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POTENTIAL APPLICATIONS OF HELIUM-COOLED HIGH-TEMPERATURE REACTORS TO PROCESS HEAT USE*

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ABSTRACT

High-Temperature Gas-Cooled Reactors (HTRs) permit nuclear energy to be applied to a number of processes presently utilizing fossil fuels. Promising applications of HTRs involve cogeneration, thermal energy transport using molten salt systems, steam reforming of methane for production of chemicals, coal and oil shale liquefaction or gasification, and-in the longer term-energy transport using a chemical heat pipe. Further, HTRs might be used in the more distant future as the energy source for thermochemical hydrogen production from water. Preliminary results of ongoing studies indicate that the potential market for Process Heat HTRs by the year 2020 is about 150-250 GW(t) for process heat/cogeneration application, plus approximately 150-300 GW(t) for application to fossil conversion processes. HTR cogeneration plants appear attractive in the near term for new industrial plants using large amounts of process heat, possibly for present industrial plants in conjunction with molten-salt energy distribution systems, and also for some fossil conversion processes. HTR reformer systems will take longer to develop, but are applicable to chemicals production, a larger number of fossil conversion processes, and to chemical heat pipes.

INTRODUCTION

An important advantage of High-Temperature Gas-Cooled Reactors (HTRs) is their ability to generate high core-exit coolant temperatures; this has implications relative to their ability to displace fossil energy with nuclear energy. To date, nuclear energy has been applied primarily to the generation of electricity and has resulted in a reduction of fossil fuel use. While the HTR is not unique in this direct application, it has certain features which extend this ability and enable it to displace considerably larger amounts of fossil fuels, particularly oil and gas. The higher thermal efficiency of HTRs means more electrical power can be generated at a given site controlled by cooling water requirements; also the advantageous safety characteristics and the relatively low effluent levels (both radioactive and nonradioactive) associated with HTR operation may permit the siting of such plants at locations where light water reactors (LWRs) and coal plants cannot be sited. While these factors can be significant, greater emphasis is being placed on HTR applications in the process heat industries for the displacement of oil and gas fuels.

Based on present materials technology, the core outlet coolant temperature from HTRs is limited to about 750°C, which leads to generation of steam at about 540°C— significantly higher than the steam generated in conventional LWRs (approximately 290°C). HTRs can generate core outlet coolant temperatures of about 950°C, which increases applications of nuclear energy to high-temperature processes, but significant materials technology development will have to be successfully completed in order to economically achieve these higher coolant temperatures. Overall, then, the HTRs which have the nearest-term application are those which have reactor outlet coolant temperatures up to 750°C, though it is anticipated that higher outlet coolant temperatures will be attained. In the on-going studies, consideration is being given to HTRs with outlet coolant temperatures of 750, 850-950, and 950-1000°C; these will be termed HTR-750°C, HTR-850-950°C, and HTR-950-1000°C, respectively.

Of the very significant quantity of process heat used in the United States, much of it based on oil and gas, a large fraction is used at temperatures below 540°C, and the HTR-750°C has the potential to meet most of the needs of the process heat industries.

As the outlet temperature of an HTR increases, a larger fraction of national process heat needs can be met; however, the fractional increase as the outlet coolant temperature increases from 750 to 950°C is relatively quite small. The higher reactor temperatures do permit HTR application to a broad range of fossil conversion processes which are expected to emerge commercially in the future. In particular, processes which make use of a steam-methane reformer can effectively utilize heat source temperatures in the 850 to 950°C range. The optimum temperature is not known at this time, but it depends upon a practical balance between process efficiency and capital investment and operating costs.

Not all fossil conversion processes, however, require use of a steam-methane reformer. For example, about 90% of the energy needs for the Exxon Catalytic Coal Gasification (ECCG) Process can be provided by an HTR-750°C system. Such a system can, therefore, supply significant amounts of energy to satisfy both industrial process heat needs and the energy needs of some fossil conversion processes.

At the highest temperatures, i.e., HTR-950-1000°C, HTRs might be utilized for chemical water splitting processes — almost certainly a longer-term development, but one that could become important in the future when a hydrogen economy might be considered practical, or when fossil fuels (including coal) are in very short supply.

HTR APPLICATION TO PROCESS HEAT USAGE IN THE UNITED STATES

Information on process heat use in the U.S. is generally reported under the category "industrial process heat," which includes manufacturing, construction, mining, and agriculture. However, the segment receiving the most emphasis in the HTR program is manufacturing, in which the major energy users are the chemical, primary metal production, petroleum, paper, and stone-clay-glass-concrete industries. Manufacturing accounts for 80% of the energy consumption in the industrial sector.

