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# ASSESSMENT OF VERY HIGH TEMPERATURE REACTORS IN PROCESS APPLICATIONS

by

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# ASSESSMENT OF VERY HIGH TEMPERATURE REACTORS IN PROCESS APPLICATIONS

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Abstract

In April 1974, the United States Energy Research and Development Administration (ERDA) authorized General Atomic Company, General Electric Company, and Westinghouse Astronuclear Laboratory to assess the available technology for producing process heat utilizing a very high temperature nuclear reactor (VHTR). The VHTR is defined as a gas-cooled graphite-moderated reactor. Oak Ridge National Laboratory has been given a lead role in evaluating the VHTR reactor studies and potential applications of the VHTR.

Process temperatures up to the 760 to 871°C range appear to be achievable with near-term technology. The major development considerations are high temperature materials, the safety questions (especially regarding the need for an intermediate heat exchanger) and the process heat exchanger.

The potential advantages of the VHTR over competing fossil energy sources are conservation of fossil fuels and reduced atmospheric impacts. Costs are developed for nuclear process heat supplied from a 3000-MW(th) VHTR. The range of cost in process applications is competitive with current fossil fuel alternatives.

## INTRODUCTION

The Very High Temperature Nuclear Reactor (VHTR) is defined as a gas-cooled graphite-moderated reactor. There are a number of large industrial process heat applications that could utilize the VHTR. These include coal conversion to synthetic gas or liquid fuels, hydrogen production by thermochemical water splitting, and hydrogen or synthesis gas ($H_2$ + CO) production for use in direct reduction of iron ore, refining of petroleum, and refining of liquids derived from oil shale and tar sands.

While nuclear process heat is the main focus of this assessment, the VHTR technology has unique applications for electric power production which serve as a secondary incentive for its development. The VHTR can be used with a thermal energy storage system for load following and meeting peak electrical loads or it can produce electricity at high efficiencies by using an advanced topping or bottoming cycle. Chemical energy from a VHTR could be piped long distances to dispersed locations where the energy would be released at local power or heat producing facilities.

In recent years there has been increased international interest in the possibility of using the VHTR as a source of high-temperature process heat. The Federal Republic of Germany has initiated a substantial program to develop the VHTR, associated nuclear coal conversion processes and a chemical heat pipe system. The Japanese Atomic Energy Research Institute has initiated a comparable program to develop a nuclear steelmaking system.

In the U.S., several private sources initiated investigations of nuclear process heat. A topical meeting on the subject, sponsored by the American Nuclear Society, was held at Los Alamos in October 1974.[1]

In April 1974, the United States Atomic Energy Commission, now Energy Research and Development Administration (ERDA), authorized General Atomic Company, General Electric Company, and Westinghouse Astronuclear Laboratory to assess the available technology for producing process heat utilizing very high temperature nuclear reactors.[2,3,4] The concepts and technology are evaluated for producing process stream temperatures of 649, 760, 871, 982, and 1093°C (1200, 1400, 1600, 1800, 2000°F). The Oak Ridge National Laboratory was requested by ERDA to prepare an overall assessment of the incentives for developing the Very High-Temperature Reactor (VHTR), the technical and economic feasibility of the reactor and associated process, and the research and development requirements. Many government and private organizations have contributed to this effort. Three major ORNL reports are being prepared to present the results of this work.[5,6,7]

## TECHNOLOGY

The VHTRs are thermal reactors utilizing helium as coolant and having all-ceramic cores composed of graphite moderator and enriched uranium-thorium fuel. This combination has enabled the gas-cooled reactor to develop coolant outlet temperatures far higher than those of other reactor systems. The three vendor design studies present features which encompass most of the available technology, as illustrated in Table I.

