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NATIONAL NEED FOR UTILIZING NUCLEAR ENERGY FOR PROCESS HEAT GENERATION*

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ABSTRACT

Fossil fuel resources are used for generating large amounts of energy, with oil and gas being burned in large quantities to supply heat for many industrial processes and for residential, commercial, and industrial space heating. In general, there appears to be limited resources of oil and natural gas available to countries after the year 2000, and it is important to conserve these resources for easing future international energy concerns, as well as for use in transportation and in production of chemicals. The future production of synthetic fuels from oil shale and coal also appears important similar reasons, and such production will require large quantities of process heat. A number of reactor types can be utilized to generate nuclear process heat; those considered here are light water reactors (LWRs), heavy water reactors (HWRs), gas-cooled reactors (GCRs), and liquid metal reactors (LMRs). LWRs and HWRs can generate process heat up to 280°C, LMRs up to 540°C, and GCRs up to 950°C. Based on the studies here, the total estimated United States process heat market corresponds to 310-370 GW(t) after the year 2025, with 75-120 GW(t) for process steam (temperatures < 260°C), 20-35 GW(t) for process heat (temperatures greater than 260°C but less than 540°C), 30 GW(t) for district heating, 30 GW(t) for resource recovery, 85 GW(t) for chemicals production, and 70 GW(t) for synthetic fuels production. The above reactor types can contribute to these different markets in accordance with their coolant temperature capability.

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1. INTRODUCTION

While nuclear energy has been utilized rather significantly for electricity production, it has found little application to date for process heat use. Nonetheless, there is a substantial potential market for use of nuclear process heat and such use could conserve important quantities of fossil fuels. Of the primary fossil fuels, i.e., coal, oil and natural gas, coal is the most abundant, and oil and natural gas are the most convenient to utilize. It is anticipated that oil and natural gas, which are largely equally convenient to use, will be in relatively short supply sometime after the year 2000, and that their prices will rise significantly. At the present time, about 90% of the non-electrical energy consumed for industrial and residential and/or commercial needs in the United States is generated from oil and natural gas. If this continues until after the year 2000, there will be upward pressure on the price and availability of oil and natural gas, which could have a large detrimental effect on national balance-of-payment conditions, on "energy independence" status, and on the well-being of a number of other nations, as well deprive some nations of "convenience" fuels. While coal could be an alternative to oil and natural gas as an energy source, burning of coal (and other fossil fuels to a lesser extent) generates environmental concerns related to air quality, acid precipitation, and carbon dioxide formation. The use of nuclear energy for displacing oil and natural gas is advantageous since the environmental effluents associated with nuclear power plants are very low, and much lower than those from fossil power plants. Further, replacement of oil and natural gas with nuclear fuel leads to more essential uses for fossil fuels, such as for transportation and for the production of chemicals. Overall, it is the need to conserve oil and natural gas in the future, and to decrease the environmental impact of energy use, which drives the need for nuclear process heat.

2. FOSSIL FUEL USE IN THE UNITED STATES

Table 1 summarizes the 1983 energy consumption in the United States by sector and by fuel source; as shown, of the total energy consumption of 74.5 exajoules, the non-electric energy consumption by the industrial sector was 17.8 exajoules (approximately 24% of the total), and the non-electric energy consumption by the commercial and/or residential sector was 10.2 exajoules (about 14% of the total). This non-electric energy for the two sectors combined was provided almost entirely by the burning of fossil fuels, with oil and natural gas providing 90% and coal 10%. In the industrial sector alone, 15.2 exajoules were provided by burning oil and gas. A significant opportunity for the saving of oil and gas by substitution with nuclear process heat appears to exist in the above secotrs, with the largest potential being in the industrial sector. This is discussed below.

The industrial sector includes the industries associated with agriculture, mining, construction, and manufacturing. Of these, and based on extrapolation of past analyses,[2,3,4] the manufacturing industries consume about 80% of the industrial sector energy consumption, with the major manufacturers (from a process heat consumption viewpoint) being the paper, chemicals, petroleum refining, primary metals, and the stone, clay, glass and concrete industries. These five industries account for about 2/3 of the process heat consumed in the industrial sector, with the chemicals, petroleum refining, and primary metals industries accounting for about 55% of the industrial sector. Process steam applications within these industries involve process temperatures from about 38°C (100°F) up to about 260°C (500°F). Although steam is often generated at temperatures above 260°C, the high temperature/high pressure steam is generally used for electrical power generation first and then extracted from steam-electric turbines for process heat applications at lower pressures (cogeneration). Such cogeneration is not included below in the consideration of process energy.

