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MASTER

850 °C VHTR PLANT TECHNICAL DESCRIPTION

by
PROJECT STAFF

Prepared under
Contract DE-AT03-76SF71061
for the San Francisco Operations Office
Department of Energy

DATE PUBLISHED: JUNE 1980

GENERAL ATOMIC COMPANY

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ABSTRACT

This report describes the conceptual design of an 842-MW(t) process heat very high temperature reactor (VHTR) plant having a core outlet temperature of 850°C (1562°F). The reactor is a variation of the high-temperature gas-cooled reactor (HTGR) power plant concept. The report includes a description of the nuclear heat source (NHS) and of the balance of reactor plant (BORP) requirements. The design of the associated chemical process plant is not covered in this report. The reactor design is similar to a previously reported VHTR design having a 950°C (1742°F) core outlet temperature which was the result of several years of preliminary study funded both by General Atomic Company (GA) and by the Department of Energy (DOE).

The concept is a nuclear-heated chemical process plant whose product is hydrogen (or a mixture of hydrogen and carbon monoxide) generated by steam reforming of a light hydrocarbon mixture. The NHS design is also applicable to other process applications requiring a similar high-temperature energy source. In this design, reactor heat is transported to the externally located process portion of the plant by secondary helium loops, which are coupled to the primary helium reactor coolant loops.

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TABLES (Continued)

1. INTRODUCTION

This report provides a description of the conceptual design of an 842-MW(t) very high temperature reactor (VHTR) based on the high-temperature gas-cooled reactor (HTGR) concept and having a core outlet temperature of 850°C (1562°F). This report is companion to another that describes a VHTR with a core outlet temperature of 950°C (1742°F) (Ref. 1-1).

The HTGR is characterized by a graphite-moderated, helium-cooled thermal reactor core within a multicavity prestressed concrete reactor vessel (PCRV). The use of an inert single-phase gas as the reactor coolant, combined with the use of graphite for the fuel cladding and core structure, allows the HTGR to develop core outlet gas temperatures much higher than those of other reactor systems. The VHTR exploits this capability to provide a nuclear heat source (NHS) that is thermally competitive with conventional fossil-fired sources for use in process industries.

The plant design addressed in this report is a nuclear-heated chemical process plant whose product is hydrogen (or a mixture of hydrogen and carbon monoxide) generated by steam reforming of a light hydrocarbon mixture. The VHTR NHS design is also applicable to other process applications requiring a similar high-temperature energy source. In this design, the reactor heat is transported to the externally located process portion of the plant by secondary helium transport loops, which are coupled to the primary helium reactor coolant loops. In addition to providing the high-temperature heat source required for the reforming process, the nuclear heat is also used to generate high-temperature, high-pressure steam in sufficient quantity to meet both process needs and electrical power generation needs internal to the plant operation. The selected system design does not generate electrical power in excess of the plant requirements.

The plant thermal output of 842 MW(t) was chosen to utilize an already constructed core design and to conform to user requirements. The primary helium temperature conditions meet the requirements of the chemical process while staying within the structural limits of the Hastelloy X material in the intermediate heat exchanger (IHX). The reactor core outlet temperature of 850°C (1562°F) represents a near-term compromise between the temperature requirements of the reforming process and the temperature limitations of materials presently used for high-temperature components within the primary system. The core return temperature of 427°C (800°F) is based on obtaining appropriate heat transfer characteristics within the reactor core, satisfying fuel temperature limitations, and supplying an adequate temperature potential for the steam generator. The primary system pressure level of 5 MPa (725 psia) is consistent with the approaches followed in HTGR-steam cycle (HTGR-SC) designs and with the 950°C (1742°F) VHTR design.

The design described in this report provides a comparison with the higher-temperature (950°C) VHTR design and a data base for continuing system design. This data base includes plant cost estimates, modeling for a plant optimization computer code (PHRED), and system and component design studies.

The report includes a description of the NHS and of the BORP requirements. It does not cover the design of the associated chemical process plant.

REFERENCE

1-1. "842 MW(t) Process Heat VHTR Reference Plant Design," DOE Report GA-A15277, General Atomic Company, to be published.

2. GENERAL DESCRIPTION OF THE PLANT

The plant design utilizes the 842-MW(t) Fort St. Vrain (FSV) HTGR-SC power plant reactor core configuration, which is the same core configuration employed for the 950°C (1742°F) VHTR (Ref. 2-1). The core and primary coolant systems are mounted in a multicavity PCRV (Fig. 2-1) similar in design to that used in the large HTGR-SC power plant, with the core cavity offset from the vertical center line of the PCRV and the primary and auxiliary loop components in separate cavities beside the core cavity. The NHS incorporates two primary reactor coolant loops and one core auxiliary cooling system (CACS) loop. The primary loops are safety class and are used together with the CACS loop to provide safe shutdown of the reactor. Table 2-1 lists the major plant parameters.

Figure 2-2 shows the plant cycle diagram, and Fig. 2-3 shows the arrangement of the PCRV and reactor containment. Primary coolant helium flows downward through the reactor core and divides equally between two identical coolant loops, each containing a helium-to-helium IHX, a helium circulator, and a helium shutoff valve. In each loop the heated helium first passes upward through the IHX and is then pumped back to the core inlet plenum by the helium circulator, completing the circuit. The primary helium shutoff valve is located at the circulator discharge and serves to prevent backflow through the loop when the loop is not operating. Helium conditions at the core inlet are 4.99 MPa (724 psia)/426°C (800°F), and the core outlet temperature is 850°C (1562°F). Secondary helium enters the IHX at 5.24 MPa (760 psia)/349°C (660°F) and exits at 793°C (1460°F).

The IHXs (Fig. 2-4) are modularized, straight-tube, counterflow heat exchangers. The primary helium circulators (Fig. 2-5) are single-stage axial-flow compressors with electric motor drive. Speed is controlled by a variable frequency power supply.

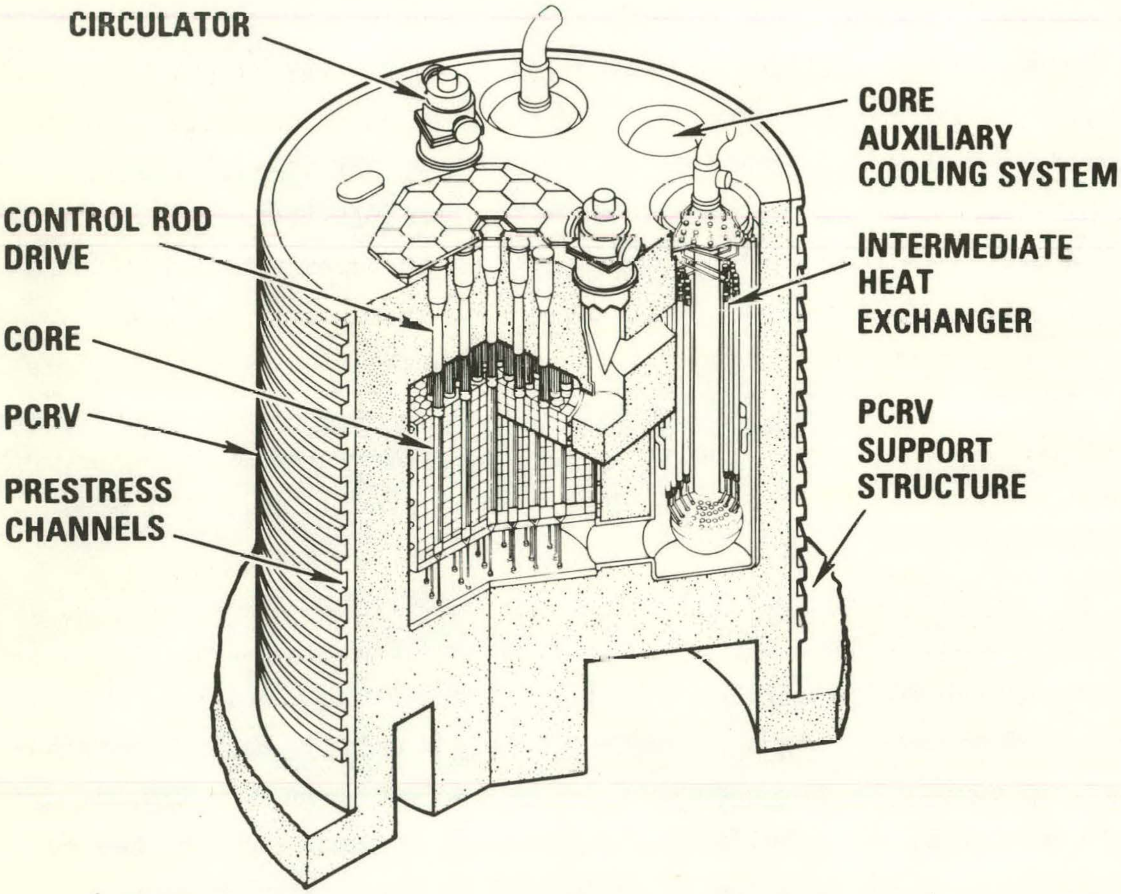

Fig. 2-1. 842-MW(t) VHTR reactor arrangement

TABLE 2-1
MAJOR 842-MW(t) VHTR PLANT PARAMETERS

Construction site	Eastern Pennsylvania	
Access	Road/rail	
Type of cooling	Process plant cooling	
Life	40 yr	
Nominal reactor power	842 MW(t)	
Plant layout	Single unit with layout designed to accommodate second unit	
Nominal primary helium conditions		
Flow rate	383 kg/s (3.04×10^6 lb/hr)	
Pressure	4.99 MPa (724 psia)	
Core inlet temperature	426°C (800°F)	
Core outlet temperature	850°C (1562°F)	
Nominal secondary helium conditions		
Flow rate	369.2 kg/s (2.93×10^6 lb/hr)	
Pressure	5.24 MPa (760 psia)	
IHX outlet temperature	793°C (1460°F)	
Reformer outlet temperature	605°C (1121°F)	
Steam generator outlet temperature	327°C (620°F)	
Fuel cycle	High-enrichment uranium/thorium or	20%-enriched uranium/thorium
Core power density	6.3 W/cm^3	6.3 W/cm^3
Fuel lifetime	3 yr	3 yr
Refueling cycle time, all reloads	1 yr	1 yr
Carbon/thorium ratio		
Initial core	170	350
Reload cores	185	600
Recycle starting, first plant	Reload 7	Reload 7
Fissile material	UC_2	UC_2
Fertile material	ThO_2	ThO_2
Conversion ratio	0.76	0.60
Fast fluence	4.9×10^{21} nvt	4.5×10^{21} nvt
Burnup	43,000 MWd/MT	(later)

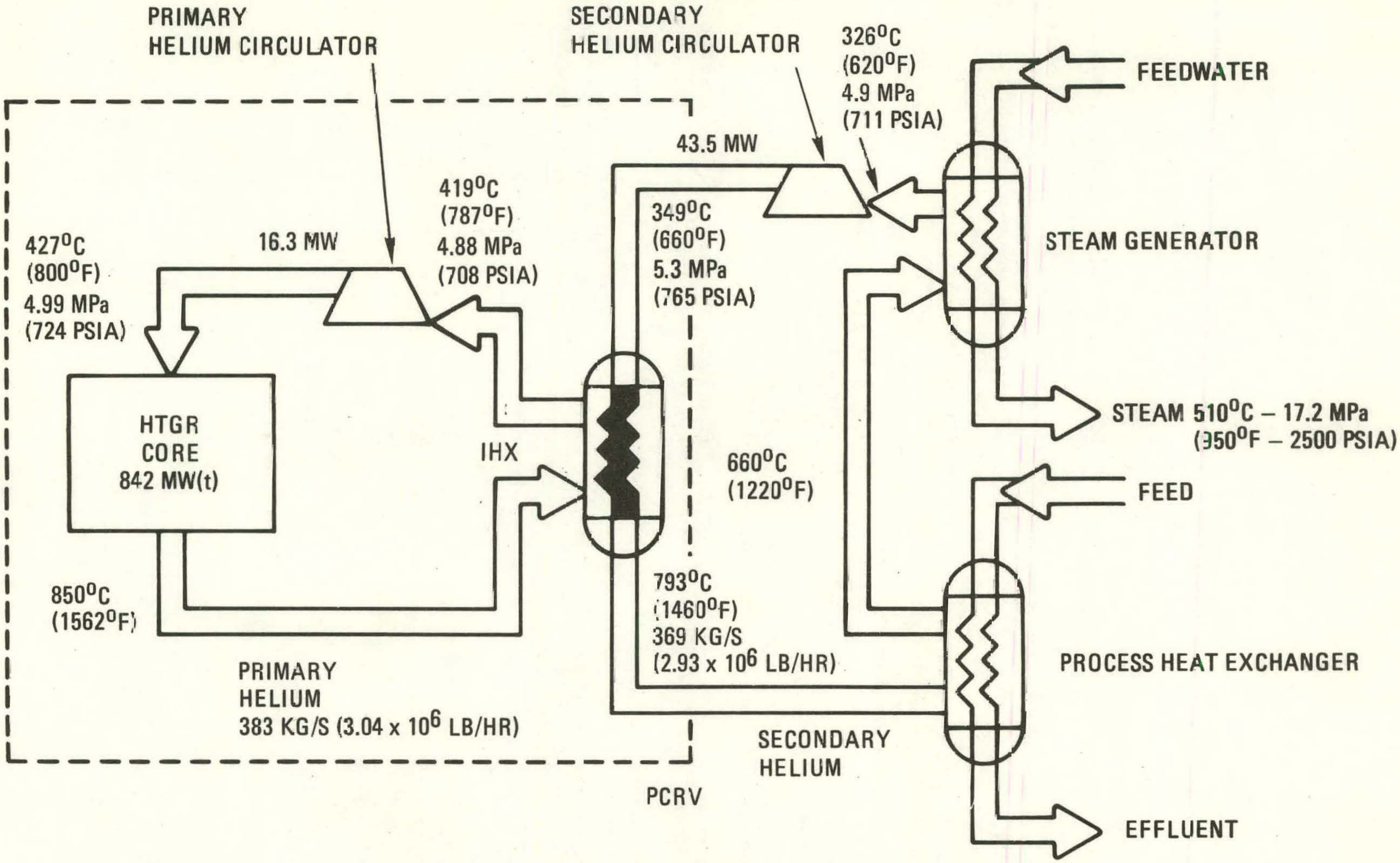

Fig. 2-2. 842-MW(t) VHTR heat balance diagram

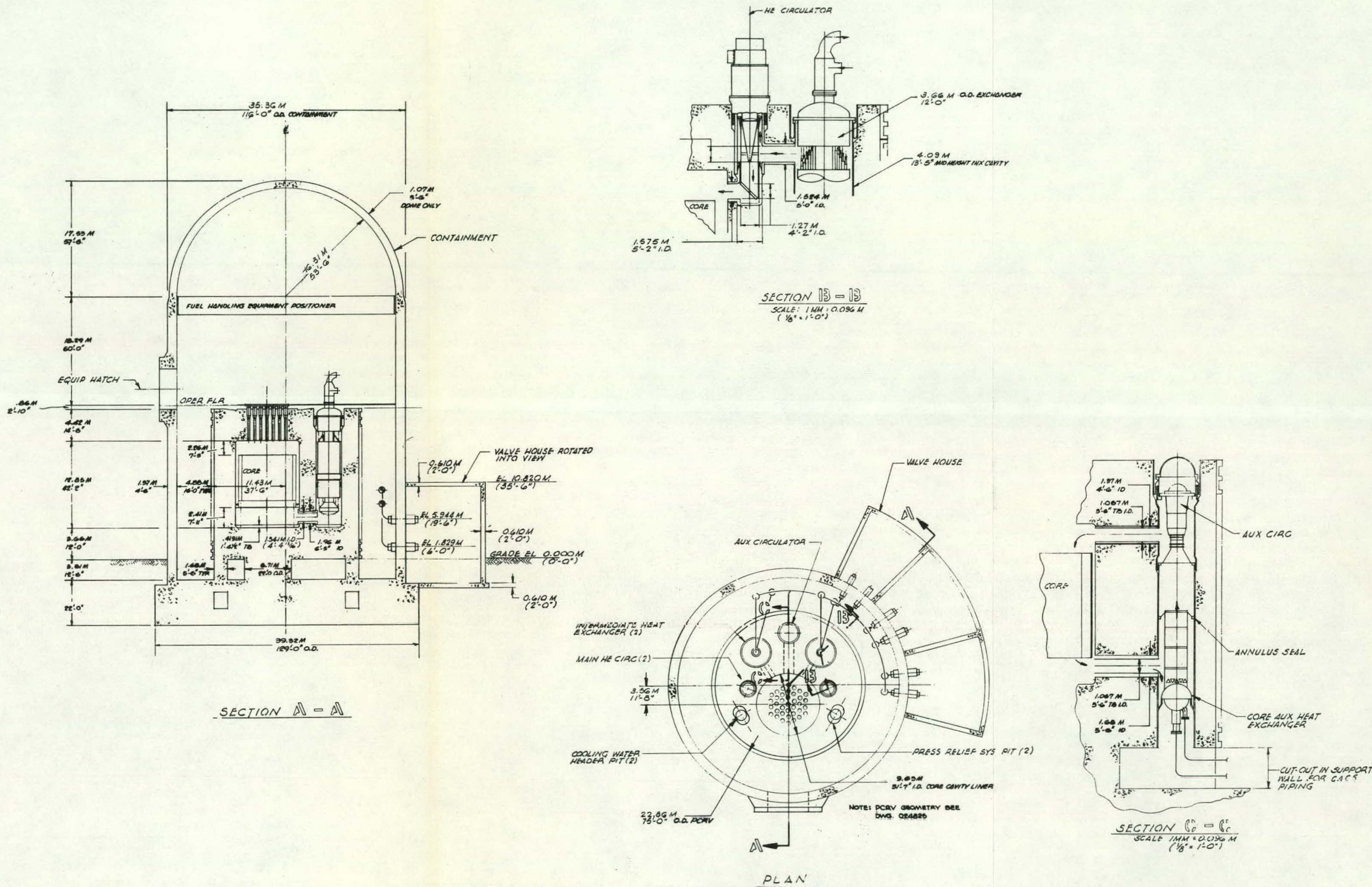

Fig. 2-3. Final arrangement of two-loop, side cavity PCRV for 842-MW(t) VHTR

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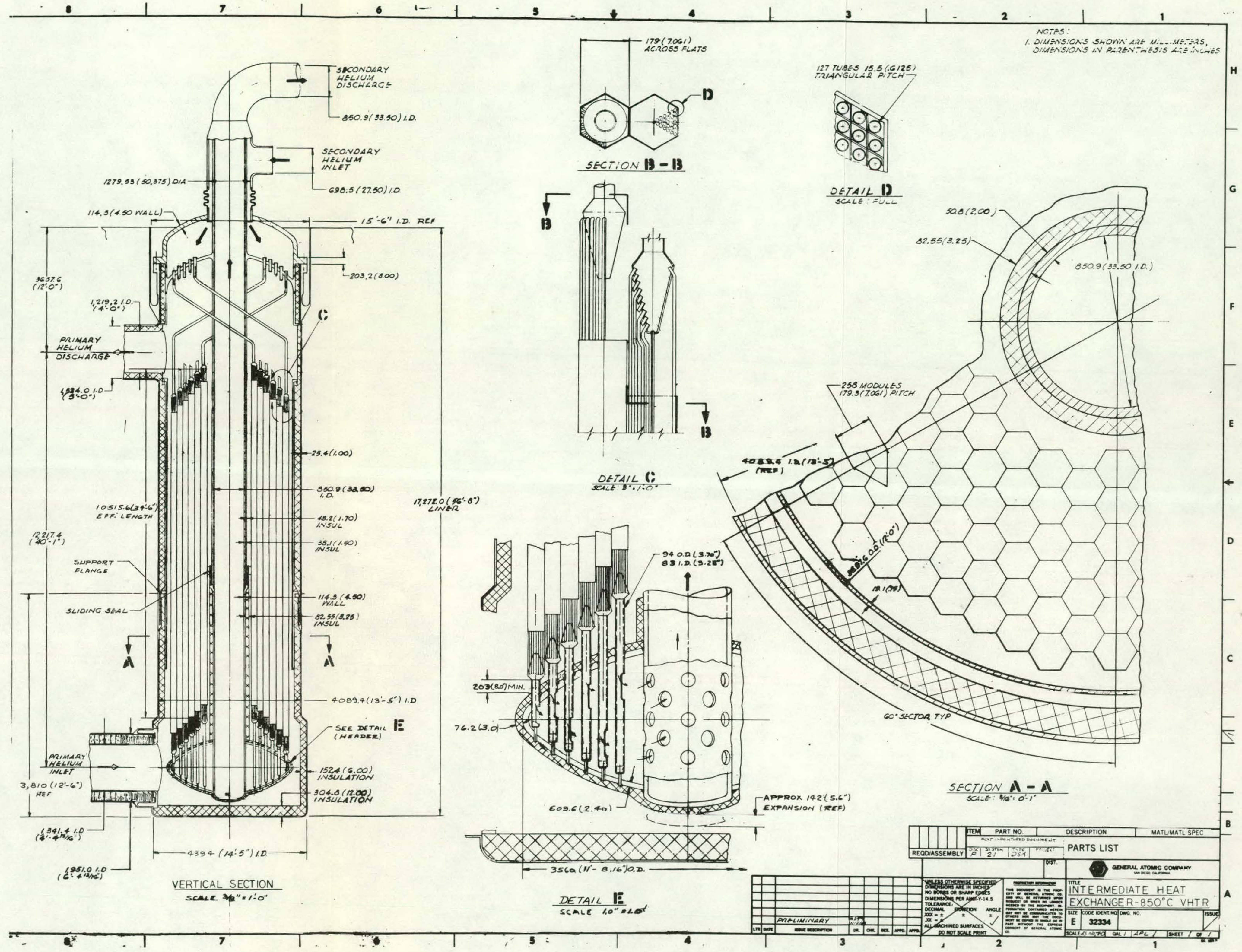

Fig. 2-4. VHTR intermediate heat exchanger for 850°C (1562°F) core outlet temperature

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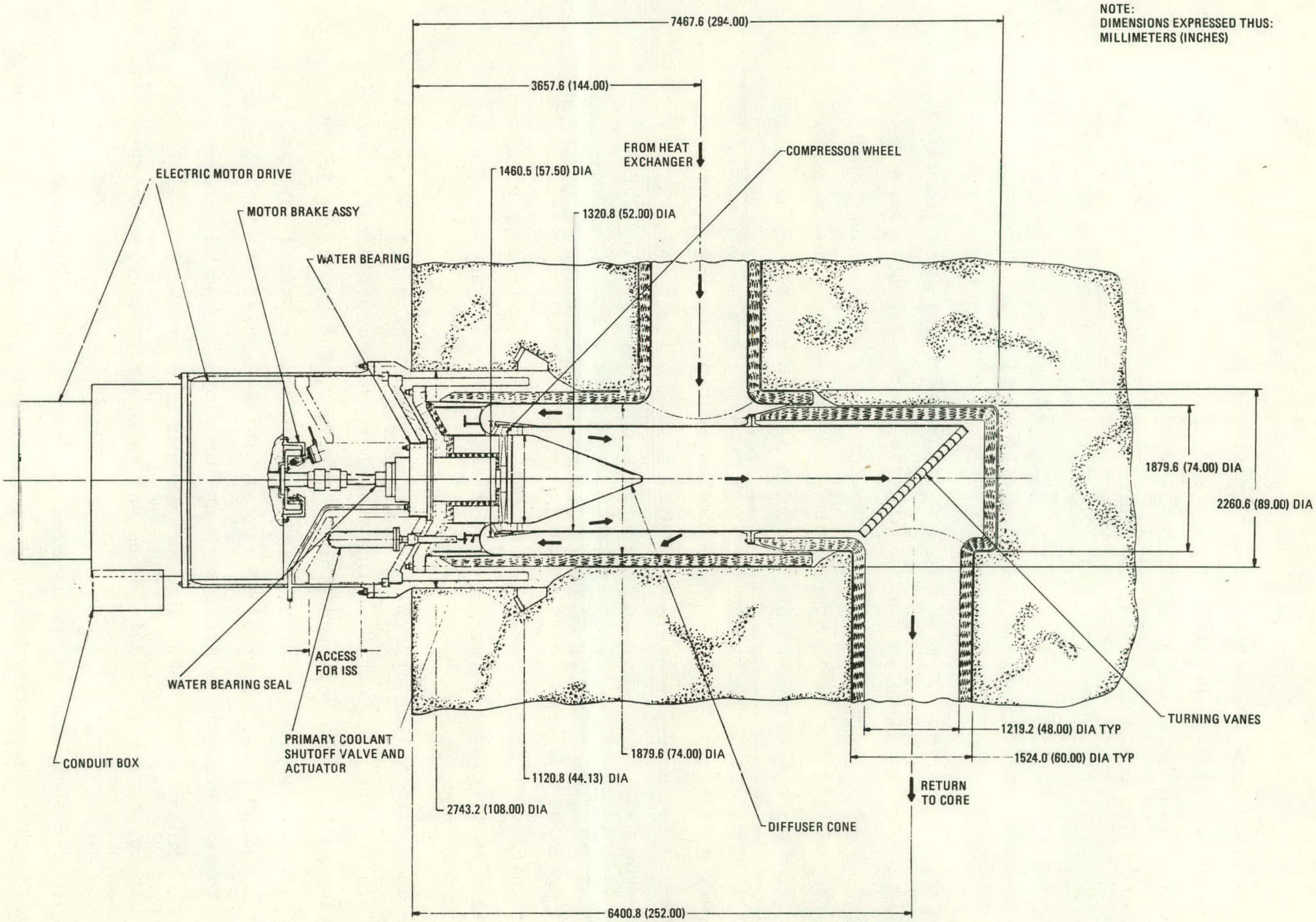

Fig. 2-5. Arrangement of primary helium circulator within PCRV

The CACS loop contains a water-cooled auxiliary heat exchanger (CAHE) (Fig. 2-6), an auxiliary helium circulator (Fig. 2-7), and a helium shut-off valve. The arrangement of the loop is similar to that of the primary loop, with helium coolant passing downward through the core, flowing upward through the auxiliary heat exchanger, and then being pumped by the circulator back to the core inlet plenum. The loop shutoff valve is located between the heat exchanger and the circulator suction.

The PCRV (Fig. 2-3) is a vertical cylinder with the core located in a cylindrical cavity which is offset from the vertical center line of the PCRV. Beside the core cavity are two smaller vertical cavities, each containing the IHX for one of the two primary coolant loops. The primary helium circulators are in separate cavities between the IHX cavities and core cavity and above the core cavity. This facilitates access for maintenance of the circulators as well as replacement of the IHX (if ever required). A third vertical cavity contains the CAHE and auxiliary circulator for the CACS loop. Horizontal ducts connect the primary and auxiliary loop component cavities with the core inlet and outlet plenums. The PCRV contains a water-cooled steel liner with thermal barrier on the gas-side surfaces. Radial prestress of the PCRV is provided by circumferential wire winding and vertical prestress by linear tendons.

The secondary helium system transports the heat from the IHX to the process plant. Because leakage within the IHX can produce direct communication between the secondary and primary circuits, the secondary helium pressure level is set slightly higher than that of the primary system, creating a modest pressure gradient that inhibits leakage of the reactor helium into the secondary system, without imposing sizable long-term pressure loadings on the IHX. The secondary helium pressure is also consistent with process-side requirements and reformer strength considerations.

Figure 2-8 shows the secondary coolant system piping arrangement. A separate, complete secondary helium loop is provided for each primary loop. Each secondary helium loop incorporates a steam/methane reformer, a steam

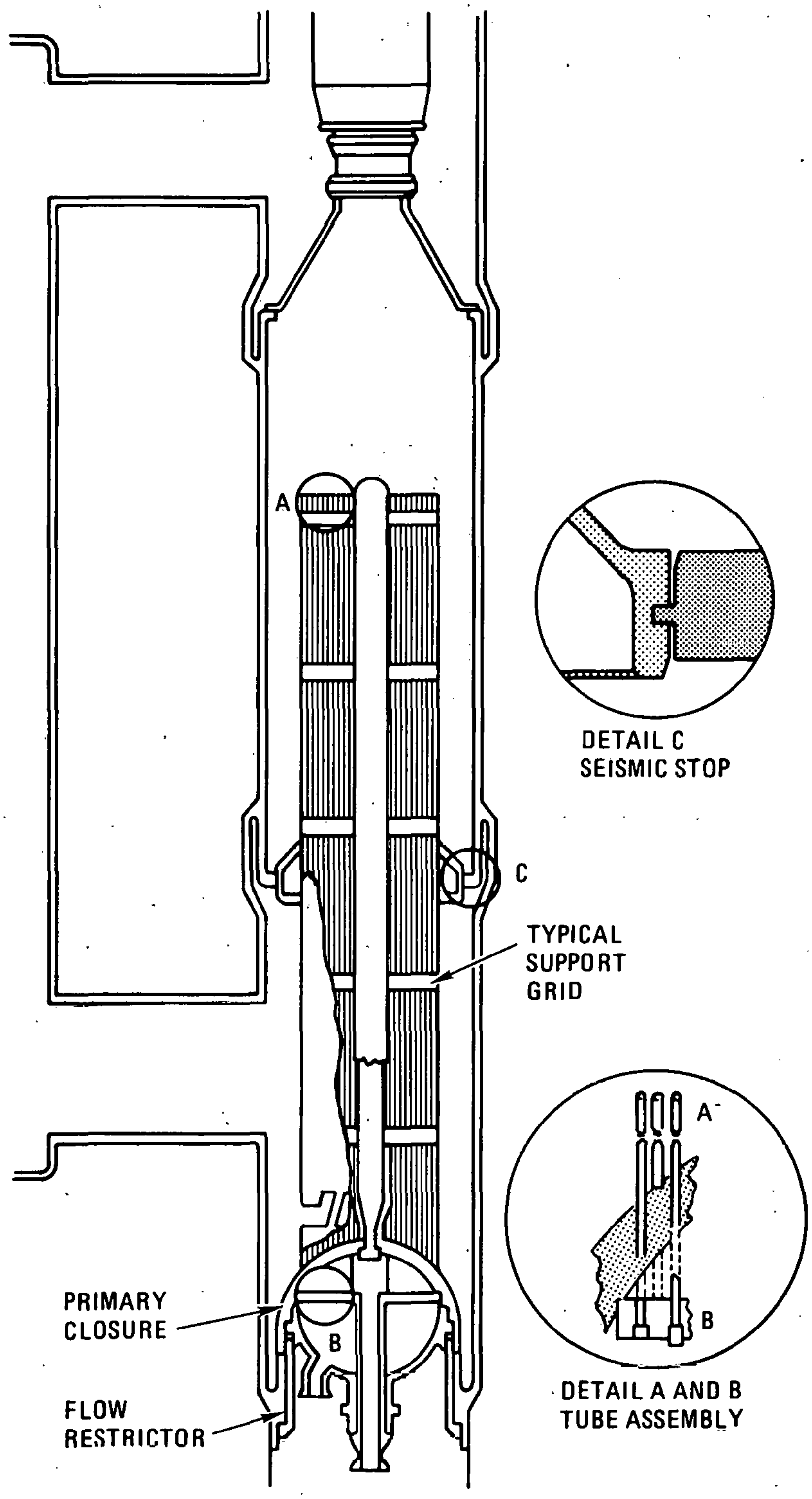

Fig. 2-6. Basic mechanical arrangement of bayonet tube CAHE

generator, a secondary helium circulator, and related helium piping and valving. Secondary helium is pumped through the IHX by the circulator, heated, passed to the reformer at high temperature, passed to the steam generator, and returned to the circulator to complete the circuit.

