DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

GA-C14822
(6/30/78)

167/61/8-2

PROCESS HEAT REACTOR DESIGN AND ANALYSIS

SEE LETTER DATED
JULY 31, 1978

Quarterly Progress Report

for the period

April 1 through June 30, 1978

by

Project Staff

General Atomic Project 3253
San Francisco Operations Office

Department of Energy

Contract EY-76-C-03-0167

Project Agreement No. 61

ATO3-76SF71061

This is an informal progress report prepared for the contracting agency. The results and data may be preliminary or tentative and therefore are subject to revision or correction. This report may contain patentable material on which patent applications have not yet been filed and further distribution of this report should not be made without the prior approval of the contracting agency or the contractor.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
MGW

GENERAL ATOMIC COMPANY

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ABSTRACT

This report summarizes the third quarter FY-1978 results of concept design studies at General Atomic Company (GA) for an 842-MW(t) VHTR utilizing an intermediate helium heat transfer loop to provide thermal energy for the production of reducing gas ($H_2 + CO$) by steam-reforming a light hydrocarbon. Basic carbon sources may be coal, residual, or oil shale.

The report summarizes the various plant configurations selected for the study and presents the conceptual plant layout drawings. Results of design studies on the intermediate heat exchanger are also presented. The status of the performance/optimization code development is discussed, and completion of the core auxiliary cooling system study is summarized.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

CONTENTS

ABSTRACT	iii
1. INTRODUCTION	1-1
2. CONCEPT DESIGN	2-1
2.1. Status Summary	2-1
2.2. Plant Layout Alternates	2-2
2.2.1. Fort St. Vrain Type PCRVs	2-3
2.2.2. Large HTGR Side Cavity Type PCRVs	2-20
2.2.3. Thermal Barrier Conceptual Study	2-21
2.2.4. Plant Layout Evaluations	2-27
2.3. IHX Studies.	2-27
3. PERFORMANCE/OPTIMIZATION PROGRAM	3-1
3.1. Status Summary	3-1
3.2. Computer Program Development	3-1
3.2.1. Program Logic Structure	3-1
3.2.2. Component Model Development	3-7
3.3. Reformer/Process Performance	3-8
4. SAFETY-RELATED DESIGN	4-1
4.1. Status Summary	4-1
4.2. CACS Studies	4-2
4.2.1. CACS Description and Operation	4-4
4.2.2. CACS Design Criteria	4-5
4.2.3. Method of Analysis	4-6
4.2.4. Material Temperatures	4-7
4.2.5. Transient Analysis Results	4-9
4.2.6. Design Features	4-11
4.2.7. He/He CAHE Design Parameters	4-19
5. REFERENCES	5-1

FIGURES

1.	Concept 1, Large HTGR type, three loops	2-5
2.	Concept 2, FSV type, three loops	2-7
3.	Concept 3, Large HTGR type, two loops	2-9
4.	Concept 4, FSV type, two loops	2-11
5.	Concept 5, Large HTGR type, one loop	2-13
6.	Concept 6, FSV type, one loop	2-15
7.	Containment designs	2-17
8.	VHTR core support pad assembly	2-23
9.	VHTR bottom head thermal barrier.	2-25
10.	Reformer flow sheet model	3-9
11.	Comparison of cryogenic separation flow sheets.	3-10
12.	Schematic representation of CACS model	4-3
13.	Transient temperature response of lower cross duct thermal barrier	4-10
14.	Temperature transients during DBDA cooldown with pure helium coolant	4-12
15.	Temperature transients during pressurized cooldown with pure helium coolant	4-13
16.	Basic mechanical arrangement of bayonet tube CAHE	4-16
17.	Bayonet tube arrangement	4-17

TABLES

1(a).	VHTR intermediate heat exchanger values for one heat exchanger for 1-loop plant.	2-29
1(b).	VHTR intermediate heat exchanger values for one heat exchanger for 2-loop plant.	2-32
1(c).	VHTR intermediate heat exchanger values for one heat exchanger for 3-loop plant.	2-35
2.	VHTR intermediate heat exchanger pressure loss.	2-42
3.	Values of independent design variables	3-5
4.	Summary of primary helium loop performance	3-6
5.	Comparison of temperature approach	3-12
6.	Effect of feed composition and separator pressure	3-13

TABLES (Continued)

7.	Major design parameters and data for 842-MW(t) VHTR core . . .	4-8
8.	Water-cooled CACS performance data	4-14
9.	Major CAHE design data for water-cooled design	4-18
10.	Helium-cooled CACS performance data	4-20

1. INTRODUCTION

Work leading to conceptual definition of an 842-MW(t) process heat VHTR for syngas ($H_2 + CO$) production (or other processes) continued during the third quarter of FY-1978. Results for this period are reported herein.

Plant arrangement studies have resulted in the development of the primary system layout drawings for the one-, two-, and three-loop designs for both Large HTGR and Fort St. Vrain (FSV) type vessels. The intermediate heat exchanger (IHX) sizing study for the alternate helical tube design was completed and is discussed in this report. The straight tube counterflow IHX design, however, will continue to be the preferred design approach.

Thermal analysis of emergency cooling transients has been performed, and the core auxiliary cooling system (CACS) requirements have been defined. Preliminary sizing studies were completed for two alternate core auxiliary heat exchanger (CAHE) concepts (i.e., water-cooled and helium-cooled designs) and are discussed in this report.

The development of the VHTR system performance/optimization code (PHRED) has progressed to include test verification of the program logic in achieving energy and mass balance in the reactor plant.

2. CONCEPT DESIGN

2.1. STATUS SUMMARY

During this reporting period, the conceptual design effort addressed development of plant layout drawings and various system and design issues that affect the VHTR arrangements. Six configurations of the 842-MW(t) VHTR were selected for study, and conceptual design drawings of each have been prepared. Three configurations have heat exchangers in side cavities adjacent to the core cavity, similar to GA's Large HTGR steam cycle (HTGR-SC) design, while the other three configurations have heat exchangers in cavities below the core cavity, similar to the arrangement employed in the HTGR constructed at FSV.

The configurations include one-, two-, and three-loop designs. Heat exchangers have been sized for the plants and mechanically arranged to fit. The selected heat exchanger design is an axial counterflow unit. Helically wound units with enhanced heat transfer surfaces have also been studied.

Electrically driven helium circulators have been chosen for the primary system, a choice currently adopted for the HTGR-SC design. The secondary system circulators are commercially available centrifugal machines with steam turbine drives.

The (safety class) main loops are employed for emergency as well as normal operations. Consequently, the number of core auxiliary loops (to provide the required redundancy) varies as the number of main loops varies. The core auxiliary heat exchangers have been sized for the required heat duty by using the code (RECA3) which computes the transient behavior following reactor emergency shutdown. The results of the analysis indicate the auxiliary circulator power is approximately the same as for the

Large HTGR-SC unit. It was found necessary to raise the temperature limitation on the lower cross duct thermal barrier cover plate about 56°C (100°F) above Large HTGR-SC values. The higher temperatures encountered with the VHTR in comparison with the HTGR-SC necessitate a cover plate material change.

Cost studies of the six configurations have been initiated and initial results obtained. The capital costs appear slightly higher for the FSV type arrangements, but the cost uncertainties are believed larger than the observed differences. Criteria and weighting factors for evaluating the six designs have been prepared and evaluations will begin shortly.

2.2. PLANT LAYOUT ALTERNATES

The initial screening study of prestressed concrete reactor vessel (PCRv) configurations conducted during the first quarter of FY-1978 (Ref. 1) examined nine possible variations, including two-, three-, and four-loop designs, with single cavity and multiple cavity PCRvs of different types. Of these nine, four were eliminated from further consideration and five were selected for further study. The four-loop designs, including the German THTR single cavity design, were eliminated.

Work during the second and third quarters of FY-1978 was directed at more detailed development of one-, two-, and three-loop designs, with variations of both the FSV type PCRv (components below the core) and the Large HTGR type PCRv (components beside the core). The concept of three separated IHX bundles in a single cavity (alternate 5 of the first quarter FY-1978 study) proved to be unattractive upon more detailed development, and instead the concepts with one IHX, two circulators, and two auxiliary cooling loops were examined.

Arrangement drawings for six concepts were prepared:

Concept 1. Large HTGR type, three loops (Fig. 1)

Concept 2. FSV type, three loops (Fig. 2)

Concept 3. Large HTGR type, two loops plus one auxiliary loop (Fig. 3)

- Concept 4. FSV type, two loops plus one auxiliary loop (Fig. 4)
- Concept 5. Large HTGR type, one loop plus two auxiliary loops (Fig. 5)
- Concept 6. FSV type, one loop plus two auxiliary loops (Fig. 6)

The arrangements include the PCRV, primary coolant system components, containment building, support mat, secondary helium piping within the containment, and piping penetration valve enclosure structures.

