CONF-8110127--3

DE82 008530

STATUS OF THE UNITED STATES NATIONAL HTGR PROGRAM

INTRODUCTION

It has long been recognized in the nuclear community that the High Temperature Gas-Cooled Reactor (HTGR) offers a unique potential for expanding the role of nuclear technology in meeting future requirements for energy. The high temperature capability of the HTGR offers increased efficiency and flexibility in the production of high quality steam for industrial processes in addition to electricity and may provide the optimum basis for accessing incremental markets in the industrial and transportation (via synfuels) energy sectors.

This paper will describe the status of the U.S. HTGR Program and will provide some comments regarding its future prospects. In doing so a brief background will be provided, the cooperative effort among government, energy users, and suppliers will be described, the present technical status of the program will be summarized and some conclusions derived from results to date.

HISTORICAL DEVELOPMENT

Based upon pioneering studies at Oak Ridge National Laboratory (ORNL) in the 1940's and the European gas cooled reactor program in the 1950's, the Peach Bottom HTGR was committed in 1957 under the joint sponsorship of 53 U.S utilities. General Atomic Company was the principal supplier of the reactor system. In 1967 Peach Bottom became the first HTGR to produce electricity. Subsequently, the Peach Bottom plant was operated by the utility, Philadelphia Electric Company, for a period of 7-1/2 years and achieved a remarkable 88% nuclear steam supply system availability over that period. The successful development of Peach Bottom led naturally to the commitment of Ft. St. Vrain and in the 1971-74 time frame commercial orders for ten large HTGR's ranging from 770 - 1200 MWe were accepted by General Atomic Company. Initial design and licensing efforts were well under way when economic conditions in the wake of the 1974 oil embargo precipitated the cancellation of several of the orders and the subsequent withdrawal of the HTGR option.

Following the withdrawal of the HTGR commercial option in 1974, the HTGR program entered a period of reassessment. Over 1974-77, a series of limited Energy Research and Development Administration (ERDA)/Department of Energy (DOE) studies were sponsored to consider various applications of the HTGR and to determine whether sufficient incentives existed to justify major federal support. The results of the ERDA/DOE studies endorsed the following principals for conducting an HTGR program in the U.S.:

- The users of the technology should play an active role in the direction and development of the technology to assure that the ultimate product is commercially acceptable and to utilize, where possible, normal user-supplier relationships.
- An equitable basis must be determined for the assumption of costs and risks by the government, user industry and supplier industry. Critical in this regard is to assure that both the user and supplier industries have vested interests in the success of the program.

Formation of GCRA

In response to the requirement for active user industry involvement, 6 utilities formed Gas-Cooled Reactor Associates in February 1978. In the ensuing period, utility participation and support have grown to include 29 utilities representing approximately 25% of the U.S. installed electrical generation capacity. GCRA utilities have a substantial investment in and experience with nuclear power representing approximately 25% of on-line nuclear capacity and about 40% of the capacity under construction. Most recently, user support has grown to include 9 major industrial firms whose interest is centered primarily upon process steam/process heat applications. Industrial contractors currently involved in the program include General Atomic Company, General Electric Company and Combustion Engineering. ORNL is the lead government laboratory associated with the program.

Cooperative Program

The evolving program will be a cooperative endeavor among government, utilities/energy users, and suppliers to define the direction of the HTGR Program and to achieve an equitable balance of investment, risk, and benefit if a lead commercial plant project is initiated. In the current definition phase of the program, the role of government is to provide information and technology which supports the development of important HTGR applications and which provides both to the government and to the private sector a basis for decisions regarding a lead project initiative.

An important element of this program has been the international cooperation that has evolved, significantly reducing overall program costs. Efforts will continue to enhance and extend these cooperative efforts.

Near Term Program Direction

In FY 1980 an intensive review was conducted of the HTGR options which were proposed for near term deployment. Included in the evaluation were the Steam Cycle/Cogeneration, Gas Turbine, and Reforming variants of the HTGR. On the basis of that review, the Steam Cycle/Cogeneration concept was identified as having the highest potential for a near term project initiative. The Gas Turbine was determined to be more appropriately developed as a follow-on option due to its increased development risk and marginal incentives relative to the Steam Cycle. While the Reforming version of the HTGR was found attractive with respect to its ultimate potential for energy transport, the information available was insufficient to warrant a definite conclusion regarding the incentives for near term deployment. Accordingly, the current HTGR Program in the U.S. is focused to provide a Lead Project decision basis for the Steam Cycle/Cogeneration concept. In parallel, advanced HTGR concepts such as the Reforming HTGR are being further developed as a basis for understanding their appropriate role and timing for development.

HTGR APPLICATIONS

HTGR Nuclear Heat Source

The HTGR Nuclear Heat Source being developed in the U.S. comprises a helium-cooled, graphite-moderated advanced converter reactor which operates on the uranium/thorium fuel cycle. The HTGR Nuclear Heat Source typically operates in the range of 650-1000°C core outlet temperature. Key features of the HTGR reactor system in the U.S. are its coated particle fuel, prismatic graphite and ceramic core design, single phase inert helium coolant, and Prestressed Concrete Reactor Vessel (PCRV). The design of the HTGR Nuclear Heat Source is further described in Refs. 1, 2 and 3 for the Steam Cycle/Cogeneration, Gas Turbine, and Reforming applications respectively.

