Fusion Energy in Context: Its Fitness for the Long Term

A rationale for long-term energy sources suggests that some forms of fusion may be worth the wait.

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Summary. Long-term limits to growth in energy will be imposed not by inability to expand supply, but by the rising environmental and social costs of doing so. These costs will therefore be central issues in choosing long-term options. Fusion, like solar energy, is not one possibility but many, some with very attractive environmental characteristics and others perhaps little better in these regards than fission. None of the fusion options will be cheap, and none is likely to be widely available before the year 2010. The most attractive forms of fusion may require greater investments of time and money to achieve, but they are the real reason for wanting fusion at all.

Fusion is under fire. Once almost everyone's candidate as the technological key to the long-term energy future, harnessing on Earth the process that powers the stars has lost at least the universality of its allure. The task of proving terrestrial controlled fusion scientifically feasible has turned out to be far more consumptive of time and money than anyone thought likely when the challenge was first taken up in earnest in the 1950's, and the early claims that fusion power would be cheap, clean, and absolutely safe have had to be qualified and requalified, as the technologists' understanding of fusion and the public's skepticism about technological miracles grew apace. In the late 1970's, with fusion technologists increasingly confident that the threshold of energy break-even is finally within reach, a few (but prominent) voices on opposite sides of the highly polarized energy debate are asking, who needs it?

Sniping at fusion from one side are some who believe that its approach is unsuitable in principle; that is, that large, centralized electricity sources are part of the problem rather than part of the solution (*1*). Undermining the case for fusion from the other side (and somewhat less directly) have been assertions that everything fusion might someday be able to do can already be done by fission breeder reactors (*2*).

Is fusion an idea whose time passed between the conception and the delivery? Or is there still a niche for it in the environment in which long-term energy sources must compete? What, in short, is its fitness as a long-term energy option? In this article I explore this issue in two steps: first, with a brief discussion of the nature of the energy problem in time perspective, leading to a list of elements of a rationale for new energy sources; and, second, with an evaluation, in terms of this rationale, of fusion's prospects as they appear today.

Nature of the Energy Problem

The heart of the energy dilemma is that production and use of energy exert both positive and negative influences on well-being, as indicated diagrammatically in Fig. 1 (*3*). Supplying energy to the economy contributes to the production of a stream of economic goods and services generally supportive of well-being; but the disruptions of the social, biological, and geophysical components of the environment that arise from the processes of getting, converting, and using energy detract from well-being by diminishing the stream of environmental (nonmarket) goods and services these components provide.

It follows from the nature of the two-sided relation between energy and well-being that it is possible in principle, at some specified level of energy use already achieved and for a specified mix of technologies providing it, that a further increase in the acquisition and use of energy will produce incremental damages to well-being (that is, the sum of incremental economic and environmental costs) that exceed the incremental benefits. This level would constitute a rational (as distinct from a strictly physical) "limit to growth" for energy—susceptible in principle, of course, to modification in time with changes in the technologies of energy supply and use (*4*). It is possible, in short, to suffer from having too much energy, too soon, as well as from having (in the more traditional view of the energy problem) too little, too late.

Pondering energy issues in this symmetric framework, in fact, suggests a particularly useful way to contrast short-term and long-term perspectives concerning what "the energy problem" actually is. Historically, analysts have been preoccupied with the economic side of the relation between energy and well-being, and this preoccupation continues to dominate most people's perceptions of the nature of the energy problem. It has been presumed that the economic benefits of adding to energy supply invariably outweigh the sum of the economic and environmental costs. Accordingly, the main energy-related threats to well-being in the short term have been seen as problems of "too little": depletion; rising prices; falling security of supply of the energy sources—petroleum and natural gas—on which industrial society has become most heavily dependent; and the high economic costs and long time delays associated with the immediately identifiable alternatives to conventional oil and gas supplies, namely Arctic and offshore oil, imported liquefied natural gas, expanded coal production, fission reactors, and solar collectors. The complex of issues intertwined in this "too little" perspective includes, among others, the political ramifications of the world's growing dependence on a relatively small number of petroleum exporting nations; the differential impacts of rising energy prices on rich and poor, as nations and as individuals; and the uncertainty and dispute concerning the degree to which

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more efficient end use of energy can be elicited by higher prices or by regulation, without undue economic disruption.

Gradually intruding on this perspective has been a growing interest in energy's effects on well-being through the environmental linkages. Since the late 1960's, in fact, increased attention to identifying and quantifying environmental costs and to incorporating them in the decision-making process has established the principle that they can be important enough to justify postponement, significant modification, or even abandonment of specific energy supply projects (*5*). Environmental costs of energy supply that have come under intensified scrutiny in this period include, among others, direct damage to human health caused by effluents of fossil fuel combustion; exposure of human populations to big disasters with small probabilities, such as nuclear reactor accidents and dam failures; disruption of service functions of environmental processes by effluents and physical transformation in fuel extraction, processing, transportation, and conversion; contribution of nuclear power to the rate and extent of proliferation of nuclear weapons; preemptive use of scarce resources (such as western water for coal development); and social impacts of precipitous regional development in support of energy facilities (such as mines, ports, and synfuels plants).

These pervasive concerns are more than a mere perturbation on traditional views of the energy problem. They suggest that what the political trauma over short-term energy choices increasingly reflects is not an inability to expand energy supply at some cost, but rather a growing perception that the cost—when economics and environment are considered together—is too high. Increased attention to the environmental side of the relation between energy and well-being—and, accordingly, to the "too much" interpretation of where energy-related threats reside—is, in fact, the initial phase of a natural transition to a perspective on the energy problem shaped more by awareness of long-term constraints than by preoccupation with short-term predicaments. It is the ever-clearer shape of the long-term future exerting its influence on the present.

For, paradoxically, the nature of the energy situation in the very long term is a good deal clearer in its general outline and characteristics than the muddle of short-term energy problems and the multiplicity of possible pathways through the middle term. In the long term, inescapably, the global rate of energy use will be nongrowing (*6*) and supplied by means sustainable in a steady state. Physically, a sustainable energy system must rely on one or more of the following: solar energy (in many forms), fission (in breeder reactors), fusion, and conceivably, geothermal energy (from magma or hot rock). Socially, a sustainable system must avoid the strains of today's inequitable allocation of energy use among the world's regions, and while it cannot be without environmental impact, the environmental disruption it causes must not increase with time. The level at which global growth stops would be determined in a rational world as that where the contribution to well-being obtained by adding another joule no longer exceeds the economic and environmental costs of getting and using it. The central energy problem in the long term is to choose the combination of sources and uses that maximizes aggregate well-being at this point where further growth no longer pays, and the problem that defines the last part of the transition by which the sustainable state is reached is to recognize the approach of this point of vanishing marginal returns soon enough to avoid overshooting it.

The perspective in which the long-term energy situation should be viewed is qualitatively different, then, from the historical-traditional perspective in which the energy problem until recently was nearly universally seen. The long-term perspective is necessarily governed by the totality of linkages in the relation diagrammed in Fig. 1, rather than being dominated by the economic linkages, because it is precisely the balancing of rates of change of costs and benefits through all the links that determine how much energy should be provided and, accordingly, how much energy-derived good can be done. Environmental characteristics of long-term energy technologies, including especially the scale and rates of change of social and environmental costs at high use rates or high

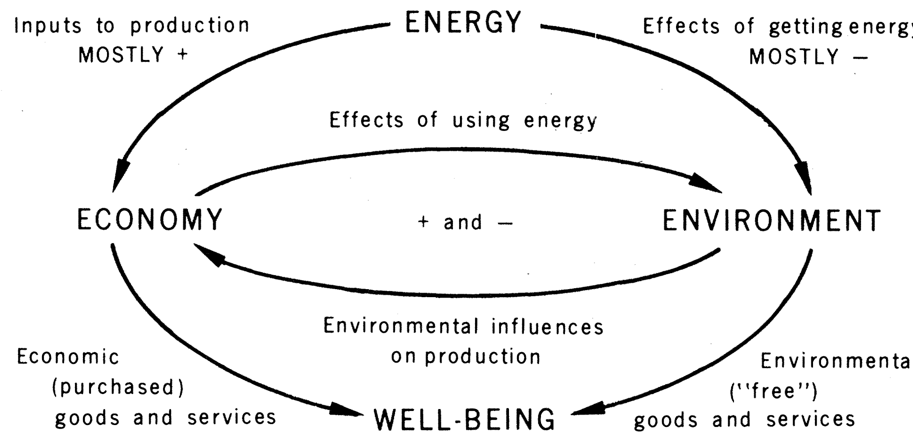

Fig. 1. Links between energy and well-being are effected by the economy and by the environment. The role of energy as an input to economic production, in combination with capital, land, labor, and nonfuel raw materials, is mainly positive; a negative dimension enters only insofar, as energy-production activities divert capital and other inputs from other sectors of the economy. Largely negative effects of getting energy on the social, biological, and geophysical environment include consequences of, for example, mining, refining, fuel transportation, and electricity generation; a positive dimension may enter, such as flood-control benefits of hydroelectric dams. The way energy is *used* in the economy may affect the environment negatively (suburbanization on cropland, offroad vehicles) or positively (sewage treatment plants, industrial emission controls). Environment, in turn, influences the economy through both environmental inputs to production (natural pest controls and nutrient cycling in agriculture) and environmental constraints on production (emissions limits) (*3*).

