F_C = Volumic fraction of fuel having a maximal temperature ≥ a given temperature

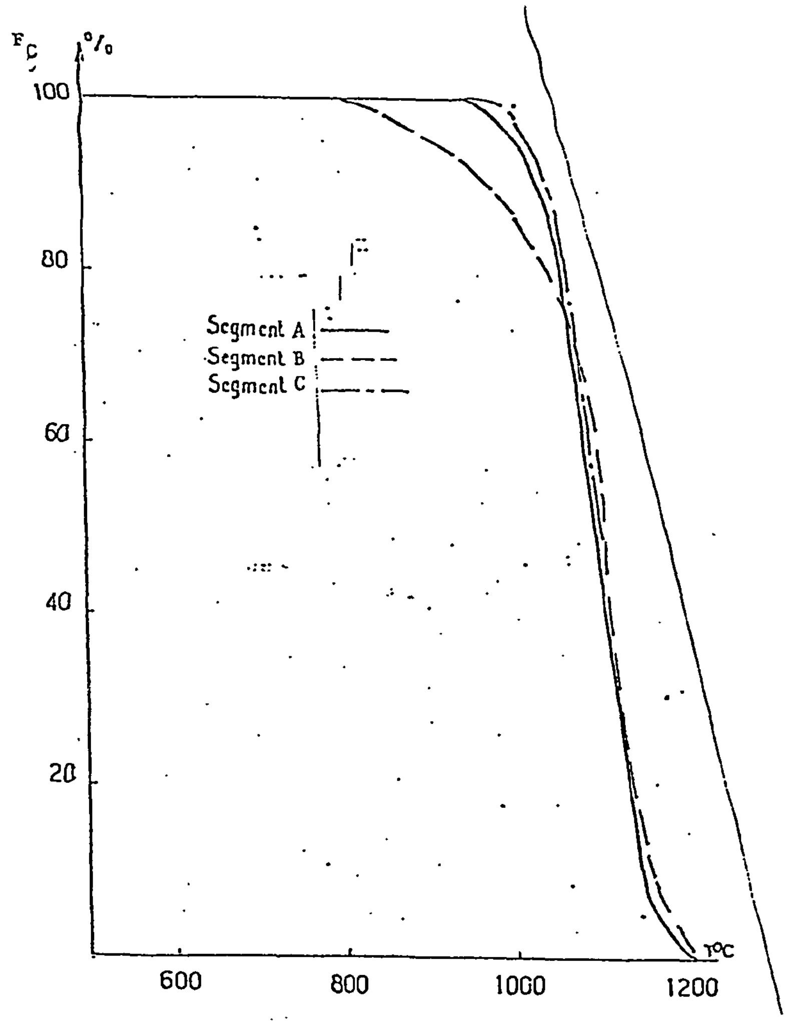

FIGURE 17 VOLUMIC DISTRIBUTION OF FUEL MAXIMAL TEMPERATURE AT BOTTOM OF LAYER 2

DESIGN AND APPLICATION FOR A HIGH-TEMPERATURE NUCLEAR HEAT SOURCE*

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ABSTRACT

Recent actions by OPEC have sharply increased interest in the United States in synfuels, with coal being the logical choice for the carbon source. Two coal liquefaction processes, direct and indirect, have been examined. Each can produce about 50% more output when coupled to an HTGR for process heat.

The nuclear reactor designed for process heat has a power output of 842 MW(t), a core outlet temperature of 950°C (1742°F), and an intermediate helium loop to separate the heat source from the process heat exchangers. Steam-methane reforming is the reference process.

As part of the development of a nuclear process heat system, a computer code, Process Heat Reactor Evaluation and Design, is being developed. This code models both the reactor plant and a steam reforming plant. When complete, the program will have the capability to calculate an overall mass and heat balance, size the plant components, and estimate the plant cost for a wide variety of independent variables.

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INTRODUCTION

The U.S. program on nuclear process heat was started in the mid-1960s and became focused on coal gasification in 1971. The program has benefited from the large high-temperature gas-cooled reactor (HTGR) generic technology program in the United States, although the specific process heat program has been smaller than the steam cycle and gas turbine programs.

Recent actions by OPEC have sharply increased U.S. interest in synfuels, and currently there are plans for several types of synfuel demonstration plants. The early timing of these plants will probably preclude a nuclear heat source, but their operation will be a necessary step toward the eventual integration of a nuclear heat source.

This paper will (1) focus on applications that are currently considered active candidates for nuclear process heat, (2) review the design conditions imposed by the process on the nuclear heat source, (3) describe the reference heat source design with emphasis on the heat exchangers, and (4) discuss a computer-based systems code that describes both the nuclear and process plants for optimization purposes.

RESOURCES VERSUS ENERGY NEEDS

As shown in Table 1, U.S. energy demands rely heavily on petroleum and natural gas. Over 75% of the bulk energy demands are met by these fuels. During the last decade, U.S. energy consumption has increased by almost 3.5% per year. At a consistent growth at this rate, the total energy consumption is doubling about every 20 years. The majority of these spiraling increases in U.S. energy consumption are being fulfilled by a mere 7.9% of the estimated total remaining recoverable U.S. fossil fuel resources, namely petroleum and natural gas. Even if President Carter's suggested rate of 2% per year could be achieved, consumption would double in 35 years.

TABLE 1
U.S. ENERGY CONSUMPTION

Resources	Joules x 10^{18}	Percent
Petroleum	38.8	46
Natural gas	26.1	31
Coal	15.2	18
Hydropower	3.4	4
Nuclear	0.8	1
	84.3	100

TABLE 2
ESTIMATED TOTAL REMAINING RECOVERABLE
RESOURCES IN THE U.S.

Resources	Joules x 10^{18}	Percent
Coal	36,300	77.3
Shale oil	6,700	14.4
Crude oil	2,100	4.5
Natural gas	1,600	3.4
Natural gas liquids	200	0.4
	46,900	100.0

As shown in Table 2, over three quarters of the estimated total remaining recoverable fossil fuel in the United States is in the form of coal. However, coal currently accounts for only 18% of the energy consumed in the United States.

It is impossible to expect natural gas, which produces over 30% of the U.S. energy, to maintain its hold over such a large share of the energy produced in the United States. The limited availability of natural gas will require that other energy resources be utilized. Since oil is the predominant fuel used in the United States, it would be a logical alternative for taking up the majority of the burden caused by reduced natural gas usage. However, President Carter has stated that oil imports will not rise above 1977 levels and domestic resources are inadequate to meet the increased demand. Coal and nuclear power remain among proven energy sources for meeting U.S. energy requirements. Coal is the most abundant remaining fossil fuel in the United States. It therefore follows that coal should be utilized to the maximum degree to meet the increasing U.S. energy requirements.

Approximately 150 billion tons (U.S.) of recoverable coal — 45 billion located near the surface and 105 billion located more deeply underground — exist in formations of thickness and depth to be mined economically utilizing present technology. However, there is a limited rate at which this resource can be utilized, a rate determined by the ability to construct the mining equipment, the transportation network, and the relocation and training of the miners. There is also considerable concern about the environmental effects that a vast increase in coal mining and utilization might bring. Large coal sites in the United States are generally in the West where water is short, the labor force is small, and environmental standards are very high. A report by the Department of Energy (DOE) has concluded that a 2 million barrel per day production level will face "rapidly increasing siting difficulties" (Ref. 1). It also concluded that only 41 sites in the United States would meet DOE environmental criteria.

