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PRIMARY SYSTEM DESIGN STUDIES FOR ADVANCED DIRECT CYCLE NUCLEAR GAS TURBINE PLANT

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ABSTRACT

Continuing studies of the Gas Turbine High-Temperature Gas-Cooled Reactor (GT-HTGR) power plant have been directed toward identification of a plant configuration with improved economic incentives over competing electric power plants. This paper outlines the studies which led to the selection of the primary system for a plant with optimized parameters from the standpoint of minimum power generating cost. As in previously reported designs, an integrated type of plant embodying multiple helium gas turbine loops was selected. The layout of the power conversion loop (PCL) components in the prestressed concrete reactor vessel (PCRV) and the development of the primary system helium gas flow paths are discussed.

The studies reported in this paper led to changes in the PCRV geometry which had a significant impact by reduction in the size of the PCRV and attendant cost savings. With orientation and configuration of the major PCL components forming the basis of these studies, some of the preliminary design considerations for the turbomachinery, heat exchangers, thermal barrier, and control valves together with maintenance considerations are discussed. The reference plant preliminary design presented is based on a 3000-MW(t) core thermal rating with a reactor outlet (turbine inlet) temperature of 850°C: the overall plant efficiency of the dry-cooled direct cycle nuclear gas turbine is 40%.

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1. INTRODUCTION

The GT-HTGR power plant combines the existing HTGR core with a closed-cycle helium turbine power conversion system. The nuclear gas turbine plant outlined in this paper is based on work performed in a phased program to prepare a reference design and obtain information on safety, control, economics, performance, and development for evaluation of a power plant utilizing a 3000-MW(t) reactor core.

This work is a continuation of conceptual design activities for the plant and major components, earlier work having been discussed previously (Refs. 1-4). Continuing preliminary design efforts during 1976 were aimed at establishing a plant with improved economic incentives compared with the previously established reference design (Ref. 3). The design of a new power plant of this type is an evolutionary process, with changes being made in the direction of minimizing total power generating cost by maximizing cycle efficiency and minimizing both capital and operating costs.

As discussed in earlier papers (Refs. 1, 3, 4), an integrated plant was selected in which all of the major power conversion components and entire helium inventory are contained within the PCRV. A major change in the orientation of the horizontal turbomachinery within the PCRV had a significant impact on plant capital cost reduction. As reported in previous papers, a plant embodying multiple gas turbine loops was adopted. Based on a nonintercooled cycle with a high degree of heat recuperation, an optimization study (Ref. 5) was performed to identify the cycle parameters for the dry-cooled plant. In the economic-performance optimization and sensitivity studies, analytical models of the major components and plant structures were generated, and an overall plant configuration and major cycle parameters were selected to give minimum total power cost. With a turbine inlet temperature of 1562°F (850°C), a maximum system pressure of 1150 psia (7.93 MPa), and a compressor pressure ratio of 2.5, a plant efficiency of 40% is projected for the dry-cooled plant.

2. THERMODYNAMIC CYCLE AND PERFORMANCE

The plant design and performance data are based on a twin 3000-MW(t) reactor arrangement with a turbine inlet temperature of 1562°F (850°C), which represents a modest increase in the core outlet temperature that can be delivered now by HTGRs intended for steam application. This temperature is below the level where turbine blade cooling is necessary, and existing nickel-base alloys that are utilized in industrial open-cycle gas turbines can be used. The salient cycle parameters are shown in Table 1 and the cycle diagram is shown in Fig. 1. For the given reactor outlet temperature, the optimization studies identified the major cycle independent variables to give minimum power generating cost, and these are briefly discussed below.

Compared with previous studies, the system maximum pressure was increased slightly to 1150 psia (7.93 MPa). This pressure level gives high gas density and compact turbomachinery, heat exchangers, and ducts and is only a modest extension of PCRV structural design practice. The design point compressor pressure ratio was increased slightly to 2.50. With a recuperator effectiveness of 0.898, this pressure ratio is still slightly less than optimum for maximum efficiency, but it was chosen to reduce the number of compressor and turbine stages, which is strongly influenced by the low molecular weight, high specific heat helium working fluid. In the plant and component layout studies emphasis was placed on selecting internal flow path geometries to minimize system pressure loss, since this has a significant effect on the performance of a closed-cycle gas turbine. With a 1562°F (850°C) turbine inlet temperature, the plant rating, with twin 3000-MW(t) reactor cores, is 2400 MW(e), and the cycle efficiency is 40% for the dry-cooled plant.

TABLE 1
GT-HTGR PLANT CYCLE PARAMETERS

Turbine Inlet Temperature, °F (°C)	1562 (850)
Compressor Pressure Ratio	2.50
Compressor Inlet Temperature, °F (°C)	79 (26)
Maximum System Pressure, psia (MPa)	1150 (7.93)
System Pressure Loss Ratio	0.0703
Recuperator Effectiveness	0.898
Cooling Water Outlet Temperature, °F (°C)	334 (168)
Turbine Isentropic Efficiency (across blading), %	91.8
Compressor Isentropic Efficiency (across blading), %	89.8
Turbine Disk Cooling Flow[a], %	3.6
Turbomachine Bypass Leakage[a], %	0.30
Recuperator Plus Precooler Bypass Leakage[a], %	0.75
Generator Efficiency, %	98.8
Primary System Heat Loss, MW(t)	2 x 13.2
Station Auxiliary Power, MW(e)	2 x 10.5
Station Efficiency, %	40.0
Net Electrical Power, MW(e)	2 x 1200
Reactor Thermal Power, MW(t)	2 x 3000
Compressor Helium Flow Rate/Loop, lb/sec (kg/sec)	1265 (574)

[a] All bypass flows based on compressor flow rate.

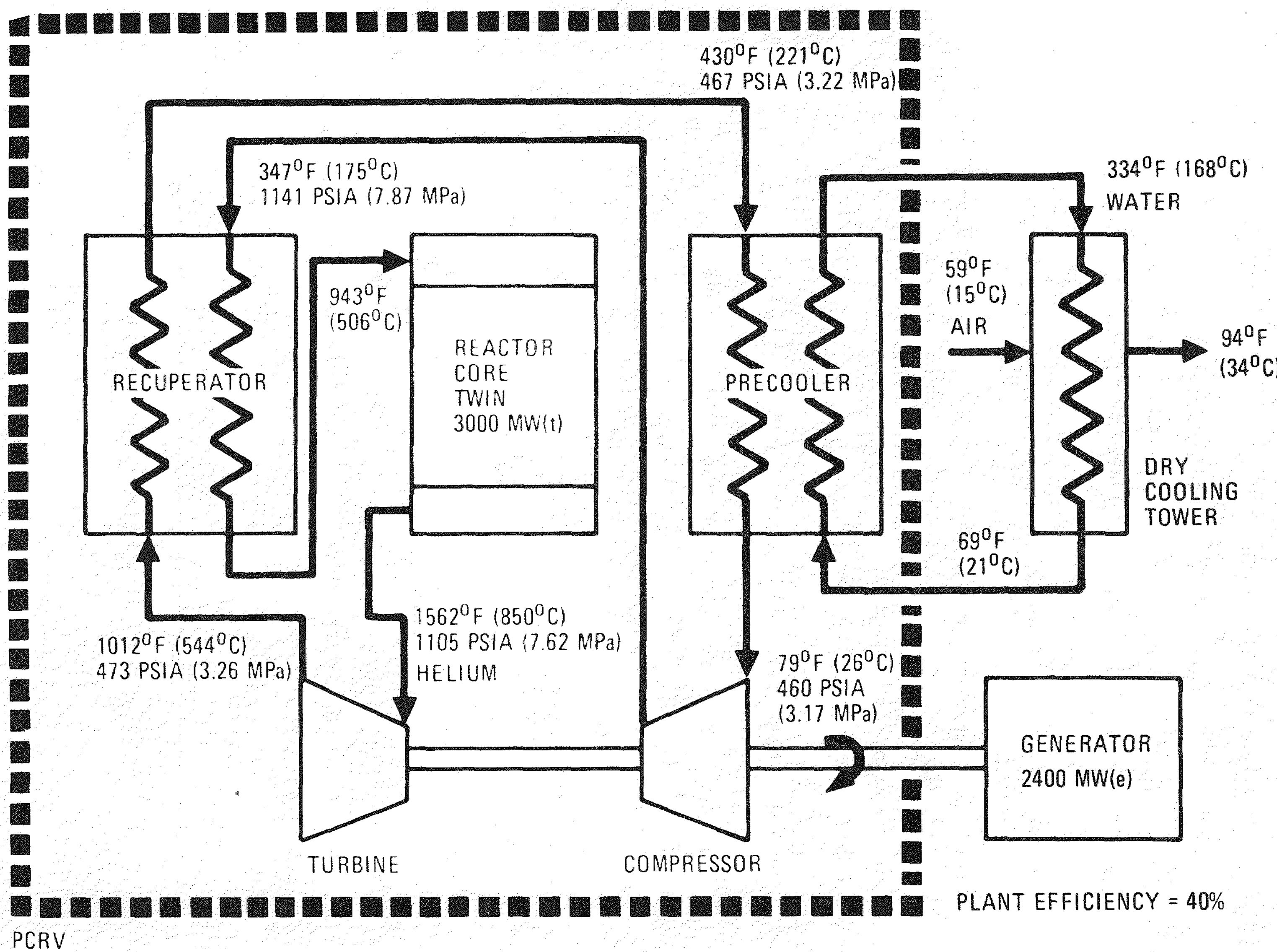

Fig. 1. Cycle diagram for dry-cooled GT-HTGR plant with twin 3000-MW(t) reactor rating

3. PRIMARY SYSTEM DESIGN

A decision was made early in the program to adopt an integrated primary system on the basis of both safety and economic considerations, and to avoid the necessity of providing for the adequate protection of large external high-pressure vessels and ducts. The compact integrated power plant provides inherently high reliability against pressure boundary failures that could result in rapid depressurization. With the power conversion machinery inside the PCRV, an appropriate equipment maintenance philosophy was established. While access is provided for turbomachine inspection and minor repairs, including journal bearing removal, the design is not predicated on the necessity for man access for component installation and removal. A simplified isometric diagram of the GT-HTGR power plant primary system is shown in Fig. 2. All primary components, with the exception of the electric generators, are housed within the PCRV, which is 118 ft (36 m) in diameter and 111 ft (34 m) high.

For the 3000-MW(t) core rating, a preliminary primary system design embodying three gas turbine loops was selected. The resulting 400-MW(e), 60 Hz, turbomachine can be designed within current rail transportation limits and can be accommodated in the PCRV horizontal cavities. For a machine of this rating, a conservative design for the full life of the plant is possible with uncooled turbine blades made from existing nickel-base alloys.

The reactor core in the GT-HTGR plant utilizes the same prismatic fuel and core configuration developed for the steam cycle HTGR. The core is contained in a central cavity 37 ft (11.3 m) in diameter and 47 ft (14.4 m) high.