Table 1. Fusion reactions of greatest interest. The reactants are D, deuterium; T, tritium; n, neutron; and p, proton. The characteristic temperature is that at which the confinement quality (density × mean confinement time) needed for energy break-even is minimized (1 keV ≈ 11 × 10^6 °C).

Reaction	Characteristic temperature (keV)
*Fusion**	
$D + T \rightarrow {}^4He + n + 17.6$ MeV	25
$D + D \rightarrow {}^3He + n + 3.2$ MeV	150
$D + D \rightarrow T + p + 4.0$ MeV	150
$D + {}^3He \rightarrow {}^4He + p + 18.3$ MeV	100
${}^{11}B + p \rightarrow 3\,{}^4He + 8.7$ MeV	200
Tritium breeding†	
${}^7Li + n$ (fast) $\rightarrow T + {}^4He + n$ (slow)	N.A.‡
${}^6Li + n$ (slow) $\rightarrow T + {}^4He$	N.A.

*Exothermic reactions involving D-^{6}Li and p-^{6}Li also exist, as do others not shown, but they do not appear to offer advantages commensurate with their difficulty, compared to those listed. †Natural lithium is 92.6 atomic percent ^{7}Li and 7.4 atomic percent ^{6}Li. ‡N.A., not applicable.

Table 2. Energy content of potential nuclear fuel resources. Energy yields are assumed to be (in kilowatt-hours per gram) 10,000 for lithium, 21,000 for boron-11, 96,000 for deuterium, and 13,000 for uranium (corresponds to 60 percent of the potential nuclear energy of the uranium mined). One terawatt-year = 8.76×10^{12} kWh = 30 quads = 0.03 Q; in 1976 the U.S. energy use was 2.5 TW-year and the world energy use was 8.5 TW-year.

Resource	Basis	Fuel (10^{12} g)	Energy yield (TW-years thermal)
	Reasonably assured resources		
U.S. lithium to three times 1975 prices	Pegmatites > 6000 ppm Li, brines > 35 ppm Li (*8, 51*)	6	7,000
U.S. boron-11	Reserves at 1971 prices (*52*)	30	70,000
Deuterium in seawater	33 g/m^3, 50 percent recovery* (*53*)	23,000,000	250,000,000,000
U.S. uranium	Ores > 25 ppm U (*54*)	12	18,000
	Probable resources		
Boron-11 in seawater	4 g/m^3, 50 percent recovery* (*55*)	2,700,000	6,500,000,000
Lithium in seawater	0.17 g/m^3, 50 percent recovery* (*55*)	120,000	140,000,000
	Speculative resources		
World terrestrial lithium	14 times U.S. supply reasonably assured†	84	1,000,000
World terrestrial uranium	14 times U.S. supply reasonably assured†	170	2,500,000
Uranium in seawater	0.003 g/m^3, 50 percent recovery* (*55*)	2,000	3,000,000

*The 50 percent recovery factor was assumed somewhat arbitrarily, on the grounds that a gradual change in the concentration of feed to a separation process, to half its initial value, would probably pose no insuperable problems. †World exploration for lithium has been scanty. Tabulations of world uranium resources are limited to high grades (> 1000 ppm) and do not include the Soviet Union or China. An exceedingly rough estimate of what might be found worldwide was obtained here by multiplying the U.S. figures by 14, the ratio of world to U.S. ice-free land area.

cumulative usage, become central rather than peripheral factors in choosing one mix of sources over another.

The foregoing view of the energy problem in time perspective provides a basis for exploring the rationale for developing and choosing among long-term energy sources. The most important ingredients of such a rationale can be grouped under the headings: fuel supply, energy cost, timing, environment, systems compatibility, and diversity. In what follows, I discuss the main criteria applicable to each heading and review the status and prospects of fusion with respect to these criteria, with occasional comparisons to other candidate long-term sources (*7, 8*).

Fuel Supply

With respect to fuel supply, the criteria appropriate for long-term sources are inexhaustibility, reliability, and geographic distribution. I take inexhaustibility to mean, for practical purposes, the capacity to supply energy at rates comparable to the global rates for marketed energy forms today [about 8 thermal terawatts (*9*)] for tens of thousands of years or more. Reliability of fuel supply I take to mean freedom from unpredictable interruptions. This criterion is not unrelated to geographic distribution of the fuel supply, under which I mean to suggest that a source whose fuel supply is possessed in abundance by all or nearly all potential users is preferable to a source whose fuel supply is controlled by a few. Finally, it is convenient to consider under fuel supply the availability of construction materials not formally part of the fuel but essential to the conversion of the energy supply into usable forms.

The fusion fuels of greatest interest as terrestrial energy sources drive the reactions listed in Table 1, of which the least demanding technically is the deuterium-tritium (D-T) reaction. Deuterium is present in seawater to the extent of 33 grams per cubic meter and was being extracted with straightforward technology for sale at 30 or 40 cents per gram in the early 1970's. Tritium, by contrast, is nearly nonexistent in nature and must be produced by neutron bombardment of lithium, which thus is the limiting fuel resource for D-T fusion. How much energy one obtains in practice from 1 g of natural lithium must be determined from detailed neutronics calculations accounting for the configuration of specific reactors (including the presence or absence of neutron-multiplying materials such as beryllium, and the degree of enrichment of the lithium in ^{6}Li); the range for reactor configurations studied to date spans values from about 6,000 to 20,000 kilowatt-hours per gram of natural lithium (*8*). If the technically more demanding D-D reactions are fully mastered, then burning 1 g of deuterium completely (that is, burning all the product ^{3}He and T with additional D) gives 96,000 kWh. Helium-3, like tritium, is practically nonexistent in nature [1 part per million (ppm) of natural helium, which is itself a scarce element], so the D-^{3}He reaction cannot stand alone; it is a possibility only if D-D reactions or T production from lithium with subsequent decay are used to obtain the ^{3}He. The extremely demanding proton-^{11}B reaction is limited by boron (80.4 atomic percent ^{11}B, 19.6 atomic percent ^{10}B) and would yield 21,000 kWh per gram of ^{11}B if it could be harnessed.

The energy contents of U.S. and world fusion fuels are shown in Table 2, with the energy content of uranium resources (used in breeders) shown for comparison. Evidently, neither fusion fuels nor fission fuel for breeders are exhaustible on time scales of practical interest. Presently identified U.S. terrestrial lithium could run D-T fusion reactors at a rate corresponding to ten times the 1976 U.S. electricity generation for 1000 years; identified U.S. terrestrial uranium resources at grades of ore above 25 ppm U are 2.5 times this large, if breeders can extract 60 percent of the uranium's theoretical energy content. The world as a whole is not likely to turn out to be significantly less well endowed with terrestrial uranium and lithium than the United States, although substantial nonuniformity of geographical distribution is to be expected. In the long run, both this problem and any absolute shortage of terrestrial lithium or uranium that might otherwise develop probably will be alleviated by the development of economical extraction from seawater. In short, with respect to fuel supply fusion has a quantitative advantage, in the very long term, over fission with breeders, but little practical advantage: the difference between, say, 6 million TW-year of uranium and 140 million TW-year of lithium will hardly impress present-day policy-makers, in a 10-TW world, as a telling argument for choosing fusion. (By the same token, on time scales of policy interest neither fusion nor fission is less inexhaustible than solar energy; they all satisfy this particular criterion equally.)

