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Energy for the Long Run: Fission or Fusion?

Factors such as hazards, technological costs, and development time are the significant points of comparison for the two most likely long-term energy sources

The present search for inexhaustible energy sources is characterized by conflicting claims, misinformation about both the potentials and the hazards of the possible sources, and a general frustration about the prospects for the eventual commercialization of any of the proposed schemes. The problems have arisen in part because the proponents and critics of various energy sources have almost always written separate appraisals of what each energy form can accomplish. Therefore, in comparing the two most likely and controversial long-range energy sources—fusion and fast-breeder fission—we have brought together a group of proponents of both kinds of nuclear power, to try to achieve an accurate presentation of the arguments for—and against—each course at this time. We recognize that other forms of energy, such as solar, will make a contribution in the next century, but compared to the potential of nuclear energy, the fraction of the total energy supply that nonnuclear sources can provide will be small, and thus we have not considered those sources here.

We make no claims for having reached a final word on these issues. Indeed, because development of fusion reactors is at a very early stage—not even an experimental device to prove scientific feasibility has yet been produced—our conclusions must be tentative. While many of the general problems associated with the two kinds of reactors are fairly well understood, other more specific problems are much less well understood. (See *ref. 1* for more complete documentation.)

It should also be made clear that we are not comparing fusion reactors to the present light-water moderated fission reactors (LWRs). Uranium resources are not sufficient to fuel the required number of LWRs much after the turn of the century. If the fission process is to provide energy beyond the 21st century, the world must convert from LWRs, which utilize only 1% of the potential energy in uranium, to breeder reactors, which use about 60% to 70%. While the fundamentals of nuclear-energy release are the same for both types of fission reactors, there are significant differences in the technologies required to convert the nuclear energy to electricity.

Both fission breeders and fusion reactors are, in terms of fuel supply, potential providers of very large, almost indefinite amounts of electricity (Table 1). The most likely fuel for fission breeders is uranium 238; that for fusion systems is deuterium and lithium. Even if the prices of these fuels rise to several times the present values, the total cost of electricity in either system would not be significantly affected. If the substantial amounts of both uranium and lithium that we know are available at about $100/kg are exhausted, extracting either of these fuels at several times more than today's costs will still be economically feasible. Including other possible fuels for both systems in our calculations will only make the outlook more favorable.

The choice between fission and fusion will therefore have to be made on grounds other than fuel resources. Relevant considerations include potential biological and social hazards, costs of research and development, capital costs, technical complexity, and time factors. Before we compare the alternatives in these areas, however, we must look at the present status of fission and fusion reactors.

Where things stand

The nuclear processes involved in fission and fusion breeder reactors are fundamentally different. In fission, the most common reaction used produces plutonium from uranium via the steps

$$^{238}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}\mathrm{U}$$

$$^{239}\mathrm{U} \xrightarrow[\beta^-]{23.5\ \mathrm{min}} {}^{239}\mathrm{Np}$$

$$^{239}\mathrm{Np} \xrightarrow[\beta^-]{2.33\ \mathrm{day}} {}^{239}\mathrm{Pu}$$

While ^{238}U is not fissionable by neutrons with energies below 1.4 MeV, ^{239}Pu is fissionable by neutrons of any energy. Since each fission event in ^{239}Pu produces about 3 neutrons, as much—perhaps even more—Pu is produced in the overall reaction than

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is burned up: thus the name *breeder*. The fundamentals of the production of Pu have been known and utilized for over 30 years.

The most likely reaction to be used in fusion reactors is the one in which deuterium and tritium are combined as follows:

$$D + T \rightarrow n + {}^4He$$

Since there is no significant natural source of tritium on the earth, the tritium supply must be continually replenished by "breeding" it from the element lithium:

$${}^6Li + n \rightarrow T + {}^4He$$

$${}^7Li + n \rightarrow T + {}^4He + n$$

The capture of the additional neutron from the ^7Li reaction in ^6Li insures that more tritium is produced than is burned up, thus allowing an excess of fuel to be produced. At the present time it is not the breeding of tritium that keeps us from building fusion reactors, but the containment of the D and T for long enough times and at high enough temperatures to produce large amounts of neutrons.

To make some quantitative comparisons between these two means of producing energy, representative designs must be chosen. As a fission system, we have chosen the Liquid-Metal Fast-Breeder Reactor. The LMFBR clearly dominates research and development programs on breeder reactors around the world, making it by far the most likely breeder for commercialization. Historically, fast neutron breeder reactors have been preferred to thermal breeders because of the higher fuel utilization in the fast reactors. Liquid-metal-cooled fast reactors have received much more attention than gas-cooled reactors for reasons partly technical and partly historical, and no prototype gas-cooled fast reactors are under construction at present. Among various existing LMFBR designs we chose the German/Belgian/Dutch prototype fast-breeder reactor SNR 300 because we had full access to all the details of the program (see Fig. 1 for a schematic drawing of the reactor).

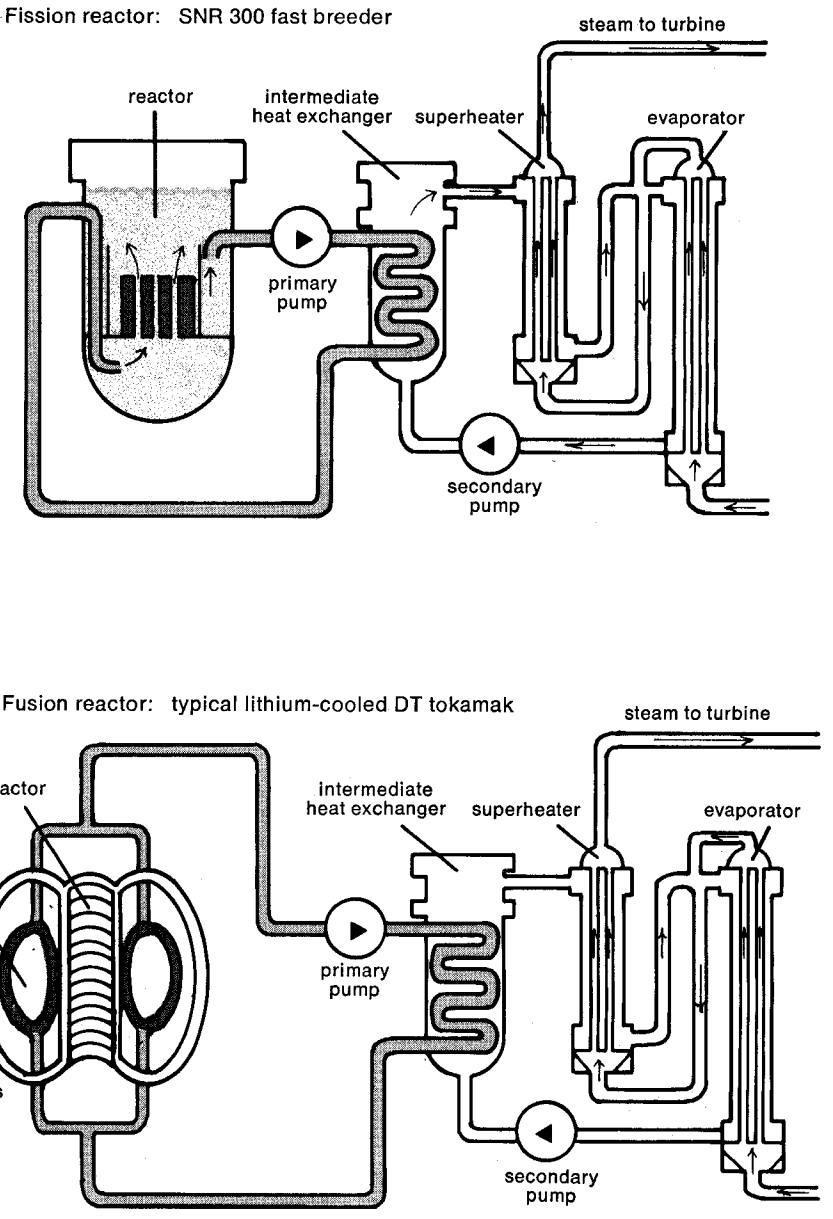
Selecting a representative fusion system is difficult, because it is impossible to state with any certainty which configuration will actually lead to a working reactor. At present, most

