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MASTER

HTGR PROCESS HEAT PROGRAM DESIGN AND ANALYSIS

FY-79
FINAL REPORT

by
PROJECT STAFF

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

DATE PUBLISHED: DECEMBER 1979

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ABSTRACT

This report summarizes the results of concept design studies at General Atomic Company during FY-79 for an 842-MW(t) Very High Temperature Reactor (VHTR) utilizing an intermediate helium heat transfer loop to provide thermal energy for the production of hydrogen or reducing gas (H_2 + CO) by steam-reforming of a light hydrocarbon. Basic carbon sources may be coal, residual oil, or oil shale.

The report summarizes conceptual design tasks conducted on the prestressed concrete reactor vessel, thermal barrier, intermediate heat exchanger, reformer, and steam generator. The substantial completion of first generation programming for a performance/optimization code and the preparation of a topical safety report and other safety evaluation studies are reported. The completion of balance of plant criteria specifications and a balance of plant cost estimate is also reported.

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TABLES (continued)

1. INTRODUCTION

1.1. GENERAL

This report summarizes the work accomplished under DOE Contract DE-AT03-76SF71061 during the period October 1, 1978, through September 30, 1979. This is a continuation of the work performed under Contract EY-76-C-03-0167, Project Agreement 61, reported in Ref. 1-1.

During FY-78, alternate conceptual arrangements for an 842-MW(t) VHTR utilizing a secondary helium heat transfer loop to provide thermal energy for the production of reducing gas (H_2 + CO) or hydrogen by steam-reforming of a light hydrocarbon were developed and evaluated. In parallel with the arrangement studies, development of a VHTR parametric design computer code was initiated to guide and support nuclear system and process plant definitions and parameter selections. During FY-79, the plant design concept definition initiated in FY-78 was further defined in several critical areas, first generation programming for the parametric design computer code was substantially completed, a topical safety report was prepared, balance of reactor plant design criteria were developed, and cost estimating to support the computer code cost programming was performed.

1.2. SUMMARY PLANT DESCRIPTION

The plant design is a nuclear-heated chemical process plant whose product is hydrogen (or a mixture of hydrogen and carbon monoxide) generated by steam-reforming of methane. The nuclear heat source (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 circuits. 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 size is the same as the 842-MW(t) Fort St. Vrain (FSV) High-Temperature Gas-Cooled Reactor - Steam Cycle (HTGR-SC) power plant. The core and primary coolant systems are enclosed in a multi-cavity prestressed concrete reactor vessel (PCRV) similar in design to that used in the large HTGR-SC power plant, with the core cavity offset from the vertical centerline of the PCRV and the primary and auxiliary loop components in separate cavities beside the core cavity. The reference plant NHS design 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 1-1 lists the major plant parameters.

Figure 1-1 shows the plant cycle diagram, Fig. 1-2 shows an isometric cutaway view of the PCRV, and Fig. 1-3 shows the arrangement of the PCRV and reactor containment. Table 1-2 lists preliminary primary and secondary loop system conditions. Primary coolant helium flows downward through the reactor core and divides equally between two identical coolant loops, each containing a helium-to-helium intermediate heat exchanger (IHX), a helium circulator, and a helium shutoff valve. In each loop the heated helium first passes upward through the IHX and then is pumped back to the core inlet plenum by the helium circulator, completing the circuit. The helium shutoff valve is located at the circulator discharge and prevents backflow through the loop when the loop is not operating. Helium conditions at the core inlet are 5.00 MPa (725 psia)/475°C (887°F), and the core outlet temperature is 950°C (1742°F). This high core outlet temperature was selected because it is close to the upper limits of the capabilities of the HTGR core and because it is favorable to a wide variety of chemical processes

TABLE 1-1
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	342 kg/s (2.71 x 10^6 lb/hr)	
Pressure	5.0 MPa (725 psia)	
Core inlet temperature	475°C (887°F)	
Core outlet temperature	950°C (1742°F)	
Nominal secondary helium conditions		
Flow rate	342 kg/s (2.71 x 10^6 lb/hr)	
Pressure	5.3 MPa (765 psia)	
IHX outlet temperature	899°C (1650°F)	
Reformer outlet temperature	660°C (1220°F)	
Steam generator outlet temperature	398°C (748°F)	
Fuel cycle	High-enrichment uranium/thorium	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 x 10^{21} nvt	4.5 x 10^{21} nvt
Burnup	43,000 MWd/MT	(later)
Thorium loaded	5755 kg/yr	(later)
U-233 recycle	(later)	(later)
U-235 recycle	(later)	(later)
Total uranium recycled	(later)	(later)
U-235 makeup	(later)	(later)
Total uranium makeup	(later)	(later)

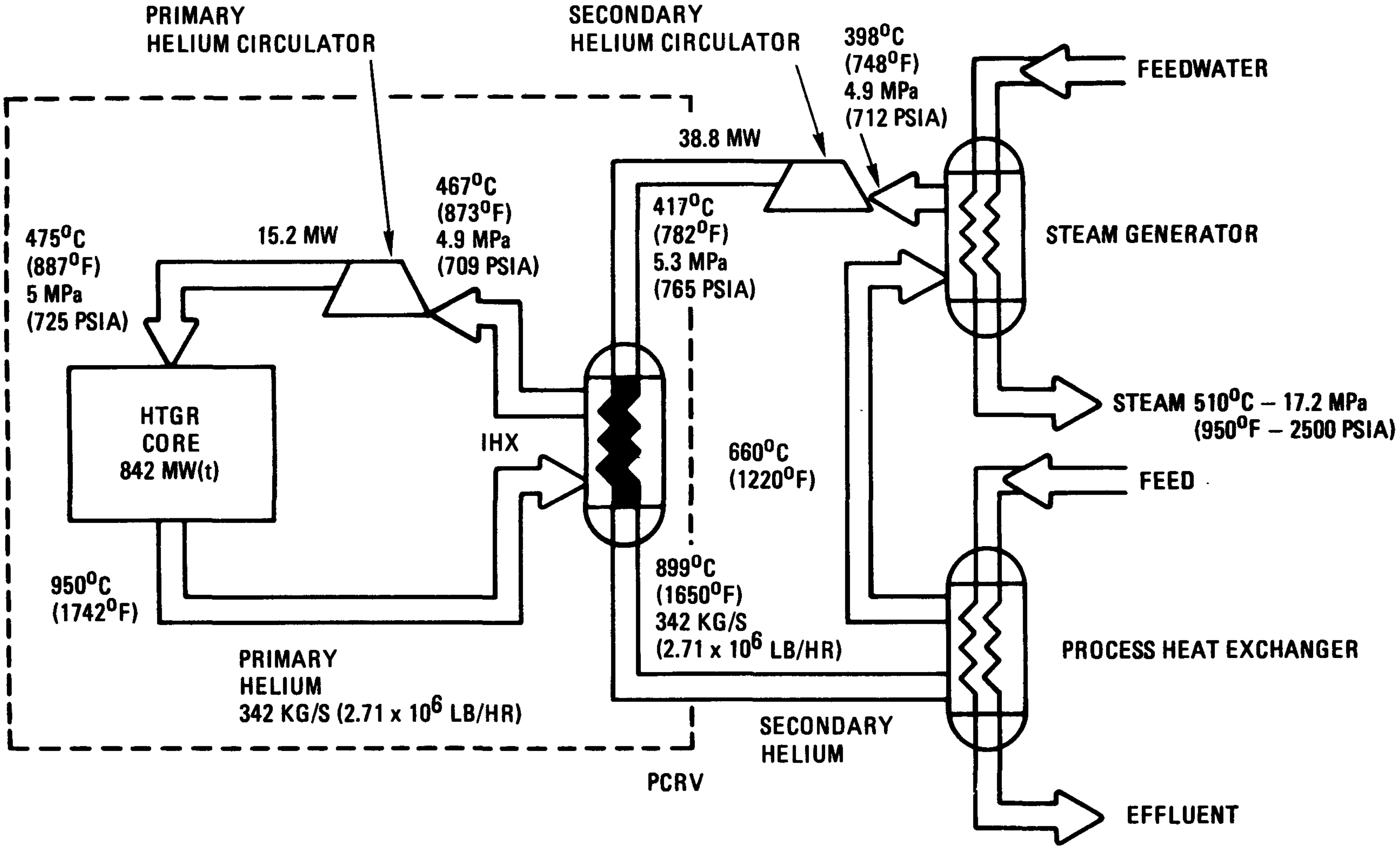


Fig. 1-1. 842-MW(t) VHTR heat balance diagram

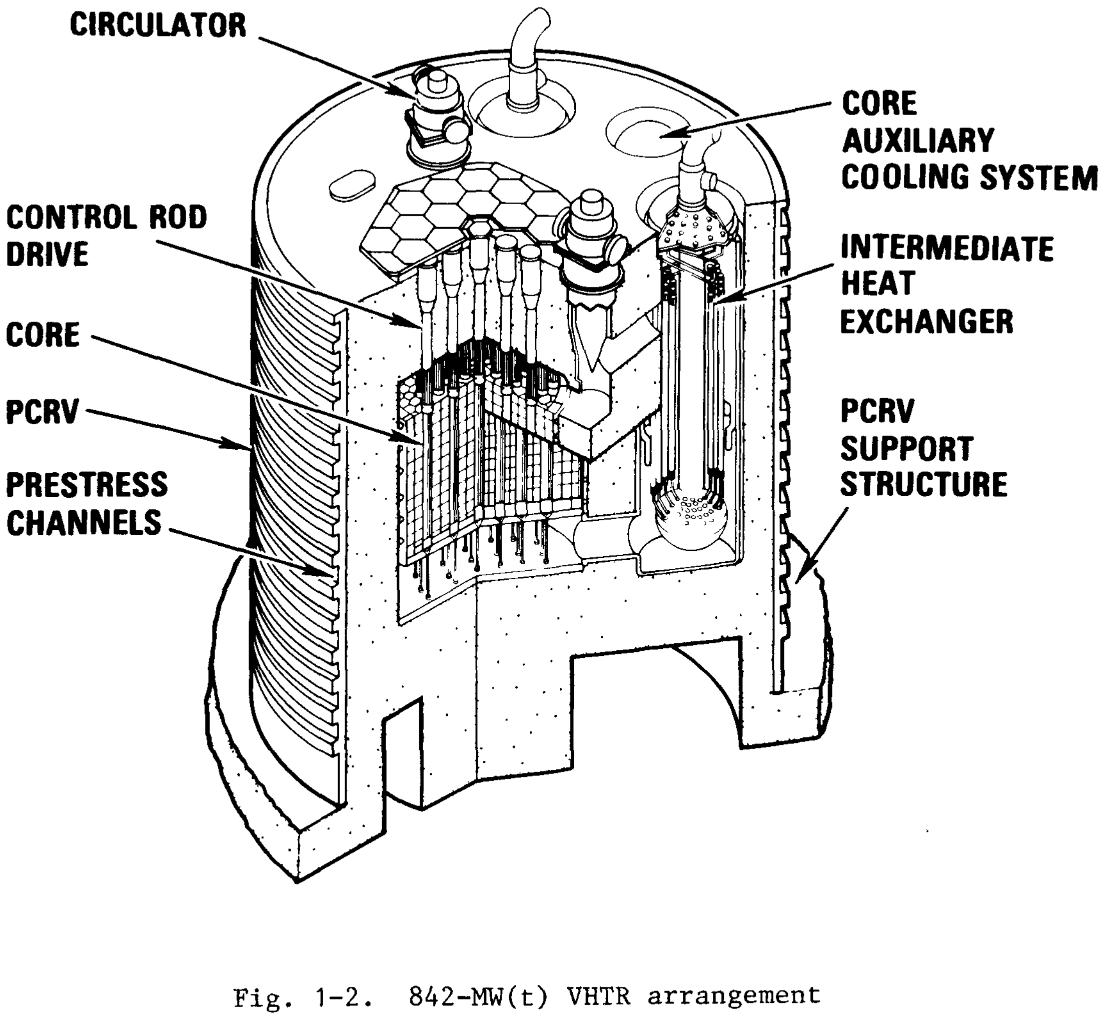


Fig. 1-2. 842-MW(t) VHTR arrangement

TABLE 1-2
PRIMARY AND SECONDARY LOOP SYSTEM PARAMETERS

Location/Description	Temperature [°C (°F)]	Pressure [MPa (psia)]
Primary System Parameters		
Core inlet	475 (887)	4.99 (724)
Core outlet	950 (1742)	4.96 (719)
IHX inlet	946 (1735)	9.95 (718)
IHX outlet	467 (872)	4.90 (710)
Circulator inlet	467 (873)	4.89 (709)
Circulator outlet	476 (888)	5.00 (725)
Core power:	842 MW(t)	
Helium flow rate:	342 kg/s (2.71 x 10^6 lb/hr)	
Circulator power:	15.2 MW(t)	
IHX heat duty:	849.9 MW(t)	
Primary loop heat losses:	6.0 MW(t)	
Secondary System Parameters		
IHX inlet	419 (787)	5.24 (760)
IHX outlet	899 (1650)	5.13 (744)
Reformer inlet	897 (1647)	5.05 (733)
Reformer outlet	660 (1220)	5.03 (730)
Steam generator inlet	659 (1219)	5.02 (728)
Steam generator outlet	398 (748)	4.96 (719)
Circulator inlet	398 (748)	9.95 (718)
Circulator outlet	419 (787)	5.27 (765)
Helium flow rate:	342 kg/s (2.71 x 10^6 lb/hr)	
Reformer heat duty:	420 MW(t)	
Steam generator heat duty:	466 MW(t)	
Circulator power:	38.8 MW(t)	
Secondary loop heat losses:	3.1 MW(t)	

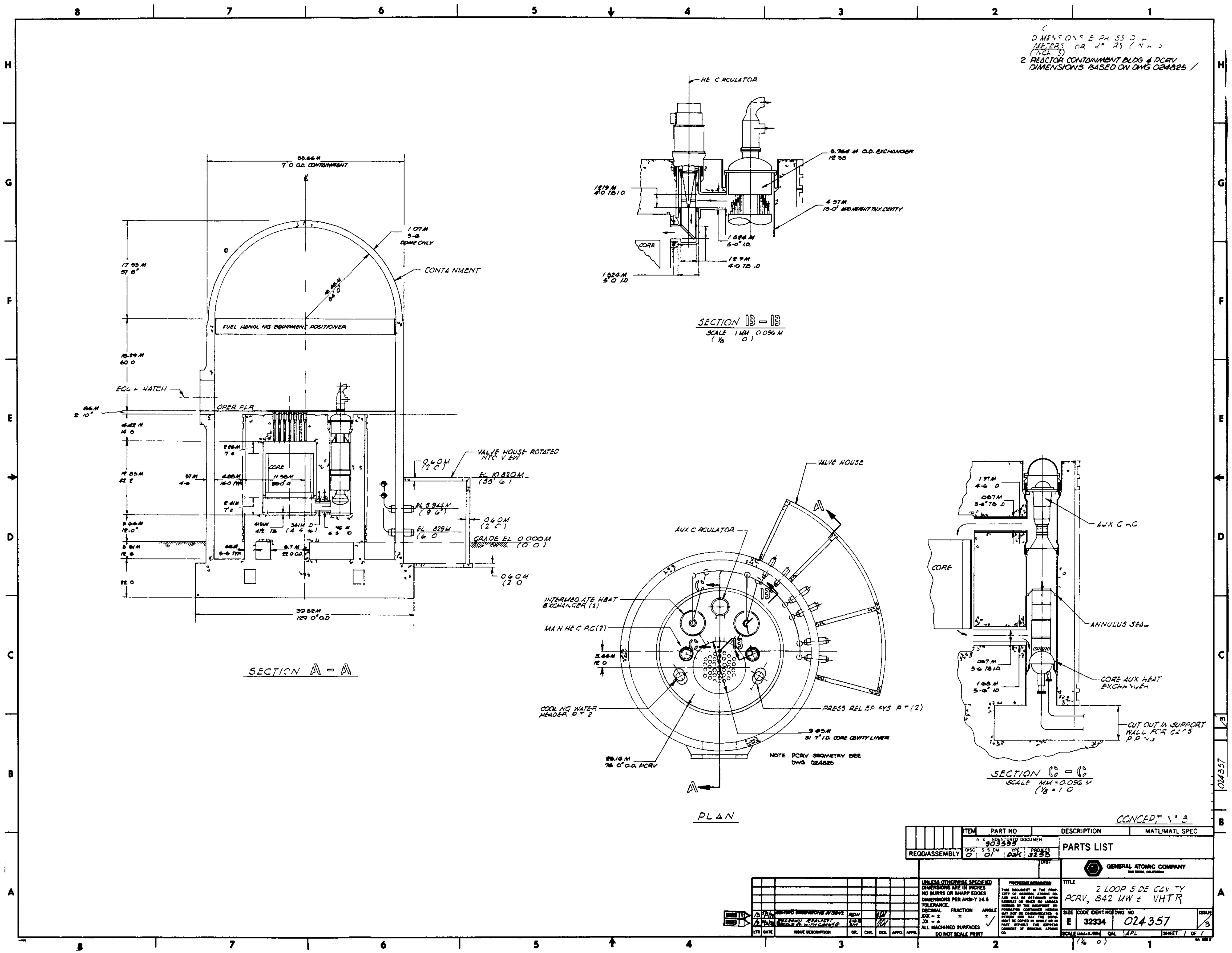


Fig. 1-3. Arrangement of PCRV and reactor containment

for synfuel production. Secondary helium enters the IHX at 5.24 MPa (760 psia)/419°C (787°F) and exits at 899°C (1650°F).

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 pressure gradient that inhibits leakage of the reactor helium into the secondary system should any crack or break in the IHX occur. The secondary helium is maintained at a pressure level near that of the primary helium to minimize long-term pressure loadings on the IHX. The pressure level maintains acceptable pressure loadings on the reformer consistent with the desired process-side pressure level.

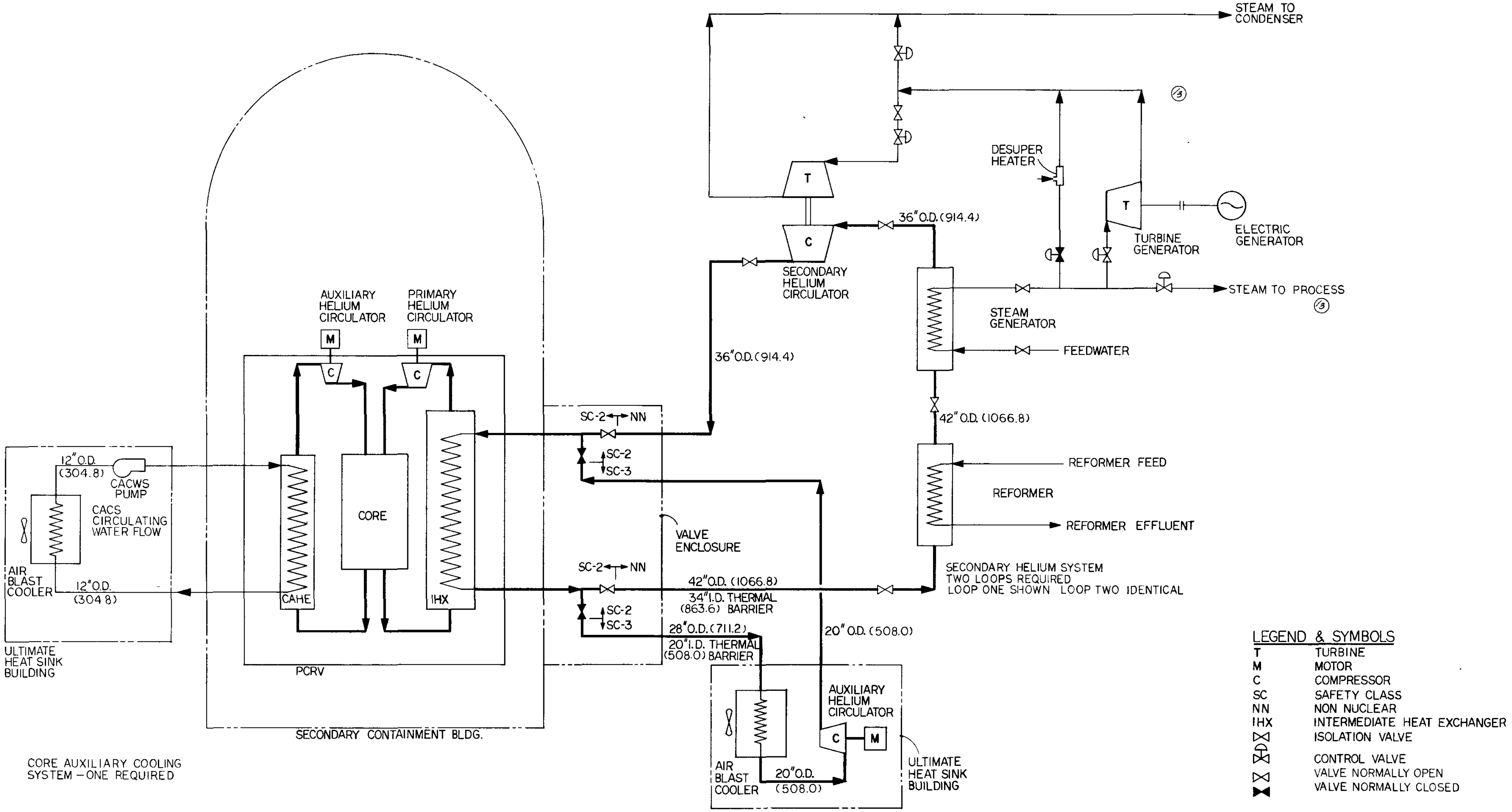
Figure 1-4 shows the secondary coolant system piping arrangement. A separate, complete secondary helium loop is provided for each primary loop. Each secondary helium loop incorporates a steam/methane reformer, a steam generator, a steam-turbine-driven helium circulator located near the steam generator, and related helium piping and valving. Secondary helium is forced through the IHX by the helium circulator, heated, passed to the reformer at high temperature, then 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, a motor-driven helium circulator, and the associated helium piping and valving.

Figure 1-5 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. 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.

NOTES:

1. DIMENSIONS EXPRESSED THUS INCHES (MILLIMETERS) OR AS $\frac{\text{INCHES}}{\text{(MILLIMETERS)}}$



342 MW(T) VHTR SECONDARY HELIUM PIPING DIAGRAM

Fig. 1-4. Secondary coolant system piping schematic

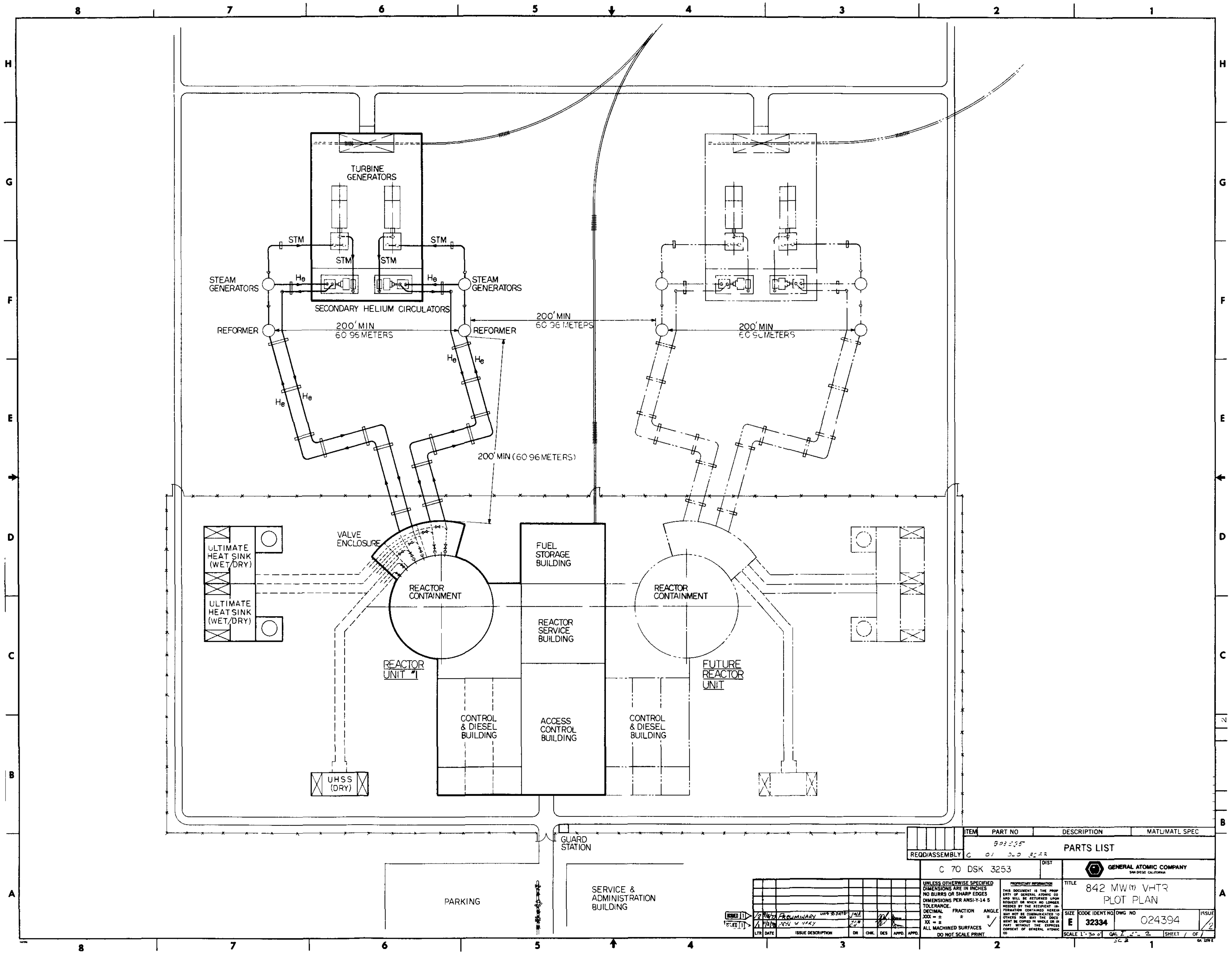


Fig. 1-5. 842-MW(t) VHTR conceptual plot plan

1.3. WORK PERFORMED IN REPORTING PERIOD

Concept design work in FY-79 included further development of the design of the PCRV thermal barrier, PCRV structure, IHXs, reformers, steam generators, and shutdown core cooling systems. Thermal barrier work included preparation of a design and development plan, thermal sizing, and design layouts. Preliminary designs for the reformers and steam generators were completed. Creep buckling in the IHX tubes and return duct was investigated, and the IHX mechanical design was further developed. A preliminary structural design and layout drawings for the PCRV were prepared. Power requirements for the primary and secondary helium circulators during shutdown core cooling were defined.

First generation versions of all reactor plant design and performance subroutines for the parametric design computer program were completed, a simplified process plant model was incorporated, and a series of test runs was performed. Costing subroutines were also substantially completed. Convergence of the design and performance calculations was achieved. It is expected that the program run time, however, will be substantially reduced by future improvements in the iteration logic programming.

The major safety and licensing effort was the preparation of a topical safety report (Ref. 1-2). The report identifies those VHTR features which are particularly important from safety and licensing viewpoints and provides qualitative discussions based on the available level of the plant design. A study of depressurization accidents was also performed, and the safety implications of the use of a helium-cooled core auxiliary heat exchanger (CAHE) were evaluated.

A preliminary Balance of Plant Requirements (BOPR) specification was prepared. Conceptual steam turbine system and plant electrical system designs were completed, estimates of the primary and secondary coolant system helium inventories were prepared, and a draft of a reference plant design report was completed.

A cost estimate of the balance of reactor plant (BORP), which includes all auxiliary systems and structures associated with the reactor and secondary helium system, was prepared. This estimate provides a basis for costing subroutines for the parametric design computer program.

REFERENCES

1-1. "Process Heat Reactor Design and Analysis, Final Report," DOE Report GA-A15137, General Atomic Company, February 1979.

1-2. Deremer, R. K., D. D. Orvis, and J. N. Sharmahd, "Process Heat Reactor Safety Evaluation Report," DOE Report GA-A15523, General Atomic Company, to be published.

2. CONCEPT DESIGN

2.1. STATUS SUMMARY

During FY-79, the conceptual design effort included preparation of a thermal barrier design and development plan, thermal sizing, and design layouts for the thermal barrier; development of preliminary designs for the reformers and steam generators, investigation of creep buckling in the IHX tubes and return duct; further development of the IHX mechanical design; structural design of the PCRV, and definition of shutdown cooling power requirements.