General Atomic believes that nuclear process heat can materially improve these problems of coal production and environmental impacts by increasing the production of synfuels from a given amount of coal.

COAL TO SYNFUEL PROCESSES

COAL TO LIQUID FUEL PROCESSES

General Atomic has recently been looking at ways to produce liquid synfuel with a nuclear heat source and has examined the two major process routes: indirect and direct.

The indirect method, shown in Fig. 1, uses current state-of-the-art technology for the production of polymer gasoline/jet fuel from coal. An HTGR is integrated into the process and supplies the utilities (steam and electricity) and process heat (reforming). In the process, bituminous coal is gasified with steam and oxygen in Lurgi fixed bed gasifiers at about 2.7 MPa (400 psia). Lurgi gasifiers produce aromatic liquids and tar oil, which are scrubbed from the off-gas and recovered as by-products. The gasifier off-gas is then treated for carbon dioxide and hydrogen sulphide removal in "Rectisol" units where CO_2 and H_2S are absorbed and then stripped from the -48°C (-55°F) recirculating stream of methanol.

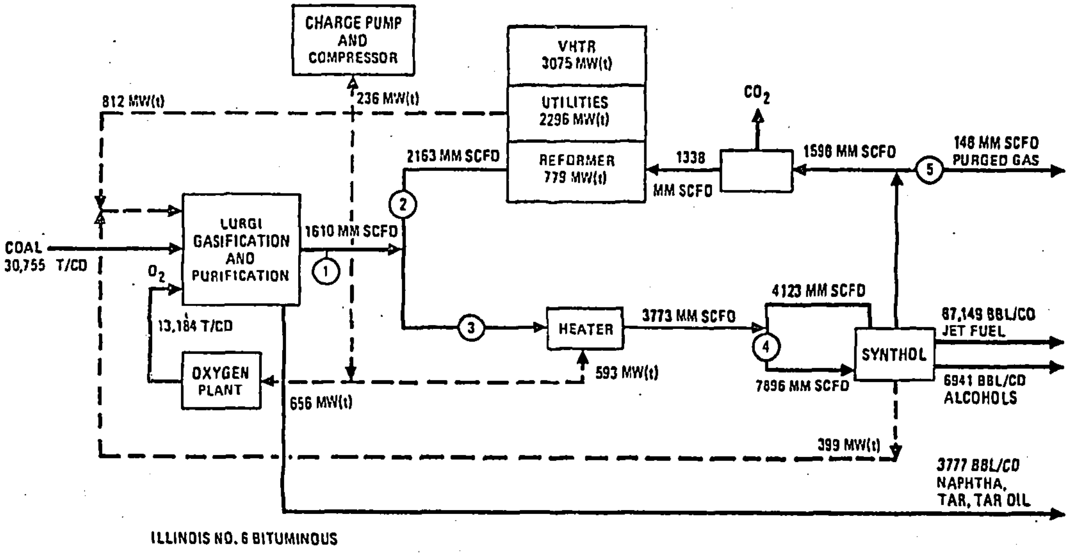

Fig. 1. Coal to jet fuel: via Lurgi-Fischer-Tropsch synthesis

After purification, the feed gas (stream 1) and a recycled tail gas stream (stream 2) from the Fischer-Tropsch synthesis section are mixed (stream 3), reheated, and then mixed with a Synthol internal recycle gas stream before entering the Synthol fluid bed reactor (stream 4). CO and H_2 react in the presence of an iron powder promoted with small quantities of Group I or Group III metals. The reactor temperature is controlled by oil coolers. Heat absorbed by the oil is used to generate plant steam. Reaction products are scrubbed and condensed from the synthesis off-gas. Chemical products (alcohols and ketones) are separated from the oil products by dissolution in water. The hydrocarbon products are highly olefinic and are catalytically polymerized to form gasoline and/or jet fuel.

A portion of the tail gas from the Synthol reactor is purged to prevent nitrogen buildup in the system (stream 5). The rest of the tail gas is scrubbed to remove CO_2 and recycled through a very high temperature reactor (VHTR) reformer, where the 25 mole % methane composition can be reformed to hydrogen and carbon monoxide for reuse. The steam-to-carbon ratio in the reformer is ~1.5. The heat recovered from the 760°C (1400°F) reformer outlet stream is used to produce the reformer steam.

The second process is the direct process, as shown in Fig. 2. The coal liquefaction step could be any of the processes currently under development, such as SRCII (Gulf), Donor Solvent (Exxon), or H-Coal (Hydrocarbon Research Inc.). The process produces coal liquids by mixing (slurrying) dried, finely ground coal with a coal liquid product. Hydrogen is added to the resulting slurry and the mixture is then heated to 400°C (750°F) at 10 MPa (1500 psi) with steam from the HTGR, where the hydrogenation reaction proceeds with cold hydrogen added for temperature control. The resulting products are separated into a fuel oil and light distillate product which is further treated with hydrogen to produce jet fuel. A portion of the product, containing coal ash, which has a catalytic effect on the coal hydrogenation reaction, is recycled to make the coal slurry. A slurry of undissolved coal and ash is sent to a coker to increase the yield of fuel oil product by about 24%. The coke product from the coker is mixed with steam and oxygen and sent to a Texaco partial oxidation reactor to make a product of the hydrogen used in the process and yield an environmentally acceptable neutral ash. The methane produced is used as feedstock to the steam-methane reformer which is heated by the HTGR.

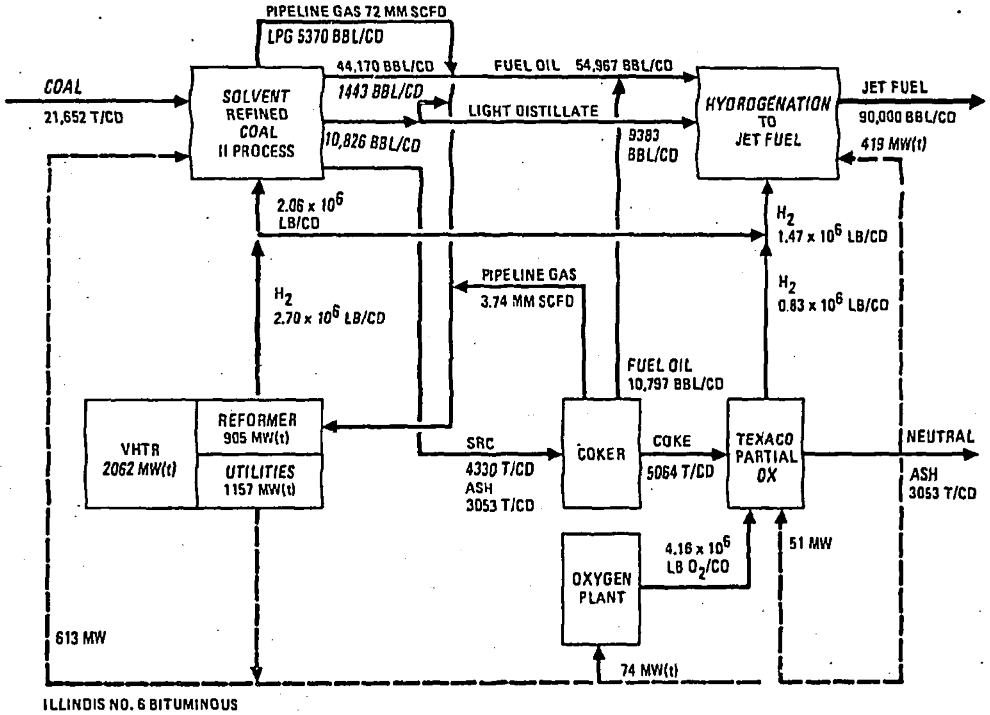

Fig. 2. Coal to jet fuel: using VHTR reforming for H_2 (prime) and using HTGR for utilities