In addition to a fusion reactor's lithium needs for burnup for production of tritium, the part of its lithium inventory that is not burned must also be taken into account—this ranges from 40 to more than 1000 metric tons per gigawatt of electric capacity in conceptual reactor designs published to date (*10*). Beryllium for use as a neutron multiplier in some D-T reactor designs entails a consumption requirement of about 90 tons of beryllium per thermal TW-year and an inventory of as much as 240 tons per electrical gigawatt (*8*). Presently identified U.S. high-grade beryllium resources would support little more than 100 GWe at this inventory figure, but much larger deposits at lower concentrations are known. The high inventory requirements for lithium and beryllium in some designs are more realistically thought of as economic incentives to find designs more frugal of expensive materials than as barriers to large-scale use of fusion. To the extent that designs chosen for manufacture require materials for which the nonfusion markets are small by comparison to potential fusion needs, of course, the rate of growth of the fusion generating capacity could be constrained by the rate at which the industries supplying these materials can be expanded.

Cost of Energy

Under this heading one must consider not only the fuel cost but also the construction costs of conversion facilities; the associated interest, insurance, and return on investment; and the nonfuel operating and maintenance costs. Cost of any postconversion cleanup operations, including eventual decommissioning of facilities, must be accounted for, as must the capital and operating costs for the systems that distribute the energy to the point of end use. Performing such calculations in a systematic way that is comparable from one energy source to another is difficult even for sources that are operating today, more so for long-term options.

The fuel cost for fusion reactors—that is, the cost of fuel materials and (possibly) neutron-multiplying materials actually consumed—will certainly be low. Consumption of lithium in a D-T reactor would contribute about 0.005 mill per electrical kilowatt-hour (kWhe) to generating costs, at the present market price of lithium of $20 per kilogram; deuterium at the present market price of $400 per kilogram would contribute less than 0.001 mill/kWhe in either D-T reactors or more advanced reactors based on D-D reactions carried to completion. (One mill = 0.1 cent; coal at $20 a ton contributes about 8 mill/kWhe to electric generation costs.) Beryllium consumed in neutron-multiplying reactions needed in some D-T reactor designs might contribute 0.007 mill/kWhe at mid-1970's beryllium prices (*8*).

With respect to construction costs, however, fusion's prospects are less favorable. At this stage I do not think it possible to predict the cost of a commercial reactor to within even a factor of 2 (*11*), but the technological complexity of virtually all approaches to fusion described to date makes it very unlikely that the cost could be as low as for a fission plant of comparable output. This notion is given some concreteness in Fig. 2, which indicates schematically the functional complexity of a generalized fusion reactor, and in Table 3, which compares characteristics of the main reactor subsystems for magnetic confinement D-T fusion reactors and fission reactors. The only one of these aspects in which the complexity and intrinsic engineering difficulty of fusion seems less than that of fission is recycling of bred fuel. Some additional perspective on the demanding requirements of fusion is provided in Table 4. Problems associated with the high flux of energetic neutrons shown there include the likelihood that the parts of the reactor's structure closest to the fusion plasma will have to be replaced at intervals of 2 to 10 years because of loss of structural integrity under the intense bombardment of fusion

Table 3. Comparison of technological characteristics of fusion and fission reactors. The fusion system is D-T–fueled, magnetically confined. Fission characteristics are common to light-water reactors and liquid-metal fast breeder reactors.

Function	Deuterium-tritium fusion	Fission
Fuel supply to core	Pulsed or continuous injection of hydrogen isotopes at precisely controlled rates	Insertion of solid fuel elements in batches at intervals of months
"Ignition"	Heat fuel to 10^8 °C by means of microwaves, magnetic compression, high-current neutral beams, lasers, or electron beams	Withdraw control rods
Fuel confinement and isolation	Precisely tailored, dynamically controlled magnetic fields (strength of order 10^4 to 10^5 gauss), probably of complex geometry, produced by superconducting (4°K) or cryogenic (77°K) coils (to keep fuel in), plus vacuum liner and pumps capable of holding number density inside to less than 10^{-5} of atmospheric (to keep environment out)	Precision-machined, cylindrical reactor vessel of high-alloy steel
Energy removal	Convert kinetic energy of 14-MeV neutrons to heat in blanket external to core (thickness ≈ 1 m) and remove by circulating liquid metal, molten salt, or helium	Convert kinetic energy of fission fragments and 2- to 3-MeV neutrons to heat in solid fuel and remove by circulating water or liquid metal
Recycling of bred fuel	Continuous on-line extraction of T at low concentration from circulating coolant	Remote, batch extraction of plutonium at moderate concentration from highly radioactive fuel

Table 4. Some operating conditions in magnetic confinement D-T fusion reactors compared to those in liquid-metal fast breeder reactors (*8*). Note especially the lower power density in the fusion system, meaning that the fusion reactor must be physically bigger, hence more materials-intensive, to produce the same output. Numbers are approximate.

Condition	D-T fusion	LMFBR
Operating pressure in core (atm)	100	1
Average power density in core (W^{-1} cm^{-3})	10*	300
Neutrons per gigajoule of energy yield	3×10^{20}	7×10^{19}
Fast neutron (>0.1 MeV) flux in core (neutrons cm^{-2} sec^{-1})†	5×10^{14}	4×10^{15}
Power flux in neutrons (W^{-1} cm^{-2})	200	600
Helium production in steel structure by fast neutrons (atomic ppm year^{-1})	200	5

*Pulsed systems may have much higher power densities during the pulse. †The fusion neutron spectrum consists of a nearly monoenergetic peak at 14 MeV (from D-T reactions) plus a broad distribution of backscattered neutrons of lower energies. The fast-fission neutron spectrum is broad with a peak around 0.6 MeV. The faster fusion neutrons do a disproportionate amount of damage, as the high helium production from (n, α) reactions indicates.

neutrons, and the high cost of routine maintenance on internal parts of the reactor made radioactive by those neutrons. Extraordinary vacuum pumping and impurity-control requirements and the need in many approaches to handle large amounts of internally circulating electric power to run the fuel injection–heating systems also contribute to the expectation of high construction costs for fusion reactors.

Tables 3 and 4 are based on essentially steady-state, magnetic confinement of D-T fuel. Approaches that use pulsed magnetic fields to achieve densities and pressures too high to be sustained in steady state may permit simpler geometries and fuel handling, but these economic advantages will be canceled at least partly by the energy storage requirements of pulsed systems and by the severe structural problems accompanying high-repetition thermal cycling and mechanical stresses. The use of inertial rather than magnetic confinement replaces expensive superconducting magnets with expensive high-power lasers, electron beams, or heavy-ion accelerators. Problems of fuel injection, energy removal, vacuum maintenance, and tritium recycling will be similar—or similarly expensive—to those of pulsed magnetic systems.

The use of advanced fuels, such as the D-D reaction chain, may simplify some matters—for instance, by reducing the amount of output power carried by neutrons and by eliminating the need to breed tritium. In a steady-state, pressure-limited system the attainable power density with D-D is about 100-fold lower than with D-T (*12*). This would seem to mean much more volume for a particular output, which together with the better confinement quality needed for D-D would mean higher construction costs. But the theoretical advantage of D-T fusion may not be fully exploitable if, as seems likely, the power density in D-T machines is limited not by the pressure that can be contained but by the tolerable neutron energy flux across the vacuum wall (in megawatts per square meter). In that event, D-D machines would not have to be so much bigger than D-T ones, and the cost penalty associated with this and with the need for better confinement might be substantially offset by simplicity gained in other respects (*13*).

The appealing idea that the cheapness of fusion fuel may offset fusion's likely construction-cost disadvantage is based on the low burnup costs cited above. Unfortunately, even in considering fuel costs one must account for the capital

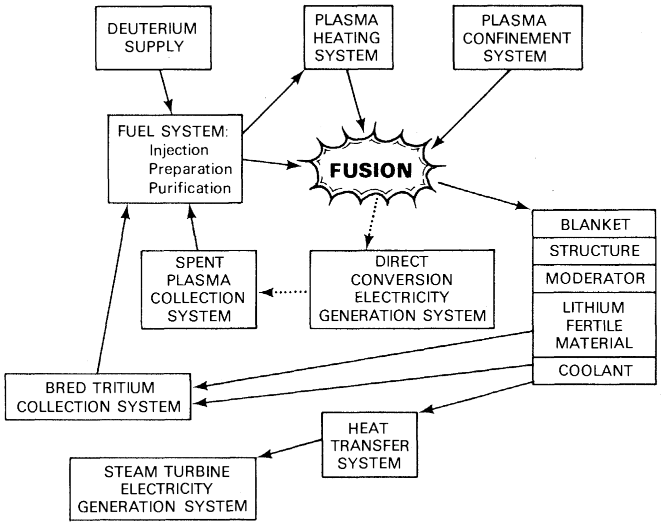

Fig. 2. Schematic of system functions in a generalized D-T fusion reactor. Many of these systems are necessarily more complicated than systems performing analogous functions in a fission reactor. Direct conversion to electricity of energy carried by charged particles (dotted lines) is necessary for the success of some reactor types and optional for others. [Adapted from (*11*)]

Table 5. Characteristics of magnetic-confinement fusion schemes.