2.2.1. Fort St. Vrain Type PCRVs

The general arrangement of the PCRV for Concepts 2,* 4,* and 6* is similar to that of the FSV PCRV in that the heat exchangers and helium circulators are located below the reactor core and return helium to the core is conducted up through an annular passage between a core shroud structure and the core cavity liner. However, it differs from the FSV arrangement in three respects:

1. Circumferential wire winding is used instead of linear tendons for horizontal prestressing.
2. Heat exchangers and circulators are located in individual cavities below the core rather than in a single cavity. This avoids the need for a structurally independent core support floor and results in a shorter PCRV with improved seismic design.
3. The PCRV is located within a conventional reactor containment building designed to contain the primary coolant release following reactor depressurization accidents. (In contrast, the FSV reactor building is designed for controlled leakage rather than as a pressure-containing structure.) This requires a different approach to the PCRV support structure and to provisions for equipment installation and removal.

*These designs are considered proprietary to General Atomic and are the subject of an "invention disclosure."

Figure 7 illustrates three approaches to the design of the containment, support structure, and provisions for equipment handling. In all three concepts (2A, 2B, and 2C), the PCRV support consists of a thick slab that transmits gravity and seismic loads to the containment wall, providing space below for piping and equipment handling. While these features are considered to be conceptually feasible, they represent departures from recent PCRV design experience and would entail some design development.

Inherent in this type of vessel arrangement is the need to provide sufficient space below the reactor to permit heat exchanger and circulator replacement. This requirement poses a unique design situation for the containment and mat. Concept 2C offers the preferred integration of this vessel arrangement with a viable containment scheme. The advantages and disadvantages of the three concepts are discussed below.

2.2.1.1. Concept 2C. As shown in Fig. 7, equipment installation and replacement are conducted through the refueling hatch, with the component passed vertically through a penetration in the support slab to the "handling chamber." Helium lines also penetrate the support slab and exit at a grade-level valve house. This arrangement permits the vessel support slab to be located at the elevation of the containment mat.

Gravity and lateral loads are resisted by soil pressure acting on the mat outside the containment wall. It is anticipated that this arrangement will most efficiently resist radial shear associated with design basis depressurization accident (DBDA) pressure loads on the containment while maintaining a relatively low profile and minimizing the seismic problems with the core and fuel handling machine encountered in previous single cavity PCRV designs.

Measures to isolate the lower chamber from earth pressures may be necessary. This can be accomplished by placing a compressible material (polystyrene or polyurethane foam) outside the walls and backfilling with lean concrete. This procedure has been employed on existing plants to control loading imposed on Class 1 structures.

Fig. 1. Concept 1, Large HTGR type, three loops

Fig. 3. Concept 3, Large HTGR type, two loops

Fig. 5. Concept 5, Large HTGR type, one loop

Fig. 7. Containment designs

PAGES 2-12 to 2-18
WERE INTENTIONALLY
LEFT BLANK

2.2.1.2. Concept 2A. This concept also represents a feasible approach and may pose fewer construction problems than Concept 2C. Characteristics that make it less desirable than Concept 2C include:

1. The need for a large penetration in the region of high base shear at the junction of the containment wall and mat.
2. The location of the vessel support at grade level, about 21.3 m (70 ft) above the mat, which will introduce large shears into the containment wall, cause substantial amplification of seismic disturbances to the core and top-head region, and impose large radial shear loads on the PCRV support slab due to DBDA pressure in the upper and lower chambers.

2.2.1.3. Concept 2B. This concept has the smallest containment volume, which is achieved by incorporating a large-diameter penetration and decoupling the handling chamber from the containment. Both of these features introduce structural design issues. It is not clear that the mat can be designed for DBDA loading with the proposed 12.2-m (40-ft) diameter penetration. The closure for this penetration is unprecedented and would require development of the handling equipment. Design of the mat to span the void introduced by the handling chamber also presents a unique foundation problem.

The recommendation that Concept 2C be adopted is based on a cursory review of the three concepts and their anticipated structural response. As stated earlier, all are departures from current design precedent. If it is decided to pursue these concepts further, it will be necessary to perform scoping analyses of PCRV support slab and containment interaction and to obtain more detailed evaluation of the lower chamber and foundation design problems.

2.2.2. Large HTGR Side Cavity Type PCRVs

PCRv Concepts 1, 3, and 5 are variations of the side-mounted, multicavity vessels introduced in the British Hartlepool and Heysham AGR plants and of several designs developed in studies of large HTGR-SC plants. Several arrangement studies at GA have demonstrated the advantages of offsetting the reactor core from the geometric center of the periphery of the vessel in terms of vessel diameter and plant arrangement. The use of this approach for VHTR Concepts 1, 3, and 5 permits a reduction in vessel diameter of about 1.8 m (6 ft) relative to arrangements with the core cavity in the center of the vessel.

The offset core, multicavity PCRv configuration has been chosen for the Large HTGR-SC program. No major impact on design confidence for this configuration relative to concentric core, multicavity PCRvs has been identified. While concrete stress distributions are somewhat more complex for an asymmetric cavity arrangement, the analytical capability for prediction of elastic response and the establishment of bounds on time dependent effects and ultimate strength as developed for symmetric vessels is equally valid and applicable. No need for additional methods development before committing to this configuration has been identified in the HTGR-SC program. However, a confirmatory model test to facilitate licensing and demonstrate design adequacy is currently planned.

2.2.2.1. Containment Building Arrangements. For these studies the reactor containment building was sized consistent with current HTGR plant practice, allowing annular space for PCRv wire winding and space above the refueling floor level for refueling equipment handling. Containments were assumed to be constructed of reinforced concrete with hemispherical domed heads. Space was allowed for PCRv re-tensioning operations without removal of piping or other major equipment. It was assumed that installation and removal of major equipment in the PCRv, such as the IHXs, would be accomplished by means other than the building crane, such as hydraulic jacking. For all concepts except Concept 6 (one IHX, two CACS loops, components below the

core), the PCRVR is located centrally in the containment. For Concept 6 the PCRVR is offset from the containment centerline to allow space for the large equipment removal hatch in the PCRVR support mat.

Containment isolation valves in the secondary helium and auxiliary heat exchanger cooling water piping are located in Class 1 structures adjacent to the containment. Separation walls are provided to prevent accidents that disable one loop from affecting other loops. Containment piping penetrations are separated by a minimum ligament of three penetration diameters. Flexibility is provided in the piping routing to allow for thermal expansions between the PCRVR piping connections and the containment penetrations. Because PCRVR piping connections are on the top head in the side cavity concepts, greater lengths of within-containment piping are required than for the bottom cavity concepts.

Containment design pressures, based on conditions following depressurization accidents, are estimated to be in a range similar to that for Large HTGR-SC plants. Minimum containment wall thickness requirements are expected to be limited by construction and shielding requirements rather than by pressure design. Therefore, the same thickness was assumed for all concepts.

2.2.3. Thermal Barrier Conceptual Study

A brief conceptual study was conducted to define the design of the thermal barrier to support the costing exercises. Also included was a recommendation for the design of the bottom head support pad assembly.

The lower plenum sidewall thermal barrier cover plates illustrated in Fig. 8 are approximately 0.6 m^2 by 13 mm thick. Each panel is supported from the liner by an integral central fixture with four studs (with a considerable degree of redundancy) attaching to the liner. This is an inherent safety feature in that the loss of a stud does not induce a significant eccentric load reaction on the central fixture or panel. The remaining

portion of the thermal barrier consists of high-temperature fibrous insulation blankets and oxide dispersion strengthened (ODS) seal sheets. With this system some degree of thermal barrier component replaceability is possible.

The bottom head thermal barrier and support pad assembly, shown in Fig. 9, is similar to the HTGR-SC baseline design. However, due to the core outlet temperatures in the VHTR, a change in materials is warranted. The design function of this region is twofold: (1) to take the direct impingement of the core outlet flow and (2) to support the core support floor blocks and posts.

The surface taking the direct impingement is slip cast fused alumina, hexagonal block with an approximate area of 0.8 m^2 (8.6 ft^2). This material will sustain normal operating temperatures in excess of 870°C (1598°F) as well as faulted conditions to approximately 1650°C (3002°F). Immediately beneath this block is a similar slip cast fused silica block which, being less thermally conductive, will reduce the thermal impedance. Separating the silica block from the lightly compressed insulation composite is a Hastelloy-X seal sheet. The remaining portion of the thermal barrier is standard Class A except for the cover plate and pad container material, which is stainless steel.

The post support assembly consists of a series of ceramic pads designed to carry the load of the floor blocks and post while minimizing the heat transfer to the liner. The assembly is segmented primarily to reduce the thermal stresses in the pads. As currently designed the upper four pads are high-density, high-purity alumina. (The uppermost pad(s) could conceivably be changed to silicon nitride if creep becomes a factor.) The lower pad is silica. During installation the stack is located in relation to a stainless steel cup with alumina dowels.

Fig. 8. VHTR core support pad assembly

Fig. 9. VHTR bottom head thermal barrier

PAGES 2-25 to 2-26
WERE INTENTIONALLY
LEFT BLANK

2.2.4. Plant Layout Evaluations

The differences in major construction material requirements between the six concepts do not appear to be excessive and are compensating to some extent. In general, the side cavity concepts result in a larger PCRV concrete volume and tensioning steel requirements but somewhat smaller liner/thermal barrier and containment building requirements than the bottom cavity concepts. For both side cavity and bottom cavity concepts, the single IHX design appears to require a somewhat larger PCRV and containment building than the multiple IHX designs.

