

NUCLEAR REACTORS FOR HIGH TEMPERATURE PROCESS HEAT;
A SURVEY OF REACTOR TYPES AND TEMPERATURE REGIMES

Donald P. MacMillan and J. Douglas Balcomb

Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87544

INTRODUCTION

The annual energy consumption of the US in 1970 was about 72×10^{15} Btu, and of this about 20% was used to furnish process heat. The term "Process Heat" is very commonly used in a narrow sense, referring to heat obtained from steam boilers at temperatures up to perhaps 230°C. In the following discussion, process heat will be taken to include heat supplied for process purposes up to the highest temperatures which material properties will permit.

The comparative economic attractiveness of nuclear energy as a source of process heat is likely to be subject to substantial alteration in coming years as the balance of energy sources changes in response to cost and availability. Indeed, it is clear from the large volume of literature published that interest in supplying process heat from nuclear sources is intense. However, the great bulk of this interest has to do with low temperature heat and in particular with desalination, usually combined in some way with electric power production. Another concept that has received considerable attention is typified by the Agro-Industrial Complex suggested by workers at ORNL. In such a complex, the nuclear reactor is used as a source of energy for chemical processing, but generally as electricity and not directly as thermal energy from the reactor.

It is evident, especially in the last few years, that there is growing interest in direct use of high temperature thermal energy from nuclear reactors as a source of process heat. This is especially true in Germany and Japan, and it is the opinion of some that we are at the threshold of economic feasibility of applications of nuclear energy as evidenced by the increasing consideration being given to solution of design and material problems.

The growing shortage of gas and oil in the US clearly points to the need for major emphasis to be placed on the gasification and liquefaction of coal. Most of the heat requirements of oil refineries for operations such as cracking and distillation are in the range of 300 to 550°C and could be met by adaptation of existing nuclear reactors although this will not be economically attractive until the price of petroleum products is higher. However, the use of nuclear heat to reduce consumption of coal as a source of energy in the gasification process has attracted interest. A key reaction in many of the processes being considered for that purpose is the endothermic reaction between C and H₂O to produce CO and H₂. The temperature required for this reaction is in the range of 1050-1150°C and the required heat is produced at the expense of coal. If the energy requirements for gasification were met by nuclear energy, the consumption of coal could be limited to supplying the carbon atoms required for the hydrocarbon synthesis. In view of the limitations of the world's coal and the huge rate of hydrocarbon consumption that exists, the saving could be very significant.

The distribution of manufacturing process heat among industry groups is shown qualitatively in Table 1. The four largest users account for about three fourths of the demand. The primary metals industry group is by far the greatest consumer

*Work done under the auspices of the U. S. Atomic Energy Commission.

TABLE 1

PROJECTED HEAT CONSUMPTION BY
U.S. MANUFACTURING INDUSTRIES IN 1967^a

Industry Group	Btu x 10 ¹⁵	% of Total
Primary Metals	4.678	32
Petroleum and Coal Products	3.522	24
Chemical and Allied Products	1.614	11
Stone, Clay, and Glass Products	1.256	9
Food and Kindred Products	0.907	6
Paper and Allied Products	0.656	5
Textile and Mill Products	0.227	2
All Other Industrial Groups	<u>1.692</u>	<u>11</u>
Total	14.552	100

^aAfter Tarrice (1)

of energy and the iron and steel industry dominates by using about 85% of the energy of the group. The technical problems of supplying nuclear heat directly in the iron and steel industry are typical of the problems of utilizing nuclear heat for chemical processing. The energy derived from the coke used in the blast furnace is about equally divided between that used to heat the ore, limestone and air blast, and that which acts as a reducing agent. Thus, supplying the needed heat from a nuclear source would decrease the coke requirement by up to a factor of two. This can be a consideration of growing importance because reserves of coal suitable for making high quality coke are becoming scarce and the price is bound to reflect the growing scarcity. The temperature required depends somewhat on the character of the feed materials but is about 900°C. As will be seen, this is well above the temperature that is available from power reactors in use today but is within reach of some reactor concepts that are under development.