The profile of the process heat energy market is not easily characterized and detailed data which give a clear picture are sparse. A profile for steam and direct heat use based on 1977 data is given in Table 2.[3,4] The data cover manufacturing process energy requirements for 249 utility districts. More recent data would lead to different totals, but are less likely to affect the distribution. The industrial sector total of coal, natural gas, and oil use in 1977 was 23.0 exajoules compared with 17.8 exajoules in 1983. Thus, the totals in Table 2 might be adjusted downward proportionately; however, the use of nuclear process heat would not come into being in a major way before the year 2000, and some growth in process heat use would be expected in a growing economy. Also, Table 2 does not consider all process heat markets in the United States, although it does cover the major ones. Further, there is significant potential for cogeneration of electricity which is not included in Table 2. At the same time, cogeneration is a "soft" market from an "industrial" viewpoint (not from a "utility" viewpoint), inasmuch as more electricity will probably be bought from utilities in the future. Also, there is a trend for industry to use more electricity for all purposes in the future, such that growth in fuel use for process heat would be limited. Overall, it appears that the process heat market in the year 2000 and later is reasonably represented by Table 2 for the United States. For other countries who are now becoming more industrialized, the process heat/steam market should grow markedly, and world demand for process heat/steam should provide a growing market for nuclear process heat applications.

In addition to the information in Table 2, the physical location of energy use is required to evaluate the potential market for nuclear process heat. Nuclear energy plants generally need to generate substantial power to be economic, which indicates that sufficient industry should be located within 15-30 km of a nuclear plant to justify a nuclear process heat plant. Individual plant locations for the primary manufacturing industries within the United States using process steam in large quantities were identified in a preliminary study;[2] 119 locations were found where there exists a concentrated industrial steam load of at least 63 kg/s [500,000 lb/hr requiring about 150 MW(t) per location] within a 3.2 km (2-mile) radius [subtotal requirement of about 18 GW(t)]. An additional 24 locations had a combined industrial steam requirement of at least 252 kg/s [2,000,000 lb/hr, requiring about 600 MW(t) per location] within a circle of 16 km (10 miles) diameter [subtotal requirement of 14 GW(t)], and 19 further locations had a combined requirement of at least 504 kg/s [4,000,000 lb/hr, requiring about 1200 MW(t) per location] within a circle of 32 km (20 miles) diameter [subtotal requirement of about 23 GW(t)]. Summing up the above gives a process power requirement of about 55 GW(t). In the above it was recognized that not all of the steam generated in a given plant may be replaceable on an economic basis. Significant steam is often produced by the combustion of process residuals; these materials, if not used for steam generation, may have little or no alternate value. Examples of such fuels are the black liquor and wood-waste of the paper industry, certain refinery gases of the petroleum industry, and the blast furnace gas of the iron and steel industry. To avoid neglecting this factor, estimates were developed of the nominal fractional range of steam production that is met using process residual fuels in plants within each industry. On the average, about 87% of the steam sources were judged replaceable.

In subsequent evaluations which were not limited to process steam use,[3] it was found that about 23% of manufacturing process energy is consumed by 101 large plants requiring greater than 500 MW(t) per plant [subtotal of about 50 GW(t)] and about 58% of manufacturing process energy is consumed by 1200 large plants requiring greater than 100 MW(t) per plant [subtotal of 120 GW(t)]. The above gives a total of about 170 GW(t).

The above values can be compared with the energy consumed as given in Table 2. The energy use in Table 2 corresponds to energy output of boilers and furnaces; to convert to fuel energy use, the efficiencies of the boilers and furnaces are needed. An overall efficiency of 80% is used here, which tends to be higher than actual, and underestimates fuel use. This leads to a total fuel energy requirement of 14.6 exajoules per year, or the equivalent of 463 GW(t); energy for steam use would be equivalent to 265 GW(t) and direct heat use would be equivalent to 198 GW(t).

The above illustrates several things: first, there is a very large total process heat market, but it is distributed; second, there are significant quantities of process heat utilized in a number of localized areas; and, third, the temperature of the process heat required varies significantly with process applications. These factors will be addressed after the temperature characteristics of nuclear process heat are discussed.