In considering the HTGR for electrical generation and process heat applications, inherent characteristics of the HTGR Nuclear Heat Source are of considerable importance. Among such characteristics are the following:

1. As noted above, the HTGR fuel and structural elements which establish the core geometry are comprised of ceramic-based materials. Thus, the inherent temperature limitations of reactors with metallic core elements are eliminated. The HTGR, therefore, is the only current nuclear concept under development with projected process heat capabilities above 550°C and thus capable of competing with fossil fuels for higher temperature applications. Current LWR technologies are limited to about 290°C.

2. The inert, single-phase, gaseous coolant, the large heat capacity coupled with low power density in the core, the coated particle fuel design, the substantial temperature margins in the core structure, and the confinement of the primary system within the PCRV lead to inherent safety and operating characteristics which are expected to facilitate licensing and to ease constraints on proximate siting and thus minimize energy distribution costs.

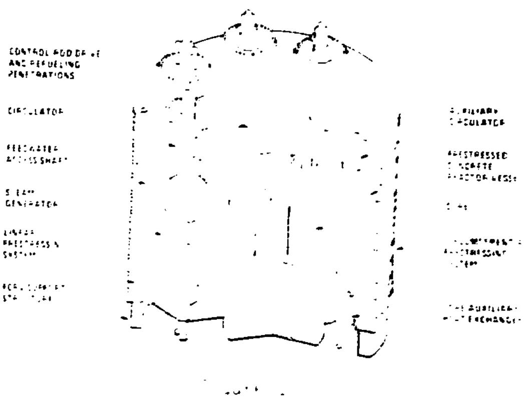
3. The low primary system contamination resulting from the coated particle fuel design and from the inert primary system coolant will be a significant factor in achieving reduced maintenance down-time and hence the high availability commensurate with industrial process heat applications.

Depending upon the specific application, the basic HTGR Nuclear Heat Source can be utilized in conjunction with various heat transport concepts. In the present U.S. HTGR Program, primary consideration is being accorded to the Steam Cycle/Cogeneration concept. This concept and other HTGR applications under consideration are identified in the following sections.

Steam Cycle/Cogeneration

The Steam Cycle/Cogeneration version of the HTGR comprises a flexible nuclear steam supply system (NSSS) (Figure 1) which can be utilized by producing various combinations of electricity and/or process steam for utility and industrial applications. In this system, high-quality steam is generated at the elevated conditions of approximately 17 MPa/540°C with the primary helium gas conditions maintained in the low range of HTGR capability at less than 700°C. The plant features a modular four loop primary coolant system that can be scaled up or down by varying the number of loops from two to six while maintaining the basic NSSS configuration. The current design is based on many of the components and systems demonstrated at Fort St. Vrain. In addition, several key design changes have been made as a result of Fort St. Vrain experience plus accommodating the functional requirements of the utilities associated with GCRA.

2240 MW(t) HTGR SC/C



The current reference design of the 2240 MW(t) HTGR-SC/C was established in FY 1979 (Ref. 4,5) as a specialized variant for electrical generation. There remains a strong utility interest in such specialized systems as a result of its potentially advantageous siting, licensing, and operational characteristics. Electric generation costs using the HTGR-SC/C system are perceived as being approximately equal to those of conventional LWR systems.

In the more recent U.S. HTGR Program, the principal design emphasis is being placed upon cogeneration applications of the HTGR-SC/C. The basis for this emphasis is the potential for near term deployment of a system which could impact the current technical and economic reliance on fossil fuels.

While substitution of electricity for other process heat/process steam energy sources could favor an increased role for nuclear energy, the low energy-conversion efficiencies associated with current electrical generation technologies are an important factor which must be considered. For current light water reactor (LWR) systems, an efficiency in the range of 30-35% is typical. The HTGR steam cycle technology demonstrated at Fort St. Vrain improves that figure to nearly 40%. Modern fossil fuel units typically generate electricity with an efficiency in the range of 35-40%. In substituting electricity for other energy forms, the present low conversion efficiencies are manifested in the following ways:

- The total energy resources required are substantially increased.
- The cost advantage of nuclear fuel is generally overcome by the low conversion efficiency for electrical generation.
- The environmental burden associated with heat rejection is substantially increased.

A more promising approach to the direct use of nuclear-derived heat appears to be found in large-scale nuclear cogeneration. In such concepts, electricity is typically produced as a topping cycle employing high-temperature, high-pressure steam. The reduced-pressure steam is then utilized for process energy input. In the idealized case, nearly the total energy output from the nuclear heat source is productively used either for electricity generation or for process heat. The advantages of this approach are relatively obvious:

- The energy losses normally associated with electricity production can be substantially reduced.
- A substantial net reduction in total energy resources may be achieved relative to separate production of steam and electricity.
- A net savings may be realized by both the electrical rate payer (due to improved generation efficiency) and the industrial heat user (due to the low cost of nuclear fuel).

With regard to the latter point, the potential savings to the nation as a whole is impressive. Using 1980 U.S. energy consumption data (Ref. 6) and assuming 35% average efficiency for electricity production, if 10% of the reject energy could be recovered via cogeneration, the value of that energy at current oil prices ($30/barrel) would be in excess of $8 billion/year.