A safety-class shutdown heat removal system is connected to each secondary helium loop. The shutdown system for each loop contains an air-to-helium heat exchanger for heat removal, an electric-motor-driven auxiliary helium circulator, and the associated helium piping and valving.

Figure 2-9 shows a conceptual plant plot arrangement. The plot is arranged to be compatible with a twin reactor plant installation using common fuel handling and storage facilities. The twin plant is proposed in order to meet the high availability requirements of the user. Reactor auxiliary structures are arranged similar to current HTGR-SC plant concepts. A minimum separation distance of 61 m (200 ft) is maintained between safety-related reactor plant structures and the reformers in the secondary helium loops.

There are no significant differences between the configurations of the 850°C (1562°F) VHTR and the 950°C (1742°F) VHTR. The differences arise in the temperatures around the primary and secondary loops, the materials that are selected for components, and the changes made to the reformer and steam generator to keep the conversion to hydrogen high.

REFERENCE

2-1. "842-MW(e) Process Heat VHTR Reference Plant Design," DOE Report GA-A15277, General Atomic Company, to be published.

NOTES
1. DIMENSIONS ARE EXPRESSED THUS; MILLIMETERS (INCHES)

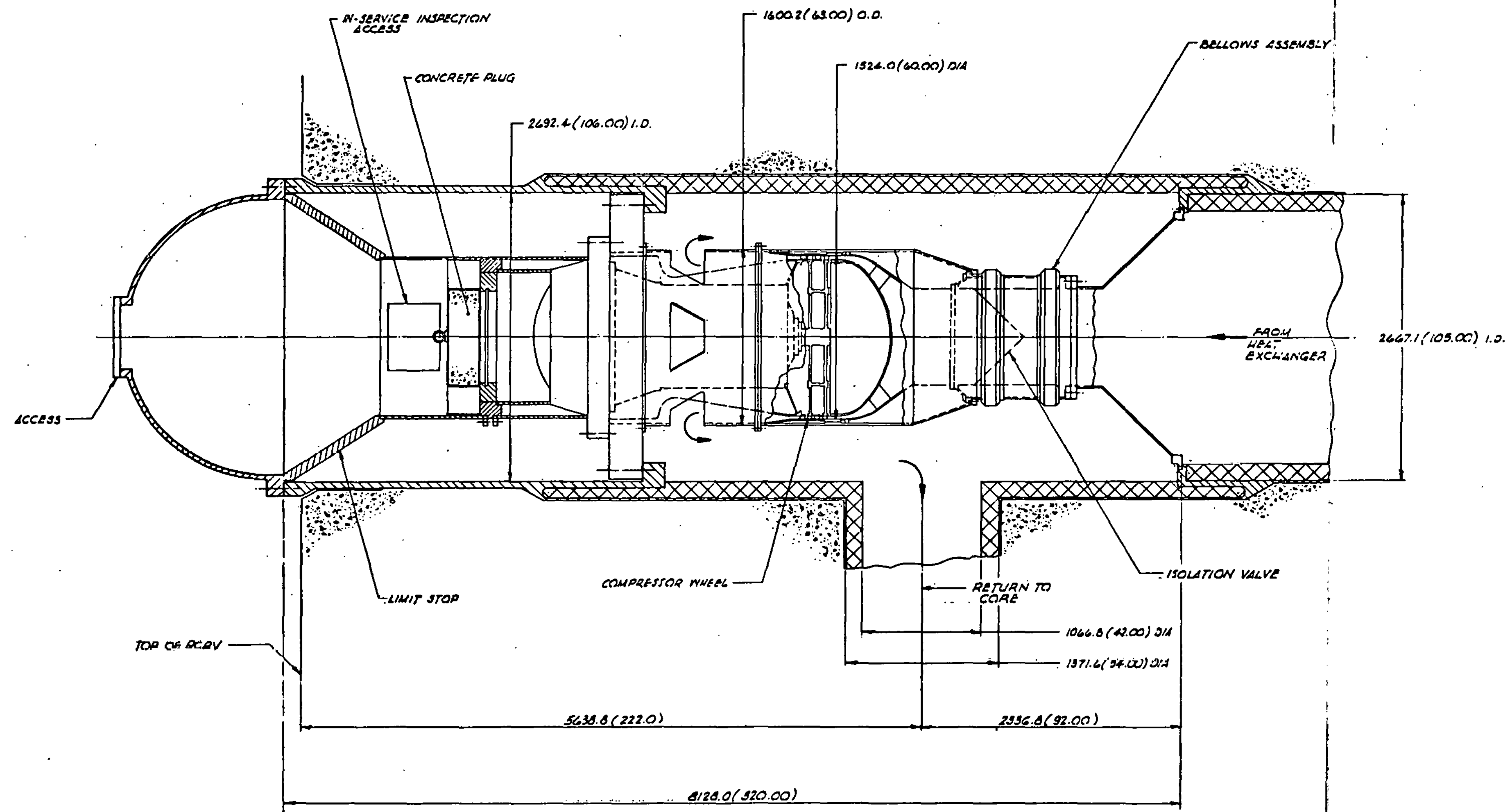

Fig. 2-7. Arrangement of auxiliary helium circulator

PARTS LIST

GENERAL ATOMIC COMPANY

AUXILIARY CIRCULATOR - 842 MWt VHTR

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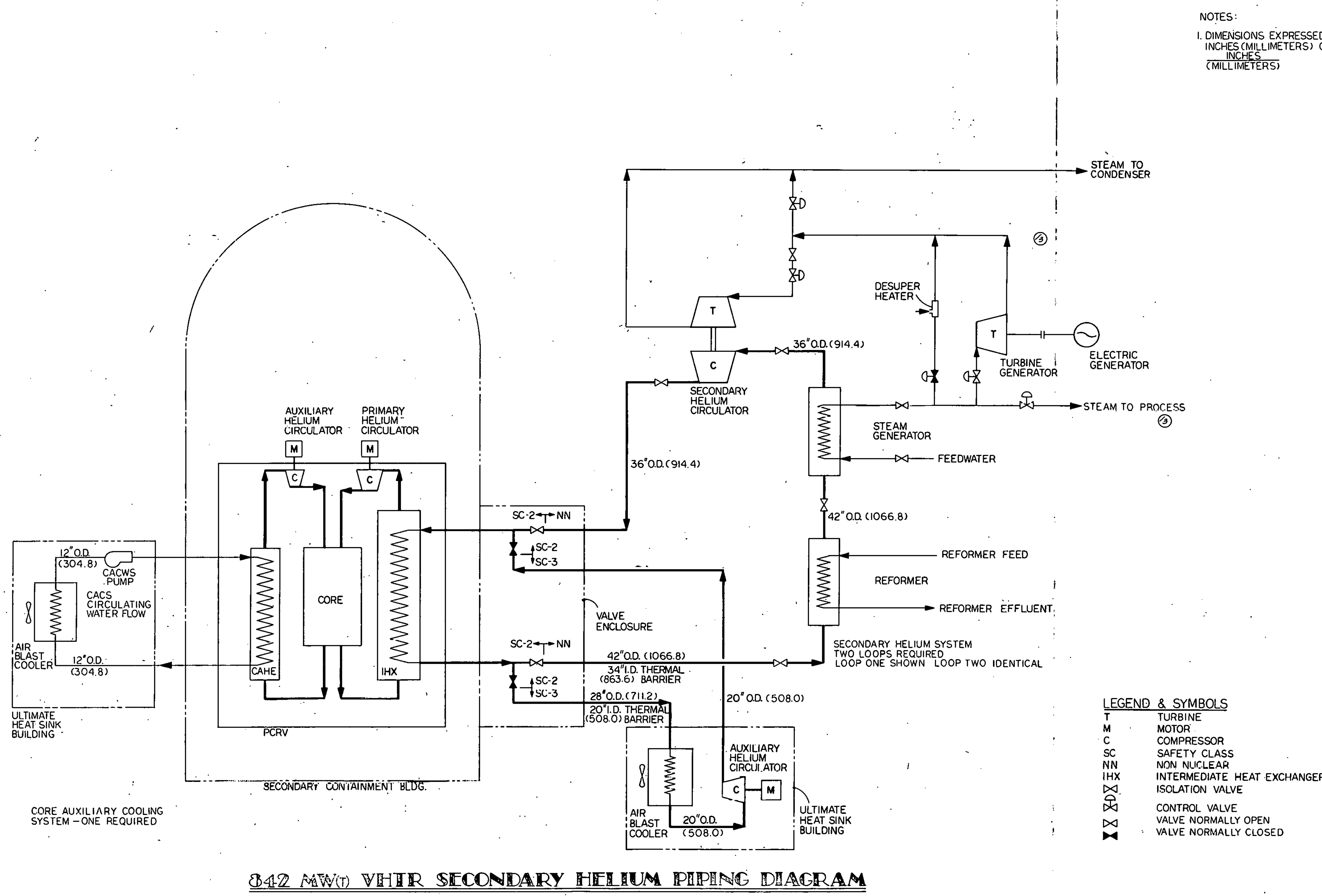

Fig. 2-8. 842-MW(t) VHTR secondary helium piping diagram

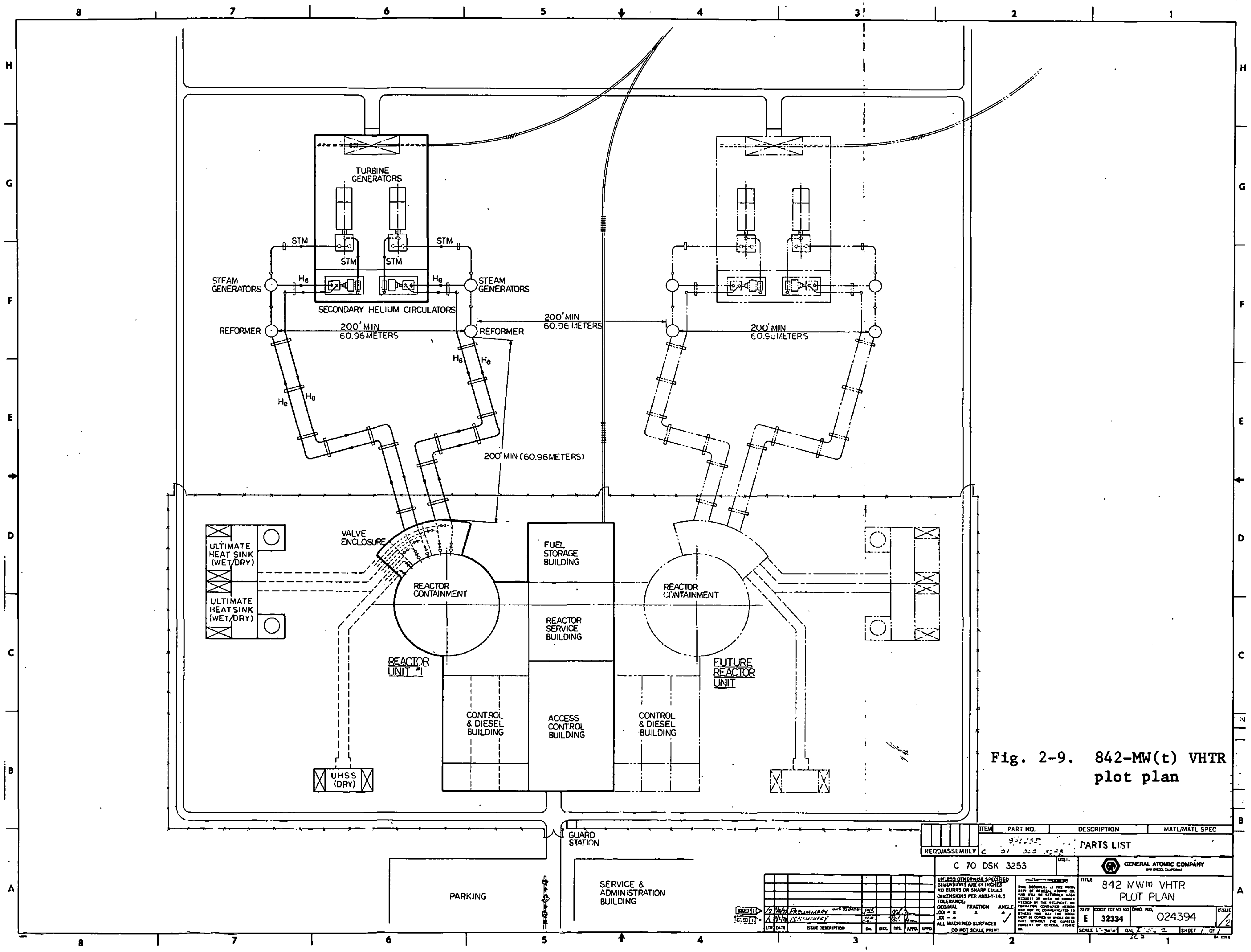

Fig. 2-9. 842-MW(t) VHTR plot plan

3. OVERALL PLANT SPECIFICATIONS

3.1. NHS PERFORMANCE

Preliminary cycle calculations have been performed for steady-state full-flow helium conditions. Table 3-1 summarizes the major system parameters and assumptions used in the performance calculations.

Figure 2-2 shows the system flow diagram and identifies the location for the various cycle conditions around each of the loops. Table 3-2 gives the calculated cycle parameters and plant performance.

3.2. NUCLEAR SAFETY

The preliminary design criteria for the VHTR pertinent to nuclear safety are discussed in this subsection. The philosophy is identical to that for the 950°C (1742°F) VHTR and should be easier to implement because of the lower temperatures involved. At this stage of the conceptual design, emphasis is on design features important to safety, accidents that must be considered, and safety objectives to be attained. The general approach to safety for the HTGR-SC is given in Ref. 3-1.

The VHTR is designed to conform to all state and Federal regulations pertinent to safety. Principal of these are:

10CFR20 Standards for protection against radiation (contains occupational exposure limits).

10CFR50 Licensing of production utilization facilities (describes the "as low as practical" operating releases in Appendix A as well as in the section titled "General Design Criteria").

TABLE 3-1
MAJOR SYSTEM PARAMETERS AND GROUND RULES
USED IN VHTR PERFORMANCE CALCULATIONS

Primary Loop	
Core power	842 MW(t)
Core inlet temperature	426°C (800°F)
Core outlet temperature	850°C (1562°F)
Maximum helium pressure	4.99 MPa (724 psia)
Helium circulator efficiency	0.75
Secondary Loop	
IHX inlet temperature	349°C (660°F)
IHX outlet temperature	793°C (1460°F)
Maximum helium pressure	5.24 MPa (760 psia)
Helium circulator efficiency	0.75
Fraction of heat removed through reformer[a]	0.40
Fraction of heat removed through steam generator[a]	0.60

[a] Fraction of heat removed is defined as

$$\frac{Q_{Reformer}}{Q_{Reformer} + Q_{Steam\ Generator}} \text{ and } \frac{Q_{Steam\ Generator}}{Q_{Reformer} + Q_{Steam\ Generator}} .$$

TABLE 3-2
PRIMARY AND SECONDARY LOOP SYSTEM PARAMETERS

Location/Description	Temperature [°C (°F)]		Pressure [MPa (psia)]	
Primary System Parameters				
Core inlet	426	(800)	4.992	(724)
Core outlet	850	(1562)	4.953	(718.4)
IHX inlet	846.5	(1555.8)	4.945	(717.2)
IHX outlet	418.6	(785.4)	4.891	(709.4)
Circulator inlet	410.4	(787)	4.883	(708.2)
Circulator outlet	427	(800.7)	5.000	(725.0)
Core power:	842 MW(t)			
Helium flow rate:	383 kg/s (3.04 x 10^6 lb/hr)			
Circulator power:	16.3 MW(t)			
IHX heat duty:	851.4 (MW(t)			
Primary loop heat losses:	6.9 (MW(t)			
Secondary System Parameters				
IHX inlet	348.9	(660)	5.24	(760)
IHX outlet	793.3	(1460)	5.15	(746.4)
Reformer inlet	792.1	(1457.8)	5.07	(736)
Reformer outlet	650.0	(1121)	5.06	(733.5)
Steam generator inlet	604.9	(1120.9)	5.04	(731.5)
Steam generator outlet	326.5	(619.7)	4.91	(711.9)
Circulator inlet	326.5	(619.7)	4.90	(710.6)
Circulator outlet	348.9	(660.1)	5.27	(765.0)
Helium flow rate:	369.2 kg/s (2.93 x 10^6 lb/hr)			
Reformer heat duty:	358.4 MW(t)			
Steam generator heat duty:	533.6 MW(t)			
Circulator power:	43.5 MW(t)			
Secondary loop heat losses:	2.9 MW(t)			

10CFR100 Reactor site criteria (provides limits for the design basis accident of the reactor).

Highlights of these regulations are described below:

1. Criterion No. 10 states that the reactor systems shall be designed so that the specified fuel design limits are not exceeded. For the VHTR, this fuel limit is a temperature limit of 1428°C (2700°F) on the ceramic-coated fuel particle, a value greatly in excess of cladding temperature limits in reactors having metallic-clad fuel rods. Thus, if the fuel should somehow exceed this temperature limit, there would be no subsequent fuel puddling or possibilities for secondary criticality. The VHTR has an advantage over other reactor systems owing to its ceramic core, its large thermal inertia, and its single-phase coolant which prevents any power excursions from causing significant temperature changes with associated consequences.

2. Criterion No. 35 states that an emergency cooling system must be provided such that no loss of reactor coolant will impair the safe cooling of the core or cause further accidents. For the VHTR, this cooling is to be provided by means of the two main loops, each designed and constructed to the quality level demanded for safety-related components, and by means of a single additional auxiliary loop. The objectives here are several-fold:

   a. The main loops have more cooling capacity than auxiliary loops, and this better limits fuel temperature excursions following loss of coolant.

   b. The mixed cooling system provides diversity, which limits the possibilities for common mode failure and provides a more reliable emergency cooling system.

c. The failure of a main loop is more likely to be found during the normal operating mode than during an emergency demand mode, and loop failure is easier to accommodate during a normal shutdown than during an emergency shutdown.

d. The emergency cooling loops have typically contained water in HTGR-SCs. Since in-leaking water (such as from auxiliary heat exchangers) can react strongly with hot graphite and fuel particles and since the VHTR core is hotter than an HTGR-SC core, the avoidance of such water-containing emergency cooling loops is preferred.

e. The use of the main heat exchanger to transfer core heat in an emergency mode reduces requirements for primary loop heat exchangers, reduces the number of cavities required in the PCRV, and avoids the concomitant enlargement of the PCRV.

The requirement that the main loops perform emergency cooling necessitates an appropriate quality level of construction for each IHX and other main loop components, e.g., primary circulator and circulator drive. The option for an auxiliary main loop circulator is kept open should it prove more cost effective. However, electrically driven main circulators are employed because they can be supplied from a variety of power sources (house load, grid, diesel generator sets, etc.), and they simplify plant preoperational testing, startup, and shutdown operation.

Each of the cooling loops will have by itself sufficient capacity to safely shut down the reactor, i.e., to prevent excessive fuel and component temperatures and to assure integrity of the primary system containment.

It is not expected to be convenient to upgrade both the main loops and the entire secondary loop. Instead, a helium-to-air (possibly with an intervening fluid) heat exchanger, placed between the hot and cold legs of each secondary helium loop, provides the appropriate emergency cooling capacity. An auxiliary circulator to circulate the helium through this emergency heat dump is also provided in each secondary loop. This circulator is completely different from the main (nonsafety-related) secondary circulator which is located by the process plant. A related requirement is the upgrading of the main loop piping (to the point where the emergency heat dump system is connected) to the necessary quality assurance level to fulfill the desired emergency purpose. Dual isolation valves in the secondary lines are required to isolate the safety portion of the piping from the nonsafety portion. These valves are to be arranged so as to provide closure of the secondary containment piping penetrations.

The VHTR utilizes a prismatic fueled core with the same type of fuel particles employed in HTGR-SC and gas turbine-HTGR (HTGR-GT) designs. The safety requirements for these systems and the VHTR are the same in principle. The major problem in each reactor system is to ensure that the component design limits are not violated by any design basis accident. Accidents setting these design limits usually comprise failure of any item of operating equipment followed by a failure of a single item of safety grade equipment. The latter has usually implied that one of the emergency cooling loops is unavailable. Only if the initiating failure does not require an emergency shutdown may credit for normal operating equipment be used to assess the accident consequences. In the case of the VHTR, the failure of a main loop may not necessarily require an emergency shutdown of the reactor. However, it is prudent at this point of the conceptual design to expect that it may. Certainly, the failure of a water-cooled CAHE with a significant ingress of water would require an emergency shutdown. (Therein lies the motivation for a helium-cooled CAHE.) Given the single failure criterion, it becomes necessary for the remaining functional emergency loop to have sufficient capacity (100%) to remove all residual heat from the core, including heat caused by fission product decay.

The primary concern during the shutdown following the initiating accident is that no components critical to safety exceed their temperature limits. Critical components are thermal barrier cover plates in the upper and lower cross ducts, since their failure could block the cooling flow. In assessing the transient conditions, a 5-min delay is assumed in starting the diesel generator sets which supply emergency electric power.

The VHTR is designed so that the transient conditions following any accident are no more severe than for other HTGR systems having lower normal operating core outlet temperatures. This is achieved by lower core power density (i.e., relatively higher thermal inertia) and relatively larger emergency cooling capacity. The use of the main loops is particularly appropriate because cooling is limited mostly by heat transfer surface area; the main IHX units are much superior to the CAHE in this respect.

Significant initiating accidents which must be considered in the transient analyses include the following:

1. Loss of primary coolant through a leaking closure [design basis depressurization accident (DBDA)].

2. Leaking IHX.

3. Leaking CAHE (water inleakage).

4. Sudden loss of secondary coolant due to a seismic event (common failure to both main loops).

5. Reformer explosion (pressure pulse on IHX).

The separation distance between process plant and reactor systems is addressed by the following general criteria:

1. Separation distance refers to the distance between any process plant unit or aggregate of units and any reactor component needed for the safe shutdown of the reactor. (In other words, there will be various separation distances.)

2. The separation distance shall be such that no postulated accident to the process unit(s) in question can impair the safe shutdown of the reactor.

3. In postulating the accident, conditions shall be assumed (process temperatures, flows, pressures) that are derived from a logical malfunction sequence and combined to maximize the consequences.

4. Once the accident(s) is postulated, the process plant is not permitted to change either physically or in its operating conditions such that accident conditions can arise that are either more frequent or more hazardous than those considered under item 3.* (This implies that the process plant accident conditions should reflect not just actual plant arrangement and conditions but others of any greater seriousness that might reasonably be expected over the plant lifetime.) Assurance that these design bases are unchanged will be provided by a local safety committee whose actions are appropriately documented for Nuclear Regulatory Commission (NRC) inspection. Failure to meet these requirements will shift the burden of safety cognizance from the plant management to the NRC, which may mean that the process plant will be included within the reactor site boundary.

5. In assessing the consequences of process plant accidents, consideration is given to direct and indirect explosions, missiles generated from these explosions, and sequences which

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*See 10CFR50-59.

modify the consequences of the initiating accident. Consideration is also given to the consequences of clouds of flammable gas which may drift from the process plant toward the reactor. In assessing these latter consequences, due consideration shall be given for effects such as prevailing winds, gas buoyancy, mass diffusion, air mixing and dilution, and for reasonable operator action (e.g., reactor shutdown). However, such consideration shall identify critical assumptions in analyzing the accident consequences so that control or alarm action may be taken to ensure that these critical assumptions have very high probabilities of being valid.

6. The reactor plant shall be designed to provide breathable air for reactor operations whenever the outside atmosphere is contaminated by effluents resulting from malfunctions/accidents of the process plant.

Satisfaction of the above criteria requires that the process plant be designed, that separation distances be determined, and that accident sequences be developed and analyzed. Consequently, it will not be possible to design the reactor plant independently of the process plant unless penalties for subsequent hardening of the reactor plant are accepted.

3.3. OPERATION AND CONTROL

A complete description of the entire plant, comprising integrated reactor and process portions, is not currently available. Consequently, no details of operations and control have been developed. However, some qualitative information is provided below based on experience extrapolated from the HTGR-SC and from a few preliminary calculations of VHTR loop dynamics (Ref. 3-2).

The VHTR is an easy reactor to operate (1) because it has a large negative reactivity coefficient and a single-phase chemically inert primary coolant and (2) because it has a ceramic core with a large thermal inertia so that any (highly unlikely) power excursions are not translated into large temperature excursions.

For the most part, the reactor portion control for the VHTR will be analogous to that for the HTGR-SC. In the latter, the primary power level demand signal is derived from comparing actual steam pressure downstream of the main throttle with the demanded steam pressure. In the case of the VHTR, the power demand signal will probably be derived from comparing actual helium temperature drop across the reformer and steam generator with the demanded temperature drop. The significance of this comparison is that it is performed quite distant from the reactor and that an increased power demand signal will require changes to the power control rod position as well as increases in primary and secondary circulator speed. In other words, owing to the relatively long transport time in the secondary loops, a quick response of the plant to changes in reformer or steam generator demand is unlikely. At the same time, rapid changes to the feedstock supply and to concomitant process power demands are also to be avoided, since the process chains cannot respond quickly either. Thus, the plant will generally have a slow response and will be quite unlike the HTGR-SC, which must respond to load changes of up to 3% per minute and to 10% steps.

The process side is split into independent trains to facilitate startup (the trains are brought on line one at a time), to minimize the design requirements of the auxiliary (fossil-fired) standby steam boiler, to permit partial plant operation when one train is shut down for maintenance, and to obtain a higher overall average capacity factor. Each train is controlled as a separate subsystem. It is presently envisaged that this control will extend through the secondary helium loop. This particular requirement needs to be confirmed, since it can result in flow temperature distortions at the inlet to the core when one loop is running at a different power level from its neighbor(s).

Preliminary studies (Ref. 3-2) have been made to assess the impact on the reactor system (both primary and secondary loops) owing to a loss of process gas supply or loss of steam which affects reformer power demand. The system responses were found to be mild and to have little impact on design requirements for the heat exchangers within the system.

3.4. TRANSIENT PERFORMANCE

Representative transients have not been generated for the VHTR. Qualitatively, the VHTR is a slow-responding plant moving in conjunction with a slow-moving process plant. Transient performance requirements in terms of temperature overshoots and numbers of temperature cycles will be less than for the HTGR-SC. (See also Section 3.3.)

Emergency and faulted transients due to reactor faults will be similar to those for the HTGR-SC and are shown in Table 3-3.

The absence of faulted transients due to steam/water leaks into the primary system is to be noted. Such transients are to be avoided by design because of the greater consequences of such inleakages at the higher core temperatures of the VHTR.

3.5. SHIELDING AND SOURCE STRENGTH

Source strengths of fission products released from the core under design conditions are determined as a basis for assessing release quantities in the event of a DBDA and to establish radiation doses for inspection, maintenance, and overhaul purposes. Shielding requirements are then established depending on the nature of the inspection, maintenance, and overhaul operations.

The fission products released from the core have not been quantified. However, core studies (Ref. 3-3) have been performed for the 950°C (1742°F) 842-MW(t) VHTR to assess the broken fuel particle fractions, which

TABLE 3-3
REPRESENTATIVE PLANT TRANSIENTS
40-YEAR PLANT LIFE

Plant Transients	Design No. of Occurrences for Plant
Emergency Transients	
Slow primary system depressurization	2
Rod withdrawal with core power to flow trip	2
Loop shutdown with helium valve failure	3
Failure of circulator speed control	2
Loss of primary helium flow (failure of nonsafety control)	3
Shutdown of all main loops [false plant protection system (PPS) signal]	2
Operating basis earthquake (OBE) with reactor trip	1
Loss of secondary helium flow (failure of nonsafety control)	3
Gross failure of nonsafety portion of secondary helium piping	1
Faulted Transients	
Sudden depressurization and shutdown with CACS	1

are strongly indicative of fission product release. In general, the higher core outlet temperature of the VHTR (compared with the HTGR-SC) would enhance the fraction of failed fuel particles. However, the use of a 6.3 W/cm^3 power density, a 3-yr fuel cycle, power (grey) control rods, and a 10-row fuel block (similar to that used in the FSV plant) leads to acceptable failed fuel fractions. The release quantities in the event of a DBDA will be modest and, in conjunction with the secondary containment, will be a negligible hazard to the public (10CFR100 limits). The VHTR design releases will conform to the "as low as practical" requirements of 10CFR50 and will also be lower than the occupational exposure limits of 10CFR20.

The major concern is expected to be the release of cesium (either as the Cs-133 or Cs-137 isotopes) which can diffuse through the wall of intact fuel particles. This problem, while not presently quantified, poses difficulties for man-access to primary system internals, the IHX being of primary concern. Presently, the plant has been configured with side wall cavities from which the IHX may be readily lifted into a shielding casket for handling under controlled conditions. Therefore, it is permissible to design the IHX for a shorter life than the 40-yr plant lifetime.

A significant factor in the fission product activity levels in the primary circuit is whether highly enriched or low-enriched uranium is to be used as the fuel (see Table 2-1). The latter has been considered as a means of reducing the potential for diversion of weapons grade material as part of the national program to prevent nuclear weapons proliferation. However, the low-enriched uranium-thorium (LEU-Th) cycle not only has a higher fuel cost (for a reprocessing cycle) but also releases more fission products owing to a higher fuel particle failure fraction. The higher failure fraction is due to the fact that plutonium carbide in the fuel particle has greater mobility under temperature gradients than uranium carbide. (Plutonium breeds from the U-238 of the LEU-Th fuel.) Resolution of this fuel choice is expected to occur in the near future. Procedures and equipment for inspecting and replacing primary system components will be devised accordingly.

3.6. AVAILABILITY, MAINTENANCE, AND TESTING

3.6.1. Availability

The VHTR is designed to achieve a 90% capacity factor, which is higher than the 70% value typical of nuclear electric power plants. This is a consequence of operating the nuclear process heat plant at 100% load whenever it is available. Daily and weekly electric load variations are simply not present. Implications of this capacity factor requirement are as follows:

1. VHTR components will experience more time at full load than comparable HTGR-SC components for the same reactor lifetime, but will be subjected to fewer temperature cycles.