General Atomic has developed the High-Temperature Gas-Cooled Reactor (HTGR) as a commercial steam-generating reactor for use by utilities. The Peach Bottom Reactor [115 MW(t), 40 MW(e)] was operated successfully by Philadelphia Electric Company from June 1967 to October 1974 and proved the feasibility of the concept. GA has built a much larger HTGR at Fort St. Vrain [842 MW(t), 330 MW(e)] which has thus far been operated only at low power levels. The standard commercial HTGR (helium outlet temperature of 1400°F or 760°C) is modified for process heat purposes by placing a process heat exchanger in series with and upstream of the steam generator.[2] As in other current HTGR designs, all the primary system components are contained in one large prestressed concrete reactor vessel (PCRV) because of the advantages offered by this form of construction. Steam-methane reforming was selected by GA as a typical high-temperature process; and the reformer was assumed to be located within the PCRV. The GA study was based on the assumption that an intermediate heat exchanger (IHX) would not be required. If an IHX is required, reactor exit helium temperatures would have to be increased well above the reference 1620°F (882°C) to reach 1400°F maximum process temperature.

The Pebble-Bed Reactor (PBR) developed by Kernfor-

Table 1

Comparison of the Three Vendor Concepts

| | General Atomic | General Electric | Westinghouse |
|---|---|---|---|
| Basis of very high temperature nuclear reactor design | Modification of HTGR concept | Pebble bed concept based on German technology | Prismatic fuel concept based on nuclear rocket technology |
| Reactor core type | Hexagonal graphite blocks containing separate coolant and fuel passages, solid cylindrical fuel rods | Pebble bed core<br>Graphite sphere fuel element | Hexagonal graphite blocks, hollow cylindrical fuel rods with central coolant channel |
| Reactor coolant | Helium | Helium | Helium |
| Reference thermal power | 3000 MW(t) | 3000 MW(t) | 3000 MW(t) |
| Pressure vessel concept | Prestressed concrete reactor vessel | Prestressed concrete reactor vessel | Prestressed cast iron reactor vessel |
| Fuel composition | •Fully enriched U feed ($UC_2$) with thorium ($ThO_2$) fertile material<br>•Triso coating for both fissile and fertile particles | •Low enriched (9.01%) $^{235}U$ fuel<br>•Uranium-thorium fuel alternate<br>•Triso coated $UO_2$ fuel particles | •Fully enriched U feed ($UC_2$) with thorium ($ThO_2$) fertile material<br>•Triso coated fissile particles<br>•Biso coated fertile particles |
| Average fuel residence time | 3 years | 3.8 years | 4 years |
| Power density of core | 8.4 watts/cm$^3$ | 5 watts/cm$^3$ | 10 watts/cm$^3$ |
| Reactor core δP | 16 psi | 6 psi | 5 psi |
| System pressure | 725 psia | 600 psia | 1000 psia |
| Core inlet temperature | 770°F (410°C) | 482°F (250°C) | 807°F (431°C) |
| Reference maximum process temperature | 1400°F (760°C) | 1500°F (816°C) | 1600°F (871°C) |
| Core outlet temperature | 1600°F (871°C) | 1742°F (950°C) | 1850°F (1010°C) |
| Maximum fuel temperature | 2475°F (1357°C) | 2030°F (1110°C) | 2158°F (1181°C) |
| Type process | Steam-hydrocarbon reformer | Steam-hydrocarbon reformer | Thermochemical water splitting |

schungsanlage (KFA) Jülich, differs from the HTGR primarily by having the fuel contained in graphite moderator balls. These balls are loaded into and withdrawn from the reactor during operation. The PBR concept was selected by GE for their VHTR design.[3]

KFA has built and is operating the Arbeitsgemeinschaft Versuchsreactor (AVR) [46 MW(t), 15 MW(e)], an experimental steam-generating PBR. The AVR has operated at a helium core outlet temperature of 950°C (1742°F) since February 1974. A larger PBR, The High Temperature Reactor (THTR) [768 MW(t), 300 MW(e)], is under construction and scheduled for 1978 operation. This steam generating reactor will have a helium outlet temperature of 750°C, in the same range as commercial HTGRs.

The GE PBR places all primary system components into a PCRV. Primary helium coolant flows through the core and exits into five loops, each containing an intermediate heat exchanger (IHX) and a steam generator (SG). A secondary helium stream is heated in the IHX and transported out of the reactor vessel to an external process heater, which GE assumes to be a steam-methane reformer.

