CONF-800983--1

GA-A16052

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HIGH TEMPERATURE HEAT EXCHANGE – NUCLEAR PROCESS HEAT APPLICATIONS

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This is a preprint of a paper to be presented at the Joint Japan/U.S. Heat Transfer Seminar, September 29 to October 3, 1980, Tokyo, Japan, and to be published in the Proceedings.

Work supported in part by
Department of Energy
Contract DE-AT03-76SF71061

GENERAL ATOMIC PROJECT 7200
SEPTEMBER 1980

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HIGH TEMPERATURE HEAT EXCHANGE - NUCLEAR PROCESS HEAT APPLICATIONS

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ABSTRACT

The high-temperature gas-cooled reactor (HTGR) is unique among nuclear systems in its ability to serve as a heat source up to 1000°C, high enough for many industrial uses of energy, including steelmaking, coal liquefaction and gasification, and in the future, large scale thermochemical production of hydrogen. The HTGR process heat applications have been studied at General Atomic for many years in programs sponsored by the Department of Energy (DOE) and process heat user industries (steel, chemical, and gas).

The first generation of HTGR was designed to take full advantage of modern steam plant technology, as exemplified by the Peach Bottom and Fort St. Vrain reactors. The study of advanced HTGR process heat variants [also termed very high temperature reactors (VHTR)] is aimed at further exploiting its unique high-temperature capability.

The unique element of the HTGR system is the high-temperature operation and the need for heat exchanger equipment to transfer nuclear heat from the reactor to the process application. This paper discusses the potential applications of the HTGR in both synthetic fuel production and nuclear steel making and presents the design considerations for the high-temperature heat exchanger equipment.

INTRODUCTION

Energy consumption in the industrialized nations has spiraled upward during the past decades. As Table 1 shows, petroleum and natural gas meet more than 75% of the U. S. energy demands (Ref. 1). However, petroleum and natural gas comprise only 7.9 % of the estimated total recoverable U.S. fossil fuel resources.

As Table 2 shows, coal comprises more than 75% of the estimated total remaining recoverable U.S. fossil fuel. However, coal accounts for only 18% of the U.S. energy consumption.

TABLE 1
U.S. ENERGY CONSUMPTION
(1979)

Resources	J x 10^{18}	%
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.
(1979)

Resources	J x 10^{18}	%
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

Natural gas, which provides more than 30% of the U.S. energy demands, cannot be expected to maintain its hold over such a large share of U.S. energy production. Limited natural gas availability will require using other energy resources. Since oil is the predominant fuel used in the U.S., it seems a logical alternative to assume most of the burden. However, domestic resources are inadequate to meet the increased demand, and the U.S. urgently needs to move away from its heavy reliance on foreign oil. Coal and nuclear power remain among proven energy sources to meet U.S. energy requirements. Coal, the most abundant remaining fossil fuel in the U.S., forms the basis for the emerging synfuel programs.

Japan faces the same dilemma of increasing its energy consumption and relying more heavily on imported oil. The steel industry, one of the largest Japanese energy consumers, uses more than 20% of the national energy. The Japanese steel industry ranks first in coal, gas, and electricity consumption and third in oil consumption.

Thus, a steel industry switch to alternative energy sources would be particularly meaningful. Japan has directed effort toward designing and developing an experimental 50-MW(t) VHTR with a helium outlet temperature of 1000°C (1832°F). Both governmental and industrial suppliers are participating in this national project. The Japan Atomic Energy Research Institute (JAERI) is scheduled to start construction on the 50-MW(t) VHTR in 1984.
The energy future of both the U.S. and Japan will depend on improved energy efficiency, conservation, and development of new energy sources.

HIGH-TEMPERATURE HTGR APPLICATIONS

The HTGR offers a unique heat source for either power generation or process heat production, since its operating temperature is significantly higher than that of other nuclear reactor types. A key feature of the HTGR is the nuclear reactor core, which uses helium as the primary coolant, has ceramic-coated fuel particles containing uranium and thorium, and employs graphite as the moderator and structural material. The helium heat transfer medium used as the primary coolant is chemically inert and remains in a gaseous phase under all possible operating conditions. The entire primary coolant system of the HTGR is contained in a prestressed concrete reactor vessel (PCRV), which provides the necessary biological shielding and pressure containment. The aforementioned elements of the HTGR offer unprecedented safety characteristics.