Table 1. World energy resource picture

World resources	*Energy content (Terawatt-years)*
Uranium to $100/kg used in light-water reactors	100
Recoverable oil known as of 1976	430
Gas, oil, and coal ultimately recoverable	2,600
Uranium to $100/kg used in fast-breeder reactors	11,000
Lithium to $60/kg used in fusion reactors	11,000
Yearly consumption	*Rate (terawatts)*
1975 worldwide	8.6
total for 8×10^9 people at 6 kw per capita	48.0

* 1 terawatt-year = 10^{12} watt-years

Figure 1. Schematic diagrams of an SNR-300 fast-breeder reactor and a typical lithium-cooled, deuterium-tritium-fueled tokamak reactor reveal that, while energy is released in different ways in the two kinds of reactors, the rest of the electrical plant is much the same in design and size. Actual nuclear reactions take place in the light blue areas.



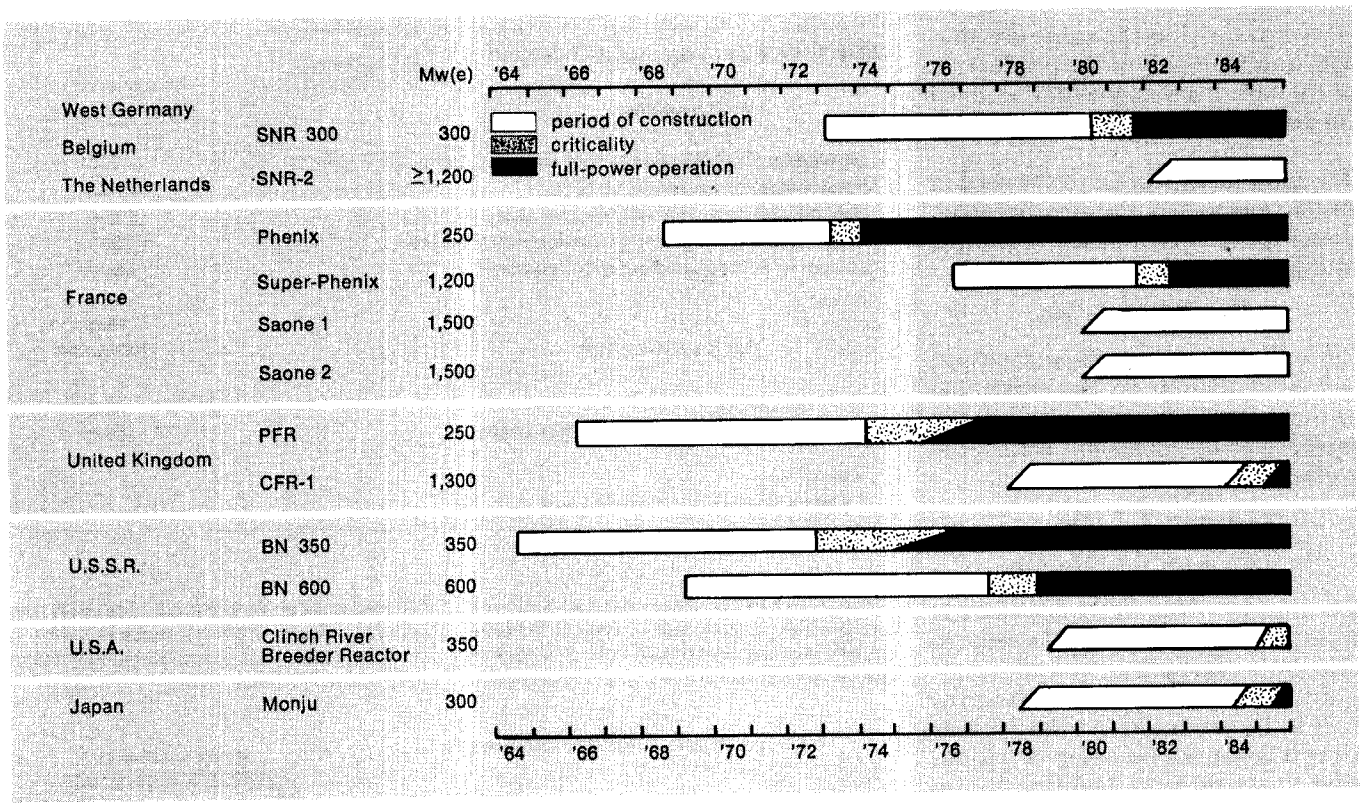


Figure 2. Development of prototype fission fast-breeder reactors is proceeding at different paces in various countries. Note that full-power operation of these reactors does not indicate full-scale commercialization: many problems, such as the closure of the fuel cycle, must be worked out even at this stage. The French Phenix Reactor operated at 85% of full power until August 1976, when engineering difficulties cut this back to about 65%; full-power operation was not restored until the spring of 1978. The U.S. is at present reassessing its commitment to the Clinch River Breeder Reactor.

designs for reactors have been based on what is called the tokamak concept, which seems to provide the greatest promise of success from a scientific standpoint. A tokamak system has a toroidal geometry and complex magnet configuration that make it a very difficult system to design for electricity production. Perhaps some other approach to fusion (e.g., mirrors, laser-driven systems) will eventually lead more easily to a reactor than will the tokamak approach. We have chosen to discuss here the liquid-lithium, stainless-steel–structure tokamak because more extensive and detailed information has been accessible for this design than seems to be available for other approaches. Figure 1 shows a schematic diagram of one of the 12 full-scale tokamaks studied so far.

The status of both fission and fusion systems is best described with regard to three thresholds of feasibility: scientific, engineering, and commercial. The scientific feasibility of fission fast-breeder reactors was demonstrated during the 1950s in the U.S., the U.K., and the U.S.S.R. Since that time, the engineering has developed along two lines. The Enrico Fermi Fast Breeder Reactor represents the early line, which used metallic fuels and produced tens to a few hundred megawatts of thermal energy. The second line, represented here by the LMFBR, is that of potential commercial reactors using mixed oxides of plutonium-uranium as fuel. Reactors in this line have a much higher power density, producing up to 1,500 megawatts of power each.