2. VHTRS will probably be constructed in multiple units to provide an assured heat source for the process trains. (Provision for temporary cross-coupling of hot helium supply lines is a related requisite. This follows because it is time consuming to bring a process train up to design operation owing to temperature rate change limitations of many sequential process units and to the complexity of coupling to the feed and return lines of the various process streams.)

3. Higher standards of component and subsystem reliability are required for the VHTR than for the HTGR-SC, since there are no slack periods which permit shutdowns of short duration to remedy accumulated maintenance items and because the owner is less likely to have alternative low-cost power than an electric utility.

4. Because the capital-intensive process plant will be on standby (at least on some of the trains) when the VHTR is shut down for refueling, there is a strong requirement to minimize this refueling interval, unless it coincides in both time and

duration with the process plant shutdown for maintenance. The latter (coincidence of duration) is expected to be unlikely; thus, there is strong incentive for the VHTR to be fueled on-line. Twin unit plants are also favored for the same reason.

High availability is an essential requirement of the VHTR, since the process plant will have few alternative heat sources, unlike a nuclear power plant feeding an electric grid. The numerical requirement for availability will be established by a comparative study of the capital costs, operating costs, and availabilities offered by competing energy sources.

3.6.2. Refueling, Maintenance, and Testing

The VHTR plant utilizes the same reactor refueling procedures and equipment as the HTGR-SC power plants. Because the PCRV and most equipment items in the VHTR are the same or very similar to those in the HTGR-SC, maintenance and testing procedures also are very similar. The plant is designed to comply with all applicable maintenance and testing requirements of Federal design criteria, regulatory guides, and industry codes.

3.6.2.1. Refueling. The planned annual refueling time, starting and finishing with a pressurized reactor vessel, is 20 days or less.

3.6.2.2. Maintenance. The total planned downtime, including refueling, is 31 days per year or less. Nuclear steam supply (NSS) equipment within the PCRV to be replaced on a regular basis is listed in Table 3-4.

3.6.2.3. Testing. NSS equipment and systems are designed for inservice testing when required by applicable codes and standards to verify safety related functions. Safety-related equipment and systems are designed for testing during operation when the period for testing may be less than the period for shutdown maintenance.

TABLE 3-4
EQUIPMENT WITHIN THE PCRV TO BE REPLACED
ON A REGULAR BASIS

Component	Design Life (yr)
In-core and IHX temperature instrumentation (at 80% capacity factor)	4
High-temperature filter (at 80% capacity factor)	1
High-temperature adsorber (at 80% capacity factor)	4[a]
Replaceable reflector elements immediately adjacent to active core (at 80% capacity factor)	8
Power rods	8[b]

[a] Assumes 50% duty over 4 yr.

[b] Includes 4 yr in core and 4 yr withdrawn.

3.6.3. Inservice Inspection

The basic information documents for inservice inspection of gas-cooled reactors at GA are Refs. 3-4, 3-5, and 3-6, which are all specific to the HTGR-SC plant. Many items are the same or similar in the VHTR, and the principles are applicable where the details differ. PCRV inspection procedures are the same for the VHTR as for the HTGR-SC and are covered in the above references. Major VHTR equipment that has inspection considerations which differ from those of HTGR-SC equipment is discussed below.

3.6.3.1. Intermediate Heat Exchanger. Any small IHX leak will cause secondary helium to enter the primary system because the secondary pressure is higher. This would eventually be detected and the malfunctioning loop would be shut down. In the event of a large leak, the primary pressure and secondary pressure in the affected loop would quickly equilibrate, and some fission products might be carried into the secondary circuit. The amount carried over would be small and would enter a closed loop, since the containment isolation valves would close; thus, no radioactivity would escape to become a hazard to the public or operating personnel. Moreover, auxiliary cooling, if required, would be operable owing to the redundant loop capacity.

A requirement to inspect or plug individual tubes would involve a change in the current IHX concept and has not been considered heretofore. The current IHX concept provides for leak testing and plugging of modules by the use of a suitable machine. (Even the module leak test may not be meaningful unless the helium makeup requirements to the loop are significant.)

The IHX design will incorporate provisions for remote visual inspection where possible. Supporting structures will be in compression, or provisions for remote inspection of welds in tension will be incorporated.

Tube bends in module inlet and outlet tubes will be designed to permit volumetric inspection from the bore of the tube.

The IHX is a safety class 1 component. Large pressure-containing portions of the unit on the primary side may require 100% volumetric inspection of the welds, but inspection of individual tubes may not be necessary because of their small size. The module attachment tubes are probably included in the inspection requirement. Supporting structures in compression are expected to be exempt from volumetric inspection, but remote visual inspection is desirable to detect buckling or corrosion.

3.6.3.2. Shutdown Cooling System Equipment. The relationship of the shutdown heat removal system heat sink to the IHX and primary loop is shown schematically in Fig. 2-8. Redundancy is provided by the fact that the reactor always has more than one IHX, each equipped as shown with a heat sink capable of removing 100% of the core decay heat with the reactor either pressurized or depressurized. The process loop is connected in parallel with the shutdown cooling loop and can be valved off from it.

The portion of the circuit in Fig. 2-8, which is required to transport the heat from the IHX to the heat sink, is a safety class 2 system. One feature of the inspection requirements for a class 2 system is that inspections can be limited to the equivalent of one loop in a multiloop configuration. If a problem area is discovered, the same portion of all loops must then be inspected. The net effect is that, barring problems, the inservice inspection burden for class 2 systems is practically independent of the number of loops. Pipe welds can be inspected without removal of the internal thermal barrier. The piping design will provide for some form of visual inspection of the internal thermal barrier.

3.6.3.3. Secondary Coolant Loops. Except for the portions involved in shutdown cooling, the secondary loops are non-nuclear. It is expected that the piping, reformers, steam generators, and circulators will be inspected in accordance with conventional industrial practice for petrochemical plants. Because of the economic penalties associated with unplanned outages, this is expected to include extensive inspection during planned maintenance periods and on-line monitoring by available methods.

3.7. ENVIRONMENTAL REQUIREMENTS

Environmental requirements include the design for both safety- and nonsafety-related systems, but with special emphasis on the former under emergency and faulted conditions.

Environmental effects to be considered include (1) hot helium jets (primary and secondary helium sources), (2) missiles from component failure (such as the reformer and hydrogasifier), (3) overpressures resulting from explosions in the process plant, (4) noxious fumes resulting from process plant malfunction, and (5) high temperatures and pressures in the containment building resulting from secondary piping failure.

Analysis of the accidents, their frequency, and their consequences will establish design extremes. The VHTR design will address the consequences by separation, plant layout, shielding, or system redesign as required.

For the VHTR, the most extreme environment arises from failure of the primary or secondary (more likely) helium pressure boundaries. It may be necessary to address the consequences by active cooling means to keep the environmental conditions for safety-related components within their design bounds.

3.8. SEISMIC REQUIREMENTS

The preliminary seismic design criteria for the structures and components in the NHS and the preliminary seismic response at support points of major NHS structures and components will be given in a plant specification (Ref. 3-7). The loads are NHS/BOP; interfaces are not presently available.

The following criteria apply:

Seismic level OBE/safe shutdown earthquake (SSE)	0.15/0.3 g at ground level
Soil conditions	Soft soil to unweathered rock
Shear wave velocity	122 to 2438 m/s (400 to 8000 ft/sec)
Soil shear modulus	24.8 MPa to 17.2 GPa (3.6×10^3 to 2.5×10^6 psi)

3.9 BALANCE OF REACTOR PLANT (BORP)

3.9.1. Reactor Auxiliary Systems and Structures

The VHTR plant incorporates reactor auxiliary systems and structures following designs similar to those of the HTGR-SC power plants. These include the reactor containment building (RCB), reactor service building (RSB), plant control building (PCB), reactor plant cooling water system (RPCWS), helium supply system, core auxiliary cooling water system (CACWS), fuel storage facility, radioactive waste systems, and control and electrical systems.

The design of the reactor support systems for the VHTR is expected to closely parallel that of HTGR-SC systems except for size and capacity specifications, which will be established to suit the VHTR requirements.

The helium supply system must be designed to provide handling and storage for both the primary and secondary helium systems. Only one CACWS loop is needed for the VHTR, with additional reactor cooling heat rejection provided by the air-cooled heat exchangers in the main loop shutdown cooling systems. The RPCWS, fuel storage facility, and radioactive waste systems will be similar in design to those of the HTGR-SC, but sized for the VHTR requirements.

3.9.2. Reactor Containment Building (RCB)

The RCB is a hemispherically domed, category 1, steel-lined, reinforced concrete structure (Fig. 2-3). The diameter is based on the PCRV diameter plus a 4.876-m (16 ft 0 in.) annulus. The 4.876-m (16 ft 0 in.) annulus provides for a 2.438-m (8 ft 0 in.) wire-winding machine clearance and a 2.438-m (8 ft 0 in.) steel bench structure that supports auxiliary system components; heating, ventilating, and air conditioning (HVAC); cable trays; and piping access around the PCRV.

The containment height provides for a 3.810-m (12 ft 6 in.) high support ring on which the PCRV is anchored and a refueling floor above the PCRV on which the refueling equipment is positioned. Above the refueling floor is a structural support system for handling the refueling equipment. The maximum height of this equipment is 18.288 m (60 ft 0 in.) above the refueling floor. The containment dome hemisphere starts at this elevation.

The PCRV sits on a 0.762-m (2 ft 6 in.) thick concrete fill mat, which rests on the containment liner. This fill mat is keyed for axial seismic restraint. The total structure rests on a base mat of site-dependent size.

The structural support system for fuel handling also includes an auxiliary crane with a minimum capacity of 90,718 kg (100 tons).

Access into the containment is attained through an access hatch at the refueling floor level that allows the rail-mounted fuel transfer cask to travel between the containment and RSB. An emergency personnel air lock is provided in the lower portion of the containment.

Electrical trays penetrate the containment adjacent to the control and diesel building. Three division separations of cables are maintained to satisfy the two-out-of-three logic utilized for safety; the electrical supply is to be separated per 10CFR50 requirements.

A valve enclosure housing the secondary helium and CACWS valves is located on the outside of the containment. This structure is seismic category 1 and provides missile protection for the containment isolation and shutdown cooling system valving.

3.9.3. Plot Plan

Figure 2-9 shows a conceptual plant plot plan arranged to be compatible with a twin reactor plant installation using common reactor fuel handling and storage facilities.

A minimum separation distance of 60.96 m (200 ft) is maintained between the safety-related reactor plant structures and the reformers, as discussed in Section 3.2. A separation distance of 60.96 m (200 ft) is also maintained between the reformers in adjoining process plant trains. Separate secondary helium piping loops for each primary coolant loop are maintained (see Section 4.7.4.).

The building arrangement is similar to that of the HTGR-SC plant in that the orientation of structures maintains similar relationships. In this arrangement, the RCB is positioned 180 deg from the RCB for the future reactor unit. A transition area functions as a penetrations and nuclear equipment building. The RSB and fuel storage building, which are shared facilities, are positioned between the two RCBs.

Rail access to the fuel storage building is provided for fuel shipping. A control and diesel building (CAD) is located near the RCB for each reactor to reduce cable run lengths. For the future reactor, the CAD is required as a separate structure. An access control structure is placed adjacent to the RSB and CAD, which allows personnel access control to all portions of the plant.

The location of the valve enclosure on the RCB varies with the orientation of the process plant. A section for CACWS valving is provided in the main valve enclosure, and separation is provided between the secondary helium piping for each loop. The CACWS piping and secondary helium shutdown cooling system piping pass through tunnels below grade to the ultimate heat sink structures. Two structures are provided, each housing equipment for one main loop and one also housing equipment for the CACS loop. Each one of these structures contains cooling towers for the nuclear service water cooling systems. Structural separation between each main loop and CACS loop equipment is provided. Location of these structures is determined by site and wind direction conditions plus separation for nuclear safety requirements.

All structures in the nuclear island are seismic category 1 except the access control building and the portion of the RSB above the refueling floor.

3.9.4. Steam System

Figure 3-1 shows a preliminary cycle diagram for the steam produced by the steam generator in one of the two secondary helium system loops. The steam is used to meet the reforming process and electrical power generation needs of the plant and is also used to drive the circulator in the secondary helium loops.

Steam from the steam generator in each secondary helium loop at 16.65 MPa (2415 psia)/510°C (950°F) is split, with 94.38 kg/s (749,200 lb/hr) going to the process and the remaining 38.44 kg/s (305,100 lb/hr) partially expanded through a high-pressure turbine to produce electric power. Exhaust steam from this turbine at 3.79 MPa (550 psia)/312°C (593°F) goes to a condensing turbine which drives the secondary helium circulator. The turbine generator for each loop produces 12.0 MW(e).

Both turbines are fairly standard, commercially available units. The high-pressure turbine is adapted from the high-pressure section of a 150-MW utility turbine. The circulator drive turbine is similar to a boiler feedpump turbine for large power plants.

The condensate is returned to the process, where it is mixed with the process steam which has been condensed, treated, and heated before return to the steam generators. No deaerator is provided, since deaeration is

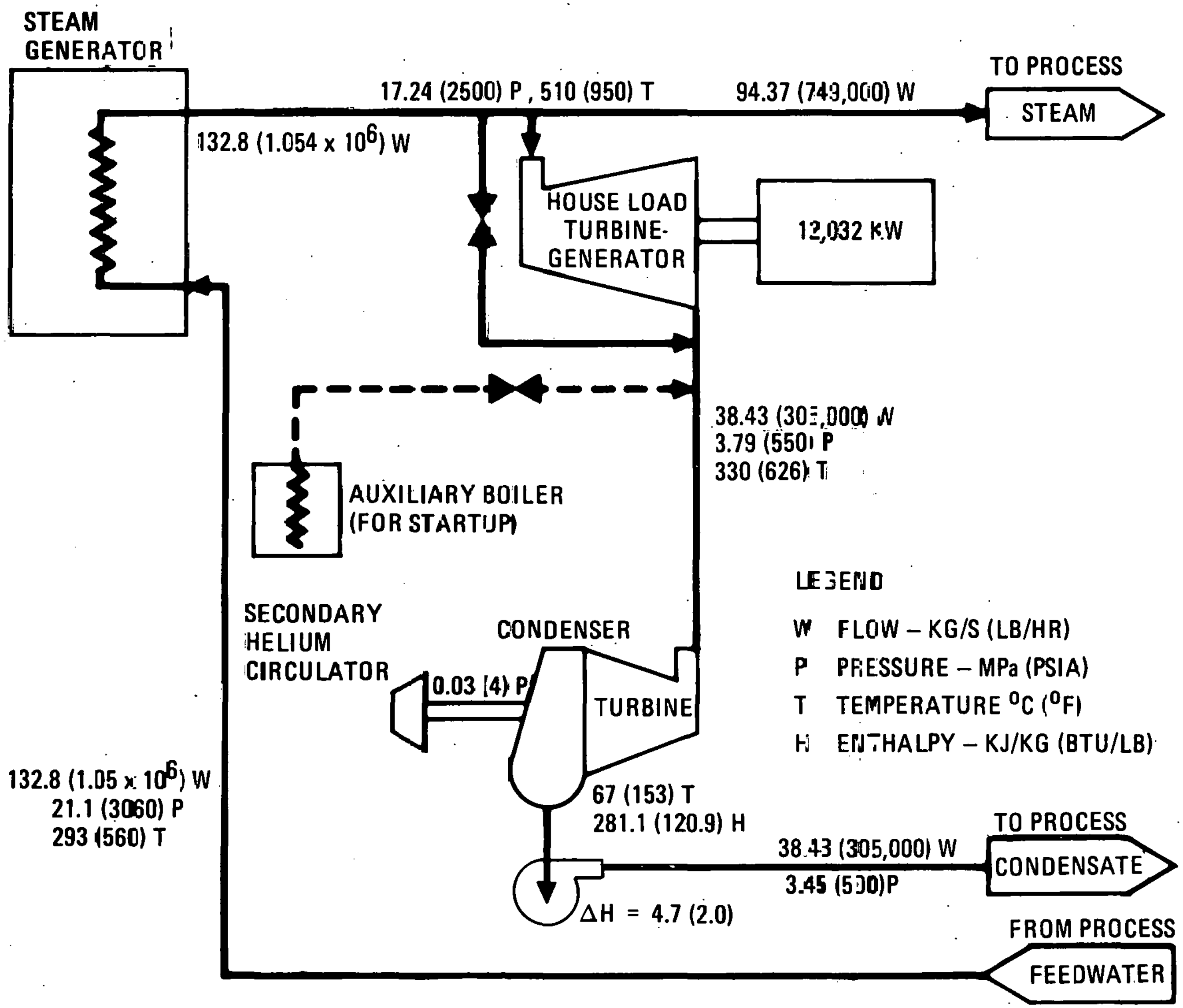

Fig. 3-1. Steam turbine system heat balance

assumed in the condenser. The moisture in the turbine last stage was limited to 12%, which sets the backpressure at 27.5 kPa (4 psia). Members of General Electric's steam turbine division were consulted, and they agreed that 12% moisture is acceptable with this type of turbine.

An auxiliary boiler to provide steam for the secondary helium circulator turbine during startup is shown on the cycle diagram. One boiler should serve for both loops. Electric motors will obtain power from the outside grid during startup.

3.9.5. Electrical System

Figure 3-2 shows a conceptual single line diagram for the VHTR plant and BORP, including the steam system turbine generators. Table 3-5 gives a preliminary estimate of reactor plant and BORP electrical loads. For illustrative purposes feeds to motor control centers are indicated, but the actual distribution to small 480-V motors [less than 75 kW (100 hp)] has not been estimated.

Single- or two-speed pony motors are indicated for emergency drive of the main helium circulators. Variable speed can be provided if required but would substantially increase costs. Alternatives to the pony motors are to provide special transformer power supplies for the main circulator motors fed from the 1E, 4160-V bus or to provide small diesel generators rated at 13.8 kV to feed each of these motors. Both of these approaches may have a licensing problem, i.e., circuit isolation, and thus have not been chosen for presentation.

The electrical system is intended to allow startup of one nuclear steam loop (including power requirements of a second loop in standby condition) on one outside line with subsequent startup of the process plant once the steam loop is operational (no internal power generation required). Once internal power generation is established, a second steam loop can be started with subsequent startup of the second process plant

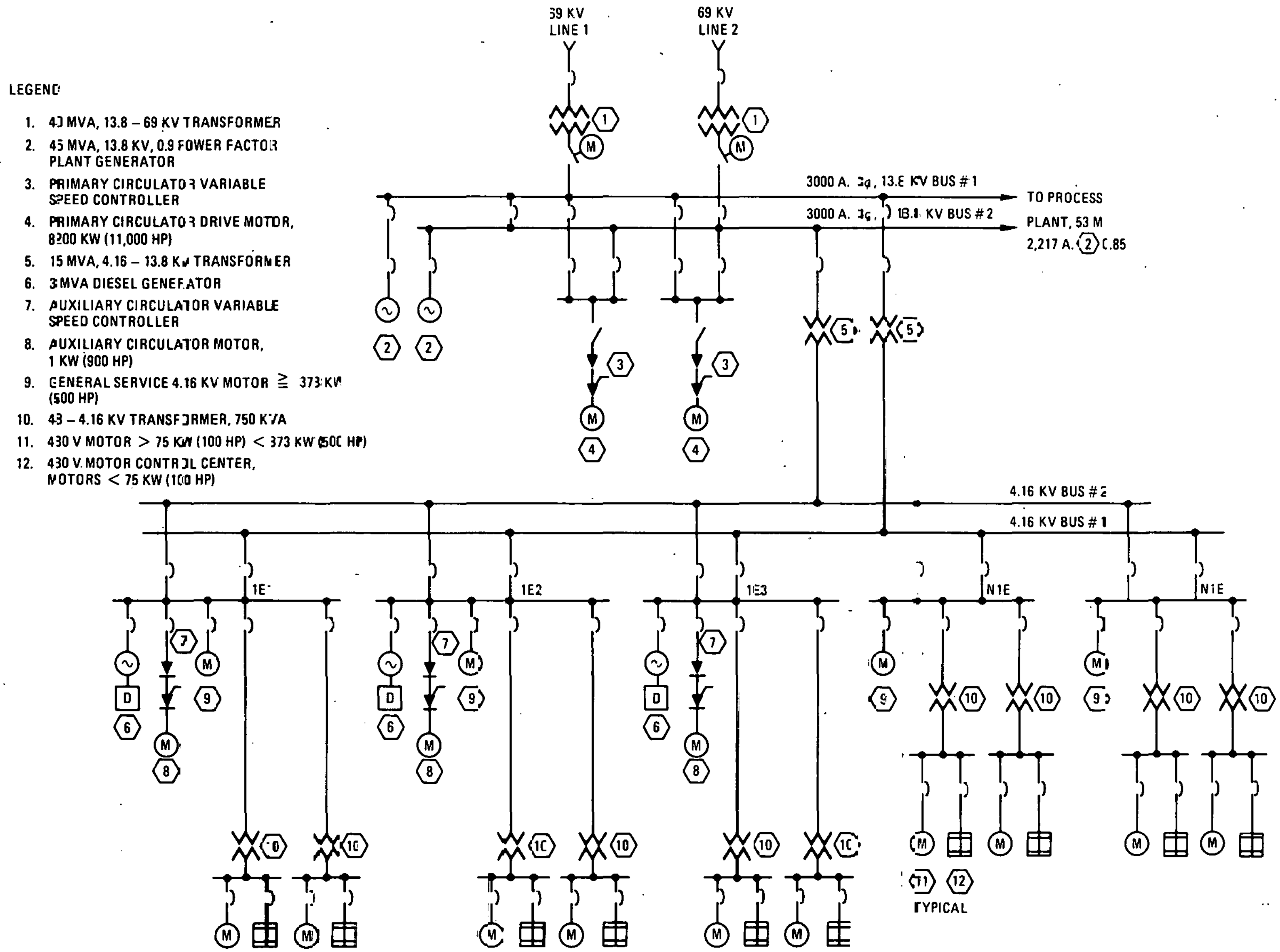

Fig. 3-2. VHTR single-line diagram

TABLE 3-5
842-MW(t) VHTR PRELIMINARY ELECTRICAL LOAD ESTIMATE

Item No.	Load Description	No. Req'd	Service		Total for Item	
			Normal	Emergency	kVA	Volts
1	Primary He circulators, 14.6 MW at 0.95 power factor and 0.96 efficiency	2	X		16,000	13,800
2	Primary He circulator pony motor	2		X	1,000	4,160
3	Auxiliary circulator drive motor	1		X	740	4,160
4	Secondary He loop auxiliary circulator motor	2		X	1,800	4,160
5	Service water pumps	3	X		420	480
6	He transfer compressor primary	1	X		90[a]	480
7	He transfer compressor secondary	1	X		125	480
8	Secondary containment chiller	2	X		1,350	4,160
9	Bearing water module	2	X	X	350	480
10	Non-IE 0.48-4.16 kV transformers[b]	4	X		2,215	4,160
11	1E 0.48-4.16 kV transformers[b]	3	X	X	1,680	4,160
12	Reactor plant cooling pumps	3	X	X	375	480
13	Reactor plant cooling fans	8	X	X	480[a]	480
14	Cooling tower fans	4	X		400	480
15	N_2 recondenser	2	X		100[a]	480
16	CACW pumps	3		X	300	480
17	Fire pump	1	--	--	Fire only	480
18	Instrument air compressor	2	X		25[a]	480
19	Control building chiller	2	X	X	400	480
20	Feedwater pump, 879 kW each	2	X		2,332	4,160
21	Circulating water pumps, 168 kW	4	X		900	480
22	Condensate pump, 195 kW	2	X		525	480
	Total maximum demand, kVa		26,072	6,805		

(a)This load is added to 480-V transformer load.

(b)Transformer loads are only for loads less than 100 kVA.

process loop. With both internal generators operating, no outside power would be required.

Startup could be expedited if power were available from both outside lines. This would permit the entire facility (nuclear and process) to be started in any desired sequence suitable to the process plant.

An alternate startup procedure would be to bring up the nuclear systems on one outside line and subsequently start the process systems as the electrical generators develop power.

The two offsite power supplies and the 1E diesel generators are required by NRC regulations to assure the adequacy of the "Engineered Safeguard Systems" power supplies. Each of these systems must be continuously available and of adequate capacity to meet the 1E system requirements for safe reactor shutdown and subsequent reactor cooldown.

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4. NHS SYSTEMS

4.1. PRESTRESSED CONCRETE REACTOR VESSEL (PCRV)

The PCRV is a thick-walled, cylindrical, prestressed and reinforced concrete structure. The PCRV is 22.86 m (75 ft 0 in.) in diameter and 20.93 m (68 ft 8 in.) high. The general arrangement of the PCRV is shown in Figs. 4-1 and 4-2. It has a central cavity, offset from the vertical centerline of the PCRV, 9626 m (31 ft 7 in.) in diameter by 12.857 m (42 ft 2 in.) high which contains the reactor core. Beside the core cavity are two 4.09-m (13 ft 5 in.) cavities, each containing the IHX for one of the two primary coolant loops. The primary helium circulators are in separate cavities adjacent to the respective IHX cavities in the top head of the PCRV. A third vertical cavity contains the CAHE and auxiliary circulator for the CACS loop. Horizontal ducts connect the primary and auxiliary loop component cavities with the core inlet and outlet plenums. Two reactor plant cooling water system (RPCWS) header pipe chases, with pressure relief valve pits at the top, are also located beside the core cavity. Two additional cooling water header pits are provided in the PCRV wall underneath the main circulator cavity. The PCRV employs high-strength concrete of 44.8 MPa (6500 psi) to satisfy the structural and biological shielding requirements. Bonded reinforcing steel (ASTM A615, Grade 60) in the PCRV concrete is used for crack distribution and gives the PCRV ductility under hypothetical overpressure conditions.

The PCRV is designed for a maximum cavity pressure of 5.350 MPa (776 psig) and is provided with a water-cooled steel liner with thermal barrier on the gas-side surfaces. Radial prestress is applied by circumferential wire winding; vertical prestress is applied by linear tendons. Both types of prestressing use 1/2-in. diameter strands with a guaranteed ultimate strength of 270 ksi.

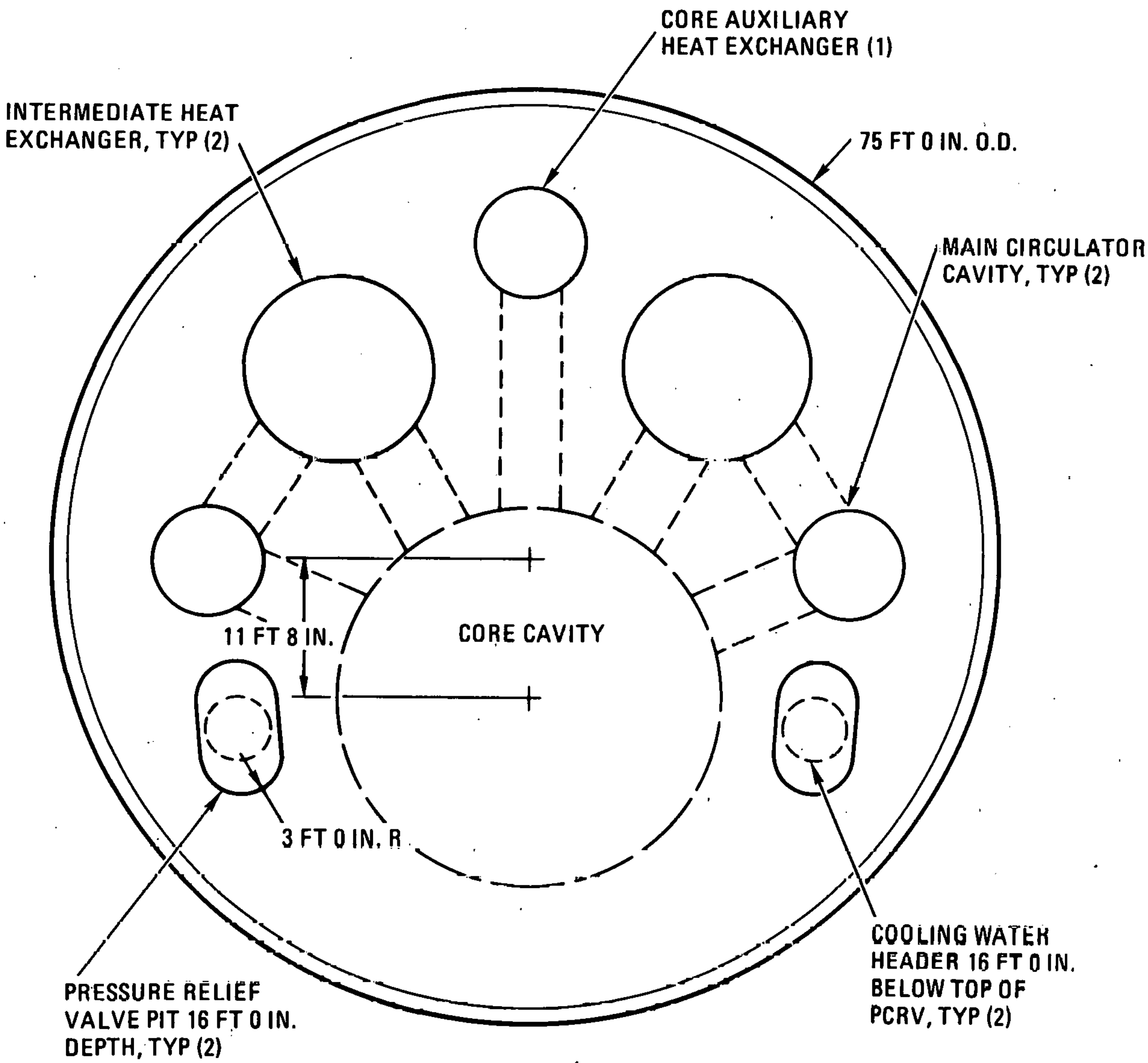


Fig. 4-1. PCRV general arrangement - top head plan

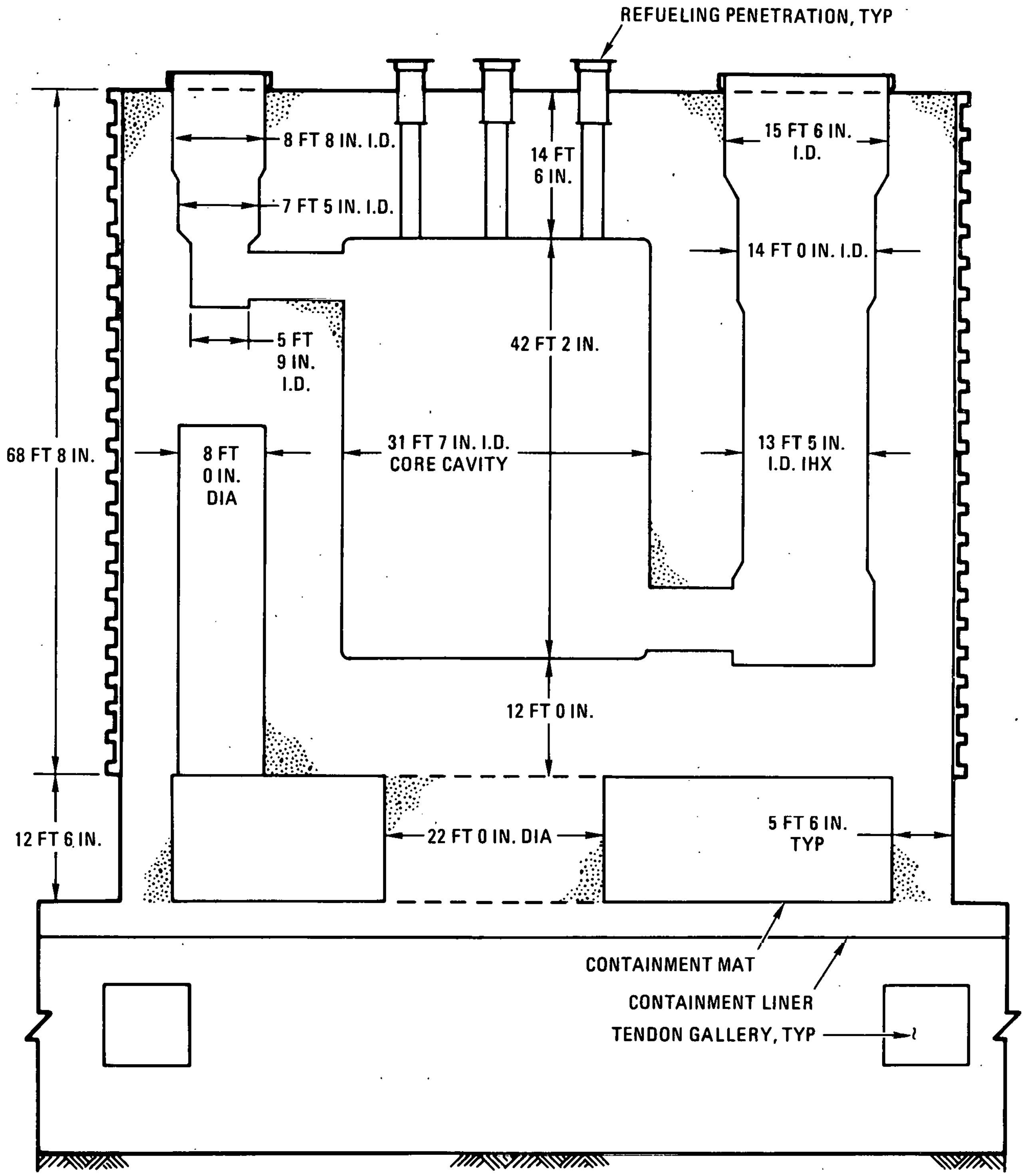


Fig. 4-2. PCRV general arrangement - vertical section

The PCRV diameter is dictated by the requirements of the tendon layout in the inner and outer radial ligaments and the biological shielding requirements between the outside periphery and the core cavity. The height is stress governing, and the IHX component was accommodated within the space provided.