As discussed in Section 2.2.1, the FSV type bottom cavity concepts are considered to present more structural design and construction problems than the side cavity concepts, and side cavity concepts have the advantage of being able to use much of the PCRV design development conducted for the HTGR-SC.

Material take-offs for the six concepts have been made, and preparation of comparative cost trends is in progress. Cost estimates will be combined with evaluation of other factors (plant performance, maintainability, availability, design credibility/feasibility, development requirements, licensing/safety, constructability, sizing flexibility, etc.). Results of the evaluation and subsequent development work will be reported in the fourth quarter of FY-1978.

2.3. IHX STUDIES

During this reporting period, efforts were concentrated on attempts to reduce the size of the IHXs and then, in the necessary areas, to complete the designs in sufficient detail to support the comparative costing exercises.

The size reduction attempts were aimed primarily at reducing the length of the IHXs to better accommodate the mounting position beneath the

core in the vertical plant configuration. A cross-flow type heat exchanger was tried using helically wound 12.7-mm (1/2-in.) o.d. tubes. Vertical and horizontal pitches were varied to adjust the shell side pressure loss, and the results indicated a reduction in IHX length was theoretically possible. However, the use of helical tubes requires a larger tube bundle diameter in order to maintain the shell side pressure loss at a reasonable level. In addition, although the tube pitch required to reduce the length may be acceptable from a fluid dynamic standpoint, it appears to be too low for practical design of the radial tube support plates.

A version of the helically wound heat exchanger using finned tubes was also tried. This design yielded improved results over the non-finned tubes but still did not produce a heat exchanger smaller than the roughened straight tube design. In all the helically wound tube versions, the limiting factor was the size of the ligaments in the tube support plates. For this study, a "conventional" support plate design such as that used in the HTGR-SC steam generator design was adopted. It is possible that further design efforts in the tube support area could produce a method which would make these limits less stringent.

The same basic 127 straight tube module described in the last quarterly report (Ref. 2) for the heat exchangers was chosen for all plant configurations. Thus, the active bundle lengths for the IHXs in the one-, two-, and three-loop plants are identical. The major difference between these heat exchangers is the number of modules employed: the one-loop plant IHX requires 516 modules, the two-loop plant IHX requires 256 modules for each loop, and the three-loop plant IHX requires 169 modules for each loop. As described in Ref. 2, these tube modules are subheadered to form a full homogeneous tube field broken only by the center-mounted return duct for the secondary gas and by a 3-mm (1/8-in.) thick shroud around each module. Each of the module subheaders is welded to a lead tube. The hot end lead tubes, which are made of Inconel 617, are larger than the 2-1/4 Cr-1 Mo cold end lead tubes (see Table 1) and are curved slightly to penetrate the hot conical header.

TABLE 1(a)
 VHTR INTERMEDIATE HEAT EXCHANGER
 VALUES FOR ONE HEAT EXCHANGER FOR 1-LOOP PLANT

Primary He flow rate	113.7 kg/s (902.3×10^3 lb/hr)
Primary He inlet temperature	950°C (1742°F)
Primary He inlet pressure	4.95 MPa (718 psia)
Primary He discharge temperature	470°C (878°F)
Secondary He flow rate	113.2 kg/s (898.7×10^3 lb/hr)
Secondary He inlet temperature	417°C (782°F)
Secondary He inlet pressure	5.274 MPa (765 psia)
Secondary He discharge temperature	899°C (1650°F)
Secondary He discharge pressure	5.183 MPa (751.8 psia)
Heat transferred	881.2 MW (3.01×10^9 Btu/hr)
Heat transfer surface area	21,232 m ² (228,542 ft ²)
Mean temperature difference	34°C (94°F)
Number of tubes per HX	65,532
Number of tubes per module	127
Number of modules per HX	516
Module tube	
O.D.	11.1 mm (0.4375 in.)
Material	Inconel 617
Wall thickness (hot section)	1.52 mm (0.06 in.)
Length (hot section)	1.83 m (6 ft)
Wall thickness (cool section)	1.09 mm (0.043 in.)
Length (cool section)	1.38 m (24.2 ft)
Mean tube side film coefficient	1516 W/m ² ·K (267 Btu/hr-ft ² -°F)
Mean shell side film coefficient	2243 W/m ² ·K (395 Btu/hr-ft ² -°F)
Mean tube wall coefficient	23.2 W/m·K (13.4 Btu/hr-ft-°F)
Module lead tubes (hot end)	
O.D.	116.8 mm (4.6 in.)
Wall thickness	16.76 mm (0.66 in.)
Average length	1.83 m (6 ft)
Material	Inconel 617

TABLE 1(a) (Continued)

Module lead tubes (cold end)

O.D.	76.2 mm (3.0 in.)
Wall thickness	6.35 mm (0.25 in.)
Average length	3.66 m (12 ft)
Material	2-1/4 Cr-1 Mo

Module subheaders (hot end)

Max. O.D.	152.4 mm (6 in.)
Max. wall thickness	38.1 mm (1.5 in.)
Length	406.4 m (16 ft)
Material	Inconel 617

Module subheaders (cold end)

Max. O.D.	152.4 mm (6 in.)
Max. wall thickness	31.75 mm (1.25 in.)
Length	406.4 m (16 ft)
Material	Inconel 617

Center return duct

Hot section

O.D.	922 mm (62.25 in.)
Wall thickness	165.1 mm (6.5 in.)
Length	3.05 m (10 ft)
Material	Inconel 617
Thermal barrier	82.5 mm (3-1/4 in.) on outside surface

Center section

O.D.	1619.2 mm (63.75 in.)
Wall thickness	139.7 mm (5.5 in.)
Length of section	6.77 m (22.2 ft)
Material	
Thermal barrier	82.5 mm (1-3/4 in.) on inside surface

TABLE 1(a) (Continued)

Cold section	
O.D.	1538 mm (60.55 in.)
Wall thickness	99.1 mm (3.9 in.)
Length of section	3.8 m (12.5 ft)
Material	Inconel 617
Thermal barrier	82.5 mm (1-3/4 in.) on inside surface
Hot end header	
Max. O.D.	3142 mm (123.7 in.)
Max. wall thickness	365.8 mm (14.4 in.)
Length	1029.1 m (40.5 ft)
Material	Inconel 617
Tube plate	
O.D.	442 m (17.4 ft)
Thickness	121.9 mm (4.8 in.)
Material	2-1/4 Cr-1 Mo
Tube bundle outer shroud	
Hot section	
Thickness	12.7 mm (0.5 in.)
Max. length	279.4 m (11 ft)
Material	Incoloy 800
Cold section	
Thickness	12.7 mm (0.5 in.)
Length	495.3 m (19.5 ft)
Material	2-1/4 Cr-1 Mo

TABLE 1(b)
 VHTR INTERMEDIATE HEAT EXCHANGER
 VALUES FOR ONE HEAT EXCHANGER FOR 2-LOOP PLANT

Primary He flow rate	113.7 kg/s (902.3×10^3 lb/hr)
Primary He inlet temperature	950°C (1742°F)
Primary He inlet pressure	4.95 MPa (718 psia)
Primary He discharge temperature	470°C (878°F)
Secondary He flow rate	113.2 kg/s (898.7×10^3 lb/hr)
Secondary He inlet temperature	417°C (782°F)
Secondary He inlet pressure	5.274 MPa (765 psia)
Secondary He discharge temperature	899°C (1650°F)
Secondary He discharge pressure	5.191 MPa (757.9 psia)
Heat transferred	437.2 MW (1.49×10^9 Btu/hr)
Heat transfer surface area	10,534 m ² (113,385 ft ²)
Mean temperature difference	34°C (94°F)
Number of tubes per HX	32,512
Number of tubes per module	127
Number of modules per HX	256
Module tube	
O.D.	11.1 mm (0.4375 in.)
Material	Inconel 617
Wall thickness (hot section)	1.52 mm (0.06 in.)
Length (hot section)	1.83 m (6 ft)
Wall thickness (cool section)	1.09 mm (0.043 in.)
Length (cool section)	7.38 m (24.2 ft)
Mean tube side film coefficient	1516 W/m ² ·K (267 Btu/hr-ft ² -°F)
Mean shell side film coefficient	2243 W/m ² ·K (395 Btu/hr-ft ² -°F)
Mean tube wall coefficient	23.2 W/m·K (13.4 Btu/hr-ft-°F)
Module lead tubes (hot end)	
O.D.	116.8 mm (4.6 in.)
Wall thickness	16.76 mm (0.66 in.)
Average length	1.5 m (5 ft)
Material	Inconel 617

TABLE 1(b) (Continued)