Scheme	Tokamak	Mirror	High-density pinch
Plasma geometry	Toroidal	Variations on cylinder or sphere	Linear (long cylinder) or toroidal
Ratio of plasma pressure to magnetic pressure (β)*	0.05–0.10	0.5–1	0.7–1
Peak ion density in a reactor (cm^{-3})	10^{14}	10^{14}	10^{17}
Duty cycle in a reactor	100 minutes on, 10 minutes off	Continuous operation	Pulsed
Critical problem areas	Heating	Reducing losses through mirrors	Stability
	Fueling	Direct conversion of charged-particle energy to electricity	Reducing end losses in linear systems
	Scaling of confinement Quality with size	Scaling of confinement Quality with size	

*This figure measures how effectively the confining magnetic field is used; the higher the β, the more plasma pressure is confined for particular external field strength. Because magnetic field strength is expensive, β can be considered an economic figure of merit. Unfortunately, a high β also means that plasma-generated magnetic fields can significantly distort the external fields; this effect destroys the stability of the tokamak confinement at high β values and might restrict the workable β in tokamaks to about 5 percent.

Table 6. Major magnetic fusion experiments.

Designation	Explanation	Location	Plasma volume (m^3)
	Tokamaks		
ST	C-Stellerator rebuilt as Tokamak	Princeton	0.4
D-II	Doublet-II	San Diego	1.2
ATC	Adiabatic Toroidal Compression Experiment	Princeton	0.07
Alcator	High-field Tokamak with cryogenic magnets	Cambridge	0.1
Ormak	Oak Ridge Tokamak	Oak Ridge	0.8
TFR	Tokamak Fusion Reactor	France	0.8
PLT	Princeton Large Torus	Princeton	5
T-10	Tokamak-10	Soviet Union	30
D-III	Doublet-III	San Diego	22
JT-60	Japanese Tokamak	Japan	60
TFTR	Tokamak Fusion Test Reactor	Princeton	35
JET	Joint European Tokamak	United Kingdom	180
T-20	Tokamak-20	Soviet Union	400
EPR	Experimental Power Reactor	?	500
	Mirrors		
2XIIB	Beam-driven mirror machine	Livermore	0.006
MFTF	Mirror Fusion Test Facility	Livermore	0.1
TMX	Tandem Mirror Experiment	Livermore	1.7
	Pinches		
Scyllac	Toroidal theta pinch	Los Alamos	0.8
ZT-II	Toroidal Z-pinch	Los Alamos	0.9

charges on the inventories of lithium and, for some designs, neutron-multiplying materials. These charges may amount to 50 times burnup costs in liquid lithium systems and as much as 500 times burnup costs in systems using solid lithium compounds and beryllium as a neutron multiplier. In the latter case the sum of burnup and inventory charges could equal the 5 mill/kWhe fuel-cycle cost (fuel fabrication and reprocessing, plus burnup and inventory) that has been estimated for a liquid-metal fast breeder reactor (LMFBR) (*8*). A liquid-lithium D-T fusion system needing no beryllium could be said to have a 4.5-mill/kWhe fuel-cycle cost advantage over the LMFBR (ignoring that part of the fusion reactor's construction and operating costs ascribable to tritium recycling), but at a 15 percent fixed-charge rate and 70 percent capacity factor, it would take only a construction-cost differential of $185 per kilowatt electric to eat up the 4.5 mills.

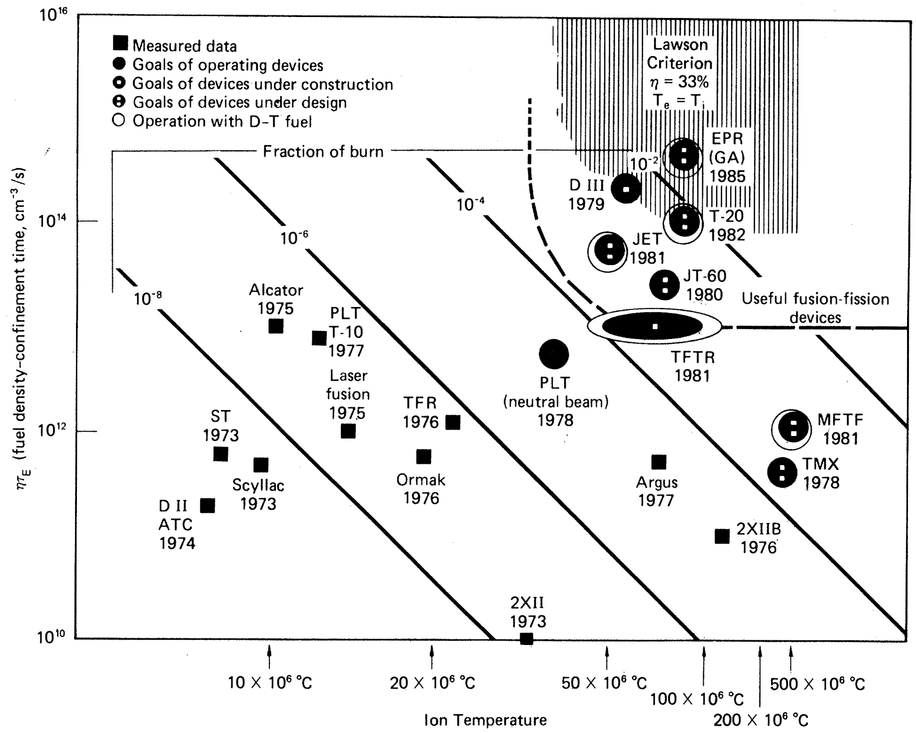

Fig. 3. Progress toward scientific feasibility of controlled fusion. Burn fraction refers to the fraction of injected fuel that would react if it were a mixture of deuterium and tritium. As of 1977, only Argus (a laser fusion experiment) has actually used tritium. The broken line below and to the left of the Lawson region indicates the less demanding threshold where fusion-fission hybrid devices become of possible interest. [From (*25*)]

Concerning the cost of electricity from fusion, then, one can only say at present that it seems unlikely, arguing from technical complexity, to be less than the cost of electricity from fission breeder reactors (which is itself uncertain by a factor of at least 2), and it is not even certain to be less than the cost of electricity obtained by various means from sunlight (which is at present uncertain by a factor of at least 5). For many applications not requiring the high thermodynamic quality of electricity, solar energy is virtually certain to be more economical than either fusion or fission, especially in view of solar's savings from dispensing with the expense of transmission and distribution (*14*). All this is not to say that fusion is unattractive, but only that no compelling case can be made for choosing it, on present evidence, on the basis of likely cost of energy.

Timing

Here the two main criteria for judging a new source can be summed up in two questions: When can we have it? How fast can we expand it? The importance of the answers to both questions depends in some measure on factors that will affect the timing of the *need* for a transition from exhaustibles to inexhaustibles, but that are presently clouded by varying degrees of uncertainty. These factors include the elasticity of energy demand with respect to price; supplies of oil and gas available at prices below, say, $4 to $5 per gigajoule (1 GJ ≈ 10^6 Btu's); supplies of uranium ore of sufficient quality for use as feed to light-water reactors; and environmental (including sociopolitical) constraints on expanded use of coal and fission (*15*).

When will fusion be available? To unravel a semblance of an answer from the tangle of research results, predicted performance of experimental devices yet unbuilt, and long-range program plans of the Department of Energy and its predecessors here and counterparts abroad, it is necessary to distinguish among two general approaches to the goal, three stages of feasibility, and a spectrum of degrees of urgency in pursuing the enterprise.