A two-dimensional analysis of the PCRV was performed to ascertain the stress flow in the ligaments. The stresses were found to be within limits and were close to being optimum.

The PCRV includes cavity liners, penetrations, closures, the thermal barrier on the gas-side surfaces of the liner, and two independent pressure relief trains, as well as the concrete-embedded portions of the PCRV cooling water system, PCRV structural instrumentation, and data acquisition equipment. A wire-winding machine will be used during vessel construction for circumferential prestressing.

The PCRV functions as the primary containment for the reactor core, the primary coolant system, and portions of the secondary coolant system. The PCRV also provides the necessary biological shielding and minimizes heat loss from the primary coolant system. The prestressed concrete portion of the PCRV and those portions of the penetration unbacked by concrete, including their closures, form the primary coolant pressure-resisting boundary. The cavity and penetration liners, including closures, form the continuous gas-tight boundary of the PCRV. Penetrations and closures also restrict the leakage area for flow from the vessel to acceptable limits in the event of postulated failures. Liner and penetration anchors transmit loads from internal equipment support structures to the PCRV concrete. The PCRV, in turn, transmits these loads to the vessel support structure. During construction, the liners serve as formwork for the concrete. The liner details are shown in Fig. 4-3.

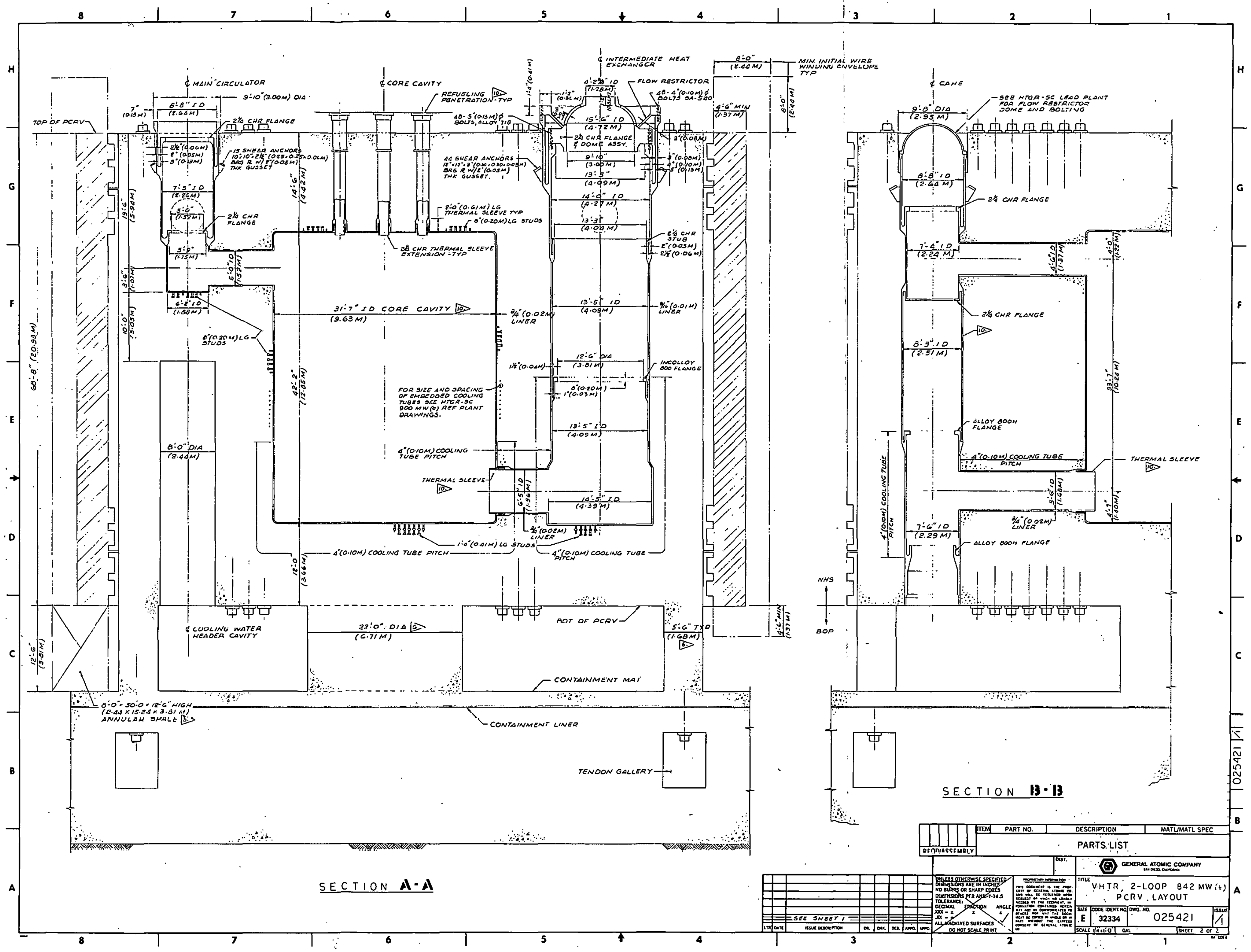


Fig. 4-3. 842-MW(t) PCRV liner details

Figure 4-4 is a layout of the core and reactor internals which was prepared to establish the core cavity dimensions. The FSV HTGR active core geometry was maintained, with provisions for mounting the side-cavity PCRV in accordance with current HTGR-SC design practice, including replaceable and permanent reflector block dimensions and lateral restraint devices. Thermal barrier thicknesses appropriate for VHTR temperatures were used (see Figs. 4-6 and 4-7). The inlet plenum height was determined by requirements for fuel handling equipment and the lower plenum height by the hot duct dimensions.

The PCRV design chosen for the VHTR is very similar to that used in the 950°C (1742°F) VHTR design (Ref. 4-1). This is a variation of the side-mounted, multicavity vessels introduced in the British Hartlepool and Heysham Advanced Gas-Cooled Reactor (AGR) plants and of several designs developed in studies of large HTGR-SC plants. Several arrangement studies at GA have demonstrated the advantages of offsetting the reactor core from the geometric center of the periphery of the vessel in terms of vessel diameter and plant arrangement. The use of this approach permits a reduction in vessel diameter relative to arrangements with the core cavity in the center of the vessel and facilitates separation between process, safety, and refueling systems.

No major impact on design confidence for this offset core configuration relative to concentric core multicavity PCRVs has been identified. While concrete stress distributions are somewhat more complex in the offset core arrangement, the analytical capability for prediction of elastic response and the establishment of bounds on time-dependent effects and ultimate strength as developed for symmetric vessels is equally valid and applicable. No need for additional methods development before committing to this configuration has been identified; however, a confirmatory model test to facilitate licensing and demonstrate design adequacy is likely to be required.

The linear prestressing system (LPS), consisting of high-capacity tendons, provides longitudinal prestressing to the PCRV to counteract stresses from vertical pressure loads in the cavities and penetrations and thermal loads in the concrete. The circumferential prestressing system (CPS), consisting of bands of prestressed strand wound in concrete channels on the exterior PCRV cylindrical surface, provides circumferential prestressing to the PCRV to counteract stresses from horizontal pressure in the cavities and penetrations and thermal loads in the concrete.

The liner provides a gas-tight primary coolant boundary covering the surfaces of cavities, communicating ducts, and access openings inboard of any penetration or closure anchorage system. The liners are continuously welded, 12.7 to 25.4 mm (0.5 to 1 in.) thick carbon steel membranes. Welded studs are attached to the outside surface of the core cavity liner and the flat bottom head of the IHX and circulator cavity liners. Welded studs are used, as required, in other regions to anchor the liner to the PCRV concrete.

Penetrations, including the shear anchors, which are embedded in the surrounding concrete, are constructed from carbon steel. The penetrations are joined to the adjacent liners to maintain the continuity of the membrane enclosing the primary coolant. The embedded portions of penetrations have continuously welded cooling tubes at a pitch similar to that of the adjacent liner. Each penetration includes a gas-tight steel closure which may be separate from or integral with the internal equipment. An example of an integral closure is a heat exchanger tubesheet. Penetrations which are routinely accessed, such as those for refueling, are fitted with double-gasketed gas-tight bolted closures. Purified helium is supplied to the annulus between the closure gaskets at 0.02 MPa (2 psia) above the PCRV upper plenum pressure so that any leakage of the inner gasket will be purified helium into the reactor primary coolant. Any outward leakage will also be purified helium. Closures not normally removed are welded to the liner.

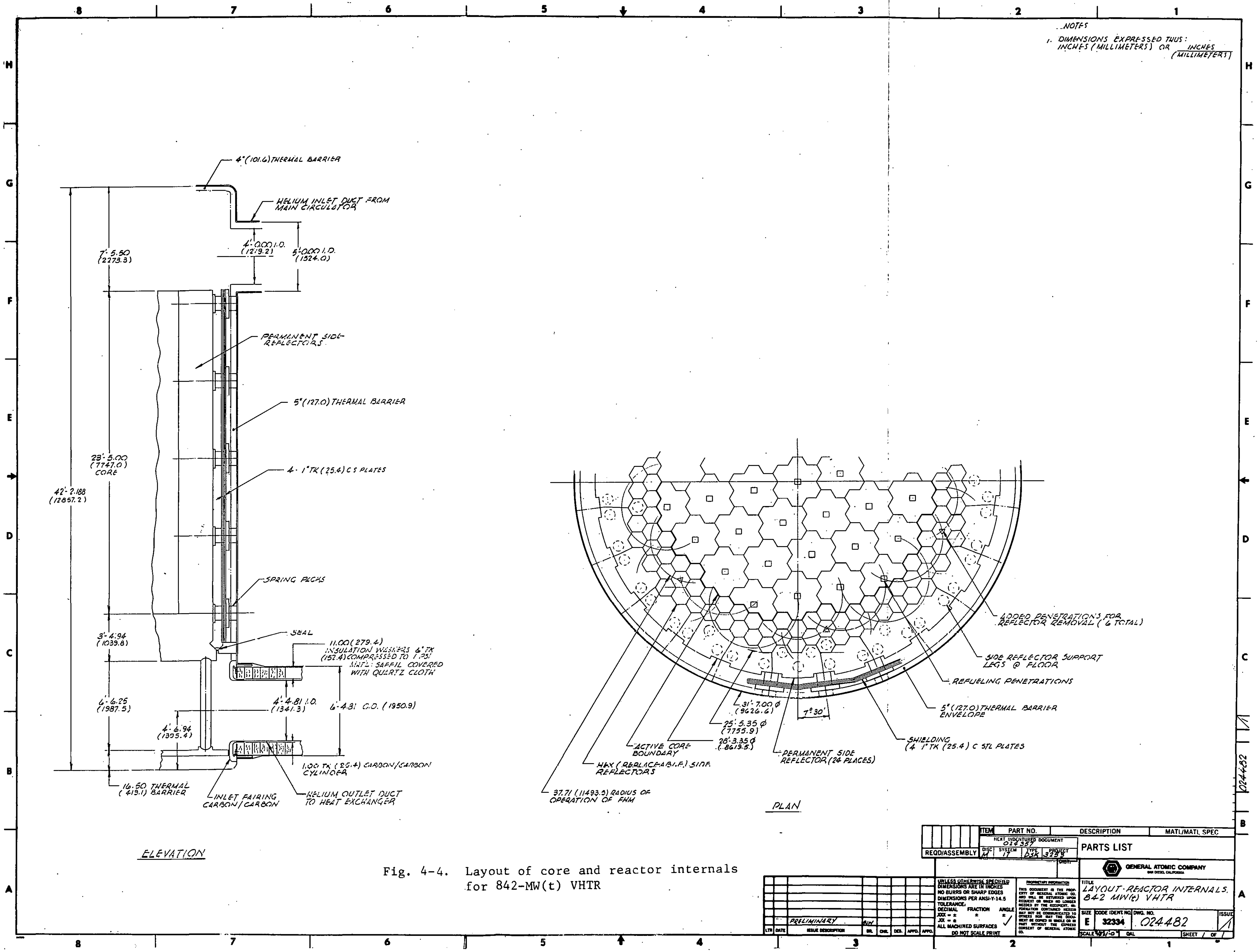


Fig. 4-4. Layout of core and reactor internals for 842-MW(t) VHTR

Flow restrictors are provided, as required, on penetrations and closures to limit the leakage flow area in the unlikely event of failure of the penetration/closure. This is accomplished by plugs held in place by structural members either external or internal to the pressure boundary.

The PCRV cooling water system consists of 1-1/4 in. Schedule 40 tubes connected to two independent loops which are both normally operating simultaneously. Adjacent tubes are not connected to the same loop. Where possible, counterflow exists between adjacent tubes. The cooling water tubes are continuously welded to the outside surface of the liner, except at local discontinuities such as field splices. Cooling tubes have a pitch range of 101.6 to 203.2 mm (4 to 8 in.). Additional PCRV cooling tubes are embedded in the concrete approximately 203.2 mm (8 in.) from the core cavity sidewall liner to reduce the effect of nuclear heating. Supply and return piping connects both the embedded and welded tubes to the BOP headers located in the cooling water pipe chases.

A PCRV pressure relief train consists of a block valve, a pressure relief valve, and a rupture disk. A simplified schematic of a single relief train is shown in Fig. 4-5. The block valve is capable of isolating a pressure relief train under the following conditions:

1. In the event of relief valve leakage.

2. To permit in-place testing of a relief valve.

3. To permit maintenance of relief train components during plant shutdown.

4. To terminate blowdown if a relief valve should fail to reseat.

The pressure relief valve is closed during normal plant operations. It is automatically opened for pressure relief of the PCRV when its preset

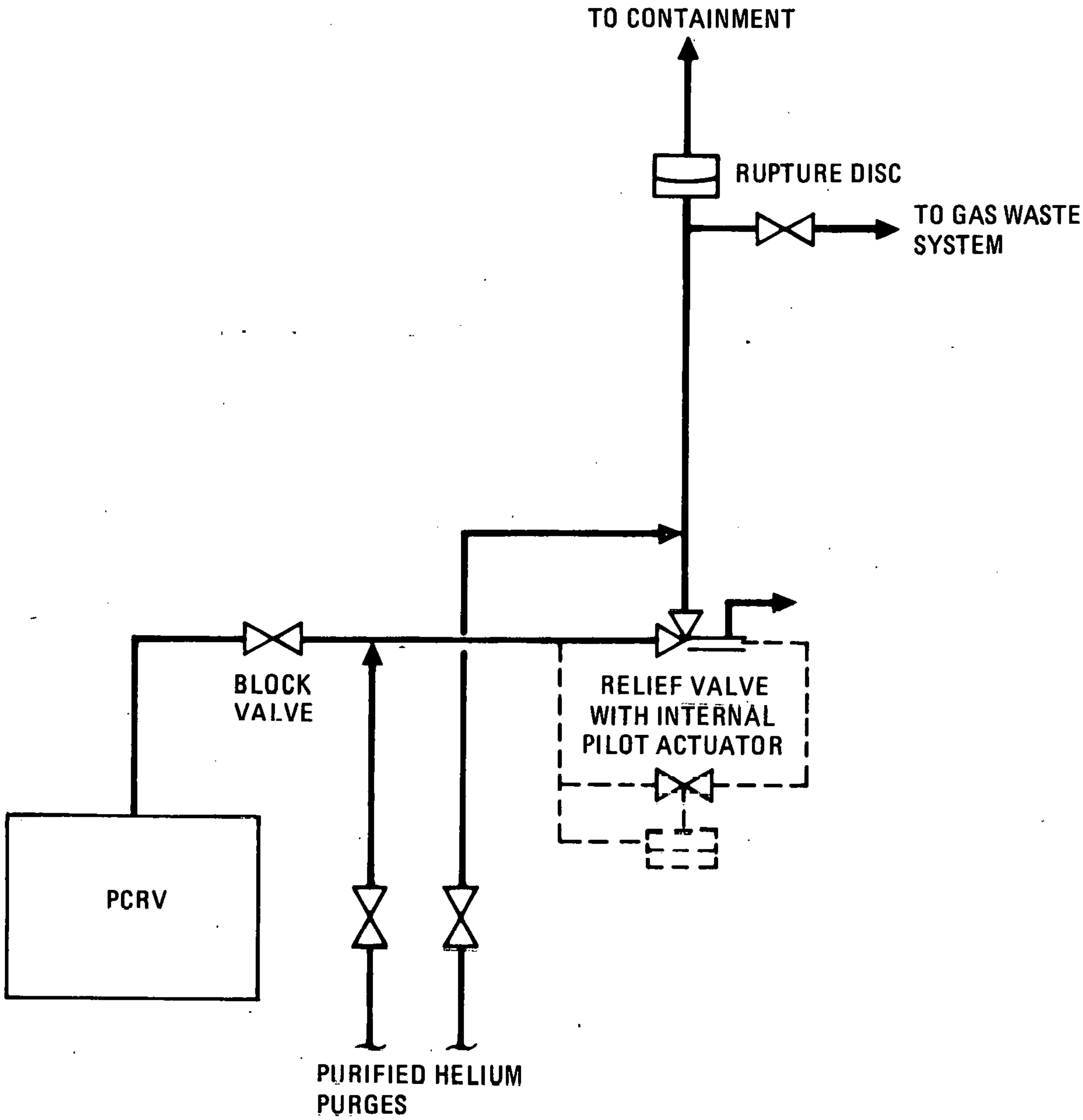


Fig. 4-5. Schematic of single pressure relief train

pressure is reached, and it remains open until its (reduced) reseating pressure is attained. The spring-loaded, pilot-actuated safety relief valve is automatically opened by the process fluid (PCRV helium) pressure. It can also be manually operated by a remote, helium-actuated pilot valve (e.g., for valve testing and calibration). During normal plant operations, the rupture disc holds negligible pressure on the sealed disc. When activated by a PCRV overpressure, the disc is ruptured (after opening of the relief valve), and primary coolant gases are discharged directly into the containment building.

The HTGR thermal barrier typically consists of layers of fibrous mineral insulation compressed against the PCRV liner by metal cover plates and seal sheets. The compression is effected by attachment fixtures which are connected to the liner. Thermal protection is provided wherever necessary to satisfy the PCRV temperature limits. This necessitates the employment of different grades or classes of thermal barrier, depending on the specific heat duty requirements within a designated area or zone. Thermal barrier zones for the VHTR, shown in Fig. 4-6, are defined as dictated by temperature environment and geometric considerations. Table 4-1 provides a current estimate of the major temperature limits of the thermal barrier. Since definition of temperature limits is not yet complete, Table 4-1 is given only as a general guide.

The thermal barrier has been separated into 18 zones, based on service temperature and liner geometry considerations. The thermal barrier has also been divided into three classes (B1, B2, C) based on hot surface temperature. The preliminary thermal barrier sizing calculations proceeded according to the following sequence:

1. Thickness determination based on insulation properties. A factor of 2 times the thermal conductivity was used. Therefore, the fibrous insulation thickness is at least twice that which would result in the maximum liner overall temperature of 66°C (150°F).

2. Thickness determination based on hot spot examination. The effect of attachment fixtures on thickness was determined in accordance with a maximum liner hot spot temperature limit of 121°C (250°F).

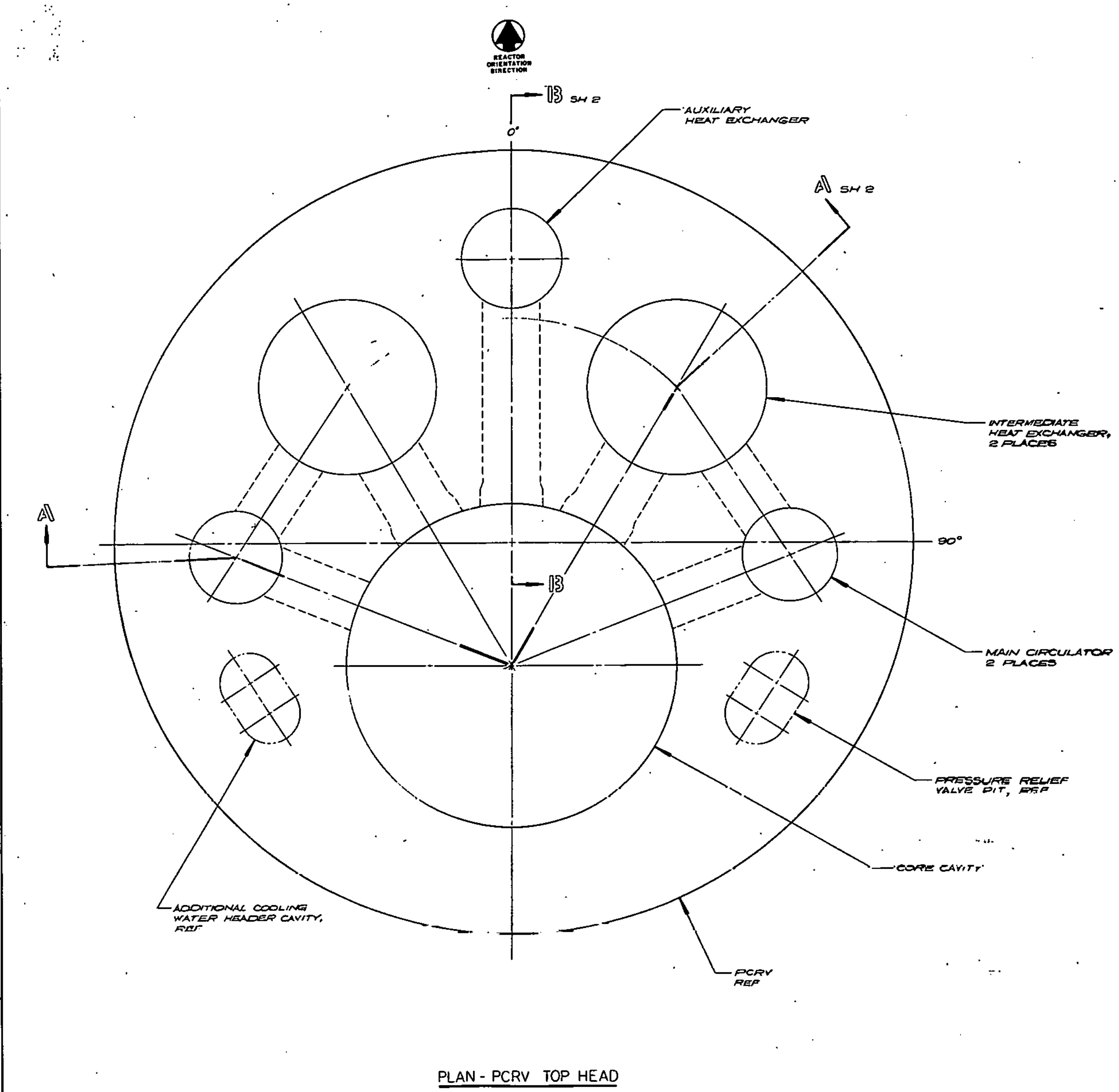
3. Final determination of thickness values based on the results of (1) and (2), plus any additional design factors.

In these calculations, the liner thickness was assumed to be 19 mm (0.75 in.). Anticipated liner cooling tube pitches are 102 mm (4 in.) for regions exposed to core outlet temperatures and 152 mm (6 in.) for intermediate-temperature regions and regions exposed to core inlet temperatures.

TABLE 4-1
THERMAL BARRIER MAXIMUM TEMPERATURE LIMITATIONS
[°C (°F)]

Class	Normal and Upset	Emergency (10 hr)	Faulted (1 hr)
B1	621 (1150)	816 (1500)	ND[a]
B2	910 (1670)	982 (1800)	1093 (2000)
C	945 (1730)	1371 (2500)	1649 (3000)

[a] Not yet defined.



NOTES:

1. INSTALLATION PER GA SPEC NO. 900008.
2. AREA GIVEN IS TOTAL AREA PER REACTOR AND IS MEASURED AT LINER SURFACE.
3. UNLESS OTHERWISE STATED DIMENSIONS PERTAIN TO THE PCRV LINER.
4. DIMENSIONS ARE GIVEN IN MILLIMETERS, ENGLISH UNIT SHOWN IN PARENTHESIS (INCHES) UNLESS OTHERWISE NOTED

5. CLASS B1: TYPE 316 STAINLESS STEEL
   CLASS B2: INCONEL 713 LC
   CLASS C: 1. GRAPHITE AND SLIP CAST FUSED SILICA FOR FLOOR BLOCKS.
   2. SILICON NITRIDE, ALUMINA AND FUSED SILICA FOR SUPPORT PADS
   3. TYPE 316 STAINLESS STEEL COVERPLATE AND CONTAINERS SAFFIL & KAOWOOL INSULATION

6. ZONES 9 & 14 SPECIAL CONSTRUCTION REF: 024847 Z9, Z14 SIMILAR TO: Z9

ZONE	CLASS (5)	QTY	INSTALLED THICKNESS	AREA (2)	DRAWING NO.	DESCRIPTION
1	B1	2	76 (3.00)	154 M² (1654 FT²)		MIDDLE, INTERMEDIATE HEAT EXCHANGER CAVITY
2		2	76 (3.00)	85 M² (914 FT²)		UPPER INTERMEDIATE HEAT EXCHANGER CAVITY
3		2	76 (3.00)	25 M² (263 FT²)		INTERMEDIATE HEAT EXCHANGER OUTLET DUCT
4		1	76 (3.00)	63 M² (675 FT²)		TOP HEAD, MAIN CORE CAVITY
5		1	102 (4.00)	74 M² (800 FT²)		UPPER SIDEWALL, MAIN CORE CAVITY
6	B1	1	102 (4.00)	233 M² (2505 FT²)		MIDDLE SIDEWALL, MAIN CORE CAVITY
7	B2	1	127 (5.00)	69 M² (742 FT²)		LOWER SIDEWALL, MAIN CORE CAVITY
8	C	1	442 (17.42)	68 M² (781 FT²)		BOTTOM HEAD, MAIN CORE CAVITY
9	B2	2	203 (8.00)	35 M² (375 FT²)		INTERMEDIATE HEAT EXCHGR INLET DUCT
10						— NOT USED —
11	B2	2	127 (5.00)	217 M² (2348 FT²)		LOWER INTERMEDIATE HEAT EXCHANGER CAVITY
12	B1	1	76 (3.00)	26 M² (289 FT²)		UPPER AUXILIARY DUCT
13	B1	1	127 (5.00)	27 M² (290 FT²)		UPPER AUXILIARY CAVITY
14	B2	1	203 (8.00)	34 M² (367 FT²)		LOWER AUXILIARY DUCT
15	B1	1	127 (5.00)	46 M² (492 FT²)		MIDDLE AUXILIARY CAVITY
16	B2	1	127 (5.00)	35 M² (380 FT²)		LOWER AUXILIARY CAVITY
17	B2	1	— NO INFORMATION —			PERIPHERAL SEAL
18	B1	2	76 (3.00)	92 M² (1002 FT²)		MAIN CIRCULATOR CAVITY
19	B1	2	76 (3.00)	28 M² (305 FT²)		MAIN CIRCULATOR OUTLET DUCT

TOTAL: 1311 M² (14121 FT²)

CLASS	TOTAL AREA/CLASS	B1	B2	C
M²		853	390	68
FT²		9183	4207	731
%		65	30	5

ITEM	PART NO.	DESCRIPTION	MATL/MATL SPEC

NEXT INDENTURED DOCUMENT 903886 — PARTS LIST

VHTR, 2 LOOP, 842 MW(t) 850 °C COT.

