Fission: The Pro's and Con's of Nuclear Power

Of all the major new sources of energy, nuclear fission has received the most support, and its technology is correspondingly the most well developed. About 25 nuclear power plants have received operating licenses in the United States, another 117 are planned or under construction, and the U.S. Atomic Energy Commission (AEC) is committed to spending several billion dollars in the development of the next generation of reactors, the breeders. Some estimates are that nuclear reactors will rapidly become the dominant source of heat for generating electricity, perhaps by the end of the century. Nonetheless, there is growing concern in the scientific community about the extent to which research funds are concentrated on this energy option and about the consequences of large-scale use of nuclear fission as a source of power.

The concerns include operating hazards, particularly the chances of a serious reactor accident, the difficulties of safeguarding the fissionable materials used as reactor fuels, and the still unsolved problem of long-term storage for radioactive wastes. Technological failures, earthquakes and other unforeseen natural disasters, and human actions ranging from carelessness to deliberate sabotage appear to be of unusual moment with nuclear power systems. Indeed, because of the consequences to human health and to the environment of any large release of radioactive substances, nuclear fission is potentially the most hazardous of all sources of energy.

At the same time, nuclear fission has substantial advantages over traditional sources of energy. Air pollution from the consumption of fossil fuels is still a problem, and nuclear power plants do not emit particulates, sulfur oxides, or other combustion products. Nuclear fuels are a compact source of energy, resulting in less mining and lower transportation costs than, for example, coal; the water pollution, land disruption, and human injuries associated with mining are correspondingly reduced. As a source of energy, fission could help to replace rapidly depleting fossil fuel reserves or conserve them for their value as chemicals.

The means of transforming heavy elements—uranium, thorium, and plutonium—into heat energy include both light water reactors (LWR's) of the type now in use and breeder reactors, which are being rapidly developed in the United States and in other countries. Breeder technology and the AEC's economic claims for the U.S. breeder program have been discussed in previous articles (*Science*, 19 November 1971 and 28 April 1972); in this article the overall characteristics of nuclear fission as a source of energy, together with its potential advantages and disadvantages, are reported.

LWR's Use Uranium Inefficiently

The reactors in commercial service today utilize less than 1 percent of the energy in naturally occurring uranium —they consume the fissionable ^{235}U isotope while converting only small amounts of the more plentiful ^{238}U into fissionable plutonium. In consequence the fuel supply for these reactors is limited and is considerably smaller than, for example, known coal reserves. For this reason, LWR's were never considered as more than a stopgap by the early prophets of nuclear power, and commercial utilization is an outgrowth of the successful effort to develop nuclear power plants for submarines. Breeder reactors—which produce more fissionable material than they consume and thus can theoretically utilize between 50 and 80 percent of the uranium and thorium resources —will ultimately be necessary if fission is to become a major source of energy.

Nuclear power plants based on LWR's are clearly a commercial success. But the expansion of the nuclear power industry in this country and in countries that depend on the United States for fuel-processing services has not had entirely the intended impact on the domestic energy picture. Indeed, this expansion has had the perverse effect of stimulating the strip-mining of coal to supply power for the gaseous diffusion plants used to concentrate or enrich ^{235}U for nuclear fuels. Conventional generating stations that are operated by the Tennessee Valley Authority and that are heavily dependent on strip-mined coal provide most of the electricity for the enriching facilities.

Although LWR's are the predominant type of reactor in service today, they have relatively low thermodynamic efficiencies, about 32 percent. High-temperature gas-cooled reactors of the type just now coming into commercial service in the United States appear to have several advantages, including higher efficiencies (about 39 percent) and more efficient use of fuel resources. Still other designs have been developed —for example, a reactor with heavy water coolant, which is used in Canada, and a CO_2-cooled model, which is used in Great Britain.

Most nuclear power plants now in operation discharge their waste heat directly to lakes or rivers, a practice that has drawn the opposition of environmentalists. Because of their low efficiencies, LWR's must get rid of about 40 percent more waste heat than modern fossil-fired plants. Expected shortages of cooling water in many parts of the country, however, may well force the adoption of systems that discharge heat to the atmosphere. An AEC study estimates that dry cooling systems now under development would raise the cost of power from light water reactors by about 12 percent, but would permit much greater flexibility in siting of power plants. If gas-cooled reactors can be operated at still higher temperatures, the helium coolant can potentially be used to drive air-cooled gas turbines directly, eliminating the steam cycle and the need for cooling water altogether.

