The low activity gaseous waste stream is circulated through a tank, High Efficiency Particle Air (HEPA) and carbon filters before it is monitored and discharged to the atmosphere. The higher activity gaseous waste stream is circulated through a train of HEPA filters, tank, cooler, moisture separator, heater, and charcoal beds before being monitored and discharged. The two systems for the low and higher activity gas streams are separate, but have two connections between them to direct waste gas from the low activity system to the higher activity system in case the low activity system receives gas with a higher activity.

Elaborate monitoring is provided for the stack discharge to keep a detailed account of isotopic discharges.

Solid Radioactive Waste Management and Component Decontamination System. The Solid Radioactive Waste Management and Component Decontamination System performs the following functions for all four reactor modules:

- Provides collection solidification, packaging, and storage facilities for radioactive materials prior to their shipment offsite for disposal.

- Provides for radioactive decontamination and drying of parts and small components.

- Provides solidification for decontamination solutions and wet solid wastes.

The total solid radioactive waste for the GT-MHR is estimated to be 70 m^3 per year per module.

A spent resin tank is provided for storage of spent resin. This tank has a standpipe through which waste is transferred to the solidification system when the tank is pressurized with service air. This permits resin to be moved without passing through restrictions such as those associated with pumps. An underdrain using wedge wire screens permits resin dewatering while the tank is pressurized. An internal blade mixer slurries the resin prior to transfer operations. Should more slurry water be needed, demineralized water may be added through the spray header.

The solidification system is a prepurchased system that integrates container movements, solidification agent bulk storage waste addition to waste containers, drum inspection, and truck bay waste processing. A decanting tank collects all types of waste intended for solidification. Waste can be precisely metered from here to a waste container where it is then mixed with the solidification agent.

The overhead bridge crane is an integral part of the system operation and is fitted with drum lifting mechanisms which are compatible with the drumming station design. Pan, tilt and zoom capabilities are part of the television viewing system on the crane and permit monitoring of drumming operations, storage areas, and truck bays.

A dry active waste sorting room is equipped with fume hoods and radiation scanning equipment for locating and segregating items that are contaminated.

Component decontamination equipment allows components such as valves and small pumps to be decontaminated prior to maintenance. The decontamination equipment consists of tubs where chemicals can be used to dissolve contaminants and demineralized water can be used to rinse components. Ultrasonic cleaners along with a water lance are also used to remove contaminants.