The power conversion loops are located symmetrically around the central core cavity as shown in the simplified plan view of the PCRV in Fig. 3. Each loop includes a helium gas turbine, a recuperator, and a precooler. The three turbomachines are oriented in a horizontal delta arrangement, and

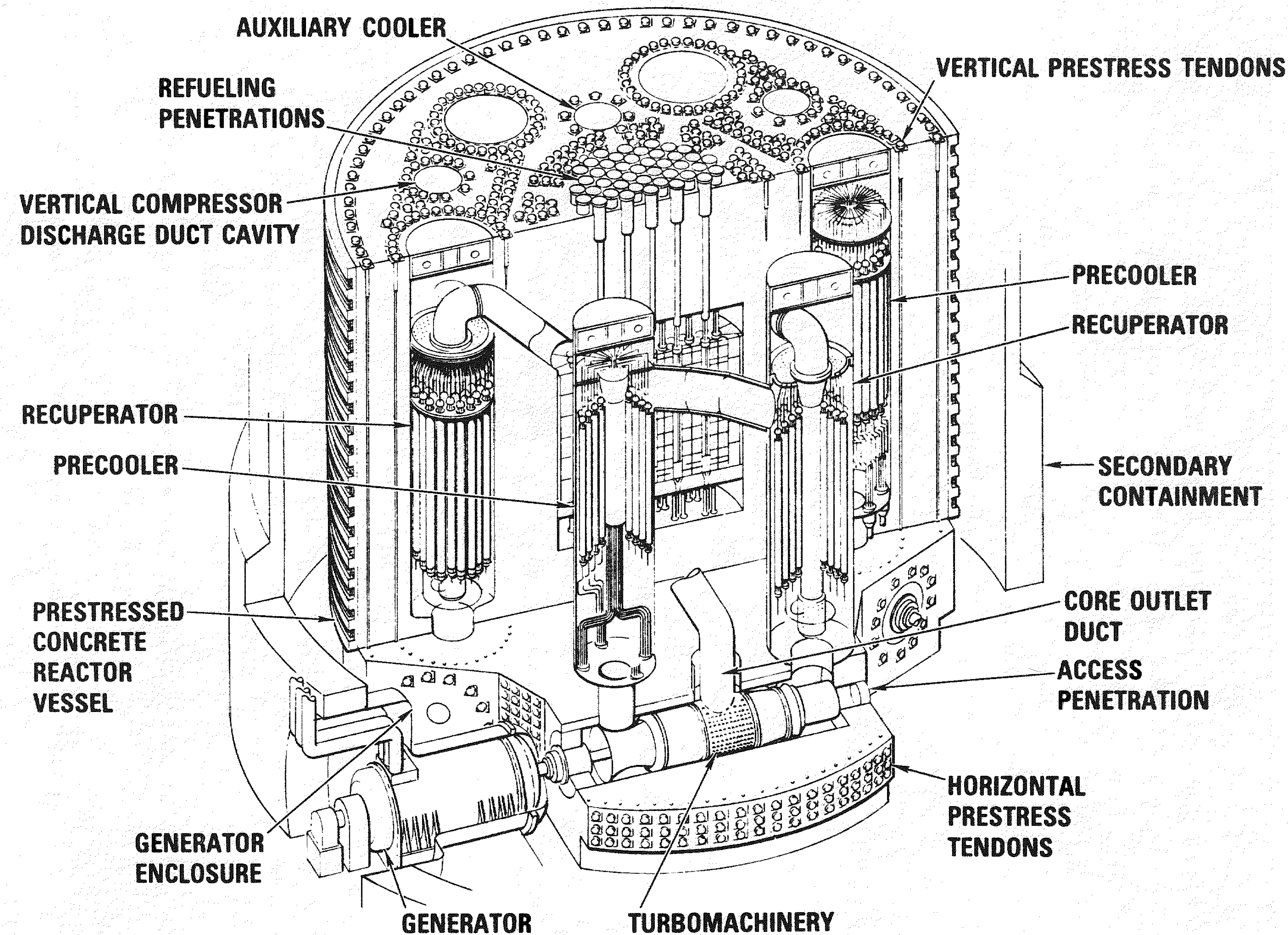

Fig. 2. Integrated GT-HTGR power plant incorporating 3000-MW(t) reactor core and three power conversion loops

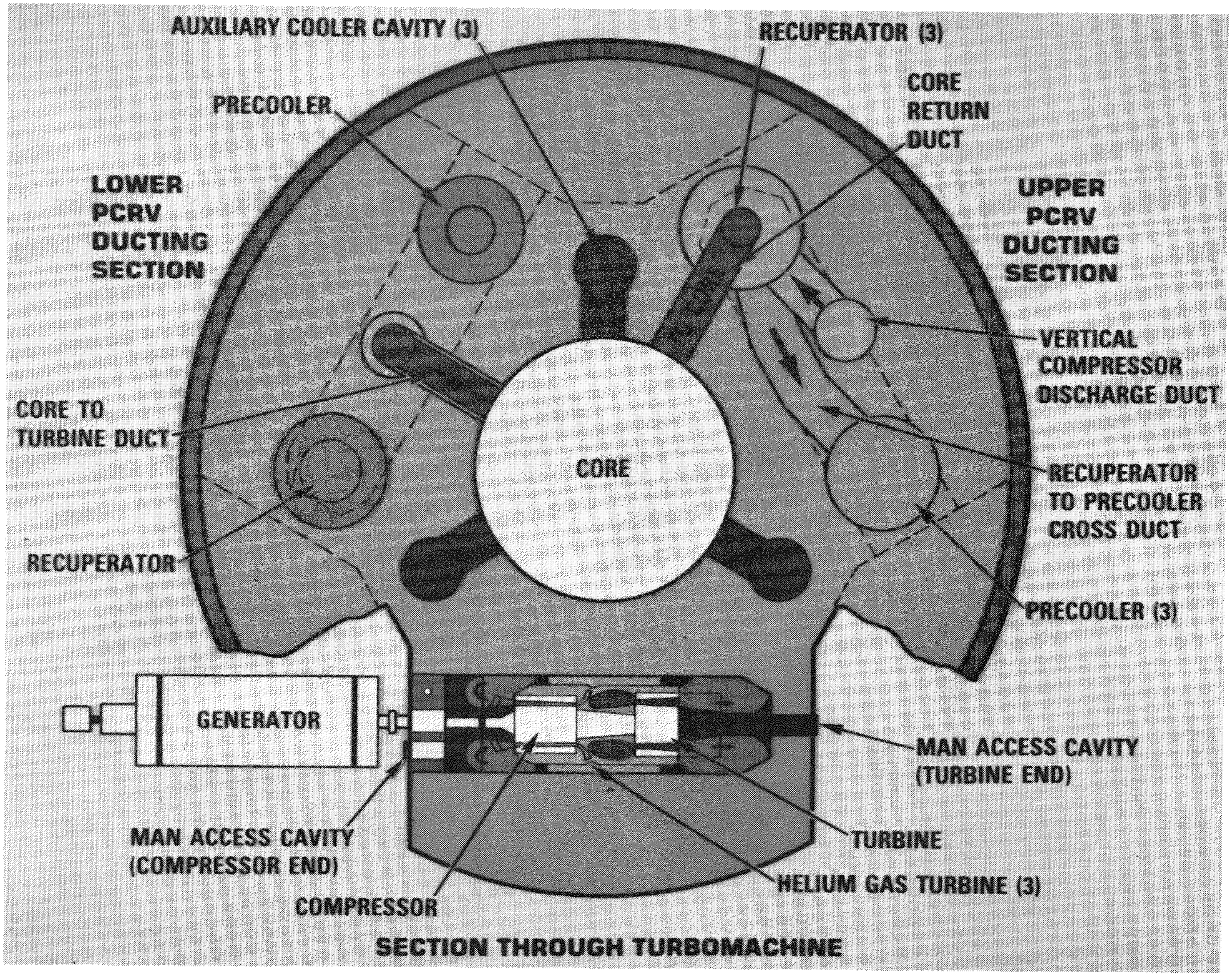

Fig. 3. Plan view of PCRV showing delta arrangement of turbomachinery cavities for three loop GT-HTGR plant

the heat exchangers are installed in vertical cavities arranged within the PCRV wall, two for each loop. The components are connected by large internal ducts within the PCRV. The internal surfaces of all PCRV cavities and ducts are lined with an impermeable steel membrane and covered with a thermal barrier designed to limit system heat losses and control concrete temperatures.

The horizontal turbomachine cavities are located directly below their associated loop heat exchangers, with the axis of the cavity oriented in a chordal direction rather than radial as reported for the previous plant reference design (Ref. 3). This was a significant change permitting a reduction in vessel size since the length of the turbomachine no longer controls the diameter of the PCRV. This arrangement places the recuperator directly above the turbine exhaust and the precooler above the compressor inlet and provides easy access to both ends of the turbomachine.

A simplified (and schematically developed) vertical section through a power conversion loop is shown in Fig. 4. Elevation views through the PCRV are given in Figs. 5 and 6 to show the core exit and inlet ducts, respectively. Referring to Figs. 3 through 6, the flow paths for each power conversion loop are as follows. The helium coolant flows downward through the reactor core, into the core outlet plenum. The hot gas from the core outlet plenum flows radially outward through the three large ducts to the turbine inlet, which is located in the center of the machine. The vertical portion of the core outlet duct is concentric with the compressor outlet duct. The gas flows through the turbine and exits into a plenum located directly under the recuperator. It then flows upward through a short duct and enters the recuperator on the shell side, exiting below the upper recuperator tubesheet into the recuperator-precooler cross duct. The warm gas from the recuperator flows through the horizontal cross duct into the shell side of the water-cooled precooler, where its temperature is reduced further. The cool gas from the precooler flows downward through another short vertical duct into the compressor inlet plenum and passes through the compressor to exit near the center of the machine. High-pressure

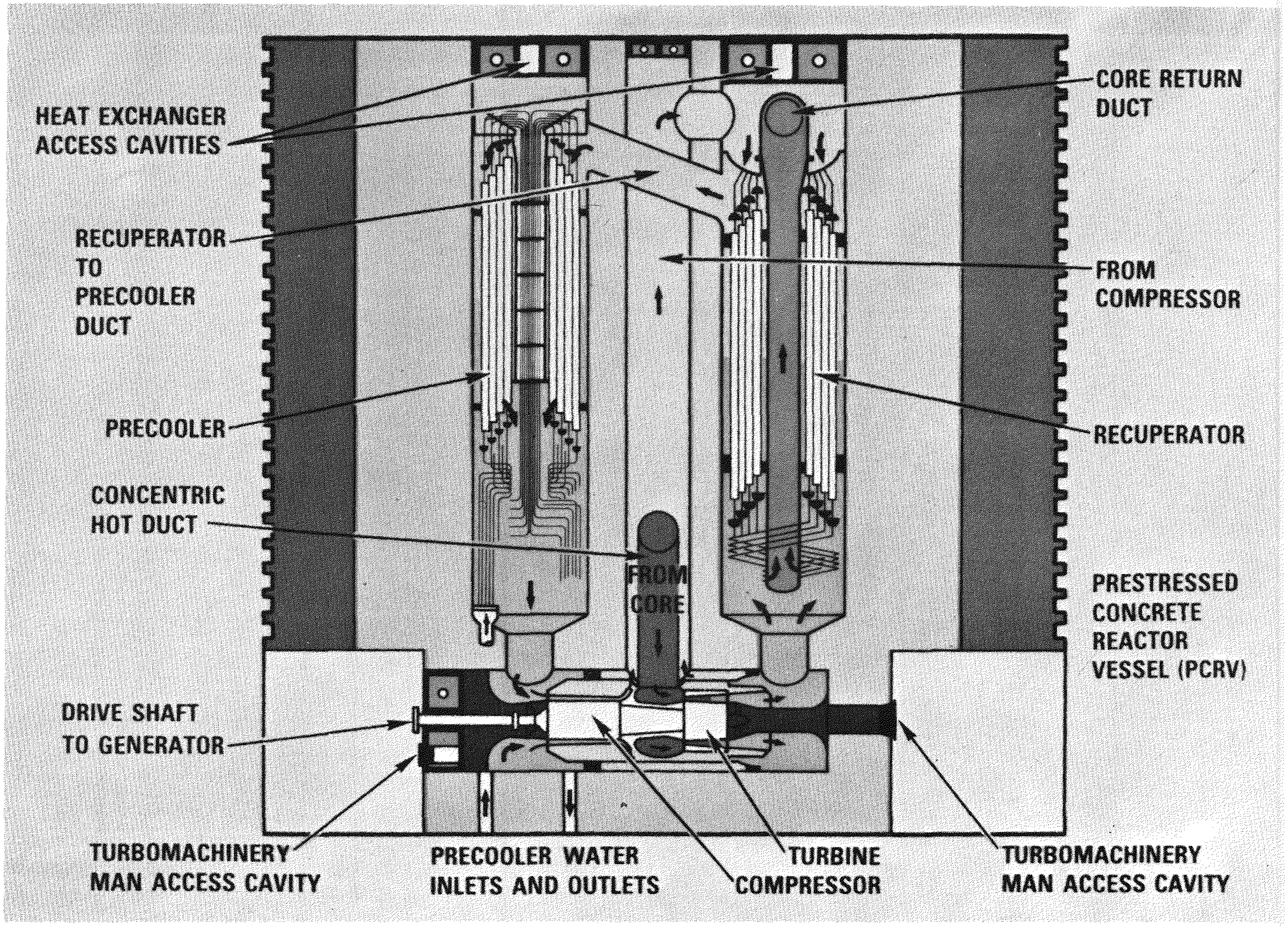

Fig. 4. Schematically developed elevation section through GT-HTGR plant PCRV showing primary helium flow path