Module lead tubes (cold end)	
O.D.	76.2 mm (3.0 in.)
Wall thickness	6.35 mm (0.25 in.)
Average length	3.05 m (10 ft)
Material	2-1/4 Cr-1 Mo
Module subheaders (hot end)	
Max. O.D.	152.4 mm (6 in.)
Max. wall thickness	38.1 mm (1.5 in.)
Length	406.4 m (16 ft)
Material	Inconel 617
Module subheaders (cold end)	
Max. O.D.	152.4 mm (6 in.)
Max. wall thickness	31.75 mm (1.25 in.)
Length	406.4 m (16 ft)
Material	Inconel 617
Center return duct	
Hot section	
O.D.	1079.5 mm (42.5 in.)
Wall thickness	114.3 mm (4.5 in.)
Length	3.05 m (10 ft)
Material	Inconel 617
Thermal barrier	82.5 mm (3-1/4 in.) on outside surface
Center section	
O.D.	1137.9 mm (44.8 in.)
Wall thickness	99.1 mm (3.9 in.)
Length of section	6.77 m (22.2 ft)
Material	Inconel 617
Thermal barrier	82.5 mm (1-3/4 in.) on inside surface

TABLE 1(b) (Continued)

Cold section	
O.D.	1071.9 mm (42.2 in.)
Wall thickness	66.0 mm (2.6 in.)
Length of section	3.50 m (11.5 ft)
Material	Inconel 617
Thermal barrier	82.5 mm (1-3/4 in.) on inside surface
Hot end header	
Max. O.D.	2199.6 mm (86.6 in.)
Max. wall thickness	256.5 mm (10.1 in.)
Length	8.38 m (27.5 ft)
Material	Inconel 617
Tube plate	
O.D.	4.12 m (13.5 ft)
Thickness	91.4 mm (3.6 in.)
Material	2-1/4 Cr-1 Mo
Tube bundle outer shroud	
Hot section	
Thickness	9.53 mm (0.375 in.)
Max. Length	3.35 m (11 ft)
Material	Incoloy 800
Cold section	
Thickness	9.5 mm (0.375 in.)
Length	495.3 m (19.5 ft)
Material	2-1/4 Cr-1 Mo

TABLE 1(c)
 VHTR INTERMEDIATE HEAT EXCHANGER
 VALUES FOR ONE HEAT EXCHANGER FOR 3-LOOP PLANT

Primary He flow rate	113.7 kg/s (902.3×10^3 lb/hr)
Primary He inlet temperature	950°C (1742°F)
Primary He inlet pressure	4.95 MPa (718 psia)
Primary He discharge temperature	470°C (878°F)
Secondary He flow rate	113.2 kg/s (898.7×10^3 lb/hr)
Secondary He inlet temperature	417°C (782°F)
Secondary He inlet pressure	5.274 MPa (765 psia)
Secondary He discharge temperature	899°C (1650°F)
Secondary He discharge pressure	5.193 MPa (753.2 psia)
Heat transferred	288.6 MW (0.985×10^9 Btu/hr)
Heat transfer surface area	6954 m ² (74,852 ft ²)
Mean temperature difference	34°C (94°F)
Number of tubes per HX	21,463
Number of tubes per module	127
Number of modules per HX	169
Module tube	
O.D.	11.1 mm (0.4375 in.)
Material	Inconel 617
Wall thickness (hot section)	1.52 mm (0.06 in.)
Length (hot section)	1.83 m (6 ft)
Wall thickness (cool section)	1.09 mm (0.043 in.)
Length (cool section)	7.38 m (24.2 ft)
Mean tube side film coefficient	1516 W/m ² ·K (267 Btu/hr-ft ² -°F)
Mean shell side film coefficient	2243 W/m ² ·K (395 Btu/hr-ft ² -°F)
Mean tube wall coefficient	23.2 W/m·K (13.4 Btu/hr-ft-°F)
Module lead tubes (hot end)	
O.D.	116.8 mm (4.6 in.)
Wall thickness	16.76 mm (0.66 in.)
Average length	1.2 m (4 ft)
Material	Inconel 617

TABLE 1(c) (Continued)

Module lead tubes (cold end)

O.D.	76.2 mm (3.0 in.)
Wall thickness	6.35 mm (0.25 in.)
Average length	2.4 m (8 ft)
Material	2-1/4 Cr-1 Mo

Module subheaders (hot end)

Max. O.D.	152.4 mm (6 in.)
Max. wall thickness	38.1 mm (1.5 in.)
Length	406.4 mm (16 in.)
Material	Inconel 617

Module subheaders (cold end)

Max. O.D.	152.4 mm (6 in.)
Max. wall thickness	31.75 mm (1.25 in.)
Length	406.4 mm (16 in.)
Material	Inconel 617

Center return duct

Hot section

O.D.	922 mm (36.3 in.)
Wall thickness	99.1 mm (3.9 in.)
Length	3.05 m (10 ft)
Material	Inconel 617
Thermal barrier	82.5 mm (1-3/4 in.) on outside surface

Center section

O.D.	983.5 mm (38.22 in.)
Wall thickness	85.3 mm (3.36 in.)
Length of section	6.77 m (22.2 ft)
Material	Inconel 617
Thermal barrier	82.5 mm (1-3/4 in.) on inside surface

TABLE 1(c) (Continued)

Cold section	
O.D.	927.1 mm (36.5 in.)
Wall thickness	57.1 mm (2.25 in.)
Length of section	3.5 m (11.5 ft)
Material	Inconel 617
Thermal barrier	82.5 mm (1-3/4 in.) on inside surface
Hot end header	
Max. O.D.	1917.7 mm (75.5 in.)
Max. wall thickness	205.7 mm (8.1 in.)
Length	609.6 mm (24 in.)
Material	Inconel 617
Tube plate	
O.D.	3.51 m (11.5 ft)
Thickness	101.6 mm (4 in.)
Material	2-1/4 Cr-1 Mo
Tube bundle outer shroud	
Hot section	
Thickness	9.5 mm (0.375 in.)
Max. length	279.4 m (11 ft)
Material	Incoloy 800
Cold section	
Thickness	9.5 mm (0.375 in.)
Length	495.3 m (19.5 ft)
Material	2-1/4 Cr-1 Mo

The conical header receives the 899°C (1650°F) secondary helium from the tube modules and delivers it to the center return duct. The header is made of Inconel 617 and is designed to minimize the length of the header, which still accommodates all the module lead tubes and does not require an unrealistic wall thickness. Design conditions followed those imposed on the module tubes, which included both normal and nearly balanced inside and outside pressures and an emergency loss of inside pressure condition. The header thickness is influenced by the ligament efficiency in the lead tube penetration region, the height and angle of the core, the pressure and temperature of the material, and the buckling instability during the condition of short-term loss of internal pressure. A trade-off between lead tube pitch and core angle versus core thickness and height was therefore made, the results of which are shown in Table 1. In addition, 76-mm (3-in.) thick stiffening rings were added between horizontal tube rows on the inside surface to help reduce the buckling instability.

The hot lead tubes meet the outside surface of the cone perpendicularly and are welded to nozzles machined into the core forging. This method reduces the hole diameter in the cone to the inside diameter of the lead tube and thereby improves the ligament efficiency over that obtained if the tubes penetrated the surface.

The large end of this truncated cone is closed with a dished head which is mounted with the concave side outward. This mounting method both shortens the assembly and reduces its thickness required for the loss of inside pressure condition. It is designed to withstand the small [345 kPa (50 psi)] long-term differential pressure on its convex side.

The small end of the truncated cone is welded to the center return duct. A 3-m (10-ft) portion of the hot end of this duct is covered with 83 mm (3-1/4 in.) of thermal barrier on the outside surface, causing the duct to run slightly hotter than the 899°C (1650°F) secondary helium flowing within it. At this point the inside diameter of the center return duct is expanded by 45 mm (1-3/4 in.) so that thermal barrier of this

thickness may be applied to the inside surface. The primary coolant gas outside the duct ranges from 843°C (1550°F) down to the discharge temperature of 470°C (878°F) in this area and thus acts as a coolant for the now bare outside surface. The duct wall thickness is reduced here (see Table 1) and once again at the low-temperature end before passing through the tubesheet. The center return duct is also designed for short-term loss of internal pressure.

The tubesheet is of spherical design with its concave side facing in. As shown in Table 1, the tubesheet is relatively thin [76 mm (3 in.) for the three-loop design]. This is possible because of the absence of the loss of internal pressure design restraint. It is postulated that this requirement will apply only to loss of secondary coolant pressure, during which time the primary coolant pressure must be maintained. If primary pressure is lost, the secondary pressure can be reduced so that the near-balanced condition is maintained.

The center return duct passes through the 2-1/4 Cr-1 Mo tubesheet and is attached through a thermal sleeve. It then passes out through the cavity closure.

The cold end lead tubes are made of 2-1/4 Cr-1 Mo and are the same diameter for all plant configurations. These tubes are welded to the cold end conical subheaders, which are similar to the hot end subheaders described above but made of 2-1/4 Cr-1 Mo. The lead tubes are wound partially around the center return duct to provide a projected horizontal run of 1.2 m (4 ft) to provide sufficient flexibility to accommodate the 14.3-mm (9/16-in.) expansion differential between the tube modules and the center return duct. The tubes are then led up to penetrate the tubesheet in a 140-mm (5-1/2-in.) pitch triangular pattern. The tubes are welded to nozzle extensions on top of the tubesheet.

The tubesheet is supported by a cylinder which is bolted to the edge of the PCR/V cavity and is covered by the cavity closure. Details of

secondary restraints and flow restrictors have not yet been worked out but will be similar in nature to those in other HTGR closures.