Recent adjusted fuel use percentages have been published (1), as have industrial energy data for the U.S. in 1979 (2,3). Similar information relative to 1990 estimated use, considering both high and low demand cases, and certain fuel switching trends, is also available (4). Table 1 provides summary information on industrial energy demand estimates for 1990, 2000, and 2020, again with high and low cases, and considering a continuation of previous fuel switching trends. These projections do not include direct nuclear energy contributions to process heat supply.

Estimates of fossil energy consumption in 1980 by the manufacturing sector for process heat (5) are given in Table 2.

As shown in Table 2, about 18.9 EJ/yr was used in 1980 for process heat by the manufacturing industry; about 76% of the process heat was used at temperatures below 540°C and about 43% was below 260°C. Further, 46% of the energy was used as steam and 54% for direct heat. This implies that most of the process steam was at temperatures below 260°C. While only a small fraction of energy was used directly as process steam at temperatures greater than 260°C, a significant amount of energy (approximately 30%) was used as direct heat in the 260–540°C temperature range. There appears to be a significant potential market for HTR-750°C systems as applied to the process industries; this application of nuclear energy is accentuated when electricity production and energy distribution efficiencies are included. At the same time, relatively little process energy was used in the 540–927°C temperature range. Therefore, while the HTR-750°C appears significant for process heat application in the manufacturing sector, there is little advantage in having a higher temperature HTR for these applications unless temperatures above 927°C can be distributed.

Table 2. Manufacturing sector (1980 estimate) — fossil energy consumption for process heat (5).

Energy as:	EJ/year	%
Steam	8.7	46
Direct heat	10.2	54
Total	18.9	100
Energy by temperature range:		
<260°C	8.2	43
260–540°C	6.3	33
540–927°C	0.5	3
>927°C	3.9	21
Total	18.9	100
Energy by fuel:		
Oil	4.0	21
Coal	3.9	21
Gas	9.8	52
Other	1.2	6
Total	18.9	100

The distribution of industrial process heat as a function of temperature (6) for the year 1976 is given in Fig. 1. Taking into consideration preheat energy and the different base years, Fig. 1 is in reasonable agreement with the distribution values in Table 2. Fig. 1 indicates that for distributed energy at temperatures above about 540°C, a significant increase in market potential occurs only when the temperature reaches about 950°C or above.

In general, the preceding data indicate that large quantities of fossil fuels, particularly gas and oil, are being consumed by the process industries— i.e., about 15 m^3/s oil equivalent (over 8 million bbl/d). Further, a significant fraction (about 1/3) of process energy is used in the 260–540°C temperature

Table 1. Industrial purchased energy demand (4), EJ/year.

Source	1979[a]	1990 Low case	1990 High case	2010 Low case	2010 High case	2020 Low case	2020 High case
Petroleum	9.4	7.3	7.5	4.3	6.0	5.6	6.6
Gas	9.1	5.9	6.1	13.0	12.1	13.6	16.6
Coal	3.8	10.2	11.0	7.5	9.4	9.7	11.6
Electricity	3.0	4.5	4.8	5.4	5.8	6.8	7.9
	25.3	27.9	29.4	30.2	33.3	35.7	42.7

[a]From reference (2) with road oil and asphalt included in the industrial consumption.

range. Estimates for future years (Table 1) indicate the use of fossil fuels for process heat will be rather stable, and with some growth. This assumes that nuclear power is not used directly. There is an obvious long-term need for process heat energy. If nuclear sources can supply a major fraction, this would have a large influence on the long-term importation of oil and gas.

Industrial process heat users are widely dispersed, most plants using only relatively small amounts of energy, and the few largest facilities consuming most of the energy. About 70% of process heat, e.g., is consumed (5) by plants rated above 10 MW(t). These plants are often concentrated in specific industrial areas (7); there are more than 25 sites in the United States which within a 10-mile radius individually need more than 1000 MW(t) in process energy, and there are at least 20 additional sites which, within a 20-mile radius, individually use more than 2000 MW(t). There is clearly a significant market for HTR applications to the process industries if the thermal energy can be distributed economically.