The first generation of HTGRs was designed to take full advantage of modern steam plant technology, as exemplified by the Peach Bottom and Fort St. Vrain reactors (Ref. 2). The study of advanced HTGRs is aimed at further exploitation of the unique high-temperature capability made possible by the all-graphite core, inert gas coolant, and ceramic-coated fuel particles.

Process Heat Plant Concept

The high-temperature heat available from the HTGR makes it suitable for many process applications. The high-grade heat can be used to produce reducing gas, hydrogen, and synfuel, using coal, lignite, residual oil, or oil shale as the carbon source. The HTGR can also serve as the heat source for thermochemical water-splitting processes to produce hydrogen without carbon, and it may be useful in large-scale energy transport and storage systems for industrial or utility applications.

The HTGR process heat plant is envisaged as 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 energy is transported to an 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 enhancing plant safety and offering considerable flexibility for alternate applications.

References 3 and 4 reported a process heat plant based on a reactor core thermal rating of 842 MW(t). This value corresponds to the HTGR steam cycle constructed and operating at Fort St. Vrain for the Public Service Company of Colorado. Figure 1 shows an isometric view of the nuclear heat system for the HTGR-process heat (HTGR-PH) plant. The system consists of two loops, each embodying an intermediate heat exchanger (IHX) and primary system circulator. Figure 2 shows a loop diagram