A consideration of the greatest importance today in any use of nuclear energy is that little or no radioactivity be released into the environment. This rules out processes in which one or more of the reactants pass through a nuclear reactor. The most practicable design for process heat reactors therefore employs a heat transfer fluid contained in a closed loop, circulating through the reactor and passing heat to the process materials by a heat exchanger external to the reactor. In addition to confining fission products to the reactor, this approach has the added advantages of avoiding some chemical compatibility problems of reactor fuel elements and core materials with the process material to which heat is being delivered, and of keeping the processed material free of induced radioactivity. The addition of a second heat transfer system, however, does impose the penalty of increased differential between

fuel temperature and the temperature imparted to the process materials.

Not surprisingly, the feasibility of using low temperature process heat is dominated more by cost considerations than technical problems, while technical problems mount as the upper limits of reactor temperature are approached.

Water-Cooled Reactors

The major focus of power reactor development in the US has been on water-cooled reactors which rely almost entirely on slow neutron induced fission of ^{235}U . These may be divided into two main categories, the Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR). Numerous variations of these reactors have been made but, because the output temperature of all of them lies in a rather narrow range, the two main classes will be dealt with in general terms.

Following development of the PWR for submarine propulsion, the first commercial electric power plant was put in operation at Shippingport in 1957. This reactor was followed by many others which have incorporated improvements, mostly notably an increase in burn-up from about 8000 to about 33000 MWd/t. The fuel material is usually slightly enriched UO_2 ($\sim 3\%$ ^{235}U) clad in zircalloy or stainless steel which presents a barrier to escape of fission products. Problems which tend to limit the performance of PWR fuel include fuel swelling and fission gas pressure, irradiation effects on fuel and cladding, stress corrosion of stainless steel cladding and oxidation and hydriding of zircalloy cladding. The output temperature is modest, falling in the range 260° to 350°C , though pressures are high, up to 2500 psia to prevent boiling. Useful heat is extracted from the primary hot water coolant loop through a heat exchanger located inside the reactor containment vessel. In the usual case where electricity is desired, steam is generated in the heat exchanger and supplied to a turbine. If process heat were desired, the steam, usually at $\sim 260^\circ\text{C}$ and ~ 720 psi could be used to transport heat to the desired process. Alternatively, in some instances, it might be desirable to transfer heat directly from the primary pressurized water core coolant loop through a heat exchanger to one or more of the materials to be processed. Safety considerations would probably determine whether such direct heat transfer was acceptable or whether instead a secondary heat transfer loop between the primary heat exchanger and the desired heat sink was preferable.

The BWR power reactor prototype was built at Vallecitos and put in operation in 1957. The fuel material of reactors of this type is usually UO_2 with zircalloy cladding. The output saturated steam temperature is 250° to 300°C at steam pressure of about 1000 psia and burnup is of the order of 30,000 MWd/t.

For electric power generation, the steam produced in the reactor core goes to a turbine. If steam were desired for process purposes it might be used directly or, for greater safety against escape of fission products from the core, a heat exchanger could be interposed between the primary steam loop and the process heat sink.

There has been substantial interest in the possibility of superheating the steam produced by BWR reactors in order to increase the efficiency of turbine power generation. These efforts have resulted in output temperatures in the range 440° to 580°C , a very significant increase. However, the corrosion conditions to which the fuel cladding is subjected are more severe than in the basic PWR and BWR. Radiation damage, attack by oxygen from radiolysis and deposit of chlorides on the cladding occur, with the result that no fully satisfactory cladding has been adopted.