The two approaches are magnetic confinement and inertial confinement, within each of which exist a variety of alternative schemes and one leading contender of the moment. The first approach relies on powerful magnetic fields to hold together the hot fusion fuel (a fully ionized plasma with a temperature of the order of 10^8 °C) long enough for an appreciable fraction to react. The scientific difficulties of doing this have occupied a sizable research community in most industrial nations for the last 25 years (*7*). The leading contender among magnetic confinement schemes today is the class of toroidal devices called tokamaks; the primary and secondary backup schemes are mirror machines and pulsed, high-density, pinch devices. Table 5 summarizes some characteristics of these three classes of devices and lists some of the critical problem areas that each class must confront.

In the inertial confinement approach, the idea is to compress small pellets of fusion fuel virtually instantaneously to densities of order 10^4 times that of normal solids, by irradiating them symmetrically with pulsed high-power lasers (the leading contender), electron beams, or heavy-ion beams. The resulting conditions of density and temperature permit a significant fusion energy release before the attendant pressure overcomes the inertia of the pellet's constituents and it flies apart. The idea for this approach dates to around 1960, but it has been pursued vigorously only since the beginning of the 1970's (*16*). Critical problems include developing lasers that can deposit, on target, pulses of laser light containing 10^5 to 10^6 J in a pulse length of 10^{-9} second or less, at a high repetition rate and with high efficiency of conversion of electrical input to laser output, or developing relativistic electron beams or beams of heavy ions with similarly demanding performance; and developing target-pellet designs that facilitate high compression and high gain (ratio of fusion output to input to the pellet).

The three stages of feasibility that must be considered are scientific, technological, and commercial. Scientific feasibility for fusion means achieving, in the laboratory, simultaneous conditions of fuel temperature, density, and confinement time that would lead, if they occurred in a reactor, to an output power exceeding the input power. Technological feasibility means building a device that actually produces a net output in usable form and in continuous operation—such a device must incorporate sophisticated fuel-handling and energy-conversion equipment not needed for a scientific feasibility demonstration, as well as solve problems of continuous (or, for pulsed systems, high-repetition-rate) operation of magnets, lasers, vacuum pumping systems, and so on. Commercial feasibility means developing a product that can produce continuous and reliable output power without a small army of Ph.D.'s in continuous attendance, and at a cost perceived as reasonable in the context of fusion's benefits in comparison with other energy sources available in the same time period. (Commercial feasibility need not mean that the cost per kilowatt-hour is as low as that for other sources, if fusion is seen to have important advantages in terms of environment or compatibility.)

The threshold of scientific feasibility is generally taken to be defined by the "Lawson criterion" derived by the British physicist of that name in the late 1950's. He showed, with some reasonable assumptions, that a D-T–fueled fusion reactor could produce net power if the confinement parameter $n\tau$ exceeded 10^{14} cm^{-3} sec at an ion temperature around 10^8 °C (n is the fuel ion number density in number per cubic centimeter and τ is the mean confinement time in seconds) (*17*). The basic idea embodied in the Lawson criterion applies to inertial confinement as well as to magnetic confinement, but where the latter might achieve the break-even condition with $n = 10^{14}$ cm^{-3} and $\tau = 1$ second, the former would do so with perhaps $n = 10^{26}$ cm^{-3} and $\tau = 10^{-12}$ second.

Figure 3 indicates progress toward the scientific feasibility of fusion, by both approaches, on a plot of $n\tau$ against ion temperature. The type, location, and size of machines shown in Fig. 3 are given in Table 6. The great increases in fusion research budgets in the last decade (from $27 million per year in fiscal year 1968 to $311 million in fiscal year 1978 for magnetic confinement fusion in the United States, for example) are due in substantial part to the increasing size, and therefore expense, of the experimental devices being built. Machines on the scale of Ormak and 2XIIB have cost about $20 million each; MFTF and TFTR will cost roughly $100 million and $200 million, respectively.

The trend of growing machine size in magnetic confinement research has resulted from three factors that make energy break-even easier to achieve in larger devices: surface-to-volume considerations favor large systems for maintaining high temperatures against energy losses; long, open-ended systems are less sensitive to plasma losses out the ends than are short ones; and a growing body of evidence indicates that confinement-disrupting effects of certain important plasma instabilities diminish as plasma size and temperature increase (*18*). The growth in size of the devices for investigating inertial confinement fusion—meaning mainly the high-power lasers around which this approach now centers—is also easy to explain: the large pellet-compression factors needed to produce energy break-even require that very large pulses of laser light be delivered to the pellet, which requires very large lasers. The U.S. inertial confinement fusion budget for fiscal year 1978 is about $120 million (*19*).

It seems very likely that the scientific feasibility threshold for magnetic confinement fusion will be passed in the early 1980's, probably first in one of the tokamak devices. Heating the plasma to fusion temperatures was once considered one of the primary obstacles to achieving break-even in a tokamak; it now seems possible to do this by injecting high-current, high-energy beams of neutral fuel atoms across the confining magnetic field (a technology originally developed for the mirror approach). The remaining obstacle that is perhaps most likely to delay achievement of break-even in tokamaks is control of impurities, which enhance energy losses by bremsstrahlung and charge exchange and which can cause instabilities (*20*). The main obstacle in the way of scientific feasibility in mirror machines has been the particle losses out the ends, which would already be high in the absence of instabilities and have been increased in most mirror experiments to date by certain microinstabilities. Experimental results and theoretical insights in mirror research in the past 2 years, however, have indicated that the most troublesome instability can be suppressed by relatively straightforward and inexpensive means (*21*) and have revealed two promising ways in which classical end losses might be reduced. One of these is to inject the fuel off-center in a way that creates a plasma current whose diamagnetic effect is strong enough to close the otherwise open magnetic field lines along which particles would escape (the field-reversed mirror) (*22*). The other recent idea for reducing mirror end losses is the tandem mirror concept, in which the strong positive ambipolar potential produced by small mirror plasmas maintained at very high energy by powerful neutral beams serves as an electrostatic "plug" at each end of a larger, simpler mirror plasma in which most of the fusion reactions take place (*23*).

Scientific feasibility in laser fusion—meaning fusion energy output from a pellet equal to the laser energy incident on the pellet—might also be demonstrated in the early 1980's, but this possibility is harder to evaluate as some of the pertinent information is classified because of its relevance to nuclear weapons (*24*). A crucial requirement for success is a detailed understanding of how the design of the pellet and the characteristics of the input pulse of energy interact to facilitate efficient energy absorption and pellet compression without predetonation; the state of knowledge on this topic cannot be ascertained from the unclassified literature alone.

Let us suppose that, by one route or another, the scientific feasibility of fusion is demonstrated by 1985. How long might it then take to pass the further thresholds of engineering and commercial feasibility? As intractable as the first stage has proved to be, it is entirely possible that the next two will be tougher. The flavor of the engineering problem has already been suggested in the discussion of costs. The most difficult problems appear to be those associated with materials science: superconductors to withstand enormous mechanical stresses for years; mirrors and lenses to handle tens of thousands of laser pulses of devastating power daily; first-wall materials, next to the fusion plasma, which must be resistant to swelling, sputtering, blistering, cracking, and loss of strength under intense bombardment by fusion reactions, x-rays, and energetic ions, and which must also be compatible at their elevated operating temperature with the coolant and any tritium-breeding and neutron-multiplying materials; electrical insulators that can retain their properties in this hostile environment; and so on (*8*, *25*). Extraordinary demands will also be placed on vacuum technology, instrumentation and control technology, energy storage and switching technology, and systems integration. If all this can be pulled together to produce a semblance of a power reactor within 15 years or so of the scientific feasibility demonstration—that is, say, by the year 2000—it will be an amazing accomplishment. The tortuous "conceptual designs" so far published have been correctly labeled as problem-finders, not problem-solvers (*26*); utility analysts find them demonstrative mainly of what must be avoided in a device the utilities could consider practical (*27*).

Contributing to this somewhat sobering outlook, those approaches widely considered to have the best prospects for an early demonstration of scientific feasibility seem to have some of the worst characteristics from the engineering and commercialization standpoint. Tokamaks have the interrelated liabilities of complicated (toroidal) geometry, low beta (that is, poor utilization of the magnetic field; see Table 5), and large electrical output per reactor. Results obtained in the past few years suggest, however, that employing a plasma of noncircular cross section may increase significantly the value of beta attainable in tokamaks, and that they may be workable at outputs of perhaps 500 MWe rather than the 1500 to 2000 MWe once thought necessary (*20*). In the laser approach, converting scientific to engineering feasibility confronts especially formidable problems in the need to achieve high efficiencies of conversion of electricity to laser output and high pulse-repetition rates. Whether using electron beams or ion beams in place of lasers in inertial confinement systems can simplify engineering problems in that approach remains to be seen (*28*).