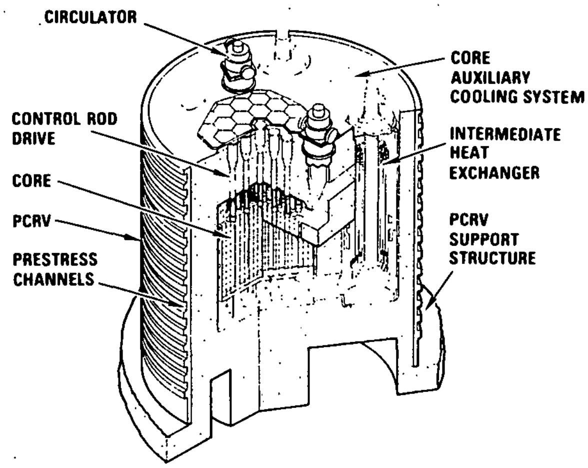

Figure 1 Nuclear heat source arrangement for 842-MW(t) HTGR-PH plant

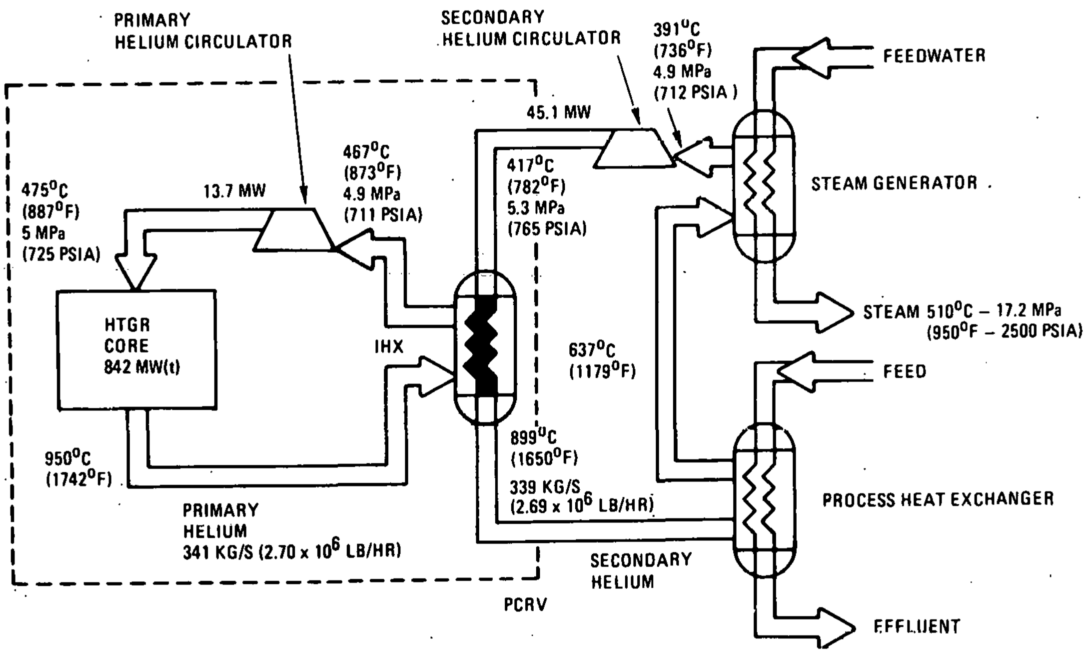

Figure 2 Cycle diagram for 950°C HTGR-PH plant

for the HTGR-PH plant. This cycle is based on a reactor outlet temperature of 950°C (1742°F), but studies are under way for an 850°C (1562°F) system. Figure 2 shows that the two secondary loops are supplied with energy from the IHXs and that each loop consists of a reformer, steam generator, and helium circulator connected in series. The HTGR-PH plant has several high-temperature heat exchangers, but this paper concentrates on various aspects of the most critical of these, namely the helium-to-helium IHX.

Integration of Nuclear Process Heat with Coal Liquefaction Processes

The vast U.S. coal resources will produce synthetic fuel via fundamentally two processes: (1) coal liquefaction and (2) coal gasification. The most readily marketable synthetic fuel would directly substitute for current liquid fuels (e.g., diesel fuel, jet fuel, or gasoline). These fuels can be made from coal, basically by adding hydrogen.

Production of liquid fuel from coal has two routes: (1) direct and (2) indirect. The direct route liquefies coal, then upgrades the basic product by hydrotreating. The Solvent Refined Coal (SRC II), Exxon Donor Solvent (EDS) and H-Coal processes are under development. The indirect route gasifies coal to produce a mixture of hydrogen, carbon monoxide, and methane, then uses this gas to synthesize, or hydrogenate, one or more liquid fuels.

Either liquefaction route can be used with the HTGR heat sources to produce synfuel from coal. The HTGR is integrated into the process to supply the utilities (steam and electricity) and process heat (reforming). Figure 3 illustrates integrating the HTGR-PH with a direct liquefaction process.

Table 3 compares the product yields with and without a nuclear heat source. Basically, adding the nuclear reactor can decrease the coal requirements by 33% per process or increase the product output by 50% for the same coal requirements.

Of the two routes for liquefying coal, only the indirect route is commercially used. This process of breaking down, then rebuilding hydrocarbons is the least efficient coal liquefaction route. Direct liquefaction, or hydrogenation, will probably become the major source of liquid fuels from coal.

Integration of Nuclear Process Heat With Steelmaking

Steelmaking would use nuclear energy as process heat to manufacture reducing agents and to supply heat at reaction temperature.

In the current refining process, iron ore, coke, and limestone are charged into a blast furance. Then air blown into the furnace under high pressure partially burns coke, producing CO, which with