A variant of the water cooled reactor which has been the object of several experimental reactors is that of using an organic coolant. The principal compound used has been terphenyl, a cyclic hydrocarbon whose boiling point is 213°C at atmospheric pressure. The boiling point being greater than that of water, the possibility of significant superheating of steam is offered. Organic compounds

inevitably decompose under heat and irradiation, and though terphenyl decomposes slowly, provision for removal of decomposition products must be made. In addition, the thermal conductivity and heat transfer characteristics of coolants of this type are poor. The relatively non-corrosive character of the organic coolants has permitted more latitude in choice of fuel and cladding than in water cooled reactors, although magnesium and alloys undergo intergranular attack and iron is not satisfactory. The hydride forming metals, i.e., Zr, Nb and Ta, are contraindicated, but aluminum and stainless steels are not attacked. Both UO_2 and a uranium metal alloy have been used as fuels. Output temperatures have ranged from 250° to 375°C and 400°C is regarded as an upper limit set by coolant decomposition.

CO₂ Cooled Reactors

The British and French nuclear power reactor programs are based on CO₂ cooled, graphite moderated reactors using metallic natural uranium fuel with a magnesium alloy cladding, Magnox. This is a Mg alloy containing 0.8% Al, 0.008% Ca, 0.002%-0.05% Be, and 0.006% Fe. The British Calder Hall reactors began operation in 1956 and a total of about 35 such reactors have been built. Reactors of this type are conservative in design and have operated with very low fuel element failure rate. An inherent and important limitation is that the practical limit of reactor output temperature is about 500°C, because of oxidation of the cladding by CO₂. The core output temperatures of this and other types of reactor are compared⁽²⁾ in Fig. 1. Indeed, the melting point of the cladding is about 645°C and, in addition, uranium undergoes a phase change from α to the lower density β at about 665°C. Problems with the fuel have been mainly;

- a) irradiation induced creep of the uranium fuel at low temperature and thermal creep at higher temperature.
- b) Swelling of the uranium at high temperature because of agglomeration of fission gas bubbles.
- c) Deformation of high temperature parts by mechanical load because of proximity to melting temperature.

In 1963 the British Advanced Gas Reactor (AGR) at Windscale began operation. This is a higher temperature modification of the CO₂ gas cooled reactor leading to more efficient power generation. The fuel element temperature limitations of the Calder Hall reactor were significantly relieved by the substitution of UO₂ for uranium metal and of stainless steel cladding for the magnesium alloy. The stainless steel alloy, containing 20% Cr, 25% Ni, resists oxidation by CO₂. However, stainless steels and nickel alloys undergo loss of ductility as a result of neutron irradiation. The output gas temperature of this type of reactor has been in the range 500° to 575°C and burnup typically 10000 MWd/t. For electric power generation, heat is transferred through a heat exchanger to steam for turbine operation. If it were desired to use the output heat for process purposes, the considerations would resemble those applying to the PWR.

Na Cooled Moderated Reactors

The concept of a sodium-cooled graphite moderated reactor was explored in two reactors, the SRE being a reactor experiment and the Hallam reactor which was built to demonstrate feasibility of the concept for electric power generation. The output temperatures achieved were in the range 500° to 650°C.

The fuel elements tested were of several types all using 304 stainless steel cladding. The Hallam reactor used a fuel alloy consisting of somewhat enriched U and 10 wt% Mo with Na thermal bond to the cladding. This type of reactor has not been pursued further.

Breeder Reactors

Consideration of the need for and feasibility of supplying high temperature process heat in the years ahead must take into account what appear to be emerging as the important factors in the energy supply situation that we are moving into. In the relatively short term the decreasing availability and accompanying increase in price of oil and natural gas suggest looking to coal and nuclear energy. Two important factors not always clearly appreciated are: a) the limitations of coal supply if the burden of substituting for oil and gas is thrown on coal, and b) the limitations of the US' and the world's supplies of low cost uranium. The first factor suggests that a shift from oil and gas to coal should not be looked upon as a long term solution to the energy supply problem and that even with our best efforts the development of large scale nuclear and other energy sources is unlikely to occur before it is badly needed.