Among the magnetic fusion alternatives that seem farther from a scientific feasibility demonstration than tokamaks are some whose simpler geometries, higher betas, and (in some cases) smaller unit sizes could offer significant advantages in terms of engineering and commercial feasibility. Thus arises an obvious dilemma—that pushing hardest the best candidates from the scientific standpoint today may not represent the shortest path to a technologically and commercially workable reactor.

Pressed by the political realities attendant on a finite pot of federal money for energy research, the Magnetic Fusion Energy Division of the U.S. Energy Research and Development Administration (now the Department of Energy) published in 1976 a program plan outlining five different strategies of research effort (termed logic I through logic V), among which the reference strategy (logic III) is designed to lead to a demonstration plant of a few hundred megawatts electric (net) in 1998, after a total research and development investment of about $15 billion in constant 1978 dollars (*29*).

This plan seems to reflect the worry that Congress may lose interest in fusion if there is no prospect of producing some electricity from it before the year 2000 more than it reflects any real logic of orderly and realistic progress toward the goal. The program milestones and decision points in logic III crowd each other so closely that major slippage seems inevitable and much wasted effort seems likely. For example, the design of the demonstration reactor is scheduled to commence 3 years *before* the initial operation of its predecessor, the experimental power reactor (a few tens of megawatts electric net power), whose design, in turn, commences 3 years before *its* predecessor (the prototype experimental power reactor) operates. Such a schedule could work only in a surprise-free future, which the history of fusion research to date gives no reason to expect. The "crash program" of logic V, purporting to lead to a demonstration plant in 1990 at a cost of $20 billion in constant 1978 dollars, is even less realistic, being reminiscent of the notion that nine women should be able to make one baby in 1 month.

Even if a demonstration reactor somehow materializes by the year 2000, and even if it works beautifully, it is hard to envision a way for fusion to capture an important share of U.S. or world electricity generation before 2015 or 2020 at the earliest. Utilities are unlikely to order such plants by the dozens until the first ones have proved themselves in operation for 5 or 10 years, and construction time probably cannot be much less than 5 years (unless some approach to fusion works in small units).

How do the other long-term sources stand with respect to timing? The scientific feasibility of fission breeders is not in doubt, and proponents argue that engineering feasibility has also been demonstrated by the operation of French, British, and Soviet fast breeders on a scale of 200 to 300 MWe. However, to the extent that the breeder's viability as a truly long-term energy source depends on actually breeding—which means not only in-core performance but also satisfactory recovery factors in separating fissile isotopes from spent fuel on a commercial scale—the threshold of engineering feasibility remains to be passed (*30*). If there are no technical or political setbacks for breeders from here on, they may at most represent 10 percent of the industrial world's electrical generating capacity by 2010.

Electricity from sunlight, directly or through its short cycles in the ecosphere, is unquestionably scientifically feasible, and in some forms it has obviously passed the threshold of engineering feasibility as well. (These forms are photovoltaics, solar-thermal-electric conversion, wind, hydropower, and combustion of biomass.) For some nonelectric applications, solar technologies are in even better shape. What remains controversial for most of them is commercial feasibility, although new information is appearing so rapidly that it is hard to make a sensible statement that will not soon be overtaken by events.

Environment

The diversity and growing policy importance of environmental issues were emphasized above in the discussion of the nature of the energy problem. Space does not permit even cursory coverage here of all the environmental ramifications of fusion. I give most attention to three classes of effects generic to nuclear sources, which facilitates comparison with the fission option (*31*): (i) occupational and public exposures to ionizing radiation as a consequence of routine operations, (ii) nonroutine releases of radioactivity due to accidents or malevolence, and (iii) links to nuclear explosive or radiological weapons.

Fusion's radiological hazards arise from two sources: radioactive tritium, which is not only a primary fuel for D-T reactors but would also be produced in approximately half the D-D reactions in advanced-fuel reactors exploiting the D-D, D-^{3}He, or D-^{6}Li possibilities; and fast neutrons, which are produced by D-T and D-D reactions and which can produce a wide variety of radioactive isotopes by neutron activation of structural and other materials near the fusion reactor core.

The inventory of tritium envisioned in a typical, early, conceptual design for a D-T-fueled tokamak reactor with liquid-lithium coolant was about 10 kg or 100 megacuries per thermal gigawatt (GWt), or perhaps 250 MCi for a reactor of one electrical gigawatt (GWe) (*8*); 40 percent of this would be "active" (that is, circulating in the breeding-separation-purification-injection systems) and the rest in cold storage as a reserve to permit continued reactor operation with the tritium recovery system down. For this fusion reactor to meet present Nuclear Regulatory Commission (NRC) "design objectives" for fission reactors (maximum exposure of 5 millirems per year through air or water at the plant boundary), releases of tritium as the oxide could not exceed roughly 1 part in 10^6 of the total

Table 7. Tritium and activation-product hazards in some hypothetical fusion reactors, with a comparison to a fission breeder; BHP, biological hazard potential. Numbers are approximate and are based on information in (*8*).

Tritium and activation products	Reference liquid lithium stainless steel, D-T tokamak	Reduced tritium inventory, vanadium D-T tokamak	Vanadium D-D tokamak	Roughly analogous hazard index for LMFBR
Active tritium inventory (BHP/GWe, 10^6 km^3 air)	0.5	0.03	0.01	100*
Tritium in cold storage (BHP/GWe, 10^6 km^3 air)	0.75	0.20†	0	1,000‡
Activation products 10^4 seconds after shutdown (BHP/GWe, 10^6 km^3 air)	500	60	20	15,000§
Activation products 10 years after shutdown (BHP/GWe-year, km^3 water)	70	0.3	0.1	3,500‖
Activation products 1000 years after shutdown (BHP/GWe-year, km^3 water)	0.01	0.00007	0.00002	5‖

*Radioactive iodines ^{131}I through ^{135}I, which dominate BHP of volatile fission products. †Assumes doubling of fractional burnup per pass and halving of reserve lifetime under breakdown of tritium extraction system. ‡Thirty percent of total fission product inventory 10^4 seconds after shutdown (approximates what could be released in hypothetical severe accident). §Sum of fission products, activation products, and actinides. ‖Radioactive wastes, assuming recycle of uranium and plutonium.

plant tritium per day (*32*); designs for tritium retention systems theoretically capable of performance one to two orders of magnitude better than this exist, but will have to be proved in practice (*8*). Figure 4 summarizes the results of a calculation indicating that sudden release of the "active" 100 MCi of tritium in our 1-GWe reactor—all as HTO—would produce about 100 times fewer early fatalities and injuries than the fission-reactor release PWR-1 considered in NRC's Reactor Safety Study (the Rasmussen report) (*33*).

The active tritium inventory in D-T fusion reactors can be reduced (in principle) by increasing the fractional burnup per pass through the plasma (that is, by improving confinement) and by reducing average holdup time in the tritium breeding and extraction systems. Several conceptual reactor designs have been published with active tritium inventories 4 to 100 times smaller than the 10^8 Ci/GWe mentioned above, most (but not all) relying on pressurized helium as the coolant and tritium breeding in solid lithium compounds (*10*, *34*). The inventory in cold storage is very much less susceptible to release than the active inventory, but also less amenable to reduction; the only possibilities are (i) increased fractional burnup, (ii) decreased plant reliability (in the form of a smaller reserve for operation without the tritium extraction system), and (iii) operation on fuel cycles other than D-T. Use of the harder-to-achieve D-D reaction, with reinjection of the tritium produced, would eliminate the need for cold storage of tritium altogether and reduce the active inventory by a factor of 3 below its value in a comparable D-T system (*8*).

Products of neutron activation are of environmental concern in three respects. First, the radiation they emit in situ will expose workers in the reactor to significant doses beyond those due to tritium, making maintenance more difficult and more expensive. This could be a major obstacle on the road to commercialization. Second, in very severe accidents some of the activation products could be volatilized and released, adding to off-site radiation doses from tritium. No data are yet available on what release fractions are plausible, but very rough hazard indices suggest that in some cases even a 1 percent release of activation products could do damage comparable to the release of 10^8 Ci of tritium oxide (*8*, *35*). Third, the presence of activation products with long half-lives means that some fusion reactor structural materials will have to be managed as radioactive wastes. That these products are mostly embedded in a solid metal structure may help make escape into the environment unlikely, but the fact that the radioactive isotopes often belong to the same element as the bulk of the structure itself makes it difficult to separate and recycle the valuable nonradioactive part and to compact the waste.