GENERAL ATOMIC COMPANY, SAN DIEGO, CALIFORNIA

TITLE: THERMAL BARRIER GENERAL ARRANGEMENT

SIZE E | CODE IDENT NO. 32334 | DWG. NO. 025423 | ISSUE A

SCALE 1/4 | SHEET 1 OF 2

A — PRELIMINARY ISSUE

DO NOT SCALE PRINT

Fig. 4-6. 842-MW(t) VHTR thermal barrier general arrangement (sheet 1 of 2)

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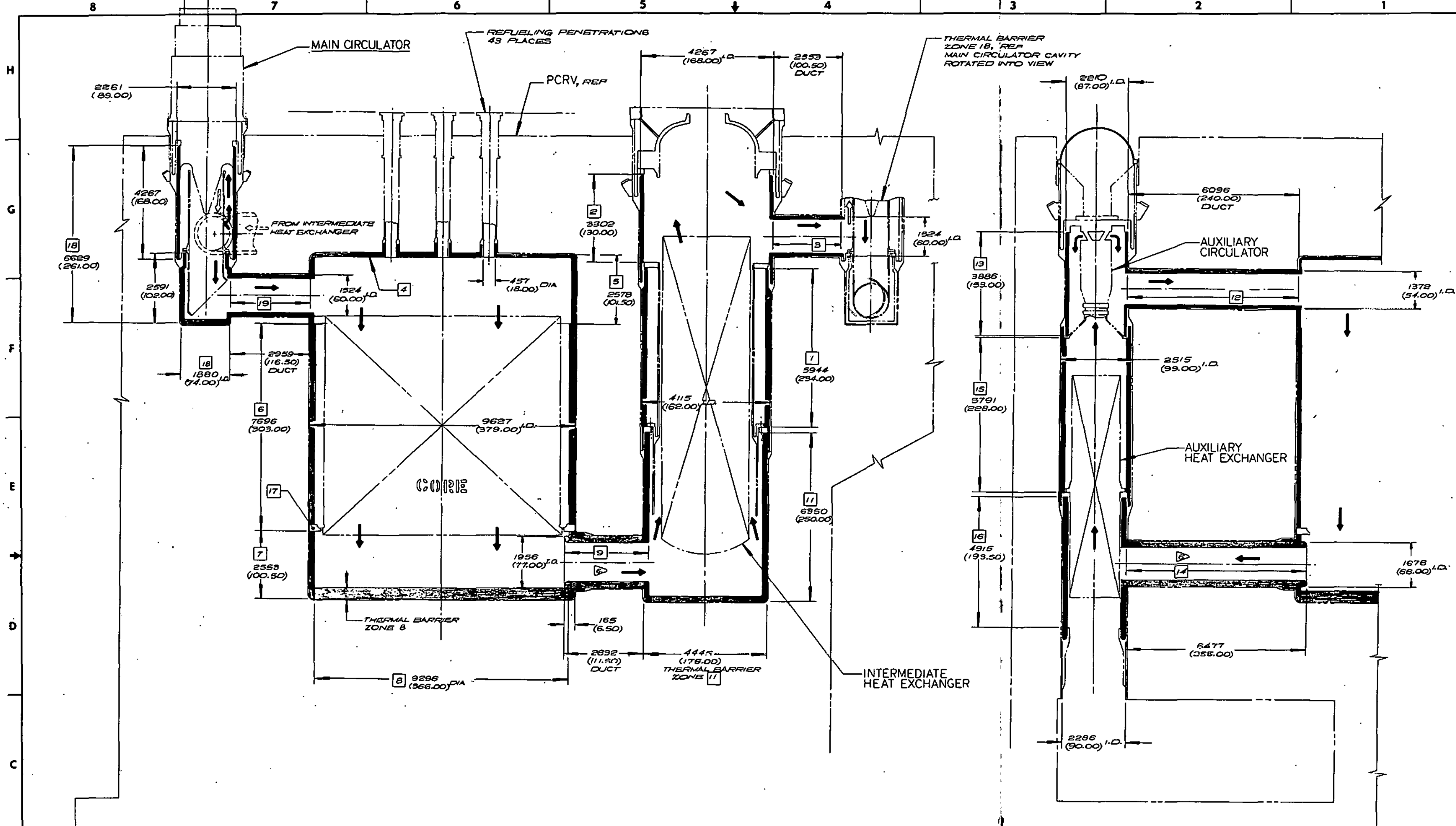

ZONE	CLASS	AVG COVER PLATE SIZE	REQD	TOTAL AREA FOR COVER PLATES M²	FT²	AVG SEAL SHEET SIZE .9 (.036) THK	REQD	AVERAGE INSULATION BLANKET SIZE	ASSY REQD	TOTAL INSULATION REQ; M² (FT²) SAFFIL 25.4 (1.0) THK		KAOWOOL 25.4 (1.0) THK		KAOWOOL 13 (½") THK		COMPOSITION OF BLANKETS – THK SAFFIL	KAOWOOL
1	B1	508×508	547	142	(1532)	610×610	383	800 × 800	240	307	(3308)	154	(1654)	154	(1654)	2@1"	1@1" & 1@½"
2		(20"×20")	328	85	(919)	(24"×24")	230	(31.50×31.50)	132	170	(1828)	85	(914)	85	(914)	2@1"	1@1" & 1@½"
3		AREA:(2.8 FT²)	94	24	(263)	AREA:(4 FT²)	66	AREA:(6.9 FT²)	38	49	(526)	24	(263)	24	(263)	2@1"	1@1" & 1@½"
4			188	70	(751)		139		68	125	(1350)	63	(675)	63	(675)	2@1"	1@1" & 1@½"
5		610×610	211	78	(844)	711×711	156	953×953	82	149	(1600)	223	(2400)	—	—	2@1"	3@1"
6		(24"×24")	613	228	(2453)	(28"×28")	454	(37.50×37.50)	256	465	(5010)	698	(7515)	—	—	2@1"	3@1"
12		AREA:(4 FT²)	63	23	(251)	AREA:(5.4 FT²)	47	AREA:(9.8 FT²)	28	53	(566)	26	(288)	26	(283)	2@1"	1@1" & 1@½"
13			64	24	(257)		48		98	108	[illegible]	[illegible]	[illegible]	—	—	4@1"	3@1"
10			111	41	(445)		82		50	183	(1968)	137	(1476)	—	—	4@1"	3@1"
18		(20"×20")	331	86	(928)	(24"×24")	232	(31.50×31.50)	145	186	(2004)	93	(1002)	93	(1002)	2@1"	1@1" & 1@½"
19		AREA:(2.8 FT²)	98	26	(275)	AREA:(4 FT²)	69	AREA:(6.9 FT²)	44	57	(610)	28	(305)	28	(305)	2@1"	1@1" & 1@½"
7	B2	610×610	194	72	(777)	711×711	144	953×953	76	276	(2968)	206	(2226)	—	—	4@1"	3@1"
9		(24"×24")	74	28	(297)	(28"×28")	55	(37.50×37.50)	64	1170	(12598)	—	—	—	—	6@1"	—
14		AREA:(4 FT²)	70	26	(278)	AREA:(5.4 FT²)	52	AREA:(9.8 FT²)	148	1980	(21318)	—	—	—	—	6@1"	—
16			85	31	(338)		63		38	116	(1250)	106	(1140)	—	—	4@1"	3@1"
11		(20"×20"), AREA:(2.8 FT²)	735	191	(2058)	(24"×24"), AREA:(4 FT²)	516	(31.50×31.50) AREA:(6.9 FT²)	340	871	(9372)	653	(7029)	—	—	4@1"	3@1"
8	C	HEX SHAPE .8 M² (9 FT²)	81	68	(731)	HEX SHAPE 1.1 M² (12 FT²)	61	IRREGULARS (6.9 FT²)	106	170	(1830)	204	(2196)	-		5@1"	6@1"
									TOTAL REQD:	M² 6435	FT² (69260)	M² 2781	FT² (29948)	M² 473	FT² (5096)		

PARTS LIST

GENERAL ATOMIC COMPANY

THERMAL BARRIER
GENERAL ARRANGEMENT

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Fig. 4-6. 842-MW(t) VHTR thermal barrier general arrangement (sheet 2 of 2)

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The types of materials selected for the various thermal barrier components are shown in Table 4-2. In general, the materials were chosen for their ability to withstand the core outlet and inlet temperatures. With creep as a criterion, the use of Type 316 stainless steel for Class B1 thermal barrier was limited to 621°C (1150°F). The size of these cover plates (Fig. 4-7) was decreed by the acoustic environment, which was assumed to be similar to the HTGR-SC. Inconel 713LC, a cast nickel-base superalloy, was selected for the Class B2 cover plates. The basis for this selection was reasonable creep resistance, castability, and expected resistance to carburization. The size was determined by acoustics and casting state-of-the-art. The Huntington oxide dispersion-strengthened alloy MA-956 was tentatively chosen as the Class B2 steel sheet material because of its expected carburization resistance.

The Class B1 insulation blankets consist of a composite of Saffil Alumina HT and Kaowool. On the basis of resiliency, Kaowool is being limited to 482°C (900°F) for long-time exposure. At the present time, the Class B2 insulation blankets are designated as all-Saffil because of its high resiliency and low compression force (hence low loads applied to the cover plates). Further analysis could result in a composite blanket which would reduce the cost.

The Class C thermal barrier is composed of Class B1 type materials plus solid ceramics designed to withstand the core outlet streaks. As can be seen in Fig. 4-8, the top block is ATJ graphite which buffers the acoustic loads and thermal shocks. The silica block designs are controlled by rapid depressurization as well as thermal shock. The insulation between the blocks and the liner is sized to control the heat transfer to the liner.

The ceramic pads act both as supports for the graphite posts and as insulators. The two upper pads are Norton NX-562 silicon nitride. This material has very good static strength which, when combined with its high thermal conductivity, results in a structure with good thermal shock

TABLE 4-2
THERMAL BARRIER MATERIAL SELECTION

Class	Cover Plate	Seal Sheet	Blocks	Pads	Insulation
B1	Type 316 stainless steel	Type 316 stainless steel	--	--	Saffil + Kaowool
B2	Inconel 713LC	MA 956	--	--	Saffil
C	Type 316 stainless steel	Type 316 stainless steel	Graphite, fused silica	Silicon nitride, alumina, fused silica	Saffil + Kaowool

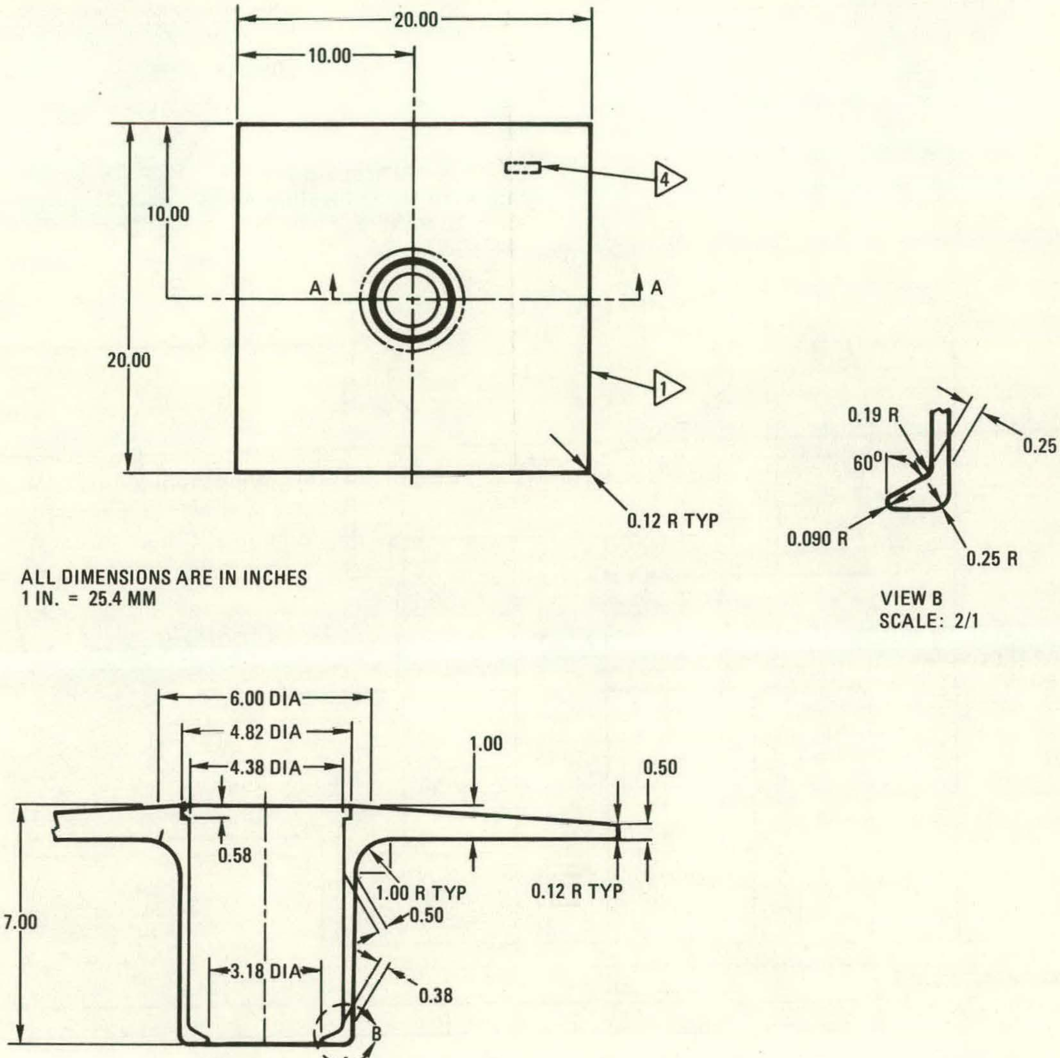

Fig. 4-7. Coverplate concept

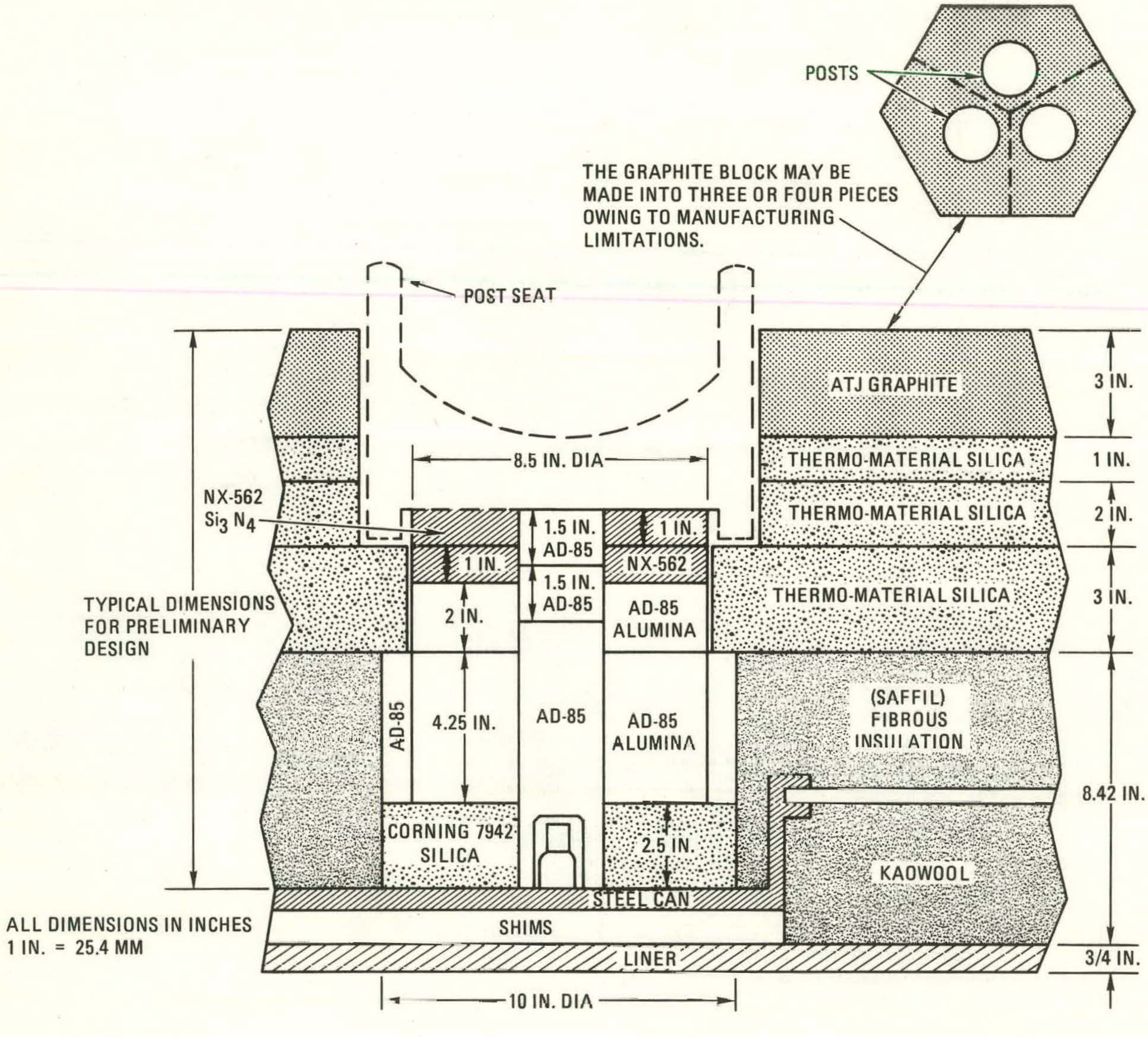

Fig. 4-8. Schematic of proposed HTGR-PH Class C thermal barrier

resistance. The next two pads are Coors AD-85 alumina. This material is a better insulator than silicon nitride and is primarily designed based on steady-state thermal stresses. The final pad is a fine grain fused silica which has good insulating properties and is designed on the basis of axial loads.

The quantities of components shown on Sheet 2 of Fig. 4-6 are approximations based on typical cover plate dimensions for the various zones. Irregularities have not been considered during this phase of the study.

4.2. REACTOR CORE AND INTERNALS

4.2.1. Core Design

The basic parameters of the core design are given in Table 4-3. Figure 4-4 shows the layout of the core and reactor internals (see Section 4.1). A core design study for a 950°C (1752°F) VHTR, based on highly enriched uranium (HEU) fuel is described in Ref. 4-2. The fuel element is very similar to that for the FSV core, which is already operating. The core comprises prismatic-shaped graphite blocks containing arrays of fuel rods and coolant holes. The major differences between the VHTR and the FSV cores are:

1. A 3-yr fuel cycle with a refueling interval of 1 yr instead of 6 yr and 1 yr, respectively.

2. Core inlet and outlet temperatures of 427°C (800°F) and 850°C (1562°F), respectively, versus 405°C (762°F) and 784°C (1444°F) for the FSV core.

3. Heavy thorium loadings.

4. Use of power control rods to reduce local power peaking.

5. BISO-coated fertile particles instead of TRISO-coated particles.

TABLE 4-3
VHTR BASIC CORE PARAMETERS

Core thermal power	842 MW
Power density	6.3 MW/m^3
Fuel block design	FSV - 10 row
Fuel in-core lifetime	3 yr
Reload interval	1 yr
Fraction of core reloaded annually	∿33%
Capacity factor	80%
Carbon/thorium initial core/reloads	170/185
Core volume	133.65 m^3
Total fuel columns	247
Standard	210
Control	37
Fuel blocks (6/column)	1482
Control rod pairs	37
Small control rods	37
Reserve shutdown hoppers	37
Total flow regions	37
Variable flow control	
Seven-column	31
Five-column	6
Axial fuel zones	4
Inlet temperature	427°C (800°F)
Outlet temperature	850°C (1562°F)

Changes 1 through 5 in combination act in a direction which leads to lower releases of fission products than those expected for the HTGR-SC, which have been the basis for previous submittals of licensing documents to the NRC. Adoption of an 850°C (1562°F) core outlet temperature instead of the 950°C (1752°F) used in Ref. 4-2 enhances the reduction in fission product release. Some of this advantage would be offset by the adoption of an LEU-Th fuel cycle instead of the HEU fuel cycle of Ref. 4-2, since fission product activity is somewhat higher with LEU-Th.

The following results of the core design studies support the technology of a prismatic fueled VHTR:

1. High temperature can be achieved with little extrapolation from current fuel technology. It is not necessary to adopt the radical system differences that would accompany a pebble bed fueled core.

2. Fuel particle failures are strongly temperature sensitive, and close control of the coolant flow distribution is required to maintain particle integrity.

3. Fission product releases, both metallic and gaseous, are influenced by fuel operating temperatures. In particular, the metallic fission product cesium will diffuse through intact BISO-coated particles, but the releases are within limits allowed by safety requirements.

4. BISO-coated fertile particles are preferred to TRISO-coated particles, because the neutron economy is better, the conversion ratio is higher, and reprocessing is simpler and less costly. The parameters selected for the core design permit BISO-coated fertile particles to be employed.

The quantity of uranium and thorium fuel in the core is chosen to maintain the neutron chain reaction at the design power level for the design lifetime. The distribution of this fuel in the core and the reloading sequence of the refueling regions are chosen to meet design constraints on power distributions, fuel and coolant temperatures, fission product release, and fuel element stresses.

The neutron chain reaction is controlled by the movement of the control rods. The control-rod pairs are used to ensure permanent shutdown; the small control rods are used to control normal power operation and load change transients; and the reserve shutdown system is used as a backup safety system for the control-rod pairs.

Helium coolant flow and hence core gas outlet temperatures are controlled by flow control valves in each refueling region, consisting of four or more fuel columns. These valves are adjustable from the control room during core operation. The flow to the regions located at the core/reflector boundary which contain less than four fuel columns is set by fixed orifices in the plenum elements on top of these regions.

A safe, controlled startup is produced by the use of several neutron sources located in the top layer of fuel elements. They provide a continuous neutron source for the fission chain reaction at near-critical and just-critical zero-power conditions. This system includes the fuel elements, the hexagonal reflector elements, the top layer/plenum elements, and the startup neutron sources.

The fuel element is a graphite block with the dual function of containing the fuel and acting as a moderator. Each fuel element consists of a hexagonal graphite block containing drilled coolant passages and also parallel fuel channels into which the individual fuel rods are inserted. The individual fuel rods contain the fuel particles distributed in a graphite matrix. The initial core elements and the reload elements, whether containing fresh or recycle fuel, are identical in geometry.

For the reference cycle with high enrichment, the fissile kernel is uranium carbide surrounded by a buffer layer of low-density pyrolytic carbon, a thinner layer of high-density pyrolytic carbon, a layer of silicon carbide which provides containment of gaseous and solid fission products, and an outer layer of high-density pyrolytic carbon which adds strength to the coating. The fertile kernel is thorium oxide surrounded by a buffer layer of low-density pyrolytic carbon and an outer coating of high-density pyrolytic carbon, which provides the containment.

For a low-enrichment fuel cycle, the fuel element design would be essentially unchanged except for the fuel rod diameter, which would most likely be reduced to accommodate the typically lower fuel loadings of this cycle. The fuel particle designs would be similar in character to those used in the high-enrichment cycle, but specific designs have not yet been selected.

The fuel elements and hexagonal reflector elements are arranged in columns supported on the core support blocks. Each support block under the major portion of the active core corresponds to one fuel region which has a central control column and six surrounding fuel columns. The fuel regions are surrounded by two rows of hexagonal reflector columns which are, in turn, surrounded by the permanent side reflector (PSR) blocks.

4.2.2. Reactor Internals Components

The VHTR reactor internals (see Fig. 4-4) are similar in design to those of the HTGR-SC and the 950°C (1742°F) VHTR design (Ref. 4-1). The graphite and metal parts of the reactor internals system form a high-temperature and radiation-resistant inner container for the reactor core, which is raised above the PCRV bottom head by posts and separated from the core cavity sidewall by an array of springs. The system provides location, support, and restraint for the reactor core, shielding for the PCRV and liner, and seals to prevent bypass of the primary core coolant gas. The support posts form a bottom plenum for mixing and distribution of the hot coolant to the steam generators and enable relative movements between the core and the PCRV.

The reactor internals include the graphite components of the core support floor, the permanent side reflector (PSR), and the core peripheral seal; a metal peripheral seal support structure, including those items which attach the structure to the PCRV liner and those which provide the interface with adjacent thermal barrier; a metal core lateral restraint and side shield assemblies; and metal plenum elements which fit over the top PSR blocks.

4.3. NEUTRON AND REGION FLOW CONTROL

The VHTR utilizes the same reactor control concept as the large HTGR-SC. The neutron and region flow control system consists of two major subsystems:

1. The neutron control subsystem, which comprises:

   a. The normal control and shutdown systems of control rod pairs, power rods, and neutron detectors (see Fig. 4-9).

   b. The reserve shutdown system (RSS).

   c. The movable in-core flux mapping and startup detector system.

2. The primary coolant flow control subsystem, consisting of variable orifices and outlet temperature thermocouples for 31 core regions.

The system utilizes ex-core flux detectors, controllers, power rods, control rods, and/or the reserve shutdown material to adjust core reactivity, as required, to meet the demands of the plant control system

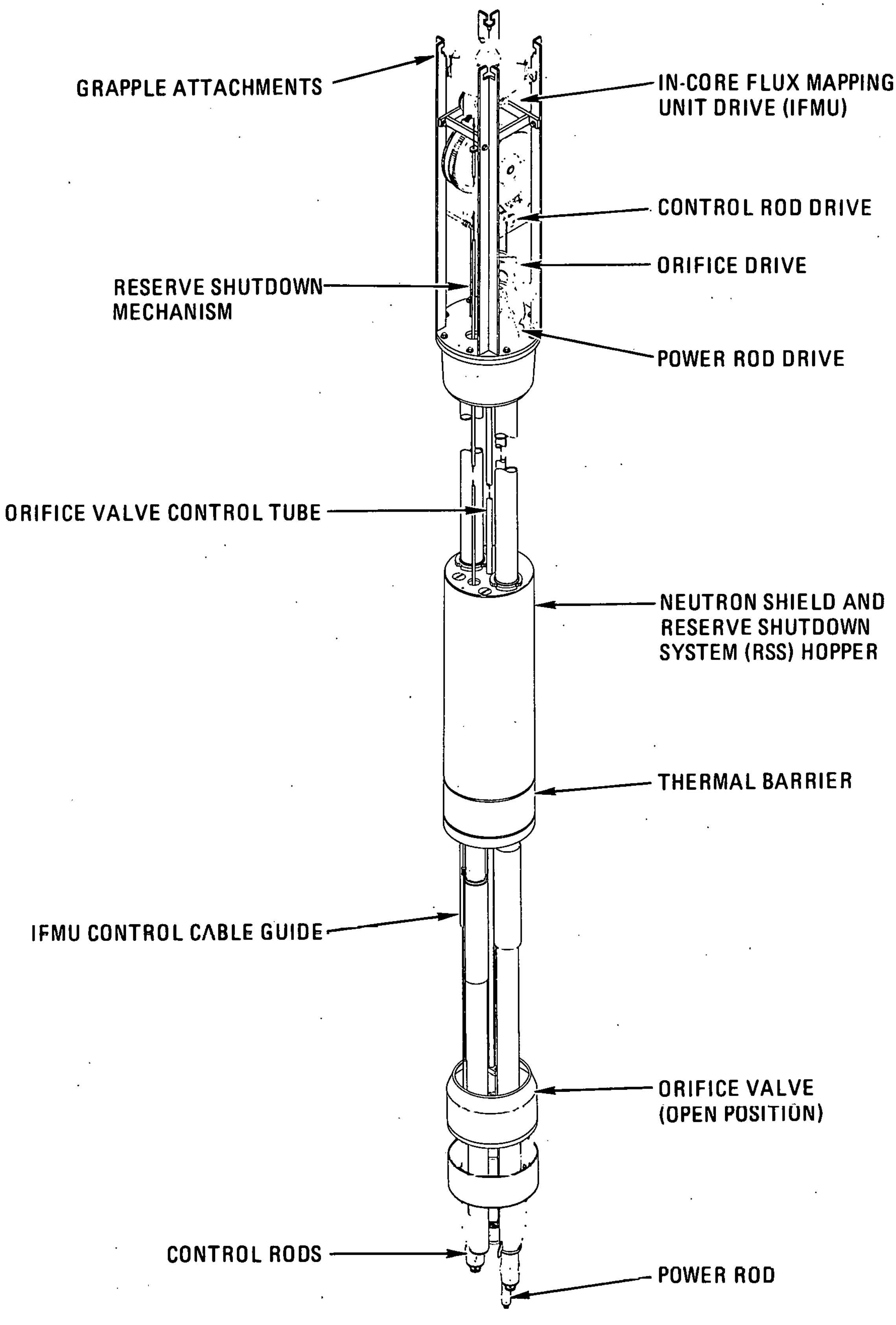

Fig. 4-9. Complete control rod and drive mechanism assembly

(PCS System 33), the plant protection system (PPS, System 32), or the plant operator. The system also adjusts the helium flow through regions of the core by incrementally positioning each adjustable core region inlet orifice valve when commanded by the plant operator. Reactor in-core flux distribution and startup-range neutron measurements are also performed by the system using movable detectors in selected core locations. This in-core instrumentation system also measures core region outlet temperatures.

Appropriate controls, together with indications of individual rod position, rod motion, rod limit of travel and slack cable, reactor power (flux), helium flow control orifice valve position, reserve shutdown system status, in-core and startup detector position and flux measurements, and core region outlet temperatures, are provided in the control room.

Penetrations into regions which do not require neutron or flow control are equipped with a shield plug assembly. Each assembly provides neutron and gamma shielding, thermal protection, and gas flow restriction for the penetration and liner. Figure 4-9 shows a control rod drive and mechanism assembly.

4.4. FUEL HANDLING AND SHIPPING

4.4.1. Fuel Handling

The VHTR utilizes the same fuel handling system as the HTGR-SC. The fuel handling system comprises all the equipment and subsystems required for the remote handling of both fuel and reflector elements and the various reactor components associated with refueling. Included is the fuel sealing and inspection equipment, which seals spent core elements and other solid waste into shipping containers prior to storage and subsequent handling by the fuel shipping system, as well as the equipment for the transfer of shipping containers between the fuel sealing and inspection facility (FSIF) and the fuel storage wells. Figure 4-10 shows the fuel element handling cycle and equipment.