Let us consider the limitations of uranium supply, Table 2. The nuclear power reactors so far put into operation all derive roughly 2/3 of their energy from fission of ^{235}U , leaving nearly unused the 99.3% of the energy potential of uranium supplied by nature in the more abundant ^{238}U which does not fission significantly in moderated reactors. Figure 2 shows a projection of the consumption rate for ^{235}U in the US and the consequent rising price. Clearly, the depletion of cheaper uranium ores leads to rapidly rising cost of uranium even in the relatively near term. This problem has led to the large amount of effort expended over many years in the US and the world on development of breeder reactors to convert ^{238}U into the fissionable ^{239}Pu while delivering useful energy. The anticipated shift of the burden of power production from thermal reactors using ^{235}U to reactors of the breeder type is expected to reduce the price rise of uranium with time as shown in Fig. 2. Furthermore, the small amount of uranium used relative to the amount of energy released will render the cost of energy quite insensitive to the cost of uranium ore. Although fission of thorium does not occur easily, thorium can be converted in nuclear reactors into the readily fissionable ^{233}U as shown in Table 3. It is therefore important that the world's supply of thorium, although not accurately known, appears to be at least commensurate with the uranium supply. The conversion of ^{232}Th into ^{233}U takes place best with a neutron flux of thermal velocities and the high temperature gas cooled reactors (HTGR's) belong to this class of reactors. In reactors of this type, the partial conversion of ^{232}Th to ^{232}U results in high burn-up and reduces fuel cost.

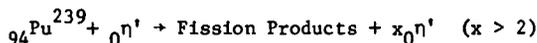
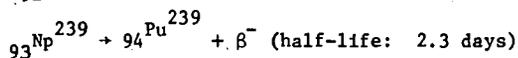
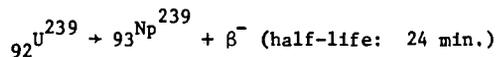
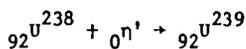
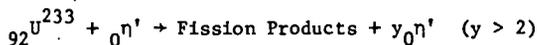
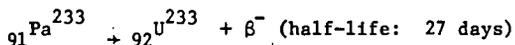
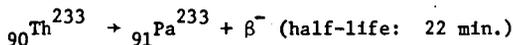
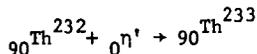
TABLE 2

<u>Price of Uranium Concentrates</u> <u>\$/pound U_3O_8</u>	<u>Tons of Uranium Resources</u> <u>at this or Lower Price^a</u>
8	594,000
10	940,000
15	1,450,000
30	2,240,000
50	10,000,000
100	25,000,000

^aAEC Report WASH 1098 (3)

The conversion of ^{238}U to ^{239}Pu does not take place to a large degree with thermal neutrons in highly moderated reactors such as are used for power production today but requires a fast neutron population, i.e., a fast reactor. Several types of breeder reactors are believed to be possible but all must have high burn-up, of the order of 10^5 MWd/t, in order to achieve low fuel cost. The most important types of breeder reactor are the liquid-metal cooled fast breeder reactor (LMFBR), the gas-cooled fast breeder reactor (GCFR), and the molten salt breeder reactor (MSBR).

TABLE 3

THE PRINCIPAL FUEL BREEDING REACTIONSUranium Breeding CycleThorium Breeding Cycle

The first two are Pu breeders and the last is a moderated reactor using the thorium breeding cycle. The first type is favored in the US and several experimental reactors have been built in this country and other countries, notably Russia, England, and France.

The breeder fuel generally contains initially about 85 wt% U and 15 wt% plutonium to provide a fissionable fuel for startup. A variety of fuel compositions has been considered, including metal alloys of U and Pu, as well as $\text{UO}_2\text{-PuO}_2$, UC-PuC and UN-PuN. Of these, $\text{UO}_2\text{-PuO}_2$ has been the principal choice, in part because of its high melting point and good compatibility with cladding and coolants, good fission product retention and relative tolerance of irradiation. Several cladding materials have been considered including mainly stainless steels as well as nickel alloys and zirconium alloys. If the reactor is operated at a useful power density, the low thermal conductivity of UO_2 results in approach to the melting point of UO_2 at the fuel element centerline and this limits reactor operating temperature. Carbide fuels have higher thermal conductivity and greater metal atom density and reactors using them would be expected to have shorter Pu doubling time. There is, however, less experience with high irradiation of carbide fuels than with oxide fuels.