Figure 2 shows the fission fast-breeder projects under development throughout the world thus far. A large set of physics and engineering test facilities are now available, the result of a heavy investment of capital, manpower, and time. The technologies for liquid sodium as a coolant and for mixed oxides as fuels are essentially in hand. Most of the current tests are devoted to proving the safety equipment and demonstrating the fuel-element performance as required in the licensing process for large power reactors of the 1,200 Mw(e) class. Preparations are now under way for the building of a semicommercial class of 1,200 Mw(e) reactors in France, the U.K., and West Germany. It is possible that these reactor systems will be completed by the late 1980s, and they may be making an input into the electrical generating grids by the 1980s. Engineering feasibility will thus have been demonstrated for fission reactors in France (*4,5*), the U.K. (*6,7*), and the U.S.S.R. (*8*) between 1974 and the mid-80s. The threshold of commercial feasibility is as yet unpredictable.

For fusion power, demonstration of scientific feasibility means creating in an experimental device a combination of fuel density, temperature, and confinement time that would lead to a net output of energy in a reactor. No such feasibility demonstration has yet taken place as of late 1978.

There are fundamentally two ways of confining the deuterium and tritium fuel at high temperatures. The first relies on the use of magnetic fields to keep the hot (about 100,000,000°K)

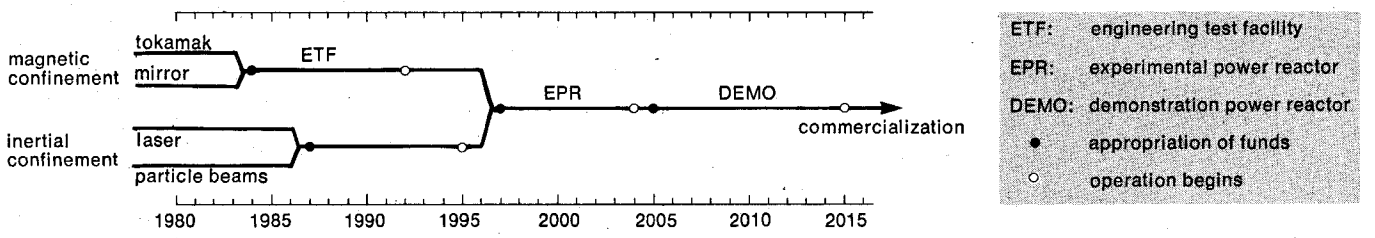


Figure 3. The proposed U.S. Department of Energy program shows that fusion reactors are at a much earlier stage of development than fission fast breeders. The best technological route toward commercialization is not even expected to be decided until the very end of the century. Nevertheless, in the U.S. program, and the comparable Soviet program, it is hoped that engineering feasibility will be demonstrated by the end of this century and that commercialization can be achieved by early in the 21st.

plasma ions away from the reactor components while they react with each other. The tokamak accomplishes this with a toroidal magnetic-field configuration. The second approach to confinement is to use high intensity beams of laser light or energetic charged particles to implode and heat a small pellet of DT to the required reaction conditions. The nuclear reactions take place so fast that it is hoped more energy can be released than was invested in the implosion before the pellet flies apart: thus the term *inertial confinement*. Of the two main approaches to the problem, magnetic confinement has the longer history (research began in the early 1950s) and the greater number of variations, of which tokamaks are one. The idea of inertial confinement for a fusion reactor dates from the early 1960s.

Many proponents of magnetic confinement believe that large DT tokamak devices, now in the late stages of design or early stages of construction, will be the first to achieve scientific breakeven. The rate of progress in magnetic confinement has been truly impressive (see Table 2), and it is hoped that newly constructed devices such as the tokamaks at Princeton and at General Atomic in the U.S. will achieve reactor operation conditions by the early 1980s. Some advocates of inertial confinement believe that laser fusion devices can also achieve scientific breakeven by the early 1980s, but this view is more controversial and is clouded by classification of relevant results.

Once scientific feasibility is achieved with either magnetic or inertial confinement of the fuel, formidable problems of materials and engineering will have to be solved before engineering feasibility can be demonstrated for a working reactor. This is unlikely to be achieved before the year 2020 even in the United States Department of Energy plan for development of commercial fusion power, which calls for a demonstration reactor to be completed by 2015 (see Fig. 3). Commercial feasibility will not be assured even when such a demonstration reactor exists, and fusion will probably not be proved commercially feasible until early in the 21st century. A contribution of more than 10% to the electricity used in industrial nations still seems unlikely before the years 2040 to 2050.

The materials problem

One of the major technical factors limiting the efficiency and economic viability of both fission and fusion breeder reactors is the degradation of materials due to radiation damage in the reactor environment. The limited lifetime of components in a nuclear plant affects the economies of nuclear power plants in six major areas: (1) thermal efficiency is limited, because reactors are restricted to lower operating temperatures; (2) operating time is limited, because time is required to change damaged components; (3) capital costs must include outlays for remote handling equipment, and (4) operating costs must cover replacement components and the installation labor; (5) the discarded parts add to the volume of radioactive wastes that must be handled and stored; (6) finally, demand for scarce elements used in the most highly damaged components will be very large.

Fission and fusion structural components and fuels share some of the same intrinsic radiation-damage problems. Irradiation-induced swelling of the fuel cladding and core structural material is probably most important in the LMFBR because of the close tolerances required for coolant flow. High-temperature helium-induced embrittlement will definitely be a greater problem for

Table 2. Plasma parameters achieved in tokamaks*

Year	Confinement time τ_E (sec)	Ion temperature T_i (Kelvin)	Density × confinement time $n\tau_E$ (sec/cm^3)	Sustainment time (sec)
1955	10^{-5}	10^5	10^9	10^{-4}
1960	10^{-4}	10^6	10^{10}	3×10^{-3}
1965	2×10^{-3}	10^6	10^{11}	2×10^{-2}
1970	10^{-2}	5×10^6	5×10^{11}	10^{-1}
1976	5×10^{-2}	2×10^7	10^{13}	1
1978	5×10^{-2}	6×10^7	2×10^{13}	1
Needed for a reactor	1	10^8	10^{14}	$\gtrsim 10$

* Data prior to 1978 from B. Pease, Culham Laboratory, U.K.

DT fusion than for fission reactors. This is mainly due to the higher-energy neutron spectrum from the DT reaction, which produces more (n,α) reactions in metals. Irradiation creep, the slow deformation of a structural component under stress at high temperature in combination with displaced atoms, will be a major problem in both types of reactors, because of the high displacement rates in the LMFBR and the high thermal stresses in a fusion reactor. Metal fatigue is also likely to be more severe in fusion reactors, especially in inertial confinement systems.

These problems have been studied for over 20 years for the LMFBR. The result has been the choice of a mixed (Pu and U) oxide fuel, 316 stainless steel as a cladding and core structural material, and B_4C as a control rod material. It is quite probable, however, that even the performance of these materials will not be sufficient for a completely economical breeder economy, and carbide fuels along with alloys containing a high percentage of nickel are being investigated for possible long-term application.

The process of selecting the optimum structural materials for fusion reactors is, by comparison, much more diverse, because the technology is in its infancy (*9*). All of the alloys proposed for use in fusion reactors suffer from one or more serious deficiencies in that environment. Aluminum alloys are restricted to quite modest temperatures. The refractory metals niobium and vanadium allow higher-temperature operation with less irradiation-induced embrittlement, but they are extremely susceptible to pickup of interstitial impurity atoms, which also causes embrittlement, and at present there is no commercial industry to supply a mature fusion economy. Molybdenum alloys are probably the best suited of the refractory metals, but major technological advances are required before large-scale reactor components made of these alloys can be effectively joined in a vacuum-tight configuration. Titanium alloys allow reasonable operating temperature, and there is very little long-lived radioactivity induced in them, but very little is known about their behavior in an intense neutron environment.