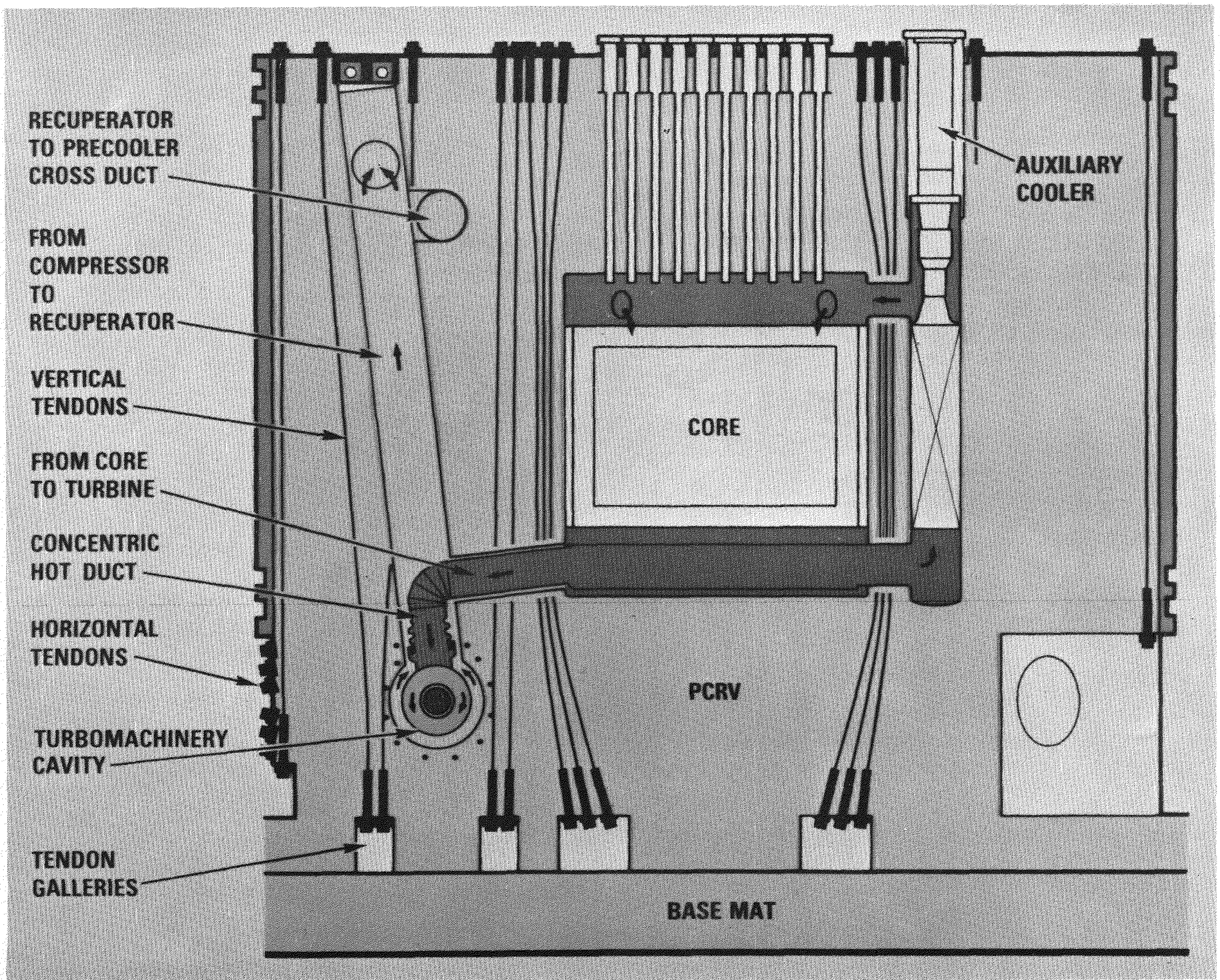

Fig. 5. Elevation through PCRV showing reactor-to-turbine duct

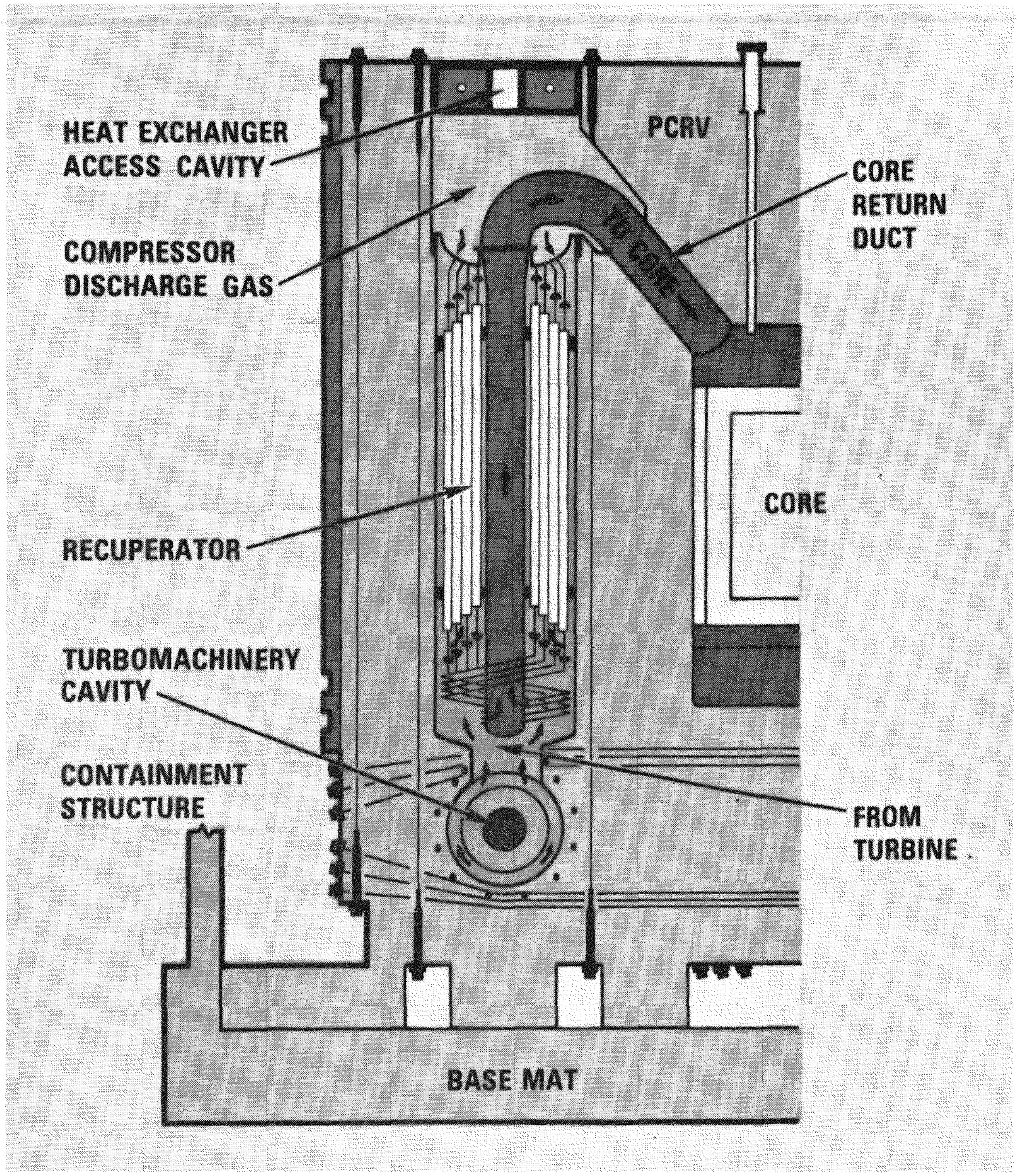

Fig. 6. Section through PCRV showing recuperator installation and core return duct

compressor outlet gas then flows upward through a vertical duct to enter the inlet of the recuperator on the tube side. It flows downward through the tubes, picking up heat from the shell side gas, and exits into a central return duct at the bottom of the recuperator. The gas then returns upward through the central duct and enters the core inlet plenum through the inclined radial ducts at the top of the core cavity.

Although the reference design outlined in this paper is a three-loop configuration, other reactor layouts with from one to four loops have been made using this basic arrangement. These have been investigated for use at core power levels of 1000 MW(t) to 4000 MW(t).

There are several reasons why the nonradial or delta arrangement was selected for the reference plant design. Among these are:

1. Minimum loop pressure drop.
2. Minimum thermal barrier cost.
3. Easier maintenance of turbomachine and heat exchangers.
4. Fewer and less complicated prestressing tendons.
5. Minimum PCRV dimensions.
6. Provision for turbomachine growth.

These advantages result in lower cost and increased cycle efficiency.

A summary of the main features of the primary system and power conversion loop is given in Table 2. Establishing the foregoing primary system preliminary design involved analyses and designs of the structures and major components to establish the internal gas flow path geometries for the selected integrated plant configuration. Significant aspects of the PCRV and major component designs are briefly outlined in the following sections.