2.2. THERMAL BARRIER

2.2.1. Development Plan

During this reporting period, a design and development plan for the VHTR thermal barriers (Ref. 2-1) was prepared. The document states the activities required for development of the VHTR thermal barrier and the sequence in which these activities must be performed. A summary of the specific objectives of this plan is given below:

1. Provide a history of previous thermal barrier design and development work supportive of the VHTR.

2. Summarize current VHTR design parameters pertinent to thermal barrier design.

3. Review the present VHTR thermal barrier design status and design issue identification.

4. Provide a plan for the remaining activities of thermal barrier development, including a sequence and an explanation of each activity.

In addition to these objectives, the plan provides a discussion of initial concept studies presented in Ref. 2-2.

The overall thermal barrier development involves a multiple-phased approach shown in Fig. 2-1. The phases are described below:

1. <u>Critical Design Issues and Initial Design Studies</u>

   Specific VHTR thermal barrier design activities up to the present time consist of the initial design studies and issues. In addition to the hot duct design concepts discussed in this reference, concepts will be developed for adjoining cavity sidewalls. Studies will also be conducted on attachment locking devices and on nonmetallic insulating components. Currently defined materials are addressed in the planning document.

2. <u>Evaluation of Design Concepts, Critical Material Evaluation, and Initial Development Tests</u>

   This phase involves parallel studies on high-temperature thermal barrier components employing all promising material combinations, namely (1) carbon/carbon composites, (2) dense ceramics, and (3) advanced metallic materials (e.g., cast superalloys). For each material combination, activities include (1) establishing a material property data base, (2) performing engineering feasibility tests, (3) performing detail design studies of such areas as support requirements, duct interfacing components, cost, and replaceability considerations, and (4) conducting support analyses showing structural and thermal performance.

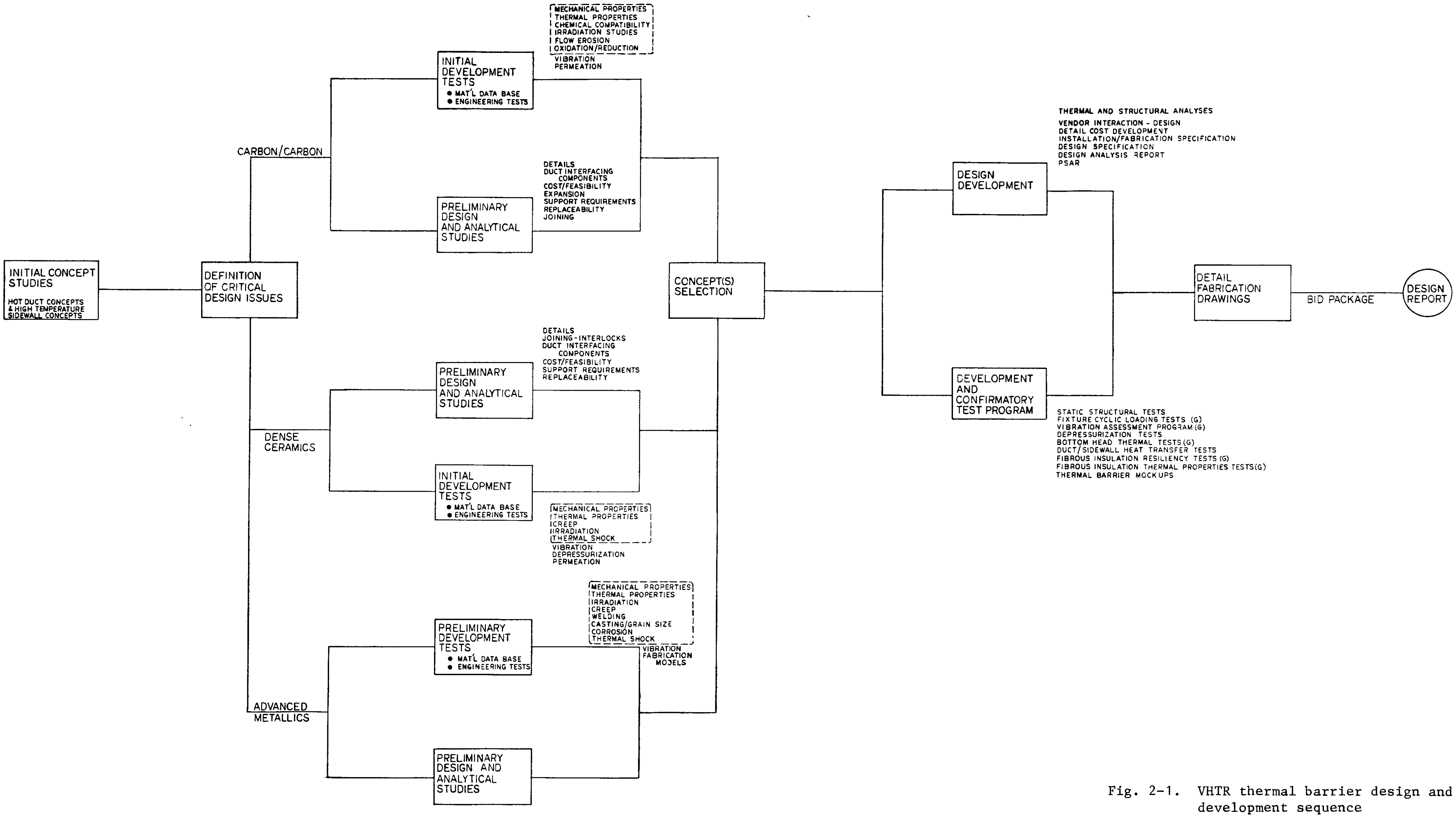


Fig. 2-1. VHTR thermal barrier design and development sequence

3. Selection of Concepts

This phase involves selection of conceptual designs for more detailed development.

4. Preliminary Design Development and Analytical Study

This phase involves detailed development of the selected concepts, including preliminary detail drawings, cost development, vendor interaction, and preparation of preliminary material, procurement, and installation specifications. The task also includes all supporting analyses and preparation of design analysis reports and preliminary safety analysis report (PSAR) inputs.

5. Engineering Test Program

An extensive program of engineering tests will be conducted, and the test results will be used in the design development and analysis activities discussed above. This test program, intended ultimately to confirm the selected concept, will include (1) static and cyclic structural tests, (2) vibration tests, (3) depressurization tests, (4) full-scale heat transfer tests, (5) fibrous insulation tests, and (6) mock-ups to resolve installation problems.

6. Final Design Phase

This phase includes preparation of the detail installation and fabrication drawing package and the design report.

2.2.2. Design Concepts

2.2.2.1. Thermal Barrier Sizing and General Arrangement. The thermal barrier has been separated into 18 zones based on service temperature and liner geometry considerations, as shown in Fig. 2-2. The thermal barrier has also been divided into four classes (A, B1, B2, C) according to hot-surface temperature. The maximum temperature limits for these classes of thermal barrier are given in Table 2-1 for normal, upset, emergency, and faulted conditions. Materials employed in each class are given in Fig. 2-2.

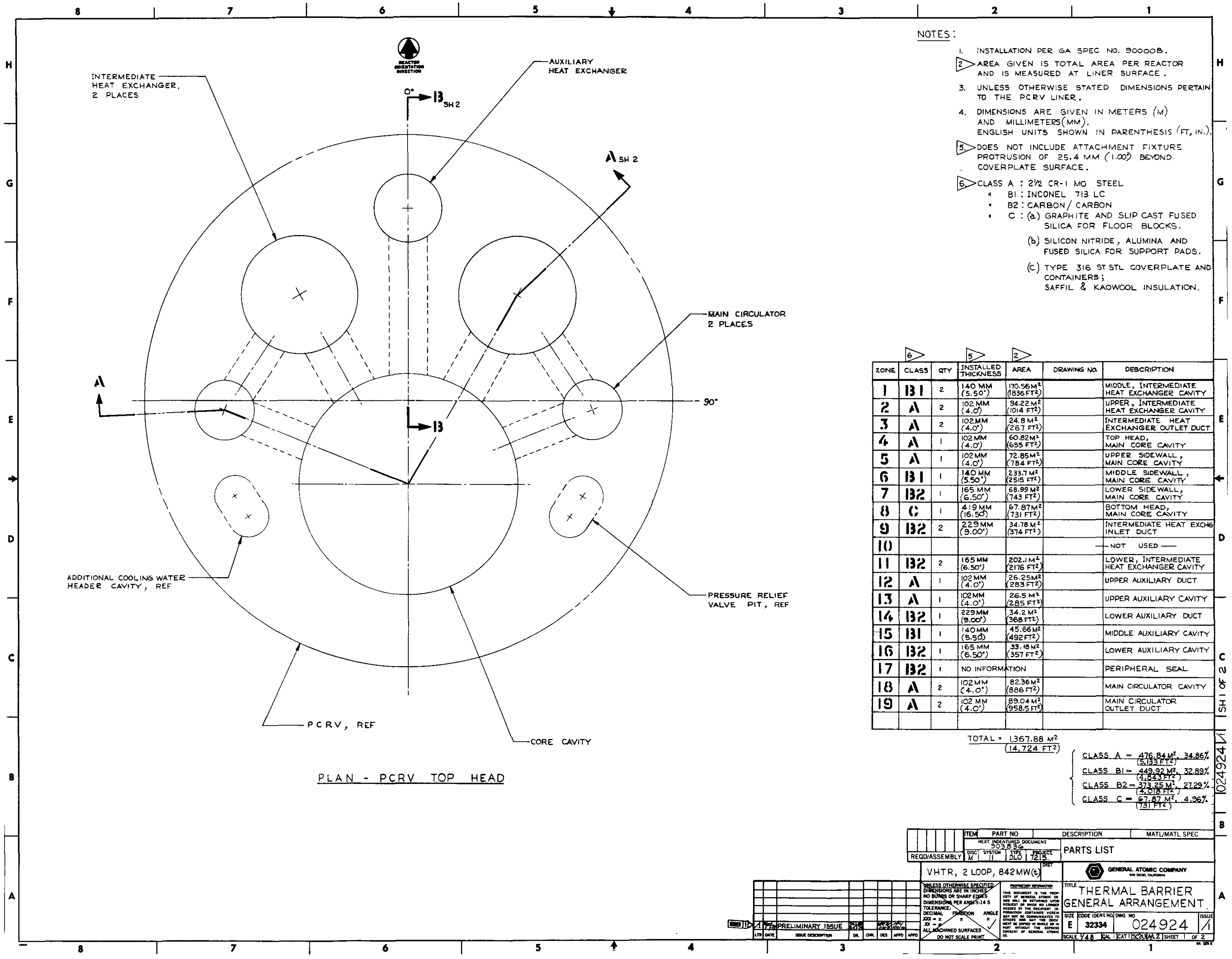
The preliminary sizing calculations were performed in the following sequence:

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 based on 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 additional design factors. These values are reflected in Fig. 2-2.

In these calculations, 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. Cooling tube pitches for each zone are given in Table 2-2.



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 METERS (M) AND MILLIMETERS (MM). ENGLISH UNITS SHOWN IN PARENTHESIS (FT, IN.).
5. DOES NOT INCLUDE ATTACHMENT FIXTURE PROTRUSION OF 25.4 MM (1.00") BEYOND COVERPLATE SURFACE.
6. CLASS A : 2½ CR-1 MO STEEL
   - " B1 : INCONEL 713 LC
   - " B2 : CARBON / CARBON
   - " C : (a) GRAPHITE AND SLIP CAST FUSED SILICA FOR FLOOR BLOCKS.
     - (b) SILICON NITRIDE, ALUMINA AND FUSED SILICA FOR SUPPORT PADS.
     - (c) TYPE 316 ST STL COVERPLATE AND CONTAINERS; SAFFIL & KAOWOOL INSULATION.

ZONE	CLASS 6	QTY	INSTALLED THICKNESS 5	AREA 2	DRAWING NO.	DESCRIPTION
1	B1	2	140 MM (5.50")	170.56 M² (1836 FT²)		MIDDLE, INTERMEDIATE HEAT EXCHANGER CAVITY
2	A	2	102 MM (4.0")	94.22 M² (1014 FT²)		UPPER, INTERMEDIATE HEAT EXCHANGER CAVITY
3	A	2	102 MM (4.0")	24.8 M² (267 FT²)		INTERMEDIATE HEAT EXCHANGER OUTLET DUCT
4	A	1	102 MM (4.0")	60.82 M² (655 FT²)		TOP HEAD, MAIN CORE CAVITY
5	A	1	102 MM (4.0")	72.85 M² (784 FT²)		UPPER SIDEWALL, MAIN CORE CAVITY
6	B1	1	140 MM (5.50")	233.7 M² (2515 FT²)		MIDDLE SIDEWALL, MAIN CORE CAVITY
7	B2	1	165 MM (6.50")	68.99 M² (743 FT²)		LOWER SIDEWALL, MAIN CORE CAVITY
8	C	1	419 MM (16.50")	67.87 M² (731 FT²)		BOTTOM HEAD, MAIN CORE CAVITY
9	B2	2	229 MM (9.00")	34.78 M² (374 FT²)		INTERMEDIATE HEAT EXCHG INLET DUCT
10						NOT USED
11	B2	2	165 MM (6.50")	202.1 M² (2176 FT²)		LOWER, INTERMEDIATE HEAT EXCHANGER CAVITY
12	A	1	102 MM (4.0")	26.25 M² (283 FT²)		UPPER AUXILIARY DUCT
13	A	1	102 MM (4.0")	26.5 M² (285 FT²)		UPPER AUXILIARY CAVITY
14	B2	1	229 MM (9.00")	34.2 M² (368 FT²)		LOWER AUXILIARY DUCT
15	B1	1	140 MM (5.50")	45.66 M² (492 FT²)		MIDDLE AUXILIARY CAVITY
16	B2	1	165 MM (6.50")	33.18 M² (357 FT²)		LOWER AUXILIARY CAVITY
17	B2	1	NO INFORMATION			PERIPHERAL SEAL
18	A	2	102 MM (4.0")	82.36 M² (886 FT²)		MAIN CIRCULATOR CAVITY
19	A	2	102 MM (4.0")	89.04 M² (958.5 FT²)		MAIN CIRCULATOR OUTLET DUCT

TOTAL = 1,367.88 M² (14,724 FT²)

CLASS A = 476.84 M², 34.86% (5,133 FT²)
CLASS B1 = 449.92 M², 32.89% (4,843 FT²)
CLASS B2 = 373.25 M², 27.29% (4,018 FT²)
CLASS C = 67.87 M², 4.96% (731 FT²)

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SIZE E CODE IDENT NO 32334 DWG NO 024924 ISSUE 1
SCALE 1/48 SHEET 1 OF 2

Fig. 2-2. Thermal barrier general arrangement (sheet 1 of 2)

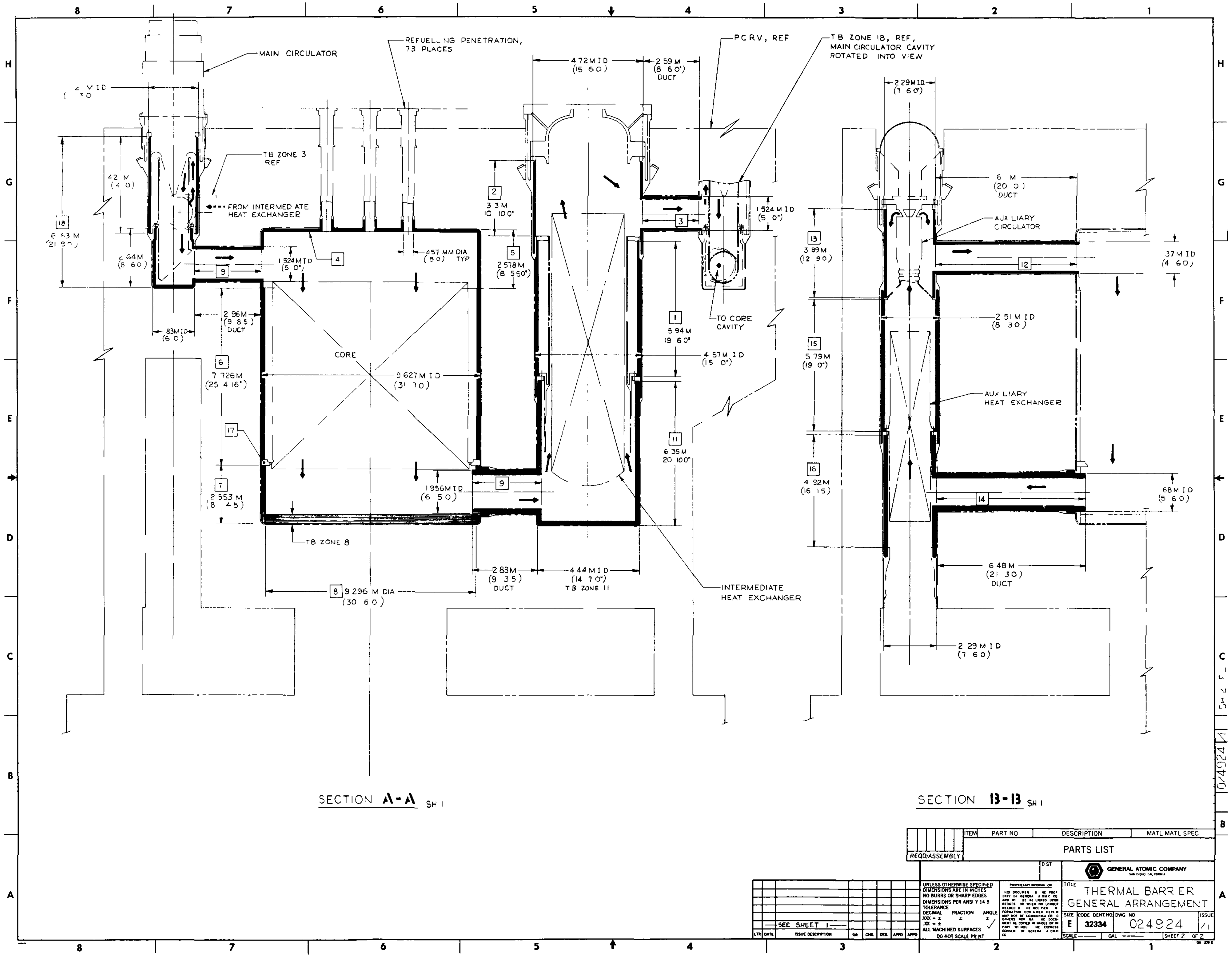


Fig. 2-2. Thermal barrier general arrangement (sheet 2 of 2)

TABLE 2-1
THERMAL BARRIER TEMPERATURE LIMITATIONS

Class	Maximum Temperature Limitation [°C (°F)]		
	Normal and Upset Conditions	Emergency Conditions (5 hr)	Faulted Conditions (1 hr)
A	482 (900)	566 (1050)	649 (1200)
B1	871 (1600)	982 (1800)	1093 (2000)
B2	982 (1800)	1093 (2000)	1204 (2200)
C	1093 (2000)	1371 (2500)	1649 (3000)

TABLE 2-2
REQUIRED THERMAL BARRIER LINER COOLING TUBE PITCHES(a)

Zone	Class	Cooling Tube Pitch [mm (in.)]
1	B1	152 (6)
2	A	152 (6)
3	A	152 (6)
4	A	152 (6)
5	A	152 (6)
6	B1	152 (6)
7	B2	102 (4)
8	C	102 (4)
9	B2	102 (4)
11	B2	102 (4)
12	A	152 (6)
13	A	152 (6)
14	B2	102 (4)
15	B1	152 (6)
16	B2	102 (4)
18	A	102 (4)
19	A	102 (4)

(a) Requirements for the peripheral seal, Zone 17, have not yet been identified.

2.2.2.2. Core Exit Plenum Thermal Barrier Conceptual Design Development. Two zones comprise the thermal barrier in the core exit plenum (CEP): the sidewall (Zone 7) and the bottom head (Zone 8). The sidewall thermal barrier is intended to be generally similar to the hot duct design utilizing coverplates. The differences are the coverplate curvature and accommodations for duct openings (Fig. 2-3).

The function of the bottom head thermal barrier is not only to protect the PCRV liner but also to provide a stabilized insulated structural base for the graphite core support posts. As shown in Fig. 2-4, the configurations consist of layered polygonal ceramic blocks with insulation blankets through which a series of ceramic support pads penetrate. The support pads are sized to accommodate mechanical loads transmitted through the support posts (including seismic conditions) as well as to act as insulators. The thermal loads dictated the thicknesses of the pads. At this time, GA recommends employing high-purity (99.5%) alumina for all but the bottom pad, which is the final insulator. For this, a high-density, fine grain silica is recommended.

The polygonal blocks are exposed to the direct gas stream and hence to the highest core outlet temperatures. The main problem is to dissipate the gas streaks, thereby minimizing the thermal shock imparted to the substrate layers. Also, the backface temperature of the top block(s) must be low enough to prevent devitrification of the silica. Figure 2-4 shows three basic concepts with three variations.

The Class C thermal barrier thickness was preliminarily set, per Ref. 2-1, at 419 mm (16.50 in.), based on one-dimensional heat flow calculations. Additional one-dimensional heat flow calculations were then performed to investigate the effectiveness of pyrolytic graphite in reducing the temperatures of underlying silica insulating blocks so that potential devitrification of these silica blocks might be avoided.

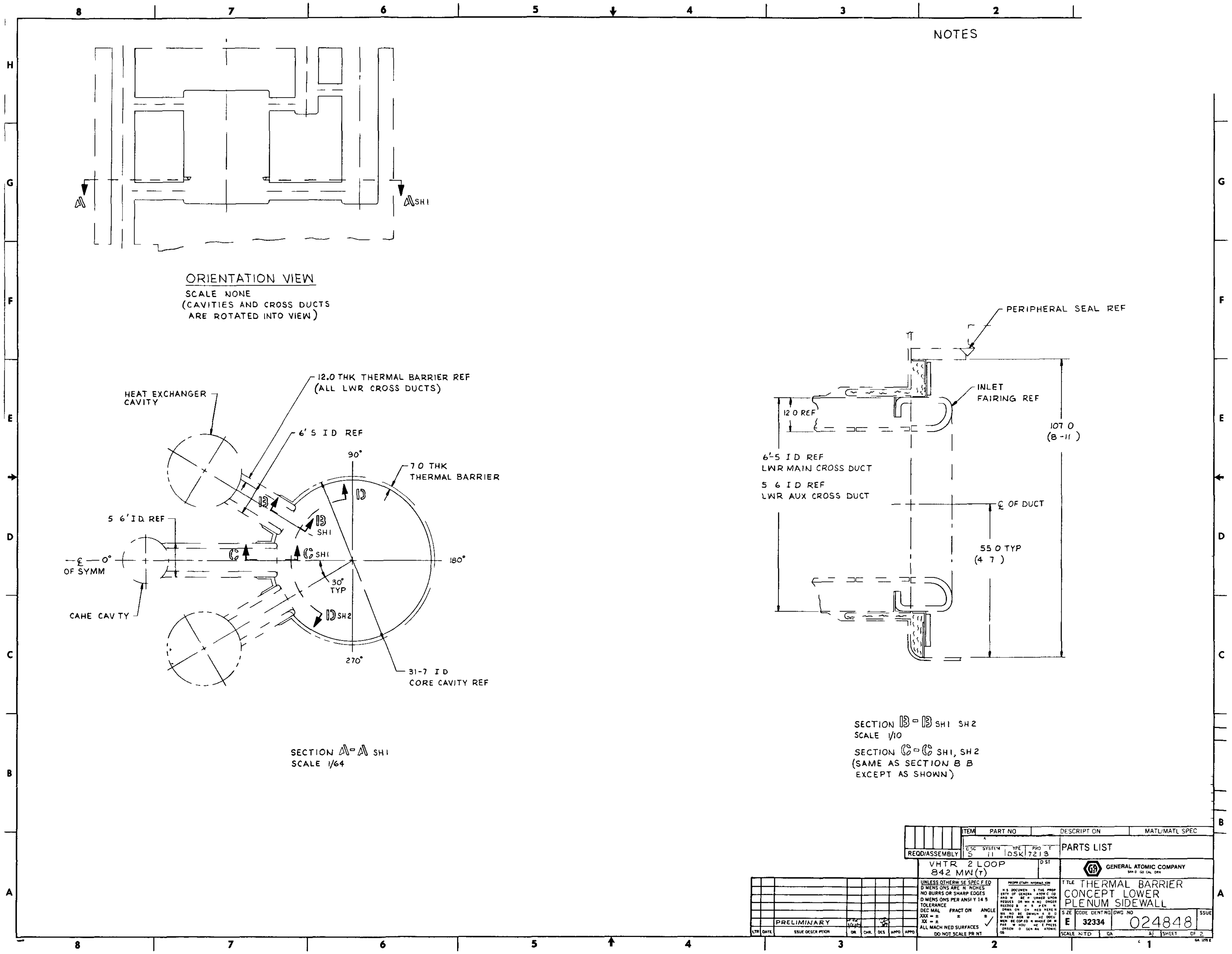


Fig. 2-3. Thermal barrier core exit plenum sidewall (sheet 1 of 2)

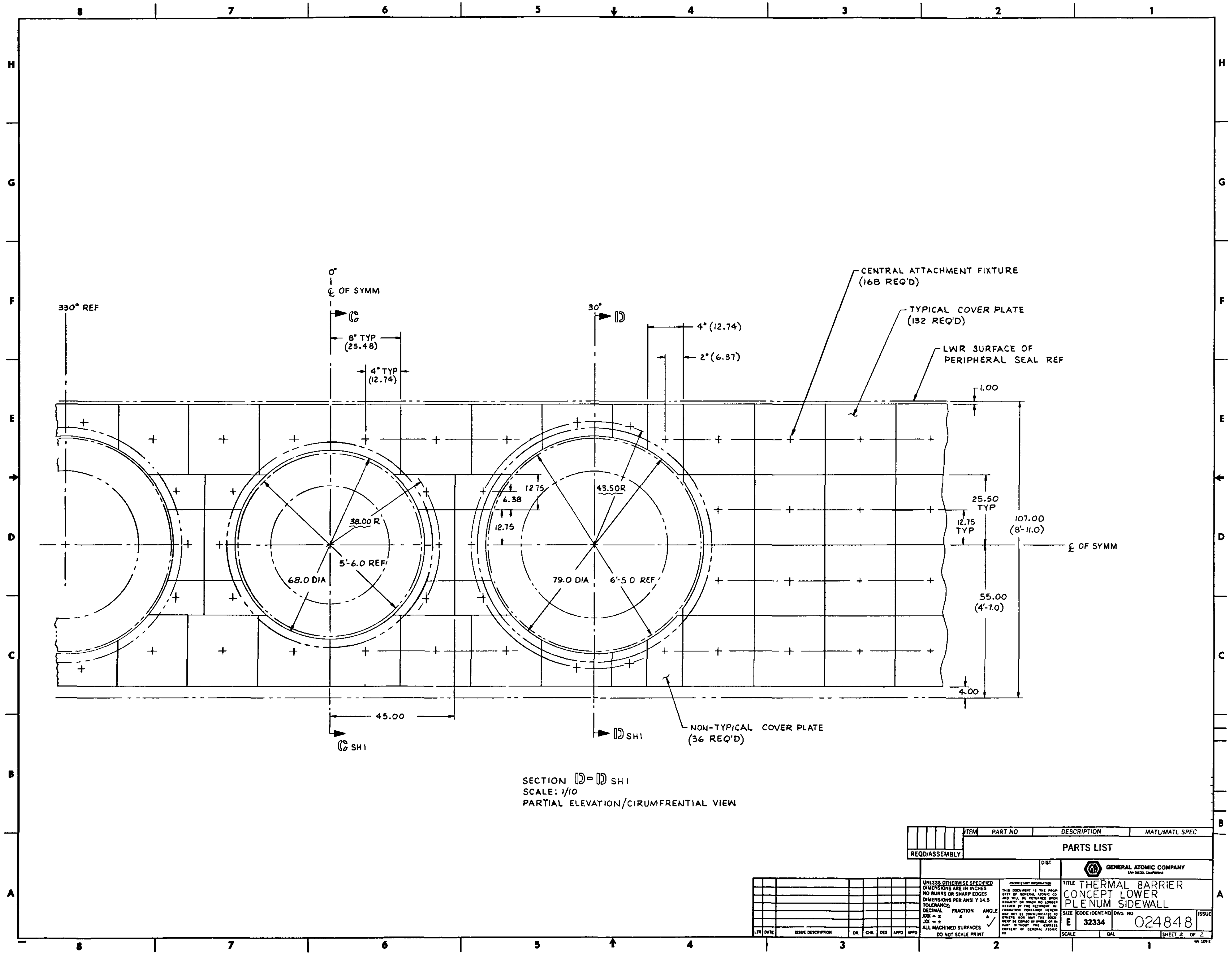


Fig. 2-3. Thermal barrier core exit plenum sidewall (sheet 2 of 2)

