Energy from breeder reactors

Reactors that consume relatively abundant uranium ores while generating more of an expensive "catalyst" than they use will be our answer to growing energy demands over the next fifty years.

Floyd L. Culler, Jr and William O. Harms

FFTF. Section of core in a mock-up of the Fast Flux Test Facility, a liquid-metal fast breeder reactor being built at the Hanford Engineering Development Laboratory in Richland, Washington.

Within the next 30 years we will call upon our resources and technology to supply more energy than has been consumed throughout all history. Population pressures, the necessity for increased living standards in the underdeveloped nations, the demands of material affluence in the technological societies, the need to improve management of our dwindling natural resources and to protect our environment will force energy demand to unprecedented levels.

Here we shall discuss estimates of the electrical-energy demand in the US over the next 50 years. According to educated assessments, such as those presented recently by Chauncey Starr,[1] our fossil-fuel reserves (if we limit use to those reserves recoverable at about twice the current costs) are only about twice as high as the cumulative demand projected for the year 2000. From a longer-range point of view, we are faced with the certainty that most of our fossil fuels will be exhausted in a few generations at best. Because of these prospects, we are turning to alternative energy sources.

Of the known energy sources, only nuclear energy from fission is technologically developed sufficiently to justify its exploitation. Within the last decade, nuclear energy has developed from a promising energy source into a principal producer of electricity. As we shall see, however, fission as now carried out in commercial nuclear reactors, which are all of a type known as converters, would soon use up the available nuclear fuel resources. Only if breeder reactors are perfected can we expect to utilize the essentially inexhaustible supply of energy that exists in reasonably assured, economical quantities.

In looking at the case for fission breeders we shall consider the technology and economics of existing and planned fission reactors, converters as well as breeders, and we shall discuss briefly some of the limitations of fission breeders.

Reactions in breeders

A fission breeder reactor is a kind of catalytic nuclear burner in which relatively inexpensive, naturally occurring U^{238} or Th^{232} is burned in such a way that the expensive Pu^{239} or U^{233} catalyst is more than self regenerated.[2] (This excess regeneration of Pu^{239} or U^{233}, in fact, will permit future operation of

Floyd L. Culler, Jr is deputy director of the Oak Ridge National Laboratory, Tennessee, and William O. Harms is Manager of the Liquid Metal Fast Breeder Reactor Program at Oak Ridge.

additional plutonium-fueled or uranium-fueled reactors.) In a conventional converter reactor, by contrast, the rare isotope U^{235} must be separated out from the U^{238} for fuel. The two-step process in a fast-neutron reactor (fission energy 10-1000 keV) that burns U^{238} is

$$Pu^{239} + n^1 \rightarrow Q + \eta n^1 + \text{fission products}$$

$$(\eta - 1)n^1 + (\eta - 1)U^{238} \rightarrow (\eta - 1)Pu^{239}$$

where Q is the energy released and η is the number of neutrons produced per fissile atom destroyed. The overall process, then, is

$$(\eta - 1)U^{238} \rightarrow Q + (\eta - 2)Pu^{239} + \text{fission products}$$

For a breeder reactor, η is greater than two, and we see that the catalyst is more than self-regenerated. The amount of self-regeneration clearly depends on the amount by which η exceeds two.

In thermal neutron reactors (fission energies less than 0.1eV), which burn Th^{232}, the processes are similar, although U^{233} replaces Pu^{239} as the catalyst. Such reactors may be either breeders or converters. The controlled thermonuclear breeder is actually another kind of catalytic nuclear burner; in this concept tritium catalyzes the burning of deuterium and Li^6.

In any potential breeder system, the important parameter is $\eta\epsilon$, where ϵ, the "fast effect," is the ratio of total neutrons produced from all reactions to those produced from the fission of fissile nuclides (those nuclides, such as U^{233}, U^{235} and Pu^{239}, that undergo fission at all energies). In all fission reactors, some so-called "fertile" nuclides (U^{238} and Th^{232}, for example) are converted to fissile nuclides; the conversion ratio CR is the ratio of fertile captures to fissile absorptions and indicates the effectiveness of this process. The maximum possible conversion ratio is $\eta\epsilon - 1$, but, because of the losses L from, for example, leakage and parasitic absorption,

$$\text{CR} = \eta\epsilon - 1 - L$$

For a fission breeder, CR must be greater than one and $\eta\epsilon$ must be sufficiently greater than two to assure that this is so. CR is then the "breeding ratio."

We gain some insight into the breeding potential of the two basic types of fission breeders—fast and thermal—by comparing the neutron budgets at equilibrium shown in Table 1.[3] (Our analysis here is limited to the reactors in the US AEC program. Further on, we shall briefly review other breeder reactors, some of which are in or near operation.) Here we have representative examples of a liquid-metal fast-breeder reactor (LMFBR) and a molten-salt breeder reactor (MSBR), each producing 1000 MW of electrical power. The advantage of fast breeders in terms of $\eta\epsilon$ is apparent. The principal reason for this advantage is that in the fast-reactor spectrum about twenty percent of the fissions are associated with fertile nuclides; for thermal reactors based on the Th^{232}–U^{233} cycle these fissions are less than 0.5% of the total. In terms of our definition, L in this particular fast breeder is 0.53, which is the sum of the last four entries under "Absorptions" (0.31) plus an amount (0.22) to account for those absorptions in fertile nuclides that result in fission rather than in production of more fissile nuclides. (These fission "losses" are, of course, beneficial to the overall breeding performance, because they result in fission of the more abundant fertile material instead of the less abundant fissile material.)

Conservation and economics

Before we can decide whether or not we need breeders, we should examine the projected total electrical-energy needs in the US and the projected nuclear portion of the total. We see in figure 1 that, according to these estimates,[4,5] a very large fraction of the projected total installed capacity must be nuclear to provide the needed energy. Now, whether or not power plants based on nuclear fission can reasonably be expected to fill the role projected for them depends not only on whether they can do it *at all*, given our known and estimated uranium and thorium reserves: Nuclear power plants must also be able to provide the energy *economically*. Figure 2, a plot of cumulative uranium requirements as a function of time for the years 1970–2030, puts these considerations into perspective.[6-8] We have assumed, in this analysis of several fission-reactor types, that the installed nuclear capacity in the US would reach 140 GW(e) in 1980, 930 GW(e) in 2000 and expand at the rate 100 GW(e) per year afterwards. Breeders are first introduced in 1980, and only breeders are installed after 2000.