Table 3 shows a comparison of nuclear and non-nuclear coal liquefaction processes. Basically, for each process the addition of the nuclear reactor can decrease the coal requirements by 33% for the same product output or for the same coal requirements can increase the product output by 50%.

TABLE 3
COMPARISON OF NUCLEAR AND NON-NUCLEAR COAL LIQUEFACTION PROCESSES

	Indirect Conventional	Indirect Nuclear	Direct Conventional	Direct Nuclear
Process	Lurgi-Fischer-Tropsch	Lurgi-Fischer-Tropsch nuclear reforming	SRC-II	SRC-II nuclear reforming
Coal feed, tons/day	46,400	30,800	32,210	21,700
Nuclear heat source				
Reforming,(a) MW(t)	--	775	--	905
Steam, MW(t)	--	2,300	--	1,155
Product Output				
Bbl/day	90,000	90,000	90,000	90,000
Tons/yr	4.4×10^6	4.4×10^6	4.4×10^6	4.4×10^6
Thermal efficiency, %	42	48	59	67
Product/coal ratio, bbl/ton	1.9	2.9	2.8	4.2
$\frac{\text{Heat in product}}{\text{Heat in coal}}$	0.42	0.64	0.59	0.95
Cost,(b) $/bbl	--	--	$29.80	$25.20

(a) Includes steam production for reformer.

(b) Coal at $25 per ton.

COAL TO PIPELINE GAS PROCESSES

There are several processes for converting coal to pipeline gas. Two basic routes, hydrogasification and steam-carbon reaction, can be matched to a nuclear heat source. General Atomic has done previous work on a coal solution hydrogasification process (Ref. 2) which will not be discussed here. This process also uses steam reforming for the hydrogen sources. The steam-carbon method with a nuclear heat source is not currently under investigation in the United States.

NUCLEAR HEAT SOURCE

The VHTR plant design addressed envisages a nuclear-chemical process whose product is hydrogen (or a mixture of hydrogen and carbon monoxide) generated by steam reforming of a light hydrocarbon mixture. The reactor thermal energy is transported to the externally located process plant by an intermediate heat transport loop. The intermediate loop provides an additional boundary between the nuclear heat source and the process, thereby improving plant safety and offering considerable flexibility for alternate applications. In addition to providing the thermal driving potential required for the reforming process, the nuclear heat is also used to generate high-temperature, high-pressure steam in sufficient quantities to satisfy both the process and electrical generation needs for the operation of the nuclear plant and reforming process plant.

The selected VHTR plant thermal rating of 842 MW(t) corresponds to the HTGR steam cycle plant constructed and operating at Fort St. Vrain (FSV) for the Public Service Company of Colorado. In addition, this size is commensurate with process heat user requirements (Ref. 3). Like other HTGRs, the VHTR has its entire primary coolant system contained in a prestressed concrete reactor vessel (PCRV) which provides the necessary biological shielding in addition to the pressure containment function. An isometric representation of the VHTR arrangement is shown in Fig. 3.

Thermal energy is removed from the reactor core by two independent primary/secondary helium systems and is supplied to separate process loops. This approach avoids the need to shut down the entire plant in the event of an upset in one of the process trains and also permits maintenance work to be carried out on an isolated secondary loop during plant operation. Three independent shutdown loops have been provided, each with the capability of full-core decay heat removal during emergency conditions.

Figure 4 presents the basic flow diagram and gives the steady-state operating conditions. The primary helium temperature of 950°C (1742°F) was established to meet the requirements of the chemical process while staying

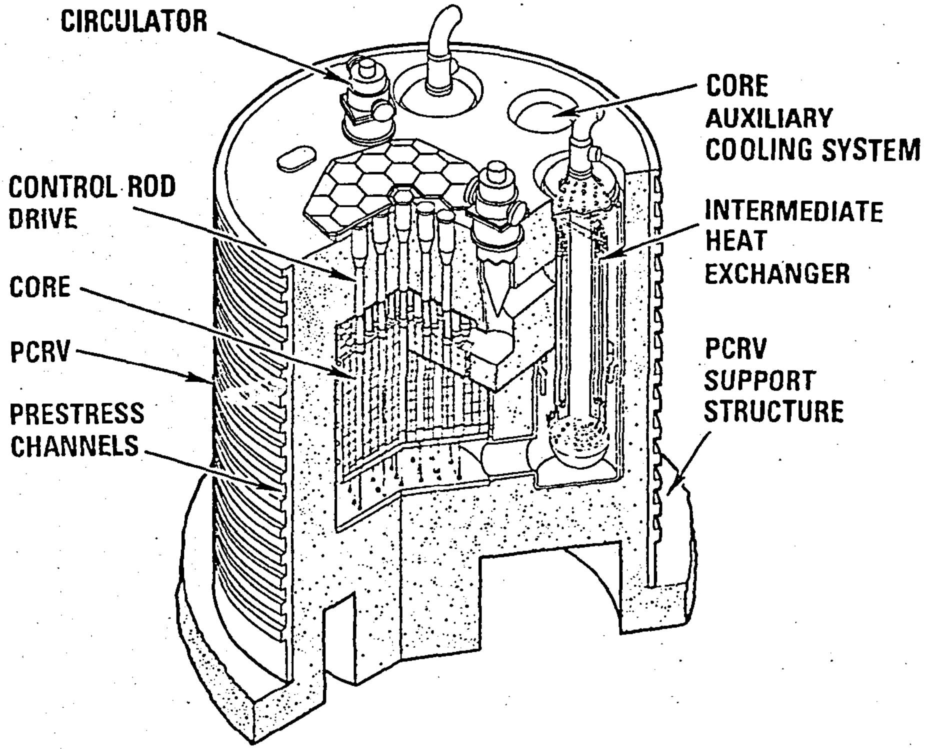

Fig. 3. HTGR-process heat source

within the structural limits of the Inconel 617 material used in the intermediate heat exchanger (IHX). Materials compatibility programs currently in progress will have a strong bearing on whether the corrosion resistance of this material is adequate at this temperature. The current work at GA is aimed at a lower core outlet temperature — in the range of 750° to 850°C (1390° to 1560°F). These lower temperatures are more compatible with a design that could lead to an earlier demonstration plant in the United States. The pressure level of 5 MPa (725 psia) is consistent with approaches followed in the FSV design.