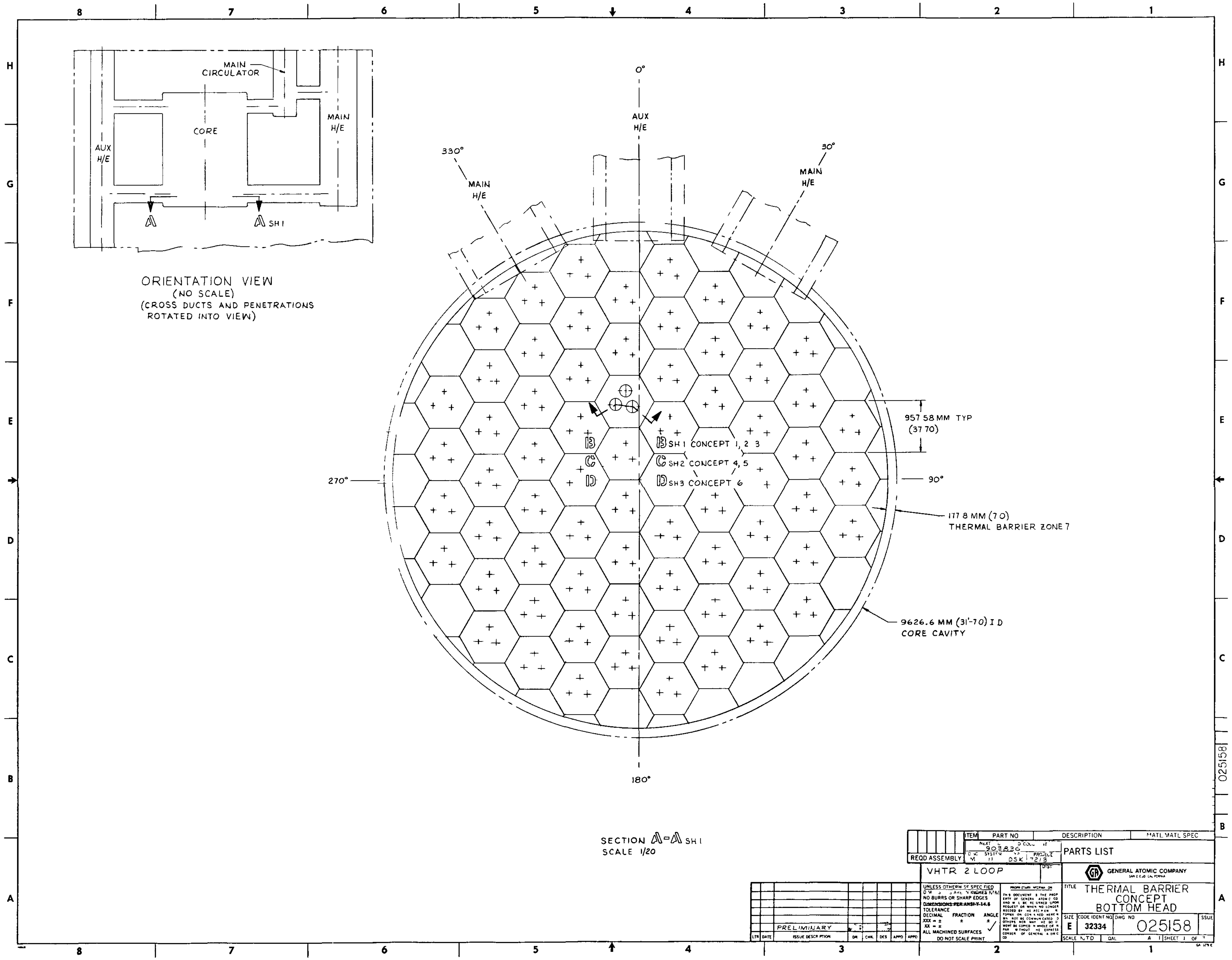


Fig. 2-4. Thermal barrier bottom head (sheet 1 of 3)

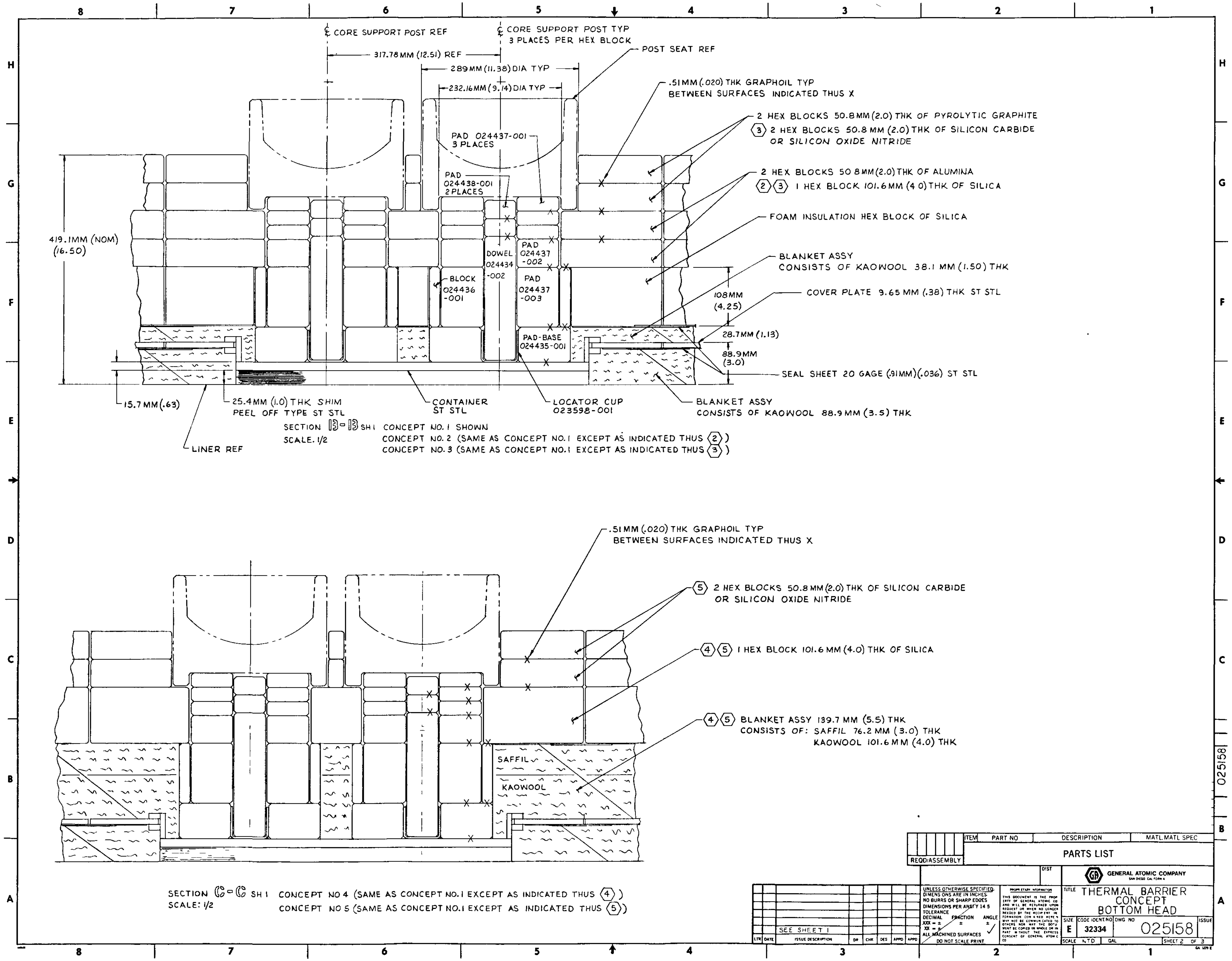


Fig. 2-4. Thermal barrier bottom head (sheet 2 of 3)

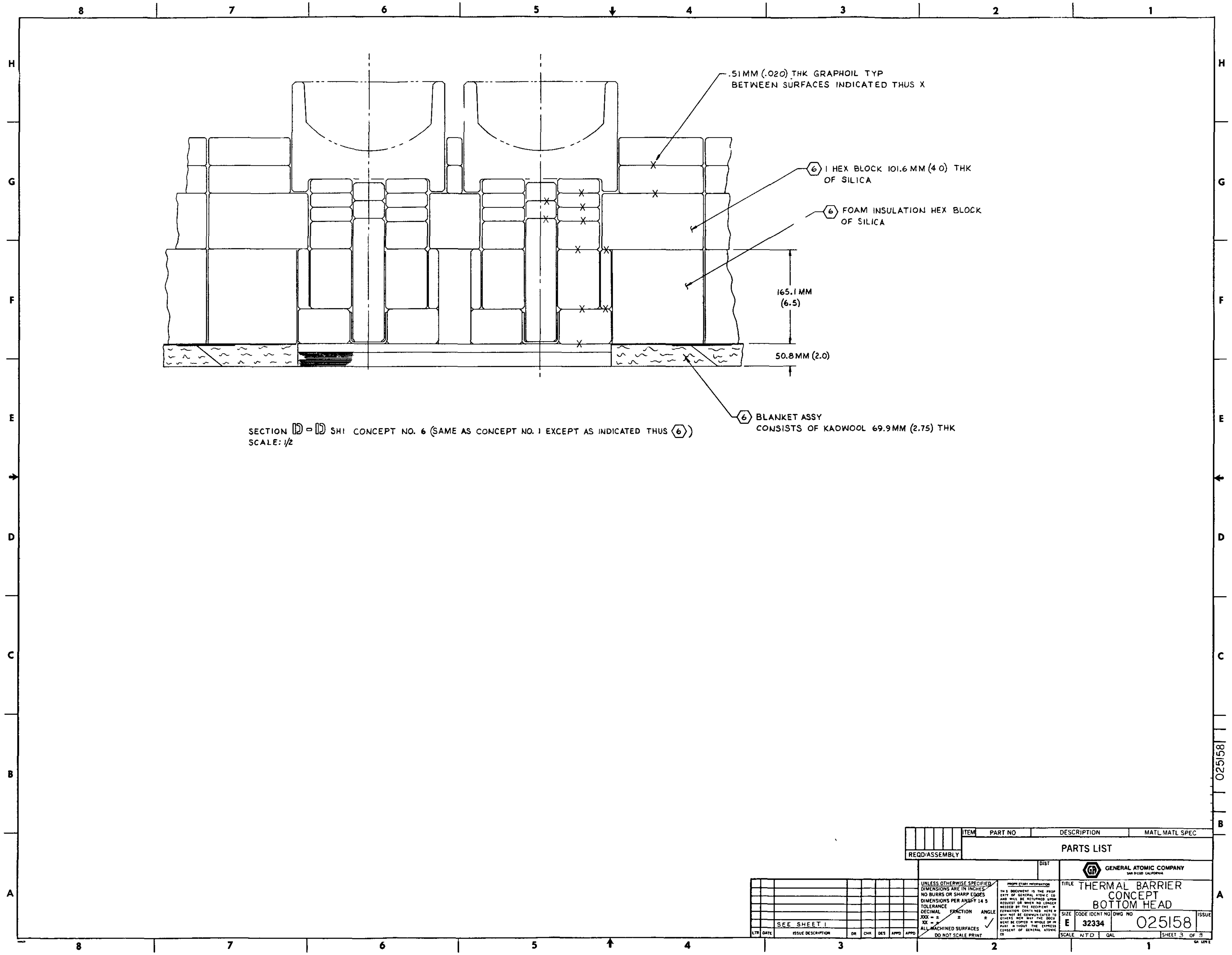


Fig. 2-4. Thermal barrier bottom head (sheet 3 of 3)

The thermal conductivity of pyrolytic graphite is extremely anisotropic, the material being highly conductive in the A-B plane and a good insulator in the C-direction. At 870°C (1600°F), the thermal conductivity of the A-B plane is about 2.16 $W/cm^2 \cdot {}^\circ C/cm$ (125 $Btu/hr\text{-}ft^2\text{-}{}^\circ F/ft$) as compared with 0.014 $W/cm^2 \cdot {}^\circ C/cm$ (0.8 $Btu/hr\text{-}ft^2\text{-}{}^\circ F/ft$) in the C-direction. Therefore, this material is useful for dissipating hot streaks, as well as reducing temperatures in underlying insulating components.

Calculation showed that a 102-mm (4-in.) thickness of pyrolytic graphite reduced silica temperatures to the acceptable 816° to 870°C (1500° to 1600°F) range, depending on the specific configuration used, where devitrification would not be expected to present a problem.

2.2.2.3. Thermal Barrier Hot Duct Conceptual Design Development. This subject is discussed in the Appendix, which is published separately.

2.3. REFERENCE REFORMER DESIGN

2.3.1. 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 (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 illustrated in Fig. 2-5 utilizes a heat exchanger that has tubes large enough to contain the catalyst material in stacked particle bed form. The feedstock is introduced

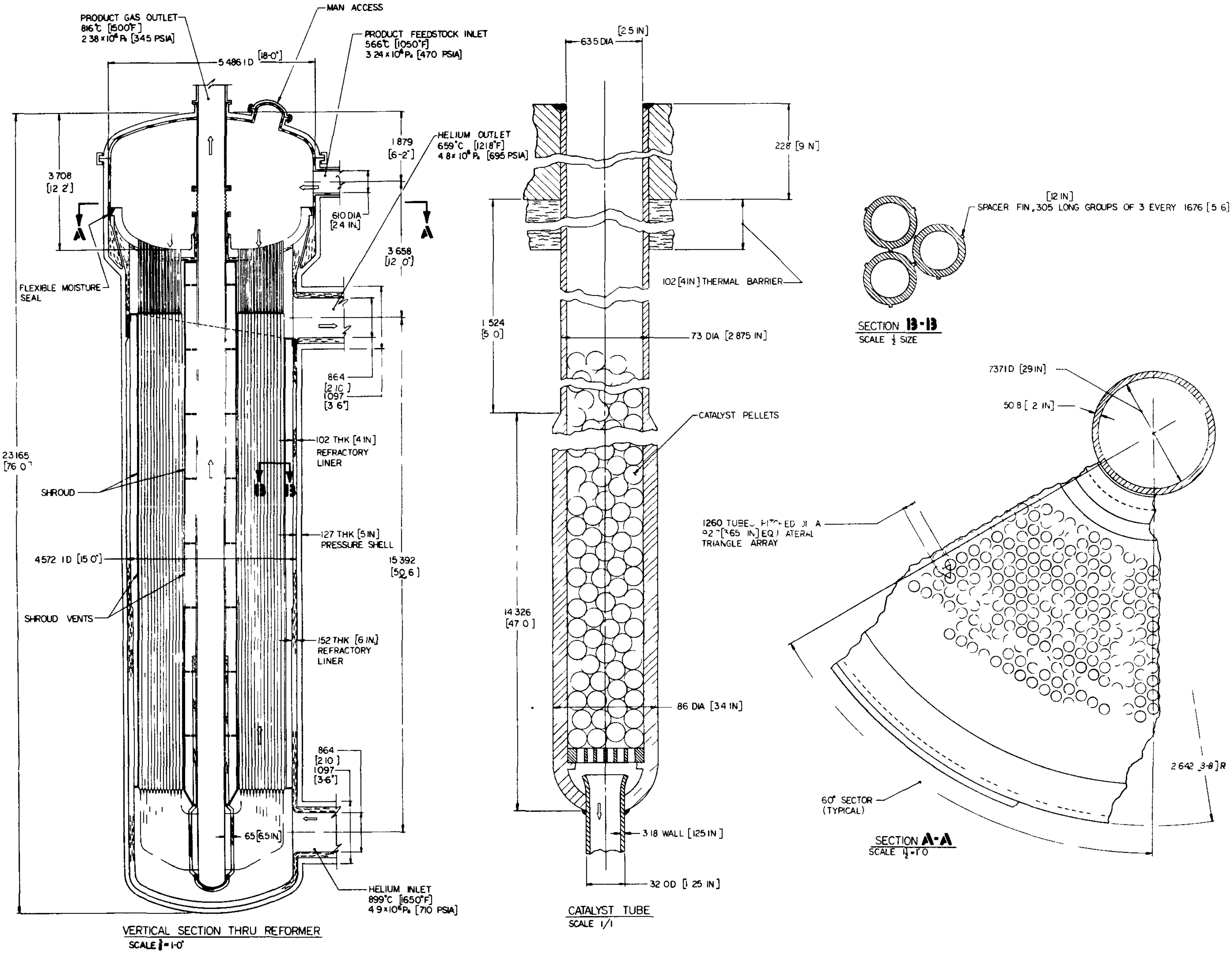


Fig. 2-5. 842-MW(t) VHTR steam-methane reformer

on the tube side of the heat exchanger and flows over the catalyst particles while being heated by the tube walls. The conversion reaction 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 in order 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 3.10 MPa (450 psia) and 3.45 MPa (500 psia).

Nominal helium pressure losses in the shell side must be minimized in order to maintain reasonable circulator power requirements. The allowable total differential pressure (shell side) was limited to less than 68.9 kPa (10 psi).

The reformers are designed to be self-supporting, withstand the normal and emergency pressure 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.

2.3.2. General Layout

The principal design parameters of the reformer are summarized in Table 2-3. As shown in Fig. 2-5, the design has the following features.

The tubes containing the catalyst are hung from a dished tubesheet 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 are connected to the CRT at the bottom of the reformer by means of 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 tubesheet, 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 up around the 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. 2-5. The tubesheet is maintained at a temperature near that of the incoming feed gas by virtue of the surface insulation below the tubesheet and the large "cooled" surface area above.

The vessel, as shown in Fig. 2-5, requires only about 102 mm (4 in.) of a refractory liner to maintain the maximum shell temperature of less than 644 K (700°F). This permits carbon steel to be utilized for the reformer vessel wall.

TABLE 2-3
REFORMER DESIGN DATA
(Flow Rates Total for 2 Units)

Helium flow rate	342 kg/s (2.71 x 10^6 lb/hr)
Helium inlet pressure	5.05 MPa (733 psi)
Helium inlet temperature	897°C (1647°F)
Helium discharge pressure	5.03 MPa (730 psi)
Helium discharge temperature	660°C (1220°F)
Process gas flow rate	192.8 kg/s (1.53 x 10^6 lb/hr)
Process gas inlet pressure	2.38 MPa (345 psi)
Process gas inlet temperature	566°C (1050°F)
Process gas discharge pressure	2.21 MPa (320 psi)
Process gas discharge temperature	816°C (1500°F)
Number of units	2
Tubes per unit	1260
Tube pitch	92.7 mm (3.65 in.)
Pattern	Triangular
Tube i.d.	63.5 mm (2.5 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)	14.329 m (47.0 ft)
Tube total surface area (outer)	4816.7 m^2 (51,847 ft^2)
Catalyst o.d.	15.9 mm (5/8 in.)
Catalyst length	15.9 mm (5/8 in.)
Shell i.d.	4.572 m (15 ft)
Weight	889,362 kg/unit (1,960,687 lb/unit)
Tubes (HK-40)	403,153 kg/unit (888,791 lb/unit)
Return pipe, Inconel 617	19,861 kg/unit (43,785 lb/unit)
Pigtails, Inconel 617	6,363 kg/unit (14,027 lb/unit)
Miscellaneous, Inconel 617	1,692 kg/unit (3,730 lb/unit)
Miscellaneous, SS	3,384 kg/unit (7,460 lb/unit)
Tubesheets, 304 SS	39,712 kg/unit (89,550 lb/unit)
Pressure vessel, carbon steel	415,197 kg/unit (915,344 lb/unit)

Process feedstock is introduced through the inlet duct which penetrates the side of the pressure vessel above the tubesheet. 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 (5/8-in.) o.d., a 6.35-mm (1/4-in.) i.d., and a 15.9-mm (5/8-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 31.8-mm (1.25-in.) o.d. pigtails which are welded to the tube and the CRT. The gas then passes up the CRT and is discharged.

2.3.3. Tube Support Structure

One of the requirements of the reformer design is that the tubes have an opening at the top large enough to extract and replenish 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 tubesheet in a typical shell-tube heat exchanger fashion.

Loading requirements on the tubesheet 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 tubesheet, tubes, catalyst, and CRT. The tubesheet must, of course, 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 tubesheet design shown in Fig. 2-5 is an approach to a perforated toro-spherical 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 tubesheet material is 316 stainless steel, which during emergency operations for short time periods can withstand tensile stresses to 124.0 MPa (18,000 psi) at 839 K (1050°F). This allows a tubesheet thickness of 229 mm (9 in.) to be used with a ligament efficiency (P-D/P) of 0.21. The ligament around the center return pipe hole, however, must be reinforced proportionate to the hole itself; hence, a tubeless area is present.

The tubesheet 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 tubesheet and the cavity liner, which amounts to about 25.4 mm (1 in.) diametrally.

2.3.4. Catalyst Tube Structure

The catalyst tubes are welded to the top surface of the tubesheet. They hang down into the reformer cavity as a tube bundle, separated by 6.35-mm (1/4-in.) spacers and held together by peripheral restraints. The top 1.83 to 2.13 m (6 to 7 ft) of each tube has a reduced outer diameter [85.7 reduced to 73 mm (3-3/8 reduced to 2-7/8 in.)] in order to open the shell side flow area for cross flow to facilitate discharge of the helium. In addition, the reduced diameter serves to increase the ligament efficiency in the tubesheet, thereby reducing its required thickness. The tube thickness reduction is possible because of the lower temperatures prevalent in the upper tube region.

Centrifugally cast tubes of HK-40 with an internal diameter of 63.5 mm (2.5 in.) are used. A small grate is located in the bottom to hold the catalyst bed. A 31.8-mm (1-1/4-in.) o.d. pigtail of Incoloy 617 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 adequate flexibility to accommodate the differential thermal expansion between the CRT and the catalyst tubes. This expansion difference will require the Inconel 617 pigtails, which operate at an average temperature of 1130 K (1574°F), to be at least 2.9 m (9-1/2 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 40.6 mm (1.6 in.). The bottom 7.47 m (24-1/2 ft) 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 1089 K (1500°F). The CRT is mounted on the tubesheet above the penetration by means of 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.

2.4. REFERENCE STEAM GENERATOR DESIGN

The steam generator for the 842-MW(t) VHTR is described in Table 2-4. One steam generator (Fig. 2-6) is included in each of the secondary helium loops. Each steam generator receives hot helium from the helium outlet duct of the reformer for that loop. The helium is passed over two closely

TABLE 2-4
842-MW(t) VHTR STEAM GENERATOR DESCRIPTION
(Values per Steam Generator)

No. units per plant	2
Overall height	13.18 m (43 ft 3 in.)
Overall diameter	2.97 m (9 ft 9 in.)
Helium inlet temp.	659°C (1219°F)
Helium inlet pressure	5.02 MPa (728 psi)
Helium discharge temp.	397.8°C (748 °F)
Helium flow rate	174.1 kg/s (1.382 x 10^6 lb/hr)
Feedwater inlet temp.	292.8°C (559°F)
Feedwater inlet pressure	21.1 MPa (3062 psi)
Steam discharge temp.	510°C (950°F)
Steam discharge pressure	17.24 MPa (2500 psi)
Steam flow rate	116 kg/s (0.920 x 10^6 lb/hr)
Number of tubes	222
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	61.87 m (203 ft)
EES-1 bundle length	3.23 m (10.6 ft)
EES-1 tube material	2-1/4 Cr-1 Mo (SA 213, T-22)
EES-1 surface area	822.75 m^2 (8856 ft^2)
EES-1 shell side ΔP	24.8 kPa (3.6 psi)
EES-1 tube side ΔP	2.22 MPa (322 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	7.96 m (26.1 ft)
SH-2 bundle length	0.40 m (1.3 ft)
SH-2 tube material	Incoloy 800H (SB 163, Gr-2)
SH-2 surface area	140.93 m^2 (1517 ft^2)
SH-2 shell side ΔP	14.5 kPa (2.1 psi)
SH-2 tube side ΔP	186.2 kPa (27 psi)

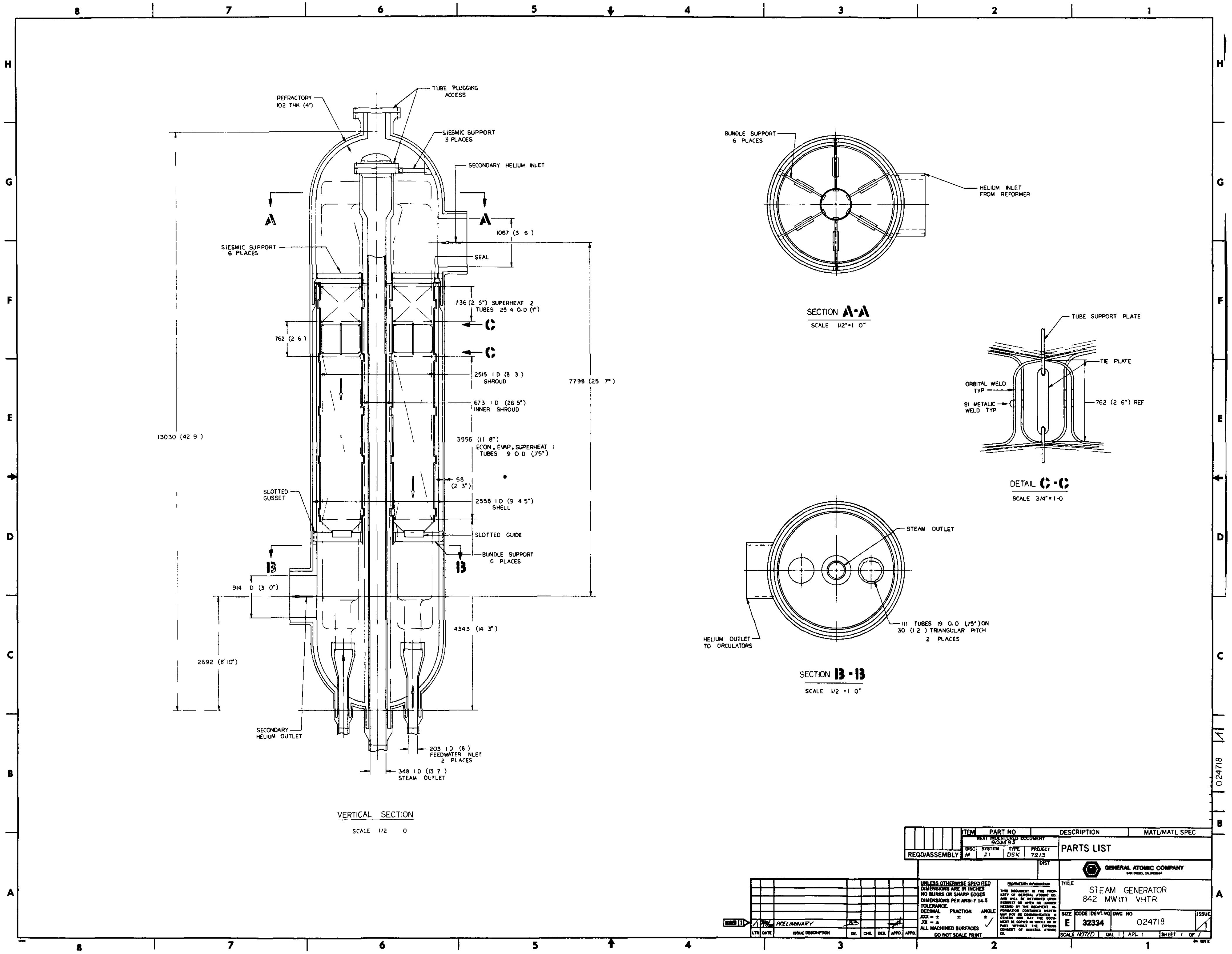


Fig. 2-6. 842-MW(t) VHTR steam generator

stacked banks of helically wound tubes so that a cross-counterflow heat exchanger is formed. The hot helium is introduced at the top and the feedwater at the bottom, resulting in 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. ducts. The ducts 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 to the starting point of each of the 222 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 (1/4 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 approximately 38 mm (1-1/2 in.) of differential expansion. These tubes are all routed in a way that results in sufficient horizontal run [102 mm (4 in.) at the cold end and 381 mm (15 in.) at the hot end], when combined with the axial run, to provide the required flexibility.