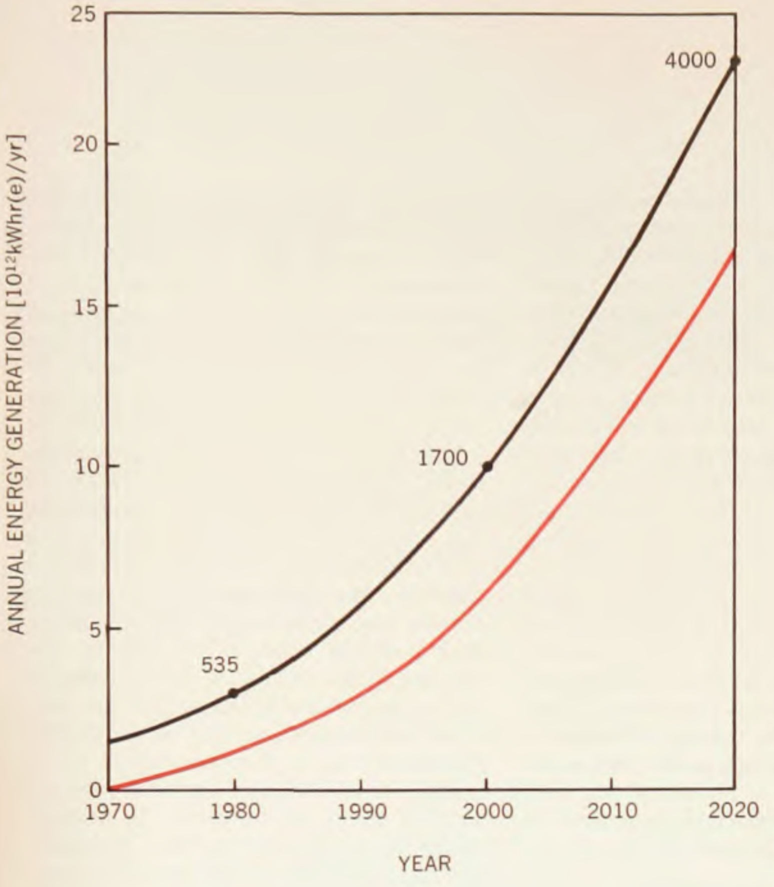
The effect of timely introduction of fission breeders is seen rather dramatically in the figure. Note that, in a power economy based strictly on light water reactors (LWR's), for which CR is about 0.6, exorbitantly high-cost ore would be needed shortly after the turn of the century, and the situation would continue to worsen with no relief in sight. High-temperature gas-cooled reactors (HTGR's), for which CR is about 0.8, would give a slightly improved but essentially similar result. (The more ore we need, the harder and therefore more expensive it is to come by. The estimated U_3O_8 fuel costs shown here[7,8] assume that about 0.36 million tons of U_3O_8 at no more than $10 per pound are reasonably assured, and our estimate of the reserves at $10–$15 per pound probably is conservative.)

The breeder reactors, on the other hand, level off our uranium needs at some point in time and at some finite U_3O_8 fuel cost; the particular time and cost at which this levelling occurs depends on the indicated breeder performance parameters—specific inventory and doubling time. The specific inventory is the amount of fissile material tied up in and out of the reactor per unit of electrical power generation; the doubling time is the number of years needed to double the entire fissile inventory of all the reactors. If, instead of the linear growth we have assumed, the installed US nuclear power capacity grows exponentially after the year 2000, the cumulative U_3O_8 needs would level off only if the doubling time of the reactor were less than the long-term doubling time of the power economy.

What we have seen graphically in figure 2 is that breeder reactors, because of their inherently efficient use of the ore, are only slightly affected by the cost of uranium. After taking into account the losses resulting from a large number of fuel recycles, as much as 70% of the energy in natural uranium is recoverable by high-performance fission breeders (compared with less than 2% for LWR's). On this basis, the energy released from one pound of uranium could be comparable to that released from 1000 tons of coal. With good fission breeding, the fuel supply becomes virtually unlimited.

Using the same study of our fuel reserves as we used in figure 2, we can estimate the effect of large-scale introduction of LMFBR's in 1968 on U_3O_8 requirements and on the demand for separating U^{235} from natural uranium (see Table 2).[9] According to this study, the US will be using uranium at $50 per pound by the year 2020 without LMFBR's, whereas with LMFBR's the cost will not exceed $30 per pound. For the present commercial LWR's, increasing the cost of U_3O_8 from $10 to $50 per pound would add about 1.25 mills per kWhr(e) to the fuel cost, nearly doubling present fuel costs. Fuel costs for the LMFBR would, as we have noted, be essentially insensitive to ore costs.

What can we say about the thorium reserves needed for a power economy based on thermal converters, or on a ther-



Estimated energy requirements in the US. According to recent studies, a large fraction of the total energy generated each year (black curve) must be nuclear (colored curve) to provide the needed power. The study projects that the total installed capacity must be 535 GW(e) in 1980, 1700 GW(e) twenty years later and 4000 GW(e) by the year 2020.
Figure 1

mal-converter breeder combination? Current estimates place the US thorium reserves that are recoverable at \$8 per pound of ThO_2 at about 100 000 tons, and we probably have an additional 400 000 tons in known favorable environments.[10] These estimated reserves, along with known thorium reserves outside the US, are large when compared with our anticipated needs, and we have excellent prospects for the development of any needed additional resources.

How the reactors perform

Before we go on to look at breeder reactors, let us consider some of the nonbreeders. In Table 3 we see some important performance parameters for representative 1000-MW(e) thermal converters (CR less than 1). Note that CR is about 0.6 for LWR's, which are based on the U^{238}–Pu^{239} fuel cycle, whereas for the high-temperature gas-cooled reactor, based on the Th^{232}–U^{233} fuel cycle, CR is about 0.8. The thermal-to-electrical conversion efficiencies listed have an importance beyond economics: LWR's without proper cooling towers or ponds have been criticized because of the relatively large amounts of waste heat produced. By comparison, the HTGR's and LMFBR's are much better because of the higher steam conditions that are possible in these systems, and their efficiencies are as good as or better than those of modern coal-fired steam plants, which have efficiencies of about 39%. Table 4 (courtesy of Leonard Bennett, ORNL) lists the status of thermal converters in the US, as of 1 January. The heading "LWR" includes both boiling-water reactors and pressurized-water reactors. We can see that, associating \$300 with each electrical kilowatt-hour, nuclear power is already a big business in the US.