TABLE 2
PRIMARY SYSTEM SUMMARY FOR 3000-MW(t) TWIN-ARRANGEMENT DRY-COOLED GT-HTGR PLANT

Plant Arrangement	Reactor Thermal Rating, MW(t)	3000
	Number of Reactors per Plant	Twin Arrangement
	Heat Rejection	Dry-Cooled Plant
	Reactor Outlet Temperature, °F (°C)	1562 (850)
	Power Conversion Loop Rating, MW(t)	1000
	Number of Primary System Loops per Reactor	3
PCRV	Arrangement	Delta
	Diameter, ft (m)	118 (36)
	Height, ft (m)	111 (34.1)
	Hot Duct Replaceability	Yes
	Man Access for Turbomachine Bearing Inspection	Yes
	Maximum System Pressure, psia (MPa)	1150 (7.93)
Turbomachine	Turbomachine Type	Single Shaft
	Compressor/Turbine Stages	18/8
	Compressor Pressure Ratio	2.50
	Generator Drive End	Compressor
	Overall Diameter, ft (m)	11.5 (3.5)
	Overall Length, ft (m)	37 (11.3)
	Approximate Assembly Weight, tons (kg)	305 (276,800)
	Number of Journal Bearings	2 (tilting pad)
	Thrust Bearing Location	External to PCRV

TABLE 2 (Continued)

Recuperator	Type (Modular Construction)	Tubular, Axial-Flow
	Number per Reactor	3
	Overall Diameter, ft (m)	16.75 (5.1)
	Overall Length, ft (m)	62.0 (18.9)
	Assembly Weight, tons (kg)	474 (430,000)
	Tube Material Type	Ferritic, 2-1/4 Cr - 1 Mo
	ASME Code Class	Section VIII
	Fabrication Location	Factory
Precooler	Type (Modular Construction)	Tubular, Axial-Flow
	Number per Reactor	3
	Coolant Fluid	Water (Single Phase)
	Overall Diameter, ft (m)	15.5 (4.72)
	Overall Length, ft (m)	73 (22.3)
	Assembly Weight, tons (kg)	445 (404,000)
	Tube Material Type	Medium Carbon Steel
	ASME Code Class	Section VIII
	Fabrication Location	Factory
Performance (Iso Conditions)	Total Plant Power, MW(e)	2400
	Plant Efficiency, %	40.0

4. PRESTRESSED CONCRETE REACTOR VESSEL

4.1. STRUCTURAL CONSIDERATIONS

Criteria, design methods, and structural principles for the PCRV used in the GT-HTGR are essentially the same as those used for the steam cycle HTGR. Moreover, a specific PCRV design has been established owing to the higher maximum system operating pressure and the inclusion of the delta array of horizontal turbomachine cavities.

The PCRV is constructed of high-strength concrete reinforced with steel bars. The PCRV is prestressed by three independent prestressing systems: (1) a longitudinal prestressing system (LPS), which consists of tendons arranged around the cavities and ducts to counteract the cavity and duct pressures in the longitudinal direction, (2) a circumferential prestressing system (CPS), which consists of multilayered bands of wire strands wound under tension into channels precast in the surface of the vessel walls, and (3) a system of diagonal tendons which replace the wire winding of the CPS in the area of the horizontal turbomachine cavities. The wire for the CPS is wrapped around the outside of the PCRV by a special wire winding machine. The desired prestress is accomplished by the proper tension, applied by the machine, and the number of wire layers. The prestressing systems are shown in Figs. 5 and 6.

The concrete walls and head sections are constructed around carbon steel liners for cavities and ducting. These liners serve as leaktight membranes to contain the reactor coolant within the PCRV cavities. The liners are anchored to the concrete by studs welded to the liners and embedded in the concrete.

Operation of the PCRV requires control of its temperature environment at all times. This is achieved through temperature control of cooling water flowing through cooling tubes welded to the concrete side of the liner. In turn, the liner is protected from the high-temperature helium by a thermal barrier, which consists of special insulation.

The minimum height of the PCRV is determined by the core cavity height and the thickness of top and bottom heads. Important factors for the overall height of the PCRV of each configuration are the arrangement and dimensional requirements of the power conversion loop components, and in particular the placement of the horizontal turbomachine cavities directly under the heat exchanger cavities. An advantage of the delta arrangement is that the vertical tendons serve both the heat exchanger and turbomachine cavities, and this results in a cost savings because of the reduction in number of tendons. The delta arrangement, in which the turbomachinery cavities are placed into the wall section and not under the core cavity as in previous designs (Ref. 3), allows a minimum bottom head thickness and therefore a minimum PCRV height. The structural adequacy of the delta PCRV design approach has been demonstrated using three-dimensional finite element elastic stress analyses.

4.2. PENETRATION CLOSURES

The HTGR technology has been used extensively in the GT-HTGR PCRV design, and early designs employed metal-concrete composite closures for heat exchanger and turbomachine cavities. However, investigations showed that overall plant construction costs could be reduced by using welded carbon steel closures and also showed that the steel closure thicknesses are several feet less than the concrete counterpart with a resulting reduction in PCRV and containment height. The steel closures are designed to the ASME Code, Section III, Division 2, with redundant pressure-retaining walls, seals, and holddown devices. The design concept of a typical steel closure is shown in Fig. 7.

The steel structure is substantially hollow, being formed of radial gussets covered by inner and outer circular plates and cylinders. During plant operation, the closure would be filled with boronated sand to improve its shielding characteristics; during periods of closure removal or in-service inspection of internal welds, the sand would be removed by a vacuum process. The plug and liner holddown includes the use of the vertical

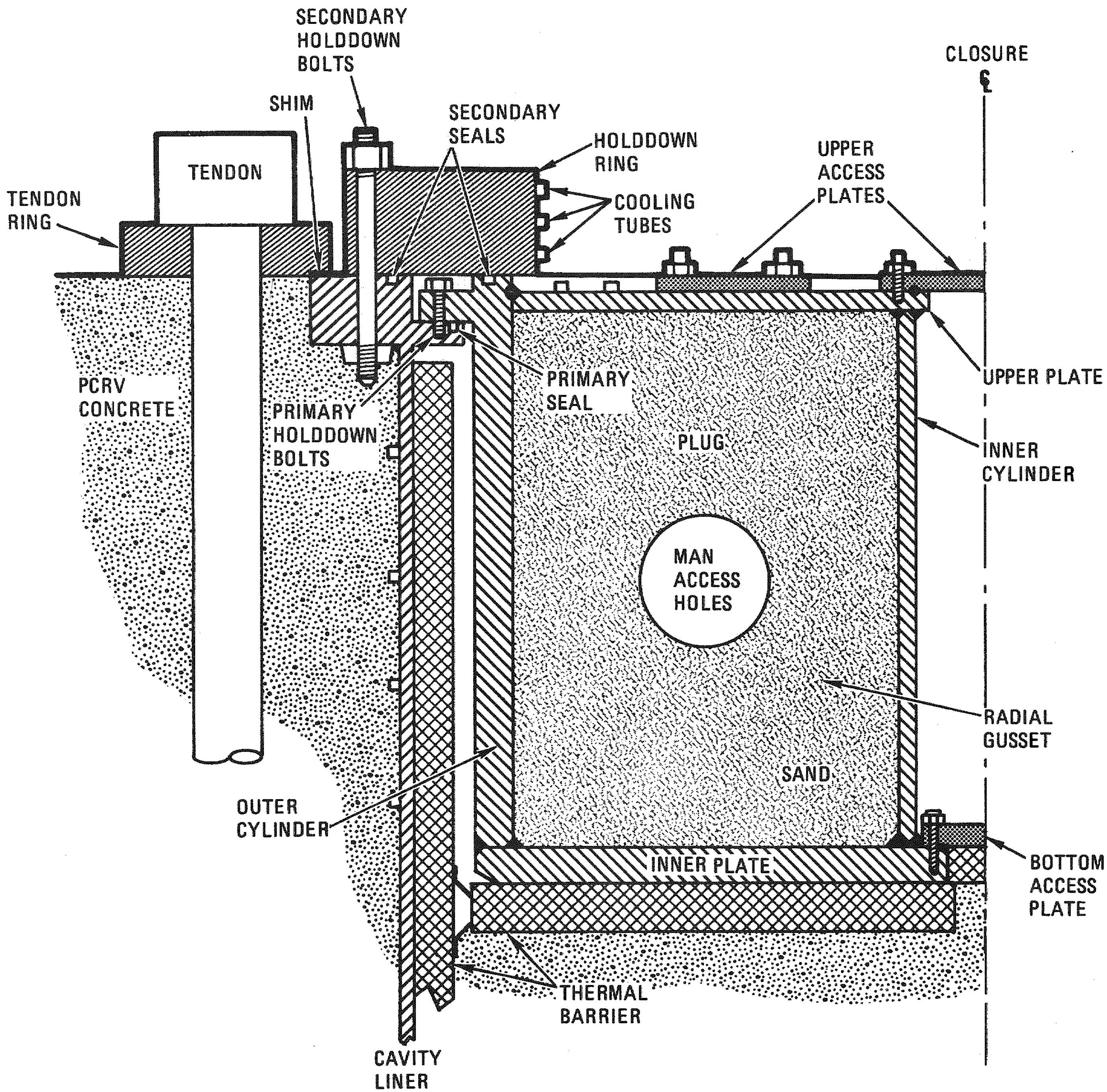

Fig. 7. PCRV steel cavity closure for GT-HTGR plant

tendons surrounding the cavity to directly restrain the liner flange through an overlapping tendon ring. The steel closure is directly bolted to the liner flange, with secondary retention through an external holddown ring. Primary sealing is enhanced in the new system because either double-weld failures or double-seal failures must occur simultaneously to allow helium leakage to the containment space. Notwithstanding this advantage, the secondary seals can be inspected or replaced without closure removal.

4.3. THERMAL BARRIER

The thermal barrier within the GT-HTGR is divided into different thermal barrier classes according to the temperature capabilities of the materials of construction used in the various configurations.

The thermal barrier consists, in general, of several layers of fibrous insulation placed adjacent to the cavity or duct liners, a layer of metallic screen material, a metallic seal sheet, and a metallic cover plate. The difference between the various classes lies in the type of fiber and metallic alloys used. The metallic cover plate is held in place by one central fastener and eight edge fasteners which span the extension gap between adjacent cover plates. Each of the central and edge fasteners is attached to the carbon steel cavity liner by four welded studs. A section of the thermal barrier, taken through a typical edge fastener location, is shown in Fig. 8. The major function of the seal sheets in the GT-HTGR is to span the thermal expansion gap between cover plates to maintain the fibrous insulation and vent cavity material in position. A typical cover plate will contain a number of small vent holes to allow the thermal barrier to vent during a rapid depressurization.