The tube bundles are composed of the EES-1 (economizer, evaporator, superheater-1) bundle and the SH-2 (superheater-2) bundle. The EES-1 bundle is the lower of the two and is composed of 222 tubes of 2-1/4 Cr-1 Mo (SA 213, T-22) steel with a 2.29-mm (0.09-in.) wall thickness. They are helically wound with a 33.02-mm (1.3-in.) radial and longitudinal pitch and are 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 0.978 m (38-1/2 in.) wide. The inner 393.7 mm (15-1/2 in.) of every other plate have 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 222 Incoloy 800H (SB 163, Gr-2) tubes with a 25.4-mm (1.0-in) o.d. and a 2.8-mm (0.11-in.) wall pitched at 38.1 mm (1-1/2 in.) radially and longitudinally. This bundle is about 0.701 m (2-1/3 ft) long and is supported by six separate support plates similar to those for the EES bundle. 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, because of the difference in temperature between the Incoloy 800H 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 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 Cr-Mo tie plate is provided to take any stresses.

The SH-2 discharge lead tubes are connected to the steam discharge header at the top of the unit. This is a cylindrical drum with a 485.1-mm (19.1-in.) i.d. and a 66.7-mm (2-5/8-in.) thick wall constructed of Incoloy 800H and having a 63.5-mm (2-1/2-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.) of refractory insulation on its entire outer surface, which carries the superheated steam down to and out the bottom of the pressure vessel. It is connected to the vessel by means of a thermal sleeve.

The pressure vessel is a 2-1/4 Cr-1 Mo cylinder with a wall thickness of 58.42 mm (2.3 in.). Its inner surface is covered by 101.6 mm (4 in.) of refractory insulation. Penetrations include a man access at the top, two 1.52-m (5-ft) i.d. hot helium inlet ducts above the tube bundles, one 1.83-m (6-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 circumvents the steam discharge duct. 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 293°C (560°F) and 20 MPa (2900 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 to about 415°C (780°F) in the first superheater, 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 is ducted to the discharge header and out of the vessel.

The hot helium enters the shell side of the bundle at the top at about 659°C (1219°F). It flows over the hot end lead tubes to the SH-2 bundle, to the EES-1 bundle, and finally over the cold end lead tubes and out the discharge duct with a temperature of about 398°C (748°F).

2.5. SHORT-TERM BUCKLING INVESTIGATION FOR IHX

2.5.1. General

A study was made to determine the short-term buckling requirements of the module tubes and the center return duct for the IHX of the VHTR. Because of the high temperatures involved, primary helium inlet of 950°C (1742°F) and secondary helium outlet of approximately 900°C (1650°F), high-temperature materials had to be used. The materials specified were Inconel 617 and Incoloy 800H. Both materials were investigated, because for purposes of cost saving the low-temperature sections of the module tubes and center return ducts can be made of Incoloy 800H and connected to the Inconel 617 sections by bimetallic welds, a process well within the state of the art.

For convenience and to be conservative, the charts for determining wall thicknesses of cylindrical tubes under external pressure of ASME Code, Section III, Div. 1, were used. In order to use this method, and because complete materials data on Inconel 617 and Incoloy 800H were not available, the method described below was applied.

The buckling strength of cylindrical tubes or ducts under external pressure depends on a geometrical factor and the strength of the material. The geometrical factor is a function of the ratios of length to diameter (L/d) and diameter to wall thickness (d/t) and is expressed by the factor A in the ASME charts. The strength factor in the charts is expressed by the factor B, and for each material or groups of materials the factor B is plotted for different temperatures.

For Inconel 617, this chart was not available. Therefore, Fig. VII-1103-2 from the ASME Code, Section III, which is a chart for nickel-chromium-molybdenum alloy, a material of similar composition, was used as a basis to construct simulated B-factor curves for Inconel 617 at higher temperatures.

This study had to cover a temperature range from 870° to 980°C (1600° to 1800°F); therefore, B-factor curves as a function of the A-factor for these temperatures had to be produced. This was done by converting the average yield strength curve to curves of B-factors by ratioing according to the slope of the yield strength curve, using the B-factor for temperatures up to 538°C (1000°F) from Fig. VII-1103-2 of the ASME Code, Section III, as a starting point for Inconel 617, as shown in Fig. 2-7. The curve was subsequently modified by changing the curved section from 565°C (1050°F) and 870°C (1600°F) to a straight line.

For Incoloy 800H, Fig. VII-1102-2 from the ASME Code, Section III, was used for the B-factor curves up to 538°C (1000°F). For the construction of the B-factor curves for higher temperatures, available minimum yield strength data from Code Case 1592 were used up to 760°C (1400°F), and for higher temperatures the average yield strength data from recent tests were applied as shown in Fig. 2-8. The B-factor curves were completed by ratioing according to the slope of the yield strength curves.

This method was applied for a range of wall thicknesses to determine the allowable external pressure P_a using the ASME Code formula

$$P_a = 1.33 \frac{B}{D_{o/t}} ,$$

where B is the B-factor and $D_{o/t}$ is the ratio of the outside tube diameter to the wall thickness.

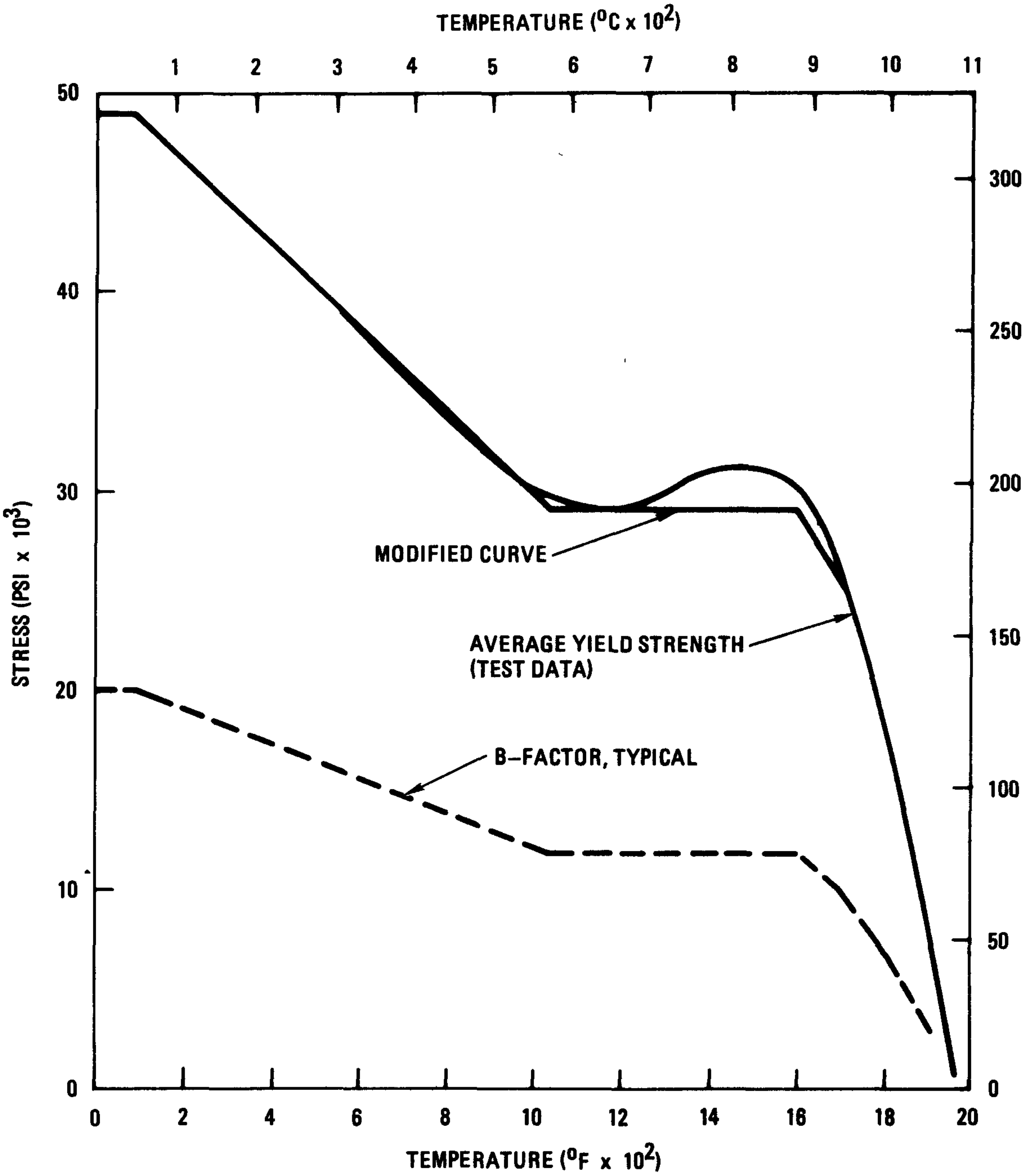


Fig. 2-7. Average yield strength and typical B-factor curve for Inconel 617

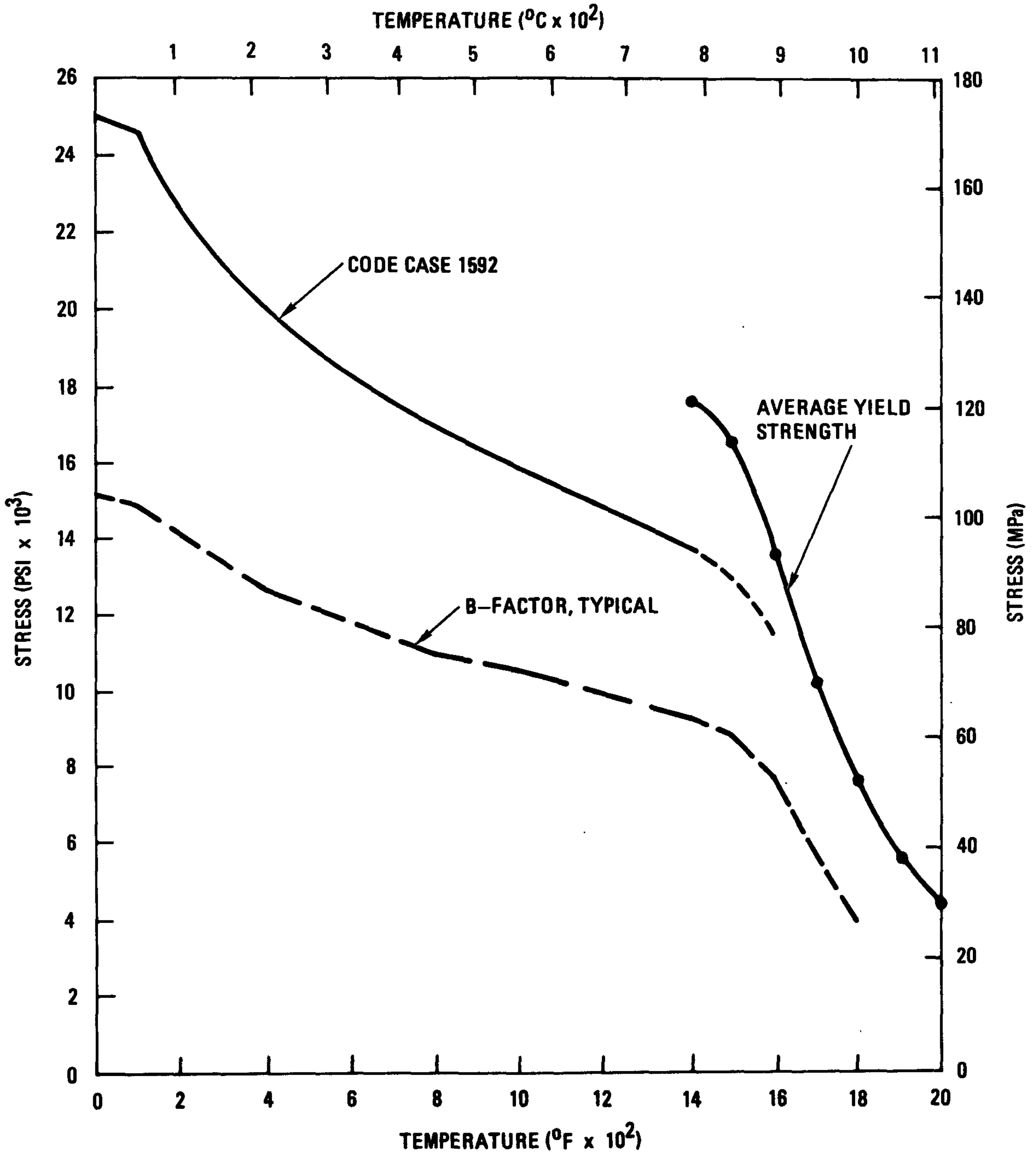


Fig. 2-8. Average yield strength and typical B-factor curve for Incoloy 800H

The procedure described above provides a conservative factor of approximately 2.5 (yield strength/B-factor) for Inconel 617, which will account for a certain degree of material imperfection and out-of-roundness of the tubes. For Incoloy 800H this factor is lower but based on actual Code data.

2.5.2. Corrosion Allowance

Due to impurities in the primary helium, an allowance for corrosion of the tube material will be made on the primary side. For the secondary side, it is assumed that the chemistry of the gas can be so controlled that corrosion does not occur.

2.5.3. Module Tubes

The following design data were used for the module tubes:

Tube outside diameter, D_o	11.1 mm (0.4375 in.)
Tube length, L	9.98 m (393 in.)
Ratio L/D_o	900
Temperature range	760°-980°C (1400°-1800°F)

For preselected wall thicknesses, the B-values have been determined for different temperatures according to the method described in Section 2.5.1, and for these values the allowable external pressures were determined using the ASME Code formula given in Section 2.5.1. The pressures thus determined were plotted, and using these curves, graphs of wall thickness for an external pressure of 5.2 MPa (750 psi) (secondary helium inlet) for different temperatures without a corrosion allowance were produced for Inconel 617 and Incoloy 800H (Figs. 2-9 and 2-10).

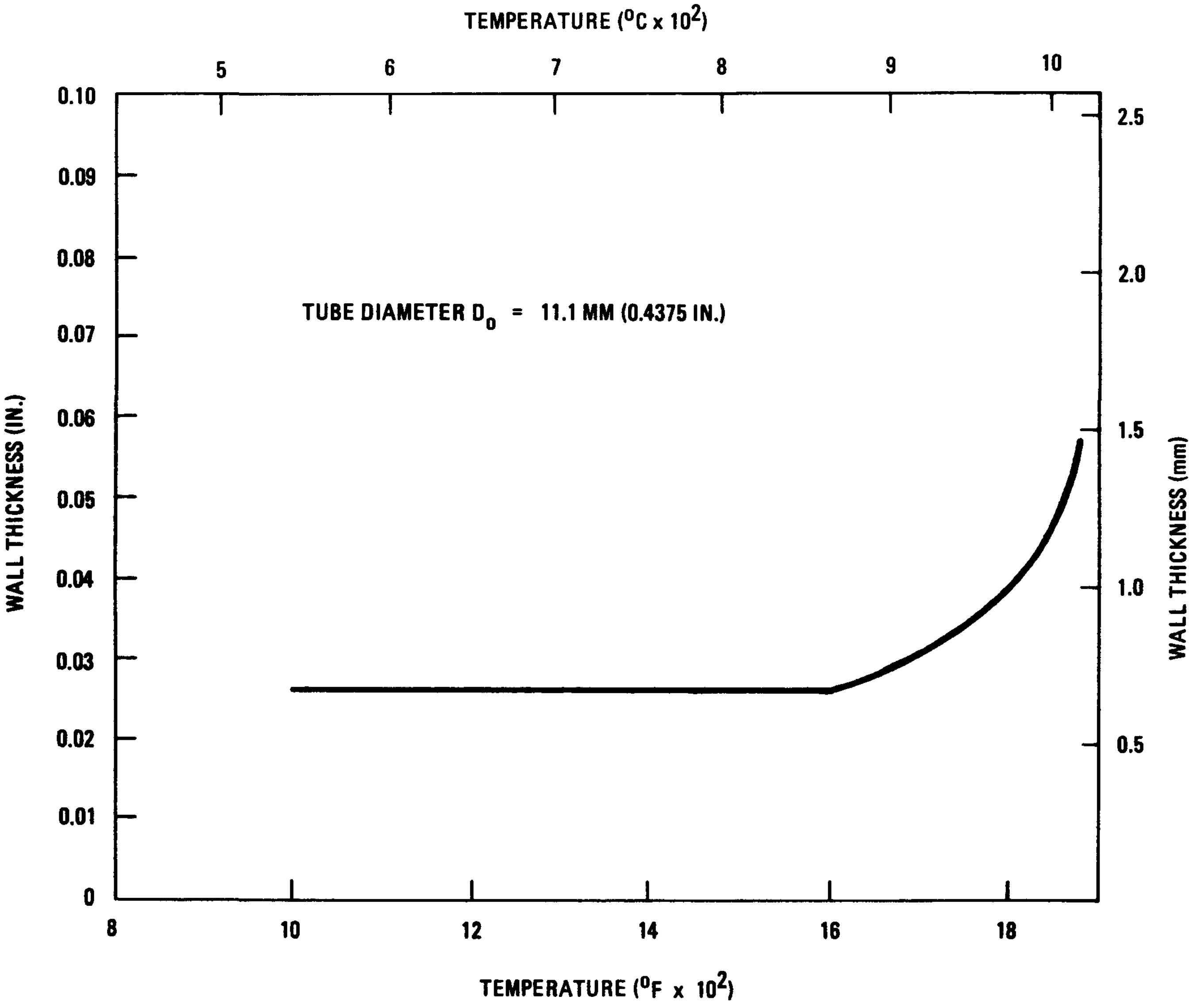


Fig. 2-9. Inconel 617 module tube wall thickness versus temperature for 5.2-MPa (750-psi) external pressure (assuming no corrosion allowance)

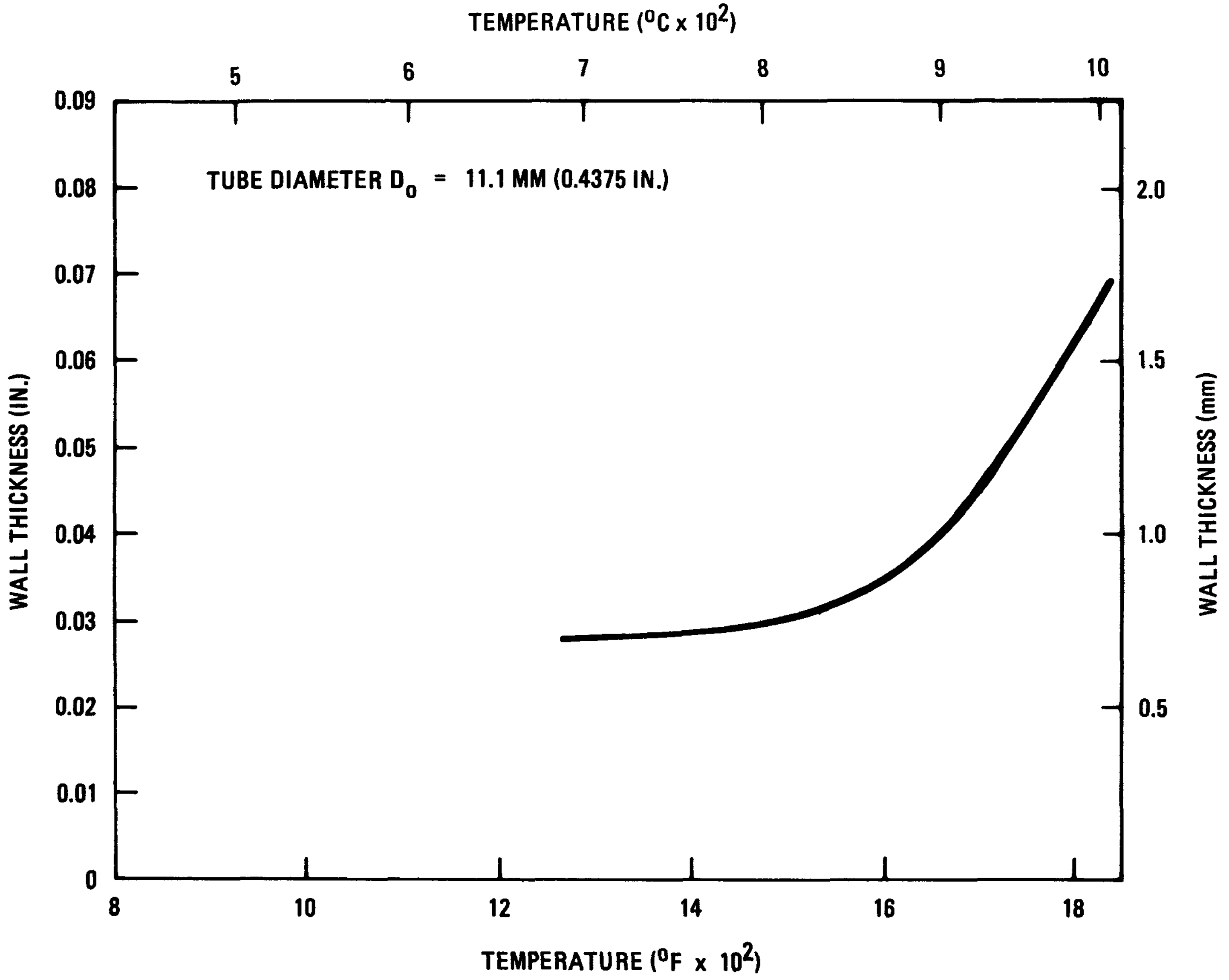


Fig. 2-10. Incoloy 800H module tube wall thickness versus temperature for 5.2-MPa (750-psi) external pressure (assuming no corrosion allowance)

2.5.4. Center Return Duct

The following design data were used for the center return duct:

Tube outside diameter, D_o	1.05 m (41.3 in.)
Tube length, L	8.03 m (316 in.)
Ratio L/D_o	7.65
Temperature range	760°-980°C (1400°-1800°F)

The procedure used to produce the plot for the required wall thickness for an external pressure of 5.2 MPa (750 psi) for different temperatures was the same as described in Sections 2.5.1 and 2.5.3. The wall thickness for an external pressure of 5.2 MPa (750 psi) and for different temperatures without a corrosion allowance is shown in Figs. 2-11 and 2-12 for Inconel 617 and Incoloy 800H, respectively.

2.6. PCRV DESIGN

During FY-79, the structural design of the PCRV for the reference plant concept was developed and PCRV arrangement drawings were prepared (Fig. 2-13). This resulted in minor changes in the PCRV dimensions established by the preliminary studies performed in FY-78: the PCRV diameter has been slightly increased and the height somewhat reduced. The basic PCRV configuration remains the same.

As reported in Ref. 2-2, the PCRV design selected from the evaluation studies performed in FY-78 is similar to that used in the current HTGR-SC power plant designs. This is a multi-cavity type PCRV with the reactor core offset from the center of the PCRV and other primary coolant system components located in cavities around the core cavity. The design is considered to have excellent seismic design capability, to have cost advantages compared with other designs, and to present fewer design uncertainties than alternative designs. Much of the design development performed for the HTGR-SC plants can be applied fairly directly to the VHTR design.

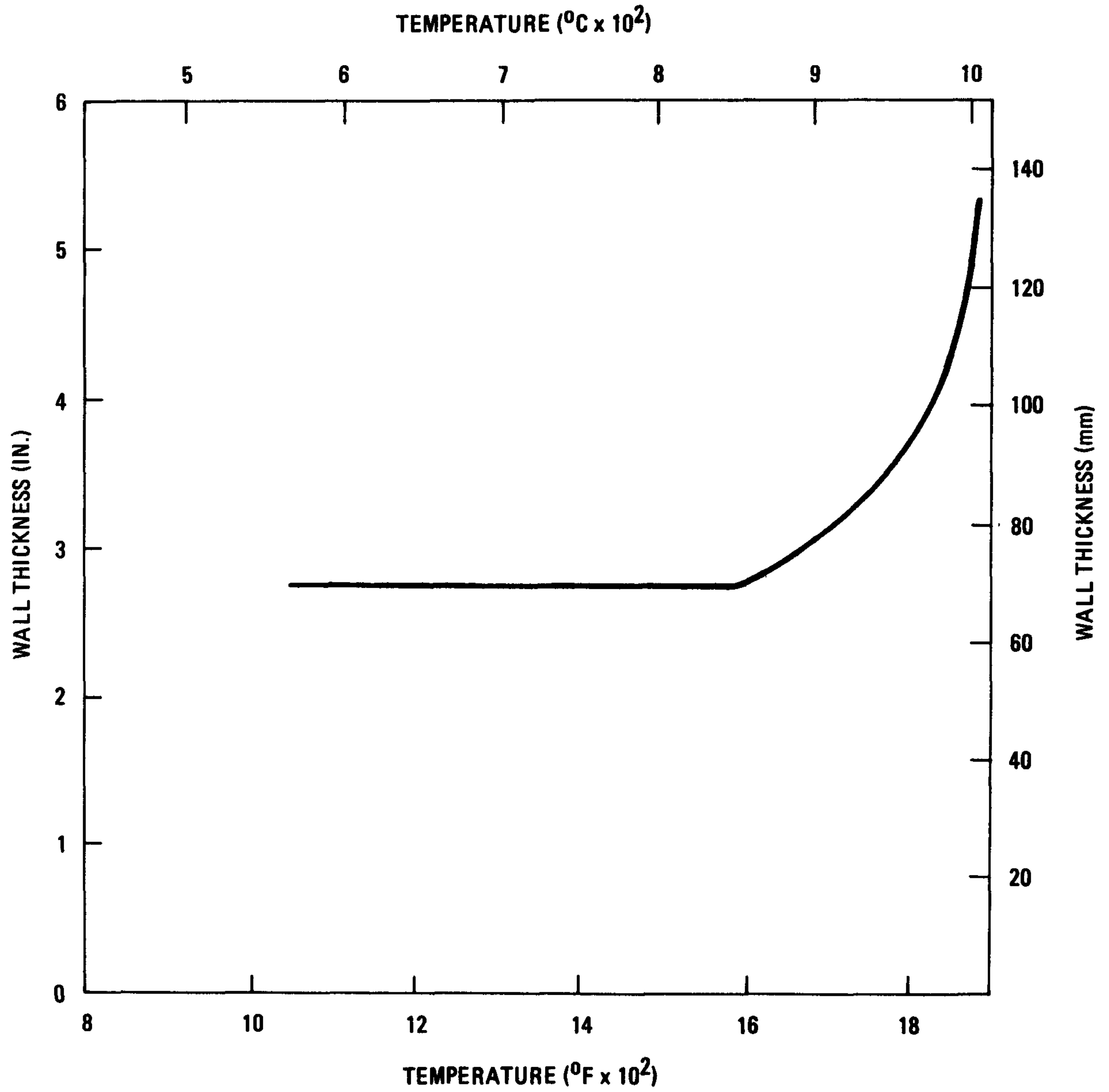


Fig. 2-11. Inconel 617 center return duct wall thickness versus temperature for 5.2-MPa (750-psi) external pressure (assuming no corrosion allowance)