Several experimental breeder reactors have been tested with output temperatures ranging from 320°C in the case of the EBR-1 to typically 400° to 600°C, Fig. 1. Some studies have been made which would lead to a somewhat higher output temperature of 650°C. The output temperature of Na cooled LMFBR's of the kind that are expected to come into use for power generation in the 80's is likely to be limited to this range. Presumably a later generation of breeder reactors might be adapted for the production of process heat. The Na coolant of the LMFBR is so strongly activated by neutrons that it would probably prove necessary to interpose a secondary Na loop between the

primary loop and the process heat sink. In fast reactors of the gas cooled type, the helium core coolant itself does not become radioactive from neutron bombardment. The radioactivity level of the coolant resulting from fission products leaking from the fuel and from activation of impurities in the gas might be kept low enough to permit transfer of heat directly to steam or to some material to be processed.

Gas Cooled Moderated Reactors

The high temperature gas-cooled type of reactor, HTGR, cooled by helium is pre-eminent by a wide margin as a potential source of high temperature process heat. The output temperature achieved extends upward from 750°C, for Peach Bottom and 785°C for Ft. St. Vrain, both intended for electric power generation, to 1300°C for the ultra high temperature reactor experiment (UHTREX), Fig. 1. Hot helium at ~ 750°C, passing through a heat exchanger, will generate steam at the highest temperature and pressure that a modern steam turbine-electric generating plant can use. If it is desired to use the heat from the HTGR for process purposes, then a choice exists between a) interposing a secondary heat transfer loop between the primary heat exchanger and the desired heat sink and b) circulating one or more of the process materials directly through the primary heat exchanger. In general, the higher the operating temperature level the more stringent the limitations on choice of materials of construction and for temperatures in excess of ~ 750°C the cost of these materials becomes of increasing importance. The potential for process heat applications in this regime are just beginning to be explored.

This type of thermal neutron reactor employs graphite as moderator and a graphite fuel element with fissionable fuel particles dispersed in it. Use of the chemically inert helium as coolant avoids problems of chemical reaction of coolant with fuel and to a large extent with structural materials in the core. The comparative absence of neutron absorbers in the core, which essentially contains only fuel and moderator, permits high specific power and very high burnup. The burnup in reactors of this class, 10⁵ MWD/t in the case of Ft. St. Vrain, promises fuel economy.

The fuel elements are based on the thorium to ²³³U conversion cycle, with ²³⁵U present as the start-up fuel. Substantial conversion helps to achieve the highest degree of fuel utilization and lowest power cost of any thermal neutron reactor system.

With variations of detailed structure, the fuel elements of HTGR's are based on the use of coated fuel particles contained in graphite. A great deal of effort has been expended in developing particle coatings and measuring their performance. The basic reason for coating the fuel is to impede the release of fission products to the coolant gas stream. Although at the highest operating temperatures it is not possible to completely retain fission products, the ratio of fission product atoms released to those born has been improved a great deal. The particles used in the Ft. St. Vrain reactor are called TRISO particles.⁽⁴⁾ The core of a fissile particle is about 200 μm in diameter and consists of (Th,U)C₂ in an atom ratio of 4.25 Th to 1 U. It is covered first with a low density layer of pyrocarbon about 50 μm thick which provides void volume to accommodate gaseous fission products, furnishes a cushion to allow for thermal expansion mismatch of core and coating, and protects the outer layers of coating substantially from damage by recoiling fission fragments. A 20 μm layer of higher density isotropic pyrocarbon greatly slows the release of iodine, tellurium and noble gas fission products. A third layer of pyrolytically deposited SiC about 20 μm thick acts as a very effective diffusion barrier, greatly improving the retention of metal fission products, notably Cs, Ba and Sr. The coating is completed by an outer layer of isotropic pyrocarbon about 20 μm in thickness. Fertile particles for this reactor contain 400 μm diameter cores of ThC₂ with the same coatings as fuel particles.