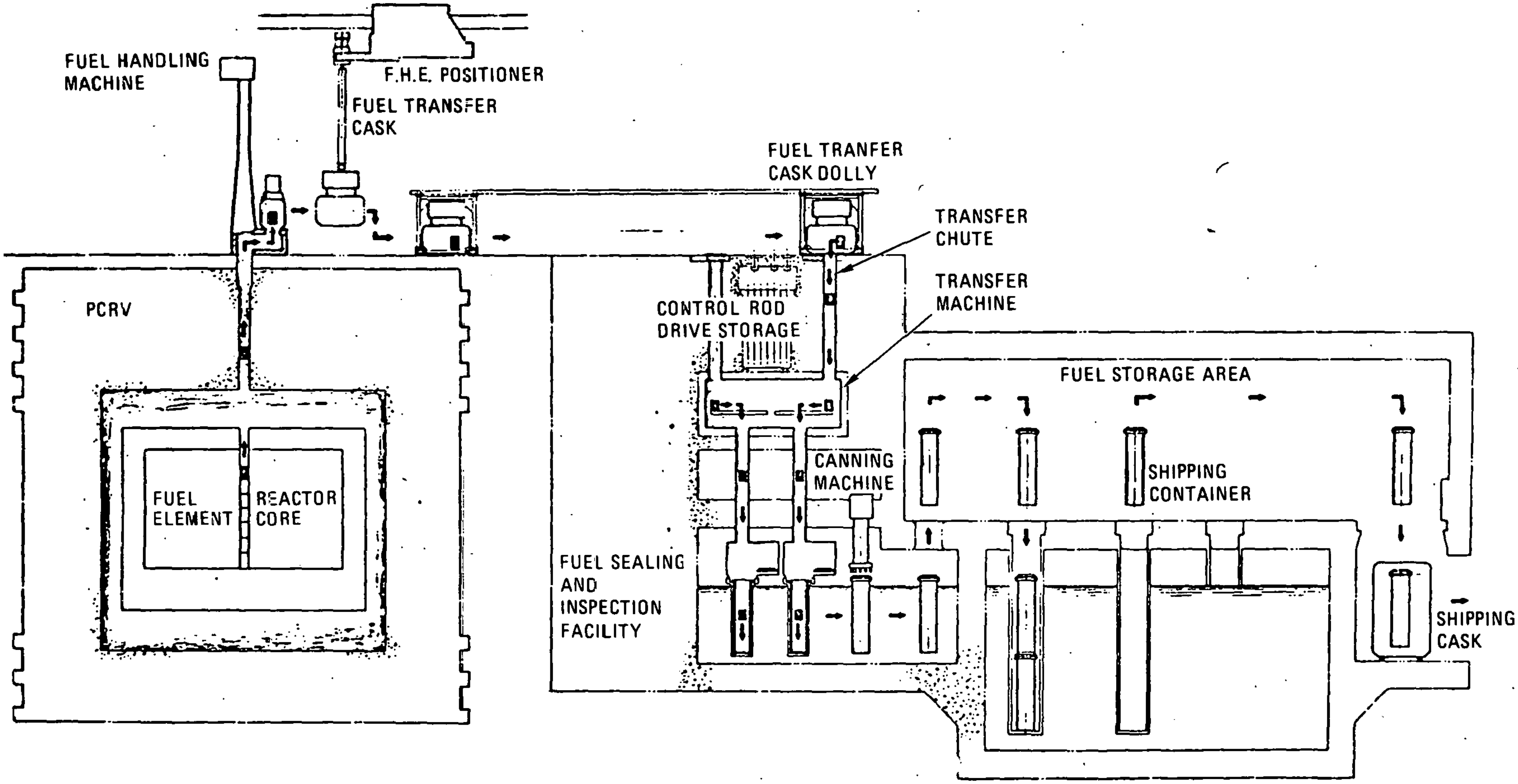

Fig. 4-10. Fuel element handling cycle

Refueling operations are predicated on a 3-yr core life, whereby one third of the reactor core is replaced each year with new fuel; replaceable reflector elements that reside adjacent to active fuel elements are replaced at 8-yr intervals. Both fuel and reflector elements are transferred through refueling penetrations in the top head of the PCRV. With a few exceptions, these penetrations contain control rod drives (CRDs) which have to be removed prior to installation of the fuel handling machine (FHM) on the refueling floor.

Each region being refueled is entirely emptied of spent fuel before the placement of new fuel.

Spent fuel and reflector elements are transferred to the fuel container loading facility, where reflector elements to be returned to the reactor are retained. The balance and the removed fuel elements are transferred to the FSIF, where they are sealed in helium-filled containers which are subsequently placed into storage.

After reactor shutdown and depressurization of the PCRV, refueling penetration hold-down plates and a refueling penetration closure plate are removed. A reactor isolation valve (RIV), which serves as a radiation and atmospheric barrier between the reactor cavity (or refueling penetration) and working personnel on the refueling floor, is attached to the refueling penetration.

The auxiliary service cask (ASC), which is designed to handle both the CRD unit and the high-temperature filters and absorbers (HTF/A), then removes the CRD assembly. The ASC is then transported to the reactor service building (RSB) by the fuel handling equipment transporter (FHET) and the CRD is placed in the CRD storage facility.

The FHM is then secured to the refueling penetration and sealed to the preplaced RIV. A fuel transfer mechanism within the FHM lowers through the refueling penetration into the reactor, picks up a fuel or reflector element, and lifts it back into the shielded portion of the machine. From there it is transferred to a fuel transfer cask (FTC). When loaded with spent fuel elements (five maximum), the FTC is transported by the fuel transfer cask dolly (FTCD) to the RSB, which is adjacent to the reactor containment building (RCB), placed to mate with a plug actuator above the fuel container loading equipment, and then passed on to the storage facility after sealing. Two FHETs and two rail systems are provided to facilitate the transfer of fuel and reflector elements between the RCB and RSB. Reflector elements are handled in the same manner as fuel elements.

When the working refueling region has been emptied, new fuel and reflector elements are brought in FTCs from storage to the FHM, which transfers the elements into the core. After the region has been refueled and the RIV closed, the FHM is detached and moved to the next refueling region. The ASC then installs a CRD assembly into the refueling penetration. The ASC and RIV are then removed, and connection of service lines and installation of the closure plate complete the process for a refueling region.

The fuel sealing facility, which operates in a helium atmosphere, inserts each fuel element into a storage canister and seals the can before it is transferred to the storage facility.

The equipment items comprising the fuel handling system and their functions are listed below.

4.4.1.1. Fuel Handling Machine (FHM). The FHM removes and replaces fuel and reflector elements. The machine forms a leak-tight containment with integral shielding.

4.4.1.2. Fuel Handling Control Station (FHCS). Located in the RSB, the FHCS provides fully automated remote control of all refueling operations within the PCRV together with an in-core viewing capability and control of some ex-vessel refueling operations, while having the capability of monitoring others.

4.4.1.3. Fuel Transfer Cask (FTC). Shielded casks are employed to convey five full-sized elements at a time between the FHM and the RSB; they are handled by the fuel handling equipment positioner (FHEP) in the RCB and the building crane in the RSB and a FTCD.

The casks provide leak-tight containments and feature an integral gate valve interfacing with both the floor valves and the FHM.

4.4.1.4. Auxiliary Service Cask (ASC). Primarily used for removing, transferring, and installing control rod drives, the cask also accommodates high-temperature filters and adsorbers and the reserve shutdown vacuum tool. The cask is conveyed between the RSB and the RCB in a horizontal position by the FHET and is handled by a FHEP in the RCB and the building crane in the RSB. The cask provides a leak-tight containment with an integral gate valve interfacing with both the floor valves and the RIV.

The cask also interfaces with the CRD storage facility.

4.4.1.5. Reactor Isolation Valve (RIV). Placed over a penetration immediately following removal of the penetration closure, the RIV provides both biological shielding for personnel on the refueling floor and a means of maintaining continuity of the helium atmosphere before and after installation of the FHM or the ASC.

4.4.1.6. Fuel Handling Equipment Transporter (FHET). The FHET is a self-propelled vehicle running on a set of elevated rails between the RCB and the RSB which can accommodate either the FHM or the ASC in a tilted position, or a circulator cask in an upright orientation.

4.4.1.7. Fuel Transfer Cask Dolly (FTCD). The FTCD is a special-purpose rail-mounted dolly operating between the RSB and the RCB which can accommodate an FTC in a vertical position. Two dollies and two rail systems are required for the plant.

4.4.1.8. Fuel Handling Equipment Positioner (FHEP). Operating in the RCB, each of two rail-supported FHEPs is capable of lifting, transporting, and positioning the FTM, the ATC, and an FTC on any one of the penetrations related to fuel handling and located in the refueling floor area.

4.4.1.9. FHEP Adapter. Used in the RCB on the FHEP when FTCs are handled, this device is required because of the height differential between the FHM, the ASC, and the FTCs in combination with the short lift distance of the FHEP.

4.4.1.10. Floor Valve (FV). Performing a similar function to the RIV, one of these valves is permanently installed over each of the transfer chutes leading to the fuel container loading facility.

4.4.1.11. Fuel Transfer Chute. The fuel transfer chutes, a BOP installation, connect the FVs in the RSB with the fuel container loading equipment.

4.4.1.12. Fuel Container Loading Assembly. Contained in a tank structure filled with helium and located below the fuel transfer chutes, the fuel container loading assembly provides for temporary storage of fuel and reflector blocks. Sorting of blocks is accommodated by a conveyer system and a turntable, while two hoists facilitate grappling and lowering of a fuel or reflector block into the FSIF. This equipment is a BOP installation.

4.4.1.13. Fuel Sealing Equipment (FSE). The FSIF, a BOP installation, incorporates the following fuel sealing and inspection equipment:

1. Fuel transfer port. This port connects the fuel container loading equipment with the helium chamber in the FSIF.

2. Helium chamber. This chamber provides a continuity of atmosphere between the FV, the fuel container loading equipment, and the conveyer chamber. A grapple arrangement inside the chamber permits removal and storage of shipping container lids within the controlled environment.

3. Conveyer. A continuous chain of water-cooled chambers accommodating a number of shipping containers, the conveyer provides both a storage facility and a means of moving containers within the FSIF, in addition to moving containers to and from a transfer position between the FSIF and the fuel storage area.

4. Canning machine. Located adjacent to the helium chamber, the canning machine removes, inserts, and torques the shipping container flange bolts and performs a seal leak test on the bolted connection.

5. Storage area hoist. Basically an overhead traveling crane, this hoist has a special grapple and guide sleeve arrangement to handle shipping containers, while maintaining them in a proper orientation between the FSIF access port and the fuel storage area and between the storage pool and the shipping cask. The hoist also handles the storage area closure plugs.

6. Control station. All equipment in the FSIF is remotely controlled from a control station located beyond the shield walls of the FSIF. Control is normally automated, but each function can be manually controlled and viewed through shielded windows adjacent to the control station.

4.4.2. Fuel Shipping

The spent and recycle fuel shipping system provides complete fuel shipping capability. The system provides equipment for the transport of spent and fresh uranium fuel elements between the reactor site and storage and/or recycle plant.

The shipping package design philosophy is based on double containment. Six spent fuel elements or five recycle fuel elements are packaged in a spent-and-recycle fuel shipping container. The container is sealed with a bolt-on lid incorporating both an elastomer and a metallic seal. Twelve shipping containers fit into a railroad shipping cask.

The fuel shipping container provides containment and facilitates handling of multiple fuel elements. The container has both a metallic O-ring and an elastomer O-ring, which provide an effective double seal at the bolt-on lid.

The shipping container is loaded with up to six spent fuel elements, and the cover (with seals) is then bolted in place. These operations are done by the sealing equipment at both the reactor site and the recycle plant. The sealed containers are stored in the cask loading area to await shipment inside the shipping casks.

Fresh fuel elements are shipped to the reactor site within the shipping containers. The container holds up to five fresh fuel elements plus the required protective packaging.

The shipping cask provides the structural, thermal, subcriticality, and shielding integrity of the shipping system. The sealed cask, with a removable cover, serves as the secondary enclosure vessel necessary to meet the double containment design philosophy.

The shipping cask holds 12 shipping containers for a total of 72 spent or 60 fresh fuel elements. Structural and shielding integrity is achieved through the use of a heavy steel outer shell, a depleted uranium gamma shield, and an inner steel shell. An inner aluminum basket aids in heat transfer and also maintains a subcritical shipping container spacing.

The cask is transported by a special-purpose railroad car. The cask is nearly horizontal on the railroad car during transport, being held by front and rear supports built into the railcar. It is erected to a vertical position prior to the loading and/or unloading operations. The entire cask is enclosed by a removable personnel barrier which restricts access to the cask by unauthorized personnel.

4.5. HELIUM SERVICES SYSTEM

The helium services system consists of the helium purification system and the PCRV seal system. These systems perform chemical purification of helium and provide purified helium to various parts of the primary helium flow circuit for use as seal, buffer, and purge gas.

The design of these systems for the VHTR will be similar to that for the HTGR-SC, but with capacity and chemical impurity removal capability adjusted to suit the VHTR requirements. The potential for large steam/water leaks into the VHTR primary coolant helium is much less than for the HTGR-SC, since there are no steam generators in the primary loops. However, capability for controlling impurity levels and providing buffer, seal, and purge helium in the VHTR secondary helium system, as well as the primary system, must be provided. It has not yet been established whether the VHTR will have separate helium service systems for the secondary loops or will have combined service systems.

The helium purification system is designed to remove helium from the coolant loops and process it to remove particulates, chemical impurities, and radioactivity so that the resulting gas can safely be used as a clean gas purge where needed throughout the plant. The helium purification system does not serve as the main radioactivity-level control within the primary coolant, except for long-lived gaseous isotopes (i.e., Kr-85). The helium purification system does, however, serve as the main chemical-impurities-level control in the primary coolant. The normal flow requirements for purified helium from the helium purification system are established by the various clean helium purge requirements throughout the reactor plant.

When the PCRV helium inventory is transferred to the helium storage system, the helium purification system removes radioactive impurities and, to as great an extent as possible, all chemical impurities. The helium purification system compresses purified helium recycled from the main and auxiliary helium circulator service systems to be used as purge gas. The system also periodically processes radioactive gas waste to separate the chemical and radioactive impurities and to concentrate the radioactive impurities.

Purified helium requirements for the VHTR primary and secondary systems have not yet been established. Table 4-4 gives the estimated primary coolant helium inventory and Table 4-5 the estimated secondary coolant inventory.

The helium purification system consists of filters, adsorbers, oxidizers, coolers, heaters, compressors, and associated piping, valving, instrumentation, and controls necessary to purify primary and secondary coolant and return the purified helium to the PCRV and the secondary coolant loops.

4.6. PRIMARY COOLANT SYSTEM

4.6.1. Intermediate Heat Exchanger (IHX)

Each of the two IHXs (Fig. 2-4) is a modularized straight-tube counterflow configuration. Table 4-6 lists IHX design data.

Hot primary helium from the core outlet cross duct enters the IHX cavity at the bottom end. The mean helium temperature is 850°C (1562°F), but hot streaks with a maximum temperature of 878°C (1612°F) are expected from a combination of region power peaking and region outlet temperature measurement tolerance. The preceding two factors contribute 10°C (18°F) and 18°C (32°F), respectively, to the hot streak. The mean temperature is used in performing thermal performance calculations, while the hot streak temperature is used in structural strength calculations.

The flow enters the cavity, transversely flowing over the hot end header. A high-temperature protective shield prohibits direct impingement of the incoming gas on the hot header. The gas then flows axially upward

TABLE 4-4
PRIMARY COOLANT HELIUM INVENTORY SUMMARY

	Inventory [kg (lb)]		
	Circulating[a]	Passive	Total
Core inlet plenum	475 (1047)	--	475 (1047)
Active core	309 (681)	--	309 (681)
Side reflector region	169 (373)	277 (611)	446 (984)
Core outlet plenum	241 (531)	--	241 (531)
Core outlet ducts	19 (42)	16 (35)	35 (77)
IHX cavities	657 (1448)	75 (165)	732 (1613)
Circulators and core inlet ducts	162 (357)	85 (187)	247 (544)
Refueling penetrations	--	360 (794)	360 (794)
CACS cavity and ducts	--	256 (564)	256 (564)
Total	2032 (4479)	1069 (2356)	3101 (6835)

[a]During normal full-power operation.

TABLE 4-5
SECONDARY COOLANT HELIUM INVENTORY SUMMARY

	Inventory, per Loop [kg (lb)]		
	Circulating[a]	Passive	Total
IHX	129 (284)	--	129 (284)
Hot pipe, IHX to reformer	209 (460)	71 (158)	280 (618)
Reformer	364 (802)	90 (198)	454 (1000)
Hot pipe, reformer to steam generator	20 (45)	6 (14)	26 (59)
Steam generator	178 (393)	--	178 (393)
Cold pipe, steam generator to circulator	64 (141)	--	64 (141)
Helium circulator	44 (96)	--	44 (96)
Cold pipe, circulator to IHX	389 (857)	--	389 (857)
Shutdown system hot piping	--	35 (77)	35 (77)
Shutdown helium circulator	--	19 (42)	19 (42)
Shutdown helium cooler	--	74 (163)	74 (163)
Shutdown system cold piping	--	61 (134)	61 (134)
Total per loop	1397 (3078)	356 (786)	1753 (3864)
Total plant, two loops	2794 (6156)	712 (1572)	3506 (7728)

[a] During normal full-power operation.

TABLE 4-6
IHX DESIGN DATA

Primary He flow rate (per loop)	191.6 kg/s (1521 x 10^3 lb/hr)
Primary He inlet temperature	847°C (1556°F)
Primary He inlet pressure	4.94 MPa (717 psia)
Primary He discharge temperature	418°C (785°F)
Secondary He flow rate (per loop)	184.6 kg/s (1465 x 10^3 lb/hr)
Secondary He inlet temperature	349°C (660°F)
Secondary He inlet pressure	5.24 MPa (760 psia)
Secondary He discharge temperature	793°C (1460°F)
Secondary He discharge pressure	5.14 MPa (746 psia)
Heat transferred	425.6 MW (1.45 x 10^9 Btu/hr)
Heat transfer surface area	12,031 m^2 (1.295 x 10^5 ft^2)
Mean temperature difference	60°C (108°F)
Number of tubes per IHX	32,766
Number of tubes per module	127
Number of modules per IHX	258
Module tube	
O.D.	11.1 mm (0.4375 in.)
Material	Hastelloy X
Wall thickness	0.89 mm (0.035 in.)
Length	10.5 m (34.5 ft)
Mean tube side film coefficient	1431 $W/m^2 \cdot K$ (252 Btu/hr-ft^2-°F)
Mean shell side film coefficient	1136 $W/m^2 \cdot K$ (200 Btu/hr-ft^2-°F)
Mean tube wall coefficient	22,083 $W/m^2 \cdot K$ (3889 Btu/hr-ft^2-°F)
Module lead tubes (hot end)	
O.D.	93.5 mm (3.68 in.)
Wall thickness	5.1 mm (0.2 in.)
Average length	1.5 m (5 ft)
Material	Hastelloy X

TABLE 4-6 (Continued)

Module lead tubes (cold end)	
O.D.	63.5 mm (2.5 in.)
Wall thickness	4.3 mm (0.17 in.)
Average length	8.44 mm (27.7 in.)
Material	2-1/4 Cr-1 Mo
Module subheaders (hot end)	
Max. o.d.	152.4 mm (6 in.)
Max. wall thickness	22.9 mm (0.9 in.)
Length	400 mm (15.75 in.)
Material	Hastelloy X
Module subheaders (cold end)	
Max. o.d.	152.4 mm (6 in.)
Max. wall thickness	22.9 mm (0.9 in.)
Length	400 mm (15.75 in.)
Material	Hastelloy X
Center return duct	
Hot section	
O.D.	0.952 m (37.5 in.)
Wall thickness	50.8 mm (2.0 in.)
Length	7.74 m (25.4 ft)
Material	Hastelloy X
Thermal barrier thickness	82.5 mm (3.25 in.) on outside surface
Cooler section	
O.D.	1.04 m (41 in.)
Wall thickness	50.8 mm (2.0 in.)
Length	4.27 m (14 ft)
Material	Hastelloy X
Thermal barrier thickness	44.5 mm (1.75 in.) on inside surface
Hot end spheroidal header	
Max. o.d.	3.78 m (12.4 ft)
Max. wall thickness	61.0 mm (2.4 in.)
Height	1.74 m (5.7 ft)
Material	Hastelloy X

TABLE 4-6 (Continued)

Tube plate	
O.D.	3.58 m (11.75 ft)
Thickness	91.4 mm (3.6 in.)
Material	2-1/4 Cr-1 Mo
Tube bundle outer shroud	
Hot section	
Thickness	9.5 mm (0.375 in.)
Max. length	3.05 m (10 ft)
Material	Incoloy 800
Cold section	
Thickness	9.5 mm (0.375 in.)
Length	7.5 m (24.5 ft)
Material	2-1/4 Cr-1 Mo

around the tube module end subheaders and into the tube field inside the outer shroud. Seals prevent the gas from bypassing the tube field. The inner seal closes the path between the center return duct and the inner row of modules. The outer seal seals the peripheral modules. These seals make sliding contact with the shroud and return duct to account for differential expansion between the various assemblies. In addition, the gas is prevented from flowing between the outer shroud and the cavity liner by a bolted ring seal.

The primary helium flows up the smooth surface tubes (shell side), across the cold end module subheaders, and into the exit plenum. Here it turns to flow transversely into the upper cross duct in the PCRV, which leads to the helium circulator.

The secondary helium enters the IHX through the annular portion of the concentric ducts and flows into the inlet plenum. From here it flows through the torispherical tube plate and enters the cold end lead tubes. These tubes are provided with sufficient horizontal run to absorb the differential expansion between the tube modules and the hot gas center return duct. The gas then flows through the module subheaders, where it is distributed to the heat transfer tubes.

The heat transfer tubes are grouped 127 to a module and joined at each end by an acorn-shaped subheader. A thin shroud surrounds each module, and strip spacers welded at their ends to the module shrouds at 1.52-m (5-ft) intervals along the module maintain tube separation.

The secondary gas flows through the module tubes, picking up heat, and flows out through the hot end subheaders. It flows through the hot end lead tubes and into the spheroidal-shaped hot header and thence up the center return duct. This hot header design is an improved version of the conical header described for the 950°C (1742°F) VHTR case (see Ref. 4-1). It uses an oblate spheroidal (approximated) plenum stayed by extensions of the hot lead tubes. This configuration allows the hot tubes to be straight and can thus better withstand the axial loads caused by differential expansion.

The secondary gas at this point is at its maximum temperature, 792°C (1458°F), but is cooler than the adjacent primary gas. For this reason, the hot end header and the center return duct are insulated on their external surfaces. At the point where the primary gas outside the center return duct has been cooled to a temperature about equal to that of the secondary gas inside the duct, the outside insulation ceases and insulation is applied to the inside of the duct. The secondary gas continues up the center return duct through the cold end tube sheet and the spherical cap to the discharge duct.

The IXH is supported at its cold end from a flange connected to the cavity liner through a thermal sleeve. The flange supports both the top dished head closure and the torispherical tube sheet. The center support duct hangs from the tube sheet and supports the hot end header. The tube modules (including their module shrouds) are supported by the hot header through the hot end lead tubes and subheaders. The heat transfer matrix shroud is supported from the liner via a thermal shield and support flange.

The ends of the modules are accessible for plugging by means of special tooling through the center return duct for the hot end and through the cold end plenum for the cold end.

4.6.2. Main Helium Circulators and Valves

The circulator consists of a single-stage axial flow compressor, a synchronous electric motor drive, a water-lubricated compressor bearing system, and a helium buffer seal system (see Fig. 2-5). Each circulator is located in a separate PCRV cavity located between the IHX and core cavity and above the core inlet plenum (see Fig. 2-3). The circulator is rigidly mounted on the circulator cavity PCRV closure. The compressor is overhung from a central housing that contains the water-lubricated bearings and seals. The motor is located vertically above and outside the primary coolant pressure boundary.

Primary coolant leaving the IHX is led through the cold cross duct into the outer annular space in the circulator cavity. As shown in Fig. 2-5, the coolant flows upward in this outer annulus and is then turned 180 deg in an accelerating curved annular duct which leads to the circulator inlet. The shape of the curved duct is designed to minimize pressure drop in the turn and to produce a uniform inlet flow velocity profile throughout the circulator blade height. After leaving the curved duct, the coolant gas flows downward through the circulator compressor and then through a diffuser. A set of turning vanes located below the diffuser exit deflects the gas by 90 deg, leading it toward the top core plenum through a short horizontal cross duct.

The circulator electric drive motor is controlled by a variable frequency power supply. At full reactor power, the motor speed is 465 rad/s (4440 rpm) and the motor shaft power is about 8.7 MW. A 200-kW pony motor is mounted on the same shaft to provide for auxiliary cooling. The compressor blading tip diameter is 1321 mm (52 in.), and the blade height is 100 mm (3.94 in.). Blading design follows conventional axial flow turbomachinery design techniques and features the same aerodynamic loading parameters used in previous circulator designs at GA. The main circulator parameters are presented in Table 4-7.

A primary coolant shutoff valve is incorporated into the circulator. It consists of a cylinder that can be lowered to intercept the flow path midway through the 180-deg turn in the circulator inlet duct. In the open valve position, the intercept cylinder is fully retracted in the space above the curved inlet duct. The primary coolant shutoff valve is operated by three synchronized, stepping-motor-driven electromechanical actuators.

TABLE 4-7
MAIN PRIMARY COOLANT CIRCULATOR PARAMETERS

Circulators	2
Normal helium flow capacity, each (at rated conditions)	192 kg/s (1.52 x 10^6 lb/hr)
Normal suction pressure	4.88 MPa (708.2 psia)
Normal discharge pressure	5.00 MPa (725.0 psia)
Static pressure rise	0.12 MPa (19.8 psi)
Primary coolant inlet temperature	419°C (786°F)
Circulator speed, rated	465 rad/s (4440 rpm)
Drive type	Synchronous electric motor
Drive motor shaft power, each	8.7 MW
Speed control	Solid-state variable frequency

A typical cross section through the bearing and seal system is shown in Fig. 4-11. Water-lubricated bearings of the shrouded-step-pocket type were adopted. Water under pressure is supplied to the bearing pockets to support the bearing load at zero speed while maintaining a gap between stationary and moving parts. Thus, no sliding friction occurs at any time during circulator operation, and the bearings are immune from wear. Rotation generates additional pressure at the steps at the end of the pockets, thereby adding a sizable hydrodynamic load and stiffness capability to the hydrostatic capability provided by the water pressure. The bearings thus operate as hybrids. A raised land surrounds the pockets to limit water leakage (this shrouding action gives the bearing its name). The same design is adopted for the radial bearings as for the thrust bearings. This type of bearing has been thoroughly developed and tested at GA and has operated successfully both on the FSV circulator and on the large HTGR main circulator prototype, which has recently been tested at the GA circulator test facility.

A main circulator service module for each circulator contains all the service system equipment associated with one circulator. Major equipment includes a surge tank, two bearing water boost pumps (one standby), two bearing water filters (one standby), a bearing water cooler, a helium/water drain cooler, an auxiliary jet supply pump, a bearing water make-up pump, two helium dryers (one being regenerated), and a regeneration heater.

The seal system associated with the circulator bearings is based on technology developed for the FSV and large HTGR programs and subsequent improvements. At the compressor end, a double-labyrinth seal is provided between the bearing system and the primary helium coolant. Purified helium buffer gas is injected between the two labyrinths; a portion of the buffer gas flows through one labyrinth into the primary coolant system, while the remainder flows through the other labyrinth into a scavenging chamber. Leakage from the compressor-side journal bearing also flows into this scavenging chamber. The resulting helium-water mixture is pumped out by jet pumps to an external separator where its components are separated; the helium is dried before being recycled into the seals. The seal system at the compressor end does not include any sliding parts and is therefore immune from wear. At the drive end, a high-pressure water seal of conventional design is used to seal the bearing system from the containment atmosphere. This seal includes sliding parts and thus requires maintenance. However, it is easily accessible, and it can be removed without disassembling the circulator and its drive motor (for this purpose, a removable shaft section is provided above the seal). Two shutdown seals in series are provided at the compressor end. These seals can be set to positively isolate the bearing system from the primary coolant system when the circulator is not operating. A brake system is used to keep the rotor from turning when the shutdown seals are set. The compressor-end seal system is of the same design developed for the large HTGR circulator and has been successfully tested at the GA circulator test facility. The drive-end seal is of entirely conventional design and is available from several manufacturers.

The drive motor is external to the primary coolant system and is mounted to an extension of the circulator penetration liner. This arrangement assures good alignment between the motor and the circulator and allows use of a solid coupling between the two machines. The motor is of the wound-rotor synchronous type, with brushless excitation; it runs on oil-lubricated pivoted pad bearings of conventional design. A brake located at the lower end of the motor allows the machine to be brought to a full stop after a brief coastdown period. The design of the motor is based on well established technology and closely parallels the design of synchronous generators of similar size.

4.7. SECONDARY COOLANT SYSTEM

The secondary coolant system consists of the subsystems and components required for transfer of heat from the primary reactor coolant system to the externally located process portion of the plant. In addition, portions of the secondary coolant system are used to transfer heat from the primary coolant system to an auxiliary heat removal system (Section 4.9) to reject

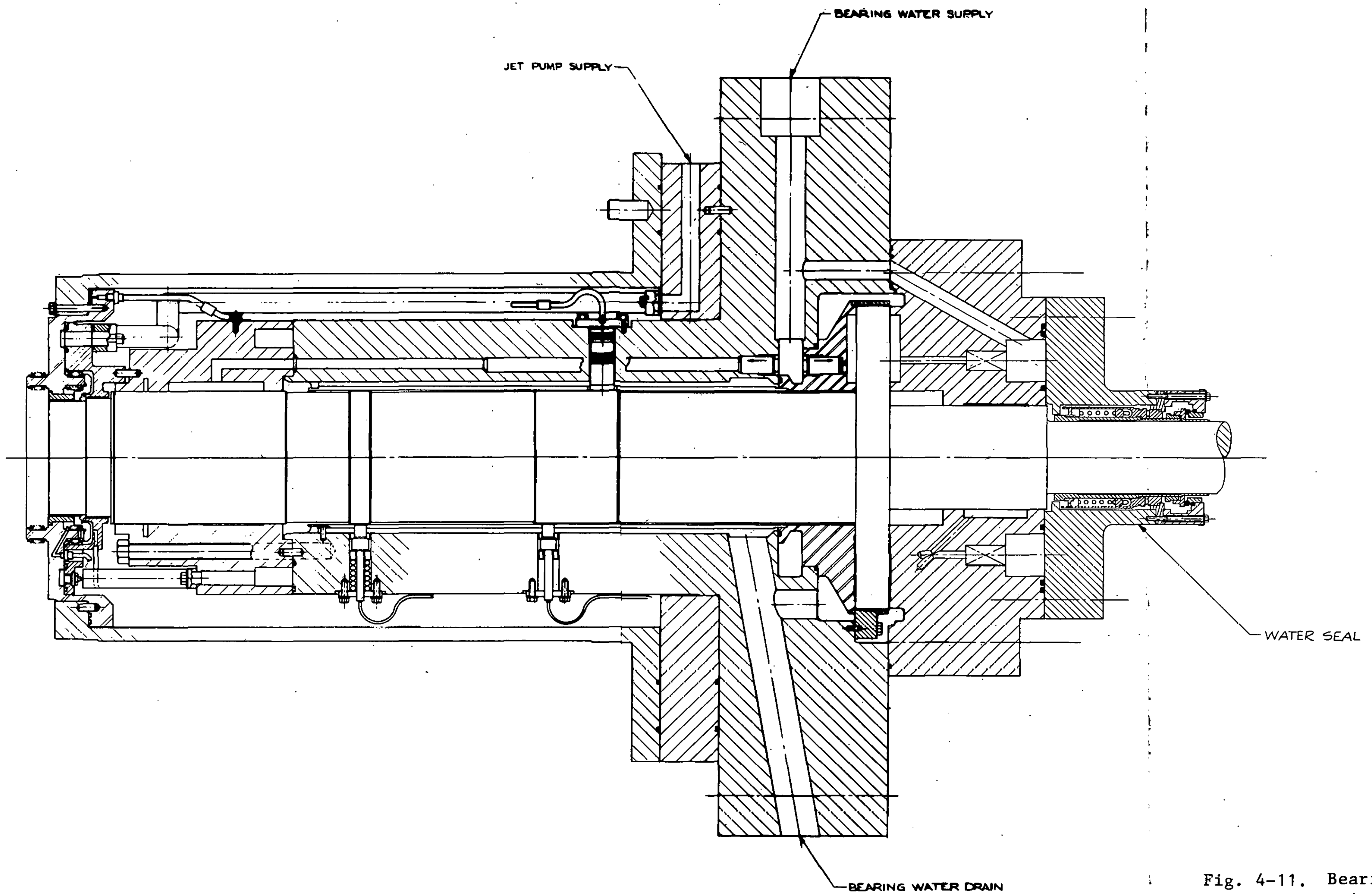

Fig. 4-11. Bearing and seal system for primary helium circulator

ITEM	PART NO	DESCRIPTION	MATL/MATL SPEC
	024357	PARTS LIST	

MAIN CIRCULATOR

GENERAL ATOMIC COMPANY

VHTR PRIMARY LOOP MAIN CIRCULATOR BEARING AND SEAL

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024498

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sensible and fission product decay heat from the core during reactor shutdown. Figure 2-8 is a diagram showing the arrangement of the secondary coolant system piping and equipment.