Relative to the fossil energy consumed in the commercial and/or residential sector a large fraction is used for heating. If central district heating were employed in a major way throughout the United States, a significant displacement of fossil fuels with nuclear process heat could take place. Since district heating can be accomplished with hot water, the required temperature of a nuclear heat source is not a limitation. However, district heating has not been utilized in any significant way in the United States, and the present institutions and social structures do not encourage it. At the same time, and from a technical viewpoint, it could be accomplished with time. A reasonable estimate of the market potential for nuclear process heat in the United States is 30 GW(t) (or about 1 exajoule per year), based on 30 locations distributing 1 GW(t) per location. In other countries where district heating is already established (e.g., in Europe), the relative market potential could be higher.

The above does not take into account the very substantial process heat needs required if there were large quantities of oil recovered from heavy oils and tar sands, and if there were large quantities of transportation fuels obtained by conversion of coal and oil shale. These needs are discussed further below.

3. CAPABILITIES OF NUCLEAR REACTOR SYSTEMS AND ASSOCIATED PROCESS HEAT MARKETS

Because of the physical separation of industry which exists today even in a localized area, nuclear heat must be transported to an industrial process for practical application. Alternatively, new industry can site around a nuclear power plant because of the access to economic process heat,[6] which reduces the transport distance and can lead to large energy generation needs. Both of these conditions are discussed below.

The potential for the application of nuclear energy to industrial process heat is influenced by the attainable temperature of the fluid used to transport the energy to the process plant. For light water reactors (LWRs) and heavy water reactors (HWRs), the generated steam temperature is about 280°C (540°F). For liquid-metal reactors (LMRs) and gas-cooled reactors (GCRs), the generated steam temperature is about 540°C (1000°F). Further, GCRs also have the potential for providing process heat at temperatures up to approximately 950°C (1740°F) using helium as the heat transport medium.

Both the low- and high-temperature reactor systems are applicable to a wide range of industrial applications including cogeneration,[6,7] and processes requiring low-temperature steam or heat. All the above reactors can also be considered for other important applications such as district heating[8] and water desalination. However, the low-temperature systems are limited to providing low-grade heat in the cogeneration mode. The higher temperature reactor systems increase the possibilities for application to a broader range of potential industrial processes involving cogeneration[7,9] and fossil fuel conversion processes.[10]

A longer-term possibility, which has been identified with the higher temperatures available from GCRs (approximately 950°C), would be the utilization of the steam-methane reforming reaction ($H_2 + CH_4 + \text{energy} \rightarrow CO + 3H_2$) for the manufacture of synthesis gas ($CO + H_2$).[10] This particular process is widely used in industry for hydrogen production, is a basic process block in the production of various chemicals such as ammonia and methanol, and is applicable to several coal and oil shale conversion processes.

Based on the above, the areas of process heat applications for the various reactor types are as follows: LWRs and HWRs - cogeneration and process heat up to 280°C; LMRs - cogeneration and process heat up to 540°C; GCRs - cogeneration and process heat up to about 950°C. Since the process steam used in industry is nearly all below 260°C (see Table 2), all the above reactors can provide the needed process steam. The potential market for nuclear process steam power is theoretically about 240 GW(t); in practice it would be less than that because the steam market is widely distributed. Based on reference 2 above, a reasonable lower limit based on present distributions would be 60 GW(t), while a practical upper limit is 90 GW(t) on the basis that about half the process heat identified for fairly large energy consuming locations in references 3 and 4 is process steam. A mean value of 75 GW(t) is estimated here. If new industry were to preferentially site around a nuclear power station, however, the process steam market could expand with time to about 120 GW(t).

Because the steam pressure increases with temperature, reactors generating high-temperature steam (rather than low-temperature steam) can more economically deliver process steam to an industry located a relatively long distance from the nuclear plant. As a result, GCRs and LMRs would be able to service larger industry areas than LWRs and HWRs. It is estimated that for a distributed industry system (present practice), GCRs and LMRs would have a market potential for process steam of 75 GW(t), while LWRs and HWRs would have a market potential of 35 GW(t). On the basis of energy centers servicing newly placed industry, all reactors would have a market potential of 120 GW(t).

As the temperature of the nuclear process heat increases to 540°C, the potential market grows to some extent, as shown in Table 2; however, the growth is not marked. On a theoretical basis the increased market would be about 70 GW(t); on a practical basis, taking into consideration distribution limitations, the increased market would probably be about 20 GW(t) which, of course, is not negligible. With new industry placed around an energy park, the increased nuclear process heat market associated with the above is estimated to be 35 GW(t).