Accumulation of fission products within fuel rods of a reactor eventually forces their removal and reprocessing to recover unused fuel. Hence transportation of the highly radioactive fuel rods and their refabrication in reprocessing facilities are part of the nuclear fuel cycle. Shipping accidents, diversion or loss during transportation, and routine releases of radiation from fuel processing plants—these facilities are not required to meet the strict radiation standards that apply to nuclear power plants and they release gaseous fission products to the atmosphere—thus become potential problems associated with nuclear power. Storage of long-lived wastes in such a manner that the heat from radioactive decay can be safely dissipated over long periods of time is also necessary. At the present scale of the nuclear power industry these are not very great problems, although attempts at diversion and other shipping problems have already occurred, but they promise to become more substantial in the future.

Reactor safety, however, has already emerged as a subject of concern. Existing types of reactors have an inherent margin of safety with respect to changes in reactivity in that small increases in temperature within the core have the effect of decreasing reactivity —a negative feedback process in the kinetics of the nuclear reactions that helps to control the reactor. Problems due to failures in the cooling system are more difficult, however, because even when the reactor is shut down, radioactive heating from fission products is an appreciable source of heat. Substantial questions about the safety of LWR's have been raised in recent months—mostly in regard to the still untested adequacy of the emergency core-cooling system (*1*). In addition, the discovery of fuel elements damaged by unknown causes in several operating reactors has led many observers to call for a moratorium on increases in the sizes and the power ratings of nuclear plants, which have been escalating rapidly.

In West Germany, a government advisory committee on reactor safety earlier this year recommended a moratorium on the licensing of LWR's in that country, pending further investigation. The committee's counterpart in the United States has repeatedly expressed concern over the possibilities of a rupture of reactor pressure vessels and has urged the AEC in vain to consider such an accident in its safety research. These and other uncertainties, including a series of malfunctions in control systems, safety valves, and other equipment in the relatively few reactors now operating, have led Henry Kendall of the Massachusetts Institute of Technology and other members of the Union of Concerned Scientists—a Boston group of scientists, engineers, and economists—to claim that the chances of a major reactor accident are by no means insignificant.

Light water reactors may continue to be the mainstay of nuclear power for several decades, but breeders—in particular the liquid metal–cooled fast breeder reactor (LMFBR)—are being developed by the U.S.S.R., Japan, several European countries, and the United States. Breeders will eventually eliminate the need for gaseous diffusion plants and will ensure a much larger supply of nuclear fuel, if they prove successful. But this new technology will intensify many of the problems associated with use of LWR's and will raise new problems.

The LMFBR differs from LWR's in that it uses unmoderated, high energy neutrons and will be operated at higher power densities—the rate of production of heat per unit volume will be about twice that of LWR's. The higher neutron fluxes within the LMFBR create materials problems that have not been entirely resolved. The liquid sodium used as coolant in the LMFBR is so reactive with both air and water that special safety precautions must be observed; it also becomes radioactive, complicating the design and maintenance of an operational power plant.

The safety problems of LMFBR's may turn out to be more severe than those of LWR's. The smaller fraction of delayed neutrons from the plutonium fuel in an LMFBR compared to that from ^{235}U in an LWR makes control of the breeder reactor a more delicate process; in essence, the reactor operates much closer to the limits of an uncontrolled chain reaction than LWR's do. Vapor bubbles or other voids in the sodium coolant have the effect of increasing the reactivity within the reactor, so that special consideration must be given in the design to ensuring that increases in reactivity will be self-controlling. The chances of a major loss-of-coolant accident in an LMFBR are expected to be less than in light water reactors; but should an accident occur, the radioactive heating would almost certainly be sufficient to melt the reactor fuel and release large quantities of fission products.

Difficulties in Developing LMFBR's

Although the design of LMFBR's will undoubtedly be continually improved, the experience up to now illustrates the complexities of the technology. One of the AEC's first pilot breeder reactors suffered a partial melting of its fuel during the course of an experiment in 1955, and the reactor was destroyed. A similar but fortunately much less serious accident occurred in 1966 during the first attempt to operate a commercial power plant incorporating an LMFBR (see Fig. 1). The high neutron fluxes within an LMFBR can cause damage to structural materials, and experiments conducted at several laboratories have recently provided evidence that stainless steel of the type planned for use in breeder reactors swells when exposed for long periods, necessitating changes in the core design to allow for its expansion.