Based on present knowledge, early fusion reactors will almost certainly use special stainless, nonmagnetic (austenitic) steel alloys. These alloys have been the subject of much research, and a great deal is known about their mechanical, physical, and thermal properties in high-temperature liquid-metal environments. Nevertheless, it is now widely accepted that most of the reactor components will not last the lifetime of the power plant. The necessity to replace damaged components quickly in a very high radiation environment will put a severe strain on the design of a fusion power plant.

Without even taking into account the degradation of parts, the low power density (about 1 Mw/m^3) in the blankets of all fusion reactors (not just tokamaks) means that the requirement for materials in a fusion reactor is likely to be in the range of 25 t/Mw(e) of steel, compared with 3 t/Mw(e) in the LMFBR (see Table 3). In addition, the replacement of damaged structural components may require about 0.2 t/Mw(e)-yr of steel for fusion, compared to 0.07 t/Mw(e)-yr for fission breeder reactors. Thus, about four times as much of what are in some cases rather scarce materials would be required to generate the same energy in a fusion economy as in a fission economy. Careful attention will have to be paid to methods of reducing those requirements for fusion, or they could prove to be the limiting factor to the amount of energy that can be produced by fusion, despite essentially unlimited fuel resources.

Materials problems, then, are much more diverse and severe in fusion reactors than in fission reactors. Without intensive long-range development programs in this area, fusion may never transcend the engineering-feasibility phase.

Radioactivity in reactors

The amount of radioactivity in the various nuclear systems has not always been calculated consistently, and thus comparisons have almost always been controversial. We are speaking here of the potentially hazardous radioactivity associated with isotopes *inside* the reactor. While only isotopes *outside* the reactor can cause harm to life, the potential hazard of the material within the system is an important point of comparison because it represents the absolute maximum problem that can occur and because it is very difficult to calculate the fraction of isotopes that could be released for each accident that might occur.

For any comparison to be useful, one must consider, on a per-unit-of-energy basis, total number of radioisotopes produced, their relative toxicity, and their half-life. Once the normalized radioisotope inventories have been calculated, they can be divided by the maximum permissible concentrations (MPCs) allowed in the environment to yield the amount of air or water that must be used to dilute radioisotopes to safe levels. The value of the radioisotope inventory divided by the MPC is called the Biological Hazard Potential (BHP).

Table 3. Critical materials requirements for the nuclear islands of fission and fusion breeder reactors

	Initial requirement in t/Mw(e)	*Average makeup in t/Mw(e) · yr**	*Total commitment over lifetime of nuclear island in t/Mw(e)*
Fission			
Steel	3.1	0.072	4.8
Sodium	2.81	—	2.8
Control Mat.	0.001	0.0004	0.01
Total	6.0	0.72	7.6
Fusion†	25	0.20	30

* For operation at 80% capacity over lifetime of plant.
† Average for UWMAK-I, UWMAK-II, UWMAK-III, PPPL, ORNL, and BNL designs.

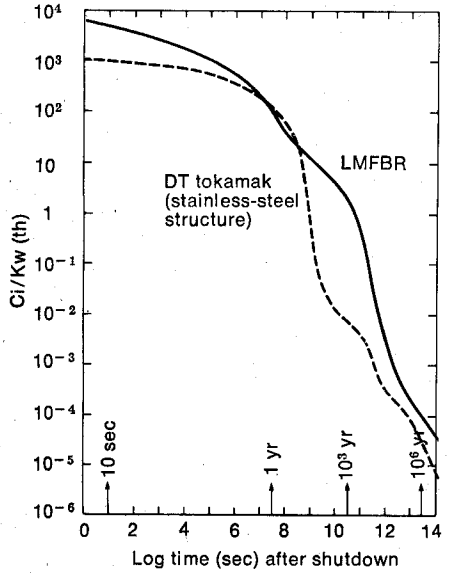


Figure 4. The radioactivity inventory for fission and fusion reactors decreases very slowly after shutdown. The difference between the levels of radioactivity in the two kinds of reactors becomes significant 10 years after shutdown; from then on, the inventory of the fusion system is from 10 to 500 times lower than that of the fission system.

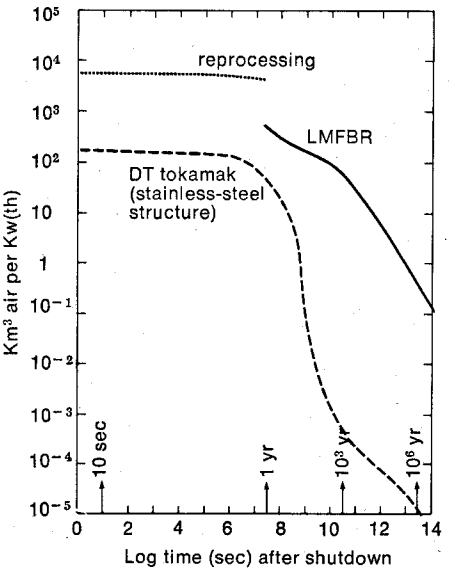


Figure 5. The inhalation hazard from the radioactive inventories of fission and fusion breeder reactor systems is measured in terms of the amount of air required per Kw(th) to dilute the inventory to the maximum permissible concentration (MPC) level set by federal regulatory agencies. This level is well below the threshold at which exposure is known to affect health. Fuel reprocessing lowers radioactive inventory of the fission system but the hazard still remains significantly higher than that of a fusion system.

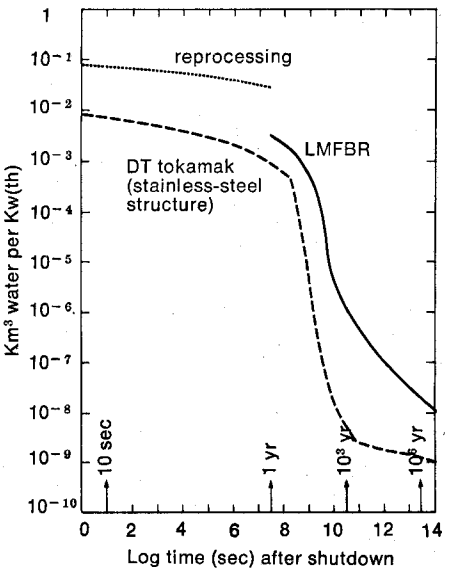


Figure 6. The ingestion hazard from the radioactive inventories of reactors is likewise measured in terms of the amount of water required to dilute the inventory to the MPC level. For water, the MPC refers to the level of radioactivity allowed in drinking water for the public.

Figure 4 compares the radioactivity of the isotopes within fission and fusion breeder reactors as a function of time after the plant has been shut down. Figure 5 compares the amount of air that would be needed to dilute the inventory of radioisotopes to the maximum permissible concentration at various times after shutdown. Such a comparison is mainly applicable to an air release immediately following an accident. Figure 6 does the same for a water dilutent. This could be representative of the amount of ground water that might be required to dilute the radioisotopes from dismantled reactor components stored underground. These figures are of course very large, because they represent absolute maximum release and they are not at all corrected for the *probability* that any of the radioactive inventory will be released into the environment.