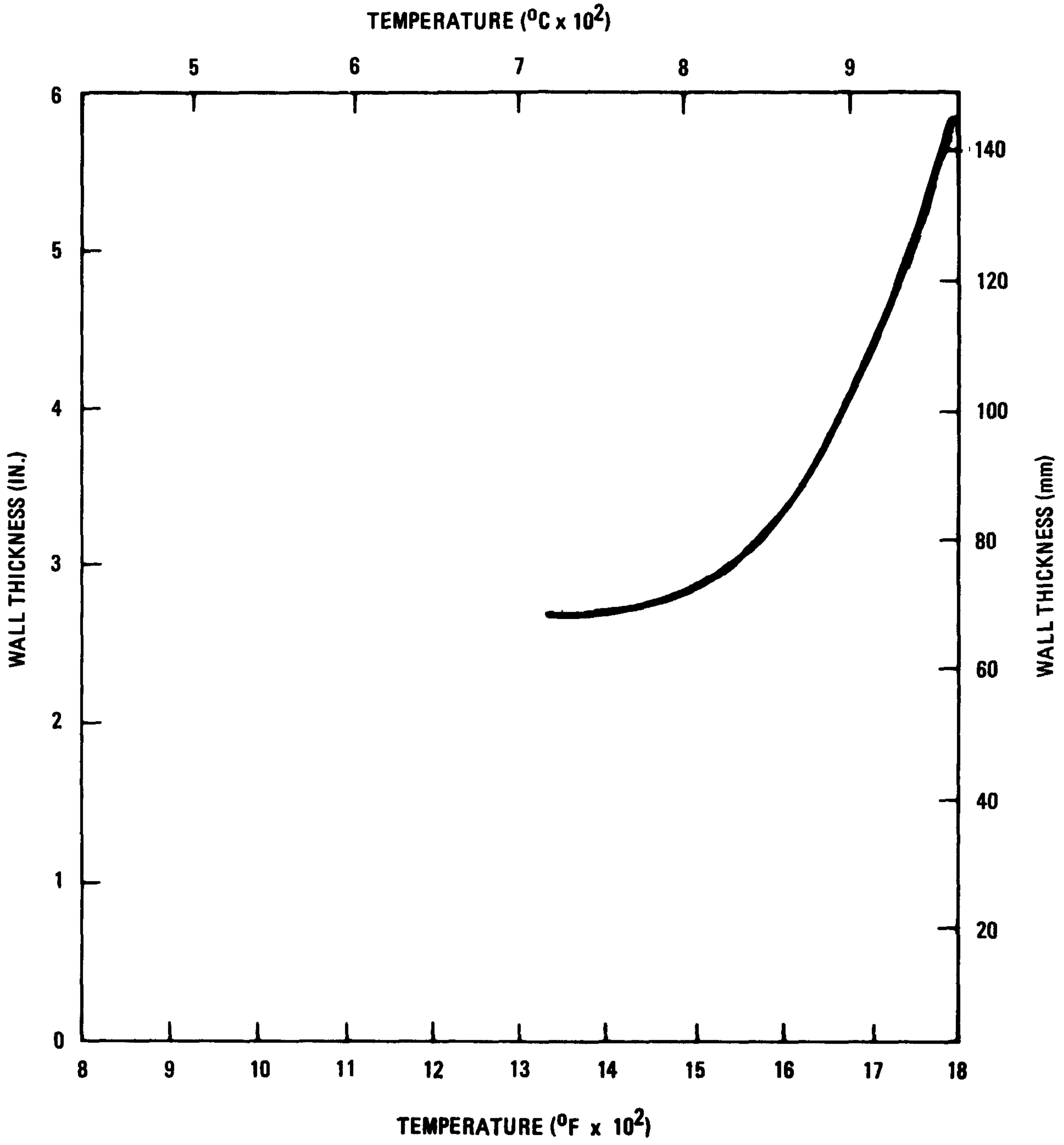
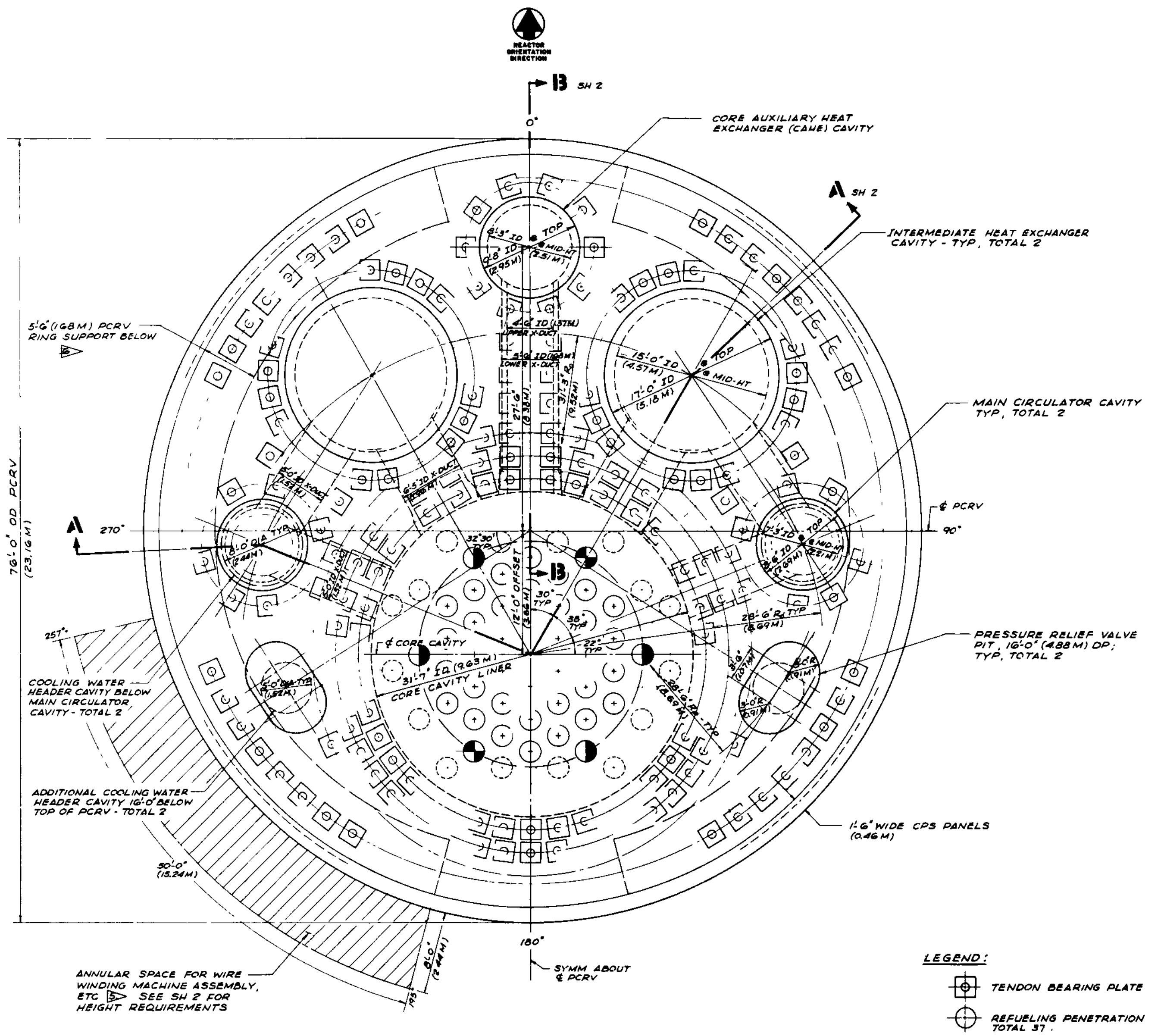


Fig. 2-12. Incoloy 800H center return duct wall thickness versus temperature for 5.2-MPa (750-psi) external pressure (assuming no corrosion allowance)



PLAN - PCRV TOP HEAD

LEGEND:

- ⊞ TENDON BEARING PLATE
- ⊕ REFUELING PENETRATION TOTAL 37.
- ◕ HIGH TEMPERATURE ADSORBER PENETRATION - TOTAL 2.
- ◑ HIGH TEMPERATURE FILTER PENETRATION - TOTAL 4
- ⊕ COLUMN SUPPORT FOR FHM AND AUXILIARY SERVICE CASK - TOTAL 16

R_C - RADIUS TO CENTER OF CORE CAVITY

R_P - RADIUS TO CENTER OF PCRV.

GENERAL NOTES:

1. PCRV DESIGN IS IN COMPLIANCE WITH "CONCRETE REACTOR VESSELS AND CONTAINMENTS", ACI-359, ASME SECTION III, DIVISION 2 CODE AND GA DOC NO. 903832.
2. PCRV SIZING AND GENERAL ARRANGEMENT OF CAVITIES IN THE PCRV LAYOUT ARE BASED ON THE INFORMATION DOCUMENTED IN GA MEMO NO. SED. PB. 19.79 DATED 3-13-78. SIZING IS PRELIMINARY AND THE OFFSET CORE PCRV DESIGN REQUIRES VERIFICATION BY ANALYSIS.
3. MATERIAL PROPERTIES AND SYSTEM PARAMETERS OF THE MAJOR STRUCTURAL COMPONENTS USED IN THE PCRV DESIGN ARE AS FOLLOWS:
   - a. SPECIFIED CONCRETE COMPRESSIVE STRENGTH AT 60 DAYS = 6500 PSI.
   - b. BONDED REINFORCEMENT PER ASTM A615, GR 60.
   - c LINEAR PRESTRESSING: 60-1/2"ϕ, 7-WIRE STRAND TENDONS; MAX. CAPACITY = 2478 KIPS (GUTS).
   - d CIRCUMFERENTIAL PRESTRESSING: 1/2"ϕ, 7-WIRE STRAND CABLES; MAX. CAPACITY = 41.3 KIPS (GUTS)
   - e MAX. CAVITY PRESSURE = 776 PSIG.
   - f MAX. DESIGN PRESSURE = 760 PSIG.
4. THIS PCRV LAYOUT DOES NOT SHOW THE REQUIRED CORE REGION OUTLET TEMPERATURE PENETRATIONS AND OTHER MINOR ISI PENETRATIONS HOWEVER, ALLOWANCE HAS BEEN MADE IN THE DESIGN FOR SUCH REQUIREMENTS.

5▷ THIS ANNULAR SPACE MEASURED VERTICALLY FROM THE CONTAINMENT MAT MUST BE KEPT CLEAR FOR WIRE WINDING MACHINE ASSEMBLY, INSTALLATION AND MAINTENANCE, STORAGE OF STRAND SPOOLS, ETC.

6▷ DIMENSIONS AND OPENINGS SHOWN IN THE PCRV SUPPORT STRUCTURE ARE SUGGESTED ARRANGEMENTS ONLY. FINAL CONFIGURATION AND LOCATION ARE PART OF THE BOP (BALANCE-OF-PLANT) DESIGN.

7 LINER MATERIALS ARE CARBON STEEL EXCEPT AS NOTED:
- PLATE TO BE SA-537, CLASS 2.
- FORGINGS TO BE SA-508, CLASS 2A.

WHERE MATERIAL IS INDICATED AS 2¼ CHROME:
- PLATE TO BE SA-387, GR 22, CLASS 1.
- FORGINGS TO BE SA-336, GR 22.

WHERE MATERIAL IS INDICATED AS ALLOY 800 H:
- PLATE TO BE SB-409, ALLOY 800 H.
- FORGINGS TO BE SB-564, CONDITION 2.

8. LINER THICKNESS TO BE 1/2 IN. EXCEPT WHERE NOTED OTHERWISE.

9. COOLING TUBE PITCH TO BE 5¾ IN. EXCEPT WHERE NOTED OTHERWISE.

10▷ DETAILS OF AUX. COOLING LOOP CAVITY LINER, CORE CAVITY LINER, CROSS DUCT LINERS AND REFUELING PENETRATIONS TO BE SIMILAR TO HTGR-SC, 900 MW(e) PLANT EXCEPT WHERE NOTED OTHERWISE.

11. ALL LINER STUDS TO BE 3/4 IN DIA. X LENGTH SHOWN ON DWG. PROVIDE ONE STUD PER 50 SQ IN. OF LINER SURFACE WHERE SHOWN ON DWG.

QUANTITIES:

1. CONCRETE (6500 PSI):
   - PCRV ______ 8110 CY
   - PRECAST PANELS ______ 534 CY
2. REINFORCEMENT (ASTM A615, GR 60):
   - PCRV ______ 324 TONS
   - PRECAST PANELS ______ 80 TONS
   - NO MECHANICAL SPLICES IN PCRV ______ 1100
3. PRESTRESSING - LPS:
   - NO. 60-1/2"ϕ STRAND TENDONS
   - LENGTH OF TENDONS (BETW CONC. SURFACES)*

	QUANTITY	LENGTH
CORE, CAHE, CIRCULATOR AND HEAT EXCHANGER CAVITIES	182	68'-8" LF
PERIPHERAL	32	87'-2" LF

* ALLOW 5LF ADDITIONAL PER TENDON FOR TENSIONING.

4. PRESTRESSING - CPS:
   - 1/2"ϕ STRAND - TOTAL LENGTH ______ 3.60 × 10⁶ LF
   - NO. STRAND LAYERS ______ 286
   - NO. 20° PRECAST PANELS ______ 156
   - NO. LOAD MONITOR PANELS ______ 6
5. INSTRUMENTATION.
   - NO LPS LOAD CELLS ______ 11
   - NO CPS LOAD MONITORS ______ 6
   - NO. PCRV SENSORS ______ 250
   - NO. LINER SENSORS ______ 175

ITEM	PART NO	DESCRIPTION	MATL/MATL SPEC

REQD/ASSEMBLY

NEXT INDENTURED DOCUMENT

DISC	SYSTEM	TYPE	PROJECT
3	11	DLO	7213

PARTS LIST

DIST.

GENERAL ATOMIC COMPANY
SAN DIEGO, CALIFORNIA

LTR	DATE	ISSUE DESCRIPTION	DR.	CHK.	DES.	APPD.	APPD.
A		PRELIMINARY					

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
NO BURRS OR SHARP EDGES
DIMENSIONS PER ANSI-Y-14 5
TOLERANCE:
DECIMAL FRACTION ANGLE
.XXX = ± ± ±
.XX = ±
ALL MACHINED SURFACES
DO NOT SCALE PRINT

TITLE
VHTR, 2-LOOP 842 MW(t)
PCRV LAYOUT

SIZE	CODE IDENT NO	DWG. NO.	ISSUE
E	32334	024825	A

SCALE 1/4"=1'-0" QAL-1, A/L-2 SHEET 1 OF 2

024825 A SHEET 1

Fig. 2-13. Two-loop 842-MW(t) VHTR PCRV layout (sheet 1 of 2)

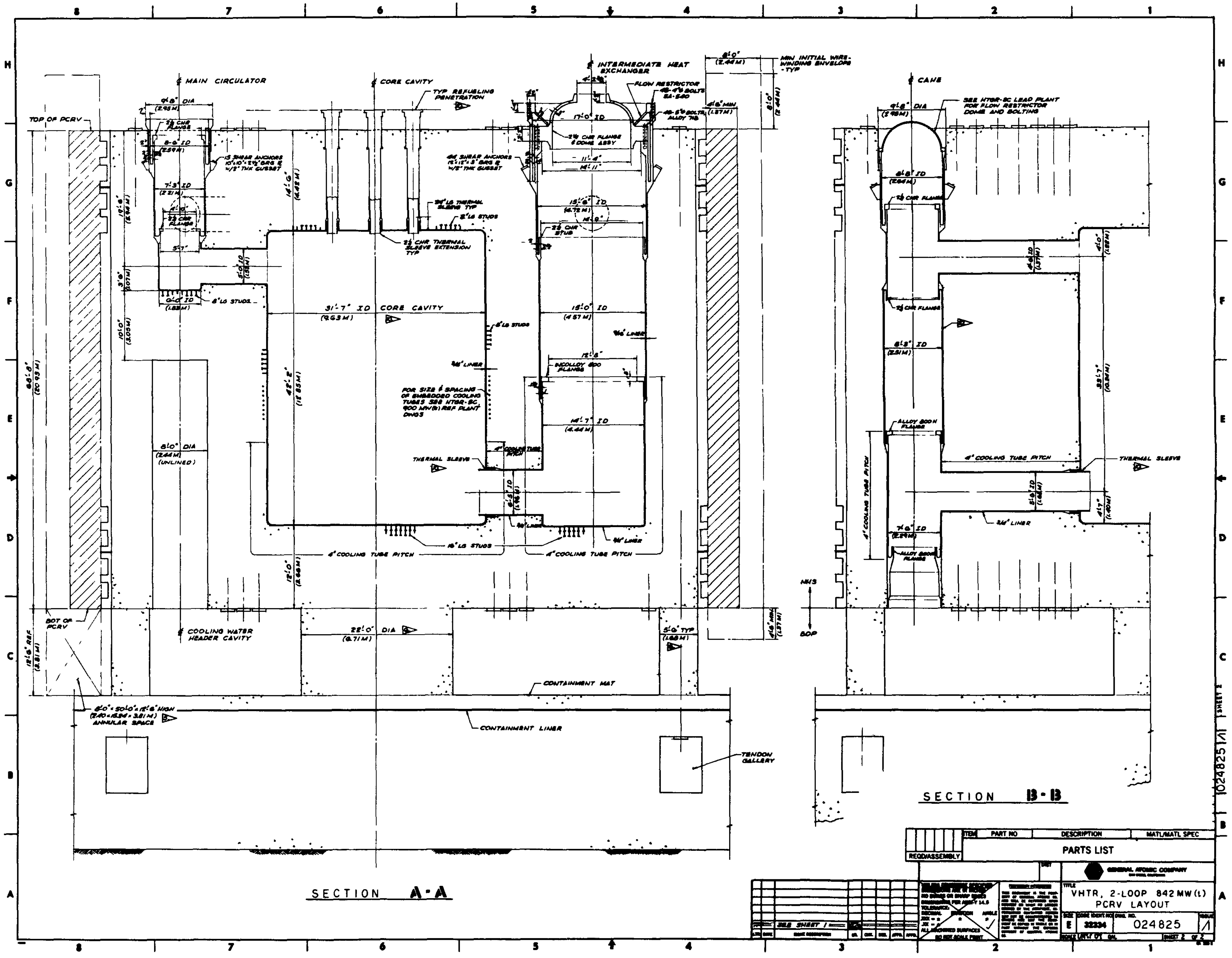


Fig. 2-13. Two-loop 842-MW(t) VHTR PCRV layout (sheet 2 of 2)

Several arrangement studies at GA have demonstrated advantages to offsetting the reactor core from the geometric center 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. Concrete stress distributions are somewhat more complex for an asymmetric cavity and/or offset core arrangement. However, the capability for predicting elastic response and ultimate strength behavior is available in analytical methods developed at GA. In addition to the analytical methods, a model test to verify design adequacy is considered desirable to facilitate licensing.

The layout of the VHTR PCRV results in a 3.66-m (12 ft 0 in.) offset of the core cavity relative to the PCRV centerline. The required biological concrete shielding between the core and outside surface of the PCRV is the governing ligament at one side. At the other side the tendon layout requirements for the IHX cavity linear tendons, rather than concrete stress, determine the inner and outer radial ligament dimensions. The PCRV height is governed by the core cavity height and stress requirements in the top and bottom heads.

Additional structural analysis is needed to verify the PCRV dimensions. A two-dimensional analysis to ascertain the prestress flow into the PCRV during construction is currently planned for FY-80. The PCRV layout drawing will be adjusted as required following the analysis. Any changes needed because of final component cavity dimensions will also be incorporated at that time.

2.7. HELIUM-COOLED CORE AUXILIARY HEAT EXCHANGER

Work was started during FY-79 on design of a helium-to-helium core auxiliary heat exchanger (CAHE). Conditions for the design included both those for a pressurized and a depressurized PCRV with air ingress. These conditions are listed in Table 2-5.

TABLE 2-5
HELIUM-TO-HELIUM CAHE DESIGN CONDITIONS

	Primary Loop Pressurized	Primary Loop Depressurized
Primary helium flow rate, kg/s (lb/hr)	17.4(138,000)	3.12(24,800)
Secondary helium flow rate, kg/s (lb/hr)	40.1(318,00)	40.1(318,000)
Primary loop nominal pressure, MPa (psi)	5.00 (725)	0.17 (24)
Secondary loop nominal pressure, MPa (psi)	4.86 (705)	4.86 (705)
Primary inlet temperature, °C (°F)	956 (1,752)	1076 (1,968)
Primary discharge temperature, °C (°F)	466 (871)	308 (586)
Secondary inlet temperature, °C (°F)	159 (318)	76 (168)
Secondary discharge temperature, °C (°F)	371 (700)	136 (276)
Heat transferred, MJ/s (Btu/hr x 10^{-6})	44.2 (151)	12.5 (42.6)

The concept pursued is the bayonet tube design, since this eliminates some rather difficult thermal expansion problems between the tubes and the tubesheets or anchor points. Some problem areas associated with bayonet tubes are as follows:

1. Larger secondary side pressure loss.
2. Poorer heat exchanger effectiveness due to heat losses to fluid from the bayonet tubes.
3. More difficult seismic support for the single-end-mounted tubes.

Design results so far have indicated that problems 1 and 2 are not particularly severe and will not compromise the design. Problem 3 has not yet been addressed, but it is felt that it can readily be solved through additional closed-end tube supports.

The sizing of the CAHE was accomplished with the aid of a counterflow helium-to-helium bayonet tube heat exchanger computer routine (HEBAYO). It solves Nusselt's parameter and friction pressure loss on an incremental length basis (the user chooses the size of the increment) and bases the solutions on fluid properties evaluated within the code at average film temperatures. It delivers results which include required tube length, surface area, calculated tube bundle o.d. for a triangular pitched solid tube field, maximum tube temperatures, maximum tube wall temperature gradient (inner and outer tubes), annulus friction and turning losses, and bayonet friction and shell side friction loss.

The CAHE was designed for the conditions listed in Table 2-5. Both pressurized and depressurized cases have been examined with secondary flow introduced into the bayonet tube and alternately into the annulus. Results indicated that the pressurized case controls the design owing to the higher heat load of the pressurized case, which requires greater surface area in spite of the lower shell side film resistance.

The preliminary sizing results are shown in Table 2-6. Tube sizes were chosen to adjust the bayonet and annulus pressure loss balance and to influence the maximum temperature of the outer tube. The required tube wall thickness was calculated prior to operation of the program. Materials used were Incoloy 800 for the outer tube and 2-1/4 Cr-1 Mo for the inner. Optimization of the tube size has not yet been addressed, and these sizes are presented as representative. Further studies will seek to adjust the tube sizes for reduction of the tube wall thermal gradients, especially in the depressurized case.

Figure 2-14 shows a mechanical arrangement of a 500-tube CAHE with the secondary flow introduced to the annulus and with counterflow primary flow. Introducing the secondary flow to the tube annulus or to the bayonet tube makes little difference in the size of the heat exchanger but does affect the tube temperatures and gradients. However, introduction of the primary flow to the closed ends of the tubes as shown in Fig. 2-14 should result in better inlet flow characteristics than the arrangement in Fig. 2-15 (secondary flow introduced to the bayonet tubes), since the primary flow is introduced axially to the tube array. Figure 2-15 is presented to indicate a flow arrangement only and does not represent a helium-to-helium CAHE design. Materials and component dimensions are listed in Table 2-6.

2.8. SHUTDOWN POWER REQUIREMENTS

The emergency power requirements for both the pony motor which drives the main helium circulator and the secondary helium shutdown circulator are given in Table 2-7 for the various design basis accidents.

The pony motor is used to drive the main helium circulator during an emergency shutdown condition if electrical power is lost to the primary circulator drive motor. The electrical power would be supplied by a safety class diesel motor generator set. Helium flow rate during the shutdown condition is sufficient to maintain component temperatures below their critical design limits. The IHX pressure drop during emergency shutdown

TABLE 2-6
HELIUM-TO-HELIUM CAHE COMPONENTS

Tubes (500)	Outer	Bayonet
Material	Incoloy 800	2-1/4 Cr-1 Mo
Outside diameter, mm (in.)	41.1 (1.62)	26.7 (1.05)
Inside diameter, mm (in.)	39.4 (1.55)	25.4 (1.0)
Length, m (ft)	3.392 (11.13)	3.911 (12.83)
Weight, kg (lb)	1528 (3368)	697 (1537)
Tubesheets		
Material	2-1/4 Cr-1 Mo	2-1/4 Cr-1 Mo
Diameter, mm (in.)	1816 (71.50)	1372 (54)
Thickness, mm (in.)	299 (11.75)	50.8 (2.0)
Weight, kg (lb)	6168 (13,600)	601 (1325)
Shroud		
Material	Incoloy 800	
Diameter, mm (in.)	1320 (52)	
Thickness, mm (in.	9.53 (0.375)	
Length, m (ft)	4.69 (15.4)	
Weight, kg (lb)	1486 (3276)	

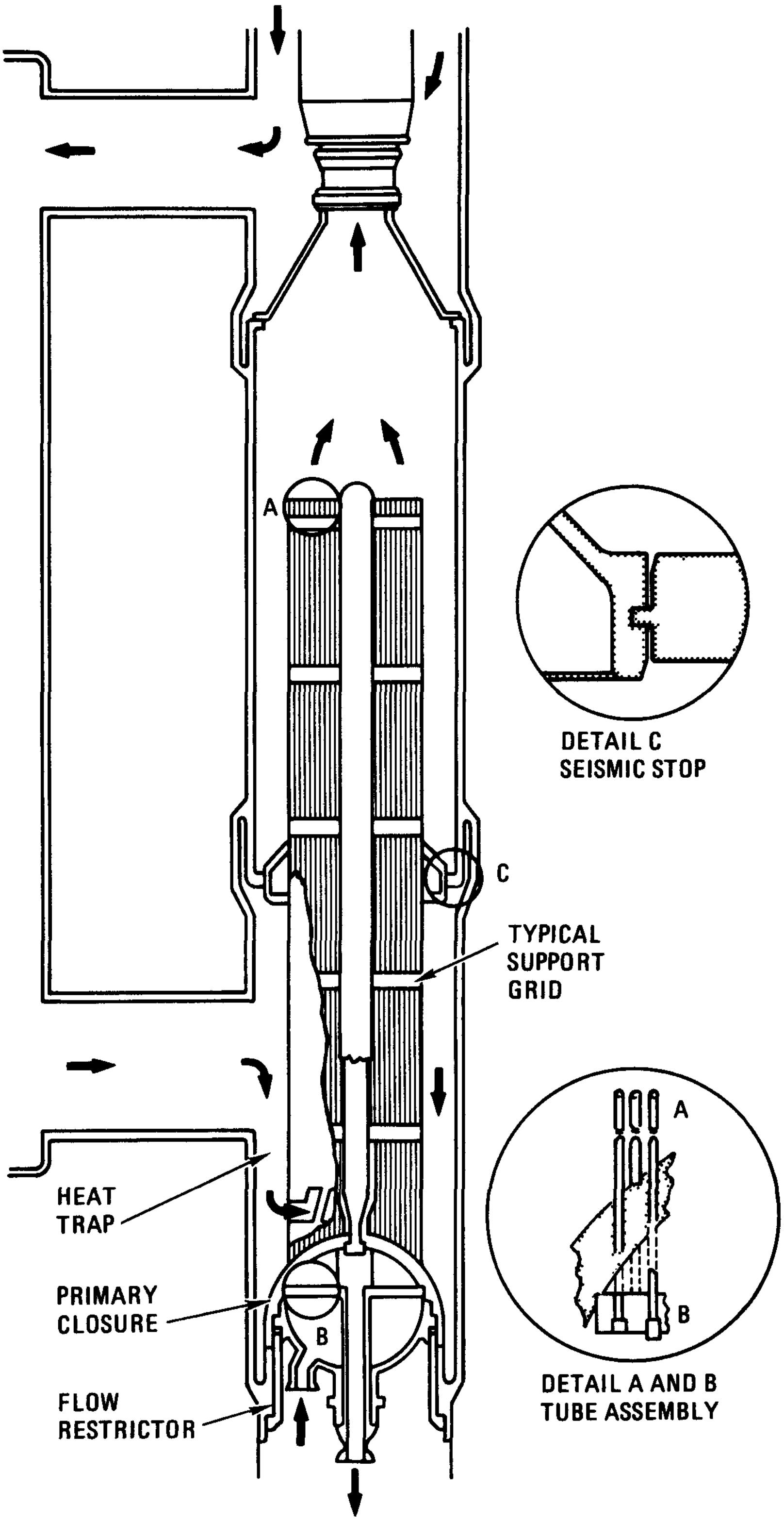


Fig. 2-14. Bayonet tube CAHE with secondary helium introduced through the annuli

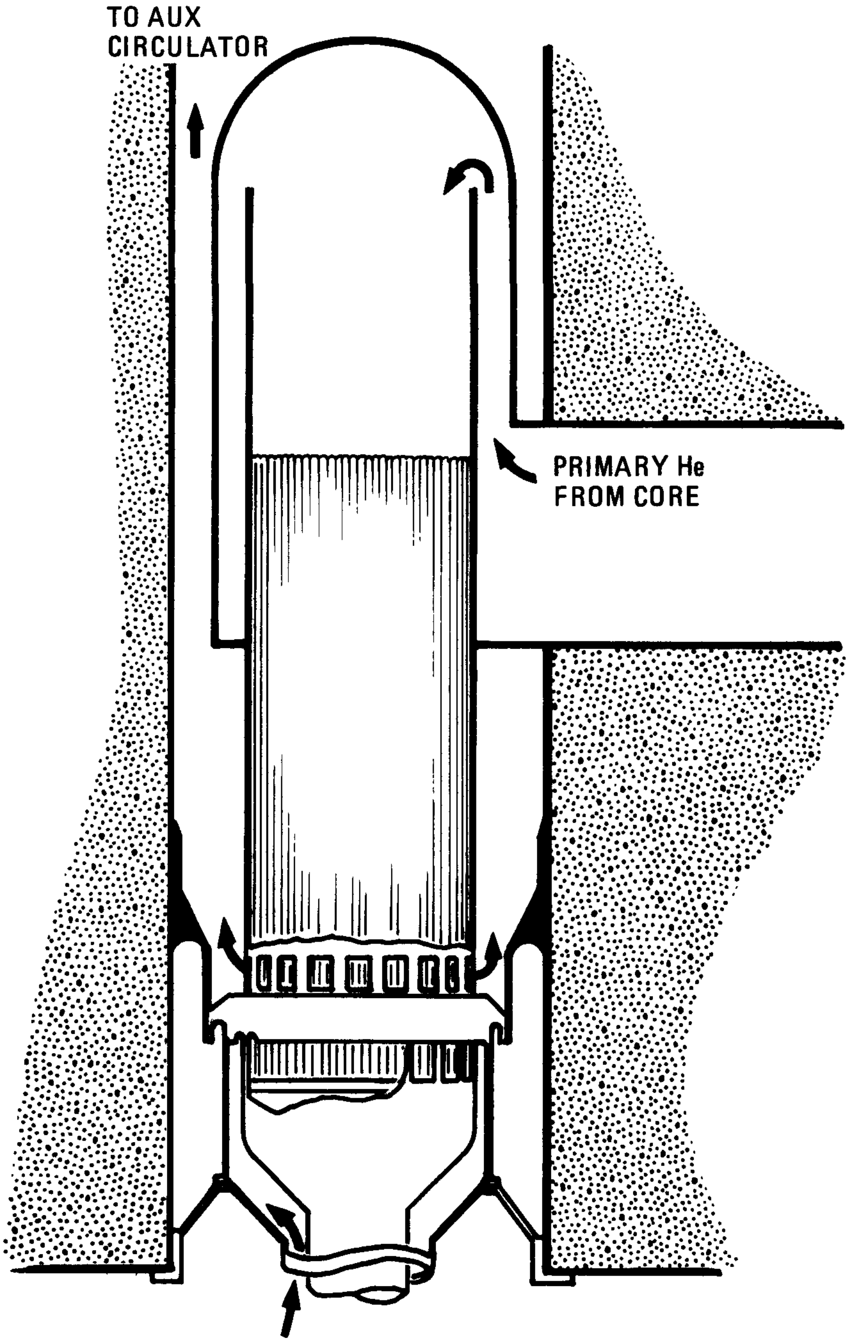


Fig. 2-15. Basic mechanical arrangement of bayonet tube CAHE with secondary helium introduced through the bayonet tubes