It might be argued that a significant fraction of process heat is used at temperatures below 260°C, and that this can be provided by light water reactors (LWRs). However, as indicated previously, even at the lower temperatures of steam use under cogeneration conditions, HTRs can generate significantly more electrical power than LWRs, particularly at the higher extraction temperatures, as shown in Fig. 2. Since nuclear power plants will undoubtedly generate electricity in addition to energy for process heat, the characteristics shown in Fig. 2 indicate that the HTR should be significantly more economic than LWRs for supplying process steam even at temperatures less than 260°C. As shown, at 225°C extraction steam temperature, the HTR can generate twice the quantity of electricity. In addition, the HTR can supply a process heat market which is about 1.8 times as large as that associated with a 260°C steam market.

The above illustrates that the process heat industry is large, dispersed, yet concentrated in specific areas and that the HTR could uniquely provide much of the process energy if the economics of energy distribution were favorable. One way of attaining favorable distribution costs is to site HTRs in nuclear power parks with co-located industrial consumers, as planned at the Bruce Nuclear/Cogeneration Power Station in Canada. A competing fuel would, of course, be coal. While coal plants have different regulatory uncertainties than do nuclear power plants and do not require as much development as the HTR, the latter would have important environmental advantages compared with coal, resulting in decreased air pollution and mining hazards, in addition to its economic advantages. Under these circumstances, it appears that a significant fraction of industrial process heat needs could be met by HTRs.

In the near term, however, the process industries already have investments in conventional gas and oil heat sources, and even though the associated fuel cost may be relatively high, there is insufficient incentive to change to a capital-intensive energy source so long as additional energy is not needed. Nonetheless, as fossil fuel costs increase, even present facilities could utilize energy from an economic distribution system emanating from a nuclear power station. This might be done by employing molten-salt sensible energy transmission and storage (SETS) systems for coupling HTRs to refineries and other process heat users. SETS molten-salt could be heated from 329°C to about 510°C by a secondary helium loop. In this application, an intermediate heat exchanger (IHX) may be required to isolate the reactor primary system from the SETS system to prevent potential ingress of molten salt into the core. The upper temperature value appears to be a conservative limit leading to low corrosion rates and good salt stability. Molten salt (MS) would be heated, stored in a hold tank, and piped to points of use. At the point of use, the sensible heat of the MS would be used to generate superheated steam for electricity generation or for process use; alternatively, the MS could be used directly in process heaters. Such a sensible heat pipe would effectively be a high-temperature industrial-district heating system; the economic transport distance has been estimated (8) to be up to about 80 km (50 miles).

HTR energy could also be transported with the chemical heat pipe (CHP), making use of an HTR-850-950°C system. The chemical heat pipe is associated with steam reforming methane to CO and H_2 at the reactor site, transporting the synthesis gas through a pipeline, and recombining the gases by catalytic methanation (an exothermic chemical reaction providing heat to users). A methane-rich stream is returned to the reformer plant, and the closed loop nature of the concept eliminates the need for combustion of coal or other fossil fuels. The most promising application of chemical heat pipes is the use of an integrated piping network in which multiple users are linked together. The chemical heat pipe has been judged to be capable of providing energy to the dispersed industrial heat and peaking and mid-range electricity markets. Preliminary evaluations indicate that CHP systems are more expensive than HTR-SETS systems for transport distances under about 250 km. The CHP might transport energy relatively economically in the long term when fossil fuels are in short supply. Further, CHP systems do broaden the potential market applications of HTRs, since the methanators could provide energy at temperatures up to about 800°C. As indicated in Fig. 1 and Table 2, about 20% of the process heat market could be served uniquely by the HTR-CHP system, if the energy distribution costs become competitive.

Market evaluations to date indicate that a reasonable target for the HTR-SETS system by the year 2020 might be about 20% of the industrial fossil fuel market. Based on the low and high cases in Table 1 and considering all fossil fuels, a range of 5.8-7.0 EJ/yr is obtained (2.6-3.1 million barrels of oil per day). This would correspond to 185-220 HTR plants generating 1000 MW(t) each. The market potential for a CHP system could be about 40% greater, or 260-310 GW(t) by 2020. These markets could be larger if future industry were to site around HTR power parks.

HTR APPLICATION TO FOSSIL CONVERSION PROCESSES

It is presently anticipated that coal and oil shale conversion processes will be used in the intermediate term (2000 and 2030) to supply a significant fraction of U S. oil, gas, and petrochemical needs (estimates of 18.4 m^3/s or 10 million bbl oil equiv/d by 2020). The HTR uniquely permits nuclear power to contribute to that conversion, and significantly increases the ratio of product fuel to fossil feedstock. The conversion of natural gas to synthesis gas for production of commercial chemicals is also a potential area of HTR application.