In the HTGR-SC/C system, the Nuclear Heat Source (NHS) is substantially identical for various combinations of steam and electricity production. As the electricity to steam ratio is varied, principal changes are found in the turbine plant. Figure 2 depicts a typical turbine plant configuration for the HTGR-SC/C application in which the relative amounts of electricity and process steam produced can be varied. In the all-electric mode, both turbine-generator (TG) sets shown are operated at full capacity. In the maximum cogeneration mode, TG No. 2 is shut down and the steam is directed to the process. By varying the output of TG No. 2 the ratio of electricity to steam can be controlled in the intermediate range.

HTGR-SC/C BALANCE OF PLANT

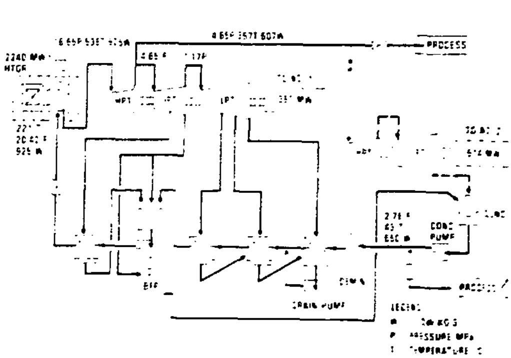


Figure 2

As depicted in Figure 3, the HTGR offers a unique capability for nuclear cogeneration. In the temperature range below about 290°C the HTGR has the ability to produce a higher fraction of electricity as a topping cycle when compared to current LWR systems. Current LWR systems are incapable of producing steam above approximately 290°C.

TYPICAL COGENERATION CHARACTERISTICS OF CURRENT NUCLEAR SYSTEMS

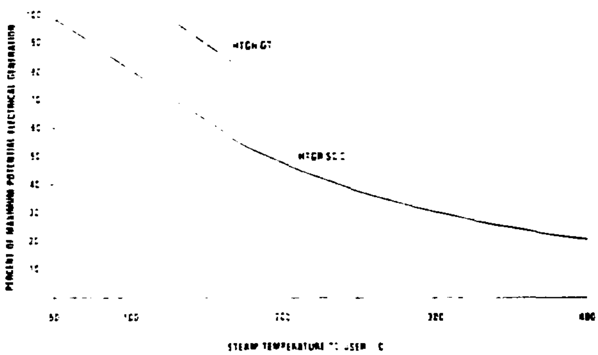


Figure 3

The HTGR-SC/C concept described above has evolved as the result of a substantial design and development effort. The resulting nuclear steam supply system (NSSS) design has further been subjected to an extensive review by the utility industry. Accordingly, the economic characteristics of the NSSS are generally considered to be well defined. Based upon a recent evaluation, joint-product cost data have been developed for a reference HTGR-SC/C case. The balance of plant considered for this case is configured similar to Figure 2 and has the potential to operate over a wide range of steam demands.

Relative joint-product cost characteristics are illustrated in Figure 4. Lines 1, 2, and 3 in the figure correspond to plant operation in the all-electric mode, at 50% of the maximum cogeneration potential, and at 100% of the maximum cogeneration potential respectively. Note that each line corresponds to the possible allocations of cost between electricity and steam for a given plant under the specified operating conditions. The cost of single-product competing technologies is indicated for both electricity and steam.

The area within the dashed lines represents the domain of cost allocation in which a joint-product cost benefit can be realized by some combination of the electric rate payer, the steam user, and the investors in the plant. Note, however, that the probable domain is considerably larger since the 1200 MW(t) coal plant is well beyond the scale normally associated with industrial applications and is based upon utility financing. Improvement in coal-derived energy costs could be realized through the use of a cogeneration cycle; however, a relative advantage would remain with the HTGR due to low fuel costs. Relative to the projected cost for oil- and gas-derived steam, the incentives for the HTGR are even more compelling. At the present time, about 84% of industrial heat in the U.S. is produced through the use of these two fuels.

HTGR-SC/C RELATIVE PRODUCT COSTS

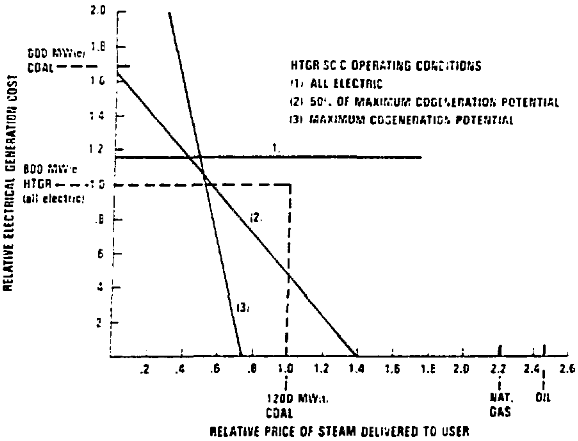


Figure 4

High Temperature Process Heat

Beyond the near term applications of the HTGR using steam cycle technology, an incremental potential may be identified for advanced HTGR systems providing direct process heat. An HTGR NHS configured for such applications is depicted in Figure 5.

The incremental potential of such a system may be illustrated through a typical example which was explored during FY 1981. In this example, the HTGR facility was configured to provide both process energy (in the form of direct heat and steam) and electrical energy for the Exxon Catalytic Coal Gasification (ECCG) process. The product of the ECCG process is methane (called Substitute Natural Gas or SNG).