The IHX in each primary coolant loop transfers heat to the secondary system. A separate complete secondary loop using helium as the heat transport fluid is provided for each primary loop. In addition to providing high-temperature heat to the primary process application, the nuclear heat is also used to generate high-temperature, high-pressure steam to meet both process and electrical power generation needs of the plant. The major components in each secondary coolant loop other than the IHX are a steam/methane reformer, a steam generator, a helium circulator, and related piping and valves.

Each loop uses a constant inventory of helium to transfer heat from the IHX to the reformer and steam generator. The helium is forced through the IHX by the helium circulator, heated, passed to the reformer at high temperature, passed to the steam generator, and returned to the circulator to complete the circuit. The secondary helium pressure level is set slightly higher than that of the primary system to prevent leakage of reactor helium into the secondary system while maintaining minimum long-term pressure gradients on the IHX. This pressure level is also compatible with maintaining acceptable pressure gradients between the secondary helium and process gases in the reformers.

Each secondary loop includes the valves and controls required to provide for (1) IHX and containment isolation at the secondary helium piping penetrations, (2) isolation of the process plant equipment from the secondary circuit, and (3) secondary helium admittance to the shutdown heat removal system.

Portions of the system between the IHX and the containment and shutdown cooling system isolation valves are safety class 2. The remainder of the system is non-nuclear.

4.7.1. Piping and Valving

Figure 2-8 is a flow diagram showing the secondary coolant piping and valving. Carbon steel is used for the hot helium piping between the IHX and reformer and between the reformer and steam generator, with internal thermal barrier to keep the pipe wall temperatures lower than 371°C (700°F). Carbon steel is also used for the externally insulated non-nuclear cold helium piping at 326 °C (619°F) between the steam generators and secondary circulators and for the cold piping between the circulators and the IHXs at 349°C (660°F). Thermal barrier in the hot piping consists of Saffil fiber and Hastelloy X cover plates (see Fig. 4-12).

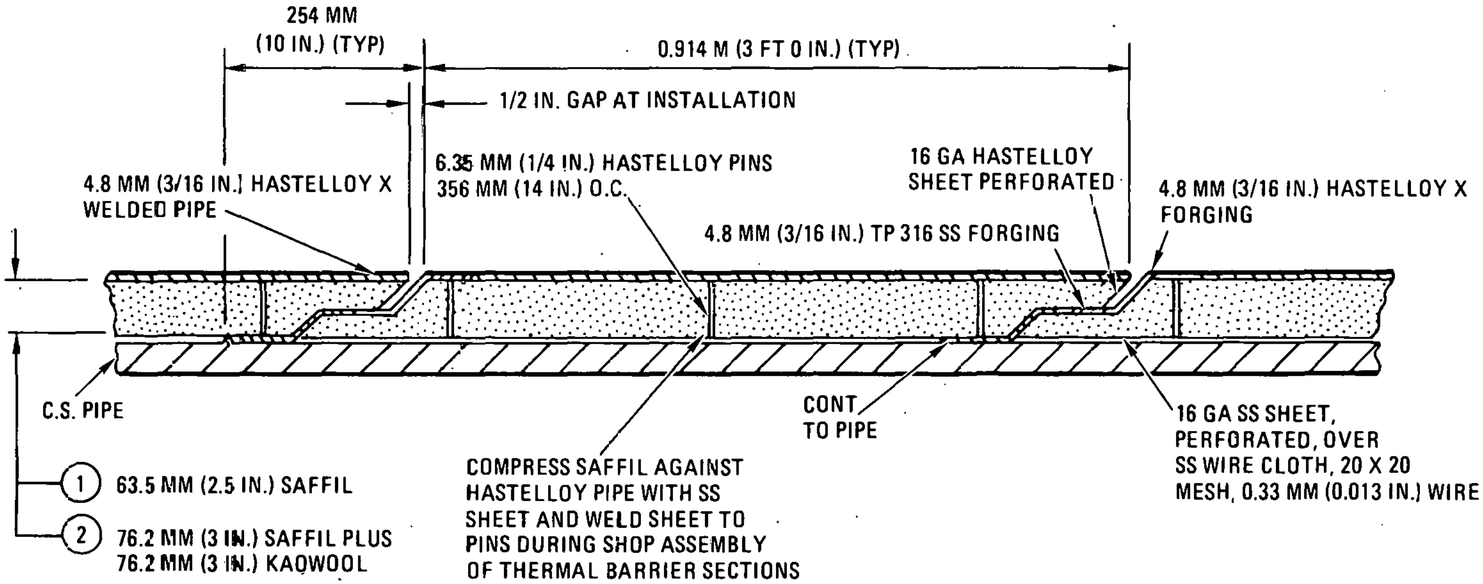
Isolation valves currently being considered are commercially available metal-seated ball valves. Valves in the hot piping (Fig. 4-13) have internal thermal barrier similar to that in the piping and small purge flows of cool helium introduced at critical parts. The material used for the body construction of the hot valves is 2-1/4 Cr-1 Mo alloy. Body material for the cold valves is carbon steel.

Flexibility is provided to absorb thermal expansions in the piping. The piping arrangement inside the containment is shown in Fig. 2-3; piping between the containment and process plant is shown in Fig. 2-8.

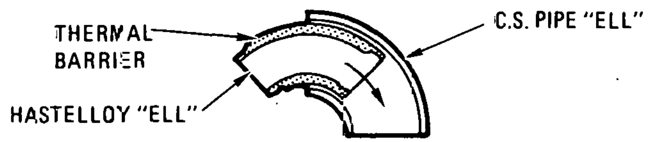
4.7.2. Secondary Helium Circulators

Secondary helium is circulated by commercial multistage centrifugal compressors. Special seals are provided to maintain reasonable helium leaktightness, and materials are chosen for compatibility with the high-purity helium service.

The 32,000-hp drive power required by each secondary circulator is provided by a commercial condensing steam turbine of the type used for power plant boiler feed pump drive. Steam is supplied to the turbines at 3.84 MPa (550 psia) from the exhausts of the turbines used for electric power generation.



1. PIPE COMPLETE WITH THERMAL BARRIER TO BE SHOP FABRICATED IN MAXIMUM SHIPPABLE ASSEMBLIES.
2. ELBOWS TO BE ASSEMBLED BY APPLYING THERMAL BARRIER TO HASTELLOY "ELL" THEN SLIDING ASSEMBLY INTO C.S. PIPE "ELL"



PROVIDE OVERLAP JOINT IN THERMAL BARRIER FROM ADJOINING PIPE SECTIONS. WELD WITH CONSUMABLE INSERT. RADIOGRAPH THROUGH THERMAL BARRIER AND/OR U.T.

Fig. 4-12. 842-MW(t) VHTR secondary helium pipe thermal barrier

The circulators are in the non-nuclear portion of the secondary system and do not require nuclear code stamping.

4.7.3. Reformers

4.7.3.1. Design Objectives. The function of the steam-methane reformer is to transfer the heat transported by the helium loop to the reformer feedstock in the presence of a catalyst. It is, in effect, an axial counterflow convective heat exchanger, but with space provided on one side (tube side) for the inclusion of the catalyst material.

The design is based on a concept which has been used in the fossil-fired reforming industry for many years, with variations required for adaptation to convective heating. The design (Fig. 4-14) utilizes a heat exchanger which has tubes large enough to contain the catalyst material in stacked particle bed form. The feedstock is introduced on the tube side of the heat exchanger and flows over the catalyst particles while being heated by the tube walls. The conversion reaction described in Section 2.1 takes place during the passage through the bed, requiring that heat be supplied to the tubes over the entire active length. In fossil-fired reformers, this heat input is supplied by means of radiant energy from many fuel burners or gas jets located adjacent to a row of catalyst tubes.

To adapt this concept to a secondary helium loop convective heat source, the tubes are grouped together to form a gas-to-gas tube-and shell heat exchanger. The hot helium is introduced on the shell side at the hot end of the catalyst tubes, flows counter to the product gas around the tubes, and is discharged at the cold end.

Pressure loss limitations are imposed on the reformers to limit the pumping requirements on the helium side and the feedstock inlet pressure level. Excessive feedstock pressure causes the conversion reaction to be inhibited. An upper limit for the inlet pressure was therefore chosen to be between 2.76 MPa (400 psia) and 3.10 MPa (450 psia).

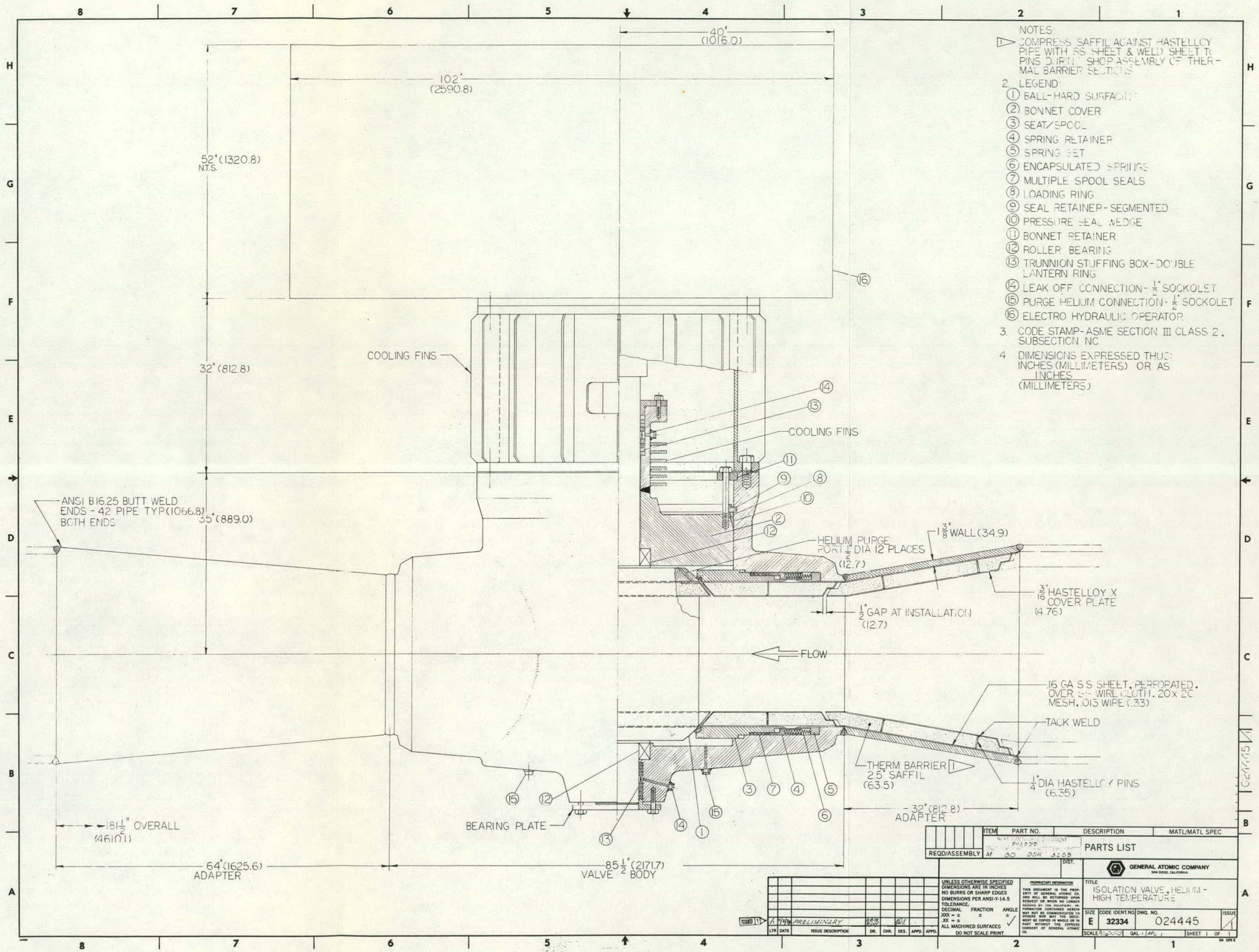


Fig. 4-13. 842-MW(t) VHTR isolation valve in secondary helium hot piping

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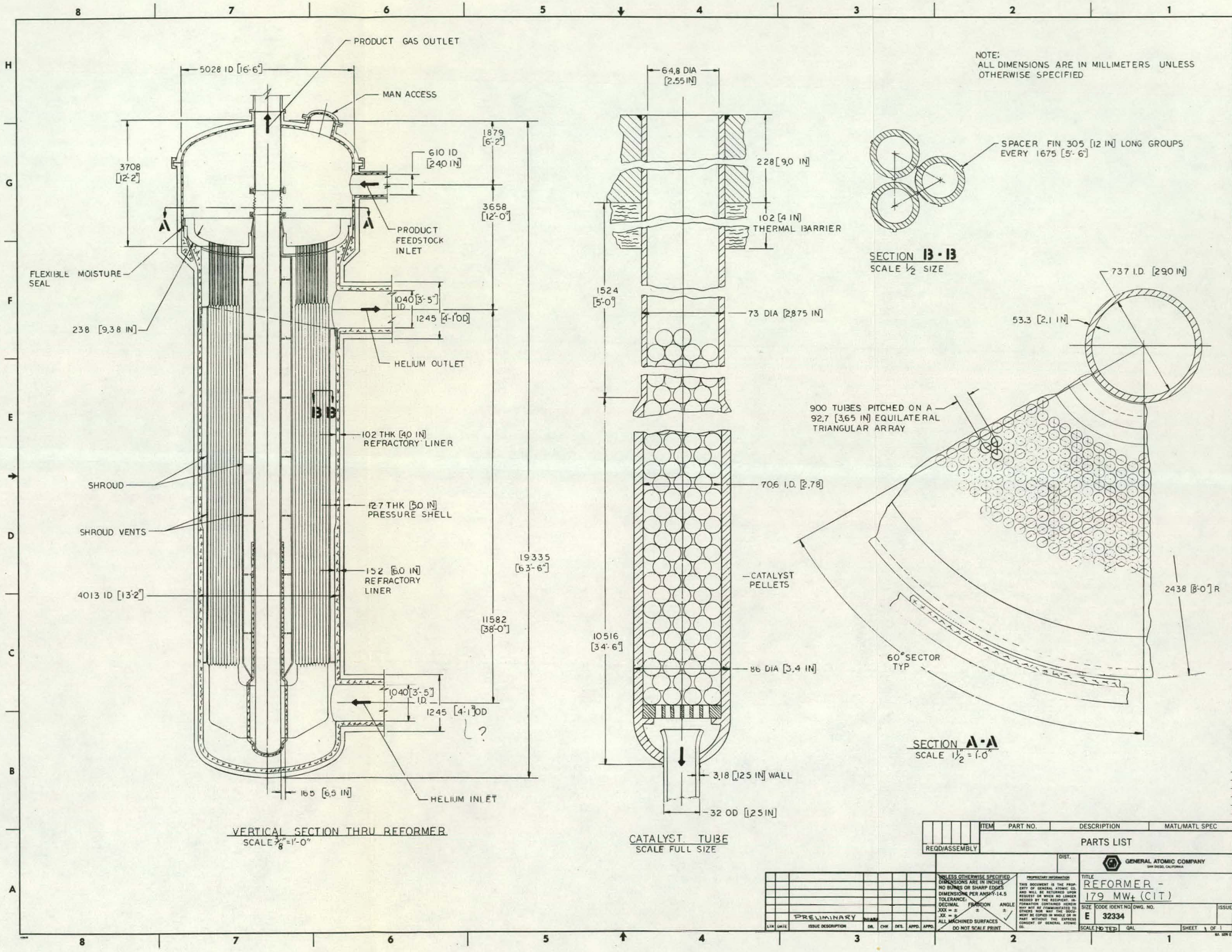

Fig. 4-14. Reformer for 842-MW(t) VHTR with 850°C (1562°F) core outlet temperature

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Nominal helium pressure losses in the shell side must be minimized to maintain reasonable circulator power requirements. The allowable total differential pressure (shell side) was limited to about 82.7 kPa (12 psi).

The reformers are designed to be self-supporting, withstand the normal and emergency pressures imposed on them, withstand temperature gradients and excursions, be maintainable, and have a useful life of 40 yr. In addition, three primary maintenance operations are considered in the mechanical design of the reformer:

1. Removal and replacement of the catalyst with minimum disruption of operations.

2. Plugging of both ends of a leaking tube with minimum disruption of operations.

3. Removal and replacement of the entire reformer assembly.

The reformers do not require nuclear code stamping.

4.7.3.2. General Layout. The principal design parameters of the reformer are summarized in Table 4-8. The design, as shown in Fig. 4-14, has the features described below.

The tubes containing the catalyst are hung from a dished tube sheet which is suspended from a thermal sleeve attached to the outer shell. The tubes are packed in a triangular pitch array around a centrally located common return tube (CRT) and connected to the CRT at the bottom of the reformer by small-diameter pigtails. The pigtails provide a flow path for the product gas and sufficient flexibility for accepting the difference in thermal expansion between the catalyst tubes and the CRT. The CRT is also hung from the dished tube sheet, which it penetrates, and continues out of the reformer vessel. The hot helium is introduced through the side of the vessel at the bottom of the tube bundle, from whence it flows around the

TABLE 4-8
REFORMER DESIGN DATA

Helium flow rate, per unit	184 kg/s (1.46 x 10^6 lb/hr)
Helium inlet pressure	5.01 MPa (736 psi)
Helium inlet temperature	790 K (1455°F)
Helium discharge pressure	5.03 MPa (729 psi)
Helium discharge temperature	623 K (1154°F)
Process gas flow rate, per unit	102.4 kg/s (0.813 x 10^6 lb/hr)
Process gas inlet pressure	3.03 MPa (439 psi)
Process gas inlet temperature	839 K (1050°F)
Process gas discharge pressure	1.39 MPa (201 psi)
Process gas discharge temperature	710 K (1310°F)
Number of units	2
Tubes per unit	900
Tube pitch	92.7 mm (3.65 in.)
Pattern	Triangular
Tube i.d. (upper section)	64.8 mm (2.55 in.)
Tube i.d. (main body)	70.6 mm (2.78 in.)
Tube o.d. (upper section)	73 mm (2.875 in.)
Tube o.d. (main body)	86 mm (3.4 in.)
Tube length (center of bundle)	10.5 m (34.45 ft)
Tube total surface area (outer)	2563.8 m^2 (27,598 ft^2)
Catalyst o.d.	15.9 mm (5/8 in.)
Catalyst length	15.9 mm (5/8 in.)
Shell i.d.	4.0 m (13.17 ft)
Weight	889,362 kg/unit (1,098,367 lb/unit)
Tubes (HK-40)	403,153 kg/unit (338,083 lb/unit)
Return pipe, Incoloy 800	19,861 kg/unit (45,391 lb/unit)
Pigtails, Incoloy 800	6363 kg/unit (9585 lb/unit)
Miscellaneous, Incoloy 800	1692 kg/unit (3730 lb/unit)
Miscellaneous, SS	3384 kg/unit (7460 lb/unit)
Tube sheet, 304 SS	39,712 kg/unit (86,243 lb/unit)
Pressure vessel, carbon steel	276,055 kg/unit (607,875 lb/unit)

outside of each catalyst tube to a region where the tubes have a reduced outer diameter to promote cross flow. The cooled helium flows from this region out the side of the vessel into the discharge duct. The heat losses to the cavity walls and the center return pipe are minor owing to the inclusion of flow shrouds and high-temperature thermal barriers and/or thermal insulation blankets, as shown in Fig. 4-14. The tube sheet is maintained at a temperature near that of the incoming feed gas by the surface insulation below the tube sheet and the large cooled surface area above.

The vessel, as shown in Fig. 4-14, requires only about 0.102 mm (4 in.) of a refractory liner to maintain the maximum shell temperature of less than 371°C (700°F), so carbon steel may be utilized in the vessel construction.

Process feedstock is introduced through the inlet duct which penetrates the side of the pressure vessel above the tube sheet. The feedstock flows through the plenum and into the catalyst tubes, picking up heat from the tube walls and reacting on the surface of the catalyst pellets. The conventional nickel-impregnated aluminum oxide catalyst pellets, which are randomly packed in each of the tubes, are ring-shaped and have a 15.9-mm (0.625-in.) o.d., a 6.35-mm (0.25-in.) i.d., and a 15.9-mm (0.625-in.) length. They are supported at the bottom of the tube by a grate which allows the product gas to flow through. Once through the catalyst bed and the grate, the gas is conducted to the CRT by means of the 25.4-mm (1.0-in.) o.d. pigtails, which are welded to the tube and the CRT. The gas then passes up the CRT and is discharged.

4.7.3.3. Tube Support Structure. One of the requirements of the design is that the tubes have an opening at the top large enough for extracting and replenishing the catalyst pellets. In addition, since conventional catalyst tubes are to be used, the tubes must be straight. Thus, it is implied that the tubes be hung from a tube sheet in a typical shell-tube heat exchanger fashion.

Loading requirements on the tube sheet result primarily from unbalanced pressure levels on opposite sides; they also result slightly from the weight of the components. The normal operating pressure differential force will produce a net upward load which is reduced by the weight of the tube sheet, tubes, catalyst, and CRT. The tube sheet, of course, must be designed to take this load for the life of the system.

The dominating operating condition, however, is the short-time emergency case in which the process gas pressure is reduced to zero while the helium pressure and temperature remain unchanged. This case produces a net upward force. The opposite emergency case, in which the helium pressure is lost and the process gas pressure remains constant, produces a net downward force.

The tube sheet design shown in Fig. 4-14 is an approach to a perforated torispherical shell. This design minimizes the bending stresses which would be present in a flat sheet and allows the material thickness to be substantially reduced. The tube sheet material is 316 stainless steel, which during emergency operations for short time periods can withstand tensile stresses to 0.124 GPa (18,000 psi) at 566°C (1050°F). This allows a tube sheet thickness of 229 mm (9 in.) to be used with a ligament efficiency (P-D/P) of 0.21. The area around the center return pipe is free of tubes because the local ligament must be increased in proportion to the pipe size.

The tube sheet is supported from the cavity liner by a 1.52-m (5-ft) long thermal sleeve. This length is required to provide sufficient flexibility in the sleeve to absorb the difference in the thermal expansion between the tube sheet and the cavity liner, which amounts to about 25.4 mm (1 in.) diametrally.

4.7.3.4. Catalyst Tube Structure. The catalyst tubes are welded to the top surface of the tube sheet. They hang down into the reformer cavity as a tube bundle, separated by 6.35-mm (0.25-in.) spacers and held together by peripheral restraints. The top 1.83 to 2.13 m (6 to 7 ft) of each tube is of reduced diameter in order to open the shell side flow area for cross flow and facilitate discharge of the helium. In addition, the reduced diameter serves to increase the ligament efficiency in the tube sheet, thereby reducing its required thickness. The tube thickness is also reduced, as allowed by the lower temperatures prevalent in the upper tube region.

The cast tubes used have an internal diameter of 73 mm (2.875 in.). A small grate is located in the bottom to hold the catalyst bed. A 25.4-mm (1.0-in.) o.d. pigtail of Incoloy 800 is welded to the end of each tube. The other end is welded to the nozzle field on the lower end of the CRT. The pigtails are fabricated with a minimum diameter, consistent with reasonable pressure loss. The small diameter is desirable because it minimizes the length required to provide the needed flexibility for accommodating the differential thermal expansion between the CRT and the catalyst tubes. This expansion difference requires the pigtails, which operate at an average temperature of 750°C (1380°F), to be at least 2.7 m (9 ft) in length. Some coiling of the innermost pigtails around the CRT will therefore be necessary.

The catalyst tubes were sized to provide sufficient internal volume for the catalyst material and gas flow volume. The wall thickness was determined by means of a computer analysis of instantaneous and long-term creep-buckling resistance with the tubes in the operational and emergency conditions. Several start-of-life ovality values were assumed. The analysis used an elastic creep program, the results of which were compared with ASME Code high-temperature criteria.

The CRT has an internal diameter of 0.737 m (29 in.) and a wall thickness of 53.3 mm (2.1 in.). The bottom 7.47 m (24 ft 6 in.) is covered with a 76.2-mm (3-in.) refractory outer liner. This maintains the maximum CRT temperature at about that of the process gas, 710°C (1310°F). The CRT is mounted on the tube sheet above the penetration by a welded thermal sleeve. The sleeve insulates the mechanical connection by providing a long conduction path and also provides flexibility for the thermal expansion differences.

4.7.4. Steam Generators

One steam generator (Fig. 4-15) is included in each of the secondary helium loops. They each receive hot helium from the helium outlet duct of the loop reformer. The helium is passed over two closely stacked banks of helically wound tubes such that a cross-counterflow heat exchanger is formed. The hot helium is introduced at the top and the feedwater at the bottom, making a vertical, uphill boiling, once-through steam generator. The entire assembly is enclosed in an insulated steel free-standing pressure vessel. The feedwater is brought into the vessel in two 203.2-mm (8-in.) i.d. pipes. The pipes are supported by thermal sleeves and terminate at two 127-mm (5-in.) thick tube plates.

The cold end tube bundle lead tubes are welded to the tube plates and lead up to the starting points of each of the 314 tubes in the main tube bundle. The purpose of these lead tubes is to connect the tube bundle to the feedwater tube plates and to provide sufficient flexibility to absorb about 6 mm (0.25 in.) of relative thermal expansion movement between the bottom of the bundle and the tube plates. Similarly, flexible lead tubes are provided at the hot end or superheater outlet end of the bundle to connect the bundle with the discharge steam header and to absorb ∿38 mm (∿1.50 in.) of differential expansion. These tubes are all routed to provide sufficient horizontal run [0.5 m (20 in.) at the cold end and 2.6 m (8-1/2 ft) at the hot end], which with the axial run provides the required flexibility.

The tube bundles are composed of the economizer, evaporator, superheater-1 (EES_1) bundle, and superheater-2 (SH_2) bundle. The EES_1 bundle is the lower of the two and is composed of 314 tubes of 2-1/4 Cr-1 Mo (SA 213, T-22) steel with a 19.0-mm (0.75-in.) o.d. and a 2.29-mm (0.09-in.) wall thickness. They are helically wound with a 33.02-mm

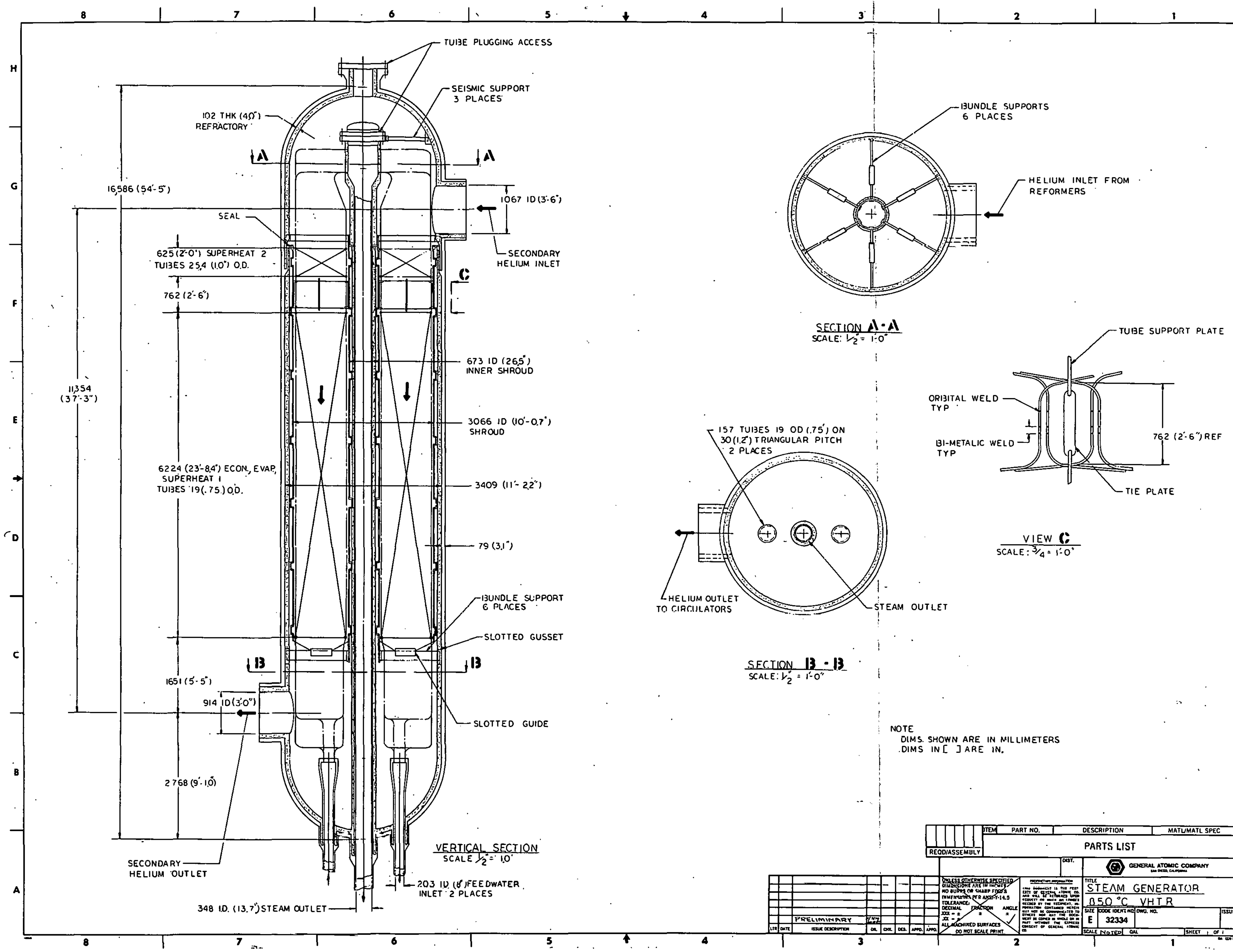

Fig. 4-15. Steam generator for 842-MW(t) VHTR with 850°C (1562°F) core outlet temperature

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(1.3-in.) radial and longitudinal pitch and supported by six 25.4-mm (1-in.) thick 2-1/4 Cr-1 Mo support plates. Wear sleeves and wedges are used between the tubes and the plate holes. The plates are 1.14 m (45.05 in.) wide. The inner 393.7 mm (15.50 in.) of every other plate has slots instead of holes to allow for differential expansion between the tubes and the plates. The remaining three plates have only holes, which support the tubes with sufficient rigidity to avoid undue aerodynamic vibration. The plates themselves are allowed to move radially with the tubes to reduce expansion loads. They are restricted from vertical movement by the mounting tabs keyed to the inner and outer shrouds and by the sliding spider mount at the base of the plate.