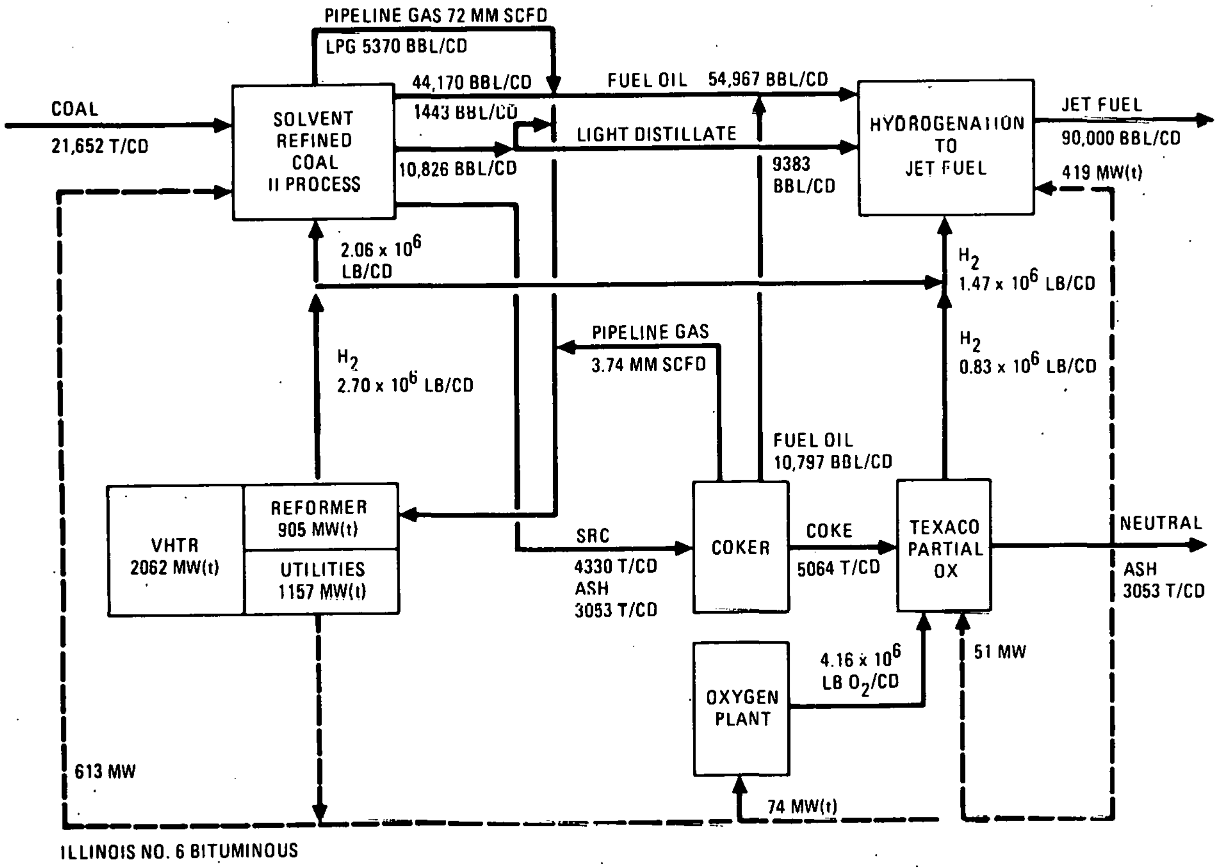

Figure 3 Coal to jet fuel, using VHTR reforming for H_2 (prime) utilities

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

Process	Indirect		Direct	
	Conventional	Nuclear	Conventional	Nuclear
	Lurgi-Fischer-Tropsch	Lurgi-Fischer-Tropsch nuclear reforming	SRC-II Conventional	SRC-II nuclear
Coal feed, tons/day	46,400	340,800	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
Ratio of heat in product to heat in coal	0.42	0.64	0.59	0.95

[a]Includes steam production for reformer.

residual coke, reduces the iron ore to molten pig iron. In this process, coke is both reducing agent and heat source. Nuclear energy steelmaking would use direct reduction. Iron ore, while remaining solid, is reduced into sponge iron by a reducing gas (hydrogen or a mixture of hydrogen and carbon monoxide). The HTGR heat produces a reducing gas by steam-reforming a light hydrocarbon, such as natural gas (CH_4), naphtha, or liquefied coal. The reaction

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

occurs best at high temperatures and requires a considerable amount of heat. Hot reactor helium would meet both these requirements. The hot carbon monoxide-hydrogen mixture produced by the reforming reaction will reduce iron oxide to sponge iron. Thus, the heat needed to reduce the oxide is indirectly supplied by the hot helium from the HTGR (Ref. 5).

The directly reduced sponge iron can then be refined to steel in an electric furnace; electric power would be produced from a portion of the HTGR heat. Thus, the nuclear reactor provides all the energy needed to reduce the iron oxide and to make the steel. The hydrocarbon is only the reducing agent and not combusted for process heat. Figure 4 illustrates integrating the HTGR into a system to directly reduce iron ore.

HIGH-TEMPERATURE HEAT EXCHANGER

Both the Japanese and the U.S. process heat programs use the high-temperature helium-to-helium IHX. This heat exchanger transfers high-grade thermal energy [up to 1000°C (1832°F)] from the reactor core to the end process.

Although applications for high-temperature energy comprise a much broader spectrum than the helium-to-helium IHX can handle, this heat exchanger represents a key element in successful nuclear-process-heat programs. The IHX design will require major programs in materials development, heat exchanger design, and fabrication techniques.

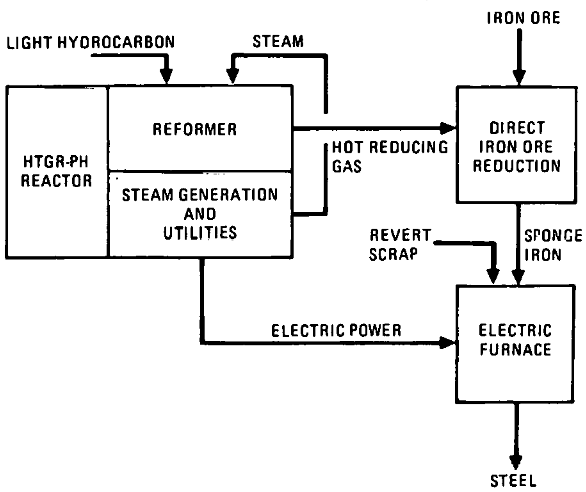

Figure 4 HTGR for direct reduction of iron ore

Heat Exchanger Design Considerations

1. The heat exchanger designs should use tubular construction and conventional fabrication techniques for state-of-the-art reliability.