The processes under development for fossil fuel conversion to gas and/or oil include oil shale retorting and coal liquefaction and/or gasification.

The products, thermal efficiencies, and energy needs are summarized in Table 3 for a number of processes (9). Several utilize significant amounts of high-temperature energy, mostly associated with use of an HTR-reformer system (HTR-850-950°C). An exception is the Exxon Catalytic Coal Gasification (ECCG) Process; an HTR-750°C can supply about 90% of the total primary energy need. Of the coal conversion processes being examined at this time, the ECCG Process appears to be one of the most promising relative to HTR use.

In general, use of HTRs in the direct coal liquefaction processes saves a relatively small amount of coal (15-20%); HTR use in the coal gasification and oil shale recovery processes can reduce consumption of the fossil fuel by 20-35%.

Independent of environmental impacts or fossil fuel resource conservation, the cost of production of the product may be at least as great as that for non-nuclear processes; however, as the cost of fossil fuels increases and assuming additional environmental restrictions will be imposed upon fossil conversion plants, HTRs will tend to become relatively more economic. Institutional problems are a major concern for any synthetic fuel plant; also, a reformer HTR will require a long and expensive development program prior to general commercial application. Important consequences, however, would be the reduced consumption of coal, water, and land resources, as well as reduced emissions of pollutants such as SO_2, NO_x, CO_2, and particulates which would result from HTR use.

Application of reformer HTRs to the generation of synthetic fuels from coal and oil shale to generate 5 million barrels of oil equivalent per day would lead to about 100-250 GW(t) of HTRs by the year 2020; the level is dependent upon the conversion process mix.

Prior to HTR-850-950°C application to coal and oil shale conversion processes, HTR-reformer systems might be used for the production of chemicals from methane; the synthesis gas produced by the reforming of methane can be used (following further processing) or the production of ammonia, methanol, hydrogen, and other chemicals based on Fischer-Tropsch type processes. Methanol can be the feedstock for production of gasoline, and ammonia for fertilizers. Chemicals production is currently being accomplished using natural gas as the feedstock to the reformer as well as the fuel. As the price of natural gas rises under free market conditions (it will likely follow the equivalent price of distillate oil), burning natural gas for energy may become more expensive than using an HTR as the energy source. Oil and natural gas prices will likely be in the range of $100/barrel between now and the year 2000, corresponding to $18/million Btu. Natural gas at the higher prices would be too expensive to burn as fuel, but could still be economic as a feedstock. Under such circumstances, HTR-850-950°C systems could be a useful energy source for reforming methane. Of course, coal could be gasified as an alternative, and competition would exist between the nuclear reformer and the coal gasifier.

Table 3. Summary of energy requirements for candidate synfuels processes (9).

Product (source)	Process	Process thermal efficiency (approx.)	Process energy needs[a] in MW(t): High-temperature heat 760°C–870°C	High-temperature heat 650°C–760°C	High-temperature heat 480°C–650°C	Process steam	Electrical MW(t) = 3 X MW(e)	Total
			*					
Syncrude (oil shale)	Union-B	70	168		484		345	997
	Paraho	70	145		390	140	340	1015
	Tosco-II	70	185	583	54	27	300	1149
	Hytort[c]	60	←	670	→	←	710 →	1380
Transport Fuels (coal)	H-Coal	60	b		305	680	1120	2105
	SRC-II	65	290		300	535	15	1140
	Texaco & Mobil-M	50			296		770	1066
	Lurgi & Mobil-M	55				243	1250	1493
SNG (coal)	Exxon catalytic	65	50	70	60	1130	540	1850
	Winkler	50			136	800[d]	590	1526
	Lurgi 100 bar				No data available			
Syngas (coal)	Texaco	65			237		249	486
	Koppers-Totzek	55			118		1230	1348
	Lurgi slagging	70				194	705	899
	U-gas	75			188			188
	Westinghouse	75		87	53			140

*For methane reformer. Heat requirements can be lowered to 650-760°C (1200-1400°F) level with lower process efficiency.

[a]Based on plant capacity of 0.092 m^3/s (50,000 B/D) oil equivalent.

[b]Hydrogen from partial oxidation process; not included since feed would have no other use.

[c]For Eastern oil shale.