The SH_2 bundle is similar to the EES_1 bundle, except that it is composed of 314 25.4-mm (1-in.) o.d. Incoloy 800 (SB 163, Gr 2) tubes with a 2.8-mm (0.11-in.) wall, pitched at 38.1 mm (1.50 in.) radially and longitudinally. This bundle is about 0.625 m (24.6 in.) long and is supported by six separate support plates similar to those for the EES. The SH_2 plates are supported vertically by the EES plates with a radially sliding mount. The plates are constructed of 2-1/4 Cr-1 Mo steel, which with the difference in temperature between the Incoloy 800 tubes and the plates provides a better expansion match than if the tubes and plates were made of the same material.

The SH_2 and the EES_1 tube bundles are separated by 0.91 m (3 ft) to provide room for the bimetallic weld assembly. The SH_2 tubes are welded to the EES_1 tubes with individual shields to protect the welds from hot helium impingement. A 2-1/4 Cr-1 Mo tie plate is provided to take any stress.

The SH_2-discharge lead tubes are connected to the steam discharge header at the top of the unit. This is a 485.1-mm (19.1-in.) i.d. cylindrical drum with a 55.1-mm (2.17-in.) wall thickness constructed of Incoloy 800H with a 63.5-mm (2.50-in.) triangular pitch hole pattern into which the lead tubes are inserted and welded. This drum has a man access dome for tube plugging and initial welding bolted to the top end. The bottom is welded to a 2-1/4 Cr-1 Mo steam return duct. This is a 348-mm

(13.7-in.) i.d. duct with 102-mm (4-in.) thick refractory insulation on its entire outer surfaces, which carries the superheated steam down and out the bottom of the pressure vessel. It is connected to the vessel by a thermal sleeve.

The pressure vessel is a 2-1/4 Cr-1 Mo cylinder with a wall thickness of 78.7 mm (3.1 in.). Its inner surface is covered by 101.6 mm (4 in.) of refractory insulation. Penetrations include a man access at the top, a 1.07-m (3.5-ft) i.d. hot helium inlet duct above the tube bundles, one 1.52-m (3-ft) i.d. cool helium discharge duct below the bundles, two 203-mm (8-in.) i.d. feedwater inlet ducts supported by thermal sleeves, and one 348-mm (13.7-in.) i.d. steam discharge duct at the bottom also supported by a thermal sleeve.

Inner and outer shrouds are placed at the inner and outer diameters of the tube bundles to provide radial boundaries for helium flow. The tube support plates are keyed to these shrouds by means of tabs which allow radial movement. The shrouds are mounted on the main support spider at the bottom of the EES_1 bundle and are provided with lateral restraints and helium bypass seals at their upper ends.

The entire tube bundle support system and shroud assembly is supported by the spider support assembly. This is a six-legged beam assembly, which bridges the pressure vessel and has a center ring that surrounds the steam discharge header. Each of the legs is supported by a mounting lug welded to the vessel wall. The support assembly is sized to support the tube-plate assembly weight plus aerodynamic loads and loads caused by differential thermal expansions.

In operation, the feedwater is introduced in the bottom coils at about 294°C (561°F) and 20.7 MPa (3000 psia). As the feedwater progresses through the economizer section, the temperature is increased to about 360°C (680°F) where the vapor and liquid phases are present in the evaporator section. The steam cools to about 356°C (673°F) as heat is added, and the pressure decreases until saturation occurs. The temperature increases in the first superheater to about 415°C (780°F) where the steam passes from the EES_1 bundle to the SH_2 bundle. Here the steam temperature is increased to about 510°C (950°F), and then the steam is led to the discharge header and out of the vessel.

The hot helium enters the shell side of the bundle at the top at about 605°C (1121°F). It flows over the hot end lead tubes to the SH_2 bundle, flows to the EES_1 bundle, and finally flows over the cold end lead tubes and out the discharge duct with a temperature of about 327°C (630°F).

System parameters are outlined in Table 4-9.

4.8. CORE AUXILIARY COOLING SYSTEM (CACS)

The NHS portion of the CACS includes the auxiliary helium circulator and drive motor, motor control, diffuser and valve, CAHE, and control instrumentation and hardware.

The function of the CACS is to provide an independent means of cooling the reactor core with the primary system pressurized or depressurized. The capability of the CACS is such that cooling is provided to maintain the temperatures of all components in the PCRV within safe limits. The CACS is capable of removing 100% of the core residual and decay heat for safe cooldown from 102% of reactor steady-state power level under pressurized and depressurized conditions.

Heat removal is accomplished by forced circulation of the primary coolant, with air or water inleakage, by the auxiliary circulator. The core coolant gas is circulated through the CAHE where the heat is delivered to the CACWS for disposal to the atmosphere.

TABLE 4-9
842-MW(t) VHTR STEAM GENERATOR DESCRIPTION
(Values per Steam Generator)

No. units per plant	2
Overall height	16.59 m (54 ft 5 in.)
Overall diameter	3.57 m (11 ft 8-1/2 in.)
Helium inlet temperature	605°C (1121°F)
Helium inlet pressure	5.05 MPa (732 psi)
Helium discharge temperature	327°C (620°F)
Helium flow rate	184.5 kg/s (1.465 x 10^6 lb/hr)
Feedwater inlet temperature	294°C (562°F)
Feedwater inlet pressure	20.7 MPa (3000 psi)
Steam discharge temperature	510°C (950°F)
Steam discharge pressure	17.24 MPa (2500 psi)
Steam flow rate	132.3 kg/s (1.05 x 10^6 lb/hr)
Number of tubes	314
EES_1 tube o.d.	19.05 mm (0.75 in.)
EES_1 tube wall thickness	2.29 mm (0.09 in.)
EES_1 tube length	147.8 m (485 ft)
EES_1 bundle length	7.22 m (23.7 ft)
EES_1 tube material	2-1/4 Cr-1 Mo (SA 213, T-22)
EES_1 surface area	2779 m^2 (29,914 ft^2)
EES_1 shell side ΔP	∿25.5 kPa (3.7 psi)
EES_1 tube side ΔP	∿2.58 MPa (374 psi)
SH_2 tube o.d.	25.4 mm (1.0 in.)
SH_2 tube wall thickness	2.79 mm (0.11 in.)
SH_2 tube length	11.06 m (36.3 ft)
SH_2 bundle length	0.625 m (2.05 ft)
SH_2 tube material	Incoloy 800H (SB 163, Gr 2)
SH_2 surface area	277.2 m^2 (2984 ft^2)
SH_2 shell side ΔP	9.66 kPa (1.4 psi)
SH_2 tube side ΔP	165.5 kPa (24 psi)

Overall CACS performance has been calculated for a 950°C (1742°F) hot helium temperature VHTR at three design points which correspond to peak duties in three transient cases. These cases are core cooling (1) with depressurized PCRV and pure helium, (2) with depressurized PCRV and air ingress, and (3) with pressurized PCRV. The performance parameters for these cases are listed in Table 4-10. For the present 850°C (1562°F) hot helium VHTR, the CACS performance parameters have not been calculated, but they are expected to differ only slightly from the parameters listed in Table 4-10. The CACWS is a BOP system, providing water and heat rejection to the CAHEs, and is part of the CACS. Overall CACS performance as described herein is based on the assumption that the NHS portions of the CACS interface with a CACWS, which is approximately defined by the parameters given in Table 4-11. Although this table is the result of calculations performed for a 950°C (1742°F) hot helium temperature plant, it can also be used with acceptable approximation for the present 850°C (1562°F) VHTR plant.

4.8.1. Core Auxiliary Heat Exchanger (CAHE)

The CAHE is a straight-tube bayonet heat exchanger (see Fig. 2-6). Hot gas from the lower cross duct enters the bottom of the straight-bayonet tube bundle and flows upward through the tube bundle parallel to the tubes. Water flows countercurrent to the helium flow inside the tubes. Smaller-diameter core tubes convey the water to the upper end of the heat transfer tubes. The water exits the core tube and flows through the annulus between the two tubes to the bottom of the tube bundle, gaining heat on the way, as shown in Fig. 4-16.

The straight bayonet tubes extend upward from a tube sheet, which is welded into the bottom of the CACS cavity in the PCRV; the tubes are welded to the tube sheet. At the opposite or upper end, the tubes terminate in a cap welded to the end of the tubes. This system forms the primary coolant pressure boundary of the heat exchanger. The core tubes are connected to a tube plate inside the water box of the heat exchanger, which

TABLE 4-10
WATER-COOLED CACS PERFORMANCE DATA
FOR A 950°C (1742°F) HOT HELIUM TEMPERATURE VHTR
(Individual Loop Data Based on One "100%" Loop Operation)

Water pressure	10.3 MPa (1500 psia)
Water flow rate	134.0 kg/s (1.06 x 10^6 Btu/hr)
Design air dry bulb temperature	43.3°C (110°F)
Air blast heat exchanger surface area	273 m^2 (29,400 ft^2)
Air blast heat exchanger effectiveness	0.40
Helium circulator efficiency	0.75
Helium circulator maximum power	670 kW (900 hp)
Helium circulator maximum speed	372 rad/s (3550 rpm)
<u>Pressurized Cooldown System Parameters</u>	
Helium flow rate	18.9 kg/s (1.50 x 10^5 lb/hr)
CAHE heat duty	44.3 MW(t) (151 x 10^6 Btu/hr)
Helium temperature	
CAHE inlet	916°C (1681°F)
CAHE outlet	466.1°C (871°F)
Water temperature	
CAHE inlet	158.9°C (318°F)
CAHE outlet	235.5°C (456°F)
CAHE pressure drop	10.3 kPa (1.5 psi)
Circulator power	77.6 kW (104 hp)
Circulator speed	71.2 rad/s (680 rpm)
<u>Depressurized Cooldown (Pure Helium System Parameters</u>	
Helium flow rate	3.13 kg/s (2.5 x 10^4 lb/hr)
CAHE heat duty	12.5 MW(t) (42.6 x 10^6 Btu/hr)

TABLE 4-10 (Continued)

Helium temperature	
CAHE inlet	1001°C (1834°F)
CAHE outlet	307.8°C (586°F)
Water temperature	
CAHE inlet	75.6°C (168°F)
CAHE outlet	97.2°C (207°F)
Containment backpressure	165 kPa (24 psia)
CAHE pressure drop	10.0 kPa (1.4 psi)
Circulator power	379 kW (508 hp)
Circulator speed	372 rad/s (3550 rpm)
Depressurized Cooldown (Air Ingress) System Parameters	
Helium flow rate	6.7 kg/s (5.3 x 10^4 lb/hr)
CAHE heat duty	13.07 MW(t) (44.6 x 10^6 Btu/hr)
Helium temperature	
CAHE inlet	1001°C (1834°F)
CAHE outlet	296.1°C (565°F)
Water temperature	
CAHE inlet	77.2°C (171°F)
CAHE outlet	99.4°C (211°F)
Containment backpressure	165.0 kPa (24 psia)
CAHE pressure drop	17.2 kPa (2.5 psi)
Circulator power	670 kW (900 hp)
Circulator speed	372 rad/s (3550 rpm)

TABLE 4-11
CACWS DESIGN DATA FOR A 950°C (1742°F) HOT HELIUM TEMPERATURE VHTR

Water pressure in pressurized case	10.3 MPa (1500 psia)
Air blast heat exchanger area, per loop	4647 m^2 (50,000 ft^2)
Air blast fan power requirements, per loop	(later)
CACWS pumping requirement, per loop	100 kW (135 hp)
Pressurizer Configuration	
Air blast heat exchanger configuration	
Air flow	(later)
Approach air velocity	(later)
Number of vane-axial fans	(later)
Diffuser length	(later)
Fan efficiency	(later)
Number of tube rows	(later)
Tube diameter	(later)
Tube pitch	(later)
Fin density	(later)
Fin height	(later)
Fin thickness	(later)
Ambient Conditions	
Maximum temperature	43°C (110°F)
Minimum temperature	-34°C (-30°F)
Minimum atmospheric pressure	0.093 MPa (13.5 psia)
Water flow rate	134 kg/s (1.06 x 10^6 lb/hr)
Water temperature (DBDA)	
Inlet	97°C (207°F)
Outlet	76°C (168°F)
Water temperature (pressurized cooldown)	
Inlet	236°C (456°F)
Outlet	159°C (318°F)

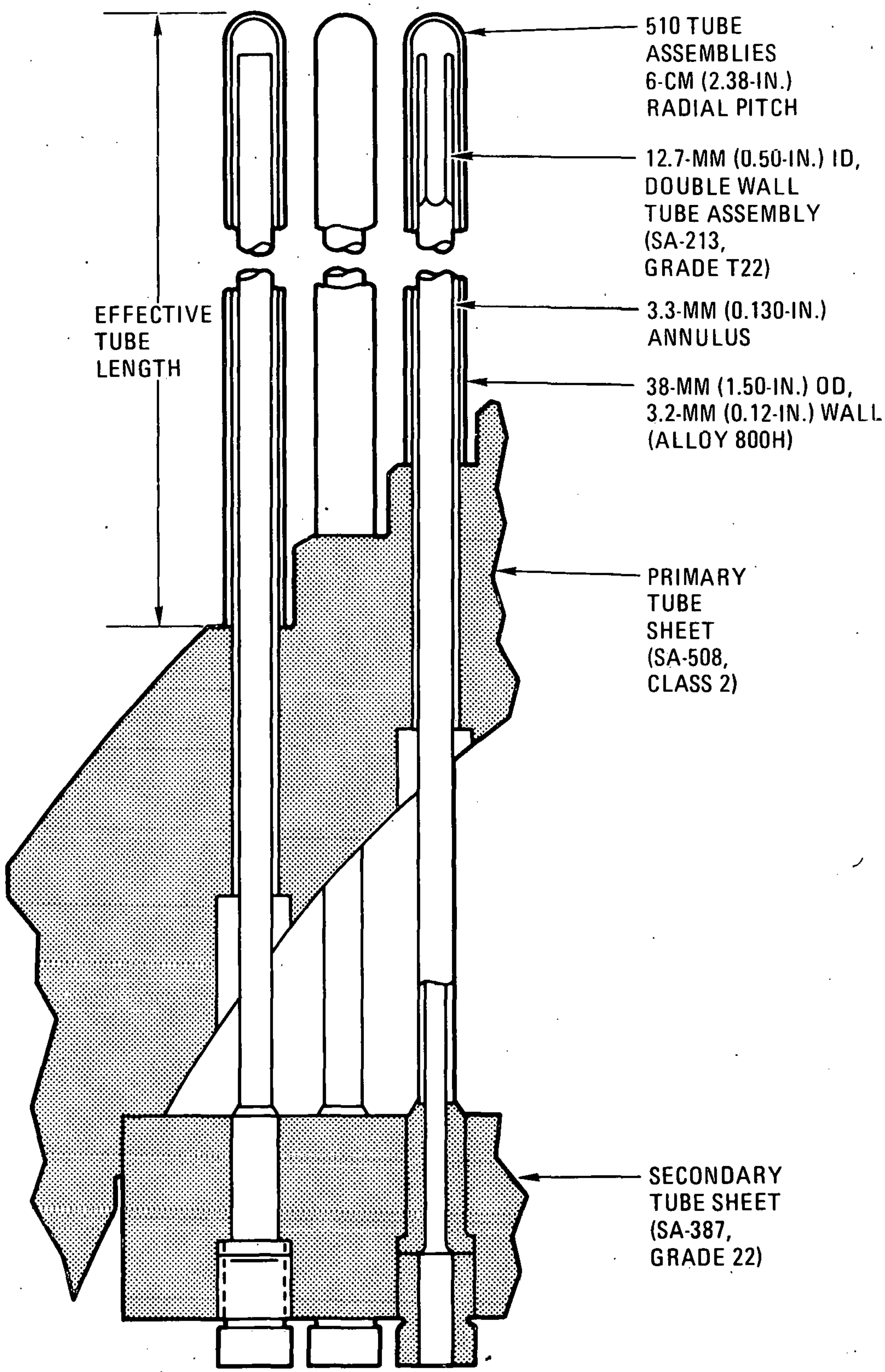

Fig. 4-16. Bayonet tube arrangement

separates the hot and cold water flow streams and serves as a support for the core tubes. A closure head is then bolted onto the bottom of the heat exchanger, forming the lower end of the water box and the water/containment pressure boundary. The connections for the inlet and outlet water piping penetrate the bottom head. The outlet connection, in the center of the water box, goes through an opening in the core-tube tube plate into an internal conduit to the outlet water piping connection. The inlet nozzle is off center; flow to the heat exchanger enters the plenum below the core-tube tube plate and then flows directly into the core tubes.

A flow restrictor at the bottom of the heat exchanger ensures that if the primary coolant pressure boundary should fail, the resulting leak would be very small. Table 4-12 summarizes the design data for the CAHE.

4.8.2. Auxiliary Circulator

Primary coolant is circulated through the core auxiliary cooling loop by the auxiliary circulator, which is illustrated in Fig. 2-7. The circulator can provide 100% core cooling capability at all pressure levels, from full helium inventory to refueling status, and at the conditions resulting from a depressurization accident, when air ingress takes place and the primary coolant consists of a mixture of helium, nitrogen, and carbon monoxide.

Primary coolant leaving the CAHE flows upward through an inlet duct and then through the circulator compressor. The compressor is a two-stage axial flow machine, followed by an annular diffuser. The compressor blade tip diameter is 1524 mm (60 in.), and the blade height is 38 mm (1.5 in.). The compressor is designed in accordance with conventional axial flow turbomachinery design methods; its aerodynamic loading parameters are the same as those adopted in circulators previously designed and built at GA.

TABLE 4-12
MAJOR CAHE DESIGN DATA

Type	Counterflow bayonet tube design
Tube	
O.D.	38 mm o.d. x 3.2 mm wall (1.5 in. x 0.125 in.)
Middle diameter	25.4 mm o.d. x 2.1 mm wall (1.0 in. x 0.083 in.)
I.D.	16.9 mm o.d. x 2.1 mm wall (0.667 in. x 0.083 in.)
Surface area[a]	370 m^2 (3978 ft^2)
Tube pitch	60 mm (2.38 in.)
Tube bundle diameter[a]	1450 mm (57 in.)
Materials of construction	
Outer tubes	Inconel 617
Middle tubes	Carbon steel
Inner tubes	Carbon steel
Tube sheets	SA 508, Gr. 2, carbon steel
Tube grids	Type 316 stainless steel
Water flow velocities	
Outer tube annulus	1.2 m/s (4 ft/sec)
Inner tube	2.75 m/s (9 ft/sec)

[a] Estimated for the VHTR design.

The circulator is driven by a variable-speed electric induction motor and is mounted on an overhang at the lower end of the motor shaft. The electromechanical components of the motor are standard vertical-motor items, but the lubrication and cooling systems are of special design. Oil bath lubrication is used, with oil replenishment provided for during reactor operation so that radiation damage cannot impair motor performance. The oil falls from the baths onto the adjoining bearings through metering orifices; after leaving the bearings, the oil is pumped back to the baths by small shaft-mounted impellers. At zero speed the bearings are flooded with oil, but during operation the combined action of the impeller and the orifices keeps them merely wetted with the appropriate amount of oil. Water-cooled coils keep the oil baths at the desired temperature. A double labyrinth seal is associated with each bearing; purified buffer helium introduced between the labyrinths prevents oil vapor from entering the primary coolant system and the motor cavity. Oil vapor, mixed with helium, is confined to the oil bath space; from there, an appropriate amount of the mixture is extracted and routed from an external oil/helium separation system. The motor cavity includes an internal cooling loop which transfers the parasitic heat generated in the motor and transferred by convection and conduction from the reactor to water-cooled coils with the help of shaft-mounted circulating fans.

The auxiliary circulator and motor design closely follows the design of the auxiliary circulator for the HTGR-SC program. The lubrication and seal arrangement were successfully demonstrated at GA as part of the large HTGR development program. The electric motor is the same motor that was developed for the HTGR-SC.

An auxiliary loop shutoff valve is inserted in the inlet duct. The valve, which is the same type as the FSV primary coolant shutoff valve, operates as a check valve, preventing significant backflow through the auxiliary loop when the main circulators are operating. Upon shutdown of the main circulator and startup of the auxiliary circulators, the valve will automatically open, thereby allowing auxiliary cooling to take place.

The main operating parameters for the auxiliary circulator in the air ingress case (which determines the sizing of the machine) are shown in Table 4-13.

The auxiliary circulator service system provides a supply of purified buffer helium to prevent inleakage of motor-bearing lubricant to the primary coolant system or leakage of primary coolant into the motor casing. It removes oil vapor carried over in purge helium from the auxiliary circulators and also removes and replaces the motor bearing lubricant when an auxiliary circulator is shut down.

The helium purge flow and bearing oil change-out preparation for each auxiliary circulator is performed by its associated service module. The three service modules are piped to a common oil adsorber module where purge helium and entrapped oil are separated. Purge helium is then returned to the helium purification system. There is one bearing-oil module per plant, which is portable and which, as a maintenance item, is attached to a service module to change the bearing oil in the auxiliary circulator upper and lower bearing cavities.

4.9. MAIN LOOP SHUTDOWN COOLING SYSTEM

As discussed in Section 3.2, emergency core cooling capability for the VHTR is provided by heat rejection from the two safety-class primary coolant loops, in addition to the single CACS loop. When normal main loop cooling is interrupted, heat from the core can be transferred to the secondary coolant helium through the IHX, with primary helium circulation provided by the main helium circulators operating on pony motor drive. The heat is then, in turn, rejected from the secondary helium by a safety class shutdown heat removal system connected to each secondary helium loop.

The shutdown heat removal system is shown schematically in Fig. 2-8. The shutdown system for each loop contains an air-to-helium heat exchanger for heat rejection, an electric-motor-driven helium circulator, and the

TABLE 4-13
AUXILIARY CIRCULATOR PARAMETERS FOR AIR INGRESS CASE

Auxiliary circulators	1
Coolant gas mixture composition	40% helium, 40% N_2, 20% CO
Flow capacity	6.678 kg/s (53,000 lb/hr)
Suction pressure	165 kPa (24 psia)
Discharge pressure	183 kPa (26 psia)
Static pressure rise	18 kPa (2.6 psi)
Coolant gas inlet temperature	296°C (565°F)
Circulator speed	372 rad/s (3550 rpm)
Drive type	Induction electric motor
Drive motor shaft power	671 kW
Speed control	Solid-state variable frequency

associated helium piping and valving. The secondary helium piping between the IHXs, up to and including the containment/loop isolation valves and isolation valves connecting the shutdown heat removal system, is safety class 2. The shutdown cooling system equipment and piping are safety class 3.

The shutdown heat removal system is isolated from the secondary helium loops during normal plant operation. When normal core cooling is interrupted, the containment/loop isolation valves are closed, the isolation valves connecting to the shutdown heat removal system are opened, and the shutdown helium circulators and air-cooled heat exchangers are placed in operation.

4.9.1. Helium/Air Heat Exchangers

The helium/air heat exchangers are expected to be commercially available air blast coolers, with the helium passed inside externally finned tubing and ambient air flow fan-induced across the outsides of the tubes. Preliminary analysis of the core cooling and heat exchanger requirements indicates satisfactory heat rejection performance with this type of unit. Preliminary design data are given in Table 4-14. Nuclear coding for safety class 3 equipment is required.

4.9.2. Shutdown Helium Circulator

The shutdown helium circulators are expected to be commercially available centrifugal compressors with electric motor drive and speed control by variable frequency power supply similar to that used for the auxiliary helium circulators in the CACS loop. Special seals are required to maintain helium leaktightness at the compressor shaft, and materials must be compatible with the high-purity helium service. Preliminary design data are given in Table 4-15. Nuclear coding for safety class 3 equipment is required.

TABLE 4-14
SHUTDOWN COOLING SYSTEM HELIUM/AIR HEAT EXCHANGER DATA

Heat duty	44.3 MW (151 x 10^6 Btu/hr)
Effective heat transfer area	1858 m^2 (20,000 ft^2)
Air inlet temperature	(later)
Air outlet temperature	(later)
Helium inlet temperature	371°C (700°F)
Helium outlet temperature	159°C (318°F)
Helium flow rate	40.4 kg/s (3.2 x 10^5 lb/hr)
Helium inlet pressure	4.96 MPa (718.5 psia)
Helium outlet pressure	4.86 MPa (705 psia)

TABLE 4-15
SHUTDOWN HELIUM CIRCULATOR DATA

Maximum motor power, kW (hp)	1260 (1698)
Maximum speed, rad/s (rpm)	372 (3550)
Operating inlet pressure, MPa (psia)	4.86 (705)
Operating outlet pressure, MPa (psia)	5.0 (725)

4.9.3. Piping and Valves

The design of the helium piping and valves in the shutdown heat removal system is similar to that for the secondary coolant system (see Section 4.7.1) except for pipe sizes and code classification. Figure 2-8 shows the piping schematic, including pipe sizes and safety class. All piping in the shutdown system is safety class 3.

The hot piping between the secondary helium IHX outlet piping and the helium/air heat exchanger uses the same carbon steel material and internal thermal barrier as the secondary helium system hot piping. Piping between the helium/air heat exchanger and the circulator is carbon steel with external insulation; piping between the circulator and secondary helium system IHX inlet piping is 2-1/4 Cr-1 Mo steel with external insulation.

4.10. PLANT PROTECTION SYSTEM (PPS)

The PPS includes all of the equipment from the sensors to the input terminals of the actuated devices involved in a public protection function. The VHTR PPS design is very similar to that for the HTGR-SC, but it incorporates some protective functions specific to the VHTR.

The PPS prevents any unacceptable releases of radioactivity which could constitute a hazard to the health and safety of the public by initiating actions to protect the fission product barriers and to limit the release of radioactivity if failures occur in the barriers. To accomplish these functions, the PPS provides the subsystems listed below:

1. Reactor trip system.
2. IHX isolation system (following leak detection).
3. IHX shutdown system (to prevent tube overtemperature).
4. CACS/main loop shutdown cooling initiation system.
5. Containment isolation system.

6. PCRV pressure relief block valve closure interlock.
7. Rod bank withdrawal interlock.
8. CAHE isolation system.
9. Moisture monitoring system.

Plant availability and equipment protection are not the main functional requirements of the PPS, but lie primarily within the scope of the PCS.

4.11. PLANT CONTROL SYSTEM (PCS)

VHTR plant operation and control requirements are discussed in Section 3.3. A general definition of the functional requirements of the PCS is given below.

The PCS is an integrated system that includes the instrumentation and equipment associated with the monitoring and control of the plant. Included in the PCS are the overall plant control loops for maintaining rated secondary helium conditions during normal operation and systems which provide protection of major equipment items and serve as a first line of protection for incidents which could otherwise result in the need for PPS action. The design and supply of control room consoles and boards are included. Also included is the nonsafety-related analytical instrumentation for the NHS.

The PCS provides for safe plant operation and high plant availability, regulates reactor power, and controls the pressure and temperature of the secondary helium. The system has the capability of automatic load following over the range and rates of change required for the plant. It also remains operational during abnormal occurrences, such as loop trip, turbine generator trip, boiler feed pump loss, and process heat train loss.

The system design must be integrated with the process plant control requirements for any specific VHTR application. A typical reference design has not yet been established, but it is expected that many of the reactor-plant-related functions of the HTGR-SC PCS will be applicable.

4.12. PLANT DATA ACQUISITION AND PROCESSING (DAP) SYSTEM

The DAP system is a dual-computer-based interface between the plant instrumentation and the plant operator. The DAP services both the NSS and BOP and replaces conventional plant alarms, indicators, and recorders. Redundancy of computers and critical peripheral equipment is used for maximum availability. In addition to the two computers, this system includes redundant disc memories, programmer consoles, magnetic tape units, line printers, color CRT displays, plant operator function keyboards, and trend recorders.

This system converts certain instrument signals to engineering units and provides visual and audible alarms, periodic logs, point trending, sequence-of-event recording, post-trip review, and displays of various operator information and procedural instructions on multicolor CRTs. Various applications programs are executed in the system computers to provide operational or plant performance information. These applications programs include the following categories:

1. Core reactivity status.
2. Core temperature and power distribution.
3. Heat balance calculations.
4. Plant performance calculations.
5. Operator guides.

The DAP system performs data acquisition, processing, alarming, engineering calculations, plant performance calculations, periodic logs, and operator guidance. The DAP system does not perform any control or safety function, but monitors both of these functions automatically and independent of the operator and the PPS. The DAP system informs the operator whether the limits exceeded are safety or operation related.

It is expected that many reactor-plant-related functions of the HTGR-SC DAP system design will be applicable to the VHTR.

4.13. GAS WASTE SYSTEM (GWS)

The GWS collects all radioactive and potentially radioactive gas wastes generated in the reactor plant, excluding PCRV leakage and other equipment leakage. The system also provides sample connections for radioactivity analysis of the contained gas.

The 850°C (1562°F) VHTR GWS design is expected to be very similar to that for the HTGR-SC and for the 950°C (1742°F) VHTR. Sampling and collecting of secondary helium system gas because of potential radioactive contamination from IHX leaks must probably be included in the system capability.

A reference design has not yet been established, but the system is expected to include a process module, a vacuum tank module, compressor control modules, compressors, and storage tanks. The process module contains the piping and valving necessary to perform the following functions:

1. Send potentially radioactive gas to the system vacuum tank.

2. Discharge low-activity gases from the high-pressure surge tanks to the reactor service ventilation system.

3. Direct high-activity gases from the high-pressure surge tanks to the system compressors for transfer to the helium purification system for further processing.

The vacuum tank module contains a gas waste vacuum tank and liquid drain tank plus associated piping and valving. The gas waste vacuum tank collects radioactive gas which is to be compressed and stored in the gas waste surge tank.

The compressor control modules contain the piping, valving, and some of the instrumentation necessary to operate the compressors.

REFERENCES

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