TABLE 2-7

PONY MOTOR POWER REQUIREMENTS AND SHUTDOWN HELIUM CIRCULATOR DESIGN CONDITIONS

	Primary System Design Basis Accident	
	Pressurized	Depressurized (Air Ingress)
Pony Motor		
Power requirement, kW (hp)	63 (84)	187 (250)
Loop ΔP, kPa (psi)	1.72 (0.25)	4.13 (0.6)
Secondary Shutdown Helium Circulator		
Maximum motor power, kW (hp)	1260 (1698)	1017 (1370)
Maximum speed, rads/s (rpm)	372 (3550)	372 (3550)
Operating inlet pressure, MPa (psia)	4.8 (700)	4.8 (700)
Operating outlet pressure, MPa (psia)	5.0 (725)	5.0 (725)

Secondary Helium Shutdown Circuit Pressure	Secondary Circuit Pressurized
Circulator discharge pressure, MPa (psia)	5.00 (725)
IHX inlet pressure, MPa (psia)	4.98 (722)
IHX exit pressure, MPa (psia)	4.97 (721.5)
Airblast HX inlet pressure, MPa (psia)	4.96 (718.5)
Circulator inlet pressure, MPa (psia)	4.82 (700)

conditions is considerably less than the pressure drop across the CAHE. As a result, the maximum power requirement is only 187 kW (250 hp).

The secondary shutdown circulator utilized during an emergency shutdown transfers secondary loop helium from the IHX to the airblast heat exchanger. During its operation isolation valves block all helium flow to the reformer and steam generator. The maximum circulator power requirement is governed by the pressurized cooldown accident and results in approximately 1260 kW (1698 hp). The design assumes the secondary circuit maintains its pressure at 5 MPa (725 psia) during both emergency shutdown conditions.

REFERENCES

2-1. Brislin, R. J., "VHTR Thermal Barrier Design and Development Plan," General Atomic Company, unpublished data, December 28, 1978.

2-2. "Process Heat Reactor Design and Analysis, Final Report," DOE Report GA-A15137, General Atomic Company, February 1979.

3. CODE DEVELOPMENT

3.1. STATUS SUMMARY

The parametric design computer program PHRED (Process Heat Reactor Evaluation and Design) for the VHTR hydrogen production process heat plant is now being run with all design and performance subroutines incorporated in their final first generation version. A series of test runs was performed and checked. Costing subroutines were substantially completed, and their incorporation into the program is about 90% complete.

The most important test run for verifying the integrity of the programming in PHRED is to use an alternate case which is identical to the base case (reference design) which is entered into the program. This has been done to verify the internal consistency of the program. Tables 3-1 through 3-5 present the output printed for the base case. The reformer and process plant data are not yet formatted for output. The reference design plant, with a reactor thermal power of 842 MW and zero net cogenerated electrical power, produces a product hydrogen flow of 11.42 kg/s (90,600 lb/hr) from an input fresh methane flow of 25.44 kg/s (201,900 lb/hr) and a makeup water flow of 52.87 kg/s (419,600 lb/hr). The reformer achieves a conversion of 70.4%.

The number of loops and the complexity of the energy and mass-flow interactions result in a program run time which uses between 1 and 2 min per case, a value which is longer than ideal but not long enough to compromise the usefulness of the program. The base case (reference design computation) takes only 20 s to converge, which indicates that the 1- to 2-min value can be improved in the future as a better understanding is gained of how the independent design variables affect plant design and performance. This will make it possible to program the iteration logic to make more accurate estimates as it governs the energy-mass balance convergence computations.

TABLE 3-1
VALUES OF INDEPENDENT DESIGN VARIABLES
(ONLY THE CHANGING VARIABLES ARE PRINTED FOR CASE 1)

		BASE CASE
MAXIMUM PRIMARY HELIUM PRESSURE	(PSIA)	725.0
REACTOR THERMAL POWER	(MW)	842.0
REACTOR INLET TEMPERATURE	(F)	887.0
REACTOR OUTLET TEMPERATURE	(F)	1742.0
REACTOR CORE DIAMETER	(FT)	19.62
REACTOR CORE HEIGHT	(FT)	15.61
TOP REFLECTOR THICKNESS	(FT)	3.90
SIDE REFLECTOR THICKNESS	(FT)	4.50
BOTTOM REFLECTOR THICKNESS	(FT)	3.90
CORE COOLANT HOLE DIAMETER	(IN)	.625
CORE HOLE PATTERN PITCH	(IN)	.740
CORE CARBON/THORIUM RATIO		185.0
INTERMEDIATE HEAT EX CAVITY DIAMETER	(FT)	15.00
REACTOR OUTLET DUCT DIAMETER	(FT)	6.42
INTER HEAT EX OUTLET DUCT DIAMETER	(FT)	5.00
CIRCULATOR CAVITY DIAMETER	(FT)	7.25
REACTOR INLET DUCT DIAMETER	(FT)	5.00
NUMBER OF CACS LOOPS IN THE PCRV		1.0
NUMBER OF INTERMEDIATE HEAT EXCHANGERS		2.0
INTER HEAT EX SECONDARY INLET TEMP	(F)	787.0
INTER HEAT EX SECONDARY OUTLET TEMP	(F)	1650.0
INTERMEDIATE HEAT EX TUBE OUTER DIA	(IN)	.4375
INTER HEAT EX TUBE PITCH/DIAMETER RATIO		1.400
INTER HEAT EX CENTRAL DUCT OUTER DIA	(IN)	42.50
MAXIMUM SECONDARY HELIUM PRESSURE	(PSIA)	765.0
REACTOR-TO-REFORMER SEPARATION	(FT)	200.0
SECONDARY PIPING HOT-LEG OUTER DIA	(IN)	42.00
SECONDARY PIPING COLD-LEG OUTER DIA	(IN)	36.00
HOT-LEG THERMAL BARRIER THICKNESS	(IN)	2.87
NUMBER OF REFORMERS		2.0
REFORMER STEAM/METHANE RATIO		3.75
REFORMER PROCESS OUTLET PRESSURE	(PSIA)	320.0
REFORMER PROCESS OUTLET TEMPERATURE	(F)	1500.0
REFORMER TUBE OUTER DIAMETER	(IN)	3.500
REFORMER TUBE PITCH/DIAMETER RATIO		1.0735
REFORMER TOTAL NUMBER OF TUBES		1260.0
REFORMER CATALYST PARTICLE DIAMETER	(IN)	.500
NUMBER OF STEAM GENERATORS		2.0
STEAM GEN STEAM OUTLET PRESSURE	(PSIA)	2500.0
STEAM GEN STEAM OUTLET TEMPERATURE	(F)	950.0
STEAM GEN EES1 TUBE OUTER DIAMETER	(IN)	.7500
STEAM GEN EES1 TUBE WALL THICKNESS	(IN)	.090
STEAM GEN EES1 TRANS PITCH/DIA RATIO		2.000
STEAM GEN EES1 LONGI PITCH/DIA RATIO		1.667
STEAM GEN S2 TUBE OUTER DIAMETER	(IN)	1.0000
STEAM GEN S2 TUBE WALL THICKNESS	(IN)	.188
STEAM GEN S2 LONGI PITCH/DIA RATIO		1.50
STEAM GEN TOTAL NUMBER OF TUBES		231.0
STEAM GEN NUMBER OF TUBE LAYERS		24.0
S G CENTRAL DUCT OUTER DIAMETER	(IN)	16.25
COGENERATED ELECTRIC POWER OUTPUT	(MW)	.0
AMBIENT TEMPERATURE	(F)	70.0

TABLE 3-2
PRIMARY HELIUM PERFORMANCE SUMMARY

```
                                                        BASE
                                                        CASE

REACTOR NOMINAL THERMAL POWER  (MEGAWATTS)            842.00

THERMAL POWER ADDED BY CIRCULATORS                     15.24

TOTAL THERMAL POWER INPUT ................            857.24


THERMAL POWER TO INTERMEDIATE HELIUM                  849.92

PRIMARY LOOP THERMAL POWER LOSSES                       6.04
    THERMAL POWER LOST TO PCRV LINER                    4.10
    THERMAL POWER LOST TO CACS WATER                    1.94

PRIMARY LOOP MIXING AND KINETIC LOSSES                  1.28

TOTAL THERMAL POWER OUTPUT ...............            857.24

PRIMARY LOOP THERMAL EFFICIENCY  (PERCENT)             99.15


HELIUM PRESSURE-TEMPERATURE-FLOW SUMMARY


REACTOR INLET PRESSURE                    (PSIA)      724.26
              TEMPERATURE           (DEGREES F)       887.00
              FLOW              (MILLION LB/HR)     2.709186

REACTOR OUTLET PRESSURE                               719.42
               TEMPERATURE                           1742.00
               FLOW                                 2.709186

INTER. HEAT EXCH. INLET PRESSURE                      718.36
                        TEMPERATURE                  1734.72
                        FLOW                        1.355544

INTER. HEAT EXCH. OUTLET PRESSURE                     709.55
                         TEMPERATURE                  871.85
                         FLOW                       1.355544

CIRCULATOR INLET PRESSURE                             708.51
                 TEMPERATURE                          873.52
                 FLOW                               1.374669

CIRCULATOR OUTLET PRESSURE                            725.00
                  TEMPERATURE                         887.91
                  FLOW                              1.374669


TOTAL PRIMARY LOOP PRESSURE LOSS (PERCENT)              2.27
```

TABLE 3-3
SECONDARY HELIUM PERFORMANCE SUMMARY

```
                                                     BASE
                                                     CASE

TOTAL IHX THERMAL POWER         (MEGAWATTS)        849.92
THERMAL POWER ADDED BY CIRCULATORS                  38.77
TOTAL THERMAL POWER INPUT ...............          888.69

THERMAL POWER TO REFORMERS                         419.98
THERMAL POWER TO STEAM GENERATORS                  465.45

THERMAL POWER LOST TO AMBIENT AIR                    3.12
SECONDARY LOOP MIXING AND KINETIC LOSSES              .14

TOTAL THERMAL POWER OUTPUT ..............          888.69

2NDARY LOOP THERMAL EFFICIENCY   (PERCENT)          99.63


HELIUM PRESSURE-TEMPERATURE-FLOW SUMMARY


INT HEAT EX INLET PRESSURE            (PSIA)       759.96
                  TEMPERATURE  (DEGREES F)         787.00
                  FLOW     (MILLION LB/HR)       1.355666

INT HEAT EX OUTLET PRESSURE                        743.56
                   TEMPERATURE                    1650.00
                   FLOW                          1.355666

REFORMER INLET PRESSURE                            733.43
               TEMPERATURE                        1647.22
               FLOW                              1.355666

REFORMER OUTLET PRESSURE                           730.27
                TEMPERATURE                       1220.86
                FLOW                             1.355666

STEAM GENERATOR INLET PRESSURE                     728.42
                      TEMPERATURE                 1220.67
                      FLOW                       1.355666

STEAM GENERATOR OUTLET PRESSURE                    719.05
                       TEMPERATURE                 748.20
                       FLOW                      1.355666

CIRCULATOR INLET PRESSURE                          717.75
                 TEMPERATURE                       748.18
                 FLOW                            1.355666

CIRCULATOR OUTLET PRESSURE                         765.00
                  TEMPERATURE                      787.18
                  FLOW                           1.355666


TOTAL 2NDARY LOOP PRESSURE LOSS  (PERCENT)           6.18
```

TABLE 3-4
STEAM CYCLE PERFORMANCE SUMMARY

```
                                                       BASE
                                                       CASE

TOTAL STEAM GEN THERMAL POWER  (MEGAWATTS)           465.45
THERMAL POWER ADDED BY FEEDWATER PUMPS                 1.53
TOTAL THERMAL POWER INPUT ...............            466.98

THERMAL POWER IN STEAM TO PROCESS PLANT              253.08
THERMAL POWER TO HOUSELOAD TURBINES                   13.88
THERMAL POWER TO CIRCULATOR TURBINES                  49.85

THERMAL POWER REJECTED THROUGH CONDENSERS            145.18
THERMAL POWER LOSSES IN PIPING                        15.68

TOTAL THERMAL POWER OUTPUT ...............           466.98

STEAM LOOP THERMAL EFFICIENCY    (PERCENT)            65.55


STEAM PRESSURE-TEMPERATURE-FLOW SUMMARY


STEAM GEN INLET PRESSURE             (PSIA)         3056.25
                TEMPERATURE     (DEGREES F)          560.00
                FLOW         (MILLION LB/HR)        .918547

STEAM GEN OUTLET PRESSURE                           2500.00
                 TEMPERATURE                         950.00
                 FLOW                               .918547

HOUSE TURBINE INLET PRESSURE                        2415.00
                    TEMPERATURE                      945.51
                    FLOW                            .280144

HOUSE TURBINE OUTLET PRESSURE                        575.00
                     TEMPERATURE                     626.16
                     FLOW                           .280144

CIRC TURBINE INLET PRESSURE                          550.00
                   TEMPERATURE                       622.92
                   FLOW                             .280144

CIRC TURBINE OUTLET PRESSURE                           4.00
                    TEMPERATURE                      152.96
                    FLOW                            .280144

CONDENSER OUTLET PRESSURE                              4.00
                 TEMPERATURE                         152.96
                 FLOW                               .280144

FEEDWATER PUMP OUTLET PRESSURE                      3106.25
                      TEMPERATURE                    153.93
                      FLOW                          .280144
```

TABLE 3-5
PCRV LAYOUT AND DESIGN SUMMARY
(ALL UNSPECIFIED DIMENSIONS ARE IN FEET)

	BASE CASE
LAYOUT GUIDE - CENTER-TO-CENTER DISTANCES	
REACTOR CAVITY TO PCRV CENTER	12.13
REACTOR CAVITY TO AUX COOLING CAVITY	39.63
REACTOR CAVITY TO INTER HEAT EX CAVITY	31.29
REACTOR CAVITY TO CIRCULATOR CAVITY	29.12
REACTOR CAVITY TO WATER HEADER PIT	24.18
AUX COOL CAVITY TO INT HEAT EX CAVITY	19.96
INT HEAT EX CAVITY TO CIRCULATOR CAVITY	19.46
CIRCULATOR CAVITY TO WATER HEADER PIT	13.95
PCRV STRESSED DIAMETER	73.00
PCRV OUTER DIAMETER (WITH PRECAST PANELS)	76.00
REACTOR CAVITY DIAMETER	31.58
AUX COOLING SYSTEM CAVITY DIAMETER	9.67
INTER HEAT EXCHANGER UPPER CAVITY DIAMETER	17.00
INTER HEAT EXCHANGER MAIN CAVITY DIAMETER	15.00
CIRCULATOR UPPER CAVITY DIAMETER	8.50
CIRCULATOR MAIN CAVITY DIAMETER	7.25
CIRCULATOR LOWER CAVITY DIAMETER	6.00
PCRV COOLING WATER HEADER PIT DIAMETER	5.00
REACTOR OUTLET CROSS-DUCT DIAMETER	6.42
CIRCULATOR INLET CROSS-DUCT DIAMETER	5.00
CIRCULATOR INLET ANNULUS OD MINUS ID	2.83
CIRCULATOR OUTLET DOWN-DUCT DIAMETER	5.00
REACTOR INLET CROSS-DUCT DIAMETER	5.00
AUX COOLING UPPER CROSS-DUCT DIAMETER	4.50
AUX COOLING LOWER CROSS-DUCT DIAMETER	5.50
OVERALL PCRV HEIGHT	68.67
REACTOR CAVITY HEIGHT	42.17
REACTOR CAVITY TOP HEAD THICKNESS	14.50
REACTOR CAVITY BOTTOM HEAD THICKNESS	12.00
REACTOR CAVITY UPPER PLENUM HEIGHT	7.46
REACTOR CAVITY LOWER PLENUM HEIGHT	7.85
INT HEAT EX UPPER CAVITY DEPTH	9.12
INT HEAT EX CAVITY BOTTOM HEAD THICKNESS	11.75
CIRCULATOR UPPER CAVITY DEPTH	6.92
CIRCULATOR MAIN CAVITY DEPTH	16.33
CIRCULATOR LOWER CAVITY DEPTH	23.00
LOWER CROSS-DUCT CL TO REACTOR CAV BOTTOM	4.58
UPPER CROSS-DUCT CL TO PCRV TOP	12.00
REAC INLET CROSS-DUCT CL TO REAC CAV TOP	5.00
LOWER AUX COOL DUCT CL TO REAC CAV BOTTOM	4.58
UPPER AUX COOL DUCT CL TO REAC CAV TOP	4.00
PRECAST PANEL THICKNESS	1.5
PRECAST PANEL WIRE CHANNEL DEPTH	1.0
MAXIMUM HELIUM OPERATING PRESSURE (PSIA)	725.0
CONCRETE-LINER INTERFACE TEMPERATURE (F)	130.0

In its present form, PHRED contains about 8000 executable lines of FORTRAN and uses 43,000 words of data storage on the UNIVAC 1110 computer.

3.2. NHS CODE DEVELOPMENT

The development of the structure of the computer program PHRED has been guided by two sets of requirements. The first set defines what the program is to do, i.e., the purpose of the program and the basic pattern of its use. The second set of requirements are those defined by good programming practice.

The first three items in the original specifications for the program define the purpose of the program and the required pattern of its use:

1. The purpose of the program is to model the sizing, performance, and cost of a VHTR hydrogen production plant as a function of the selected independent design variables which describe the plant design. Plant performance will be modeled at the full-power design point, and plant cost will include capital and operating costs. The plant is made up of the VHTR and its two primary loops in a PCRV, two secondary loops which transfer heat to the reformers and steam generators, and the chemical process equipment downstream from the methane feed to the plant.

2. The program will be designed so that it is capable of running a series of cases where each case is defined by a set of values for the independent design variables and the sets of values for the independent design variables are input by the program user. Also, the program will be designed so that there is a logical "break point" in the program where the user may couple the program to any available multi-variable direct search optimization program.

3. The computer program will be designed to operate in a base case - alternate case mode. A base case, or reference design, plant is defined for the program by stored input data describing the design, performance, and cost of the reference design plant. An alternate case plant is then defined by exercising the plant model within the program using values of the independent design variables which are different from the base case values.

The programming requirements are aimed at achieving high efficiency in the use of the program over its lifetime. The program uses a structured, top-down approach to the design of the overall logic. The methods used to couple the performance computations for the various sections of the plant have been kept as flexible as possible to accommodate future design changes. Component arrangement is specified as much as possible by DATA written into the program, rather than by "hard wired" FORTRAN statements.

Figure 3-1 is a diagram of the logic structure which controls the iterations required to compute an energy-mass balance in PHRED. The "estimated variables" are the initial guesses made at the beginning of any iteration loop, and the "converged variables" are the results of iteration loop computations which must converge with some known required value. If convergence of any particular iteration loop is not achieved, that loop is started again with an improved value of the estimated variable. If convergence is achieved, then either the next lower loop is started or the computations in the next outer loop are continued. The diagram does not show all the iteration loops in the program, since many of the component models use independent iteration loops in their design-performance computations.

On a more detailed level, the design of the program logic must accommodate the selected independent design variables and iteration variables. The independent design variables are those variables which the user will

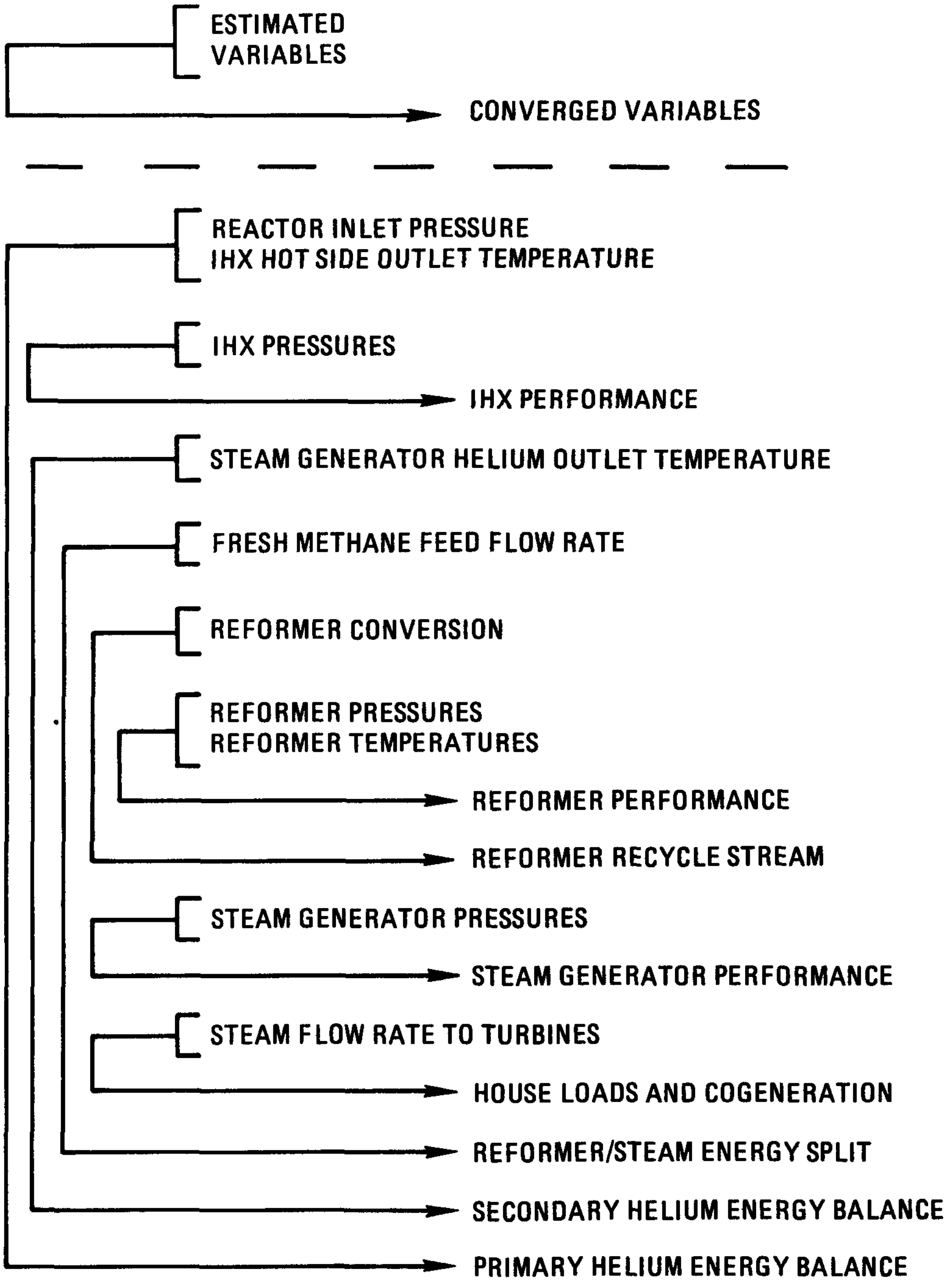


Fig. 3-1. Logic structure for PHRED showing main iteration loops for energy-mass balance computations

wish to set at specified values or use to perform parametric and optimization studies. The iteration variables are those variables used by the program logic to achieve an energy and mass balance. The goals which apply specifically to the selection of variables are:

1. The independent design variables should (a) encompass the major design decisions to be made during the design study effort and (b) contribute to developing a straightforward iteration logic structure.

2. The iteration variables should be (a) variables for which enough a priori information is available to make a fairly accurate first estimate of their value and (b) variables which exhibit a smooth, monotonic variation of the calculated value as a function of the estimated value.

In designing the logic of the computational iterations required to achieve energy and mass balances in the four interacting fluid loops (primary helium, intermediate helium, process cycle, steam cycle), it is easily seen that not only must the iterations within each loop be efficient, but the iterations involved in joining all the loops must also be efficient. The method chosen to achieve that computational efficiency is to define the independent design variables so that, for any particular case, as many as possible of the variables which determine the design and performance of the components which join the loops are fixed. This method of defining independent variables is especially important for the IHXs, the reformers, and the steam generators. How this method works for those components is described in Sections 3.2.2 and 3.2.3.

Figure 3-2 shows the four fluid loops - primary and secondary helium loops, steam loop, and process loop - as they are modeled in PHRED. Multiple parallel loops are modeled but are not shown in the figure.