4.4. GENERATOR ENCLOSURE

Compared with the previous reference plant design incorporating radial turbomachinery cavities in the PCRV bottom head (Ref. 3), the new delta

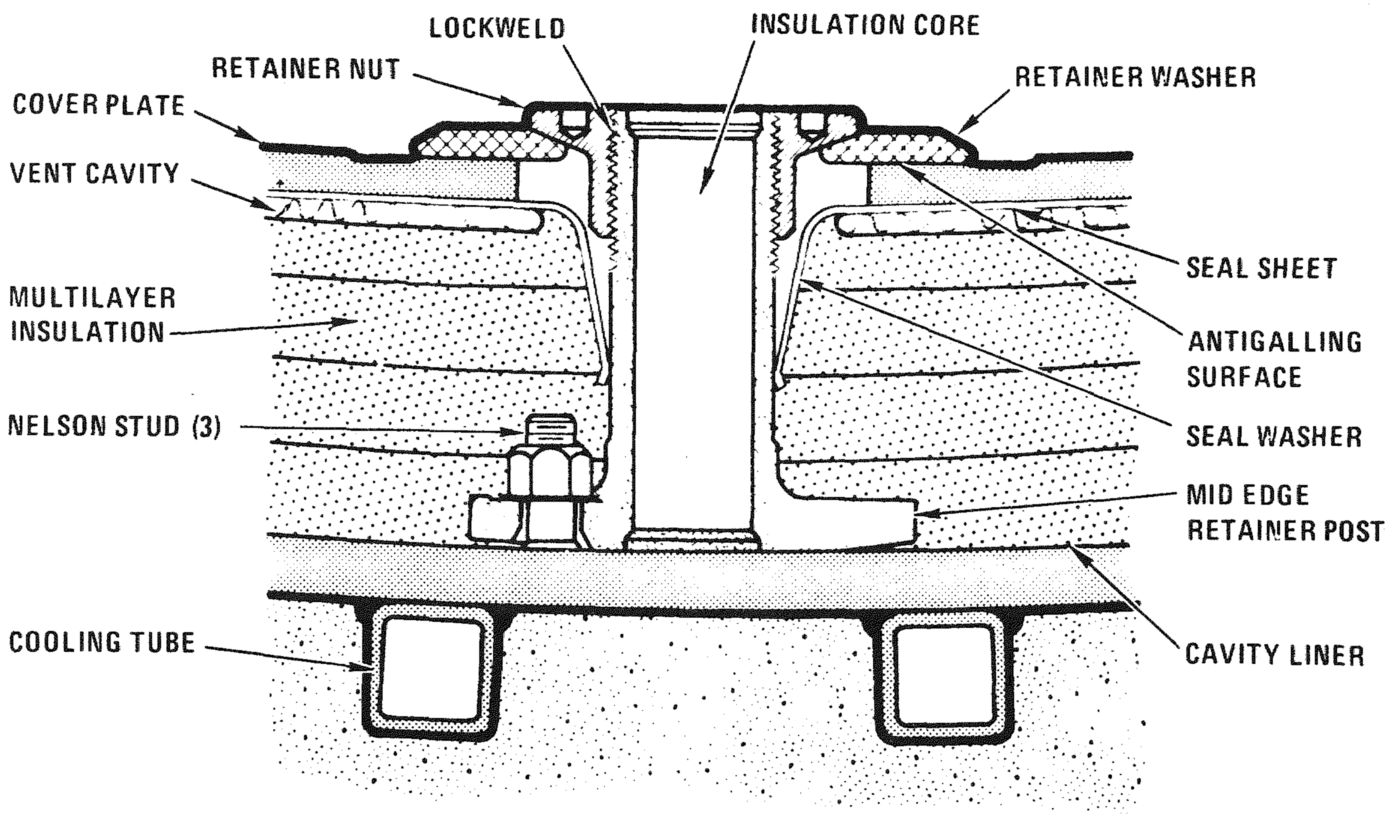

Fig. 8. Typical thermal barrier for main cavities of GT-HTGR plant

arrangement permits a generator enclosure scheme which is more efficient from the space utilization standpoint. The layout of the general enclosure is shown in Fig. 9. The generator is surrounded by a steel pressure vessel which permits an arrangement with the generator being accessible from outside the containment building. Locating the generator outside the secondary containment building results in simplification in the construction of the generator cell. This results in improved ability to control any hydrogen leakage from the generator.

5. COMPONENT DESIGN

It is not the purpose of this paper to describe in detail the design considerations for the major components of the GT-HTGR plant, since these have been reported previously (Ref. 6). However, for an integrated plant the power conversion loop components cannot be treated as isolated units, and their design and the resolution of the interconnecting gas flow path geometries must be considered during the establishment of the plant primary system configuration. During the primary system design studies, extensive layout work was done to identify the most attractive installation and orientation of the major components. The main PCL components that have a strong influence on the primary system design are the turbomachinery, heat exchangers, and to a much lesser extent the control valves. Brief descriptions of these are given below.

5.1. TURBOMACHINERY

The turbomachinery design work for the advanced GT-HTGR power plant was done by the Power Systems Division and Pratt & Whitney Aircraft Division of United Technologies Corporation. The arrangement of the helium turbomachine is shown in Fig. 10, and details of the design are given in a companion paper (Ref. 7). An extremely simple arrangement consisting of a single-shaft direct-drive turbomachine was chosen for the GT-HTGR plant. The use of a two-bearing rotor, the feasibility of which has been confirmed

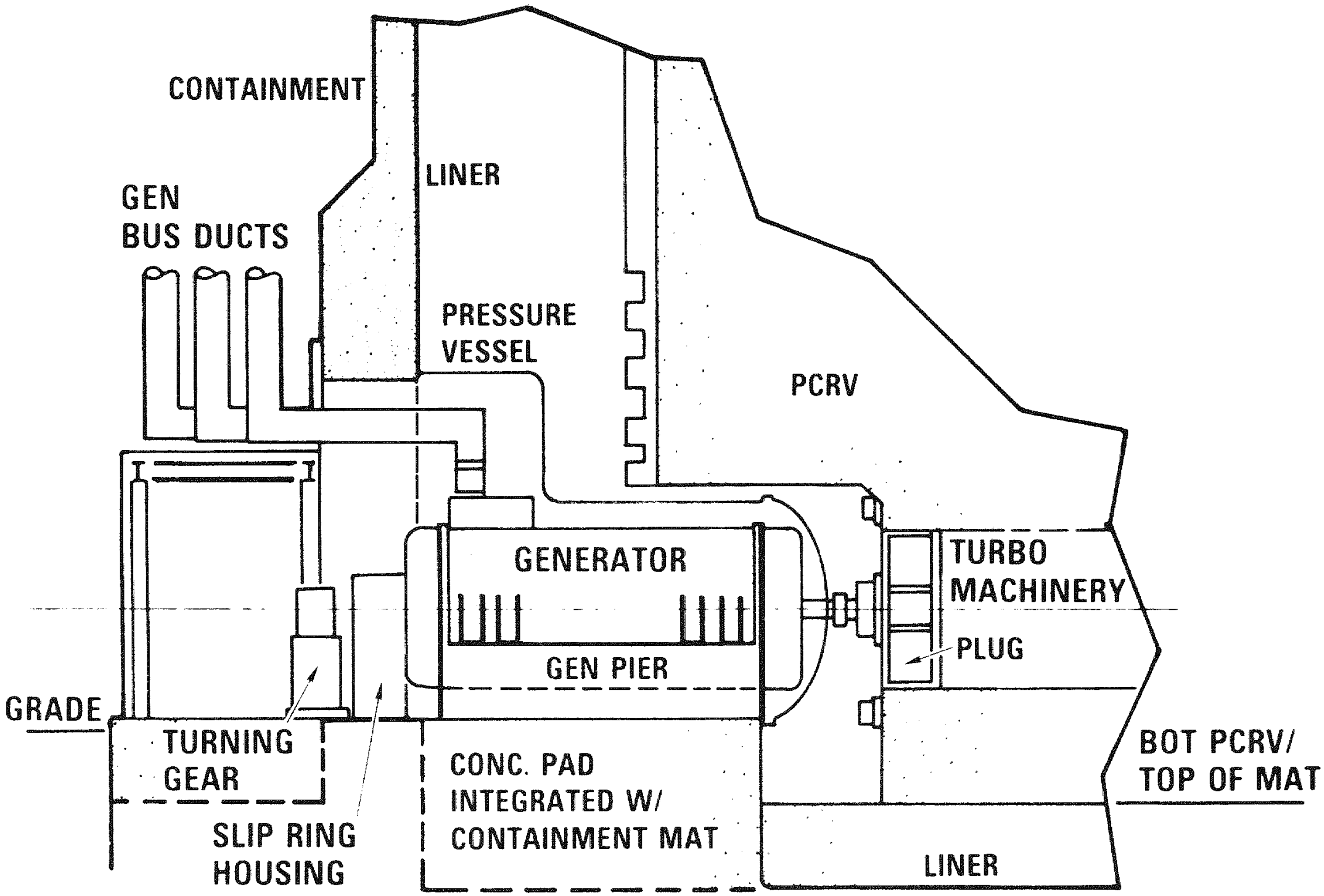

Fig. 9. Generator enclosure for integrated GT-HTGR plant

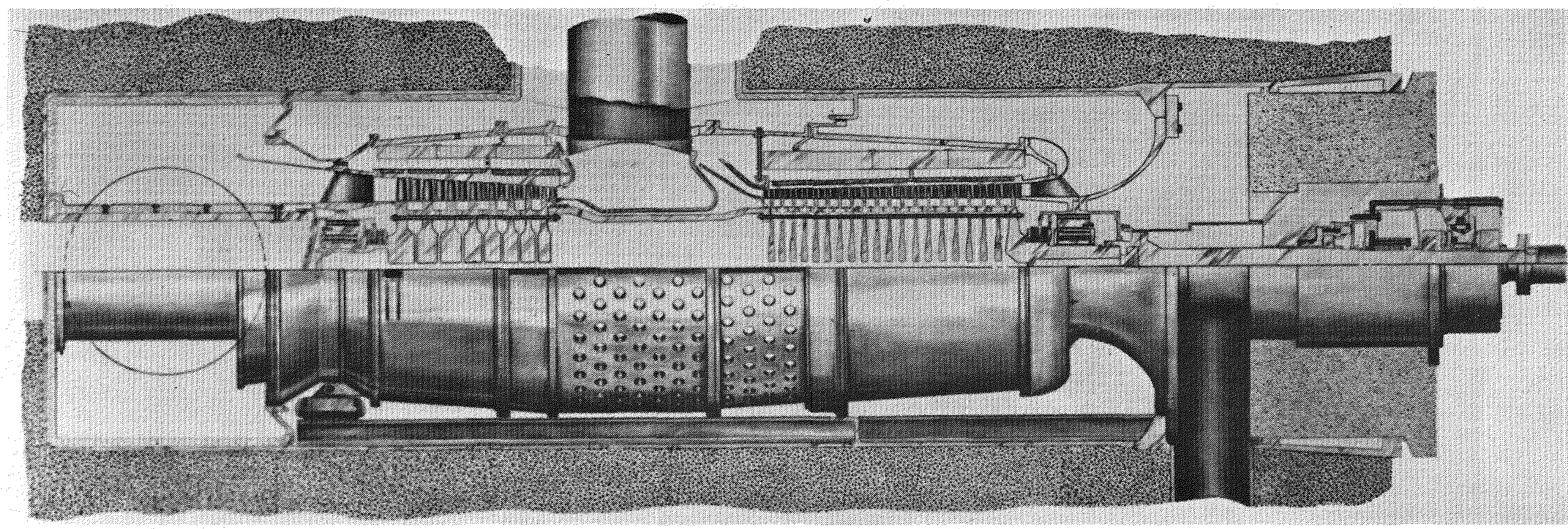

Fig. 10. 400-MW(e) single-shaft turbomachine for GT-HTGR plant

by critical speed analyses, maintained the smallest number of individual parts for the turbomachine, and tended to minimize the overall cost of the machine and ease inspection and maintenance requirements. Aerothermodynamic analyses showed that for a 400-MW(e) machine, a single turbine inlet duct (from the reactor) could be utilized, the pressure losses and flow inlet geometry to the turbine bladed section being satisfactory. The turbomachine utilizes portions of the PCRV cavity as its gas inlet and exit plenums and volutes to the maximum extent. To achieve this, the cavity is divided into three main chambers by large-diameter sliding seals located around the outer casing.

The well-established fact that the optimization (for maximum cycle efficiency) of a highly recuperated, closed-cycle system gives a relatively low compressor pressure ratio is fortunate for a high specific heat gas such as helium. The selected value of 2.50 is slightly less than optimum, but was chosen to reduce the number of compressor and turbine stages. The selected number of stages (18 compressor and 8 turbine) is comparable to much higher pressure ratio air-breathing, open-cycle industrial gas turbines. Details of the turbomachinery are given in Table 3.