The Westinghouse VHTR contains a number of novel features.[4] The reactor and its coolant loops are contained within a multi-cavity prestressed cast iron reactor vessel (PCIV). The reactor core is located within the vessel's central cavity. The vessel walls contain twelve smaller vertical cavities, or pods, in which are five high temperature intermediate heat exchangers and circulators, five gas turbines and low temperature intermediate heat exchangers, and two auxiliary cooling systems for shutdown and emergency cooling of the reactor. Reactor helium coolant enters and discharges from the pods through coaxial piping at the upper end of the cavity, while the intermediate loop, or secondary, helium coolant is introduced and leaves through the bottom of the pod. The PCIV has a continuous internal steel liner to act as a primary coolant boundary and leak-tight membrane. A thermal barrier and insulation system is used to limit the temperature of the liner and minimize the heat loss to the PCIV.

The process heat exchangers and the gas turbine-generators provide energy for a thermochemical water-splitting process based on a sulfur cycle.

All three vendor concepts appeared to have potential to achieve process temperatures in the range 1200 to 2000°F (649 to 1093°C). The GE concept has the most applicable high temperature operational background in that the AVR has been operated successfully at 950°C for extended periods. GA, on the other hand, has developed technology applicable to 3000 MW(t) designs and has the broadest technological base. The Peach Bottom outlet temperature was only 715°C (1319°F); however, it appears likely that the HTGR technology would be applicable to more elevated temperatures as well. The W concept does not have a commercial technological base comparable to the other two concepts; more development would be required.

The GA design was the only one not to use an intermediate heat exchanger (IHX), but stated that the need for an IHX had not been ruled out. GE included an IHX, with implications of some hope that additional studies would show that it could be eliminated. W made a case for the necessity of the IHX. As there does not appear to be any basic design feature or innovation which would allow one concept only to use the direct system, it is assumed that this difference at the present time is one of vendor philosophy. Further analysis of reactor safety and of radioactivity transport is required to establish whether the IHX can be eliminated for some range of process choices.

The nominal reference process temperature presented in Table I for the three concepts is indicative of the historical development of each concept. The HTGR has evolved from a very strong technology program focused on steam generation. The lowest temperature required for a reasonable process efficiency, 1400°F (760°C), has been chosen to minimize extrapolation of existing components and technology. The PBR concept is based on the technology of the AVR scaled up to commercial size; the process temperature selection of 1500°F (816°C) is a logical consequence of the AVR helium outlet temperature of 950°C, assuming the heat transport systems can be developed. The W concept is derived from the very advanced Nerva reactor technology, which operated for short times at extremely high temperatures. The water-splitting process coupled to the W reference design requires 1600°F to proceed at reasonable efficiency.

## NUCLEAR PROCESS HEAT COST

Oak Ridge National Laboratory, with assistance from United Engineers and Constructors,[8] has estimated VHTR process heat cost. Figures 1 and 2 give the range of estimated costs of nuclear process heat when supplied from a 3000 MW(t) VHTR, considering the presence or absence of an intermediate heat exchanger as a parameter. The economic ground rules used in obtaining these estimates are given in Table II.

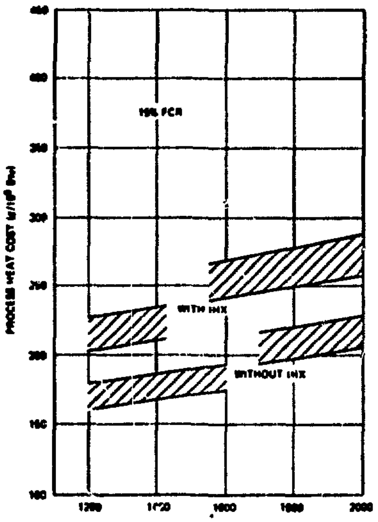



FIGURE 1. Process Heat Cost from a VHTR vs Maximum Process Temperature, Utility Financing

These costs are based on preliminary, conceptual designs, and rely heavily on vendor information. The costs which are presented may change as a result of further research and development and of more detailed design.