As can be seen in these figures, the inventory of radioisotopes for the reference systems is essentially the same (within a factor of 5) for the first 10 years after shutdown. Thereafter, the inventory in the fusion system is a factor of 10 to 500 lower than in the LMFBR for the next several hundred thousand years. The maximum potential hazard of the inventory of radioisotopes as airborne contamination in the fusion reactor is a factor of about 30 to 40 lower than for fission reactors up to the point of reprocessing. The advantage then drops to only a factor of 5 for fusion, but it increases thereafter, becoming a factor of 100,000 after 1,000 years. The potential hazard for water contamination by the fusion reactor inventory starts out a factor of 10 lower than for the LMFBR and remains so up to the point of reprocessing. Thereafter, it increases from a factor of 2 lower to a factor of 200 after 1,000 years of decay. This advantage drops to only a factor of 10 after 10^6 years.

The economic incentive to reprocess fission fuels soon after discharge in large centralized facilities means that large amounts of high-level wastes must be handled, transported, and eventually solidified for long-term storage. In principle, one could integrate the fuel cycle and the reactor, but no major LMFBR program has moved in this direction thus far. At least for the present, then, the separate hazards of the reprocessing and refabrication plants must be included in calculations of the risks that are associated with fission fast-breeder systems.

Fusion systems, on the other hand, have an integrated fuel cycle (tritium separation); and after appropriate compaction, structural steel and other waste material can directly be stored as solids. This tends to reduce the potential for a release of radioisotopes to the environment and could lessen the hazard potential associated with the final transportation of fusion reactor wastes to the ultimate storage facilities.

Finally, the use of vanadium or titanium alloys could increase the above advantages for fusion by even several more orders of magnitude over the LMFBR because their radioisotopes have much shorter half-lives. However, the uncertainty that such alloys can indeed be used in economic fusion power reactors is much larger than for stainless steel. Hopes remain that structural materials for fusion with even more favorable activation properties than steel, such as low radioisotope production rates and short half-lives, will eventually be shown to be feasible.

Normal release of radioisotopes

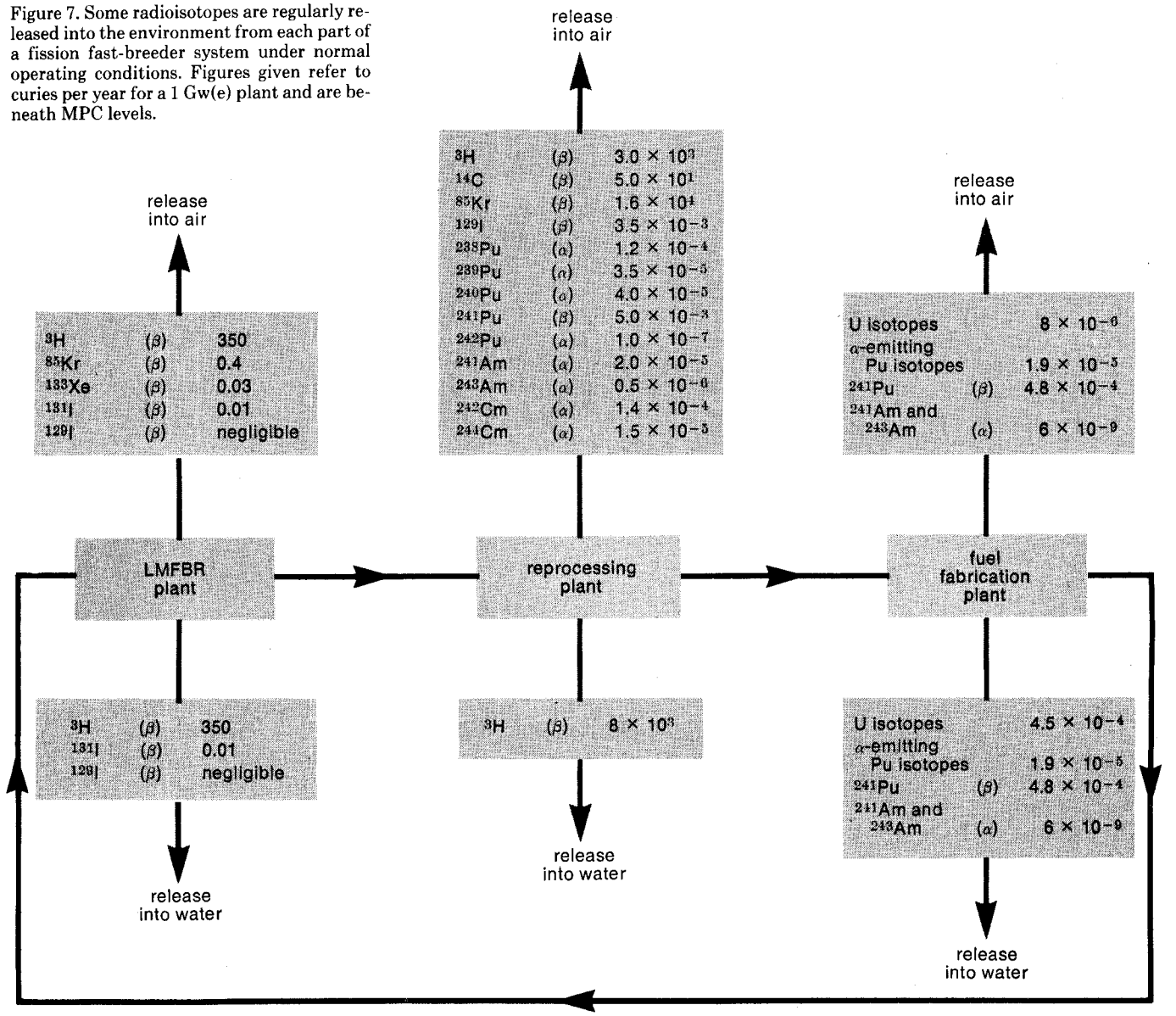
In the normal course of operation of a nuclear reactor, some quantity of radioisotopes will be released from the plant into the surrounding environment. The main radioisotopes of concern here are tritium, krypton 85, iodine 129, and the alpha emitters for the LMFBR; tritium alone for fusion reactors. Possible accident pathways are different for different systems, and the release of these isotopes can only be estimated once very specific designs have been completed. The scientific community has been in the process of analyzing the detailed LMFBR designs (and their associated fuel cycles) for the last 5 years. Unfortunately, detailed fusion reactor designs are at least 20 years away.

The point of ultimate importance, the fraction of those regularly released isotopes that are actually absorbed by humans, is difficult to calculate for the radioisotopes from both fission and fusion. Such a calculation requires a knowledge of human residence time in the contaminated area, chemical uptake in the various food chains, intake of contaminated air, food, and water, and so on. Some of these assessments have already been made for isotopes such as tritium, iodine, and cesium, but very few have been made for the metallic isotopes or for the actinides.

The release of radioisotopes throughout the entire LMFBR fuel cycle is summarized in Figure 7. In order to meet the recently proposed release limits set by the Environmental Protection Agency for large-scale power plants, annual confinement factors of 10 for krypton and 200 for iodine 129 must be achieved; that is, not more than 1/10 of the krypton isotopes flowing through the plant annually may be released and not more than 1/200 of the iodine 129. For transuranium alpha emitters, the factors are 2×10^9 in the reprocessing plant and 2×10^{10} in the refabrication plant. If a person were to stand at the fence of a facility meeting these standards and obtain all of his air and water from that area, his exposure would be well within EPA limits.