How do the existing thermal converters work? In the boiling-water reactor, the reactor itself is the steam generator, so that only one loop is involved. The water and resultant steam are forced through an assembly of metal-clad, slightly enriched UO_2 fuel elements by very large (19-foot) jet pumps and heated to about 275 deg C at a pressure of 1000 pounds per square inch to provide the energy to drive the turbine generator. BWR's must be quite large; a 500-MW(e) unit, for example, needs a vessel about 19 feet in diameter and about 60 feet high.[11]

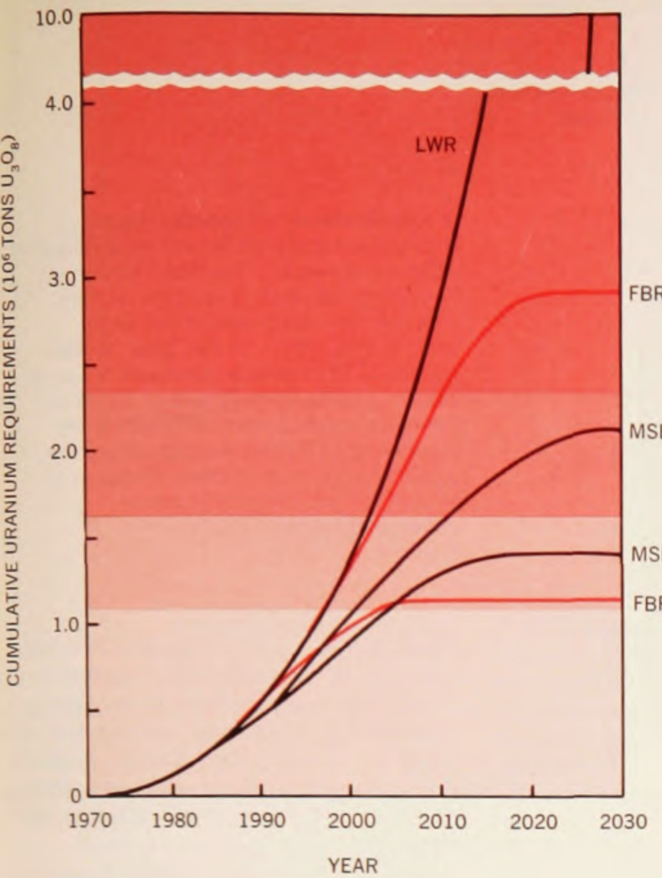
The coolant-system pressure in a pressurized-water reactor is kept at about 2000 psi, so that the water can be heated to nearly 300 deg C without boiling. This water is then piped to the steam generator, where it transfers its heat to the water in a second loop, which is kept at a much lower pressure, and produces steam to drive the turbine. The volume of the pressure vessel for a 500-MW(e) pressurized-water reactor is about one third that of an equivalent-power boiling-water reactor.

The HTGR is based on the thorium cycle, with helium as the coolant gas. Primarily because no metal is used in the structure or fuel cladding in the all-graphite HTGR core, more efficient fuel use and higher temperatures can be achieved than in LWR's. The HTGR concept[12] has been under development for about 15 years in the US; a 40-MW(e) prototype plant has been operating since 1967, and a 330-MW(e) demonstration plant is scheduled for completion this year. As we see in Table 4, four large systems are scheduled for 1978.

Breeder reactors

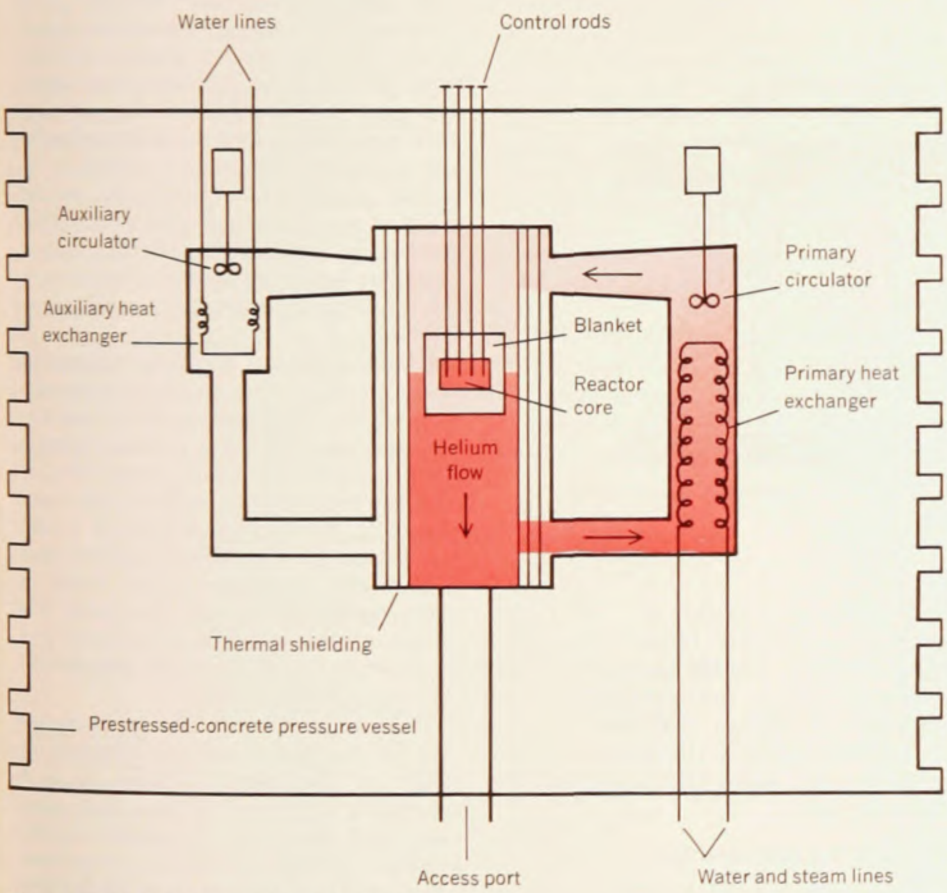
In what ways do the breeders improve on the converters? In Table 5 we see performance parameters for typical 1000-MW(e) fission breeder reactors. Note particularly the specific inventories and doubling times, and the conservation coefficients (defined here as the reciprocal of the product of the other two parameters). For a power economy growing at a linear rate, the conservation coefficient is inversely proportional to the total U_3O_8 needed to obtain a surplus of fissile fuel, or, in other words, to reach the leveling-off point for the breeder curves in figure 2. We shall consider three breeder-reactor types: the molten-salt (thermal) breeder reactor, the gas-cooled fast breeder reactor and the liquid-metal fast breeder reactor. A breeder concept known as the "light-water breeder reactor" (LWBR), based on the thorium cycle, is also under development in the US. See reference 13 for a brief description.