Although LMFBR's are the focus of most development work in this country and abroad, gas-cooled breeder reactors and a reactor that incorporates the use of molten uranium salts as both fuel and coolant have also been studied. Proponents claim that these alternative breeders have a number of theoretical advantages over the liquid metal–cooled variety, as well as some disadvantages; but they suffer as well from being less developed and hence longer-range options—a disadvantage in the current atmosphere of urgency that pervades U.S. reactor development policy. Indeed, the LMFBR program consumes almost half of all federal research expenditures on energy technologies and is accorded the highest priority by President Nixon. Construction of a demonstration power plant with a liquid metal–cooled breeder reactor is expected to begin in 1974. One AEC study projects that more than 500 breeder reactors will be in operation by the end of the century, with possibly 2000 such reactors by the year 2020.

The prospect of a nuclear power industry of that size has caused even strong proponents of the breeder to have some second thoughts. Alvin Weinberg, director of the AEC's Oak Ridge National Laboratory, points out that, with the anticipated scale of endeavor, safety factors will have to be improved, decontamination of old reactor sites will be a substantial problem, and new siting arrangements—such as grouping power plants and fuel reprocessing facilities into nuclear parks—may be necessary to minimize the transportation of radioactive materials (*2*). Weinberg raises the question of whether social institutions can cope with the demands of large-scale use of nuclear fission, demands that include long-term management of wastes, very high quality manufacturing and construction standards, and unusual skill and vigilance in the operation of all parts of the nuclear industry; he answers the question in the affirmative. Other observers are less certain.

With reactor wastes, for example, as much as 27 billion curies of radioactive materials will have accumulated by the year 2000. These materials will have to be stored for thousands of years under essentially permanent surveillance —implying a permanence to the social order and a degree of responsibility well beyond that of any earlier society.

Other concerns have to do with the fuel processing cycle for the LMFBR and the properties of ^{239}Pu, the principal fissionable isotope that is produced from ^{238}U within the breeder reactor. A kilogram of plutonium can produce as much energy as about 3 million kilograms of coal, thus making it uniquely valuable as a fuel. About 1000 kilograms of plutonium will be required to fuel a large LMFBR. If AEC estimates as to the breeding ability of these reactors are correct, the plutonium inventory will double about every 10 or 15 years, and as much as 80,000 kilograms a year may be produced in LMFBR's by the end of the century.

Handling these quantities of plutonium will present equally unique problems, however, because it is also among the most toxic substances known; for example, microgram amounts cause lung cancer in experimental animals. Federal health standards limit human exposure to a total body burden of 0.6 microgram. The radioactive half-life of ^{239}Pu is 24,400 years, making possible the essentially permanent contamination of an area in the event of a major accident. Plutonium has a critical mass of about 5 kilograms—a relatively small amount compared with the contemplated inventory of a large reactor or fuel-processing facility.

The AEC takes the position that despite the dangers of plutonium and the so-far undistinguished record of the agency and its contractors in handling and safeguarding this material (*Science*, 9 April and 5 November, 1971), its widespread use will present no unresolvable problems. But the real consequences seem to depend on how safely breeder reactors can operate in practice and on how well safeguards now being developed will work.

Technological problems can in theory be solved, but the social problems arising from the misuse of technology are less easily dealt with. In particular, the vulnerability of nuclear power plants and fuel processing facilities to sabotage and the potential for diversion of plutonium to illegal purposes could lead to difficult situations. Plutonium is worth about $10,000 per kilogram, an amount that the AEC is concerned may be an incentive for the creation of a black market. As many as 500 shipments of plutonium per week, the traffic expected by the end of the century, would offer ample opportunity for hijacking. The information necessary to construct a crude nuclear bomb is readily available—pamphlets describing the required steps have been circulated in Great Britain—and despite the fact that reactor-bred plutonium does not have the ideal isotopic composition for weapons, extremist groups that may find such a project tempting cannot be ruled out. Even without bombs, the hazards to public health and national security of plutonium diversion would be substantial.