As mentioned above, the size of an economic nuclear process plant influences the market potential. Previous discussions imply that the estimated market is based on the ability to provide nuclear units generating approximately 100 MW(t). Since the nuclear plant would undoubtedly also produce electricity, the above would imply nuclear units of approximately 300 MW(t) or more. Considerable activity is presently ongoing to develop modular GCR and LMR nuclear units of approximately 100 MW(e) capacity; the intent is to have several of these modules at a power plant site for electricity generation. If this approach is successful, one of the modules (or several of them so as to provide high process-heat availability), would be appropriate as a nuclear process heat unit, permitting a relatively large nuclear process heat market. The alternative would be to have large nuclear process heat units located at an energy park serving new industry located adjacent to the park.

Table 1 lists the commercial and/or residential sector as consuming 10.2 exajoules of energy in 1983. A portion of this energy could be provided by nuclear process heat, primarily that associated with district heating. Reference 8 reports a study for using about 1 GW(t) to power a hot water district heating system proposed for Minneapolis-St. Paul. On the basis that 30 similar areas could effectively use similar systems, a potential market of about 30 GW(t) is estimated. Any of the above reactor types could be used, so long as the distance for hot water transport is no more than about 20 km.

4. PROCESS HEAT FOR OIL RECOVERY, CHEMICALS PRODUCTION, AND SYNTHETIC FUELS

4.1 Resource Recovery

In the United States there are significant quantities of oil reserves in the heavy crude oils and in tar sands; further, the tar sands of Canada and the heavy crude oil of Venezuela represent very large oil reserves. Usable oil can be recovered by use of steam, the practical temperature of which depends upon several site conditions, with values ranging from approximately 200°C to 500°C. All the above nuclear reactor types would be appropriate at the lower temperatures, while GCRs and LMRs could produce the higher-temperature steam. Increased recovery of indigenous heavy crude oil (HCO) and initial oil production from some tar sands appears attractive now. In an evaluation[11] of the relative economics of synfuels in North America, Greene concluded that gas oil from tar sands (and hydrotreated shale oil) will be economically attractive refinery feedstocks in this decade. Various evaluations - primarily by GA Technologies Inc.[8] - indicate that the cost of suitable injection steam from GCRs is approximately 20% of that generated by firing a portion of the product oil and approximately 65% of that from coal-fired boilers.

Although there might be competition from LWRs for application to the shallower reserves, production of at least 160,000 barrels per day (bpd) of oil from United States tar sands using GCR injection steam appears highly likely by 2020-2025; for one field, this would require four 1170-MW(t) reactors. Based on California field parameters, four such reactors would produce approximately 140,000 bpd of HCO. An approximate maximum amount of nuclear process heat for resource recovery in the United States in the 2020-2025 time frame is estimated to be about 65 GW(t), corresponding to 10 tar sand plants and 4 HCO units. The most probable market potential is estimated to be about 30 GW(t). GCRs and LMRs could supply the entire market, while it estimated that LWRs and HWRs could supply about 10 GW(t) for United States conditions.

4.2 Chemicals Production

This category relates to use of GCRs for the steam reforming of natural gas, and processing the resultant synthesis gas to produce primary chemicals such as hydrogen, ammonia, and methanol; the other reactor types do not achieve high enough process temperatures for their use. Methanol can serve as feedstock for gasoline production and ammonia for fertilizers. In a study[12] of the relative economic attractiveness of GCR applications to fossil-fuel conversion processes, the steam reforming of natural gas to H_2 or methanol was found to rank first in terms of giving the largest financial present value associated with avoided feedstock cost. Use of GCRs is required because of the temperature required for the reforming process; however, significant materials development would be required to achieve satisfactory performance of GCR heat transfer and transport components.

The total United States industrial H_2 required in the year 2000 has been estimated based on information from references 13 and 14; the resulting consumption of H_2 in 2020 is estimated to be 6.6 exajoules (methanol and ammonia production are included in this estimate of H_2 consumption). The thermal power required to produce that much H_2 from the steam reforming of methane is 209 GW(t). On the basis that GCRs would supply 40% of that power, the GCR market would correspond to about 85 GW(t). (The remaining 60% would be shared between gas-fired reformers and coal partial-oxidation units.)