HTGR REFORMER (PROCESS HEAT) SYSTEM
1170 MWt

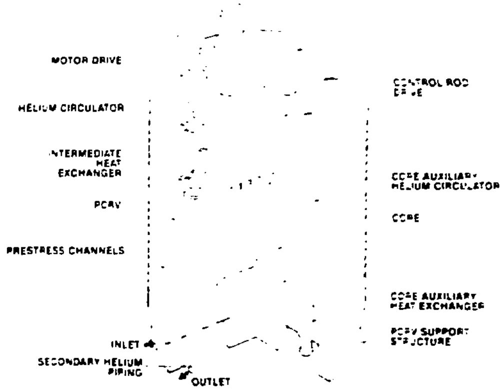


Figure 5

The ECCG process uses alkali metal salts as catalysts mixed directly with the feed coal to promote low-temperature gasification. Use of this catalyst also increases the rate of steam gasification, reduces agglomeration of caking coals, and promotes the achievement of gas compositions closely approaching gas phase methanation equilibrium. The process utilizes a fluidized bed gasification system that operates in a well-mixed mode approaching isothermality, the fluidizing gas being steam and recycle hydrogen and carbon monoxide.

Figure 6 shows the ECCG process heat requirements that have potential for HTGR coupling. Up to 997 MWt of energy at temperatures ranging from 472°F to 1575°F could be coupled to a plant designed to gasify 12,000 tons/day of coal. This process also consumes electrical power in the amount of 190 MWe. Four process steps show potential for coupling: 1) the gas preheat furnace for the gasifier, 2) the coal/catalytic drier (2nd drying stage), 3) the raw coal drier (1st stage drier), and 4) offsite boilers supplying process steam.

The use of HTGR-derived heat to replace combustion in the ECCG process results in significant savings to the environment and of coal and product gas including:

- 2940 tons/day of coal not burned,
- 230 tons/day of product methane not burned,
- 265 tons/day of ash not generated, and,
- 6908 tons/day of carbon dioxide not emitted.

The technical and economic implications of high temperature direct heat applications such as the above continue to be assessed in the U.S. HTGR Program. Future emphasis will be placed upon reducing the relatively high capital costs which appear to be associated with such systems. Unless such cost reductions can be realized, the incremental capabilities of high temperature direct heat systems may not be warranted except in specialized circumstances.

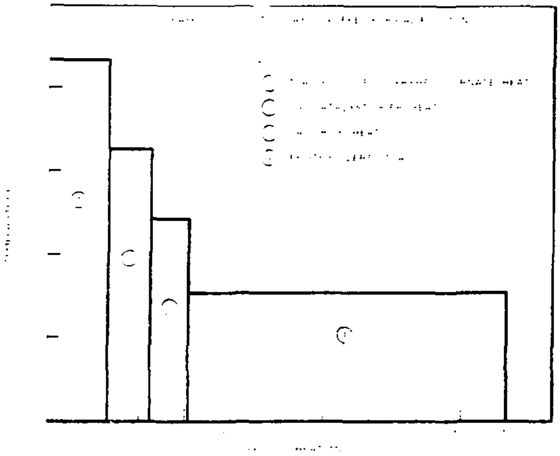


Figure 6

Steam Methane Reforming and the Thermochemical Pipeline

The HTGR is unique among nuclear energy systems in that it can operate at temperatures high enough (850°C to 1000°C) for efficient steam reforming of methane. The high temperature helium coolant is used to drive the reformer to produce hydrogen in the form of syngas and thereby chemically store the nuclear heat from the HTGR. The syngas product can be transported long distances to dispersed process heat users. Using the reverse (methanation) reaction a closed loop energy system, or thermochemical pipeline (TCP), can be formed to deliver nuclear energy to small dispersed industrial process heat users with methanators added at the user sites. Water and methane are returned from the methanator plants to the HTGR-R plant. This TCP concept is depicted in Figure 7. Furthermore, for an open loop reforming system the hydrogen in the syngas can be used as a feedstock or as a fuel for a variety of dispersed applications such as production of coal derived liquids, ammonia, and methanol and the processing of steel. Our studies indicate that implementation of the HTGR-R in these types of applications could both increase the supply of, and substitute for, fluid fuels and thus have a major impact on all global energy systems.

The benefits of such a system have been evaluated (Ref. 7) and show that the TCP energy system concept has the potential to compete with nuclear electricity and with fossil energy systems such as substitute natural gas (SNG) and local fluidized bed coal combustors for one and two shift process heat operations. Energy delivery cost projections show that at distances approximating 30 miles or greater the TCP may be the lowest cost system for delivery of energy including direct transmission of nuclear generated steam. This relationship continues for distances as great as 200 miles.

The reforming version of the HTGR is a developmental advanced system and major tradeoffs must be made to select the optimal HTGR-R plant design. Principal changes under consideration are between high or low reactor core outlet temperatures and between direct and indirect cycle reactor plant configurations.

Since reforming activity decreases below 600°C and the rate of reforming increases with elevated temperature, there is an incentive to use a higher core outlet temperature to achieve better plant performance. However, the higher temperatures usually require more expensive materials and additional technology development. The selection of the direct or indirect steam reforming configuration depends upon economical and safety/licensing considerations. For the indirect cycle (IDC) configuration, an intermediate heat exchanger (IHX) is located within the prestressed concrete reactor vessel (PCRV) and secondary helium is piped to the reformers and the steam generators located outside the containment building. The direct cycle (DC) configuration eliminates the secondary helium loops with both the reformers and steam generators located within the PCRV. The two plant design configurations and two temperature options of 950°C and 850°C result in four reactor plant cycles for comparative evaluation. However, only the 950°C DC and 850°C IDC configurations are being evaluated in the current program. The relative performance of the other two reactor plant cycles (950°C IDC and 850°C DC) will be inferred from the results of the study.