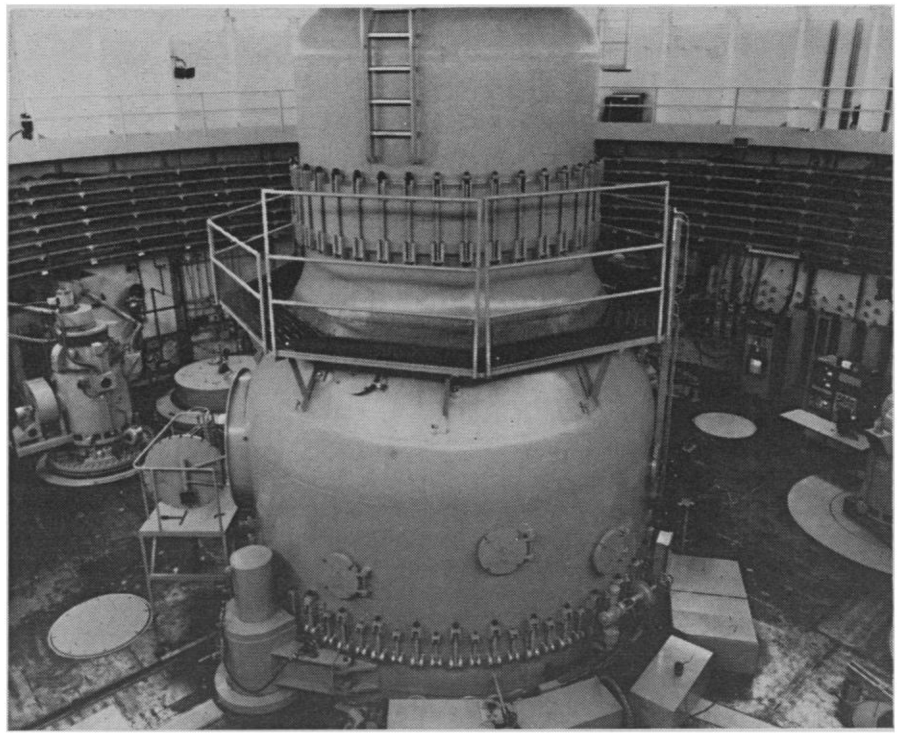

Fig. 1. Reactor vessel of the Enrico Fermi atomic power plant located near Monroe, Michigan. Completed in 1965, it incorporated a liquid sodium-cooled fast breeder reactor. In 1966, following an accident in which a loose piece of metal obstructed the cooling system, the reactor core partially melted and was rendered inoperable for several years. [Power Reactor Development Company]

Breeder reactors do have several advantages over the current generation of reactors. They will, for example, have thermal efficiencies approaching 40 percent. More significantly, the cost of an LMFBR is less sensitive to the cost of uranium, so that breeder reactors could theoretically make possible the utilization of even very low grade ores, should that prove necessary.

Spokesmen for the AEC have in the past advanced several reasons for the rapid development of the breeder technology, including an expected near-term shortage of uranium to fuel LWR's and the economic advantages of the breeder. There is no question but that breeder reactors will be needed eventually if fission is to continue to be an economic means of generating power; but there is now considerable disagreement with the AEC's admittedly conservative estimates of uranium reserves and with their optimistic estimates of how soon breeders might be economically competitive. At issue is the advisability of rushing the development of a difficult technology and hastening the accumulation of large plutonium inventories. There appears to be a growing number of scientists who believe that research on the breeder ought certainly to be continued and even broadened, but that the commercialization of this technology could well be delayed a number of years—long enough to ascertain whether other, and less hazardous, sources of energy can be made available.

The use of nuclear power thus poses a considerable dilemma. Fission can become a major source of energy for the United States and other countries, probably the only very large energy source, other than fossil fuel, for which the technology is now reasonably assured. But its widespread use may prove a mixed blessing.

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References

1. Testimony presented at the AEC Public Rule-Making Hearings on Interim Acceptance Criteria for Emergency Core-Cooling Systems, 27 January 1972, to the present, Bethesda, Maryland (transcripts may be inspected at the AEC Public Document Center in Washington, D.C.); also see D. F. Ford and H. W. Kendall, *Environment* **14** (7), 2 (1972).
2. A. M. Weinberg, *Nuclear News* **14** (12), 33 (1971); *Science* **177**, 27 (1972).