2. Only counterflow and multipass cross-counterflow designs are thermodynamically practical. The counterflow approach yields more favorable heat exchanger proportions for vertical PCRV cavity installations, lower metal temperature gradients, and lower potential flow-induced vibration.

3. Compact surface geometries are desirable, because very large heat transfer surface areas are required in the gas-to-gas heat exchangers, which must transfer heat at reactor transfer rates.

4. Since IHX materials (Inconel 617, Hastelloy X, etc.) are costly, the heat exchangers, which are important plant capital equipment items, should be designed for long life.

5. The heat exchangers must be designed in accordance with the appropriate provisions of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code.

Additional heat exchanger design constraints are created by the integrated HTGR plant arrangements, where the PCRV acts as the heat exchanger containment and support. While these arrangements remove the need for large vessels (typical of industrial heat exchangers) and for shell-side fluid couplings (connecting the heat exchangers to the primary system), additional restrictions must be accommodated:

a. Orientation. Vertical heat exchangers help minimize both PCRV diameter and prestressing complexity.

b. Diameter. Heat exchanger diameters should be minimized to avoid directly impacting PCRV and reactor containment building diameters, which are major plant cost considerations.

c. Height. PCRV (and thus the reactor containment building) height should not be governed by the heat exchangers.

d. Accessibility. The restricted accessibility of PCRV-mounted heat exchanger installations influences the heat exchanger mechanical designs in the areas of in-service inspection (ISI), tube plugging capability, and maintenance.

The IHX is the interface between the primary and secondary helium circuits and therefore must be leak-tight. For the process heat plant with a reactor outlet temperature of 950°C (1742°F), the maximum metal temperature in the IHX is 927°C (1700°F); the equivalent value for a reactor outlet temperature of 850°C (1562°F) is 835°C (1535°F). Thus, IHX metal temperatures of this order mandate using superalloys in at least the hot end of the unit. If the IHX design is to use existing materials, pressure must be balanced to meet the low allowable long-term stress levels at the temperatures mentioned above. HTGR-PH pressure is balanced by maintaining the secondary helium pressure only slightly above the primary helium pressure; thus, secondary helium inleakage to the primary system will result if leaks develop in the IHX.

International efforts are under way to design helium-to-helium IHXs for nuclear process heat plant applications; both straight-tube and helical geometries are being evaluated (Refs. 6 through 10).

Conceptual IHX mechanical designs IHX (Refs. 11, 12) are detailed enough to establish sizing and thermal performance, major structural details and load paths, mechanical provisions for assembly, ISI, maintenance, component installation and removal, and cost. Figure 5 illustrates the straight-tube counterflow design, based on Table 4 design information.

The initial design concept adopted the highly effective modular arrays to facilitate fabricating