In the molten-salt breeder reactor, liquid Li^7F–BeF_2 containing dissolved Th^{232} and U^{233} circulates through a graphite matrix. The fuel salt, in this design,[14] serves also as a blanket in the



	Doubling time (yr)	Specific inventory [kg fissile/MW(e)]	Breeding ratio
FBR	15	5.0	1.35
MSBR	21	1.5	1.06
MSBR	10	0.7	1.07
FBR	5	3.0	1.63

Effect of breeder reactors on ore needs. With LWR's only, uranium-ore needs will be so high that the cost of U_3O_8 will have risen to \$30–50 per pound (darkest-colored band) by about the year 2007 from the present \$5–10 per pound (lightest-colored band; intermediate bands are \$10–15 and \$15–30 per pound.) If breeder reactors are introduced in the mid-1980's, and only breeders are built after 2000, then ore needs and costs can be held down at a level that depends on the performance parameters of the particular reactor (see table at right of graph). For the FBR with a doubling time of five years, for example, costs would level off at the lower end of the \$10–15 per pound range, whereas for the MSBR described in Table 1 (doubling time 21 years), costs would level off at the higher end of the \$15–30 range. Figure 2

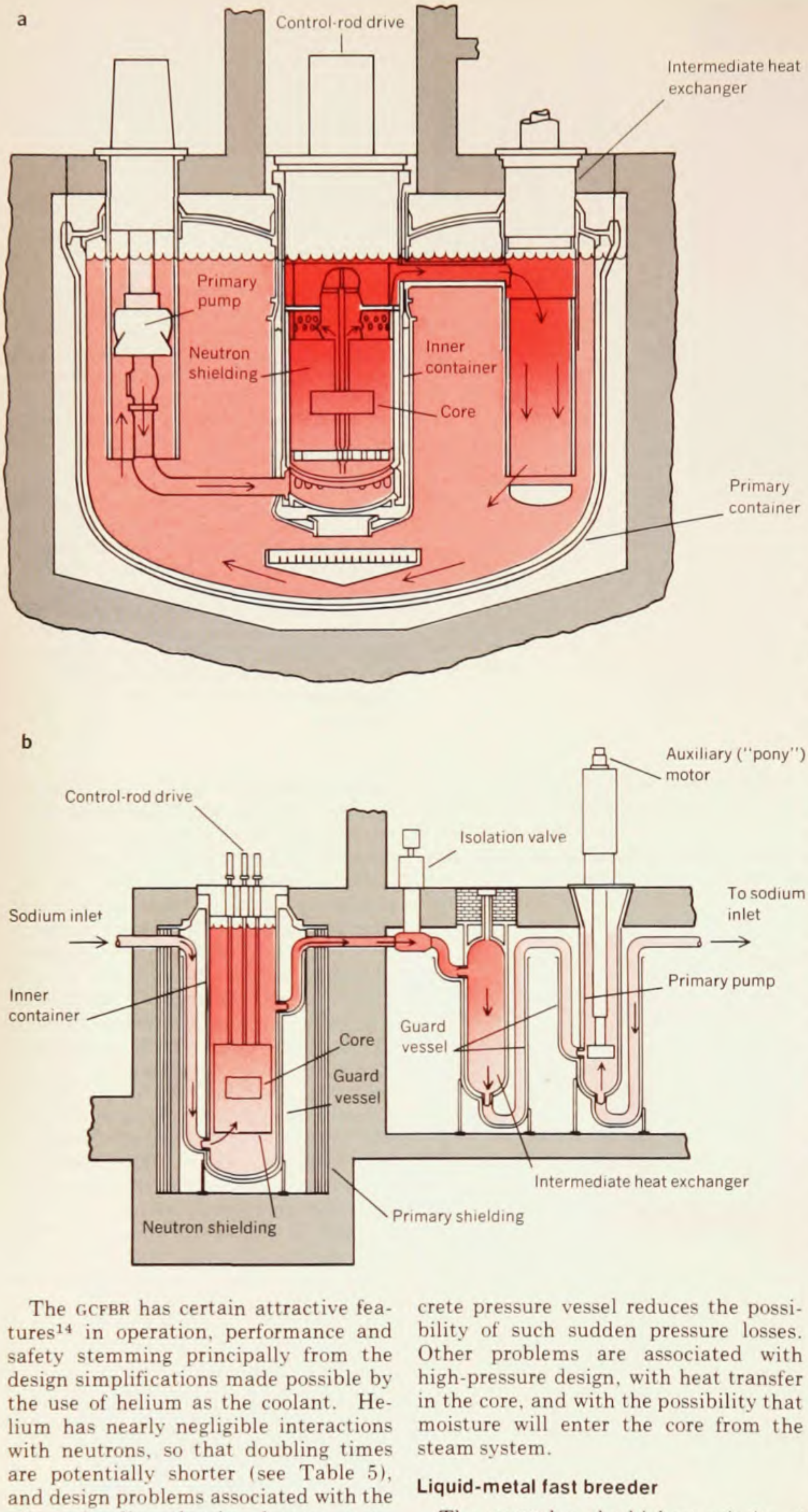


Gas-cooled fast breeder reactor (GCFBR). This cross-sectional view is of the 300-MW(e) demonstration model, whose vessel and components design is to be based on the high-temperature gas-cooled reactor. The prestressed-concrete reactor vessel is about 84 feet in diameter and about 71 feet high; the core itself is about 3 feet high. Figure 3

under-moderated region surrounding the core. Xenon, which is a particularly objectionable fission product, is sparged from the salt, and the rare earths, plus some other fission products, are removed by an on-line processing plant that also holds up Pa^{233} until it decays to U^{233}. This system can generate supercritical steam at 550 deg C.

An obvious advantage of the MSBR is that, with its fluid fuel and built-in chemical processing plant, no fuel elements need be refabricated, so that no spent fuel elements need be shipped to reprocessing plants. Balancing this advantage, however, is the disadvantage that radioactivity in the MSBR is spread over the entire circulating system, and remote maintenance, although feasible, is quite difficult. A 7.3-MW (thermal) molten-salt reactor experiment operated in the US for nearly five years; at present there are no active plans to build a large MSBR.

Development of the gas-cooled fast breeder reactor has been underway since 1961, principally under private sponsorship. Now the efforts are directed toward a 300-MW(e) demonstration plant; figure 3 is a cutaway view of the design of this plant,[15] which incorporates existing technology developed for HTGR components. It is also based on the projected development of LMFBR fuel-pins of mixed uranium- and plutonium-oxide pellets clad with stainless steel and assembled in hexagonal stainless-steel cans. The reactor core region seen in figure 3 is about ten feet high; the core itself is about three feet high.



In a liquid-metal fast breeder reactor *(LMFBR) the components can be arranged in* either of two ways. The "pot" system (a) has the reactor core and all the primary heat-transfer equipment in one large, sodium-filled tank. In the "pipe" system (b), the reactor core is contained in a small vessel, and the primary sodium is pumped through the vessel and then piped to the intermediate heat exchangers, which are outside the reactor. (These diagrams do not include the secondary, steam-generating systems.).
Figure 4

The GCFBR has certain attractive features[14] in operation, performance and safety stemming principally from the design simplifications made possible by the use of helium as the coolant. Helium has nearly negligible interactions with neutrons, so that doubling times are potentially shorter (see Table 5), and design problems associated with the effect of sodium-density changes on reactivity are avoided. Cooling with helium also reduces corrosion problems, permits visibility during refueling and maintenance and reduces thermal shock. But, in the GCFBR, sudden loss of coolant pressure must be guarded against, because it would create heat-removal problems; a prestressed-concrete pressure vessel reduces the possibility of such sudden pressure losses. Other problems are associated with high-pressure design, with heat transfer in the core, and with the possibility that moisture will enter the core from the steam system.