It appears to be no problem to achieve such confinement factors for krypton and iodine. Confinement factors of 10 for krypton are considered to be technically feasible today, whereas

Figure 7. Some radioisotopes are regularly released into the environment from each part of a fission fast-breeder system under normal operating conditions. Figures given refer to curies per year for a 1 Gw(e) plant and are beneath MPC levels.



confinement factors of 10^3 have already been achieved by cryogenic methods in large-scale prototype test facilities (*10,11*). Iodine confinement factors of 200 have already been demonstrated, and higher iodine confinement factors are within reach (*12*). For the alpha emitters, the confinement factors mentioned will be more difficult to obtain. Even though these values have already been achieved in small pilot plants, they still have to be demonstrated in large commercial facilities (*10,13*).

For fusion reactors, concern lies almost entirely with tritium, and since the fuel fabrication and reprocessing units are confined to the reactor building we have only one location to consider. The throughput of tritium (both in the dynamic fuel handling system and the tritium breeding blanket) is estimated to be about 250 MCi/Gw(e)-day. If we assume that the release rate is limited by the requirement that the tritiated water concentration cannot produce a dose greater than 5 mrem/yr in an individual who takes all of his drinking water from the plant discharge, no more than 300 Ci/day should be released. This means that the control factor has to be roughly 1 part per million per day, which is 3 orders of magnitude higher than the control achieved in present-day LWRs and a factor of 100 higher than assumed for present LMFBRs. But such improvements, while not easy, should be attainable in the next 20 years. It must be noted that while the confinement factors for both LMFBRs and fusion systems seem attainable, it remains to be seen what the cost burden will be for these controls.

Accidental release of radioisotopes

Accidents in fission and fusion breeder reactors can be divided into two kinds. The first kind we call design-basis accidents, since they are a consideration in the design of the system. Included are both *realistic* accidents—those that are known to be conceivable, though some chains of accidental events are included that are of low probability—and *hypothetical* accidents—chains of accidental events that have not been proved to be inconceivable but have a probability of occurrence that is below a given level. Realistic accidents are taken into account in the choice of core safety parameters and the design of the shutdown system. Hypothetical accidents are taken into account in the design of the cooling system and of the surrounding containment system. The second kind of accident is that caused by sabotage or acts of war. The precautions required to prevent these are more procedural than technological.

Early concerns about the safety of LMFBRs focused on control characteristics and the possibility of core recompaction (that is, the reassembling of the fuel elements in critical configuration after an accident). Accidents in this class begin with boiling of sodium in the cooling system and local fuel melting. The recompaction could be due to pressure pulses resulting from sodium-vapor explosions in the core or other unique coolant flow schemes resulting from an accident. These concerns were accentuated by the emphasis on compact cores and metallic fuel elements in breeder designs of the 1950s and early 1960s. Large cores and mixed-oxide fuels are typical of all prototype and commercial LMFBR designs in the 1970s, and it is now known that the control characteristics are substantially similar to those of the LWR. Moreover, a large and growing body of theoretical and experimental evidence supports the view that the propagation of local fuel failures in a way that leads to recompaction in the large-core, mixed-oxide-fueled LMFBR would require combinations of events and degrees of spatial and temporal coherence that are not physically realistic (*1*) (e.g. the probability of such a series of events occurring is less than once every million years).

The large LMFBR prototypes that are in operation in France and in advanced stages of construction in West Germany have undergone licensing reviews as stringent with respect to safety as the ones that are applied to LWRs. The designs of these large LMFBRs take into account the possibility of failure of two independent shutdown systems following a hypothetical large insertion of reactivity or coast-down of the main sodium pumps. The calculated consequences of melting and core disassembly in these maximum hypothetical accidents define the design characteristics of the containment systems required for licensing (strength of reactor vessel and primary piping; strength and leak rates of surrounding double steel and concrete containment structures). In addition to the pressure loads during such an accident, the long-term cooling of large masses of molten and dispersed fuel after the accident must also be taken into account.

While this capability appears to be at hand for the 300 Mw(e) class LMFBR, additional development work is needed for large LMFBR power stations. These design requirements can be met with reasonable technical effort, and as the French and German experience indicates, radiation doses can be restricted to 1 rem or less at the plant boundary in the event that a design-basis accident occurs. The overall conclusion is that the LMFBR can meet the same predetermined safety standards that are applied to other fission reactors. This may or may not also hold for the fabrication and reprocessing plants associated with the LMFBR.

Fusion-reactor safety analysis is necessarily in a much more preliminary phase, because the technology cannot be described in detail. Examination of stored energies and potential pathways for energy release in tokamak designs indicates that sudden failures of the magnet support and vacuum systems could produce enough mechanical energy to severely damage the reactor. Loss of coolant or coolant flow coupled with failure to shutdown the fusion reactor could also cause local interior structural damage. However, the characteristics of fusion plasmas and the very small amount of fuel present in the reaction chamber at any time mean that reactivity accidents will not be an important concern.

Decay heat due to neutron activation of structural materials is small enough in most designs to be much easier to handle than in fission reactors. For fusion-reactor designs where liquid lithium serves as breeding medium and coolant, the very large chemical energy stored in this coolant and the high flame temperature of the lithium-air and lithium-water reactions probably represent fusion's most important vulnerability to accidents capable of releasing sizable quantities of radioactivity. Both LMFBRs and liquid-lithium-cooled

fusion reactors require careful design of steam generators to ensure safety in the event of possible leaks that would bring water into contact with liquid metal.

The risks for many of the possible accident pathways in fusion reactors can be minimized by intelligent design, which includes the possibility of breeding tritium in ceramic lithium compounds (which would lower the inventory of tritium by one or two orders of magnitude in the region surrounding the plasma) and cooling with pressurized helium instead of liquid lithium to reduce the fire potential. Such an approach could reduce the inventory of tritium that could be released from the breeding area in an accident, though other sources of tritium in proximity to the blanket (e.g. vacuum pumps) will not be affected by the change to solid breeders. Enthusiasm about the potential flexibility in design of fusion reactors must be tempered with the recognition that there may be important trade-offs—for example, the possible need to use toxic and relatively scarce beryllium for neutron multiplication if some solid breeding compounds are employed in realistic blanket designs.

Designers of fusion systems can anticipate that the approaches they devise to control energy release from magnets, vacuum systems, coolant, and so on will be subjected to much the same critical scrutiny and demand for high reliability experienced now in fission-reactor licensing proceedings. It is too early to say how difficult it will be to survive such scrutiny, but the authors feel that it will be possible if the full attention of the engineering community is given to the problem.

Comparison of fission breeders and fusion reactors can also be made with respect to the consequences of events worse than the design-basis accidents—accidents resulting from acts of war or sabotage. Analyzing the Rasmussen Report of the U.S. Nuclear Regulatory Commission reveals that hypothetical release of a substantial fraction of the fission products and 0.5% of the actinides in an LWR—the same isotopes that are of concern in an LMFBR—would produce roughly 100 times more early deaths under adverse meteorological conditions than the release of 10 kg of tritium from a fusion plant. This much tritium could represent 10–20% of the total inventory (Fig. 8). Much in need of further investigation is what fraction of the activation products in a fusion reactor and of the actinides in an LMFBR could be released in such hypothetical events, as these fractions significantly affect the outcome. Comparative examination of delayed as well as early casualties is also needed.