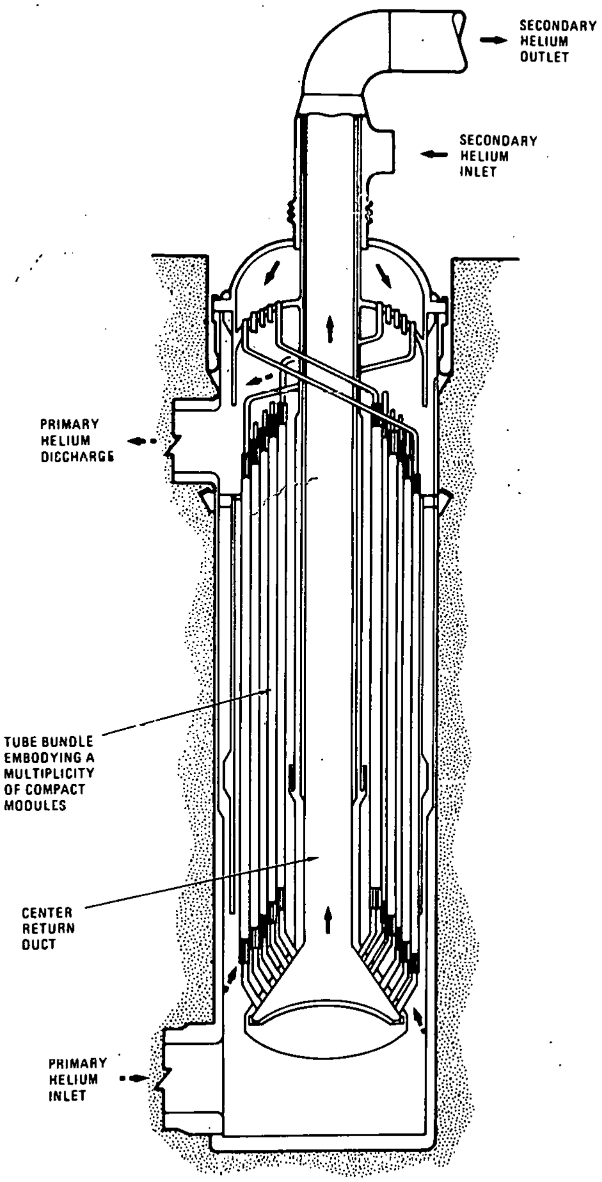

Figure 5 Overall view of modular, straight-tube IHX concept for HTGR-PH plant

TABLE 4
INTERMEDIATE HEAT EXCHANGER DESIGN DATA

Plant rating, MW(t) 842
Exchangers per plant 2
Loop rating, MW(t) 421

Fluid Circuit	Secondary Helium	Primary Helium
Fluid routing	Tube	Shell
Flow per unit, kg/s	170.7	170.7
Inlet temp, °C (°F)	419 (787)	946 (1735)
Inlet pressure, MPa (psia)	5.24 (760)	4.95 (718)
Outlet temp, °C (°F)	899 (1650)	467 (872)
Pressure loss, MPa (psid)	0.055 (8.0)	0.046 (6.6)
Effectiveness	0.91	
Log mean temperature difference, °C (°F)	52.2 (94)	
Thermal conductance per unit, MW/°C (Btu/h-°F)	8.1 (15.4×10^6)	
Heat duty per unit, MW(t)	428	
Flow configuration	Counterflow	
Type of construction	Straight tube	
Assembly type	Modular	
Tube o.d., mm (in.)	11.1 (0.4375)	
Wall thickness, mm (in.)	1.5/1.09 (0.06/0.043)	
Tube pitch	1.4	
Surface compactness, m^2/m^3	167	
Surface area per unit, m^2	10,488	
Tubes per unit	32,512	
Modules per unit	256	
Effective tube length, m (ft)	9.2 (30.2)	
Assembly diameter	4.27 (14)	
Assembly height, m (ft)	16.15 (53)	
Assembly weight, tonnes (ton)	218 (240)	
Pressure boundary ΔP, MPa (psid)	0.29 (43) pressure balanced	
Max metal temp, °C (°F)	927 (1700)	
Thermal density, MW/m^3	6.70	
Thermal flux, W/cm^2	4.03	
Tube material	Inconel 617,2-1/4 Cr-1 Mo	
ISI/repair level	Module	
Assembly location	Factory	
Transporatiaon mode	Barge/rail	
ASME Code Class	Section III	

and handling and to help promote good flow distribution. A monolithic tube field is the optimum heat exchanger packaging arrangement under development for the PCRV diameter. The IHX concept employs conical tubesheets. The headering approach based on tubesheet configurations. Since these configurations occupy less space than the hexagonal tube bundle envelope, the modular tubes must be bent locally to penetrate the desired tubesheets. This compact headering facilitates shellside fluid entry and exit, results in heat exchanger frontal area use approaching that of homogeneous tube fields, and eliminates the need for antibypass seals between modules. However, it obviously complicates module fabrication. Studies are continuing to identify more attractive alternatives.

The inlet and outlet secondary helium connections are located at the top of the unit. The secondary helium is routed downward inside the module tubes for counterflow operation. A drum header at the bottom of the unit collects the secondary helium leaving the modules, and a central return duct returns it to the top. Lead tubes connect each module to the top of the main support plate and to the drum header. The main support plate also acts as a tubesheet. The upper set of IHX lead tubes (cold end of the unit) are coiled for elasticity to accommodate module differential growth.