The weight and aerodynamic loads in the IHX are taken by the support cylinder through the tubesheet and center return duct. These loads are counteracting in the side-mounted versions but are additive in the bottom-mounted versions.

On the primary gas side, the hot helium flows into the hot end plenum past a pyrocarbon deflector plate. This plate prohibits direct impingement of the hot gas at high velocity directly on the hot header core and lead tubes. In addition, in the side cavity configuration, it aids in providing equal distribution of the incoming hot gas around the inlet plenum.

The gas then flows up (down in the vertical-mounted version) past the hot lead tubes and subheaders to the module tubes. It is contained in the module area by an outer shroud of Inconel 617 which is bolted to the cavity liner through a thermal sleeve near its midpoint. The inside surface of the shroud conforms to the tube module shrouds and provides a close fit to impede gas flow which would otherwise bypass the tube field area. A similar shroud is attached to the center return duct to perform a similar function.

Once through the module region, the primary gas flows past the cold end subheaders into the cold end lead tube region and, in the side cavity version, out the discharge duct. In the vertical-mounted version, it flows up through an annulus around the outer shroud to the discharge duct.

Pressure losses in the system were minimized as much as possible to maintain low pumping power requirements, especially on the primary coolant side. Gas flow velocities are kept fairly low in obstructed areas such as the primary gas inlet and discharge regions where the gas flows across lead tubes. Flow velocities in the tube region, both shell side and tube side, are moderately high to promote good heat transfer, a dynamic head of

about 1 kPa (0.15 psi) being prevalent. The dynamic head inside the center return duct, on the other hand, is on the order of 17 kPa (2.5 psi) to keep the duct diameter small, which is reasonable since the length-to-diameter ratio is relatively low and thus the pressure loss is low. Table 2 lists the approximate pressure losses for the IHX in each of the plant configurations.

TABLE 2
 VHTR INTERMEDIATE HEAT EXCHANGER
 PRESSURE LOSS^(a)

Configuration	Primary Loop ΔP [kPa (psi)]	Secondary Loop ΔP [kPa (psi)]
1 loop, side mounted	53.8 (7.8)	91.0 (13.2)
1 loop, bottom mounted	51.7 (7.5)	91.0 (13.2)
2 loops, side mounted	53.8 (7.8)	83.4 (12.1)
2 loops, bottom mounted	51.7 (7.5)	83.4 (12.1)
3 loops, side mounted	53.8 (7.8)	81.4 (11.8)
3 loops, bottom mounted	52.4 (7.6)	81.4 (11.8)

(a) Total pressure loss measured between the inlet duct flange and exit duct flange of the respective configuration; includes expansion or contraction loss due to the duct flow area.

3. PERFORMANCE/OPTIMIZATION PROGRAM

3.1. STATUS SUMMARY

The VHTR performance/optimization code development task continued during this reporting period. The computer code PHRED (Process Heat Reactor Evaluation and Design) was tested to verify the program logic. The test of program logic met the milestone scheduled for this quarter.

The process design codes used to model the steam-methane reforming section and the cryogenic section to produce 97% hydrogen were prepared and are presently being verified. The model of the carbon dioxide removal section will complete the process modeling.

3.2. COMPUTER PROGRAM DEVELOPMENT

The development of the computer program PHRED for parametric analysis of the VHTR hydrogen production plant has progressed to include the successful test of the program logic used to achieve energy and mass balance in the various plant flow loops and continuing effort on component performance and sizing subroutines.

3.2.1. Program Logic Structure

The logic structure was tested on the primary helium loop using a "reference design" which places three separate IHX loops underneath the reactor core cavity, giving a Fort St. Vrain type PCRV. Three CACS loops were added to test the special computation logic required by the CACS leakage flow. This configuration is not intended to reflect a final choice of the conceptual design of the PCRV, but it does completely test the types

of component models which may be required in the primary helium loop when the PCRV conceptual design is selected.

Since nearly identical logic and programming will be used for each fluid loop in the program (primary and intermediate helium loops, process loops, and steam loops), the successful test of the primary helium logic and programming serves as verification for the basic logic structure of the entire program. This is made possible by the type of loop performance computation logic used to achieve energy and mass balances. The logic will accept any series of types of components and duct segments as specified by the stored input data and will automatically converge to a state of energy and mass balance. One element of the overall program logic remains to be developed: the logic for coupling the process flow loop and the steam cycle loop. An initial definition of this final logic element has been made and is presently being checked against the results of the study described in Section 3.3 of this report.

For the computer runs made to test the logic, the reactor and the IHXs are presently modeled by short program stubs. These stubs receive and output the same data as will the eventual complete subroutines, but do not actually design or size the components. Work in the immediate future will concentrate on coupling the complete reactor and IHX design subroutines.

The design used to test the program logic was presented by 43 segments in the primary helium loop. All of the possible types of segments were represented so that all possible paths through the program could be verified. They are as follows:

1. Regular components.
 - Reactor (stub subroutine).
 - IHX (stub subroutine).
 - Circulator.

2. Special components.
 - CACS in standby mode.
3. Loop split and junction segments.
4. Pressure drop segments (10 types).
5. Heat loss segments.
 - Heat lost to outside the flow (PCRVR).
 - Heat lost to another flow segment.
 - Heat gain from another flow segment.
6. Leakage segments.
 - Flow leakage out to another segment.
 - Flow leakage in from another segment.

The subroutine which performs the computations (once around a flow loop) does not need to be changed for different loop designs. To input a new design, two things must be done. First, new strings of input data must be compiled into the program to specify reference design performance and layout. Second, new estimating equations must be added to the subroutine which calls the performance computation subroutine. This second change is required because a minimum amount of data is used to define the reference energy and mass balances for the reference design (base case) and all alternate cases.

Based on a run where nine cases were computed (the base case and eight alternate cases), convergence of the primary loop computations takes less than 0.2 s per case. This will increase in the future when the two component stub subroutines are replaced with complete subroutines.

Some effort during the quarter was directed toward programming formal output subroutines. Here again, a structured approach has led to the development of a generalized output subroutine which can be applied to all of the output pages which will be required as the program is developed. Rather than the usual approach of a mass of FORMAT and WRITE statements, the data titles, line spacing, and number of decimal places printed are all contained in or controlled by DATA statements which are specific to the data being output. The actual printing is performed by a short DO loop which uses the stored DATA to format and produce the output.

Table 3 shows the selection of independent design variable changes used in the test of the energy and mass balance logic. A series of maximum helium pressures was used with two different values of reactor inlet temperature. The list of variables is not near its expected final length. Note that the values for Case 1 duplicate the base case values. This was done to check the slightly different paths through the performance computations taken by base case and alternate case logic.

Table 4 shows the output which summarizes the primary helium loop performance for the run used to check the program logic. Note that the first alternate case is equal to the base case and that their performance is identical as required.

One very interesting detail is shown in the base case data: a temperature drop of 7.5°C (13.5°F) from the reactor outlet to the inlet to the IHX. Checking the segment data computed by the primary loop logic subroutine produces the following breakdown of temperature drop contributions:

TABLE 3
VALUES OF INDEPENDENT DESIGN VARIABLES
(Only Changing Variables Are Printed for Cases 1 Through 8)

		BASE CASE	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7	CASE 8
MAXIMUM PRIMARY HELIUM PRESSURE	(PSIA)	725.0	725.0	750.0	775.0	800.0	725.0	750.0	775.0	800.0
REACTOR THERMAL POWER	(MW)	842.0								
REACTOR INLET TEMPERATURE	(F)	867.0	887.0	887.0	887.0	887.0	850.0	850.0	850.0	850.0
REACTOR OUTLET TEMPERATURE	(F)	1742.0								
REACTOR CORE DIAMETER	(FT)	20.10								
REACTOR CORE HEIGHT	(FT)	19.61								
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								
NUMBER OF INTERMEDIATE HEAT EXCHANGERS		3.0								
NUMBER OF CORE AUXILIARY COOLING LOOPS		3.0								