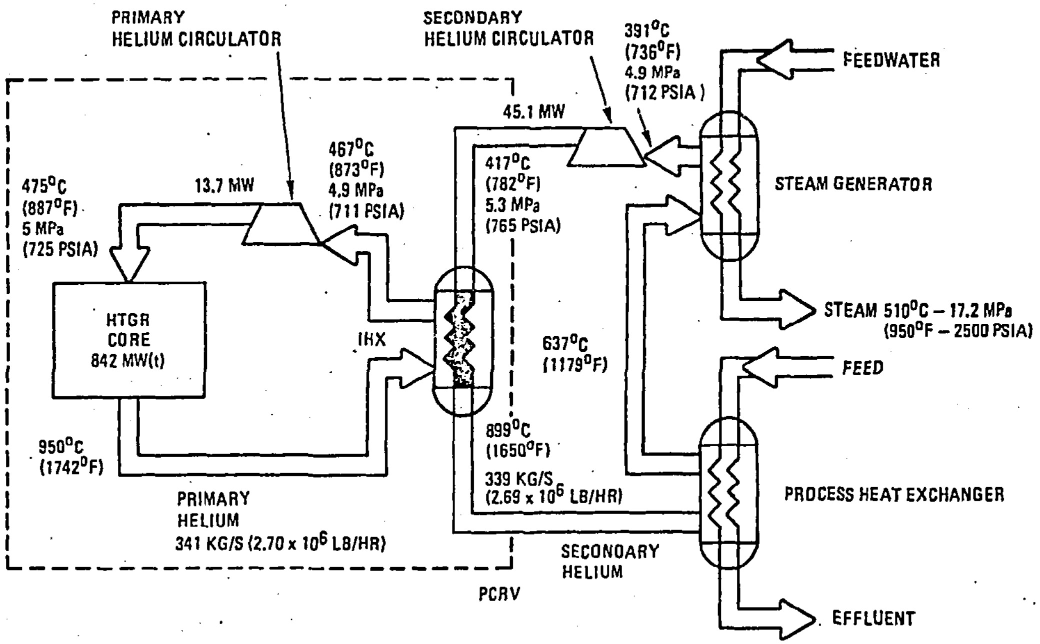

Fig. 4. HTGR-process heat flow diagram

Each primary loop includes an IHX, an electric motor driven primary helium circulator, and related instrumentation and controls. The primary coolant flows downward through the reactor core, where it is heated to 950°C (1742°F). The hot helium is collected in a plenum area beneath the core and manifolded to the two IHX units situated inside cavities beside the core. The primary helium flows upward through the IHX cavity, countercurrently transferring heat to the secondary helium. The cooled primary helium leaving each IHX is then ducted to its respective circulator, which returns it to the inlet plenum above the reactor core at 475°C (887°F).

The secondary helium system (or secondary loop) transports thermal energy from the IHX to the process plant. Because leakage within the IHX can result in direct communication between the secondary and primary circuits, the secondary helium pressure level is set slightly higher than that in the primary circuit. This prevents possible leakage of the reactor helium into the secondary system. The secondary helium is intentionally maintained at a pressure level near the primary helium pressure in order to minimize the long-term loading on the IHX, in which the combination of high temperature and material limitations requires a near-pressure-balanced operation for structural integrity.

The two secondary helium loops each consist of an IHX, a reformer, a steam generator, a secondary helium circulator, and the related piping, valves, and instrumentation. During normal operation secondary helium is heated to 899°C (1650°F) in the IHX and routed outside the PCRV to the reformer and then to the steam generator, which extracts the heat necessary for the process and auxiliary power generation. The hot helium thermal energy is split between the reformer (52%) and steam generator (48%). Cool helium is then pumped back to the IHX at a temperature of 417°C (782°F) by the secondary circulator.

COMPONENT DESCRIPTION

PRESTRESSED CONCRETE REACTOR VESSEL

The PCRV is a multicavity pressure vessel which, together with liners and penetrations, functions as the primary containment for the reactor core and the primary coolant system. The PCRV also provides biological shielding around the core and provides the necessary structural support for the nuclear heat source system. It is constructed of high-strength concrete reinforced with conventional reinforcing bars and prestressed by two post-tensioning systems, the linear prestressing system and the circumferential prestressing system. The linear prestressing system consists of individual multistrand tendons to develop the vertical prestress for the PCRV, and the circumferential prestressing system employs wire winding around the circumference of the PCRV to provide the required radial prestress. All cavities and penetrations are lined with welded steel liners which act as impermeable gas-tight membranes to contain the primary coolant. The liners are anchored by studs welded to the liners and embedded in the concrete.

Table 4 gives the pertinent design parameters associated with the PCRV and its cavities.

TABLE 4
COMPONENT DESIGN PARAMETERS

<u>PCRV</u>	
Diameter	23.2 m (76 ft)
Height	20.9 m (68.75 ft)
Core cavity diameter (1 place)	9.6 m (31.6 ft)
Core cavity height	12.9 m (42.2 ft)
IHX cavity diameter (2 places)	4.6 m (15 ft)
IHX cavity height	17.3 m (56.75 ft)
Circulator cavity diameter (2 places)	2.2 m (7.25 ft)
CACS cavity diameter (1 place)	2.5 m (8.25 ft)
Core offset from PCRV center	3.7 m (12 ft)
<u>Core</u>	
Core thermal power	842 MW(t)
Core power density	6.3 W/cm^3
Avg. core outlet temperature	950°C (1742°F)
Fuel in-core lifetime	3 yr
Core volume	133.7 m^3
Number of fuel elements	1482
Number of control rod pairs	37
<u>IHX (per unit)</u>	
Number of units	2
Type	Modular straight-tube counterflow design
Heat duty	425.6 MW(t)
Tube diameter	11.1 mm (0.4375 in.)
Heat transfer surface area	10,448 m^2 (112,460 ft^2)
Number of tubes	32,512
Number of tubes per module	127
Number of modules	256
<u>Primary Helium Circulators (per unit)</u>	
Number of units	2
Type	Single-stage axial flow
Drive	Synchronous motor
Bearing system	Water lubricated, with a buffer seal
Blading tip diameter	1295 mm (51 in.)
Blade height	97 mm (3.8 in.)
Static pressure rise	96.6 kPa (14.0 psi)
Discharge pressure	5.0 MPa (725 psia)
Circulator rated speed	465 rad/s (4440 rpm)
Motor shaft power	6.85 MW(e)
Speed control	Solid state variable frequency
<u>Core Auxiliary Helium Circulator</u>	
Number of units	1
Type	Two-stage, axial flow
Drive	Variable speed induction motor
Bearing system	Oil lubricated
Flow rate	6.7 kg/s (53,000 lbm/hr)
Suction pressure	148 kPa (21.4 psia)
Discharge pressure	165 kPa (24 psia)
Static pressure rise	18 kPa (2.6 psia)
Circulation speed	372 rad/s (3550 rpm)
Motor shaft power	670 kW (900 hp)
Speed control	Solid state variable frequency
<u>Core Auxiliary Heat Exchanger</u>	
Number of units	1
Type	Counterflow bayonet tube design
Surface area	370 m^2 (3978 ft^2)
Tube pitch	60 mm (2.38 in.)
Tube bundle diameter	1.45 m (57 in.)
<u>Secondary Helium Circulators (per unit)</u>	
Number of units	2
Type	Multistage, centrifugal
Drive	Steam-turbine
Bearing system	Oil lubricated
Flow rate	170 kg/s (1.35 x 10^6 lbm/hr)
Discharge pressure	5.27 MPa (765 psia)
Static pressure rise	362 kPa (52.6 psi)
Shaft power	22.6 MW
<u>Steam Generator (per unit)</u>	
Number of units	2
Type	Once-through, helical tube design
Overall height	13.2 m (43.25 ft)
Overall diameter	2.97 m (9.75 ft)
Heat duty	215.5 MW(t)
<u>Reformer (per unit)</u>	
Number of units	2
Type	Axial counterflow convectively heated heat exchanger
Total tube surface area	4817 m^2 (51,847 ft^2)
Heat duty	229 MW(t)
Tube material	HK-40
Tube outside diameter	86 mm (3.4 in.)