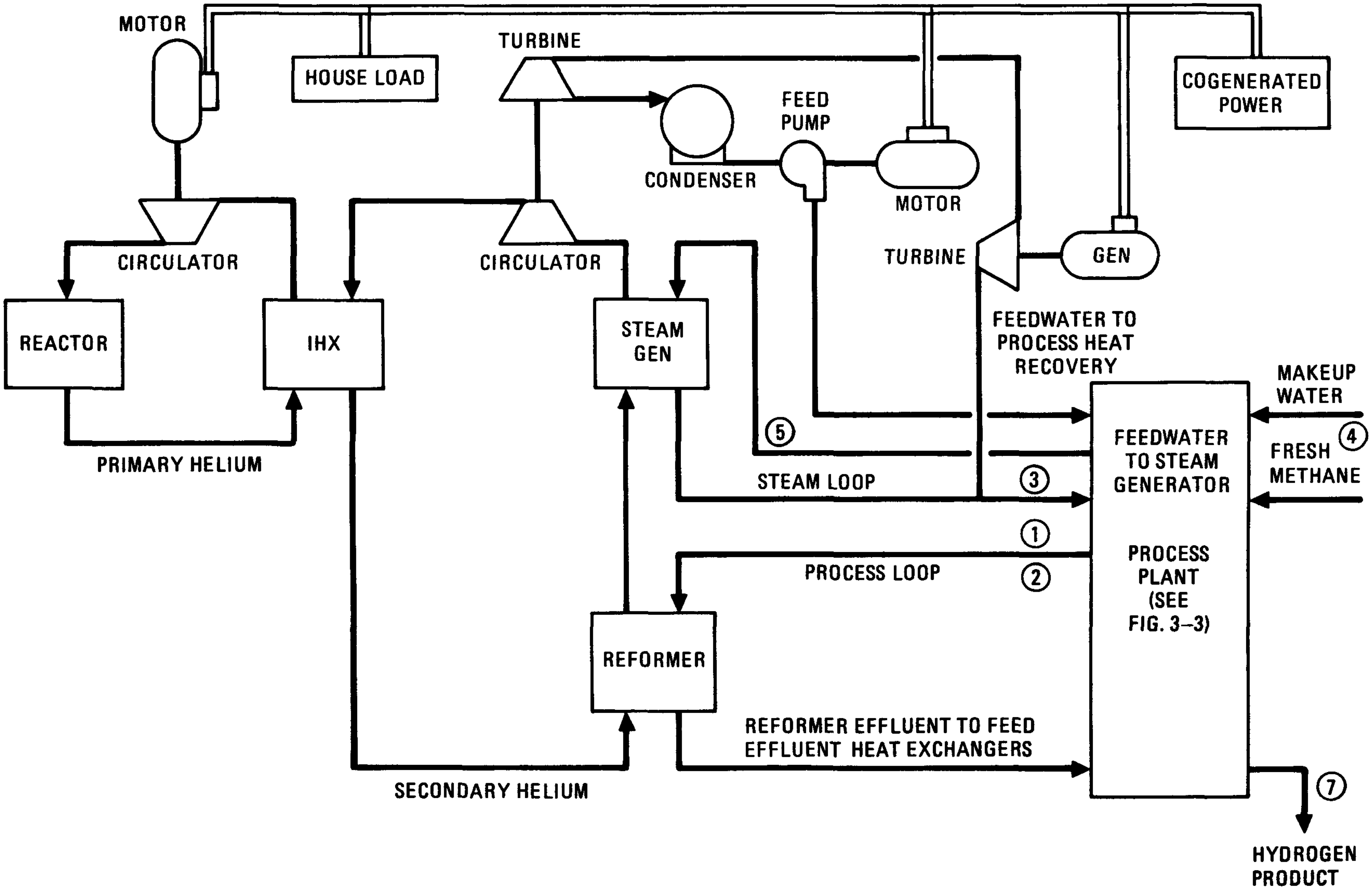


Fig. 3-2. Schematic loop arrangement for VHTR hydrogen production process plant

The primary loop performance computations begin at the reactor inlet. The inlet temperature is an independent design variable (IDV). (An IDV can be changed from one alternate design case to another, but remains fixed during the computations for any particular case.) The inlet pressure is set equal to the circulator outlet pressure (an IDV) minus an estimated duct pressure drop, a value which changes only very slightly during the iterations required to achieve an energy and mass balance. Reactor thermal power and reactor outlet temperature are both IDVs. The reactor subroutine uses the defined variables along with other reactor design IDVs to compute reactor flow rate and outlet pressure and core size, which is used as an input to the PCRV sizing computations. Note that since reactor power and inlet and outlet temperatures are known and fixed for any particular case, the computed flow rate will change only very slightly as it is affected by small changes in inlet pressure and reactor pressure drop. The small changes in flow rate occur as a result of the small real gas effects of helium pressure on helium enthalpy.

The four temperatures required to size the IHXs are defined as follows. The inlet and outlet temperatures on the cold side (secondary helium loop) are both IDVs. These two temperatures were selected to help stabilize the secondary helium computations because the majority of the run time is spent in the reformer model, which is the most "sensitive" model in the program. The primary helium inlet temperature is equal to the reactor outlet temperature (an IDV) minus a very small temperature drop in the reactor-to-exchanger flow path. The primary helium outlet temperature is an iteration variable; its value is estimated and used in the IHX sizing computations. It is easy to get an accurate first estimate for primary helium outlet temperature from an equation of the form

$$Q = \dot{m}\ C_P\ \Delta T$$

solved for the appropriate primary side temperature drop ΔT as a function of heat duty Q (closely related to reactor power), flow rate $\dot{m}$ (equal to loop flow rate plus or minus appropriate small leakages), and helium specific heat C_p (nearly constant). Convergence to an accurate IHX primary helium outlet temperature is checked at the end of the primary loop computations when the computed reactor inlet temperature is checked against its required (IDV) value. Errors in the computed reactor inlet temperature are used as guides to subsequent estimates of IHX primary helium outlet temperature until convergence is achieved. The primary side inlet pressure is determined from reactor outlet pressure minus a small pressure drop in the reactor-to-exchanger flow path. The secondary helium side inlet pressure is set at secondary loop circulator outlet pressure (an IDV) minus a small pressure drop in the circulator-to-exchanger flow path. Each time the IHX sizing subroutine is exercised, the four temperatures, the primary side flow rate, the inlet pressures, and other IDVs such as tube bundle layout dimensions are used to compute the secondary helium loop flow rate, pressure drops for both sides, and overall heat transfer tube bundle dimensions.

The primary circulator computations are relatively simple. The inlet helium properties are determined by computations of pressure drop and temperature drop due to heat loss in the IHX-to-circulator flow path. The circulator subroutine is called to compute outlet temperature as a function of outlet pressure (an IDV) and other circulator characteristics. These computations also specify the energy required to drive the circulators with electric motors.

After the circulator computations, only the circulator-to-reactor flow path computations are needed to compute the resultant values of reactor inlet pressure and temperature and check for convergence of both parameters. If convergence is not attained, the computed reactor inlet pressure is used for the starting value in the next iteration. The new estimate for the iteration variable (IHX primary side outlet temperature) is computed by using a secant method. The second estimate is computed by adjusting the first estimate by an amount equal to the negative of the temperature error at the reactor inlet. The third estimate (if required) is computed by a linear secant method, and subsequent estimates are made using a linear fractional[*] secant method.

With regard to the goals defined earlier in this section, the IDVs discussed so far do encompass the major design decisions to be made in the primary helium cycle. These are:

1. Reactor thermal power.

2. Maximum primary helium temperature (reactor outlet temperature).

3. A temperature near the minimum temperature (reactor inlet temperature).

4. Maximum pressure (circulator outlet pressure).

The IDVs also contribute to straightforward and efficient logic by defining as much as possible of the duty required of these components which link various loops, such as the IHX where both inlet and outlet temperatures on the cold side are IDVs. The iteration variable for the primary helium loop (IHX primary side outlet temperature) can be accurately estimated because it is closely related to reactor power, and that estimate is easily corrected because of its smooth variation, computed as a function of the temperature error at the reactor inlet.

The performance computations for the intermediate helium loop begin at the outlet of the IHX, since the IHX computations are completed in the primary loop computations. Flow path computations define the helium inlet conditions to the reformer. The process side inlet conditions are set by computations of preprocessing equipment performance, where the methane feed

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[*] The linear fractional secant method uses the previous three iteration values of the iteration variable and their computed errors to generate a curve of the form $Y = (aX + b)/(cX + d)$, where the next estimate of the iteration variable X gives Y equal to zero.

is mixed with steam and processed to feed the reformer. The methane mass flow rate is the iteration variable used to achieve the required energy split between the reformer and the steam generator, and the reformer conversion is the iteration variable used to compute the composition of the recycle steam fed to the reformer inlet. Using the steam properties defined so far and the remaining reformer hardware IDVs, the reformer computations are then performed to size the reformer and compute the helium side outlet temperature and pressure drop.

Flow path computations from the reformer to the steam generator define the helium inlet properties at the steam generator. The steam outlet temperature and pressure are both IDVs. The iteration variable used to achieve energy balance convergence in the intermediate helium loop is steam generator helium outlet temperature. Once the flow rate and helium inlet temperature and pressure are known, the steam generator subroutine can be used to size the steam generator, compute steam flow rate, and determine helium outlet pressure.

The circulator inlet conditions are defined by steam generator-to-circulator flow path computations, and the circulator performance is computed in the same manner as for the primary loop, with the circulator outlet pressure set as an IDV. Intermediate helium loop energy balance convergence is checked by comparing the computed IHX inlet temperature with its required value (an IDV). Subsequent estimates of steam generator helium outlet temperature are updated according to the computed error in the temperature at the IHX cold inlet, analogous to the method described for the reactor inlet in the primary loop.

The steam produced in the steam generator has three uses. It provides the steam which is mixed with fresh methane and the recycle stream to form the reformer feed; it provides heat and power (from turbo-generator sets) for the process plant; and it provides a separate flow to drive the turbogenerator for the house load (including the primary helium circulator motors) and to power the turbines which drive the secondary helium circulators. If the steam produced by the steam generators is not sufficient to supply all three uses, the iteration variable (methane mass flow rate) must be reduced to achieve a balanced energy split in the secondary helium loop. The overall energy and mass balance is also handled by using a linear fractional secant method to revise the estimated methane mass flow rate for each iteration until convergence is reached.

The logic structure of the program required to model the steam reforming of methane to produce hydrogen is extremely complex. This process has been modeled separately in a process design program called DESIGN 2000, developed and supported by the Chemshare Corporation for running on a royalty basis. The complexity, size, and computer running time of this program preclude its incorporation into PHRED as a subroutine to model the process plant. Therefore, the process plant is modeled in PHRED by a series of data tables and curve-fit subroutines which represent the results of a series of independent runs of the DESIGN 2000 program. The extent of these data will be expanded as additional process information becomes available and as studies using PHRED indicate areas of design which improve the overall plant economics.

3.3. PROCESS CODE DEVELOPMENT

3.3.1. Process Performance Model

The process performance model joins the NHS which supplies energy for the steam-methane reforming reaction

$$H_2O + CH_4 \rightarrow CO + 3H_2$$

with a process which carries out the remaining processing steps necessary to produce hydrogen at 97% purity ready for delivery to the consumer. By joining the NHS model to the process model, the interactions between the two can be fully recognized since there are significant trade-offs between process and reactor energy requirements, energy quality, and equipment performance. The design basis for the hydrogen plant is shown in Table 3-6.

TABLE 3-6
DESIGN CRITERIA FOR HYDROGEN PLANT

Feedstock composition	100% CH_4 Dry Sulfur <0.2 vppm
Feedstock conditions	10.3 MPa (1500 psia) 294 K (70°F)
Product composition	97% H_2 3% CH_4 Dry
Product conditions	10.3 MPa (1500 psia) 328 K (130°F)
By-products	None
Minimum process temperature(a)	328 K (130°F)
Makeup water	294 K (70°F) Mineral content undefined
Soil conditions	Undefined
Seismic category	Unspecified
Location	Unspecified

(a) For rejecting energy to the environment.

The process plant model receives fresh methane feed at the site boundary and reduces the pressure to that required for steam-methane reforming. The flowsheet shown in Fig. 3-3 shows the interactions between the process and the reactor plant and the heat recovery trains involved. Detailed flowsheets and descriptions can be found in Chapter 4 of Ref. 3-1. Recycle methane and hydrogen from cryogenic upgrading of the hydrogen product are added to give the total reformer feed. This feed to the steam-methane reformer is preheated by heat exchange with reformer product and steam is added. The steam-methane mixture is then reheated again to 839 K (1050°F) before flowing to the reformer, which is part of the NHS model. The steam-methane mixture is then reformed within the NHS model. The NHS varies the methane flow to change the reformer and steam generator heat duty to close the reactor heat balance.

The reformer feed is made up of three components: the fresh methane feed, recycled methane and hydrogen from the cryogenic unit, and steam. The fresh methane feed is varied by the computer program PHRED as necessary for heat balance considerations, and the two recycle quantities are calculated after an initial guess based on x, the fraction of methane reacted within the reformer, using the following equations:

$$\frac{CH_4 \text{ Reformer Feed}}{CH_4 \text{ Fresh Feed}} = \frac{1}{0.1219\, x^2 + 0.9878\, x} , \qquad (1)$$

$$H_2 \text{ Reformer Feed} = 0.01435\, (CH_4 \text{ Reformer Feed} - CH_4 \text{ Fresh Feed}) . \qquad (2)$$

The feed temperature to the reformer is fixed at 839 K (1050°F), and the steam flow to the reformer is a code input defined by the mole ratio of the steam to methane. Figure 3-2 indicates the streams that emanate from the process model and the equation numbers that describe them.

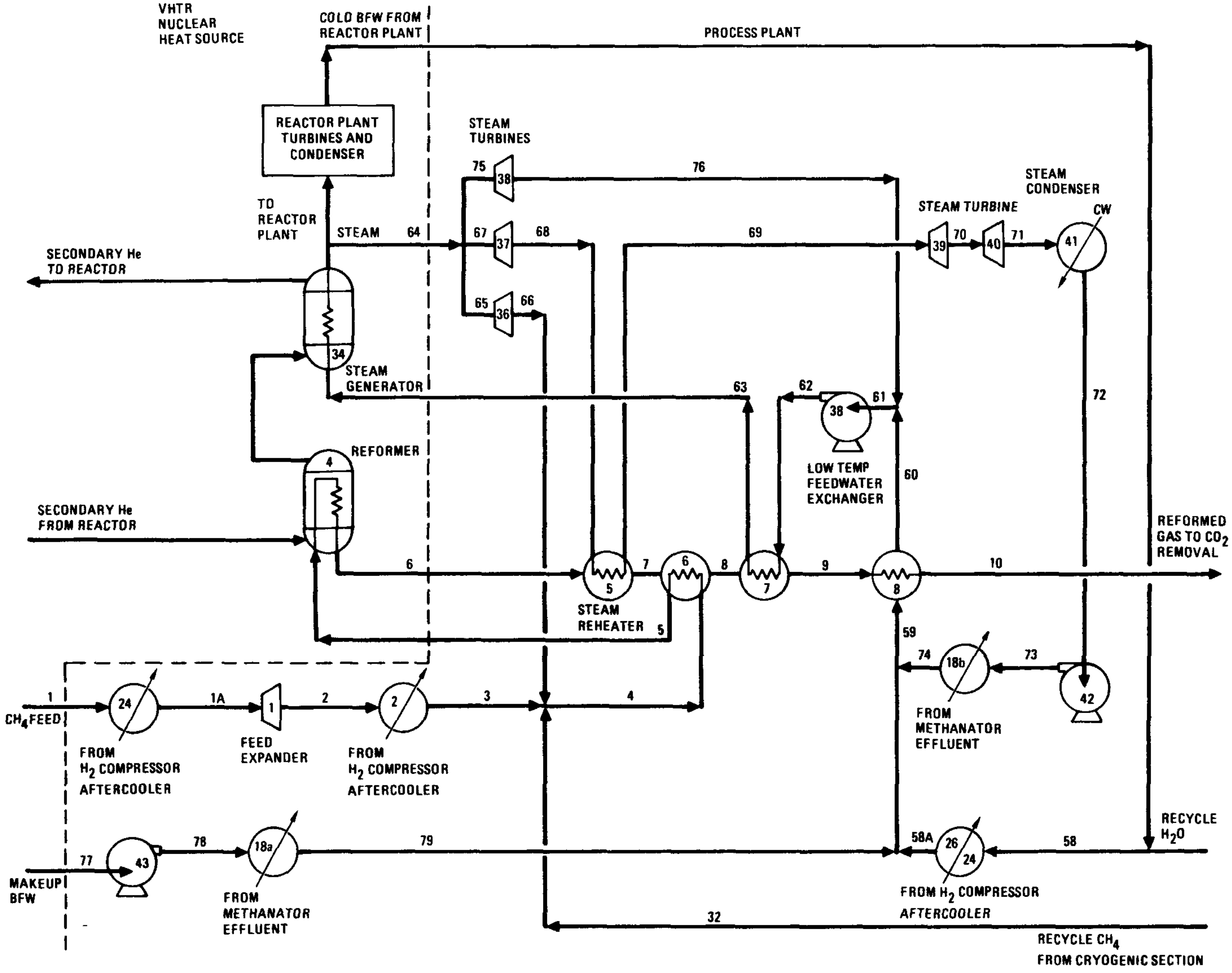


Fig. 3-3. Reforming section flowsheet with NHS tie-ins

The steam flow that is required by the process model is described by

$$\frac{H_2O \text{ to Process Moles}}{CH_4 \text{ Reformer Feed Moles}} = S/C + \left[0.050 + 0.175 \left(\frac{\Delta P}{1.241 \times 10^6} \right)^{0.25} \left(\frac{S/C}{3.75} \right)^{-0.5} \left(\frac{X}{0.699} \right)^{-0.7} \right] (3.525\, x + 0.4353\, x^2) \quad , \qquad (3)$$

where ΔP = reformer pressure drop, Pa,

S/C = steam-to-carbon mole ratio,

x = methane conversion (moles methane from reformer)/(moles methane to reformer).

The steam temperature and pressure to the process are fixed at 17.2 MPa (2499 psia) and 783 K (950°F).

The makeup water to the process is correlated by

$$\frac{\text{Makeup } H_2O}{CH_4 \text{ Reformer Feed}} = 1.828\, x + 0.2255\, x^2 \quad . \qquad (4)$$

The water flow to the steam generator can then be calculated by material balance considerations in the process and reactor plant steam requirements:

$$\text{Water to Steam Generator} = \text{Makeup } H_2O + H_2O \text{ to Process} + \text{Steam for Reactor Plant} \qquad (5)$$

The feedwater temperature to the steam generator is a function of the process heat recovery train, shown in Fig. 3-3, which recovers energy from the reformer effluent. This temperature is described by the following equation:

$$\text{Feedwater Temperature (K)} =$$

$$-192 + 1179 \left(\frac{S/C}{3.75}\right)^{0.5} \left(\frac{0.699}{X}\right)^{0.5} \left(\frac{CH_4 \text{ Ref.}}{\text{Total Steam}}\right)^{0.24} \qquad (6)$$

The total product hydrogen which is used in the economic calculations, but not in the heat and material balance calculations, is a function of the methane feed to the reformer and the conversion and is expressed as follows:

$$\frac{\text{Product } H_2}{CH_4 \text{ Reformer Feed}} = 3.528\ X + 0.4353\ x^2 \ . \qquad (7)$$

3.3.2. Output Modification of DESIGN 2000

In order to automate the calculation of costs for the process plant, a computer program has been developed which combines the three output tapes which make up a complete process design. This code produces an equipment list including a description of the process streams into and out of each equipment item. Major plant equipment included are heat exchangers and condensors, pumps and compressors, vessels, and reactors. Sample output is shown in Fig. 3-4.

3.3.3. Process Cost Model

The costs for the process plant components have been correlated from previous cost estimates (Refs. 3-2, 3-3) based on parameters which are

```
TAPE NUMBER                         01424      01424      01424      01424
EQUIPMENT NO.                       10         11         15         18
EXTERNAL NAME                          E702       E703       E706       E77A
U BTU/HR/FT2/F                        50.00      50.00      50.00      50.00
AREA/SHELL FT2                        .1814+06   .8390+05   .7141+05   .1977+05
NO. SHELLS                            1.000      1.000      1.000      1.000
SHELL PASSES                          1.000      1.000      1.000      1.000
TUBE PASSES                           1.000      1.000      1.000      1.000
T OUT SPEC  DEG F                     270.0      229.0      451.0
WATER      GAL/HR                     .1986+08   .5091+07   .0000      .1377+07
DELTA P-STR 1       PSIA              2.000      2.000      2.000      1.000
DELTA P-STR 2       PSIA              .0000      .0000      2.000      .0000
Q STR1 BTU/HR                         .2482+10   .6361+09  -.3596+09   .1720+09
DELTA Q             BTU/HR
LOG MEAN T.  F                        273.6      151.6      100.7      174.0
WATER T IN   F                        90.00      90.00      .0000      90.00
WATER T OUT  F                        105.0      105.0      .0000      105.0
................,.
STREAM INPUT # 1
STREAM NUMBER                       11         12         15         18
EQUIP CONXION                       R701-E702  E702-E703  DELP-E706  E706-E77A
                                    ( 9)-(10)  (10)-(11)  (14)-(15)  (15)-(18)
VAPOR FRACTION                      1.0000     .74493     1.0000     1.0000
TEMPERATURE F                       500.00     270.00     229.00     329.71
PRESSURE PSIA                       276.00     274.00     267.00     258.00
ENTHALPY BTU/HR                     .14679+10  .10137+10  .31086+09  .46650+09
LB/FT3       T-P                    .36411                .15707     .13484
Z-FACTOR     T-P                    .99312                1.0068     1.0061
GAL/MIN      STP
MMSCF/DAY    STP                    3678.5                2004.3     1969.9
MOLECULAR WT                        13.491     13.491     4.3770     4.4537

FLOW RATES
  LBMOL/HR

HYDROGEN                            .18725+06  .18725+06  .18719+06  .18087+06
METHANE                             18043.     18043.     18037.     19930.
CO                                  1256.0     1256.0     1255.8     .00000
CO2                                 45818.     45818.     637.32     .00000
WATER                               .15152+06  .15152+06  12947.     15477.
                                     --------   --------   --------   --------
            TOTAL                   .40388+06  .40388+06  .22007+06  .21628+06
                                         ↓          ↓          ↓          ↓
```

FOLLOWED BY STREAM INPUT NO. 2, STREAM OUTPUT NO. 1, AND STREAM OUTPUT NO. 2.

Fig. 3-4. Sample of output from equipment list code available from PHRED. The various equipment items are broken down into the following ten categories:

1. Pumps.
2. Compressors.
3. Heat exchanger.
4. Expanders.
5. Flash drums.
6. Shift converters.
7. Methanator.
8. Absorber.
9. Regenerator.
10. Cryogenic section.

The costs for the above items are correlated based on methane conversion, hydrogen from the reformer, the steam-methane ratio, and the reformer pressure drop.

The costs for each category are broken down into an FOB cost, an installed cost, a labor cost, and a material cost. Contingency and scaling factors are applied and direct and indirect costs are calculated, and an escalation factor is applied to correct for the date of the desired estimate. The total process plant investment is then calculated. This cost is used as input to PHRED to price the hydrogen product.

REFERENCES

3-1. "Process Heat Reactor Design and Analysis, Final Report" DOE Report GA-A15137, General Atomic Company, February 1979.

3-2. "Nuclear Process Heat (VHTR) Commercialization Study, Final Report," DOE Report GA-A14668, Vol. 1, General Atomic Company, December 1977.

3-3. Peterman, D. D., <u>et al.</u>, "Studies of the Use of High-Temperature Nuclear Heat from an HTGR for Hydrogen Production," NASA Report NASA CR-134919 (GA-A13391), General Atomic Company, September 30, 1975.

4. SAFETY AND LICENSING

4.1. STATUS SUMMARY

The major effort under this task during FY-79 was the preparation of a topical report (Ref. 4-1) summarizing those safety studies which are applicable to the 842-MW(t) side cavity VHTR. Although the reported studies are qualitative in nature owing to the preliminary stage of design, the report identifies and focuses on those features of the VHTR which are particularly important from safety and licensing viewpoints. These features include the IHX, the use of the IHX for shutdown cooling, and the potential impact of adjacent process plants.

New studies performed during FY-79 are summarized in Section 4.2 and 4.3. These studies relate to depressurization accidents in the primary and secondary coolant systems and the need to continue development of the helium-cooled CAHE.

4.2. DEPRESSURIZATION ACCIDENTS

The design of PCRV penetration closures in accordance with the ASME Code, Section III, Class 1, "Code Requirements for Pressure Vessels," reduces the probability of accidental depressurization of the primary coolant to the containment to a low value. However, even if this event should occur, the Accident Initiation and Progression Analysis (AIPA) study has shown that associated risks to the public would be extremely low. Containment atmosphere cleanup systems are not required to maintain offsite dose levels to acceptable values, and the containment can easily be designed to accommodate the primary coolant released from the PCRV without the need for an active heat removal system. Afterheat cooling can be provided by either the main loops or the CACS.

Secondary fluid lines that must be postulated to fail and considered in the design of the containment are the secondary helium lines. Failure of these lines in the containment is considered to be comparable to a steam line break for the HTGR-SC.

Failure of the secondary helium lines in the containment affects the containment building in a manner similar to that of a design basis depressurization accident (DBDA). However, the secondary helium is relatively free of fission products, with only small amounts of tritium released and possibly trace amounts of fission products due to small leaks in IHXs, so the consequences are more benign. Further, the helium inventory of an intermediate loop will be less than the helium inventory of the primary loop. Consequently, containment pressures and temperatures will generally be lower than those experienced from a DBDA.

The outlet leg of the IHX operates at 900°C (1650°F). Therefore, there could be some local areas in the containment where high-temperature helium jets must be considered. Nonetheless, normal design procedures would dictate that equipment required for safety be located away from the local hot areas. Consequently, this local high temperature is expected to cause inconsequential local overheating of concrete surfaces or steel coverplates.

The safety issue addressed during FY-79 that significantly impacts the primary system design is the consequence of pressure transients in the IHX initiated by a failure of the secondary helium piping. The secondary helium loop comprises nuclear safety class 2 piping out to the insolation valves and non-nuclear safety class piping beyond the valves. This classification reflects the use of this portion of the piping for emergency shutdown purposes and, if necessary, as an auxiliary fission product barrier should there be any failure of the IHX to act as the primary system pressure boundary.

The IHX is an ASME Code, Division III, Class 1 vessel, designed and qualified to exacting standards. The design must consider the following failure modes:

1. Failure of the warm secondary loop piping can lead to a large pressure differential across the warm side tubesheet of the IHX. Normally this pressure drop is small since the primary and secondary loop pressures are almost equal. However, if there were an undetected crack in the tubesheet, a significant failure could occur. This would be very undesirable since there would be a potential free flow path area to the outside well in excess of the normal 2540 mm (100 in.^{2}) typically used for design purposes. Measures to avoid or mitigate this failure include:

    a. Designing the warm side tubesheet for the maximum pressure differential (10-hr duration of this pressure differential at design temperatures is currently assumed).

    b. Performing in-service inspection of the tubesheet to detect any cracks as required by the ASME Code.

    c. Using fast-acting (1- to 2-s closure time) valves to limit the pressure differential across the tubesheet.

    d. As an alternative (though unlikely), demonstrating that the tubesheet failure does not impair safe shutdown of the reactor (primary system pressure change is small over the closure time of the secondary loop valves) and that fission product releases represent no hazard to the public or operating personnel.

    e. Introducing a pressure relief valve or a sacrificial membrane between the primary and secondary sides of the IHX.

2. Failure of the hot secondary loop piping can lead to a large pressure differential across the hot side tubesheet of the IHX. The

consequences of this failure and the design means to avoid or mitigate them are essentially the same as for item 1 above.

3. Failure of the intermediate loop piping, either hot or warm side, near the steel primary closure dome could lead to large thrusts on that dome or on the warm side tubesheet. These thrusts and their duration need to be assessed carefully because they will become design requirements for the dome and tubesheet. Anchoring of the ducts to reduce the magnitude of such thrusts will need to be explored in order to keep the above design requirements within acceptable bounds. At the same time, the anchoring must not be so rigid as to restrain the movement resulting from normal thermal expansion.

It is possible that the potential for failure of other components such as the reformer and steam generator may also need to be examined, even though these units are some distance from the reactor and are in themselves not related to nuclear safety. The question is whether their failure can be induced by a piping failure and, if so, whether it can result in more severe design requirements imposed on the primary system and containment.

Severe pressure transients are not new to the reactor industry. Pressurized water reactors (PWRs) experience very large pressure transients if primary coolant pipe failure occurs. The intermediate loop situation is similar to the PWR situation except for the relatively high temperatures expected in some VHTR applications. Although detailed analyses have not been performed to assure that failure of the intermediate helium piping can be tolerated, there are sufficient design options to provide confidence that a safe and licensable plant will be achieved.

4.3. HELIUM-COOLED CAHE EVALUATION

Because of the potential deleterious consequences of water ingress events in HTGRs, especially the VHTR, which could have higher graphite temperatures than the HTGR-SC, a helium-to-helium CAHE is being considered as an alternate to the water-cooled CAHE for the VHTR. Continued development of the helium-cooled CAHE is predicated on the unacceptability of the water-cooled CAHE in the VHTR application. This section summarizes a qualitative study of the potential for water ingress in the VHTR.