The overall machine dimensions are within the limitations imposed for rail shipment capability. In fact, the design basis casing diameter of 11.5 ft (3.5 m) allows for addition of a shielded shipping container for rail transport of a radioactively contaminated unit. The overall length and approximate weight of the turbomachinery are 37 ft (11.3 m) and 305 tons (277,000 kg), respectively. The high density of the working fluid works to the advantage of the overall design, since the external dimensions of the 400-MW(e) helium gas turbine are approximately equal to those of a 70-MW(e) air-breathing, open-cycle industrial gas turbine.

5.2. HEAT EXCHANGERS

While details of the heat exchangers have been discussed previously (Ref. 8), it is meaningful to discuss them briefly in the context of this

TABLE 3
DESIGN DETAILS FOR 400-MW(e) HELIUM GAS TURBINE

Machine	Compressor		Turbine	
Inlet Temperature, °F (°C)	79.0 (26)		1562 (850)	
Inlet Pressure, psia (MPa)	460 (3.17)		1105 (7.62)	
Pressure Ratio	2.50		2.32	
Mass Flow Rate, lb/sec (kg/sec)	1265 (574)		1214 (551)	
Rotational Speed, rpm	3600		3600	
Number of Stages	18		8	
Blading Adiabatic Efficiency, %	89.8		91.8	
Stage Number	1	18	1	18
Tip Diameter, in. (mm)	71.9 (1826)	68.3 (1735)	76.5 (1943)	86 (2184)
Hub Diameter, in. (mm)	62 (1575)	62 (1575)	66.6 (1691)	62.6 (1590)
Hub/Tip Ratio	0.86	0.91	0.87	0.73
Blade Height, in. (mm)	4.95 (126)	3.15 (80)	4.95 (126)	11.7 (297)
Number of Vanes, stator	78	121	90	50
Number of Blades, rotor	77	120	124	68

Turbomachine Overall Data

Overall Length, ft (m)	37 (11.3) (excluding exhaust plenum)
Overall Diameter, ft (m)	11.5 (3.5)
Rotor Weight, tons (kg)	67 (60,800)
Stator and Case Weight, tons (kg)	238 (216,000)
Total Machine Weight, tons (kg)	305 (276,800)
Bearings:	
Number of Journal Bearings	2
Type of Journal Bearings	5 pad tilting pad jet lubricated
Thrust Bearing Type	8 pad tilting pad, double acting
Bearing Span, ft (m)	29.0 (8.8)

paper since they are large components and have a significant influence on the integrated primary system. The combined effects of size constraint (integration in the PCRV side-wall cavities), in-service inspection, in situ repair, and maintenance and fabrication considerations have a significant effect on the choice of surface geometry, flow configuration, and mechanical design.

For the plant preliminary design, emphasis has been placed on simplicity, and both heat exchangers are of tubular construction. A simple modular array was chosen to facilitate manufacture, installation, and maintenance. Both the recuperator and precooler have high effectiveness and thermal conductance requirements, and a straight tube axial counterflow configuration was chosen to minimize the surface area and pressure loss.

In an integrated plant, the heat exchangers exert a direct influence on the overall size of the PCRV, thus creating a strong incentive for surface compactness not generally imposed on ordinary industrial heat exchangers. While the counterflow tubular configuration approach used in the design of the recuperator and the precooler yields dimensions particularly suited for PCRV cavity installations, the actual packaging of the heat transfer matrix to minimize heat exchanger frontal area requirements (thus minimizing PCRV cavity diameter requirements) is of vital importance. With the possibility of packaging both heat exchangers as full, homogeneous tube arrays within their respective cavities ruled out by practical considerations, the approach taken toward modularization of the heat transfer matrix must be selected carefully. Since homogeneous tube arrays produce the minimum possible PCRV cavity diameters, the module shape and size for a given heat exchanger design should be the combination which most nearly produces the ideality of a homogeneous tube field while satisfying the mechanical design requirements for handling and thermal growth flexibility.

Compared with the circular modules reported previously (Refs. 3, 8), recent innovations in module subheadering and shrouding techniques have resulted in a configuration of much improved packaging efficiency which has made possible a reduction in heat exchanger diameter for the same unit performance. A comparison of the two designs is shown schematically in Fig. 11. With a novel subheadering arrangement in which the tubeplate itself lies within the tube field, a contiguous hexagonal array of modules results in a more efficient utilization of frontal area. Mutually shared partitions between modules, rather than individual cans or shrouds, are possible, thus eliminating the need for intermodule bypass seals, increasing the rigidity of the modular array, and facilitating provision for shell side mixing (via perforated or discontinuous partitions).

A simplified schematic of the recuperator assembly is shown in Fig. 12. The recuperator consists of 144 hexagonal vertically oriented modules connected in parallel to a tubesheet at the top end, and to a high-pressure bottom drum header that is connected to a cylindrical return duct passing up through the center of the modular array. The unit is supported from its upper tubeplate, and with no mechanical connections at the bottom of the assembly (hot end), unrestrained growth capability downward is provided. The recuperator arrangement provides for removability, in-service inspection, and lead tube plugging. A summary of the salient features of the recuperator is given in Table 4.

A simplified schematic of the precooler assembly is shown in Fig. 13. With 144 hexagonal modules, the overall assembly is similar to the recuperator. The support system is similar to the recuperator, except that the modular array is anchored to a top support plate instead of a primary pressure-carrying tubeplate. Both the precooler water inlet and outlet lead tubes penetrate the bottom head of the PCRV, and between the modules and bottom tubesheets, the lead tubes are coiled to produce the flexibility required to accommodate differential thermal expansion. In addition to failure isolation and external lead tube plugging capability, the precooler provides for removability and in-service inspection. A summary of the salient features of the precooler is given in Table 4.

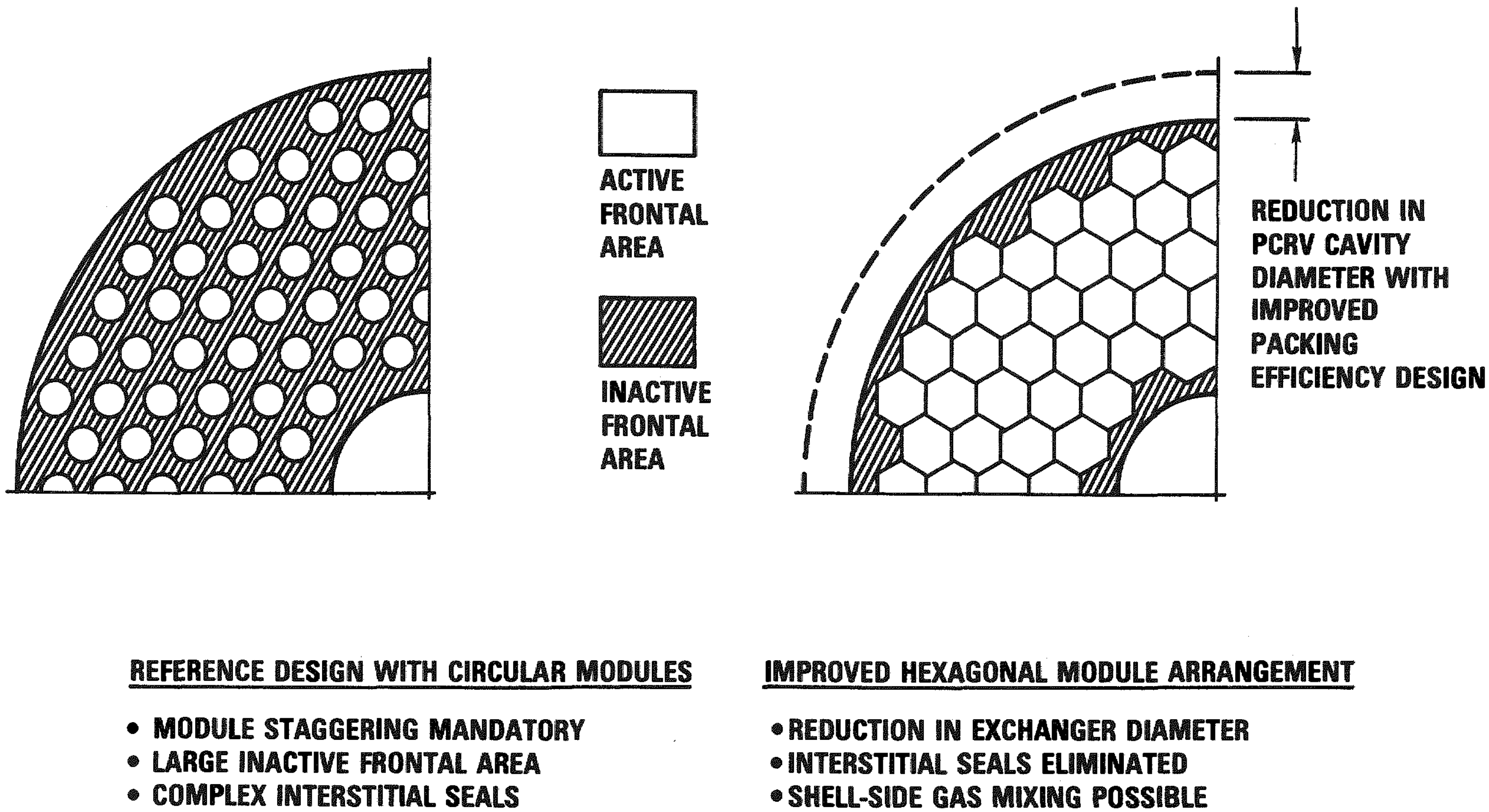

Fig. 11. Heat exchanger design improvements through utilization of a contiguous hexagonal module array