The general trend of increasing heat costs with increasing temperature results from increased costs of materials and components, and more elaborate systems to maintain the fuel at acceptable temperatures. The discontinuity in cost above 1600°F

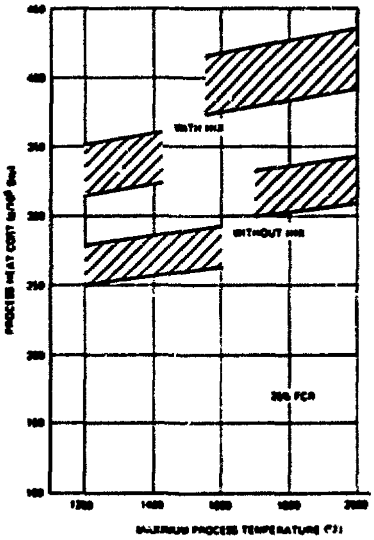



FIGURE 2. Process Heat Cost from a VHTR vs Maximum Process Temperature, Industrial Financing

Table II

Economic Ground Rules Employed in VHTR Evaluation

| | | |
|---|---|---|
| Reference Plant Size, MW(t) - 3000. | | |
| Process Heat Cost is evaluated assuming all energy from the reactor has the same value independent of the form of the energy or how it is used. | | |
| July 1976 Dollars - No Escalation. | | |
| [illegible] Plant Factor. | | |
| [illegible] and [illegible] Fixed Charge Rates. | | |
| Capital Costs Include: | Direct Costs | |
| | Indirect Costs | |
| | Interest During Construction - [illegible]/yr | |
| Fuel Cycle Cost Basis: | $U_3O_8$, $/lb | 30 |
| | Enrichment, $/SWU | 75 |
| O&M Costs - 9 x $10^6$ $/yr | | |

process temperature stems from the need to introduce exotic high temperature alloys and/or ceramics into the high temperature components.

## PROCESS HEAT APPLICATIONS

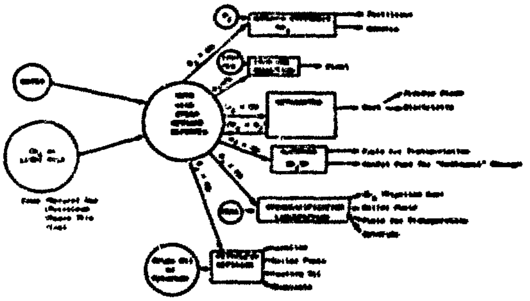
A very wide range of process heat applications have been considered. The two general alternatives which appear most promising are (1) a secondary energy depot, Figure 3, and (2) production of primary synthetic fuels, Figure 4. All applications appear to be technically achievable with development of the VHTR.

Coal Conversion. The major long-term process heat application of the VHTR is in synthetic fuels via coal conversion. Up to 132 VHTRs [3000 MW(t)] could be utilized by 2030 in synthetic fuel production.[7] However, this application could not have a significant impact until after the year 2000. The two major alternatives for nuclear coal conversion are discussed below:

(1) Hydrogasification and Hydrotreatment. When coal is exposed to hydrogen at elevated temperatures and presures (500 to 800°C, 60 to 200 atm.), there is a strongly exothermic reaction producing methane and other light hydrocarbons. Hydrogen, in turn, can be produced in a methane (light hydrocarbon) steam reformer heated by the helium coolant of a VHTR. This highly endothermic reaction is carried out usually at 680 to 850°C.

The important chemical reactions are the following:

| | | |
|---|---|---|
| Hydrogasification | $C + 2H_2 = CH_4 + 20.6$ kcal/mole | (1) |
| Steam Gasification | $C + H_2O(v) = CO + H_2 - 28.4$ kcal/mole | (2) |
| Steam Reforming | $CH_4 + H_2O(v) = CO + 3H_2 - 49$ kcal/mole | (3) |
| Shift | $CO + H_2O(v) = CO_2 + H_2 + 9.9$ kcal/mole | (4) |



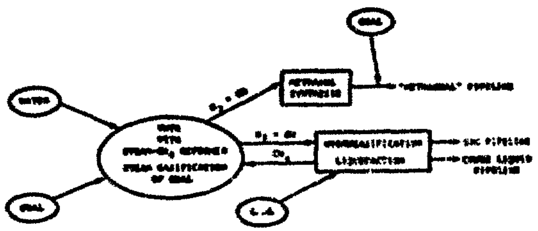


FIGURE 4
PRODUCTION OF PRIMARY SYNTHETIC FUELS

Depending on the desired product, this conversion process can be designed for net production of methane, syngas ($H_2 + CO$), or hydrogen.

Both the Germans [9,10] and General Atomic/Stone and Webster [11,12] have proposed processes using this technology for coal conversion.