Material Selection Considerations

Figure 6 shows approximate operating boundaries for various heat exchanger materials. Material temperature limits greatly constrain the high-temperature heat exchangers. Essentially, only stainless steels and the nickel- and cobalt-base superalloys can be used as metallic materials above 650°C (1200°F). The heat-resistant cast alloys have specialized applications. Figure 6 shows that the specific strength (strength/density) of metallic materials decreases very rapidly at elevated temperatures. The operating islands shown in Fig. 6 are very approximate; for a particular application, the actual properties of the candidate materials must be minutely examined over the appropriate temperature range in the operating environment. Many high-temperature systems use superalloys, and the design and fabrication of superalloy heat exchangers is a well-developed technology. Nickel- and cobalt-base wrought superalloys, such as Inconel 600, Incoloy 800H, Inconel 807, Hastelloy X, Inconel 617, and Haynes 188, have been used for elevated-temperature service. Figure 6 shows the upper limit for practical metallic heat exchanger design as 955°C (1750°F). This value represents an upper limit for using the wrought superalloys, which can readily be formed into a variety of heat exchanger surface geometries and construction types.

In the petrochemical industry, centrifugally cast tubes of 25 Cr-20 Ni steel, such as HK40, IN-519, and Manaurite 36C, have operated successfully in hundreds of plants for many years with tube wall temperatures above 982°C (1800°F). The centrifugally cast tubes in modern reformers are about 100 mm (4 in.) in diameter and have wall thicknesses of 20 mm (0.8 in.). While these cast tubes exhibit excellent high-temperature capability, they cannot be formed in the small-diameter size (11 mm) with wall thicknesses of about 1 mm, necessary for the compact surface geometry required in the process heat IHX. For the high-temperature IHX, wrought materials must suffice, and candidate alloys include Inconel 617, Hastelloy X, and Incoloy 800H.

Conclusions

As the HTGR-PH plant design progress beyond the conceptual design stage, design effort will intensify on high-temperature heat exchangers. For such long-term programs, the heat exchanger designer has an obvious responsibility to monitor international developments and to factor technology advancements into the design.

This paper outlines the IHX concept using existing technology and currently available and demonstrated materials. Advanced technologies could be incorporated by using new IHX materials (to permit higher system operating temperatures) and by adopting advanced recuperator and IHX surface geometries (to reduce cost, reduce size, and improve ISI capability and maintenance).

Both Japan and the U.S. nuclear process heat programs use the high-temperature heat exchanger.