Several ways of exploiting the improved retention of fission products are open. In reactors designed to operate at temperatures below $\sim 1300^{\circ}\text{C}$ where fission product leakage is very small, fission product cleanup in the circulating coolant may be minimized. Alternatively, advantage may be taken of the good fission product retention to facilitate operation at higher temperature without incurring the need for an extensive gas cleanup system.

The Ultra High Temperature Reactor Experiment (UHTREX) yielded an output gas temperature of 1300°C which is several hundred degrees higher than any other reactor of the HTGR type, Fig. 1. The purpose of the reactor was to demonstrate the capability of this type of reactor for producing power and high temperature process heat. The fuel elements were unclad graphite containing coated UC_2 particles. This reactor had the unique capability of permitting refueling without interruption of full power operation. There was some fission product escape from the fuel and this was continuously removed by a coolant gas purification system. The UHTREX project was terminated in 1970 because of stringent budget limitations.

The Rover project for developing a nuclear powered rocket engine pointed a way toward a type of very high powered density gas-cooled reactor capable of still higher output temperature. These reactors were intended to heat high pressure hydrogen to as high temperature as feasible before allowing it to expand through a de Laval nozzle to produce thrust. Operating temperatures of 2300 to 2500°C were achieved in reactor tests. The operating duration required was from 1 to 10 h depending upon the choice of mission. The funding of this project was terminated in early 1973. Reactor lifetime increases extremely fast with decrease in temperature and this suggests the capability of such a reactor to operate for a year or more at substantially higher temperatures than HTGR's. The fuel used in the last Rover reactor tested was a composite of graphite and uranium-zirconium carbide solid-solution with thin zirconium carbide coating to restrain corrosion by the hydrogen but no attempt was made to contain fission products and in fact substantial release occurred. Some experimental fuel elements consisting solely of uranium zirconium carbide, substoichiometric in carbon, were also evaluated for possible use at higher temperatures and longer life. If fission product retention in the fuel is a requirement, these carbide and carbide-graphite composite fuels are not well suited for use in a process heat reactor. Coated fuel particle loaded graphite fuels, such as would be suitable for a process heat reactor, were also successfully tested in Rover reactors up to temperatures of 2300°C for a duration of one hour. As in the case of UHTREX, there was substantial fission product escape from the fuel.

Economic Considerations

The large growth of the nuclear reactor industry, which has taken place despite the problems and delays of licensing, siting, construction, and financing, is due to the highly favorable economic position of nuclear power today. Nuclear fuel costs are very low (roughly the same as coal in the Four Corners area of New Mexico on an equal Btu basis) and this is the primary justification for the nuclear industry. Furthermore, current projections of fuel costs suggest that the advantage of nuclear power will increase in the future. Nuclear plants are somewhat more costly to build than other central station electrical generating stations, but not enough so to overcome their advantageous economic position. Since the annual fixed charge for capital is held constant, once a plant is built, the economic position of a nuclear reactor improves with time (in a climate of escalating fuel costs) relative to other systems with a lower fractional capitalization.

Since nuclear reactors have only been built for central station electrical power use, we can only meaningfully compare their cost with that of similar fossil fueled plants. This is done in the following table which lists capital costs (exclusive of escalation, allowance for funds during construction, contingency, taxes and utility adders) for various plants assuming startup in 1981:

	<u>Nuclear (LWR)</u>	<u>Oil</u>	<u>Coal*</u>
Capital cost, \$/kw _e	305	177	270
Capital cost, \$/kw _t	99	71	108

*with SO₂ scrubbers.