THERMAL BARRIER

The thermal barrier, in conjunction with the PCRV cooling water system, controls the temperature levels and gradients in the PCRV and minimizes heat losses from the primary coolant system. The thermal barrier design is directly based on the designs developed for the HTGR gas turbine and steam cycle plants. It has been necessary to upgrade the temperature capabilities of certain classes of thermal barriers for use in the process heat reactor because of the more demanding temperature requirements. The insulation material used is fibrous alumina and alumina silica. The fibers, in the form of mats, are firmly held against the cavity liners by cover plates. Except in the core outlet region, metallic plates of the same materials used in HTGR steam cycle plants are used. The VHTR core outlet gas temperatures require nonmetallics in this region. A carbonaceous fiber-reinforced composite is being considered for the core outlet plenum side wall and hot duct cover plates; slip-cast ceramic blocks of fused alumina and fused silica are being considered for the plenum floor cover plates. The high-temperature thermal barrier will involve developmental work.

The thermal barrier thickness, cover plate size, and method of attachment to the cavity liner vary, depending on location and required duty. Thin metallic seal sheets and sleeves are placed between the cover plates, the fasteners, and the fibrous insulation to minimize the loss of fibers into the primary system and the flow of coolant into the fiber mats. The overall thickness of the thermal barrier ranges from 102 to 229 mm (4 to 9 in.) depending on location.

REACTOR CORE

The VHTR core is the same size [842 MW(t)] and operates at the same power density as the FSV HTGR. In addition, the prismatic fuel block design is identical to the FSV design. The core consists of vertical columns of hexagonal graphite fuel moderator elements and graphite reflector blocks grouped into a cylindrical array and supported by a graphite support structure. The core is divided into 37 fuel regions, each consisting of a central fuel control element column with standard surrounding columns. This arrangement contains 210 standard fuel columns and 37 control fuel columns. Each column consists of six fuel elements, for a total of 1482 elements in the core. The coolant flow rate through each fuel region is controlled by a variable orifice mechanism at each region inlet.

The fissile fuel material is TRISO-coated uranium carbide, and the fertile material is BISO-coated thorium oxide. The uranium and thorium particles are coated with layers of pyrolytic carbon (and silicon carbide for the uranium particles) and bonded into fuel rods within the hexagonal graphite elements. The particle coatings provide the primary barrier for fission product retention. Either highly enriched uranium (HEU) or medium-enriched uranium (MEU) cores are possible. The basic structural material of the core is nuclear-grade graphite machined in the form of hexagonal blocks. These blocks also serve as the moderator and heat transfer medium between fuel and coolant.

The 3-year fuel cycle with annual refueling of one third of the core should reduce the effects of fuel age differences in the core by minimizing the local power peaks in the core, thus lowering peak fuel temperatures, neutron exposure, and consequent fission product release. Design requirements for yielding low fuel particle failure fractions, low fission product release, and low graphite block stress levels can therefore be satisfactorily met for the VHTR.

INTERMEDIATE HEAT EXCHANGER

The IHX is a nuclear-grade safety class component which transfers the heat from the primary helium circuit to the secondary helium circuit during normal operation and is also used to remove heat during emergency core cooling. This component has been designed as a modularized straight-tube counterflow heat exchanger to obtain (1) geometric heat exchanger proportions most consistent with the PCRV envelope, (2) minimum metal temperature gradients, (3) reduced helium pressure loss requirements, and (4) minimum potential for flow-induced tube vibrations. The design is similar to that of helium-to-helium heat exchangers used in the HTGR gas turbine plant. Table 4 gives pertinent design data for the IHX. Although normal operation is in a near-pressure-balanced condition, the design basis is predicated on the loss of the secondary loop pressure putting the tubes into compression. The current selection of tubing material is Inconel 617. An extensive high-temperature materials program is in progress to obtain high-temperature data for the potential materials in this application. The material selection and design of the IHX represent a substantial technical development effort.

HELIUM CIRCULATORS

Axial and centrifugal flow circulators are used to pump the helium in the VHTR primary and secondary helium loops, respectively. With the present loop arrangement, electric motors with variable frequency control are used to power the primary loop circulators and steam turbines are used to drive the secondary loop circulators. Safety class pony motors on the primary helium circulators, in addition to the main motors, and safety class electric-motor-driven circulators in the secondary loops provide helium circulation for emergency core cooling. Table 4 gives additional design information for the primary, secondary, and auxiliary circulators.

REFORMERS

The steam-methane reformer transfers the heat from the helium loop to the reformer feedstock in the presence of a nickel catalyst. It is, in effect, an axial counterflow convective heat exchanger, but with space provided on the tube side for the inclusion of the catalyst material.

Many different concepts which appear to satisfy basic reformer requirements are possible. However, the design considered in this paper is a concept which has been used in the fossil-fired reforming industry for many years, with variations required for adaptation to convective heating. This concept utilizes a shell-and-tube heat exchanger which has tubes large enough to contain the catalyst material in stacked particle bed form. The feedstock is introduced on the tube side of the heat exchanger and flows over the catalyst particles while being heated by the tube walls. The conversion reaction takes place during 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 loop convective heat source, the tubes are grouped together to form a gas-to-gas tube-and-shell heat exchanger. The hot secondary 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.

STEAM GENERATORS

The steam generator is similar to the HTGR steam cycle steam generator in bundle size and basic design; both are vertical, uphill-boiling, once-through helical-tube generators. For the VHTR, the bundles are installed in internally insulated steel pressure vessels which are located in the secondary loop and therefore are not required to be designed as an ASME Code, Section III, Class 1 component.

PLANT SAFETY AND EMERGENCY CORE COOLING

The VHTR incorporates all of the inherent safety characteristics of the HTGR power plants. These include low reactor power density, high core heat capacity, use of ceramic materials for the core and moderator, single-phase reactor coolant, and employment of a PCRV. In addition, engineered safety features are provided to reduce the probability and mitigate the consequences of accidents. These include redundant means for emergency core cooling and provisions for containment of radioactive releases.