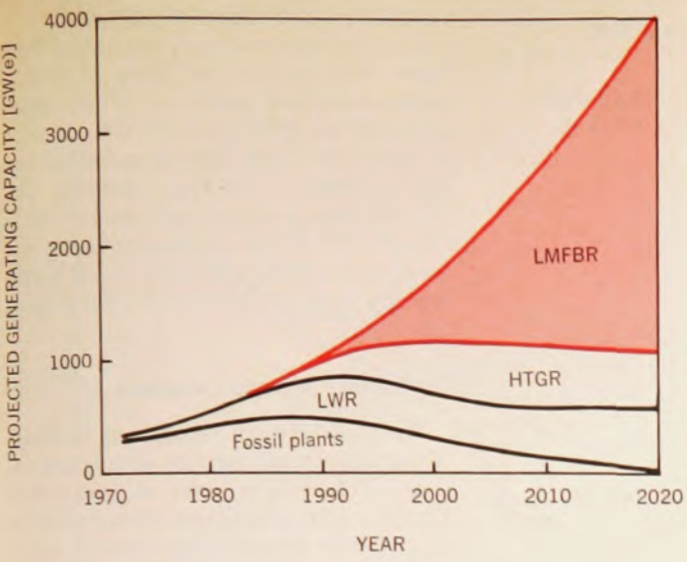
Liquid-metal fast breeder

The LMFBR has the highest priority of any fission breeder program both in the US and in other countries. (For a reasonably up-to-date review of LMFBR programs throughout the world, see the *Proceedings* of the September 1971 Geneva Conference on the Peaceful Uses of Atomic Energy.) In his June 1971 "energy message," President Nixon made a clear and explicit commitment to the LMFBR as a prime national goal. As Table 6 shows, there is considerable experience and interest in LMFBR's: Twenty-two LMFBR projects now exist world wide—eight are operable, four are being built and ten are planned.

Liquid sodium is the favored coolant for fast breeders. Sodium does have some disadvantages; for example, it is chemically reactive and becomes radioactive when exposed to nuclear irradiation. But it is an excellent heat-transfer agent; its 895 deg C boiling point permits high-temperature and low-pressure operation and allows the system to be cooled by natural circulation in the event of an emergency shutdown. This circulation advantage affords reactor designers a marked degree of freedom in the planning of emergency core-cooling systems.

Because sodium becomes radioactive in the primary system, an intermediate loop with a sodium-to-sodium heat exchanger (the "IHX") is needed between the primary-coolant and steam circuits. And the reactivity of sodium with water makes it necessary to develop steam generators for commercial plants that will either eliminate direct leaks of water into sodium or minimize the effects. Substantial developmental and engineering efforts are in progess on these steam generators.

The components in the primary system of an LMFBR can be arranged in either of two ways. Figure 4a is a schematic diagram of the "pot" system, and figure 4b shows the "pipe" system. In the pot system, a large tank filled with sodium contains all the primary heat-transfer equipment, including the intermediate heat exchangers. This arrangement ensures that the reactor core would not become uncovered in the primary system if leaks or ruptures occurred. Because of the inherent "core submergence" feature, most of the earlier, and to some extent present, de-



Projected generating capacity in US for the next 50 years. Based on the assumptions used here, the LMFBR replaces the HTGR as it enters the power system, and dominates after the turn of the century.
Figure 5

signs for large LMFBR's, particularly outside the US, have used the pot concept. (The USSR has gone both ways; the BN-350 is pipe and the BN-600 is pot.) The pot system also has a large thermal inertia, minimizing the effects of thermal transients in the primary system.

In the pipe system (see figure 4b) the reactor core is contained in a small vessel, the primary sodium is pumped through the vessel and then, by way of piping, to the intermediate heat exchangers that are located in vaults outside the reactor. In earlier large LMFBR conceptual designs based on the pipe system, the components were so situated and interconnected to the vessel that core submergence could not be absolutely guaranteed. In more recent designs, however, the criterion of core submergence has been met with elevated loops and with guard tanks:[16] The inherent independence of the separate intermediate sodium loops and the redundant feed-water supplies to the individual steam generators in each loop removes the basic concern about any accident involving loss of coolant in the primary system. The pipe system offers relatively easy maintenance and repair of components as well as greater flexibility in design, and it minimizes the problems associated with on-site manufacture.

The US program is now focused on building the Fast Flux Test Facility (FFTF, see cover) in Richland, Washington, and on completion of negotiations for the first-round 300-500 MW(e) demonstration plant (see Table 6). Just this January, the AEC announced that Commonwealth-Edison will be project manager and manager of engineering for this first US demonstration plant, and the Tennessee Valley Authority will be constructor-operator. The plant will be located within the TVA system. The estimated cost of the joint AEC-utility-industry project is nearly $500 million.

Fission breeders and power costs

Now that we know something about the important performance parameters for reactors and about the operation of breeder reactors, we can take a closer look at the kinds of economic analysis performed continuously by the AEC and its contractors. (For details on the methods, assumptions and ground rules used in a recent analysis, see reference 17.) These studies have generated information about the required reactor capacity for the years 1970-2020; figure 5 shows the relative total base-load capacity generated by each source of power included in the study. The assumptions used in the study were

- a 7% discount rate
- capital costs as estimated in reference 18 (see also reference 19)
- fuel and fuel-cycle costs as shown in figure 6
- thirty-year plant lifetime
- uranium costs as shown in figure 2
- total electrical-energy demand as shown in figure 1
- an optimal 64% time on (the computer-selected "system capacity factor")

We see in figure 5 that, based on these assumptions, the LMFBR replaces the HTGR as it enters the system. Before it ultimately declines, the LWR capacity increases for about five years after the breeder is introduced. This increase comes from the ready market provided by the breeder for the plutonium produced in the LWR and by the decreased uranium costs invoked by the breeder (see figure 2). Note the striking manner in which the LMFBR's dominate after the turn of the century.