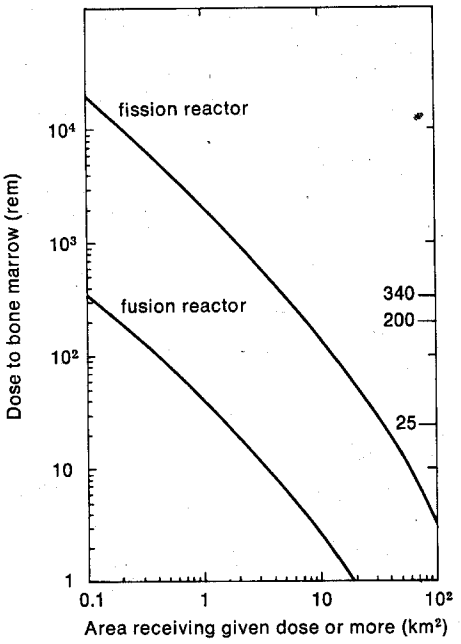


Figure 8. Plotting critical dose versus area for severe releases from fission and fusion breeder systems shows that fusion has a significant advantage over fission. To suggest the meaning of these figures: 1% of a population receiving a dose of 200 rem will die within 60 days; 50% of a population receiving a dose of 340 rem will die within 60 days. Twenty-five rem is designated by the International Commission on Radiation Protection as the emergency dose limit: that is, one-time exposure to this amount of radiation is not considered harmful.

A further caveat is in order. In a fusion reactor, most of the fuel cycle is within the reactor-containment structure. For the LMFBR there must exist, in addition, fuel-reprocessing and fuel-fabrication plants, which means that large amounts of highly radioactive wastes must be handled and transported. Analysis of the potential hazards in these parts of the fuel cycle is not yet nearly as refined as that for the LMFBR itself.

Furthermore, both LMFBR and fusion reactors will require facilities for long-term radioactive-waste management, for which accident analysis will also have to be done. The fact is that, after appropriate compacting, radioactive structural steel and other waste materials from fusion reactors can be directly stored as solids instead of being chemically reprocessed. This gives fusion systems a large advantage in terms of potential for release of radioisotopes to the environment during both transportation and storage.

Safeguarding nuclear reactors

Both fission and fusion breeder reactors hold dangers beyond their own operation and malfunctioning—namely, the possibility that materials and technology will be diverted from their peaceful use in the production of energy to the production of weapons. The hazards are not, however, the same for both kinds of system.

As fission power spreads, the associated spread of bomb-related material is more of a threat than the spread of bomb-related knowledge. (This is a problem of all forms of fission, not just breeders.) If fusion power spreads, and if the inertial-confinement approach predominates, the associated spread of bomb-related knowledge will be more important than the direct spread of bomb-related material. Neutrons from any DT fusion reactor could be used by the operators to produce fissile material, however, and thus both types of nuclear reactors pose an indirect threat of the spread of bomb-related material.

Misuse of nuclear material as a radiological rather than an explosive weapon is a threat associated with both fission and fusion. Here fusion's hazard is from the tritium, which is used in all approaches, not just the inertial-confinement approach. With respect to airborne dispersal of plutonium or tritium reactor inventories, fusion appears to have a quantitative advantage over fission of 2 to 5 orders of magnitude (see Table 4), depending on the chemical form of the materials. With respect to waterborne dispersal, the fusion reactor has only a slight advantage.

For fission power, safeguarding of fuel transport is a greater problem than safeguarding power stations or re-

processing plants. As we have mentioned, the fission fuel cycle is spread out, and it will remain so unless collocation of some parts of the fuel cycle becomes standard procedure. For fusion, the tritium for the most part remains in the power stations; transportation is necessary only when new power stations are being started up. The centralization of the problem for fusion makes the protection against theft easier than for a fission economy.

The detection of diversion of nuclear material is addressed by the Non-Proliferation Treaty, which calls for more international than national controls. For a state, the most direct route to the fabrication of a few crude nuclear explosive devices is probably the construction of centrifuges which could separate out the fissile isotope ^{235}U from the natural uranium; it is not the deployment of economically significant civilian nuclear fission power.

Establishing an equilibrium of any kind between risks, benefits, and costs is, in the first analysis, a step that entails social and political considerations as well as technical insights. At the present time the arguments seem to be mainly in the social and political arenas, as the technical issues are mostly solved.

Table 4. Summary of the radiological hazards of plutonium and tritium (normalized to a 1 Gw(e) power plant when necessary)

	Pu (LMFBR)	*Tritium (DT Tokamak)*
Inventory of reactor (kg)	3,400	25[a]
Annual flow outside reactor (kg/y)	1,600	27[b]
Hazards in Air		
Maximum permissible concentration (MPC) in air (Ci/km^3)		
Insoluble ^{239}Pu or T_2 gas	0.001	40,000
Soluble ^{239}Pu or tritiated water vapor	0.00006	200
Biological hazard potential (BHP) per gram of element (km^3 of air required to dilute 1 gram of radioisotopes to maximum permissible concentration)		
Pure ^{239}Pu or elemental T	63–1000	0.25
Reactor[c] grade Pu or T in tritiated water vapor	300–5000	50
Total amount of air required to dilute reactor inventory to the MPC level (10^6 km^3)		
Least harmful form of radioisotopes[d]	1,020	0.006
Most harmful form of radioisotopes[e]	17,000	1.25
Hazards in Water		
MPC (Ci/km^3 of water for soluble forms)	5,000	3,000,000
BHP (m^3 of water required to dilute 1 gram of radioisotopes to the MPC level)		
Pure ^{239}Pu insoluble compound	12,500	
Reactor grade Pu in soluble compound	62,500	
Tritiated water		3,300,000
BHP of reactor inventory in km^3 of water required to dilute all radioisotopes to MPC levels	210	83

[a] Roughly one half in the cold storage for backup and the other half actively circulating in reactor.
[b] At a tritium breeding ratio of 1.25.
[c] Contains ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu.
[d] Reactor grade Pu dispersed in insoluble form, tritium dispersed as T gas.
[e] Reactor grade Pu dispersed in soluble form, tritium dispersed as vapor.

Commercialization

If commercial feasibility of fission fast-breeder power stations is indeed attained between 1990 and the year 2000, this will represent roughly 50 years in the scientific and engineering feasibility stages. Approximately the same amount of time is anticipated for fusion reactors (although the uncertainty is greater), but since serious research into the scientific feasibility of fusion reactors started later, commercial feasibility of large-scale power stations will probably not be achieved until after 2020.

The economic viability of fission fast breeders requires the services of a separate fuel cycle. But such a fuel cycle can be developed on a technically and economically significant scale only when irradiated fuel is available in significant quantities from operating reactors. Thus 10 to 15 years must be added to the time required to achieve operation of commercial reactors for the completion of the full fission-breeder system. On the other hand, no separate fuel cycle will be required after a large number of fusion reactors are constructed, and therefore the point of commercial feasibility should be easier to define. Both fission and fusion breeder systems will require facilities for final waste disposal, however, and this will extend the complete time frame in both cases.

Three generations of reactors seem to be necessary before commercial feasibility for both kinds of energy sources can be demonstrated: experimental power reactors, producing 10 to a few 100 Mw(th); prototype demonstration reactors, 250 to 500 Mw(e); and semicommercial reactors, 1,000 to 1,500 Mw(e). Along with these major facilities, a large number of smaller but equally important facilities need to be developed to test various aspects of the physics, engineering, materials, and safety for both kinds of systems. Materials-testing facilities can be particularly costly and time-consuming to the overall program development. There is hardly any way to circumvent these procedures, as each generation of reactors requires higher performance characteristics, which are difficult to test in facilities existing up to that point.