The main core coolant loops have safety class components to provide emergency core cooling capability. In addition, a diverse-design safety class core auxiliary cooling loop is provided. One hundred percent shutdown core cooling capability can be provided by any one of these three loops, with the reactor either pressurized or depressurized. The reactor containment building contains releases from any postulated primary coolant depressurization accidents.

BALANCE OF REACTOR PLANT

Figure 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

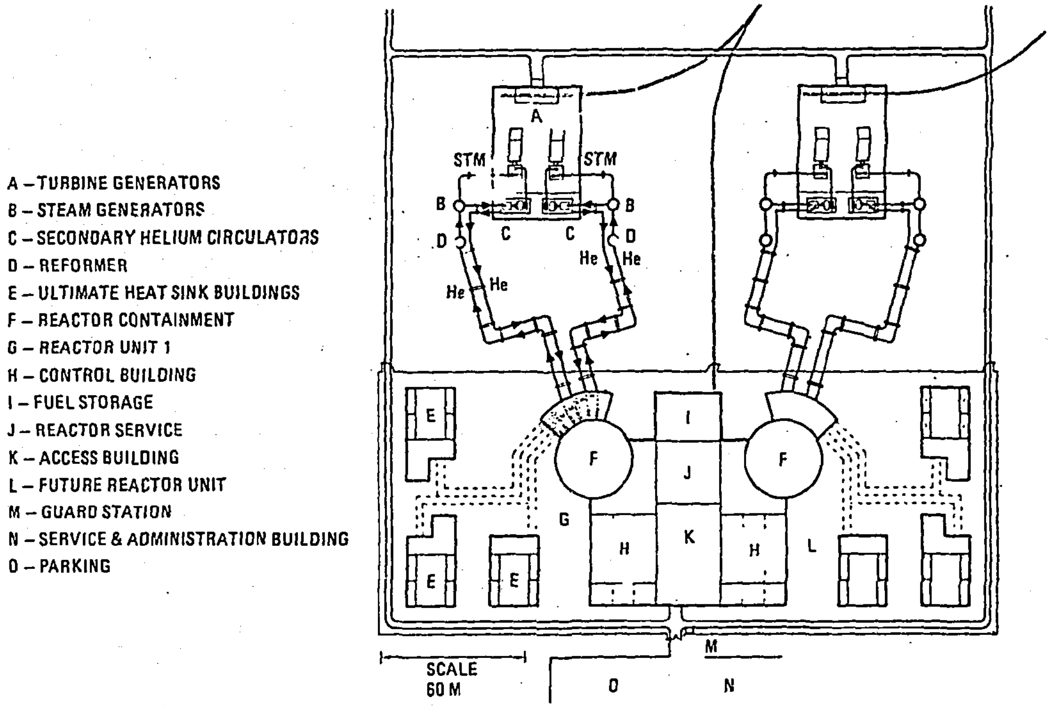

Fig. 5. Twin 842-MW(t) HTGR-process heat plot plan

are arranged similar to current HTGR power 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 to provide protection against possible failures in the process plant. A similar separation is maintained between the reformers and other equipment in adjacent process plant trains.

The secondary helium circulators and turbine-generators are located in a building near the reformers and steam generators. Equipment items required for safe reactor operation and shutdown are located in safety class protective buildings near the reactor containment. Secondary helium containment piping penetrations and isolation valves are located in protective enclosures attached to the containment. "Z"-shaped bends in the secondary helium pipes provide for thermal expansions between the containment and process plant equipment.

The design of reactor auxiliary systems is very similar to that for the HTGR power plants, except for additional facilities for helium handling and purification associated with the secondary helium loops. The Nuclear Island includes the reactor service building, which contains equipment for fuel handling and other reactor support operations; the fuel storage building, which includes a hot service facility and fuel shipping equipment; the control and diesel-generator building; the ultimate heat sink buildings, which house equipment for emergency core cooling heat rejection; and the access control building.

PLANT DESIGN AND PERFORMANCE CODE

As part of the development of the nuclear process heat work, a computer model of the nuclear heat source and the associated process plant is under development. This Process Heat Reactor Evaluation and Design (PHRED) code will be able to:

1. Calculate the complete mass flow and heat balance for the reactor plant for a wide variety of independent variables, e.g., core outlet temperature, primary loop pressure, process temperature.
2. Specify design operating conditions for all major components and calculate the size of the components based on their performance requirements, e.g., IHX, helium circulator, steam generator, PCRV.
3. Calculate the capital and operating costs of the entire nuclear heat source and associated process plant.
4. Couple to any available multi-variable direct search optimization program for system optimization studies.

The program is 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 (IDVs), and these values are input by the program user. The program operates 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 plant. An alternate case plant is then defined by exercising the plant model within the program using values of the IDVs which are different from the base case values. A list of the 52 IDVs available to the user is shown in Table 5.