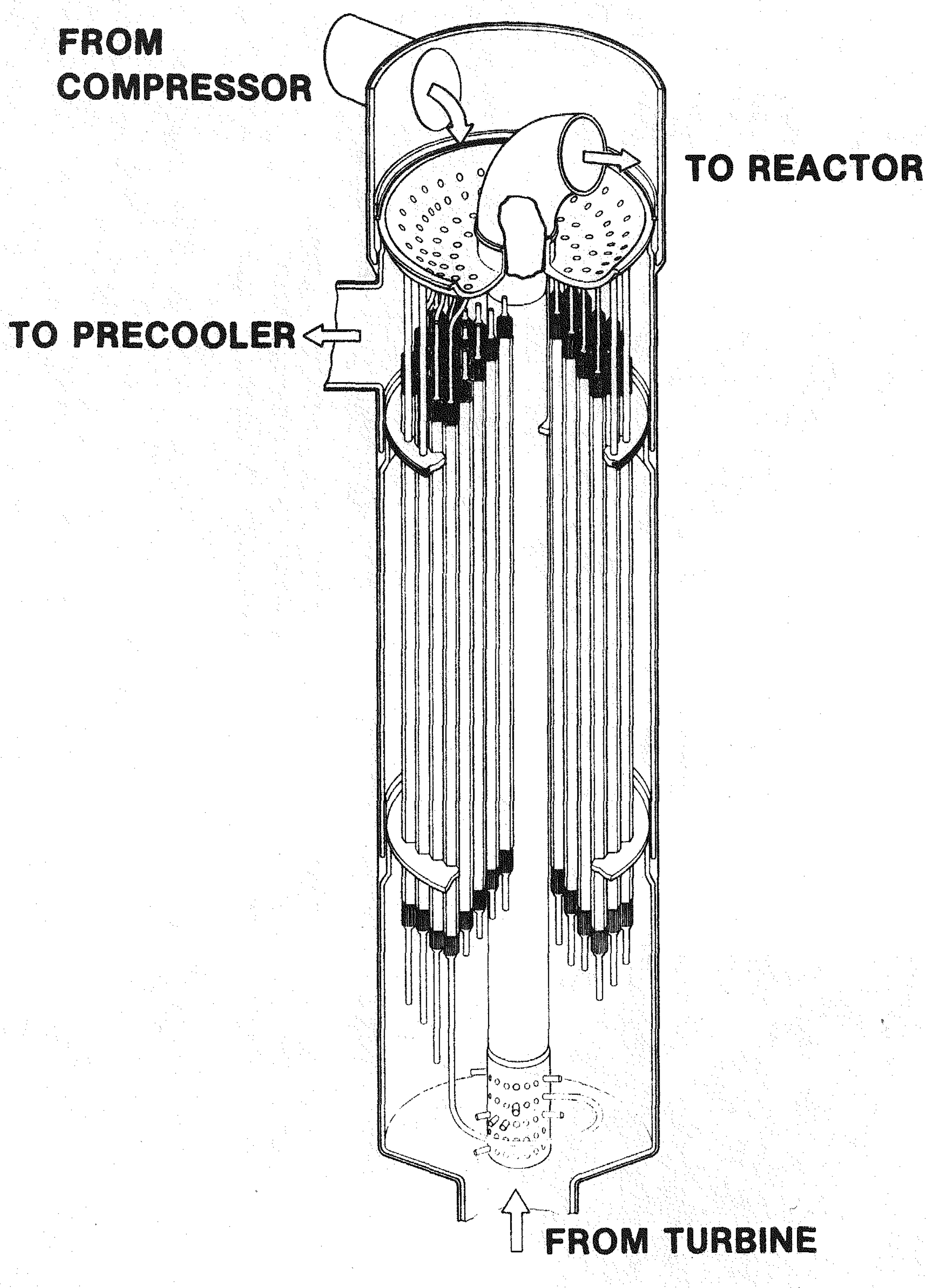

Fig. 12. Modular axial flow recuperator for GT-HTGR power plant

TABLE 4
SUMMARY OF HEAT EXCHANGER PRELIMINARY DESIGNS FOR GT-HTGR POWER PLANT
3000-MW(t) Reactor, 850°C Reference Design

	Exchanger	Recuperator	Precooler
Type	Number per Reactor	3	3
	Matrix Type	Tubular	Tubular
	Flow Configuration	Counterflow	Counterflow
	Construction	Modular	Modular
Thermal	Heat Transfer Rate, MW(t) per Reactor	2860	1740
	LMTD, °F (°C)	75.3 (41.8)	38.0 (21.1)
	Effectiveness	0.898	0.972
	Helium ($\Delta P/P$)	0.0184	0.010
Surface Geometry	Tube Outer Diameter, in. (mm)	0.4375 (11.1)	0.375 (9.5)
	Tube Wall Thickness, in. (mm)	0.045 (1.14)	0.049 (1.24)
	Tube Pitch Arrangement	Triangular	Triangular
	Pitch/Diameter Ratio	1.374	1.38
	Maximum Metal Temperature, °F (°C)	968 (520)	357 (81)
	Material Type	2-1/4 Cr - 1 Mo	Med. Carbon Steel
Tube Bundle Details	Hexagonal Module Dimension, in. (mm)	14.2 (361) A/F	13.2 (335)
	Modules/Exchanger	144	144
	Tubes/Module	547	631
	Effective Tube Length, ft (m)	39.8 (12.13)	37.0 (11.28)
	Surface Area/Reactor, ft^2 (m^2)	1.08×10^6 (100,000)	990,000 (91,900)
	Cavity Diameter (ITB), ft (m)	17.25 (5.26)	16.0 (4.9)
Overall Assembly	Approximate Overall Length, ft (m)	62 (18.9)	73 (22.3)
	Overall Diameter, ft (m)	16.75 (5.1)	15.5 (4.72)
	Module Weight, lb (kg)	5230 (2375)	5980 (2715)
	Approximate Assembly Weight, tons (kg)	474 (430,000)	445 (404,000)
	Fabrication Location	Factory	Factory

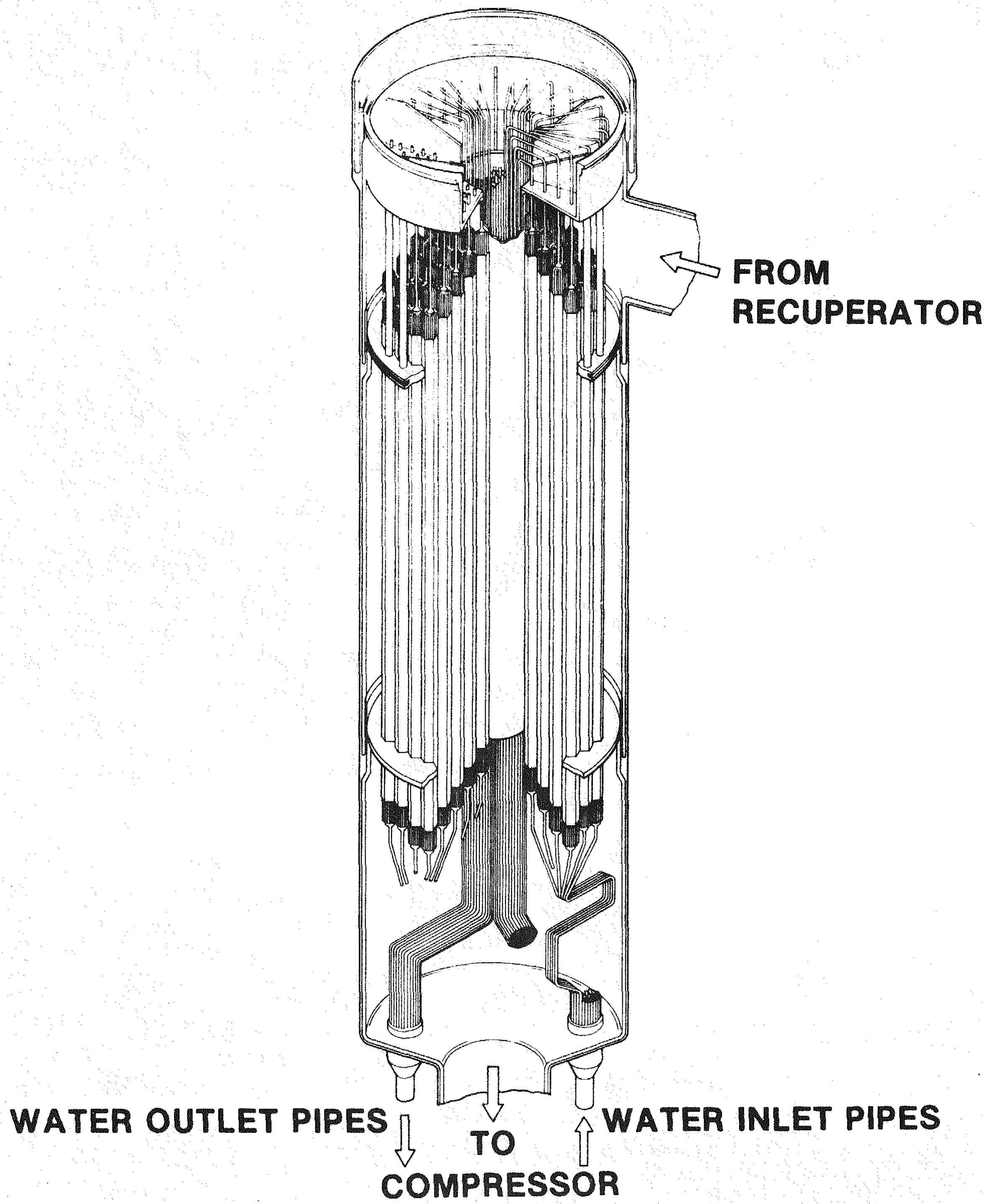

Fig. 13. Modular axial flow precooler for GT-HTGR power plant

Even though relatively high heat transfer coefficients can be realized with the single-phase working fluids, large surface areas are necessary owing to the large quantity of heat transfer. Because of the modest metal temperatures and internal pressure differentials compared with modern steam generators, the use of Code-approved lower-grade alloys of reduced cost is possible. The ferritic materials selected for both exchangers have been used extensively in industrial and nuclear plant heat exchangers. While the exchanger assemblies described below are large, state-of-the-art manufacturing methods apply and the modular approach eases fabrication, handling, and assembly. The overall size and weight of both the recuperator and precooler are similar to contemporary steam generators; and transport methods and handling and installation techniques developed for these units are equally applicable to the heat exchangers for the nuclear gas turbine plant.

5.3. CONTROL VALVES

In the GT-HTGR plant the helium control valves are integrated in the primary system, and since there are four valves per power conversion loop, their overall size and configuration must be considered during plant layout studies. Full details of the plant control scheme have been described previously (Ref. 9), so only aspects of the valve configuration and sizing will be mentioned in this paper.

Figure 14 is a simplified control valve diagram showing the position of the valves in the flow circuit. Helium inventory control and reactor outlet temperature control are useful in maximizing plant efficiency during extended part-load operation, but their response times are too great for short-term speed and load control. The prime control system must therefore be based on fast-acting primary loop valves.

The main requirement of the valve bypass system is that it be capable of limiting turbine overspeed to less than 20% for all accidents or events up through the worst case of a coupling failure with trip on backup overspeed

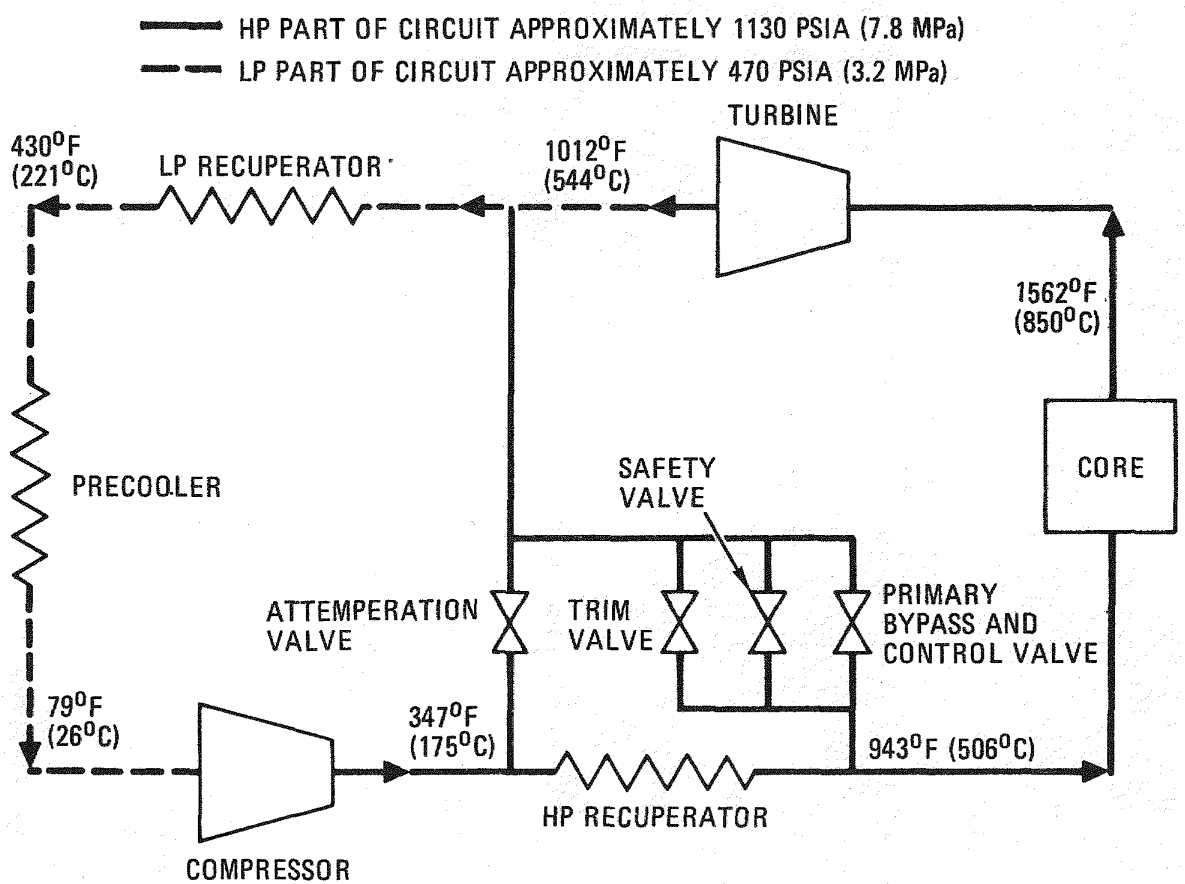

Fig. 14. Simplified control valve diagram for GT-HTGR power plant

detection. Control studies have shown that connection and gas routing from high- to low-pressure zones of the primary system is the only bypass that will satisfy the worst-case overspeed protection requirement. Single-point bypass (from compressor discharge to turbine discharge) methods are undesirable because of extreme temperature excursions to the heat exchangers and reactor.