The heat cycles, key process equipment, system configuration and overall heat balance have been defined for comparison of the major plant characteristics and cycle efficiencies of the two reactor systems being studied. System economics, reliability, performance and operability/controllability are design criteria used to optimize system design conditions. Parametric studies have been performed

THERMOCHEMICAL PIPELINE CONCEPT

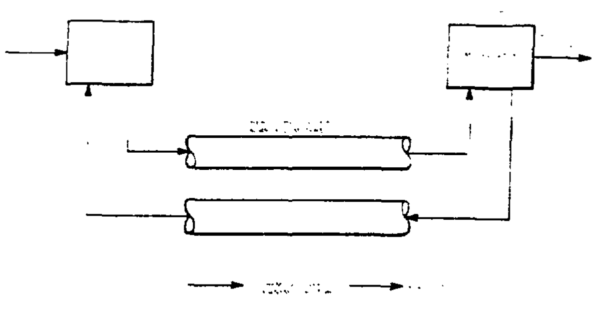


Figure 7

to define the principal plant parameters. The balance of plant (BOP) design has evolved in several stages resulting in the selection of a thermally-driven heat cycle and the incorporation of contact condenser/evaporator heat exchangers.

A layout of the HTGR direct cycle reformer plant configuration is shown in Figure 8. This passive system was found to be less costly and more reliable than the turbocompressor heat cycle considered as an alternative for the BOP system. The contact condenser/evaporator replaces the mix-feed-evaporator as the key process equipment for the reformer BOP plant system. The simplicity of the direct contact heat exchanger design will reduce component costs of the key process heat exchange equipment and increase system reliability. As the component configuration for the 950°C DC and 850°C IDC process plant are almost identical, key plant characteristics and operational capabilities for both cycles can be easily compared.

HTGR DIRECT CYCLE REFORMER PLANT CONFIGURATION

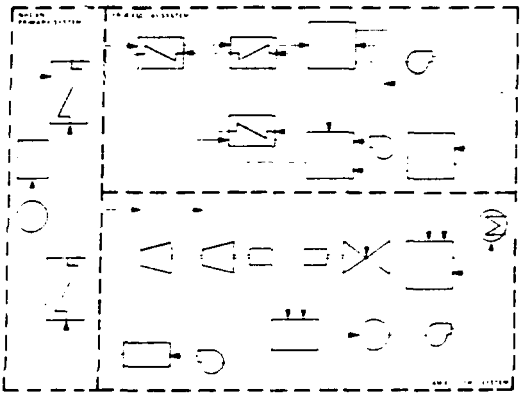


Figure 8

To maximize the cycle efficiency of the HTGR-R plant, four plant features have been incorporated into the design and operation to reduce the overall plant waste heat rejection.

1. Steam is condensed in the contact condenser to conserve the energy and as a source of heat and water supply for the reforming process. The process system operating at higher pressure is designed to allow more waste heat to be recovered into the steam-electric system.

2. The 40 psia pressure is also selected for the LP turbine to maximize the waste heat that could be recovered from the process plant.

3. The low pressure steam reheat arrangement improves the heat rate of the LP turbine.

4. The turbine feedwater is heated with the waste heat from the process system to maximize the gross power output of the steam-electric system.

A summary of the plant performance for the reference 950°C DC and 850°C IDC HTGR-R plants is presented in Table 1. The overall plant efficiency is defined as the sum of the net power output and pipeline thermochemical energy divided by the core power. It is used as a means to compare the relative overall performance of the HTGR-R for different plant design conditions. The overall plant efficiency is about 66% for the reference 950°C DC plant design and 49% for the 850°C IDC Plant. The reformer split referred to in the table is that percentage of the total energy which is input to the reformer.

TABLE 1

HTGR REFORMER PLANT PERFORMANCE

	850°D IDC	950°C DC
Reforming Pressure	25 Bar	49 Bar
Reformer Split	42%	54%
Core Power, MWt	1170	1170
Circulator Power*, MWe	-99.5	-65.6
Reformer System Pumping**, MWe	-3.6	-0.7
Heat Added by Steam System, MWt	+384	+265
Heat Rejected to Steam System, MWt	-352	-232
Pipeline Pumping**, MWe	-73.0	-33.0
Plant Heat Rejection, MWt	-580	-380
Feed Pump Power, MWe	-6.0	-6.7
Auxiliary Load, MWe	-10.0	-9.0
Gross Power Output, MWe	191.8	169.7
Electric Power, MWe 24 Hr/day Net	0	55
Thermal Energy, MWt		
Available 8 hr/day	1635	1995
Available 24 hr/day	545	665
Overall Efficiency, %	47	57

* Circulator Efficiency: Drive = 92%, Control = 96%

** Pumping Efficiency: Drive = 92%, Pumping = 84%

The current estimate of the relative delivered energy costs via the TCP show an advantage for the 950°C direct cycle plant of approximately 25% over the 850°C indirect cycle plant. The comparative costs include estimated capital and fuel costs, as well as influence of thermal efficiency differences.