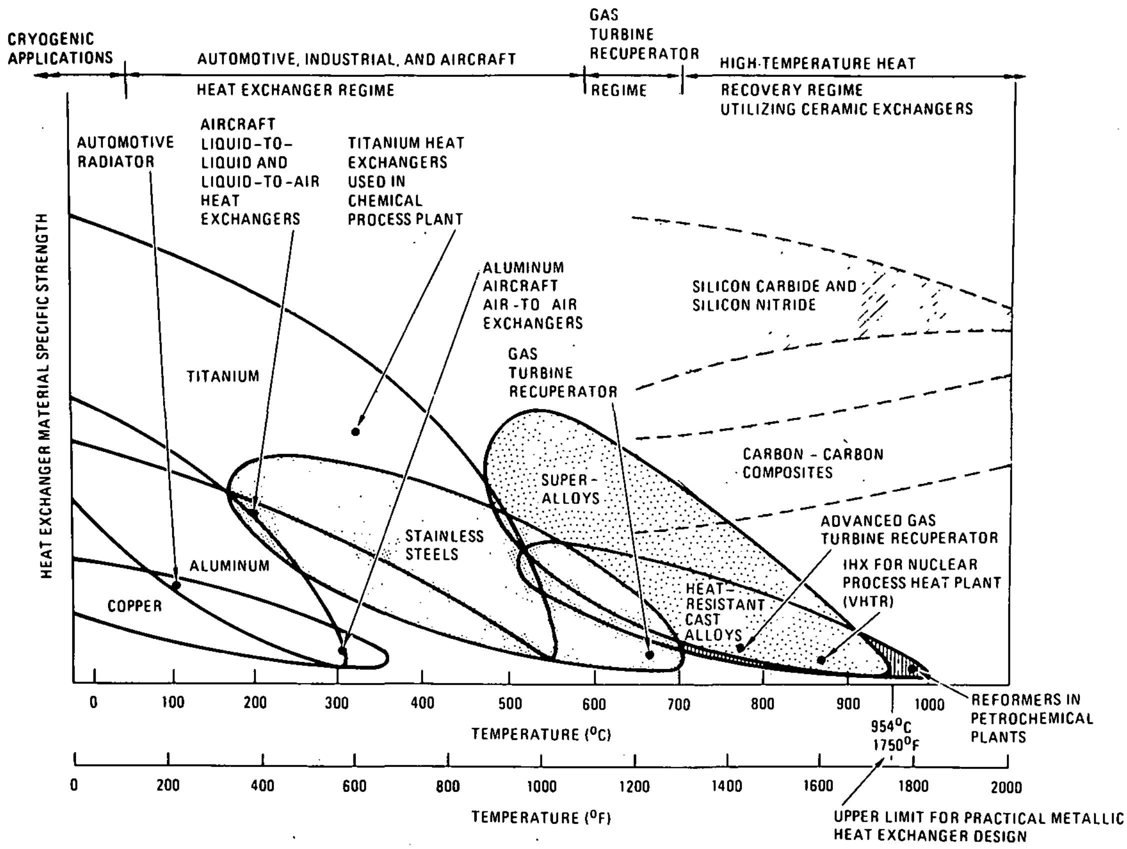

Figure 6 Approximate operating boundaries for various heat exchanger materials

These countries should encourage complementary heat exchanger design and development programs. Joint success in the developing this high-temperature heat exchanger is critical to deploy nuclear process heat programs. The current energy crisis could be substantially alleviated by introducing alternative energy sources (nuclear energy) with improved conversion efficiencies.

ACKNOWLEDGMENTS

The author would like to thank the management of General Atomic Company for permission to publish this paper. Work on the HTGR-PH plant heat exchangers has been supported by the DOE under Contract DE-AT03-76SF71061.

REFERENCES

1. Quade, R. N., D. L. Vrable, and L. Green, Jr., "Production of Liquid Fuels with an HTGR," Proceedings of 2nd Miami International Conference on Alternative Energy Sources, December 10, 1979, Miami, Florida.
2. Landis, J. W., "The GGA High-Temperature Gas-Cooled Reactor: A General Discussion," J. Brit. Nucl. Energy Soc. 12, No. 4, 367-385 (1973).
3. Vrable, D. L., R. N. Quade, and J. D. Stanley, "Design of an HTGR for High-Temperature Process Heat Applications," ASME Paper No. 79-JPGC NE-2, 1979.
4. Vrable, D. L, and R. N. Quade, "Design of the HTGR for Process Heat Applications," 15th Intersociety Energy Conversion Engineering Conference, August 18-22, 1980, Seattle, Washington.
5. Blickwede, D. J., "The Use of Nuclear Energy in Steel Making - Prospects and Problems," Nucl. News 17, No. 13, 65-68 (1974).
6. Nakanishi, T., "Development of High-Temperature Heat Exhanger on Heat Utilization from VHTR," NUCLEX 78, October 3-7, 1978, Basel, Switzerland, Paper No. A4/17.
7. Crambes, M., "Intermediate Heat Exchanger for HTR Process Heat Application," IAEA Specialists Meeting on Process Heat Applications Technology, November 27-29, 1979, Jülich, FRG.
8. Itoh, M., "Design, Construction and Operation Experience of the Helium-Helium intermediate Heat Exchanger," IAEA Specialists Meeting on Process Heat Applications Technology, November 27-29, 1979, Jülich, FRG.
9. Neimeyer, W., "Heat Exchanging Components for Coal Gasification - He/He Intermediate Heat Exchanger (IHX) and Steam Reformer," IAEA Specialists Meeting on Process Heat Applications Technology, November 27-29, 1979, Jülich, FRG.
10. Walravens, M. J., et al., "Preliminary Orientation and Parametric Survey for Very High Temperature Reactors with Intermediate Heat Exchangers," IAEA International Symposium on Gas-Cooled Reactors," October 1975, Jülich, FRG.

11. Mori, Y., "Performance of Heat Exchangers on HTGR Application," Joint ASME/AICHE National Heat Transfer Conference, July 27-30, 1980, Orlando, Florida, ASME Paper No. 80-HT-39.
12. McDonald, C. F., et al., "Heat Exchanger Design Consideration for HTGR Plants," Joint ASME/AICHE National Heat Transfer Conference, July 27-30, 1980, Orlando, Florida, ASME Paper No. 80-HT-62.

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