Figure 7 compares total power costs for the period 1970-2020 with (a) and without (b) LMFBR's; the same assumptions are used here as in figure 5. The cost range shown for fossil-fuel plants corresponds to a $5-10.50 per ton fuel cost. For the uranium-fueled pressurized-water reactor, the initial cost decrease comes from reductions in capital costs and in fabrication and reprocessing costs (because of the larger nuclear-fuel industry). Increases in the cost of uranium ore cause the subsequent monotonic increase shown for this

Table 1. Neutron Budgets for Breeder Reactors

Reactor constituent	Fast breeder (LMFBR)			Thermal breeder (MSBR)		
	Absorptions		Productions	Absorptions		Productions
	Captures	Fissions		Captures	Fissions	
Fissile nuclides	0.20	0.80	2.33	0.11	0.89	2.21
Fertile nuclides	1.42	0.22	0.60	1.075	0.003	0.01
Other heavy nuclides	0.01	0.01	0.02	0.02		
Fission products	0.07			0.02		
Structure, coolant, control	0.19			0.09		0.01*
Surroundings (leakage)	0.03			0.02		
	1.92	1.03		1.34	0.89	
Total ($\eta\epsilon$ neutrons)	2.95		2.95	2.23		2.23
Breeding ratio		1.42			1.07	

*From the beryllium (n,2n) reaction

Table 2. Effect of Introducing LMFBR's in 1986 Through the Year 2020

	U_3O_8 requirements (tons)	Maximum separative work demand (tons per year)
Without LMFBR's	5.0×10^6	300×10^3
With LMFBR's	2.4×10^6	90×10^3

Table 3. Typical Performance Parameters for 1000-MW(e) Converter Reactors

Reactor type	Specific fissile inventory [kg/MW(e)]*	Specific power [MW (t)/kg]	Fertile inventory (kg × 10^{-3})*	Conversion ratio	Efficiency (%)
LWR					
BWR	3.7	0.8	180	0.6	33
PWR	2.9	1.0	115	0.6	33
Advanced PWR	1.9	1.6	90	0.6	33
HTGR	2.2	1.0	50	0.8	43

* Assumes one-year recycle time

reactor; the uranium-fueled PWR would, obviously, be selected only in the early years when no other nuclear plants are available.

The HTGR is more economical than the uranium-fueled PWR, and large numbers of these reactors would be built until the LMFBR is introduced. Fewer HTGR's would be built after 1986, because, even when first introduced, the LMFBR turns out to be more economical than the HTGR. According to this study, the LMFBR's would capture the largest share of the market right after they enter. The slight increase in LMFBR power costs in the late 1990's reflects the anticipated short supply of plutonium during those years.

Recall, from Table 5, that the doubling time for the advanced oxide LMFBR is eight years, shorter than the estimated power-industry doubling time after the year 2000. After the turn of the century, then, the breeders should produce more plutonium than is needed to sustain their own growth. This plutonium would be used as makeup fuel in the plutonium-fueled PWR, and thereafter the LMFBR and PWR would have about equal total power costs. Note that the low costs for the plutonium-fueled PWR occur only because of the existence and proliferation of the high-gain breeder; if the LMFBR were not a source of low-cost plutonium, the PWR would have much higher fuel costs and much higher power costs.

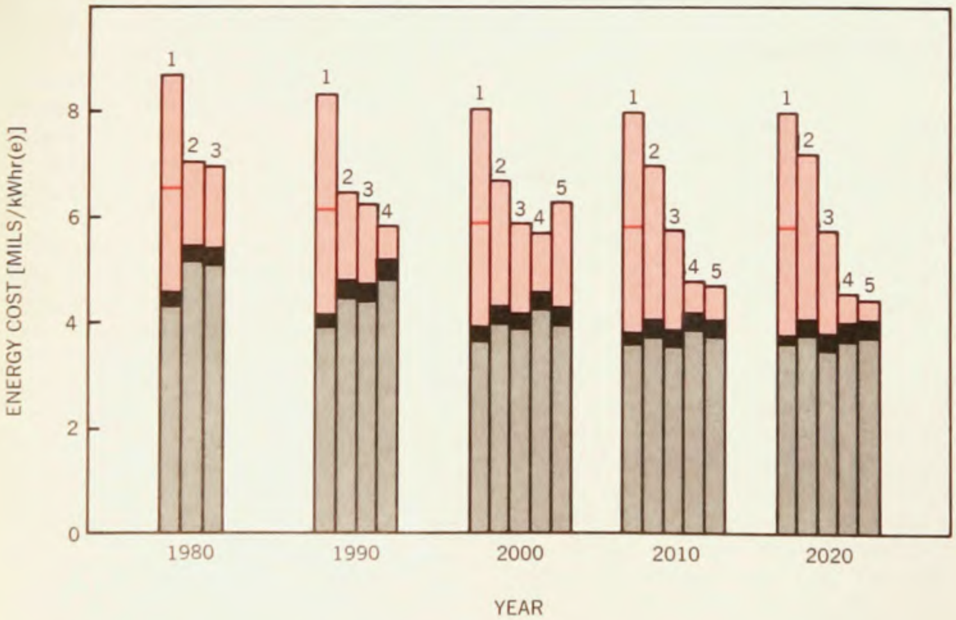
For the case without the LMFBR (see figure 7b) the price of U_3O_8, of course, increases more rapidly. The higher costs for the PWR and HTGR, relative to their costs with the LMFBR, reflect the higher price of U_3O_8. Because the HTGR has a higher conversion ratio than the PWR, its total power cost is less sensitive to rising ore costs, and it would capture most of the market after it is introduced.