(2) Direct Steam Gasification. Coal reacts with steam at elevated temperatures in a strongly endothermic reaction. The products of the reaction, $H_2$ and CO, can be converted to desired products such as methane or hydrogen.

The important chemical reactions are the following:

| | | |
|---|---|---|
| Steam Gasification | $C + H_2O(v) = CO + H_2 - 28.4$ kcal/mole | (1) |
| Shift | $CO + H_2O(v) = CO_2 + H_2 + 9.9$ kcal/mole | (2) |
| Methanation | $CO + 3H_2 = CH_4 + H_2O + 49$ kcal/mole | (3) |

Steam-carbon reaction rates become significant at about 600°C for lignite and 700°C for hard coal. The Germans propose to operate a lignite steam-gasifier at 660°C; [9] this gasifier would be a steam-fluidized bed heated internally by helium flowing through tubes. This appears to be an optimistically low temperature level.

The steam gasification process leaves a residue of char, according to United Kingdom sources; [13] the UK paper cites 750 to 850°C as reasonable temperatures for lignite gasification with 925°C recommended for "high carbon conversion." The corresponding temperature for hard coal is given as 1050 to 1100°C.

For the steam gasification process to be practical, a very high-temperature heat source and process heat exchangers would have to be developed and/or a practical catalyzed low-temperature coal reaction developed.

Nuclear Steelmaking. The most viable concept for applying nuclear energy to steelmaking combines two well-known processes: direct reduction in a shaft furnace and refining in an electric furnace.

In the direct reduction process, iron ore is reduced in the solid condition to a product known as sponge iron by a synthesis gas ($CO + H_2$) derived from steam reforming of natural gas, a reaction requiring high temperature heat. Nuclear energy may be used to provide the heat needed to produce synthesis gas by light hydrocarbon reforming for the direct reduction of iron ore.

The American Iron and Steel Institute has conducted several studies of nuclear steelmaking.[14-18] They concluded that the nuclear option for steelmaking appears to be competitive with the conventional coke oven/blast furnace process and with the direct reduction process using synthesis gas from a Koppers-Totzek gasifier. It is not competitive with synthesis gas from a conventional natural gas reformer with current natural gas prices.

Because of size mismatch, the steel industry does not appear to represent a major market for the VHTR in number of units but it may be a very important one. The Japanese have launched a major program in nuclear steelmaking, allocating about $26 million over a 6 year period. Nuclear steelmaking technology may be required to keep the U.S. steel industry competitive in the future.

Petroleum Refinery. At the request of Oak Ridge National Laboratory, the General Atomic Company conducted a study [19] to evaluate the use of a process heat version of the General Atomic high-temperature gas-cooled reactor (HTGR) as a heat source for petroleum refining and other petrochemical processes. The study investigated the technical and economic aspects of producing and transporting 1364 MW of thermal energy to a 250,000 BPD refinery, the boundary of which was located 3500 ft from the reactor. The refinery heat load was made up of 398 MW of 700°F steam and 966 MW of process heat having the capability of producing refinery process temperatures of 1050°F. The basic refinery heat balance utilized in the study was provided by Amoco Oil Company. Shell Oil Company supplied additional data on refinery heat loads, shutdown schedules, and hydrogen requirements.

Although the heat transfer system was made more complex (and expensive) by the assumption of a backup heat source, to assure very high availability, heat can be delivered to the refinery for 1.91 to 3.92 dollars per $10^6$ Btu. This appears to be in a competitive range with most fossil fuels for delivered energy cost.

Oil Shale and Tar Sands. The relative cost of oil shale recovery using the VHTR appears to be marginally competitive with conventional alternatives according to a study by Resource Analysis and Managemen. Group.[7,20] Potential benefits of the VHTR application are 24 to 50% greater yield from the oil shale resource and about 20% lower water requirement.

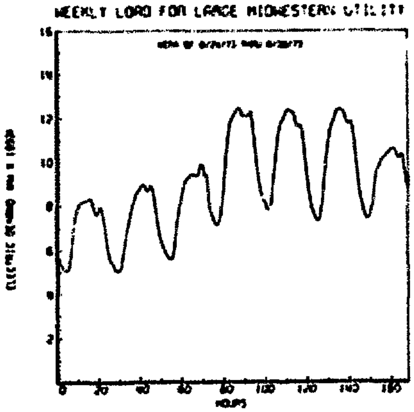
The market potential for the VHTR in shale oil recovery and processing is not projected to be significant at present. The market potential in tar sands recovery in the U.S. is nil but potential applications in Canada, Venezuela and Colombia could provide an export market.