Modular Reactor Systems

In the U.S. as in other countries, a renewed interest has developed in small, or modular HTGR reactor systems. If economically viable, such systems would offer increased flexibility which would benefit both electrical generation and process energy applications. From the electrical generation viewpoint, distributing the generation of electricity among several small reactors rather than one large reactor would allow increased system reliability for a given system capacity or, conversely, a smaller system could be developed with equivalent reliability. In a similar fashion, a smaller unit size would facilitate process energy applications which typically demand a high degree of reliability and appropriate provisions for backup energy sources. For both electrical and process energy applications the smaller unit size of modular HTGR's should result in increased siting flexibility and reduced licensing difficulty.

The crucial element to be determined is whether a modular HTGR reactor system can be devised which is economically viable. Previous evaluations have clearly led to the selection of larger systems, however, the following considerations have resulted in the current interest:

- Larger systems have become increasingly complex and expensive as regulatory requirements have evolved. Potential simplifications in smaller systems would tend to offset economies of scale.

- Site construction would be reduced relative to shop fabrication with attendant savings.

- Reactor complexes could be developed on a phased basis with reduced capital risk.

To explore these elements, modular HTGR reactor systems will be evaluated in the U.S. HTGR Program beginning in FY 1982. The market and application potential for a single, small HTGR module will be determined as well as that for multiple modules which can be linked together to provide larger power capacity. The study will focus on the adaptability of the modular concept to direct cycle and indirect cycle process heat applications for a reactor outlet temperature up to 950°C. A commercial plant option will be derived that allows comparison with the 1170-MW(t) plant configuration, currently in a more advanced state of conceptual design. This preconceptual work will lead to a scoping design and cost estimate which along with technical considerations should provide a basis for a determination regarding the incentives for modular reactor systems.

Gas Turbine

Over the period FY 1979-80, the U.S. HTGR Program was directed to a substantial assessment of Gas Turbine (HTGR-GT) technology and a comparison of its near-term incentives versus the Steam Cycle alternative.

The focal point for the study was a potential HTGR-GT commercial plant (Figure 9) having the following characteristics:

Size (MWt/MWe):	2000/800
Core Outlet Temperature:	850°C
Number of Heat Transport Turbine Loops:	2
Cooling Options:	dry, wet-assisted, binary (ammonia and steam)

HTGR GAS TURBINE SYSTEM
2000 MWt

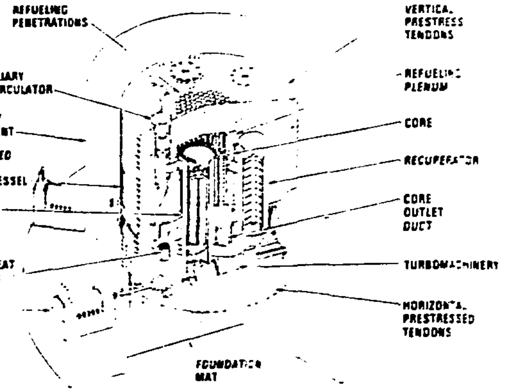


Figure 9

Principal findings of the study were that: 1) The HTGR-GT is feasible, but with significantly greater development risk than the HTGR-SC, 2) at the level of performance corresponding to the reference design, no incremental economic incentive can be identified for the HTGR-GT to offset the increased development costs and risk relative to the HTGR-SC. This result was true over the range of cooling options investigated, 3) the relative economics of the HTGR-GT and HTGR-SC are not significantly impacted by dry cooling considerations, and 4) while reduced cycle complexity may ultimately result in a reliability advantage for the HTGR-GT, the value of that potential advantage could not be quantified in the context of the current evaluation.

Although the FY 1979-80 results did not provide the basis for a high priority to be assigned to the Gas Turbine Program as the preferred lead commercial plant, the HTGR-GT continues to engender considerable interest from participating utilities. This interest stems from the potential for improved efficiencies at higher core outlet temperatures, the basic simplicity of the gas turbine cycle (lower maintenance, higher capacity factors), and low water use requirements.

Based upon encouraging results from the Steam Cycle/Cogeneration application, additional interest in the HTGR-GT is being derived from its potential cogeneration characteristics. While prior studies provide some insight regarding the cogeneration potential of the HTGR-GT, the full potential of the HTGR-GT for such applications has yet to be explored. This potential may be significant for the following reasons.

- In cogeneration applications, electricity comprises the higher value (premium) product and thus it is highly desirable that the electricity to steam ratio be maximized. As illustrated by Figure 3, the HTGR-GT is expected to offer a substantial advantage in this regard.

- The projected cost of the HTGR-GT for electrical generation is comparable to the HTGR-SC/C and LWR. Further, enhancing the cogeneration potential of the HTGR-GT by raising the precooler temperature would be achieved by reducing the effectiveness, and hence, size and cost of the recuperator (in the ultimate, the recuperator might be eliminated). Thus, enhancement of the cogeneration potential of the HTGR-GT may entail a net cost reduction for the nuclear heat source.

To confirm the above projections, system studies will be undertaken in FY 1982 to ascertain the parameters of the cycle best suited for cogeneration and to estimate the technical and economic benefits of such systems.

HTGR MARKETS

Process Heat

While substitution of nuclear energy for oil and gas appears desirable, the expanded use of nuclear energy beyond conventional electrical production will be subject to constraints imposed by the expected markets. A thorough understanding of these markets is, therefore, a first prerequisite to evaluating the prospects for nuclear energy in unconventional roles. In reflection of that fact, studies have been conducted to characterize the markets for industrial process heat and the related area of synfuels production.