In order to be useful, fast breeders and fusion reactors must fit into existing schemes and rules of electricity production. Demonstration of availability, maintainability, and repair-

ability is in itself a complex procedure that requires time. In fact, the rules and fundamental data underlying the licensing process must be developed *almost in parallel* with the reactors and facilities that are to be licensed. Public acceptance has been shown to be a problem distinct from—and perhaps harder to resolve than—licensing.

In the U.S., because its development program is so broad and stretched out, more than $10 billion are expected to be necessary for reaching commercial maturity of the LMFBR (see Fig. 9)—about 6 times the amount already spent. By contrast, in European countries the development programs seem to be narrower and more compact in time and thus are likely to be considerably cheaper. The difference in funding points to the degree of flexibility that such programs seem to have. In any event, the parallel development programs throughout the world contribute significantly to each other—which, in fact, may explain the seemingly lower cost of the European programs.

The situation for the fusion program is much less well defined, but recent projections in the U.S. program reveal that it may require $20 to $25 billion to bring fusion through the demonstration power-reactor phase, and it is not unreasonable to expect that another $5 to $10 billion will be required to progress through the commercialization stage. In contrast to the fission-breeder program, the European fusion program is much smaller and of longer duration. The Soviet program is approximately the same as the U.S. program in level of effort now, and it is expected to keep pace with the U.S. program. Therefore, it is reasonable to expect that, worldwide, as much as $50 billion may be required to reach commercial feasibility of fusion. The same benefits of international cooperation in fusion research as in fission are expected to allow for considerable flexibility in reactor design and should increase the probability of long-term success.

Energy for the long run

From this brief analysis we now come to several conclusions. First, it is of central importance that both fission breeders and DT fusion have the potential, in terms of fuel supply, of providing very large, almost indefinite, amounts of electricity. In this respect, there is no difference between them that is of any practical significance.

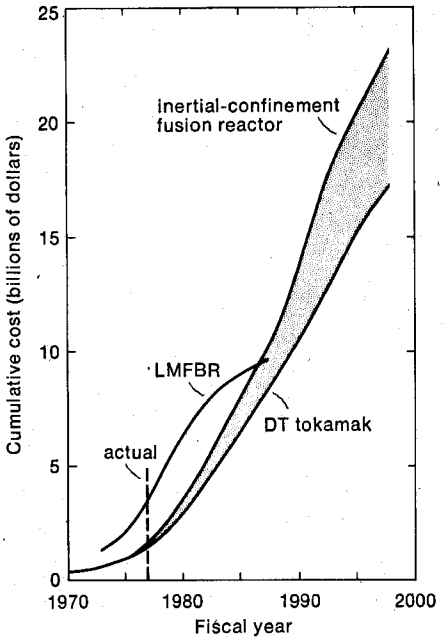


Figure 9. The projected cumulative cost of bringing fusion power to the commercial stage in the U.S. is higher than that of the LMFBR (excluding the investment in the present light-water reactor industry, with which the fast breeder shares some technology and test requirements). The curve for fusion reactors using inertial confinement is based on a rate of fiscal support for research at 33% of the level of support for the magnetic confinement approach. Costs calculated represent government funding to the end of the century, by which time private industry should be able to take over.

To solve the fuel supply problem for the indefinite future would be an enormous benefit, but we can see from this study that the benefit has its price. Both for fission breeders and for fusion, the price includes a heavy investment in research and development before the commercial stage is reached, continuing high capital costs for the commercial reactors and supporting plants, and a commitment to maintain a high degree of meticulousness and vigilance in the construction and operation of these facilities and in the sequestering of their wastes.

While there are significant differences in the basic physical processes of fission and fusion, the presently envisaged technologies for using these processes in electricity production have much in common: lack of any significant air or water pollutants; complex large-scale engineering based on large, central-station power plants; material damage and activation by neutrons; the need to contain inventories of radioactivity within the plant and to manage radioactive wastes beyond the lifetime of the reactors; and for many present designs, use of liquid-metal cooling and heat-transfer technologies.

In principle, however, the nature of the fusion process allows for a much greater degree of flexibility in the technologies used to harness it. This flexibility, if explored and utilized, offers the possibility for fusion based on the deuterium-tritium cycle to be quantitatively superior to fission in important environmental and social respects, despite the qualitative similarities already mentioned. Specifically, fusion has the potential for quantitative advantages in the form of lower hazard potential in its radioactive inventory (and, accordingly, smaller predicted consequences of hypothetical large releases); lower radioactive decay heat; smaller hazard potential and shorter hazard lifetime associated with radioactive wastes; less shipment of dangerous material outside the reactors; and small hazard potential for use of tritium as a radiological weapon (compared with plutonium in fission reactors).

There are, of course, qualitative differences in accident pathways in fusion and fission and these need to be better understood before more definitive statements can be made. With respect to the spread of the capability of making nuclear bombs, we conclude that fission spreads relevant material more than knowledge and fusion spreads knowledge (related to the inertial confinement approach) more than material.

It must be emphasized that achieving the potential environmental advantages of fusion in a practical system will require giving high priority and prolonged attention to environmental characteristics from the earliest stages of designing fusion systems. The advantages will not materialize automatically simply because fusion is fusion. Fusion systems can be envisioned that will not have the most important environmental advantages over a fission-breeder system.

The environmental advantages of fusion that are achieved will have to be weighed against the cost of achieving them. No such weighing can be done today, because the technology has so far to go and because the value that society will place on such advantages has yet to be determined.

The LMFBR, by contrast, has passed the thresholds of scientific and engineering feasibility, with commercial feasibility still to be demonstrated. Herein lies a dilemma of timing. The LMFBR meets the fundamental requirement for a long-term energy source—namely, a nearly inexhaustible fuel supply—but the timing of its development has been such that the LMFBR's commercial feasibility, as well as its environmental and social characteristics, are being judged against the yardstick of existing short-term or transitional energy technologies such as oil, natural gas, light-water reactors, and coal. Such comparisons are relevant for helping to determine the appropriate timing for commercial introduction of a technology such as the breeder, but since oil, gas, LWRs, and coal do not meet the basic fuel-supply criterion for long-term sources, they are not suitable yardsticks for judging the LMFBR's viability and desirability as a way to meet the long-term needs.

Just as part of the present predicament of the LMFBR arises from evaluating a long-term source against short-term competitors, there is a related pitfall that could damage the future of fusion. The pitfall is that the desire to bring fusion to commercial fruition in time to compete in the transition time frame (say, in the period 2000 to 2030) may lead fusion programs around the world to place a disproportionate emphasis on early engineering feasibility at the expense of potential environmental advantages. If fusion technology is steered too early in the direction of doing whatever seems necessary to produce commercial power as quickly as possible, the field may be shaped for a long time to come by approaches that exclude the environmental benefits which represent fusion's greatest asset as a long-term energy source.

It is essential, therefore, to keep separate in technology assessments the differing requirements of the short-term, transitional, and long-term phases of the energy problem. The most significant comparison of long-term sources is with each other, and that is the pertinence of our comparison of LMFBR and DT fusion here. As the needed information becomes available, such comparisons should be extended to include large-scale use of solar energy and perhaps fusion and fission fuel cycles other than the DT tokamak and the plutonium-burning LMFBR.

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