4.3 Synthetic Fuels Production

Forecasts of synfuels production in the free world in the year 2000 have been projected to be 2.5 million barrels per day (bpd) of liquids, and 3.3 million bpd including synthetic gas.[15] Projections have since trended steadily lower; however, there should be a sharp increase in energy needs beginning in the mid-1990s. For the period 2020-2025, it is estimated that the United States production rate will be 5 million bpd of synthetic fuels. This level corresponds to a potential market of 140 GW(t) for GCRs based on a product mix of half shale liquid and half coal gas. Assuming a 50% market share would require 70 GW(t). Both GCRs and LMRs could contribute to this market. The market per reactor type depends upon the fossil conversion process employed. Here it is assumed that half the market is satisfied by process temperatures up to 540°C and half by process temperatures up to 950°C. Under these conditions, LMRs could supply 35 GW(t) out of the 70 GW(t) market, while GCRs would supply all of the 70 GW(t) market.

5. SUMMARY

Nuclear reactors are potential sources for generating process heat, and their applications for such use economically competitive.[6-10] They help satisfy national needs by helping conserve and extend oil and natural gas resources thus reducing energy imports and easing future international energy concerns. Several reactor types can be utilized for generating nuclear process heat; those considered here are light water reactors (LWRs), heavy water reactors (HWRs), gas-cooled reactors (GCRs), and liquid metal reactors (LMRs). LWRs and HWRs can generate process heat up to 280°C, LMRs up to 540°C, and GCRs up to 950°C. Based on the studies considered here, the estimated process heat markets and the associated energy markets which would be supplied by the various reactor types are summarized in Table 3.

Table 1. Total U. S. Energy Consumption as a Function of Energy Source in 1983[1]
Fuel Source in Exajoules (10^{18} joules) [Quads (10^{15} Btu)]

Sector	Coal	Natural Gas	Petroleum	Nuclear	Other	Total
Electricity generation	13.9 [13.2]	3.2 [3.0]	1.7 [1.6]	3.4 [3.2]	4.2 [4.0]	26.4 [25.0]
Industrial*	2.6 [2.5]	7.1 [6.7]	8.1 [7.7]	--	--	17.8 [16.9]
Transportation*	--	0.6 [0.6]	19.4 [18.4]	--	--	20.1 [19.0]
Commercial/ residential	0.2 [0.2]	7.6 [7.2]	2.4 [2.3]	--	--	10.2 [9.7]
Total	16.7 [15.9]	18.5 [17.5]	31.6 [30.0]	3.4 [3.2]	4.2 [4.0]	74.5 [70.6]

*Exclusive of electricity generation by utilities

Table 2. Manufacturing Process Energy Requirements as Output of Boilers and Furnaces (1977 Data)[3,4]

TEMPERATURE °C	STEAM Exajoules	STEAM %	DIRECT HEAT Exajoules	DIRECT HEAT %	TOTAL Exajoules	TOTAL %
< 175	3.3	49	0.16	3	3.43	29
175-260	2.7	41	0.17	3	2.91	25
260-400	0.5	8	0.60	12	1.13	10
400-540	0.16	2	0.61	12	0.77	6
540-925	0	0	1.3	25	1.27	11
> 925	0	0	2.2	45	2.22	19
	6.7	100	5.0	100	11.7	100

STEAM, AS PERCENT OF TOTAL = 57%

DIRECT HEAT, AS PERCENT OF TOTAL = 43%

Table 3. Potential Process Heat Markets for Various Reactor Types

Market Category	Year of Market Penetration (Year of Potential)	Market Potential GW(t)
Process Steam (temp. < 260°C)	> 2000 (2020)	With present distribution: 75 for GCRs, LMRs; 35 for LMRs, HWRs With energy parks: 120 for all four reactor types
Process Heat [steam and direct heat] (260°C < temp < 540°C)	> 2000 (2020)	With present distribution: 20 for GCRs, LMRs With energy parks: 35 for GCRs, LMRs
District Heating	> 2000 (2020)	30 for all four reactor types
Resource Recovery	> 2000 (2020)	30 for GCRs, LMRs; 10 for LWRs, HWRs
Chemicals Production	> 2010 (2025)	85 for GCRs
Synthetic Fuels Production	> 2010 (2025)	70 for GCRs; 35 for LMRs
TOTAL POTENTIAL PROCESS HEAT MARKET		310-370

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