TABLE 5
VALUES OF INDEPENDENT DESIGN VARIABLES

```
MAXIMUM PRIMARY HELIUM PRESSURE
REACTOR THERMAL POWER
REACTOR INLET TEMPERATURE
REACTOR OUTLET TEMPERATURE
REACTOR CORE DIAMETER
REACTOR CORE HEIGHT
TOP REFLECTOR THICKNESS
SIDE REFLECTOR THICKNESS
BOTTOM REFLECTOR THICKNESS
CORE COOLANT HOLE DIAMETER
CORE HOLE PATTERN PITCH
CORE CARBON/THORIUM RATIO

INTERMEDIATE HEAT EX CAVITY DIAMETER
REACTOR OUTLET DUCT DIAMETER
INTER HEAT EX OUTLET DUCT DIAMETER
CIRCULATOR CAVITY DIAMETER
REACTOR INLET DUCT DIAMETER
NUMBER OF CACS LOOPS IN THE PCRV

NUMBER OF INTERMEDIATE HEAT EXCHANGERS
INTER HEAT EX SECONDARY INLET TEMP
INTER HEAT EX SECONDARY OUTLET TEMP
INTERMEDIATE HEAT EX TUBE OUTER DIA
INTER HEAT EX TUBE PITCH/DIAMETER RATIO
INTER HEAT EX CENTRAL DUCT OUTER DIA

MAXIMUM SECONDARY HELIUM PRESSURE
REACTOR-TO-REFORMER SEPARATION
SECONDARY PIPING HOT-LEG OUTER DIA
SECONDARY PIPING COLD-LEG OUTER DIA
HOT-LEG THERMAL BARRIER THICKNESS

NUMBER OF REFORMERS
REFORMER STEAM/METHANE RATIO
REFORMER PROCESS OUTLET PRESSURE
REFORMER PROCESS OUTLET TEMPERATURE
REFORMER TUBE OUTER DIAMETER
REFORMER TUBE PITCH/DIAMETER RATIO
REFORMER TOTAL NUMBER OF TUBES
REFORMER CATALYST PARTICLE DIAMETER

NUMBER OF STEAM GENERATORS
STEAM GEN STEAM OUTLET PRESSURE
STEAM GEN STEAM OUTLET TEMPERATURE
STEAM GEN EES1 TUBE OUTER DIAMETER
STEAM GEN EES1 TUBE WALL THICKNESS
STEAM GEN EES1 TRANS PITCH/DIA RATIO
STEAM GEN EES1 LONGI PITCH/DIA RATIO
STEAM GEN S2 TUBE OUTER DIAMETER
STEAM GEN S2 TUBE WALL THICKNESS
STEAM GEN S2 LONGI PITCH/DIA RATIO
STEAM GEN TOTAL NUMBER OF TUBES
STEAM GEN NUMBER OF TUBE LAYERS
S G CENTRAL DUCT OUTER DIAMETER

COGENERATED ELECTRIC POWER OUTPUT
AMBIENT TEMPERATURE
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The top-level logic is shown in Fig. 6. The major iteration loop shown on the diagram is the iterative solution required to achieve an energy and mass balance over *all the flow and energy paths in the plant.*

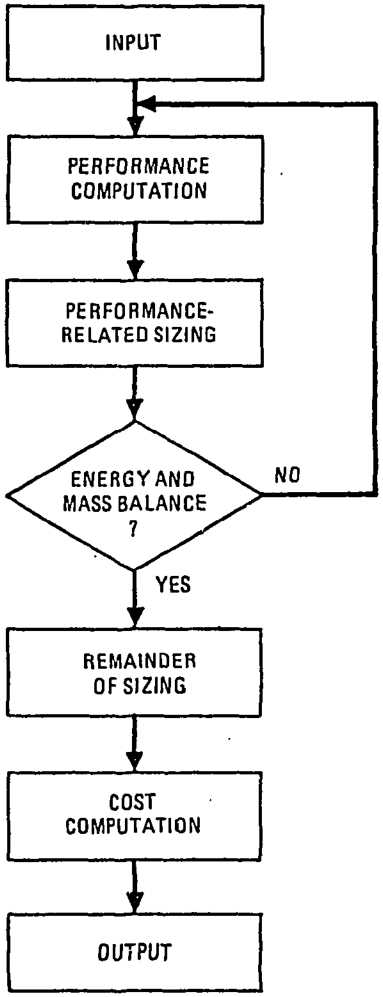

Fig. 6. Top level logic diagram for the PHRED computer program

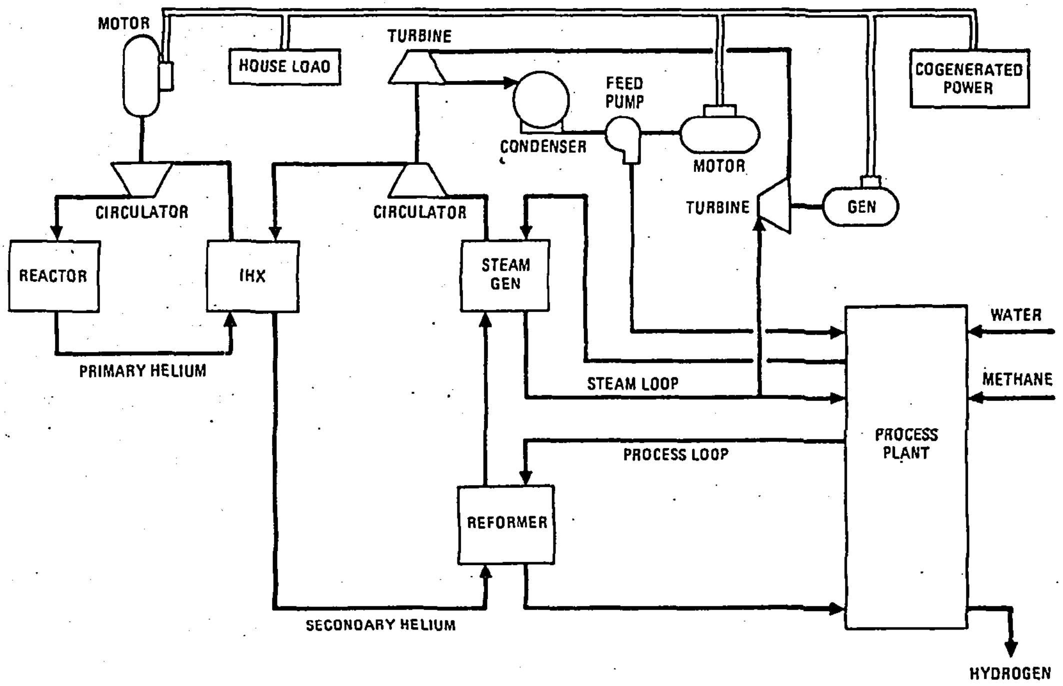

Fig. 7. Schematic loop arrangement for VHTR hydrogen production process plant

The plant design used for the reference design is that described in this paper and shown diagrammatically in Fig. 7. There are four interacting fluid loops that must be solved iteratively in order to complete the mass and heat balance: primary helium, secondary helium, steam cycle, and process cycle. In order to keep the program as flexible as possible and to match the reactor program with different process plants, the process plant is handled separately and methods of joining the two together have been developed. The reference process plant is steam-methane reforming and has been modeled using the commercially available process design code DESIGN/2000 developed by the Chemshare Corporation (Ref. 4). The data obtained are transcribed to supply a data table within the parametric design program. When programmed for a particular process, DESIGN/2000 has the capability of iteratively solving for all fluid flow streams, sizing process equipment, and establishing performance data. The results of this code are also used as input to establish the cost of the process plant.

HEAT EXCHANGERS

Since the heat exchangers are at the loop intersections, the modeling of these units is very important. These models are described briefly below.

Intermediate Heat Exchanger

The IHX heat transfer is computed using a single mode and averaged helium properties. Previous studies have shown excellent agreement between this simple approach and more complex analysis performed by iterating along the length of the bundle. For a given set of operating conditions and IHX frontal geometry, the model designs a counterflow tubular helium-to-helium heat exchanger based on the mechanical layout established for the reference design. This heat exchanger design process includes the following determinations:

1. Thermal sizing.
2. Primary and secondary side pressure losses (including parasitics).
3. Tube material selection (Incoloy 800H or Inconel 617) with the option of siting a bimetallic weld at a reference metal temperature.
4. Structural thicknesses of cylindrical pressure parts (short-term compressive loads, long-term tensile loads, and practical handling thicknesses considered in the selection process).
5. PCRV cavity envelope requirements (including parasitic height allocations).
6. Weight breakdown of IHX constituent parts.
7. Enhanced surface geometry option.

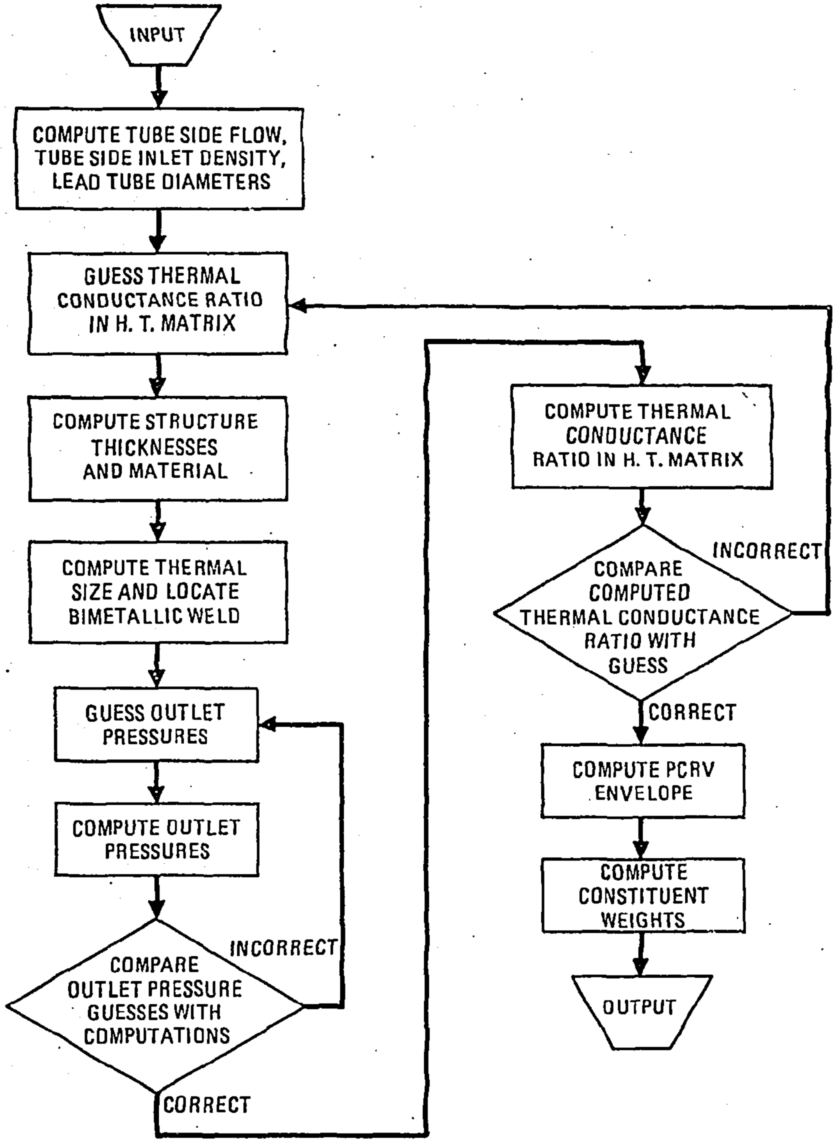

Fig. 8. IHX computer model flowsheet

A flowsheet description is given in Fig. 8. Items 3 and 4 above are the most important features of the IHX model because the material type and quantity of IHX tubing are an important VHTR economic consideration.

Since the IHX tubing cost is roughly proportional to the tube wall thickness, considerable attention was given to developing simple, closed-form correlations for computing tube wall thickness consistent with the procedures given in Section II of the ASME Boiler and Pressure Vessel Code. This entailed extrapolating available test data for the operating temperature/material regimes not covered in the Code. No additional wall thickness allowance calculations are built into the IHX model at this time. Instead, the model can accommodate a specified thickness allowance as an input IDV which is added to the calculated structural thickness prior to thermal sizing operations.