It is difficult to separate the fraction of the cost of these plants which can be charged to the nuclear reactor and its associated shielding, building, refueling equipment, electrical equipment, piping and mechanical systems (the "nuclear island"). One detailed estimate studied indicates that the fraction of the total cost attributable to this is roughly 40%. On this basis, a rough estimate of the cost of nuclear heat would be 40 dollars/kw (thermal). Addition of escalation (5% for equipment, 3% for materials, 8% for labor), allowance for funds during construction (AFDC, 8%/year), use and sales taxes, and utility cost adders (startup, licensing, training, property taxes, administration, consultants, insurance, general plant and spares, engineering, land, relocation and utilities) will bring this total up to roughly 80 dollars/kw (thermal) for a typical 8.6 year phased construction schedule. If one assumes a 16% annual fixed charge rate and a 0.85 utilization factor, the net cost of energy attributable only to the cost of capital, is roughly 50 cents/million Btu for a nuclear plant.

The projected cost of fuel in the future is as follows: (cents/million Btu).

	<u>Nuclear (LWR)</u>	<u>Oil</u>	<u>Coal (Northeast U.S.)</u>
(1973)	17	75	45
1985	27	163	91
1995	38	272	140
15 year levelized (1981-1996)	30	189	99

These comparisons indicate that nuclear heat will be an increasingly good buy in the future. The values listed for nuclear heat are based on light water reactors (PWR's and BWR's) which are the only types of reactors for which experience is available. Projections for HTGR capital plant costs are slightly higher (20%) than for LWR's, on an equal Btu basis, although the higher temperature may make the heat more valuable for some applications. The projected HTGR fuel cycle costs are roughly equal, on an equal Btu basis, to those of the LWR. Lack of experience in fuel fabrication and reprocessing creates some uncertainty in the estimates.

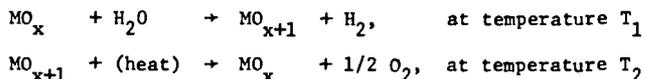
The Question of Plant Size

The foregoing economic values are based on a plant that generates ~ 3600 Mwt. While fuel cycle costs are roughly independent of plant size, the capital cost varies roughly as the plant size to the 0.42 power. Thus one is led to very large reactor sizes because of economic considerations. The AEC currently limits the size to 3600 Mwt until more experience is gained, however even larger sizes may come in the future. Few process heat applications lend themselves to such large size units and smaller units will certainly incur a cost penalty.

Hydrogen as an Energy Distribution Medium

One approach to the problem of reactor plant size which seems attractive is to convert the nuclear energy to a more suitable, transportable and convenient form and

then distribute this go-between energy to its multitudinous end users. Hydrogen is a very attractive medium to consider for this distribution system. It has a high heat content, is readily available (in H₂O), easily transportable, and ecologically attractive. It can readily be used in various industries such as ammonia synthesis, plywood drying, glass making, coal hydrogasification, metal ore reduction, petroleum refining, as well as for primary heating. The central problem is how best to make use of heat energy from a nuclear reactor for the decomposition of water. Although the indirect electrical generation/electrolysis route is technically feasible it is inefficient (28% presently, 40% ultimately may be possible). A more attractive approach from the thermodynamic viewpoint is the use of a dual temperature thermochemical cycle shown schematically by: (M stands for metal or compound and, in fact, four or more actual reactions may be necessary.)



The maximum cyclic efficiency of this process, from H₂O back to H₂O, is given simply by the Carnot relation, $(T_2 - T_1)/T_2$. The advantage of a process using a high temperature heat source is evident. If suitable reactants can be found in the temperature range of 1000°C to 1300°C, and if 80% of Carnot efficiency can be realized, then an efficiency of 60 to 65% will be achievable. These are two big ifs, but the incentive is sufficient to warrant a thorough search.

References:

1. R. R. TARRICE, "Nuclear Energy for Industrial Heat," A. Conf. 15/P/443, Second U.N. International Conference on Peaceful Uses of Atomic Energy (1958).
2. M. T. SIMNAD, Fuel Element Experience in Nuclear Power Reactors, Gordon and Breach Science Publishers, New York (1971).
3. "Potential Nuclear Power Growth Patterns," U.S. Atomic Energy Commission, Report WASH-1098 (Dec. 1970).
4. "Summary Report on the use of TRISO-Coated Particles in the PSC Reactor Plant", USAEC Report GA-8467, January 1968.