Hydrogen From Watersplitting. A number of studies under NASA support have been performed on the general subject of hydrogen production by thermochemical or electrolytic water splitting [12,21,22,23] and a comparison of watersplitting with more conventional methods of hydrogen production. The costs of hydrogen from electrolytic or thermochemical watersplitting using the VHTR are roughly competitive with one another and about a factor of 2 to 3 higher in cost than hydrogen produced from coal or from VHTR - coal hybrids.

## PEAKING POWER APPLICATIONS

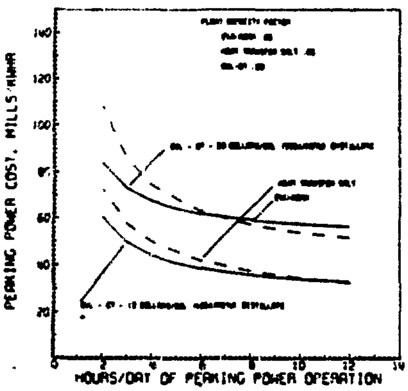
Electric demand levels are normally separated into three broad areas: base load, intermediate load, and peak load. The base load is normally provided by the newer fossil fuel, nuclear and hydroelectric plants. Intermediate and peak load power demand are currently met by (1) generation in fossil-fueled (oil and coal fired) steam plants, (2) by hydropower or pumped storage and (3) in gas turbines with high quality, expensive fuels. Except for pumped storage, which is relatively inefficient and is limited to very few sites, there is no economic, commercial system for use of nuclear energy to meet peak and/or intermediate electrical load. The combination of the VHTR and chemical (EVA-ADAM) or high temperature thermal (Heat Transfer Salt) energy storage should lead to a competitive source of intermediate load and peaking power.

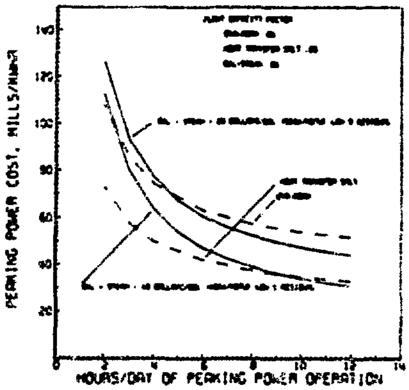
The power load of an electrical utility grid fluctuates by as much as a factor of two on a daily basis. Figure 5 presents a typical weekly load curve for a large midwestern utility. The objective of the VHTR peaking power system is to meet the daily peak demand of the grid (or a portion of that demand). Up to 120 3000 MWth VHTRs could be utilized by 2030 in peaking power applications.[7]

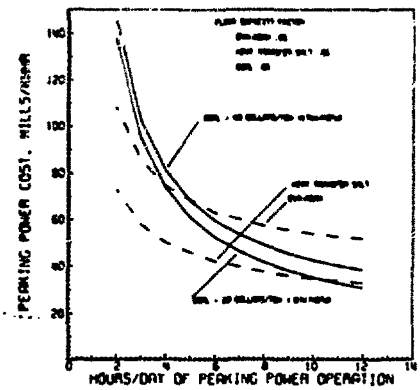



Figures 6, 7, and 8 are cost comparisons of EVA-ADAM Storage, Heat Transfer Salt Storage and three conventional power systems: gas turbines, coal-fired and oil-fired steam systems.