TABLE 4
SUMMARY OF PRIMARY HELIUM LOOP PERFORMANCE

	BASE CASE	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7	CASE 8
REACTOR NOMINAL THERMAL POWER (MEGAWATTS)	842.00	842.00	842.00	842.00	842.00	842.00	842.00	842.00	842.00
THERMAL POWER ADDED BY CIRCULATORS	17.25	17.25	16.54	15.90	15.30	15.77	15.14	14.56	14.02
TOTAL THERMAL POWER INPUT	859.25	859.25	858.54	857.90	857.30	857.77	857.14	856.56	856.02
THERMAL POWER TO INTERMEDIATE HELIUM	848.37	848.37	847.66	847.02	846.42	847.16	846.53	845.95	845.41
PRIMARY LOOP THERMAL POWER LOSSES	10.88	10.88	10.88	10.88	10.88	10.61	10.61	10.61	10.61
THERMAL POWER LOST TO PCRV LINER	10.56	10.56	10.56	10.56	10.56	10.32	10.32	10.32	10.32
THERMAL POWER LOST TO CACS WATER	.32	.32	.32	.32	.32	.30	.30	.30	.30
TOTAL THERMAL POWER OUTPUT	859.25	859.25	858.54	857.90	857.30	857.77	857.14	856.56	856.02
PRIMARY LOOP THERMAL EFFICIENCY (PERCENT)	98.73	98.73	98.73	98.73	98.73	98.76	98.76	98.76	98.76
HELIUM PRESSURE-TEMPERATURE-FLOW SUMMARY									
REACTOR INLET PRESSURE (PSIA)	723.60	723.60	746.65	773.69	798.73	723.75	748.79	773.83	798.86
TEMPERATURE (DEGREES F)	887.00	887.00	887.00	887.00	887.00	850.00	850.00	850.00	850.00
FLOW (MILLION LB/HR)	2.710813	2.710813	2.710867	2.710921	2.710975	2.598368	2.598420	2.598472	2.598524
REACTOR OUTLET PRESSURE	720.05	720.05	745.10	770.14	795.18	720.20	745.24	770.28	795.31
TEMPERATURE	1742.00	1742.00	1742.00	1742.00	1742.00	1742.00	1742.00	1742.00	1742.00
FLOW	2.710813	2.710813	2.710867	2.710921	2.710975	2.598368	2.598420	2.598472	2.598524
INTER. HEAT EXCH. INLET PRESSURE	719.25	719.25	744.35	769.44	794.52	719.49	744.57	769.65	794.73
TEMPERATURE	1728.52	1728.52	1728.52	1728.52	1728.52	1727.97	1727.97	1727.97	1727.97
FLOW	.908989	.908989	.909007	.909025	.909043	.871284	.871302	.871319	.871336
INTER. HEAT EXCH. OUTLET PRESSURE	709.25	709.25	734.35	759.44	784.52	709.49	734.57	759.65	784.73
TEMPERATURE	872.26	872.26	872.97	873.62	874.23	835.92	836.59	837.20	837.77
FLOW	.908989	.908989	.909007	.909025	.909043	.871284	.871302	.871319	.871336
CIRCULATOR INLET PRESSURE	708.55	708.55	733.67	758.78	783.89	708.86	733.97	759.07	784.16
TEMPERATURE	874.76	874.76	875.42	876.04	876.61	838.47	839.09	839.67	840.21
FLOW	.943352	.943352	.943371	.943389	.943408	.904222	.904240	.904258	.904276
CIRCULATOR OUTLET PRESSURE	725.00	725.00	750.00	775.00	800.00	725.00	750.00	775.00	800.00
TEMPERATURE	891.17	891.17	891.17	891.17	891.17	854.13	854.13	854.13	854.13
FLOW	.943352	.943352	.943371	.943389	.943408	.904222	.904240	.904258	.904276
TOTAL PRIMARY LOOP PRESSURE LOSS (PERCENT)	2.27	2.27	2.18	2.09	2.01	2.23	2.14	2.06	1.98

1.	Heat loss to upward annular flow outside the core outlet plenum:	-0.04°C (-0.07°F)
2.	Heat loss to core outlet plenum PCRV concrete:	-0.96°C (-1.73°F)
3.	Inleakage of compressor outlet helium (0.774% of flow):	-3.71°C (-6.67°F)
4.	Inleakage of CACS leakage flow at 218°F (0.055% of flow):	-0.47°C (-0.85°F)
5.	Heat loss to IHX inlet duct PCRV concrete:	-0.07°C (-0.12°F)
6.	Heat loss to IHX upper cavity wall PCRV concrete:	<u>-2.24°C (-4.04 °F)</u>
	Total temperature change in main stream:	-7.49°C(-13.48°F)

Loss No. 3 is almost half of the total; this loss would not occur in a Large HTGR PCRV as opposed to the base case Fort St. Vrain type PCRV. Loss No. 6 will likely be reduced in the real reference design, depending upon the location of the seal and support for the IHX.

Detailed checks of the type shown above were used on all segments to verify proper operation of the program logic structure.

3.2.2. Component Model Development

The performance model for the circulator is the first component model to be incorporated into the PHRED program. If the input data specify a leakage path from the circulator outlet to its inlet, the model will revise the value given it as helium inlet temperature to reflect the

mixing of the leakage flow with the circulator inlet flow. Mass flow changes caused by leakage flows are computed separately in another subroutine.

The models for the reactor and for the reformer are both complete in separate stand-alone versions, and work is presently in progress to couple them to PHRED. The models for the IHX and the steam generator are being revised to fit into the logic of the program. The data storage and output subroutines for the components are also being written and added to the program.

3.3. REFORMER/PROCESS PERFORMANCE

The process design code has been used to model the reforming and the cryogenic sections of the process. The reformer model has been dummied into the code to date. However, the reformer code for adding to the process design code has been prepared and "debugged" in-house and submitted to the process design code vendor for checking before use as a part of the process design code. This code will calculate the length of the reformer tubes, the pressure drop of the process gas, and other important parameters in the same manner as the reformer design is calculated as part of the PHRED code.

Figure 10 shows the reformer flow sheet model that has been calculated using the DESIGN code (Chemshare Corporation). Items 2 and 9 are controllers that, respectively, control the pressure of the steam mixing with the process feedstock so that the maximum power will be extracted from steam turbine 18 and control the pressure at the outlet of the reformer. The CO₂ removal section will be modeled in the next step.

Figure 11 presents variations of the basic cryogenic separation step to give a product that is 97% hydrogen at 10.3 MPa. The methane product will be recycled to the reformer feed in all cases. Case D was chosen for further study, and the results of a temperature difference study are shown

Fig. 10. Reformer flow sheet model

Fig. 11. Comparison of cryogenic separation flow sheets

in Table 5. The case using an 11.1°C temperature approach in the condensing exchanger was used for further studies of the effect of separator pressure and inlet feed composition. These results are shown in Table 6.

The modeling of the carbon dioxide removal section of the process will now proceed, and further exercising of the models completed will be performed.

TABLE 5
 COMPARISON OF TEMPERATURE APPROACH
 Flow Sheet: Case D
 90% H₂ Feed at 3.10 MPa, 97% H₂ Product at 10.34 MPa
 Basis: 1 kmol/s

Temperature Approach (°C)	Heat Exchanger Duty (MW)/ Area (m ²)	Expander Power (MW)	Compressor Power (MW)	Demand Power (MW)
5.0	7.176/ 5073	0.175	5.373	5.198
11.1	7.176/ 2342	0.363	6.643	6.280
13.9	7.176/ 1882	0.447	7.280	6.833

TABLE 6
EFFECT OF FEED COMPOSITION AND SEPARATOR PRESSURE
97% H₂ Product at 10.34 MPa
Temperature Approach: 11.1 K
Basis: 1 kmol/s

Separator Pressure (MPa)		Feed Composition (H ₂ mol %)		
		90	85	80
3.10	Heat exchanger duty, MW	7.176	7.650	8.126
	Heat exchanger area, m ²	2342	2361	2365
	Expander power, MW	0.363	0.383	0.402
	Compressor power, MW	6.643	6.592	6.545
	Fraction H ₂ recycled	0.0022	0.0041	0.0061
2.41	Heat exchanger duty, MW	7.222	7.706	8.187
	Heat exchanger area, m ²	2401	2423	2443
	Expander power, MW	0.356	0.373	0.388
	Compressor power, MW	7.764	7.653	7.517
	Fraction H ₂ recycled	0.0017	0.0031	0.0046

4. SAFETY-RELATED DESIGN

4.1. STATUS SUMMARY

Preliminary CACS performance and design parameters have been established for the small VHTR plant. A preliminary thermal transient analysis has been conducted on the critical components in the primary system. The design basis for the CACS and its components (e.g., CAHE, auxiliary circulator, air blast heat exchanger) are defined by the following postulated plant accidents:

1. Depressurized reactor cooldown with pure helium primary coolant.
2. Depressurized reactor cooldown with air ingress to the primary coolant.
3. Pressurized reactor cooldown.

The method of analysis parallels that used for the HTGR-SC. The RECA3 computer code was modified where appropriate and used to calculate the transient thermal responses of the important components under emergency conditions. Included are simulations of the core and primary coolant behavior, the emergency cooling system performance, and selected primary system components. The results were used primarily to validate the safe cooldown capability of the VHTR CACS design under a broad spectrum of postulated accident conditions.

The CACS sizing is based on one "100%" loop in operation for the cooldown transients and assumes a core bypass flow of approximately 9% (similar to FSV). The design is generic in nature and can be used in any of the proposed VHTR alternate arrangements.

4.2. CACS STUDIES

The CACS is an engineered safety system in the VHTR. It provides an independent means of reactor cooling whenever the main loops are unavailable. The CACS used in the VHTR is similar to the system employed by the HTGR-SC. It consists of the CAHE, auxiliary helium circulator, air-cooled heat exchanger, and associated pumps and piping. Figure 12 illustrates schematically the system flow diagram for the CACS.

The design philosophy for the CACS is based on two alternate concepts: one using the pressurized water-cooled CAHE design (as in the HTGR-SC) and one employing a pressurized helium circuit for heat rejection to the air blast heat exchanger. Design criteria for both designs are given in this section, but to simplify the general discussion, only the water-cooled system will be referred to.