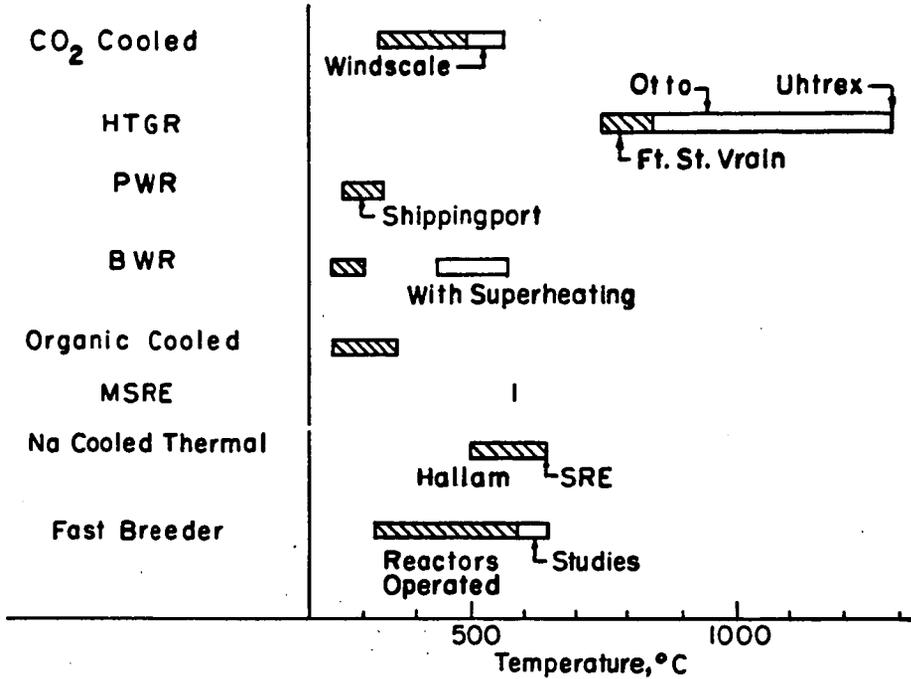


Fig.1 Output Temperature From Core of Various Types of Reactor

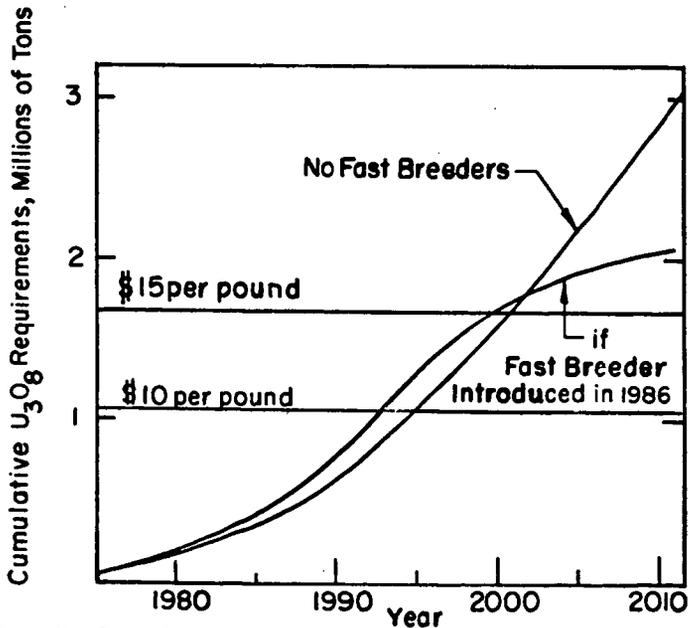


Fig.2 U.S. Cumulative Uranium Requirements