These studies have been undertaken at three varying levels of detail. At the most general level, current and projected requirements for process related energy in the United States have been identified to define the upper limit of the overall market potential. The characteristics of the market were then addressed in terms of temperature, plant size, load factors, geographical distribution, current fuel types and other pertinent variables. At this level the specific potential for various HTGR concepts can be estimated. The most detailed level evaluated involved consideration of specific sites and applications and provided a basis for consideration of institutional issues such as financing arrangements, area specific energy costs, siting issues, and similar factors. A summary of results from the more general level of detail is presented as Table 2.

Table 2

INDUSTRIAL ENERGY PROFILE (1977 DATA)

- ENERGY REQUIREMENTS AS OUTPUT OF BOILERS & FURNACES

TEMPERATURE	STEAM		DIRECT HEAT		TOTAL	
	EJ*	%	EJ	%	EJ	%
<175°C	3.27	49	0.16	3	3.43	29
175-260°C	2.74	41	0.17	3	2.91	25
260-400°C	0.54	[illegible]	0.60	12	1.14	10
400-540°C	0.16	2	0.61	12	0.77	6
540-925°C	0	[illegible]	1.27	26	1.27	11
>925°C	0	[illegible]	2.22	44	2.22	19
TOTALS	6.71	100	5.03	100	11.74	100

- ENERGY REQUIREMENTS BY PLANT THERMAL DEMAND

PLANT THERMAL RATINGS (MWt)	TOTAL PLANTS		1-SHIFT PLANTS		3-SHIFT PLANTS	
	No.	% OF ENERGY USE	No.	%	No.	%
<2 MW	305,500	[illegible]	287,500	31	1,450	[illegible]
2-20	27,000	[illegible]	13,300	34	2,500	6
20-50	2,000	[illegible]	900	13	500	5
50-100	1,100	[illegible]	400	13	200	6
100-500	1,100	34	100	9	500	47
500-1000	78	12	0	0	84	20
>1000	23	10	0	0	16	14
TOTALS	336,800	100	302,200	100	5,250	100
ENERGY USE AS % OF TOTAL:		100		14		58

- ENERGY REQUIREMENTS AS FUEL INPUT

FUELS	EJ	%
GAS	8.12	47
PETROLEUM	6.22	36
COAL	3.06	17
TOTAL	17.40	100

* Exajoules = 10^{18} Joules

- INDUSTRIAL PROCESS HEAT PROJECTIONS (EJ)

	1978	2000	2020
Direct Process Heat	4.0	5.3	6.4
Indirect Process Heat	6.9	9.9	12.1
Metallurgical Coal	2.1	2.1	2.1
Refinery, Gas Plant, Field Use	4.9	4.3	3.1
TOTAL	17.9	21.6	23.7

As a result of studies to date, a substantial and unique potential has been identified for utilization of the HTGR in meeting incremental market requirements.

Synfuels

In addition to the industrial process heat market, synfuels development comprises an area of particular interest in the consideration of nuclear energy applications. The following reasons may be cited for this interest:

- The size, probable siting, temperature requirements, and timing are compatible with the development of a high-temperature nuclear heat source such as the HTGR.
- Major environmental advantages may accrue due to reduced mining, transportation, and burning of coal for a given product output.

To evaluate the potential for synfuels, a study was commissioned by Gas-Cooled Reactor Associates (Ref. 8) to project the evolution of the market through 2020. A summary is provided in Table 3. Note that in 1980 there were no commercial-scale synfuel plants in the U.S. An independent study conducted in the same period substantially confirmed these results (Ref. 9). However, changes in the levels of support and incentives to be provided by the U.S. Government are expected to impact these results.

Table 3

U.S. Synfuels Forecast

2000	No. of Plants	Total Capacity (10^3 BDOE*)	Proc. Heat Capacity (GWt)
Gases	10	450	5
Liquids	34	1712	41
Total	44	2162	46

2020	No. of Plants	Total Capacity (10^3 BDOE*)	Proc. Heat Capacity (GWt)
Gases	41	1799	20
Liquids	160	7990	192
Total	201	9789	212

* Barrels/day oil equivalent

HTGR TECHNOLOGY DEVELOPMENT

As an integral element of the overall HTGR Program, the Technology Development Program in the U.S. is directed to the support of important HTGR applications. The present structure of the Technology Development Program incorporates five major elements which are identified below.

Fuel Technology - This element consists of activities to develop and qualify fuel for application in HTGR facilities. Included are development of fuel processes, fuel materials, fuel cycles, and fission product/coolant chemistry. Major emphasis is upon development of fuel for the low enriched Uranium/Thorium fuel cycle which will be applicable to both near term and advanced systems.

Materials Technology - This element consists of activities to characterize and qualify materials for application in HTGR facilities. Included for development are graphite, ceramic, and metallic materials. While primary emphasis is currently on Steam Cycle Cogeneration applications, materials development for advanced systems is also included.

Plant Technology - This element consists of activities which are oriented to development of analytical methods and criteria which are applicable to such areas as design, analysis, licensing, safety and reliability evaluations and risk assessment. In general, the methods developed under this element are broadly applicable for multiple HTGR applications.

Design Verification and Support - This element consists of testing activities which are initially required to support the evaluation of HTGR designs and which are subsequently required for design verification and support of the licensing process. It includes the planning, analysis, design and construction of test specimens, models, fixtures and test rigs and the validation and interpretation of test results.