Although this is a preliminary analysis, it appears that the EVA-ADAM peaking system will be competitive only if fuel prices rise considerably above their present level. As can be seen in Figure 6, the cost of a gas turbine system is not a strong function of the period of operation, but is very sensitive to fuel costs. Compared to a gas turbine system, EVA-ADAM would be competitive at higher fuel prices, only if it used as an intermediate power producer,



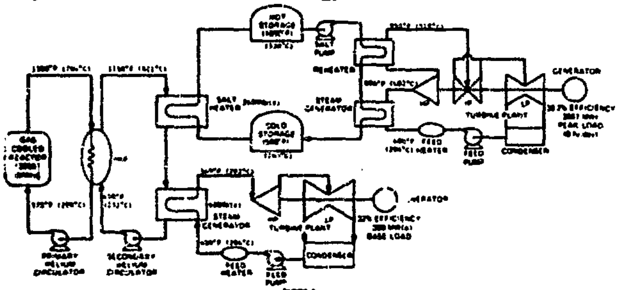

being used 6 to 12 hours per day. However, it can be inferred from Figures 7 and 8 that in this range of operation, fossil-fired steam plants would be more economical even at higher fuel costs.

The heat transfer salt system appears to be a very attractive alternative to present gas turbine peaking systems. It can be seen in Figure 6 that the heat transfer salt system is competitive with the gas turbine system even at the lower range of fuel prices. This system is more economical than EVA-ADAM because it has a lower capital investment per kilowatt of peaking power; but like the EVA-ADAM system it has a low operating cost, so it will become even more attractive as the price of fossil fuels rise. Because of its low operating costs, the heat transfer salt storage system has the additional advantage of being competitive with the steam cycle for production of intermediate load power. Figures 7 and 8 show that this system is competitive with both the oil- and coal-fired steam systems at the lower fuel prices for intermediate load applications up to about 10 hours per day or 40% plant factor.

The VHTR peaking power scheme would reduce the demand by the electric power industry for high quality fuels which have alternative uses for transportation and home heating and would provide a mechanism whereby nuclear energy could be effectively used to meet peak power demand.

Heat Transfer Salt (HTS) is a eutectic mixture of potassium nitrate ($KNO_3$), sodium nitrite ($NaNO_2$), and sodium nitrate ($NaNO_3$). It is economical and has good heat transfer properties. HTS was developed by du Pont in the thirties for use in the chemical and petroleum process industries. The usual composition by weight is 53% $KNO_3$, 40% $NaNO_2$, and 7% $NaNO_3$. Some of the more important physical properties of HTS for this application include its low melting point (288°F) and high thermal conductivity (0.33 Btu/hr ft °F), specific heat (0.373 Btu/lb °F), and heat transfer coefficient (800 to 2900 Btu/hr ft$^2$ °F over a wide range of temperatures and velocities). HTS has been widely used in many industrial applications and in very large volumes.

Figure 9 is a schematic diagram of an electric peaking power generating system based on HTS energy storage. The 3000-MW(t) system will provide 200 MW(e) continuously and 3667 MW(e) for 6 hr a day (peaking power). The system is designed to store 43,200 MWhr of thermal energy.




## CONCLUSION

Gas-cooled reactor technology is very attractive and its technical feasibility for large units appears to be established. Thus far it has not been successfully commercialized because the margin of potential superiority over other energy sources (light-water reactors) has not been decisive in any applicatic or in any country. All future applications of the gas-cooled reactor (including the VHTR) would benefit enormously from early introduction and commercial success in any one application. The prospects for near term commercialization which appear to be most favorable are the following:

1. Steam-cycle HTGR. General Atomic Corporation has indicated that it is making a strong effort to develop a competitive design. The first commercial plant could be started about 1987.

2. German VHTR. German hard-coal prices are now just under \$2/10$^6$BTU and their major source of fuel is imported oil at about the same price level. In view of the large German investment in gas-cooled reactor technology and the high price and scarcity of fossil fuels, prospects appear bright for a VHTR prototype by 1990 and commercialization by 1995.

3. Japanese VHTR. Steelmaking, based on imported coal, constitutes 20% of the Japanese demand for energy. Metallurgical coal has recently increased greatly in price and the supply has become less reliable. Japan has very strong incentives to deploy the VHTR, but is likely to import gas-cooled reactor technology at first.

4. Peaking VHTR. Of all the VHTR applications we have investigated, this would appear to have the best possibility for being competitive with other energy systems in the U.S. at an early date. An economic size prototype (1500-2000 MWt) could probably be deployed by 1990.

In the long term there is a large potential for application of the VHTR in synthetic fuels production via coal conversion, power production for daily peak electric load, and ultimately base load high-efficiency power production using high temperature cycles or gas turbines.

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