The CACS is designed to provide an independent means of cooling the reactor core and internals during the removal of reactor fission product decay heat and sensible heat with the primary system pressurized or depressurized. The capability of the auxiliary cooling system is such that it maintains the temperatures of all the components in the PCRV within safe limits. Due to the increased operating temperatures in the VHTR (in comparison with the HTGR-SC), the CACS design reflects changes to adequately maintain component temperatures during accident conditions.

The HTGR-SC limiting components and temperature limits for CACS performance are given in "Nuclear Plant Safety Specification" (Ref. 3) for upset, emergency, and faulted conditions. These limits are adhered to in general for the VHTR design except for the thermal barrier temperature limit in the lower cross duct (justification for this change is discussed in Section 4.2.4). A significant feature of the VHTR (and HTGRs) is that the critical safety component for emergency cooling conditions is not the reactor core.

Fig. 12. Schematic representation of CACS model

4.2.1. CACS Description and Operation

The auxiliary cooling loops which comprise the CACS are located between the main loops in separate PCRV cavities. Each auxiliary loop has an independent electric-motor-driven circulator. The individual loops are sized sufficiently large to enable each loop to meet all the core cooling performance requirements. Within 5 min following an accident which disables the main heat transfer loops, the auxiliary helium circulator establishes a flow of helium which removes heat from the reactor core and transfers it to the water-cooled (or pressurized helium) tubes of the CAHE. The core auxiliary cooling water system (CACWS) circulates pressurized water through the CAHE. Together, the CAHE tube circuit and CACWS form a closed loop which transfers the heat removed from the core to the ultimate heat sink (the ambient air) via an air blast heat exchanger. The auxiliary circulator and also all the pumps and fans within the CACWS are driven by electric motors. Power is supplied by an auxiliary diesel-generator system. An induction motor drives the auxiliary circulator, and a frequency converter is used to obtain variable speed capability. This is primarily needed as a means of controlling the core heat removal rate so as to ensure that boiling does not occur within the closed-loop cooling water system during the initial stages of a reactor shutdown. The pumps and fans, however, operate at constant power.

The CACS loops are maintained in a standby mode during normal plant operation. The circulating water flows through the CAHE at a rate lower than required for operation to remove reactor core heat during an accident condition. Primary helium circulation is shut off to the CAHE, but there is a small backward flow of core inlet (cold) helium past the CACS compressor and its shutoff valve. Continuous water circulation is of benefit to the CAHE in minimizing thermal shock during the start-up transient (i.e., phasing from the standby to the core cooling mode). It is also fundamental to the CACS design philosophy (Refs. 4, 5) to have simplicity of initiation and predictability of operation. The standby mode

operation results in parasitic heat removal from the primary reactor coolant system, thus reducing the heat transferred through the IHXs.

In addition to the safety function of core heat removal, the CACS is intended to remove core afterheat in a plant shutdown and refueling mode. This service does not directly relate to system performance criteria. However, it does affect circulator motor life, CAHE tube corrosion and erosion, and system maintenance options.

4.2.2. CACS Design Criteria

The design bases for the CACS and its components consist of a series of differing thermal transients for the postulated plant accidents. System analysis results in a set of performance specifications which represent the most extreme flow and temperature conditions during the transients for these accidents:

1. Depressurized reactor cooldown with pure helium primary coolant.*
2. Depressurized reactor cooldown with air ingress to primary coolant.*
3. Pressurized reactor cooldown.

These accidents are also the design basis for the HTGR-SC with the exception of inclusion of moisture ingress for the pressurized reactor cooldown. The case of the depressurized cooldown with pure helium coolant is the situation with the least effective heat transfer conditions, and it establishes the minimum CAHE area. The depressurized cooldown with air ingress is the case requiring maximum helium circulator power and thus

*Design basis depressurization accident (DBDA).

governs the CAHE helium flow resistance and helium circulator requirements. The basic requirement for the depressurized shutdown is to circulate the low-density primary coolant at a flow rate and temperature which will acceptably limit both fuel and core coolant outlet temperatures. The latter are characteristically higher than those during normal operation and must therefore be considered in terms of their effects upon the thermal barrier liner temperatures. Detailed account of the local hot streaks is taken into consideration in the analysis of the thermal barrier temperatures in the lower plenum cross duct.

During the pressurized shutdown, limiting conditions are imposed by a tendency of the primary flow to locally reverse in certain core regions where the buoyant forces become dominant. When such reversals occur, the upper plenum element assemblies in the reversed flow regions are subjected to the effects of the high-temperature up-flowing primary coolant. Also, fuel temperatures in the reversed flow regions rise because their coolant flows are reduced due to flow maldistributions. In addition, the pressurized cooldown sets the maximum heat duty and water side flow rate, which results in the highest mean CAHE water temperatures. A margin for the suppression of boiling in the CAHE tubes is also required to maintain tube-to-tube flow stability. Overall reactor plant design constraints do not permit the inherently more stable flow arrangement of cooled helium flowing down and heated water flowing up.

4.2.3. Method of Analysis

The RECA3 computer code developed to perform thermal analysis of the HTGR accident conditions was modified where appropriate and used in performing the VHTR analysis. This code is unique among the HTGR thermal analysis codes in that it provides for simulation of all primary system phenomena which are significant under emergency cooling conditions. In its basic structure, RECA3 encompasses a core model coupled to an emergency cooling performance model and also to models which simulate various other relevant aspects of the primary system behavior (i.e., thermal barrier

temperature, PCRV top head, liner cooling, etc.). Since the primary system behavior is largely governed by the core behavior, it follows that the core is modeled in a relatively high level of detail.

The core power distribution map used in establishing the steady-state conditions was identical to that used in the FSV analysis with the modification for the higher-temperature operation. Table 7 summarizes some of the major core design conditions. The range of the region peaking factor (RPF) is between 0.47 and 1.83 for steady-state operation at full power. These RPFs are assumed to remain unchanged throughout the DBDA. The value of the highest-powered core region significantly influences the hot streak temperature at the thermal barrier. Selection of this core map was made prior to the recommended maximum RPF of 1.5 (Ref. 6). The results in this analysis are therefore somewhat conservative.

4.2.4. Material Temperatures

The limiting components and temperature limits for the CACS performance are essentially the same as those for the HTGR-SC except for the thermal barrier temperature limit. Following a DBDA, the critical component is identified as the thermal barrier liner in the lower cross duct. The HTGR-SC has a critical safety limit temperature of 1093°C (2000°F) with a design margin allowance of 55°C (100°F) below the critical safety limit for the thermal barrier liner temperature. For the VHTR, this critical safety limit was raised to 1149°C (2100°F). The same design margin (55°C) was maintained; therefore, the maximum thermal barrier liner temperature allowed is 1093°C (2000°F). The temperatures in the VHTR are significantly higher than those encountered in the HTGR-SC, and therefore a material change was justified for the thermal barrier liner. A carbon/carbon (C/C) fiber reinforced composite was selected (Ref. 7) for the hot duct liner in the VHTR plant. The fiber fill insulation (SAFFIL) thickness was also increased to 28 cm (11 in.) to adequately minimize heat losses.

TABLE 7
MAJOR DESIGN PARAMETERS AND DATA FOR 842-MW(t) VHTR CORE

Reactor core power	842 MW(t)
Reactor core helium flow rate	340.6 kg/s ($2.7 \times 10^6 \text{ lb}_m/\text{hr}$)
Power density	6.30 W/cm ³
Fuel block type	10-row block
Helium coolant pressure	5 MPa (725 psia)
Reactor outlet temperature (avg)	950°C (1742°F)
Reactor inlet temperature (avg)	475°C (887°F)
Maximum region peaking factor	1.83
Maximum fuel temperature	1288°C (2350°F)
Maximum helium core outlet temperature	1139°C (2083°F)

The RECA3 code was modified to account for these design and material changes in the thermal barrier. The calculation of the thermal barrier temperature is based on the maximum hot streak temperature exiting the core.

4.2.5. Transient Analysis Results

The case of depressurized cooldown with pure helium as the primary coolant is the situation with the least effective heat transfer conditions and establishes the minimum CAHE area. For a selected CAHE, the corresponding heat duty is a trade-off between circulator pumping power and the maximum acceptable thermal barrier temperature. Figure 13 illustrates the transient temperature behavior of the lower cross duct thermal barrier liner temperature for various circulator powers. Selecting the 1093°C (2000°F) temperature as the thermal barrier material limit results in a CAHE design heat duty of approximately 12 MW(t) (42×10^6) Btu/hr). The required heat transfer surface area to maintain acceptable material temperature is 370 m² (3978 ft²). This area is required to meet the peak depressurized reactor cooldown heat duty for the case of pure helium coolant and one CACS loop functioning. The heat exchanger so sized demands a maximum circulator power of 670 kW (900 hp) to circulate the primary helium coolant and air mixture in the case of the depressurization and air ingress.

The case of pressurized cooldown with pure helium requires a maximum heat duty of 44 MW(t) (151×10^6 Btu/hr). This case sets the water flow rate at 134 kg/s (1.06×10^6 lb_m/hr) for tube side stability limits. The associated helium mass flow rate to maintain a sufficient margin for reverse flow in the core is 17.4 kg/s (1.38×10^5 lb_m/hr).