A review of the current VHTR design identified the following potential sources of water ingress to the primary coolant system of the small VHTR:

1. Water-cooled CAHEs.
2. Main loop circulators, water-lubricated bearings.
3. PCRV liner cooling system.
4. Auxiliary loop circulator, water-cooled coils.
5. Steam generator [17.24 MPa (2500 psia)] leak to intermediate loop [5.27 MPa (765 psia)] to primary loop [4.90-4.95 MPa (711-718 psia)].

Of the above sources, only the first two appear to be of any major significance from a safety point of view. The PCRV liner cooling system operates at a pressure significantly below that of the primary coolant system, except at refueling conditions, and a double barrier exists between the water and primary coolant helium. Water ingress from the cooling coils of the auxiliary circulators would be extremely small, since only a small amount of water is contained in the coils and associated systems and it is at a lower pressure than the primary coolant except at refueling conditions. The final two sources require both failure of secondary side components and failure of the safety class 1 intermediate loop heat exchanger. Since the process side of the reformer operates at a lower pressure than the intermediate loop, it is unlikely that there can be any significant inleakage of process steam and gas into the intermediate loop. The secondary side of the steam generator, however, operates at approximately 17.24 MPA (2500 psia), and therefore tube failures will cause steam to ingress into the intermediate loop. While appropriate measures must be taken to prevent large amounts of moisture from entering or existing in the intermediate loop, this source of potential moisture ingress to the primary coolant system should be insignificant. The consequences of water ingress from main loop circulator water-lubricated bearings will require investigation. Although this source is not considered in this discussion, it should be part of any significant study of VHTR water ingress.

An extensive analysis of CAHE leaks was performed in 1975 for the HTGR-SC to develop a method of protecting against CAHE leaks other than by the method of primary coolant sampling previously identified. In addition to reducing the cost of a moisture protection system for CAHE loops, there was a need to alter the accident sequence initiated by a CAHE leak occurring at power. With the design existing prior to the analysis, a CAHE leak would cause a reactor trip on high primary coolant moisture. In accordance with Nuclear Regulatory Commission (NRC) requirements at that time, loss of offsite power (LOSP) and an additional single failure also had to be assumed. For the HTGR-SC, an LOSP causes immediate loss of the main loops, and if the single failure is assumed in the non-leaking CACS loop, core cooling would be dependent on the leaking CACS for adequate forced cooling. To some degree, these concerns impact the VHTR. However, the issue of concern here is the consequence of water inleakage from a leaking CAHE and not whether or not adequate core cooling can be maintained during shutdown.

The consequences of greatest concern during CAHE leaks at full power are core and support post oxidation and the increase in primary coolant pressure. At refueling conditions, temperatures are well below the threshold temperature of steam-graphite reactions, and therefore only primary coolant system pressure is of major concern. Since VHTR graphite temperature during refueling will also be well below the reaction threshold temperature, only CAHE leaks at power will be considered further.

There is considerable difficulty in selecting a design basis CAHE leak while the reactor is at power. None of the credible tube failure mechanisms can lead to a catastrophic failure (i.e., an offset rupture) of a tube when the external helium pressure is greater than that of the water inside the tube. Nevertheless, an offset rupture of a single tube was assumed for verifying the adequacy of the CAHE leak protection system proposed for the HTGR-SC.

For an offset tube rupture, the downstream end of the CAHE comes into equilibrium with the primary coolant system while the upstream end maintains the dynamic head of the CACWS pump. This head becomes the driving force for the leak, which was calculated to be approximately 0.3 kg/s (0.6 lb/sec) for an offset rupture of the largest lead-in tube for the CAHE design at that time.

In OXIDE-3 studies of the consequences of an HTGR-SC leak at power, a conservative leak rate of 0.45 kg/s (1.0 lb/sec) for the offset rupture of a single CAHE tube was assumed. Two accident scenarios were evaluated. In the first case, the CAHE leak was evaluated assuming a plant protection system shutdown and loss of main loop cooling (LOMLC) (i.e., the accident scenario which had to be assumed with a pre-analysis protection). In the second case, the leak was evaluated assuming that the moisture monitor system was "locked-out" and an "orderly plant shutdown" took place. In both cases a total of 4536 kg (10,000 lb) of water was assumed to leak into the primary coolant system [more than 3923 kg (9000 lb)] of inleakage occurs after the CAHE is isolated). Since core temperatures control the steam-graphite reaction, it is not surprising that the orderly shutdown case resulted in less core burnoff than the case assuming early plant protection system action. It was concluded that for leak rates less than 0.45 kg/s (1.0 lb/sec), the primary coolant system overpressure trip point was not reached or exceeded and core support post-oxidation is just within emergency limits. These studies were performed for the 2000-MW(t) plant and thus were conservative for the 3000-MW(t) plant.

It is readily apparent that the higher graphite temperature of the VHTR and higher primary coolant system moisture concentration for the same CAHE leakage rate will increase the amount of burnoff over the HTGR-SC values. An increase of several hundred degrees Fahrenheit in graphite temperature will increase the reaction rate by an order of magnitude. Burnoff is roughly proportional to the square root of reaction rate. Thus, the consequences of CAHE leaks in the VHTR are expected to be worse than those for the HTGR-SC, assuming the same accident scenarios, protective system, setpoints, etc. An OXIDE-3 analysis of the VHTR will be required to provide an accurate assessment of the burnoff and increase in primary coolant system pressure. Excessive steam-graphite reaction could cause lifting of the PCRV relief valves and release of flammable gases to the containment.

The consequences of a CAHE leak at power are dependent on the assumed behavior of the main loops during the event. This assumed behavior will depend not only on process side requirements but also on NRC philosophy regarding LOMLC.

Another aspect of the problem which makes it difficult to assess the allowable extent of moisture ingress for the VHTR is the fact that criteria for the allowable graphite burnoff to maintain adequate safety margins on ultimate strength are still under development for the HTGR. Graphite strength loss is strongly dependent on the burnoff profile, and perhaps on graphite type. While burnoffs of 1% or less are considered acceptable on the basis of current knowledge, no specific criteria have been established.

It appears that leaks associated with a water-cooled CAHE might be acceptable from a safety standpoint provided proper protection systems and adequate redundancy in auxiliary cooling are employed. However, a definitive conclusion regarding the acceptability of a CAHE leak at power can be reached only when a detailed OXIDE-3 analysis is performed for the VHTR. For similar protection features and inleakage, the consequences of a CAHE leak in the VHTR will be more severe than for an HTGR-SC. The current design basis CAHE leak at power for the HTGR-SC assumes an offset rupture of a single tube. Because the external pressure is greater than the pressure inside the tube, such a failure appears to be incredible. Therefore, some relief may be obtained by redefining the design basis event for the VHTR. In addition, the CAHE leak detection system for the VHTR need not be the same as that proposed for the HTGR-SC. Nevertheless, without an OXIDE-3 analysis of a spectrum of CAHE leak accident scenarios, it cannot be concluded that associated water ingress will be a problem with the VHTR. Therefore, the evaluation of a helium-cooled CAHE has been continued.

REFERENCE

4-1. Deremer, R.K., D.D. Orvis, and J.N. Sharmahd, "Process Heat Reactor Safety Evaluation Report," DOE Report GA-A15523, General Atomic Company, to be published.

5. DESIGN CRITERIA

5.1. STATUS SUMMARY

Conceptual designs for the steam turbine system arrangement and the plant electrical system were prepared. Estimates of the primary and secondary coolant system helium inventories were also prepared. A preliminary Balance of Plant Requirements document was prepared. In addition, work on a Reference Plant Design Report was initiated.

5.2. STEAM TURBINE ARRANGEMENT

The VHTR reference plant contains two identical secondary helium loops, each of which has a reformer, a steam generator, a secondary helium circulator, an auxiliary cooling loop, and interconnecting piping.

The major part of the steam produced in each steam generator at 17.24 MPa (2500 psia) and 510°C (950°F) is supplied to the process plant for reformer feed and other uses. The remainder expands through a nonextraction turbine-generator, exhausting at 3.79 MPa (550 psia). The turbine exhaust steam supplies a nonextraction, condensing turbine which drives the secondary helium circulator. Both turbines are fairly standard, commercially available units. The turbine-generators are similar to the high-pressure section of a 150-MW utility turbine. The circulator drive turbines are similar to equipment drive turbines used in petrochemical process industries.

It is assumed that all steam that supplies the process, including the reformer, is condensed, treated, and returned to the steam generators at approximately 21.1 MPa (3060 psia) and 293°C (560°F). Any required make-up is added in the process plant.

In view of the high temperature of the feedwater returned from the process, no feedwater heaters are used with the circulator drive turbines. Deaeration is accomplished in the condensor.

As shown in the heat balance diagram in Fig. 5-1, each secondary loop provides 10,900 kW of electrical energy plus 290,000 kg/h (640,000 lb/hr) of steam to the process plant.

An auxiliary boiler to enable startup of the secondary loop circulator is sown in Fig. 5-1. If simultaneous startup of both loops is not required, one boiler can serve the entire plant.

5.3. ELECTRICAL LINE DIAGRAM

A single-line diagram (Fig. 5-2) has been prepared to show the major electrical loads and their supply. Motors below 100 hp and the various 120-V ac and dc loads are not shown. Feeds to the motor control centers, from which these loads may be supplied, are representative but do not indicate the actual quantity requirements. The same applies to the 4160-V motors shown. The loads and voltages are given in Table 5-1.

The main circulator motors are not rated as Class IE but are shown with Class IE 4160-V pony motors. The pony motors are shown as single- or two-speed motors driving the main motor through an overriding clutch. The pony motors can be variable speed but only at the price of considerable expense and additional complexity.

The electrical system shown in Fig. 5-2 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

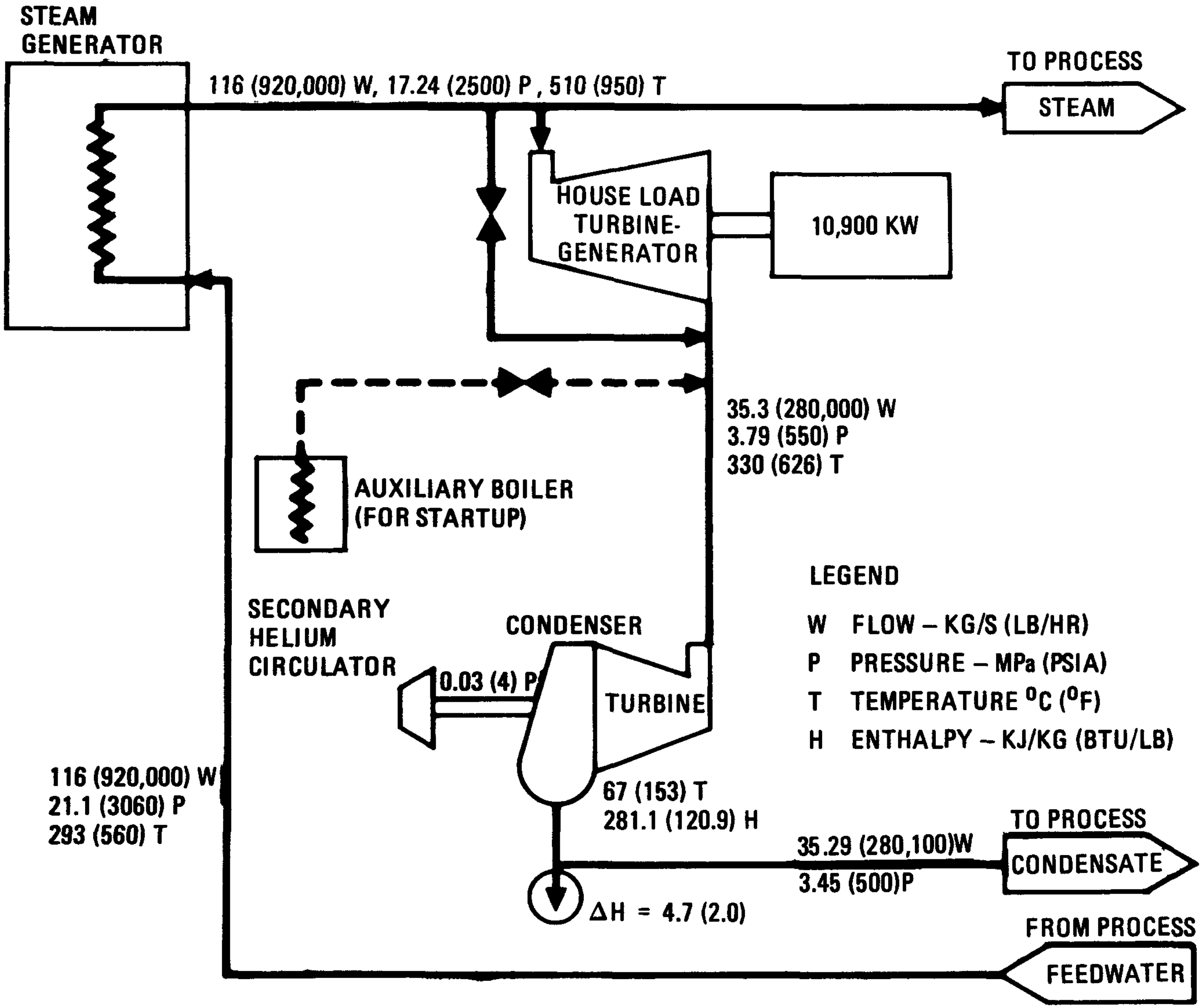
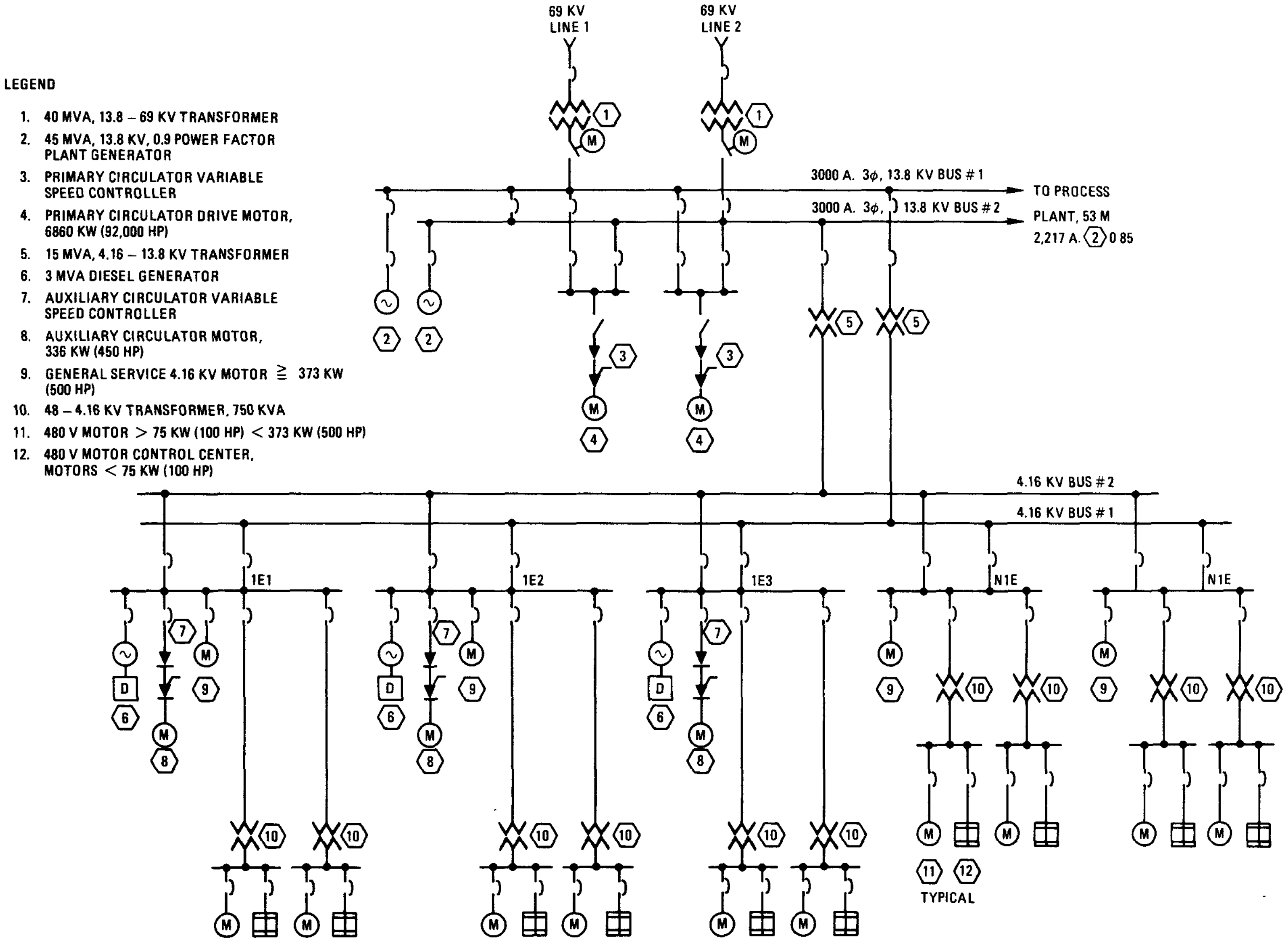


Fig. 5-1. Steam turbine system heat balance



LEGEND

1. 40 MVA, 13.8 – 69 KV TRANSFORMER
2. 45 MVA, 13.8 KV, 0.9 POWER FACTOR PLANT GENERATOR
3. PRIMARY CIRCULATOR VARIABLE SPEED CONTROLLER
4. PRIMARY CIRCULATOR DRIVE MOTOR, 6860 KW (92,000 HP)
5. 15 MVA, 4.16 – 13.8 KV TRANSFORMER
6. 3 MVA DIESEL GENERATOR
7. AUXILIARY CIRCULATOR VARIABLE SPEED CONTROLLER
8. AUXILIARY CIRCULATOR MOTOR, 336 KW (450 HP)
9. GENERAL SERVICE 4.16 KV MOTOR ≧ 373 KW (500 HP)
10. 48 – 4.16 KV TRANSFORMER, 750 KVA
11. 480 V MOTOR > 75 KW (100 HP) < 373 KW (500 HP)
12. 480 V MOTOR CONTROL CENTER, MOTORS < 75 KW (100 HP)

Fig. 5-2. Electrical single-line diagram for 842-MW(t) VHTR

TABLE 5-1
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, 13.67 MW at 0.95 power factor and 0.96 efficiency	2	X		15,000	13,800
2	Primary He circulator pony motor	2		X	1,000	4,160
3	Auxiliary circulator drive motor	1		X	900	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-1E 0.48 to 4.16 kV transformers(b)	4	X		2,215	4,160
11	1E 0.48 to 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, 870 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.

generation required). Once internal power generation is established, a second steam loop can be started with subsequent startup of the second process loop. With both internal generators operating, no outside power is required.

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

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

5.4. HELIUM INVENTORY

5.4.1. Primary Coolant System

The helium inventory within the PCRV primary system was estimated by computing the void volumes using VHTR design layout drawings and system parameters and by scaling data previously developed for HTGR-SC plants. The estimated primary coolant helium inventory for the VHTR is 1107 m^3 (39,084 ft^3) (void volume). Based on the primary system design operating conditions, the total weight of helium is 2985 kg (6581 lb) and the estimated circulating helium weight is 1983 kg (4371 lb).

In areas where detailed data were not available, such as primary loop duct lengths, penetration sizes, and CACS cooling loop design parameters, reasonable assumptions were made to determine helium volumes. The calculations are of a preliminary nature and are considered as a best estimate until more detailed drawings and information are available. A summary of the estimate is given in Table 5-2.

TABLE 5-2
PRIMARY COOLANT HELIUM INVENTORY SUMMARY

	Inventory [kg (lb)]		
	Circulating[a]	Passive	Total
Core inlet plenum	444 (979)	--	444 (979)
Active core	286 (630)	--	286 (630)
Side reflector region	158 (348)	259 (572)	417 (920)
Core outlet plenum	221 (487)	--	221 (487)
Core outlet ducts	17 (37)	15 (33)	32 (70)
IHX cavities	715 (1576)	77 (170)	792 (1746)
Circulators and core inlet ducts	142 (314)	78 (171)	220 (485)
Refueling penetrations	--	337 (742)	337 (742)
CACS cavity and ducts	--	237 (522)	237 (522)
	1983 (4371)	1002 (2210)	2985 (6581)

[a] During normal full-power operation.

5.4.2. Secondary Coolant Helium

The helium inventory of the secondary coolant system, including the shutdown cooling loops, was calculated based on the piping arrangements shown on the reference plant layout drawings and current equipment designs. Average helium pressures and temperatures in the major piping segments and in the equipment items were used. Where detailed equipment design information was not available, estimates based on previous HTGR helium inventory calculations for systems with similar equipment were used. An allowance for helium permeability in the hot pipe and equipment internal thermal barrier was included.

Table 5-3 summarizes the calculated inventories of the piping segments and equipment in the main secondary helium loops and in the shutdown cooling loops. The total system helium inventory is estimated to be 3155 kg (6955 lb) for the reference plant arrangement. Arrangements with greater separation distance between the reactor and process plant would, of course, result in a larger helium inventory.

5.5. BALANCE OF PLANT REQUIREMENTS DOCUMENT

A preliminary Balance of Plant Requirements (BOPR) was prepared for the reference design 842-MW(t) VHTR. The BOPR is a plant specification which defines the requirements that the VHTR NHS imposes on the BOP.

The BOP requirements specified in the BOPR are normally based upon a scope of supply and division of responsibility agreed upon by GA and a plant purchaser. The present issue for the VHTR assumes a typical scope of supply based on past experience and consistent with that used for the BOP cost estimate.

Federal regulations, regulatory guides, and applicable industry standards are not duplicated in the BOPR. The purchaser has the responsibility of assuring that these and the requirements set forth in the BOPR are met.

TABLE 5-3
SECONDARY COOLANT HELIUM INVENTORY SUMMARY

	Inventory, Per Loop [kg (lb)]		
	Circulating[a]	Passive	Total
IHX	117 (258)	--	117 (258)
Hot pipe, IHX to reformer	190 (419)	65 (143)	255 (562)
Reformer	336 (741)	83 (182)	419 (923)
Hot pipe, reformer to steam generator	19 (41)	6 (14)	25 (55)
Steam generator	164 (361)	--	164 (361)
Cold pipe, steam generator to circulator	57 (126)	--	57 (126)
Helium circulator	39 (85)	--	39 (85)
Cold pipe, circulator to IHX	349 (770)	--	349 (770)
Shutdown system hot piping	--	35 (78)	35 (78)
Shutdown helium circulator	--	19 (42)	19 (42)
Shutdown helium cooler	--	74 (164)	74 (164)
Shutdown system cold piping	--	61 (135)	61 (135)
Total per loop	1270 (2801)	344 (758)	1614 (3559)
Total plant, two loops	2540 (5602)	688 (1516)	3228 (7118)

[a] During normal full-power operation.

6. COST ESTIMATES

6.1. STATUS SUMMARY

A cost estimate of the BORP was prepared during FY-79. The estimate includes BORP items associated with the reactor and secondary helium system, including the turbine-generators and associated steam piping, but excludes process plant and feedwater return system equipment.

6.2. BOP COST

Table 6-1 summarizes costs for the BORP and NHS-related items considered to be in the BORP scope for an equilibrium plant. Table 6-2 gives a breakdown of the BORP costs, and Table 6-3 lists the scope of items included in each of the cost categories in Table 6-2.

The BORP estimate was updated during the fourth quarter of FY-79 to reflect more recent cost information available from the HTGR program. The basis for the BORP costs is now the estimate for an 1170-MW(t) HTGR cogeneration plant. Since the VHTR plant size is relatively close to the reference plant size, the validity of the BORP estimated cost is judged to be improved compared with the estimate reported in Ref. 6-1.

The costs for many of the buildings are the same as those in the reference plant, and the remainder are adjusted for size using costs from the reference plant estimate.

The BORP portion of the reactor plant equipment cost was scaled from the reference plant, recognizing that the cost would not be a straight line change.

TABLE 6-1
842-MW(t) VHTR BALANCE OF REACTOR PLANT COST SUMMARY
(Equilibrium Plant; January 1, 1978; $ × 10^6)

NHS-Related Items in BOP	31.4
BOP Direct and Indirect Costs	
Turbine-generator	9.0
Direct field work	147.4
Field indirects	50.5
Home office indirect and fee	57.7
Total BOP (without contingency)	264.6
Contingency	39.7
Total BOP (with contingency)	304.3
Total including NHS-related items	335.7

TABLE 6-2
842-MW(t) VHTR BALANCE OF REACTOR PLANT COST BREAKDOWN
(Equilibrium Plant; January 1, 1978; $ × 10^6)

Account Number	Description	Material and Equipment	Labor	Total
21	Structures and improvements	30,429	34,444	64,873
22	Reactor plant equipment	21,485	8,097	29,582
23	Turbine plant equipment	14,264	3,517	17,781
24	Electric plant equipment	13,219	11,610	24,829
25	Misc. plant equipment	5,351	2,585	7,936
26	Main condenser heat rejection system	--	--	--
27	Process gas equipment	155	11,233	11,388
	Total direct BORP costs	84,903	71,486	156,389
91	Engineering and construction management			
	Field distributables			50,484
	Engineering and construction management			57,731
	Total engineering and construction management			108,215
	Subtotal BORP			264,604
	Recommended budgetary contingency			39,691
	Total BORP with contingency			304,295

TABLE 6-3
SCOPE OF BORP COST ESTIMATE FOR 842-MW(t) VHTR

21. <u>Structures and Improvements</u>

    211. Yard work
    212. Containment building
    213. Turbine building
    215. Reactor service building
    217. Fuel storage building
    218A. CAD building
    218B. Administration building
    218D. Fire pump house
    218E. He storage area
    218H. Diesel cooling and fuel oil storage
    218I. Access building
    218J. Piping penetration vaults
    218S. Holding pond
    218T. Ultimate heat sink structure
    218U. Ultimate heat sink tunnels
    218V. Control room emergency air

22. <u>Reactor Plant Equipment</u>

    221. Reactor equipment
    222. Main heat transfer loop
    223. Safeguards cooling system
    224. Radioactive waste treatment and disposal
    225. Nuclear fuel handling and storage
    226. Other reactor plant equipment
    227. Instrumentation and control

TABLE 6-3 (Continued)

23. Turbine Plant Equipment

    231. Turbine generator and condensers for secondary He circulators
    232. Steam piping
    233. Turbine bypass system
    235. Turbine auxiliaries
    236. Instrumentation and control
    237. Miscellaneous
    238. Equipment installation
    239. Penetrations

24. Electric Plant Equipment

    241. Switch gear
    242. Station service equipment
    243. Switchboards
    244. Protective equipment
    245. Electrical structures and wire closures
    246. Power and control wiring

25. Miscellaneous Plant Equipment

    251. Transportation equipment
    252. Air, water, and steam service systems
    253. Communications system
    254. Furnishing and fixtures

27. Process Gas Equipment

    271. Secondary helium piping and valves
    272. Foundations and pipe supports

NHS-Related Items in BOP

- PCRV construction
- Erection of PCRV liners and penetrations
- Control rod drive and reflector storage wells
- Operational and startup test equipment
- Transportation

The turbine plant scope is markedly different from the reference plant, and appropriate adjustments were made. The turbine-generator costs for the VHTR were estimated based on published cost data. Condensing, feedwater, and condenser heat rejection system costs are not included and are assumed to be part of the process plant.

The electric plant equipment cost is scaled appropriately from the reference plant cost.

The miscellaneous plant equipment costs were developed using the same crane, communications, and furnishings costs as for the reference plant and scaling the costs for the air, water, and steam service systems.

The process gas equipment consists primarily of the secondary helium piping. The costs for this system were developed "in house" using appropriate unit piping costs derived from information provided by architect/engineers for other HTGR studies. The valve costs were based on vendor-supplied information in response to quotation requests. Insulation and thermal barrier costs were based on costs developed for other HTGR programs.

The field indirect costs are in direct proportion to the same reference plant costs based on the direct field labor.

Home office costs are included at 10% less than the reference plant costs because of the reduced scope of the VHTR plant.

The 1170-MW(t) HTGR cogeneration plant estimate did not include an Allowance for Indeterminates. Therefore, a 15% contingency has been added to the VHTR BORP costs.

REFERENCE

6-1. "HTGR Process Heat Program Design and Analysis, Semiannual Progress Report for the Period October 1, 1978 through March 31, 1979," DOE Report GA-A15405, General Atomic Company, July 1979.

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