Limitations of fission reactors

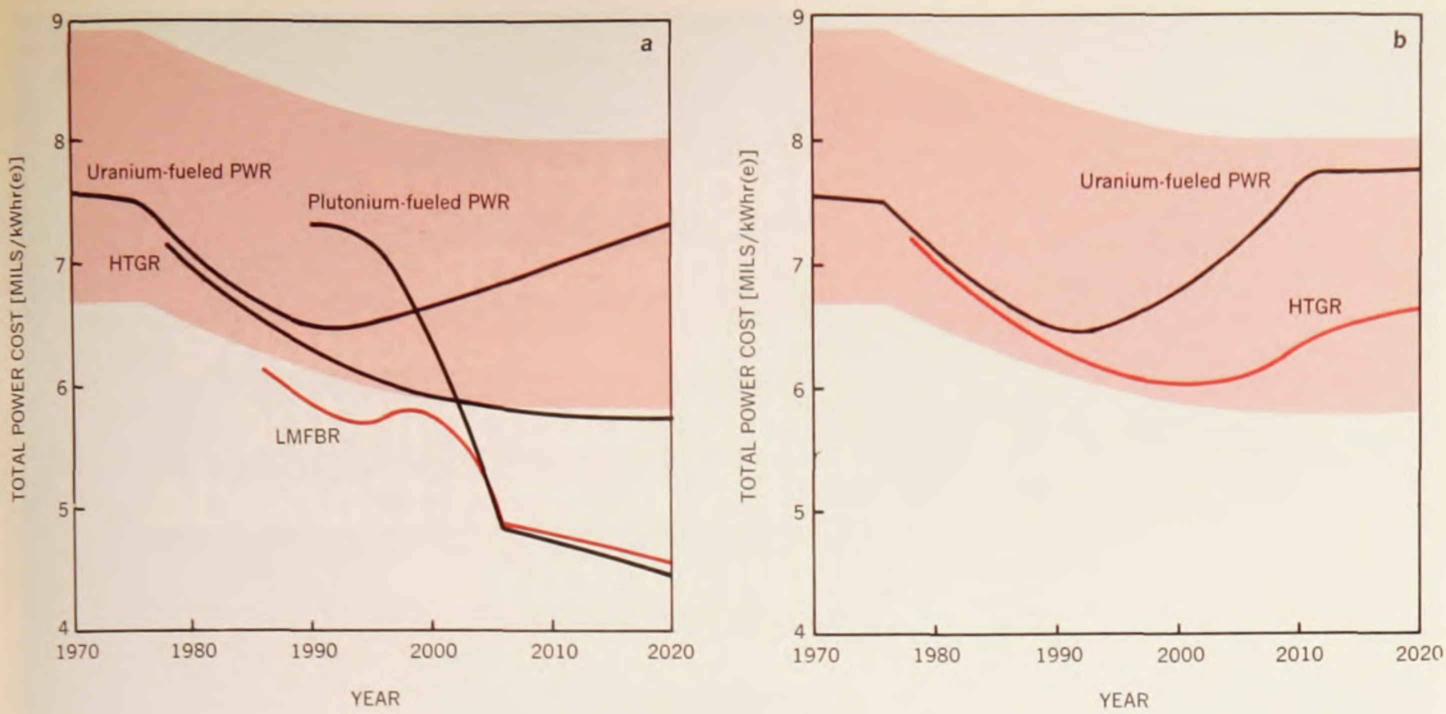
We have always recognized that use of nuclear energy carries with it certain risks. The major risks are associated with the safe, contained operation of the reactor and with the handling of radioactive material both in the reactor plant and during the fuel cycle, including the permanent disposal of highly radioactive wastes. As a society, we must continue to weigh the risks against the benefits. In the long run, our principal energy source will almost certainly be based on nuclear fission, but we must, at each stage of advancement, ensure that proper precautions are taken and that no unnecessary risk is incurred.

Unfortunately, there is no easy road to understanding reactor-safety problems, no absolute proof that can be simply and convincingly displayed. During the development process, careful attention has been paid to the details of safety by multiple protective systems and by finding ways to contain and almost eliminate the harmful results of an accident. So far these efforts have been very successful. (For more information on reactor safety, write to the Nuclear Safety Information Center at Oak Ridge National Laboratory or to the AEC.)

Changes in safety criteria during the past year or so will go a long way toward reducing the already low-level releases



Analysis of power costs for fossil plants (1), uranium-fueled LWR's (2), HTGR's (3), LMFBR's (4) and plutonium-fueled LWR's (5). Components include capital costs (gray), operating and maintenance costs (black) and fuel costs (color). For fossil plants, the study projected both minimum (colored line) and maximum (top of colored area) fuel costs. Figure 6



Effect of LMFBR's on total power costs. If LMFBR's are introduced in 1986 (a), they would capture the market after the turn of the century, with total costs well below the fossil-plant cost range (light-colored area). The slight increase in LMFBR costs during the 1990's reflects the anticipated higher price of plutonium during that time. After 2000, the LMFBR's would produce more plutonium than they need, and the excess could be used for the plutonium-fueled PWR; thereafter the LMFBR and the plutonium-fueled PWR would have nearly equal costs. Without the LMFBR (b) total power costs would not go below the fossil-plant cost range.
Figure 7

of radioactive material from operating reactors under both stable and accident conditions. As a result of years of study (and much expressed public concern), the maximum permissible radiation exposure has been lowered to 5 millirems per year for selected segments of the general population. (See the article by Joseph Lieberman, PHYSICS TODAY, November 1971, page 32.) This new limit is only a small fraction of the natural radiation (in fact, it is above the actual radiation dose released by most operating power reactors in the past) and staying within it appears to be feasible.

As the number of nuclear stations increases, so do shipments of radioactive material from mine to diffusion plant, from reprocessing plant to fuel preparation and fabrication stations, of spent fuel to reprocessing plant. Radioactive wastes from all units will increase very markedly. Very large quantities of fission products, including long-lived alpha emitters such as plutonium and the transuranics, will be moving at all times.

Our experience in moving radioactive materials, particularly large quantities of active material carefully packaged and contained in double seals or triple containers and shields, has been very good so far. But because of the nature of transportation accidents, their probability increases with the number of shipments. We can design and build containers and shields that will contain their radioactive material content under very severe accident conditions, but it would be safer to eliminate or drastically reduce the shipments.

Possibly the most important long-term problem in the use of nuclear energy is the safe disposal of fission products and radionuclides. The reprocessing plants produce more than 99% of the fission-product wastes; the fuel fabricators, if we can rely on our current experience, may be the largest sources of alpha-emitting materials when plutonium-bearing fuel is recycled to LWR's and to the future fast breeders.

The reprocessing plants must effectively contain the gaseous fission products I_2, Xe and Kr. Tritium produced in tripartite fission will exchange with the hydrogen in the aqueous solvents used in processing. Neutron-activated and trace-fuel contaminated metal scrap from fuel-element chopping will have to be reduced in volume and stored. And, finally, the fission-product liquid wastes, after protected storage in tanks for decay, must be con-

Table 4. Status of US Thermal-Converter Power Plants as of 1 January 1972

LWR's		HTGR's		Total	
Number	Total power (MW(e))	Number	Total power (MW(e))	Number	Power (MW(e))
		Operating			
18	7711	1	40	19	7751
		Under construction and on order			
104	98 634	1	330	105	98 964
		Letters of intent			
2	2500	4	3860	6	6360
124	108 845	6	4230	130	113 075
		Plans announced			
11	11 000	0	0	11	11 000
135	119 845	6	4230	141	124 075

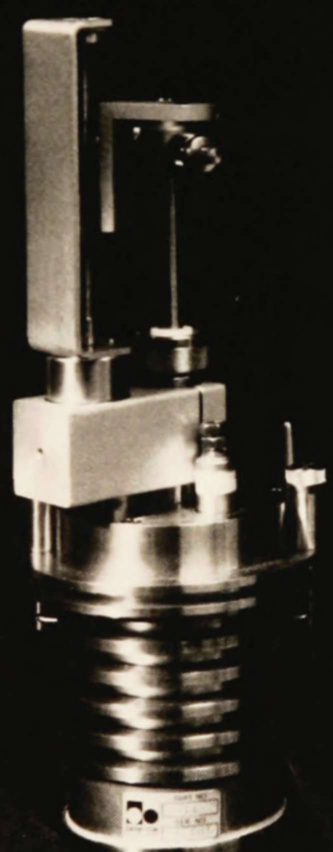


Table 5. Typical Performance Parameters for 1000 MW(e) Breeder Reactors

Reactor type	Specific fissile inventory [kg/MW(e)]*	Specific power [MW(t)/kg]*	Fertile inventory (kg × 10⁻³)	Breeding ratio	Compound doubling time (years)	Conservation coefficient [MW(e)/kg/yr] × 10²
LMFBR						
Reference oxide	3.9	0.6	70	1.27	15	1.7
Advanced oxide	2.8	0.8	55	1.34	8	4.5
Advanced carbide	2.6	1.0	58	1.50	5	7.7
GCFBR						
Reference oxide	5.0	0.5	120	1.48	10	2.0
Advanced carbide	3.1	0.9	90	1.60	4.7	6.9
MSBR	1.5	1.5	70	1.06	21	3.2

*Includes inventories both in and out of reactors

verted into essentially nonleachable ceramics and cooled to remove the heat from fission-product decay.