The air blast heat exchanger is sized for the pressurized cooldown case. The required performance is specified by an effectiveness value of 0.40. The heat duty and associated maximum water inlet and outlet temperatures are 44 MW(t) (151×10^6 Btu/hr), 235°C (456°F), and 159°C (318°F), respectively.

Fig. 13. Transient temperature response of lower cross duct thermal barrier

The temperature transients of selected parameters of importance are shown in Figs. 14 and 15 for the DBDA pure helium cooldown and pressurized pure helium cooldown, respectively. For the DBDA cooldown, the CACS start-up typically results in increasing core temperatures for the first few hours after the accident, followed by decreasing temperatures thereafter. The pressurized cooldown, however, results in a continuous reduction of temperatures. The principal component design parameters for the water-cooled CACS are summarized in Table 8 for each of the design basis accidents.

4.2.6. Design Features

The CAHE is a counterflow bayonet tube design, which in being used in the design for the Large HTGR-SC. Figure 16 illustrates the basic mechanical arrangement of the CAHE. The bayonet tube arrangement consists of three concentric tubes, as shown in Fig. 17. The incoming water flows up the central core tube and exits into the closure cap for the outer tube and then flows down the annulus between the outer tube and the intermediate tube. As it flows down, it picks up heat from the hot helium flowing up the outside of the outer tube. The annular space between the inner tube and intermediate tube is filled with non-flowing water via vent holes. This space thus acts as an insulator to reduce the regenerative heating between the incoming and outgoing water.

The CAHE diameter and height are determined by parametric studies of various bundle configurations which provide the required heat transfer duty consistent with the allowable pressure drop presented for the various design basis accidents. The variables that are available for optimization are tube size (inner, middle, and outer tubes), bundle length, tube pitch, and number of tubes. A preliminary selection of the tube size and tube pitching was identical to the CAHE design proposed for the Large HTGR-SC. The resulting tube bundle envelope diameter is approximately 145 cm (57 in.). Table 9 summarizes initial selection of the major CAHE design data.

Fig. 14. Temperature transients during DBDA cooldown with pure helium coolant

Fig. 15. Temperature transients during pressurized cooldown with pure helium coolant

TABLE 8
WATER-COOLED CACS PERFORMANCE DATA
(Individual Loop Data Based on One "100%" Loop Operation)

Water pressure, MPa (psia)	10.3 (1500)
Water flow rate, kg/s (lb_m/hr)	134.0 (1.06×10^6)
Design air dry bulb temperature, °C (°F)	43.3 (110)
Air blast heat exchanger surface area, m^2 (ft^2)	273 (29,400)
Air blast heat exchanger effectiveness	0.40
Helium circulator efficiency	0.75
Helium circulator maximum power, kW (hp)	670 (900)
Helium circulator maximum speed, rad/s (rpm)	372 (3550)

Pressurized Cooldown System Parameters

Helium flow rate, kg/s (lb_m/hr)	18.9 (1.50×10^5)
CAHE heat duty, MW(t) (Btu/hr)	44.3 (151×10^6)
Helium temperature	
CAHE inlet, °C (°F)	916 (1681)
CAHE outlet, °C (°F)	466.1 (871)
Water temperature	
CAHE inlet, °C (°F)	158.9 (318)
CAHE outlet, °C (°F)	235.5 (456)
CAHE pressure drop, kPa (psi)	10.3 (1.5)
Circulator power, kW (hp)	77.6 (104)
Circulator speed, rad/s (rpm)	71.2 (680)

Depressurized Cooldown (Pure Helium) System Parameters

Helium flow rate, kg/s (lb_m/hr)	3.13 (2.5×10^4)
CAHE heat duty, MW(t) (Btu/hr)	12.5 (42.6×10^6)
Helium temperature	
CAHE inlet, °C (°F)	1001 (1834)
CAHE outlet, °C (°F)	307.8 (586)

TABLE 8 (Continued)

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

Fig. 16. Basic mechanical arrangement of bayonet tube CAHE

Fig. 17. Bayonet tube arrangement

TABLE 9
MAJOR CAHE DESIGN DATA FOR WATER-COOLED DESIGN

Type	Counterflow bayonet tube design
Outer tube diameter	38 mm O.D. x 3.2 mm wall (1.5 in. x 0.125 in.)
Middle tube diameter	25.4 mm O.D. x 2.1 mm wall (1.0 in. x 0.083 in.)
Inner tube diameter	16.9 mm O.D. x 2.1 mm wall (0.667 in. x 0.083 in.)
Surface area ^(a)	370 m ² (3978 ft ²)
Tube pitch	6 cm (2.38 in.)
Tube bundle diameter ^(a)	145 cm (57 in.)
Materials of construction	
Outer tubes	Incoloy 800
Middle tubes	Carbon steel
Inner tubes	Carbon steel
Tube sheets	SA 508, Gr. 2, carbon steel
Tube grids	Type 316 stainless steel
Water flow velocities	
Outer tube annulus	1.2 m/s (4 ft/sec)
Inner tube	2.75 m/s (9 ft/sec)

^(a) Estimated for the VHTR design.

The gas entrance to the CAHE has a heat trap to minimize natural convection in the non-operating mode. The helium flow circuit is directed downward prior to entering the tube bundle. Thus, without forced circulation the cool gas in the CAHE tends to form a stable gas column.

A major feature of the bayonet tube design is its good access for in-service inspection. The heat transfer tubing can be fully inspected by removing the lower spherical head and withdrawing the individual inner core and intermediate tubes.

4.2.7. He/He CAHE Design Parameters

The alternate design proposed for the CACS was based on replacing the pressurized water loop with a pressurized helium loop. This would eliminate any possible water ingress to the primary system (and its associated safety issues). In addition, the in-service inspection requirement is not likely to be imposed. In making this change, however, some of the design conditions were modified. Table 10 summarizes the major design conditions for a helium-cooled CACS. Preliminary sizing indicates that the envelope size is comparable to the water-cooled design. There is, however, a considerable increase in the secondary coolant pumping power. This is the primary disadvantage of the proposed alternate design.

TABLE 10
HELIUM-COOLED CACS PERFORMANCE DATA
(Individual Loop Data Based on One "100%" Loop Operation)

Secondary helium pressure, MPa (psia)	5 (725)
Secondary helium flow rate, kg/s (lb _m /hr)	40.1 (3.18 x 10 ⁵)
Design air dry bulb temperature, °C (°F)	43.3 (110)
Air blast heat exchanger surface area, m ² (ft ²)	1858 (20,000)
Auxiliary circulator efficiency	0.75
Auxiliary circulator maximum power, kW (hp)	670 (900)
Auxiliary circulator maximum speed, rad/s (rpm)	372 (3550)
Secondary circulator efficiency	0.75
Secondary circulator maximum power, kW (hp)	946 (1268)
Secondary circulator speed, rad/s (rpm)	372 (3550)

Pressurized Cooldown System Parameters

CAHE heat duty, MW(t) (Btu/hr)	44.3 (151 x 10 ⁶)
Primary helium flow rate, kg/s (lb _m /hr)	18.9 (1.50 x 10 ⁵)
Primary helium temperature	
CAHE inlet, °C (°F)	916.0 (1681)
CAHE outlet, °C (°F)	468.1 (871)
Secondary helium temperature	
CAHE inlet, °C (°F)	158.9 (318)
CAHE outlet, °C (°F)	371.1 (700)

Depressurized Cooldown (Pure Helium) System Parameters

CAHE heat duty, MW(t) (Btu/hr)	12.5 (42.6 x 10 ⁶)
Primary helium flow rate, kg/s (lb _m /hr)	3.13 (2.5 x 10 ⁴)
Primary helium temperature	
CAHE inlet, °C (°F)	1075 (1968)
CAHE outlet, °C (°F)	307.8 (586)
Secondary helium temperature	
CAHE, °C (°F)	75.6 (168)
CAHE, °C (°F)	135.6 (276)

5. REFERENCES

1. "Process Heat Reactor Design and Analysis, Quarterly Progress Report for the Period October 1 through December 31, 1977," DOE Report GA-C14822 (12/31/1977), General Atomic Company, December 31, 1977.
2. "Process Heat Reactor Design and Analysis, Quarterly Progress Report for the Period January 1 through March 31, 1978," DOE Report GA-C14822 (3/31/1977), General Atomic Company, March 31, 1978.
3. "Nuclear Plant Safety Specification," General Atomic Company, unpublished data.
4. Gibbons, J. P., J. M. Waage, and K. W. Sieving, "The Design of 2300 MW(e) Twin HTGRs for the Philadelphia Electric Company," Nucl. Eng. Design 26, 27 (1974).
5. Wessman, G. L., and T. R. Moffette, "HTGR Plant Safety Design Basis," Nucl. Eng. Design 26, 78 (1974).
6. Rao, R., "Steady-State Hot Streak Temperature Distribution at the VHTR IHX Entry," General Atomic Company, unpublished data.
7. Black, W. E., "VHTR Intermediate Loop Hot Duct Study," General Atomic Company, unpublished data.

GENERAL ATOMIC

GENERAL ATOMIC COMPANY
P. O. BOX 81608
SAN DIEGO, CALIFORNIA 92138