Technology Transfer - Technology Transfer pertains to those activities which are directed to acquisition and utilization of information resulting from resources and facilities, both domestic and international, which are external to the HTGR Program. Specifically included are activities in support of international cooperative agreements and assimilation of data from operation of Fort St. Vrain.

Reflecting the current design and programmatic emphasis on the Steam Cycle/Cogeneration version of the HTGR, a similar focus exists in the Technology Development Program. A high fraction of Technology Development Program results, however, are expected to apply to advanced systems as well. At the present time approximately 15% of the Technology Development Program is uniquely supportive of advanced systems.

FORT ST. VRAIN STATUS

The successful development of the Peach Bottom reactor led naturally to the commitment of Fort St. Vrain, the first large HTGR to be operated commercially. Fort St. Vrain, a 330 MWe Steam Cycle

HTGR developed by General Atomic Company, first achieved criticality in January 1974 and has since been tested at power levels to about 90% and operated continuously at about 70%. In its seven years of operation, it has produced in excess of 2.6 billion kilowatt-hours of electricity for the Public Service Company of Colorado system.

The well-publicized difficulties of Fort St. Vrain have had the unfortunate effect of overshadowing some very significant achievements which hae been demonstrated through that facility. For the most part, the troubles at Fort St. Vrain have been related to design and mechanical difficulties which are not related to basic HTGR design concepts and which have no adverse implications with regard to future HTGR development. Significant examples in this regard have been re-current problems with circulator seals and service systems, and the extended shutdown for cable routing modifications.

The single notable exception has been the temperature fluxuation phenomenon which has been observed in the intermediate power range near the currently authorized power limit of 70%. Based upon extensive analysis and model testing, a modification to the core was devised by the supplier and installed by the utility. The modification has eliminated the Fort St. Vrain temperature fluxuation problem and the authorization for testing above 70% power has been granted by the Nuclear Regulatory Commission. It is expected that the phenomenon can be avoided in subsequent core designs.

Despite the difficulties encountered at Fort St. Vrain, the operating utility has reported considerable satisfaction with the inherent operating characteristics of the HTGR. Due to the large heat capacity of the core coupled with its relatively low power density, the plant has been found to accept transients and loss of equipment in a graceful manner. Operational upsets, including periods of no forced circulation cooling of the reactor have been experienced with no apparent damage to the fuel or to the plant. Particularly cited by the utility is the time available to evaluate and to respond to unexpected operational occurrences.

Another impressive aspect of Fort St. Vrain operation to date has been the minimal exposure of operating personnel to radiation. In the five years of Fort St. Vrain operation, one refueling operation has been accomplished, including extensive examination of fuel and reflector elements. Additionally, the plant has undergone considerable maintenance, including removal of four circulators following prolonged power operation. Maximum integrated exposures reported, however, are in the range of 100-220 millirems, with only 6-8 people in the plant having received exposures in this range.

In summary, Fort St. Vrain remains a major element of the HTGR Program. While difficulties have been encountered, on balance the Fort St. Vrain experience has provided positive verification of the HTGR technology. In the coming months, we look forward to achieving full power operation at Fort St. Vrain and to continuing favorable experience in operation and maintenance.

SUMMARY

In summary, the HTGR continues to appear as an increasingly attractive option for application to U.S. energy markets. To examine that potential, a program is being pursued to examine the various HTGR applications and to provide information to decision-makers in both the public and private sectors. To date, this effort has identified a substantial technical and economic potential for Steam Cycle/Cogeneration applications. Advanced HTGR systems are currently being evaluated to determine their appropriate role and timing.

The encouraging results which have been obtained lead to heightened anticipation that a role for the HTGR will be found in the U.S. energy market and that an initiative culminating in a lead project will be evolved in the forseeable future.

The U.S. Program can continue to benefit from international cooperative activities to develop the needed technologies. Expansion of these cooperative activities will be actively pursued.

ACKNOWLEDGEMENTS

The contributions and assistance of the U.S. Department of Energy, Gas-Cooled Reactor Associates, General Atomic Company, General Electric Company, and Oak Ridge National Laboratory in the preparation of this paper are gratefully acknowledged.

REFERENCES

1. "HTGR Steam Cycle/Cogeneration Application Study Report", Gas-Cooled Reactor Associates, La Jolla, California, December 1980.
2. "HTGR Gas Turbine Application Study Report", Gas-Cooled Reactor Associates, La Jolla, California, December 1980.
3. "HTGR Reforming Application Study Report", Gas-Cooled Reactor Associates, La Jolla, California, December 1980
4. "HTGR-SC 900 MW(e) Reference Plant NSSS Conceptual Design and Status Report", General Atomic Company Report GA-A15429, La Jolla, California, September 1979.
5. "2240 MW(t) HTGR-SC Conceptual Design Status Report", United Engineers and Constructors for Gas-Cooled Reactor Associates, La Jolla, California, May 1, 1979.
6. "1980 Annual Report to Congress", Energy Information Agency, U.S. Department of Energy, DOE/EIA-0173(80).

7. "Status Report on GE Activities Concerning HTGR Reforming Plant Design and Applications", General Electric Company (ARSD), Sunnyvale, California, September 1981.

8. "HTGR Market Assessment: Synthetic Fuels Analysis", TRW Report 98122-E001-UX-00 for Gas-Cooled Reactor Associates, La Jolla, California, August 1980.

9. "Synthetic Fuels Forecast to 2020", Pace Company for General Atomic Company, La Jolla, California, June 1980.