As shown in Fig. 14, there are four valves in the split-flow bypass configuration of each power conversion loop. The trim, safety, and primary bypass valves connect the core inlet to the turbine exit of each loop; the attemperation valve connects the compressor exit to the turbine exit. The primary bypass can be used in two modes: (1) it can be modulated by the control system for plant load control; or (2) it can be operated in a binary (open/shut) mode, if the safety valve fails to open, by a separate actuator as part of the plant protection system. The safety valve (nonmodulated) is actuated by the plant protection system and is a binary (open/shut) valve used primarily for turbine overspeed/overpressure protection. This valve cannot be used for load control purposes. The small trim valve makes fine adjustments of turbine speed and load and is of particular use when synchronizing with the electric power network. The attemperation valve is used to mix gases (compressor discharge and core inlet), thereby minimizing thermal shock to the heat exchangers and core during transients.

The four valves, operating in a helium environment at elevated temperature, are by no means off-the-shelf components, and conceptual designs have been established to satisfy all of the plant requirements. The initial mechanical designs followed conventional valve design practice as closely as possible. This led to the selection of isolated units with large, thick, cast valve bodies to withstand the high pressures and temperatures, and the use of many features of conventional valves. Installation of these isolated valve assemblies into cavities in the PCRV proved to be difficult because of the space-consuming thermal expansion devices, necessary because of the rigid valve-to-PCRV duct interfaces, and the resulting large growth from ambient to operating temperature. With this isolated valve approach, the valve assembly envelopes were excessive for installation in individual PCRV cavities.

At this stage it was clear that the design of the valves must be integrated with the PCRV. The conceptual design approach for all four valves involved eliminating the large cast valve bodies (pressure bearing) and installing the valve assemblies directly in individual cavities in the vessel. The complete valve assembly (including the seat) can be readily installed and removed from the cavity. Elimination of the pressurized body eases thermal expansion problems, and thermal shock effects during transient operation will be minimized. A simplified view of the integrated approach for the safety valve is shown in Fig. 15. The four valves are installed in separate cavities in the top head of the PCRV and are accessible for inspection and maintenance. The position of the valve cavities in the vessel was established from layout studies to determine the simplest routing of the interconnecting ducts for the four valves in each PCL.

6. MAINTENANCE CONSIDERATIONS

With all of the power conversion machinery installed inside the reactor vessel, maintenance aspects must be considered during the plant conceptual design phase. The primary criterion of the GT-HTGR plant maintenance and inspection plan is to provide, at a reasonable cost, maintenance and inspection facilities, equipment, and component design that will permit the realization of maximum plant availability. It is therefore a matter of policy to design all of the related maintenance facilities for economy and convenience, both for planned and unplanned maintenance. All primary system equipment will be designed for full plant lifetime, with no limited-life parts. Moreover, all components except some in the reactor cavity are designed for remote handling techniques with equipment that provides for retention of the helium atmosphere within the PCRV, and also provides any needed radiation shielding. Typically, the primary system components are moved to a service facility for decontamination for either remote or contact

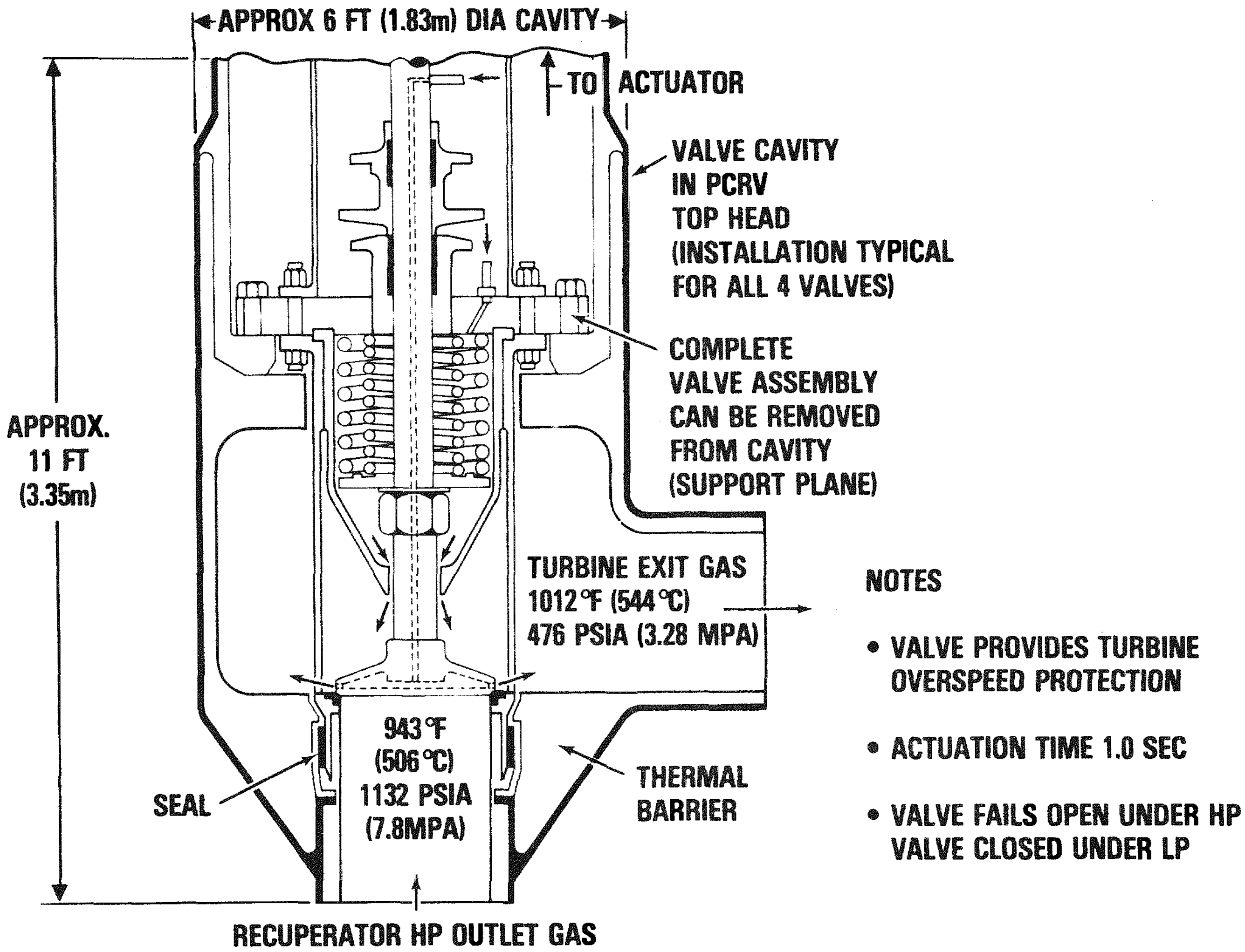

Fig. 15. Safety valve for GT-HTGR plant; valve assembly is shown integrated in PCRV

maintenance work, or for shipment offsite to other facilities. The maintenance requirements must thus provide for the replacement of some items which have been designed to last the plant lifetime, but fail due to unforeseen circumstances. The items in this category are the heat exchangers, valves, and some portions of the thermal barrier. Turbomachinery changeout is regarded as a planned maintenance activity.

An important part of the formulation of the maintenance plan has been to provide for in situ maintenance whenever practical. The degrees to which in situ and service facility maintenance operations can be carried out depend upon the radiological environment in and around the equipment in question. The maintenance equipment will be designed so that it is convenient for the more economical direct-contact approach if the activity levels are acceptable. The maintenance plan, however, will be formulated for conservatively high activity levels. The objective will be to provide equipment to deal economically with anticipated activity levels; at the same time, the plan will permit advantage to be taken of low activity levels when they occur. For the GT-HTGR plant, heavy emphasis will be placed on diagnostics and, where possible, a large portion of the periodic inspection and repair should be performed in situ. Turbomachine blading, bearings, instrumentation, and service systems should be accessible.

In general, equipment will be removed for maintenance and overhaul only if the records raise a question concerning the ability of the component to perform satisfactorily. Performance monitoring and measurements of deflections, eccentricity, vibration, acoustics, critical clearances, and lubrication parameters, in addition to temperature and pressure, are key items in the successful implementation of this approach.

7. SUMMARY

The basic three-loop plant design described in this paper has an efficiency (dry-cooled) of 40%. The design also attained a substantial and recognized cost advantage, as well as additional competitive features, compared with other nuclear electric power plants (Ref. 10). The data from the assessment of the GT-HTGR power plant (Ref. 10) quantify the advantage as a 12% reduction in capital cost as compared with twin wet-cooled PWRs of the same thermal power. The economic assessment indicates that when commercialized, the GT-HTGR is potentially the lowest-cost alternative among the converter reactors and that it may compete effectively with the LMFBR.

The primary system design studies were done for a twin 3000-MW(t) reactor plant with dry cooling. The advanced plant design still utilizes a multiloop gas turbine approach and a modest turbine inlet temperature (compared with open-cycle industrial gas turbines) of 1562°F (850°C), thus permitting the use of uncooled turbine blades made from existing nickel-base alloys. The combination of comprehensive optimization and primary system layout studies led to a simpler plant arrangement of improved performance and reduced capital cost.

From the analytical sensitivity studies, changes in the following areas were made compared with the previous reference design: (1) slightly increased reactor outlet temperature, (2) higher system maximum pressure, (3) a compressor pressure ratio increase from 2.35 to 2.5, and (4) slightly higher heat exchanger thermal conductance requirements.

The plant layout studies resulted in a substantially improved configuration with much simplified gas flow paths, which resulted in a decrease in system pressure loss. The adoption of an improved heat exchanger sub-headering configuration with better utilization of flow frontal area resulted in recuperator and precooler cavity diameter reduction for the same performance. This design improvement extended beyond just the heat exchangers themselves, since it allowed a reduction in diameter of the PCRV and secondary containment building, thus resulting in a substantial savings. The reduction in diameter of the PCRV was also made possible by changing the horizontal orientation of the turbomachinery cavities from a radial to a delta configuration for the three-loop plant. With this arrangement the length of the turbomachine no longer controls the diameter of the vessel. A significant advantage of the delta PCRV arrangement is improved access to the turbomachine for inspection and maintenance.

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