The quantity and variety of radioactive isotopes produced by neutron activation in D-T fusion reactors depend on the designer's choice of materials for the parts of the reactor exposed to a high neutron flux and on the way these parts are arranged. But the choice is constrained by many requirements, other than low activation, that materials for fusion reactors must meet: in addition to special properties such as high thermal conductivity or low electrical resistivity which are needed for certain functions, one must also look for such properties as fabricability, retention of strength at high temperature, resistance to structural damage by neutrons and ions, and compatibility with coolants and breeding materials (*8*).

Stainless steel seems a natural candidate for the main structural material in D-T fusion reactors, because experience with it in demanding, high-neutron-flux situations (in fast fission reactors) is more extensive than with other materials; but its neutron activation in a D-T fusion reactor would be severe. Niobium, a potentially attractive candidate because of its good properties at high temperature, has an initial activation comparable to that of stainless steel, although it is superior to steel at decay times from one to a few hundred years. From the activation standpoint, the most attractive metallic alloys that have been identified to date employ vanadium, titanium, and aluminum; the activation of one such alloy (80 percent vanadium and 20 percent titanium) 30 years after re-

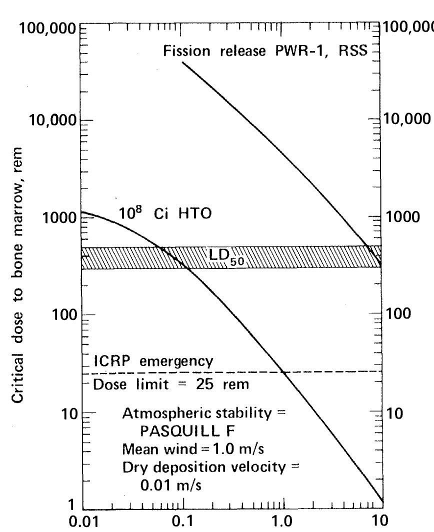

Fig. 4. Results of applying the consequence model of the Reactor Safety Study to "worst-case" accidental releases in D-T fusion and fission light-water reactors. Critical dose means 100 percent of the dose delivered in the first 7 days after exposure plus half the dose from days 8 through 30. The LD_{50} is the dose fatal within 60 days to half those exposed, in the absence of heroic medical measures. The tritium inventory in fusion reactors may be reduced greatly below the value shown by improvements in design, but no account has been taken here of possible release of fusion activation products. Note that reducing the tritium inventory fivefold would reduce to zero the expected prompt fatalities from the worst-case HTO release. [From (*35*)]

moval from the reactor is entirely negligible except for activation of any trace contaminants (*8, 36*). This potential for virtually eliminating the long-lived-waste problem means that the suitability of vanadium-titanium alloys in other respects deserves the most vigorous investigation.

Employing the D-D reaction chain in place of D-T does not reduce neutron activation as much as might be supposed. The number of neutrons per unit of fusion energy production is about the same for D-D (with reinjection of product ^{3}He and T) as for D-T, although the energy carried by the neutrons themselves is smaller. Calculations indicate that the induced radioactivity with D-D ranges from 35 percent of that with D-T in vanadium to 78 percent in stainless steel (*8*). Doing away with the complexity of tritium breeding would permit greater simplicity of the blanket design and more flexibility of the materials choice in the D-D case, however, with possible activation benefits.

Table 7 summarizes the tritium and activation-product hazards in some different hypothetical fusion reactors, based on the foregoing discussion and on data largely from (*8*). It is evident that the substantial quantitative advantage of the reference D-T fusion reactor compared to fission becomes essentially qualitative as one moves to a minimum tritium inventory, low-activation materials, and finally D-D. Conceivably, other innovations will permit still further reductions in neutron activation. Possibilities mentioned in the literature include woven graphite "curtains" to moderate the neutrons before they reach the vacuum wall (*37*); a nonmetallic structural material such as graphite fibers or silicon carbide (*38*); and designs (possibly suitable for inertial confinement systems and pulsed high-density Z-pinches) in which the fusion plasma is surrounded by free-flowing liquid lithium without an intervening solid wall (*10, 39*).

Accident risk involves not only the inventories of hazardous materials in reactors but the probability that these materials will escape. In the absence of operating experience or even a firm design for a fusion power plant, the difficulty of analyzing the probability of accidents of various kinds is even greater than for fission (*40*). On the basis of stored energy and potential pathways for its release, however, one can make a few preliminary assertions. The largest source of stored energy in any fusion reactor cooled by liquid lithium is the chemical energy in the lithium itself (~ 50,000 GJ/GWe), which reacts vigorously with air, water, and even concrete. Thermal energy stored in the coolant and energy stored in superconducting magnets are two to three orders of magnitude smaller. Magnets must be designed so that faults do not cause sudden release of the energy, but that does not appear inordinately difficult (*41*). Reactivity excursions are virtually certain to be terminated by loss of plasma to the walls, but even if all the fuel in the plasma at one time were somehow to react, the fusion energy released would only be of order 100 GJ in a 1-GWe reactor. Radioactive afterheat from activation products would be one to two orders of magnitude below that due to fission products in a fission reactor, with emergency cooling correspondingly easier and probably manageable by passive means. In short, if liquid lithium could be avoided, the potential for internally generated major accidents in fusion reactors would seem to be small. And the small radioactive inventories in low-activation, reduced-tritium fusion reactors should make their attraction for saboteurs small as well.

The question of links to nuclear weaponry seems increasingly to be the sociopolitical Achilles heel of nuclear fission. Fusion is not entirely free of such links. Any fusion reactor running on D-T or D-D reactions produces sufficient neutrons to transmute fertile material to fissile material, usable in fission bombs, at a high rate. There are two consolations. First, any such production operation would require the elaborate and prolonged cooperation of the legitimate operators of the reactor, so this is mainly a problem of national intentions, not of action by terrorists. Second, and more arguably, fusion reactors are unlikely to be available outside countries that today have a fission-weapons capacity for another 30 years, by which time either the international weapons proliferation problem will be well on its way to political solution, or every interested country will have gotten fission bombs by other routes.

With respect to links to *fusion* weapons there are two issues: tritium and knowledge. The first is almost certainly of little importance. Whereas lack of access to fissile materials has been a significant technical barrier to the spread of fission weapons, and getting the fissile materials is a significant part of the task of getting a fission bomb, having fusion fuels (of which tritium is only one of the possibilities) is by comparison a very minor part of the much more difficult task of getting a fusion bomb. The spread of knowledge is another matter. Although it is well known that the approaches to fusion power by way of magnetic confinement are not relevant to the design of fusion explosives, both the classification shroud covering aspects of inertial confinement fusion and explicit statements on the matter in official unclassified documents (*24*) indicate that some inertial confinement work is thought to be relevant to fusion bombs. To the extent that lack of certain insights and degrees of technical sophistication have limited the spread of fusion bombs until now, just as lack of fissile material has limited the spread of fission bombs, the spread of inertial confinement fusion research may be spreading a limiting ingredient for fusion weaponry. It is impossible to know, without recourse to the classified literature, how tight the link really is, but the very tightness of the classification lid belies the attempts of some in the controlled-fusion community to disparage its importance. I believe this problem must be counted a major liability of inertial confinement fusion, unless and until someone can show, on the basis of arguments that can be scrutinized and debated openly, why it is not.

Finally, a few environmental effects not unique to nuclear sources may be mentioned. Effects of processing fusion fuels and construction materials seem likely to be of second order—that is, neither appreciably bigger than analogous effects of the other long-term options nor as important as other kinds of effects of all the options (*8, 42*). Land use for fusion power plants and associated facilities should be somewhat less than for fission breeders (since the fusion fuel cycle almost certainly will be simpler), and there should be at least equal flexibility in permitting siting away from ecologically fragile regions; total area requirements and siting flexibility will be better than those of many of the large-scale solar options. Discharge of waste heat in first-generation fusion plants should be comparable to that from fission breeder reactors; the net heat addition of both to the global environment is somewhat worse than for solar alternatives, for which a net addition occurs only to the extent that the collector is "blacker" than what would be there in its absence. Advanced fusion reactors may be able to achieve efficiencies of conversion of fusion energy to electricity as high as 70 or 80 percent (*12*), but advanced fission breeders have the potential for improved efficiency too, and all systems can achieve higher effective efficiencies by delivering heat in useful form as well as electricity. Environmental effects of the uses to which abundant energy from fusion may be put are a serious concern, but this is equally an issue for any of the long-term sources (*43*).