Where and how should these wastes be sequestered, and what is the strategy for keeping them from contact with any part of the natural environment? The short-lived gases Xe and I_2 will be retained in the chemical plant until they decay. Tritiated water, in quantities limited because of a special oxidation step in the pretreatment of chopped fuel, will be collected and stored for short-term decay. Solids containing fission products and alpha emitters may be stored in the extensive bedded-salt formations that exist in the central US; bedded salt is believed to be the safest formation for the disposal of radioactive wastes. Other natural formations could be used, such as gypsum beds, deep dry granites and possibly other rock formations. Cooled subsurface concrete vaults and liquid-waste tanks are believed to be less favorable. It may, eventually, be possible to separate effectively plutonium and alpha-emitting materials from the shorter-lived heat-producing fission products. The alpha-emitting elements could then be recycled to the reactor as part of the fuel and would burn out in time.

Not all the safety problems are associated directly with radioactivity. Local increases in power-station heat releases can aggravate the problems associated with "urban heat domes." This type of heat pollution occurs when rising warm and dry air diverts regional winds upward over the city, isolating the polluted urban air. Thus, an unplanned perimeter of large heat sources around a city of the future, placed to give the cheapest transmission costs to urban load centers, can create conditions that would increase all types of air pollution.

These problems could be greatly reduced by large nuclear "parks," carefully located and preplanned. These large parks might have a combined total of 40 000 to 50 000 MW(e) with appropriate facilities for chemical reprocessing, fuel fabrication and, perhaps, waste disposal. They would be located to take advantage of cooling water, perhaps offshore in coastal regions. They would have to be heavily tied in with other large energy parks, to provide for accidental or planned shutdown. They also should be isolated from urban centers to allow for proper heat dispersal and as additional protection in the very improbable event that a reactor or other nuclear station released radioactive materials.

The option to use energy from nuclear fission, we repeat, involves risks that must be carefully evaluated and controlled. Those of us in the nuclear community think that the potentially adverse effects of nuclear energy can be and are being controlled. We believe that a safe and compassionate energy-production technology can be developed

Table 6. LMFBR Projects Worldwide

Name	Country	Power MW(t)	Power MW(e)	System type	Initial operation
		Operable			
BR-5	USSR	5		pipe	1959
Dounreay	UK	60	15	pipe	1959
EBR-II	US	62.5	20	pot	1963
Fermi	US	200	67	pipe	1963
Rapsodie	France	40		pipe	1967
SEFOR	US	20		pipe	1969
BR-60 (BOR)	USSR	60	12	pipe	1970
BN-350*	USSR	1000	150	pipe	1972
		Under construction			
PFR	UK	600	250	pot	1972
Phenix	France	600	250	pot	1973
FFTF	US	400		pipe	1974
BN-600	USSR	1500	600	pot	1976
		Planned			
KNK 2	West Germany	58	20	pipe	1973
JEFR	Japan	100		pipe	1974
PEC	Italy	140		pot	1975
SNR	West Germany	730	300	pipe	1976
JPFR	Japan	750	300	pipe	1976
Demo No. 1	US	750–1250	300–500	pipe	1978–1980
CFR	UK	3125	1250	pot	1979
Demo No. 2	US	750–1250	300–500	?	?
1000 MW(e)	France	2500	1000	?	1980
1000 MW(e)	West Germany	2500	1000	?	1982

*Construction of this dual electric-power and desalting plant was completed in 1971.

with nuclear energy. But this view must be evaluated by society as a whole.

* * *

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References

1. C. Starr, Sci. Amer. **225**, no. 3, 37 (1971).
2. A. M. Weinberg, R. P. Hammond, Amer. Scientist **58**, 412 (1970).
3. Conceptual Plant Design, System Description, and Costs for a 1000 MWe Sodium Cooled Fast Reactor, Table 2.11, page 91, GEAP-5678, December 1968; Molten Salt Reactor Program Semiannual Progress Report, 28 Feb. 1971, ORNL-4676, page 42.
4. M. J. Whitman, A. N. Tardiff, P. L. Hofmann, *Proceedings* of the Fourth UN International Conference on the Peaceful Uses of Atomic Energy, Geneva, 6–16 September, 1971 (to be published), Table III.
5. Potential Nuclear Power Growth Patterns, WASH-1098, December 1970, page 6.
6. M. W. Rosenthal, P. R. Kasten, R. B. Briggs, Nuclear Applied Technology **8**, 107 (1970).
7. R. L. Faulkner, *Proceedings* of the Fourth UN International Conference on the Peaceful Uses of Atomic Energy, Geneva, 6–16 September 1971 (to be published), Table 1 and figure 7.
8. Reference 4, Table II, case A.
9. Reference 4, Table IV.
10. (Paper identified in reference 7.)
11. M. Shaw, M. Whitman, Sci. Technol. **n75**, 22 (1968).
12. R. G. Bernier, A. J. Goodjohn, Commercial Power Generation from HTGR Nuclear Steam Systems, Gulf-GA-10415, 11 Nov. 1970.
13. M. Shaw, J. W. Landis, R. B. Laney, M. Rosenthal, W. H. Layman, Nucl. Eng. Int. **15**, 899 (1970).
14. M. W. Rosenthal, E. S. Bettis, R. B. Briggs, W. R. Grimes, P. N. Haubenreich, H. E. McCoy, L. E. McNeese, *Proceedings* of the Fourth UN International Conference on the Peaceful Uses of Atomic Energy, Geneva, 6–16 September 1971 (to be published).
15. B. Pelland, H. Tschirky, Neue Tech. **A13**, 150 (1971).
16. P. Murray, *Proceedings* of the Northwest Electric Light and Power Association Meeting, Portland, Oregon 1971.
17. (Paper identified in reference 4.)
18. H. I. Bowers, M. L. Myers, Estimated Capital Costs of Nuclear and Fossil Power Plants, ORNL-TM3243, 5 Mar. 1971.
19. H. E. Vann, M. J. Whitman, H. I. Bowers, *Proceedings* of the Fourth UN International Conference on the Peaceful Uses of Atomic Energy, Geneva, 6–16 September, 1971 (to be published). □