[d]Steam at 950°C.

Estimates (10) of U.S. industrial hydrogen requirements from 1980 to 2000 indicate about 1.07 EJ/yr of hydrogen is needed in 2000 for ammonia and methanol production; an extrapolation to 2020 indicates a requirement of about 2.0 EJ/yr at that time. If all production were by steam reforming, the natural gas required as fuel in 2020 would be about 2.87 EJ/yr. Using HTR-850-950°C systems as the source of reforming energy for 50% of the above capacity would require about 45 GW(t) of HTRs.

HTR APPLICATION TO WATER SPLITTING

Increasing the outlet helium temperature of HTRs to 950-1000°C permits such reactors to be considered as energy sources for hydrogen production through thermochemical water splitting processes. Such applications will likely be slow in evolving due to the very significant materials development problems which need to be overcome for operation at the very high temperatures, the need to develop a commercial water-splitting process, the institutional problems associated with large-scale hydrogen use ("hydrogen economy"), and the relatively high cost of the hydrogen produced by such means. Pure hydrogen produced by water splitting is currently estimated to be quite expensive relative to hydrogen produced indirectly from coal (although it might be less expensive than current production by electrolysis). A great premium would have to be assigned to the elimination of coal consumption and of carbon dioxide emission or; alternatively, the available coal would have to be very expensive.

CONCLUSIONS

The most immediate application of HTR process heat in the U.S. appears to be its use in cogeneration systems generating high-temperature process steam and electricity. However, there are a number of longer-range applications which separately, as well as collectively, constitute very significant potential markets. Such applications include sensible and chemical heat pipes, steam/natural gas reforming to syngas for chemicals production, and use in coal/shale conversion processes producing synthetic fuel gases and liquids.

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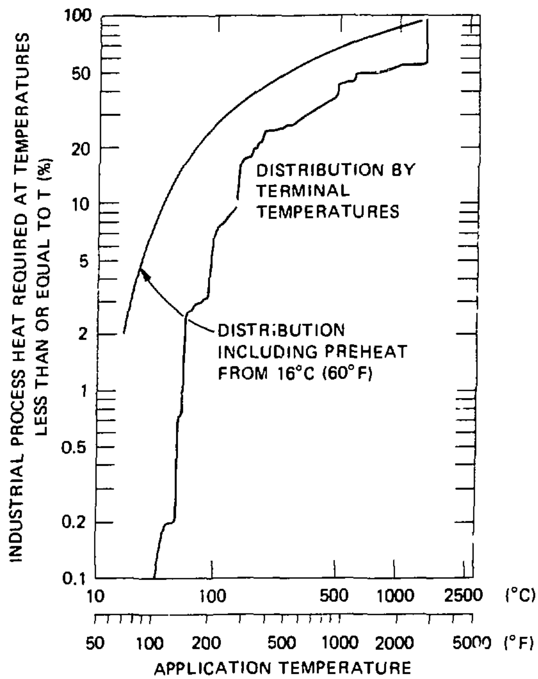

Fig. 1. Cumulative Distribution of Process Heat Requirements (6) (1976 estimate)

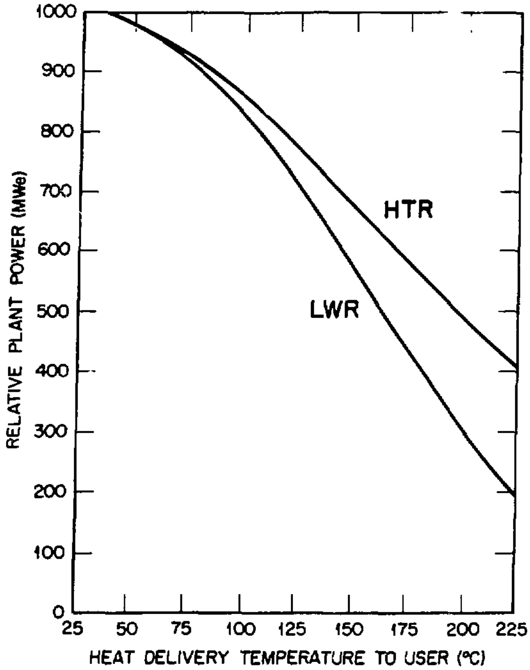

Fig. 2. Approximate Variation of Plant Output with Temperature of Delivered Bottom Energy. (Based on Information from J. M. Neill, Advanced Energy Concepts, Feb. 1981)