Work to refine the IHX model is continuing, and it is expected that this upgrading will continue as more materials data and design technology improvements become available.

Reformer

The reformer model utilizes a reformer sizing program originally developed by Los Alamos Scientific Laboratory. This model will determine the reformer tube length, heat duty, process outlet composition, and helium outlet conditions when given the following set of IDVs:

1. Tube inside diameter.
2. Tube pitch/diameter ratio.
3. Steam/methane ratio.
4. Methane-steam inlet temperature.
5. Methane-steam outlet temperature.
6. Methane-steam outlet pressure.
7. Catalyst diameter.

This model calculates, for each increment of length along the tube, the helium side heat transfer coefficient, process side heat transfer coefficient, and temperatures as well as the reforming reaction rate.

This reformer model has also been adapted to operate as part of the process design model within DESIGN/2000 (Ref. 4), so both the secondary loop model and process model utilize the same reformer model.

Steam Generator

The steam generator model is taken from the standard steam generator design computer program used at General Atomic, but it has been reworked so that it requires less computer run time than its standard version. The tube bundle configuration used is a helical coil design. The IDVs used to define the steam generator design are:

1. Inner diameter of the outer bundle shroud.
2. Outer diameter of the inner bundle shroud.
3. Number of tube rows.
4. Longitudinal tube pitch.
5. Stress margin (determines tube diameter).
6. Outlet steam temperature.
7. Outlet steam pressure.

The computations are performed over small increments of the length of the bundle, from the hot end toward the cold end, and the bundle is divided into three main sections: economizer, evaporator, and superheater. The length of each section of the bundle and the associated pressure drops are the major dependent variables computed by the model.

INTERACTION OF PROCESS PLANT AND NUCLEAR PLANT

The major link between the nuclear plant and the process plant is the steam generator and the reformer. The steam generator is the key item in coupling the two systems. The steam produced in the steam generator has three uses. It provides the steam which is mixed with methane to form the reformer feed; it provides heat and power (from turbogenerator 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, then the iteration variable (methane mass flow rate) must be reduced to achieve the overall plant energy and mass balance. The overall energy and mass balance is obtained 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 DESIGN/2000. 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 this 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.

CONCLUSIONS

1. The current U.S. energy picture provides a bright future for synfuel programs based on coal. Process development plans are being firmed up, and demonstration size plants should be started in the near future.
2. Current analysis of the inclusion of HTGRs in the synfuel program shows a major advantage in coal savings and environmental impact but no particular cost advantage at present U.S. coal prices.
3. A conceptual design for the nuclear process heat plant at 950°C (1742°F) core outlet has been developed based on the General Atomic steam cycle and gas turbine work. For some applications, notably coal gasification by steam-carbon reaction of bituminous coal and thermochemical watersplitting, the 950°C (1742°F) temperature may be required. For steam-methane reforming, lower temperatures are still efficient and are being examined.
4. The PHRED code currently under development will be a powerful tool in establishing the overall system parameters for an optimized nuclear heat source-chemical process plant.

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BASIC LAY-OUT, ARRANGEMENT AND DESIGN CRITERIA OF HEAT COMPONENTS OF THE "NUCLEAR COAL GASIFICATION PROTOTYPE PLANT (PNP)"

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1. Introduction

Since 1975, the companies Bergbau-Forschung GmbH, GHT Gesellschaft für Hochtemperaturreaktor-Technik mbH, Hochtemperatur-Reaktorbau GmbH, Kernforschungsanlage Jülich GmbH und Rheinische Braunkohlenwerke AG - are working jointly on the Project "Prototype Plant Nuclear Process Heat (PNP)", with promotion of the "Bundesminister für Forschung und Technologie" 1) and of the "Minister für Wirtschaft, Mittelstand und Verkehr des Landes Nordrhein-Westfalen" 2).

The objectives of the project are the development of a high-temperature reactor, with a core outlet temperature of 950°C, suitable for various process heat applications, and the development and testing of the appropriate coal gasification technology.

In the initial stage of the project, various alternative methods were examined in respect to the gasification of lignite and hard coal for various gasifications products.

In order to restrict the number of different variants and the development effort itself, only such gasifications schemes were selected, which would allow the processing of all types

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1) Federal Minister for Research and Technology

2) Minister for Economics, Small Business, and Transport of the State of North Rhine/Westfalia