Compatibility

"Systems compatibility" covers a number of criteria. One is compatibility of the supply-delivery system with the pattern of end-use requirements, with respect to the form, quality, and geographic distribution of energy. Another is compatibility of a particular long-term source with other energy-supply options we have and others we might want: Are the sources complementary in the kinds of needs met? Are there symbioses? Does the implementation of one source facilitate evolution or transition to better ones? (This last aspect may be seen as a sort of temporal compatibility—that is, whether a particular source is compatible both with the requirements of short- and middle-term predicaments and with a graceful transition toward the requirements of the eventual steady state.) Yet another criterion might be called social compatibility, meaning that the ideal energy source should not intrude on values and social choices outside the energy-supply sector itself; or, more bluntly stated, that energy sources should be chosen to fit the sort of society we want and not vice versa. A final criterion is regional compatibility. There is no reason to suppose that the optimum long-term mix of energy technologies will be the same in different regions of the world (or indeed that the timing of transitions will be the same), any more than the ingredients of present-day energy predicaments are identical from region to region. This regional variation imposes the additional condition on sound choices that those made in one region be compatible with those made in another; that is, for example, that choices made in industrial nations should not foreclose options that would be desirable in developing regions and should even, where possible, facilitate or complement them.

All of the foregoing aspects of compatibility are related in varying degrees, as indeed are all the other ingredients of the rationale so far considered—fuel supply, energy cost, timing, and environment. The ingredients affect each other, and certain characteristics of a particular energy source—for example, the minimum size of practical units and the potential for nonelectric applications—affect all of them. I treat these two aspects of fusion first.

With respect to scale, most discussions of fusion have assumed that tokamaks would be the approach of choice for building reactors, and this approach indeed appears at present to be interesting only in sizes of perhaps 500 MWe or larger. Such large units have disadvantages with respect to siting flexibility, construction time, total capital costs, usability of rejected heat in such large blocks, reserve capacity required to back the unit up, and suitability for use in developing countries (*44*). Approaches to fusion other than tokamaks, however, may lead to reactors that are economically attractive in much smaller sizes. Some laser-fusion approaches may work out at about 100 MWe (*25*), high-density pulsed Z-pinches could be attractive in the same size range (*39*), and a preliminary design for a field-reversed mirror reactor indicates the possibility of reactors as small as 10 MWe (*22*). It is premature to conclude that fusion reactors have to be huge.

With respect to nonelectric applications, opportunities for productive use of heat rejected from thermal electricity generation are more diverse the smaller the reactor is, but there are possibilities in industrial centers for big reactors as well. The situation for heat utilization is not markedly different from that for fission reactors, except insofar as the development of small fusion reactors along the low-radioactivity lines identified above may permit much more flexible siting. The ability to produce liquid and gaseous chemical fuels (such as carbon monoxide from carbon dioxide or hydrogen from water) by using energy from fusion is of enormous intrinsic interest and is starting to receive increased attention (*45*). Energy leaves a fusion plasma in the form of neutrons, microwaves, x-rays, and charged particles, the division among these categories depending on the fusion fuel and the operating conditions; some of the energy can be shifted rather readily into other parts of the electromagnetic spectrum (such as the ultraviolet) as well. Conceivably, photochemistry and radiolysis employing neutrons, x-rays, and ultraviolet could be used for direct production of carbon monoxide, hydrogen, and methane from carbon dioxide and water, although the likelihood of attractive conversion efficiencies has yet to be demonstrated. If the efficiencies turn out to be low, decomposing water by thermochemical means or combined thermochemical-electrolytic processes will be more attractive; in that case the only advantage of fusion over fission or solar energy for driving the conversion processes would be any environmental or economic advantage it may have over these as a source of heat and electricity.

Possible direct applications, other than fuel production, of the special forms in which fusion delivers its energy are at present too speculative to warrant discussion here (*46*), save those associated with the concept of fusion-fission hybrid reactors. Hybrid reactors consist of a fusion core surrounded by a blanket in which fusion neutrons are used to (i) cause fission reactions in an otherwise subcritical configuration, whereby the energy output from a device whose fusion core alone would be subeconomic can be made interestingly high; (ii) initiate fertile-to-fissile conversions for the purpose of fueling pure fission reactors elsewhere; and (iii) transmute the long-lived radioactive wastes produced in fission reactors to shorter-lived isotopes (*47*). Hybrids appear to combine most of the complexities of both fusion and fission in a single device, and they have most of the environmental liabilities of both parents as well: substantial inventories of tritium, activation products, fission products, and fissile materials usable for bombs; complicated plumbing; and stored energy sources characteristic of both fission and fusion (*48*). Hybrids may have some safety advantage over, say, LMFBR's in terms of the likelihood of criticality accidents, and they might offer environmental advantages in a systems sense if they facilitated a fission economy based on a proliferation-resistant fuel cycle or enabled fission to be based in the long term on converter reactors safer than the breeders that would otherwise be required (*49*). Most recent analyses suggest that hybrids would be economically uninteresting as power producers (application i) and uninteresting from virtually every standpoint as waste transmuters (application iii). In the fission-fuel–producing role, they seem economically interesting in the United States and most other places only if two (some think unlikely) things happen at once: electricity use grows very rapidly and nuclear fission's share of the electricity market grows very rapidly. Nevertheless, proponents point out that hybrids satisfy temporal compatibility nicely, being a natural bridge between what we have (fission) and what we may want (pure fusion), and the Soviets are planning to turn their biggest tokamak (T-20) into a hybrid (*50*).

Regarding the compatibility of fusion systems, exclusive of hybrids, with future coexisting options, it may be reiterated that the surest bet to occupy some sizable section of the energy menu in the long term is solar energy. We know too little about either the future size and shape of human society or the possibilities of solar technology to be confident that sunlight and its immediate derivatives can everywhere do everything our descendants want (or should have) from their energy sources. It does not seem unlikely that in many places there will be a niche for a source that complements solar—most probably in the role of supplying compact, central-station power in medium (10 MWe) to large (1 to 5 GWe) blocks, but possibly also for portable fuel production. Fusion and fission are the evident competitors for that niche and, although they may coexist for a while, one or the other eventually will win the competition.

Conclusion

Fusion, like solar energy, comprises many different technologies, and some of them are more attractive than others. It is becoming clear that characteristics discussed in this article under "environment" and "compatibility" will be central in shaping energy choices for the long term, and this suggests that fusion research and development should give greater emphasis to systems that do not have to be big and to those that minimize social and environmental risks. From the latter points of view, it would be desirable to avoid (i) weapons-relevant inertial confinement schemes, (ii) hybrids driving proliferation-vulnerable fission fuel cycles, (iii) liquid-lithium coolant, and (iv) stainless steel and other high-activation structural materials.

An intensive push for early commercialization of fusion reactors is likely for a number of reasons to favor approaches that do not meet many of these goals. Tokamaks are the closest to scientific break-even of the present main approaches, but they probably have to be large. The nuclear industry has more experience with liquid-metal cooling than with helium or other possible fusion coolants, so liquid lithium seems likely to be used in early systems. There is far more experience with stainless steel in intense neutron fluxes than with any other candidate material, making steel the probable choice for any attempt at early commercialization. And a fusion-fission hybrid could produce a net energy output sooner than any pure fusion device, if net output at the earliest possible date is really what Congress and the Department of Energy want.

I believe that early commercialization is the wrong goal, indeed a dangerous one. Fusion's attraction is not as an interim energy source, to compete with coal and light-water reactors, and it would be a mistake to try to dictate its timing (or its cost) by the standards appropriate to interim sources. It will be slow in coming—probably making no substantial contribution to the world energy supply until at least two decades into the next century—and it is likely to be expensive; but it is interesting anyway because of the likelihood it can fit the demanding niche determined by the nature of the energy problem in the long term. Probably the awkward fusion reactors that emerged from crash programs initiated now would fit that niche better than would LMFBR's, but whether they would be sufficiently better to be worth the cost is problematical. In pursuing early engineering feasibility, we would be likely to sacrifice much of the potential advantage that attracted money and talent to the fusion enterprise in the first place.

It is too early, in short, to pick the best path to a fusion reactor and start sprinting along it. Pursuing approaches that can work in small sizes, finding ways to minimize tritium inventories, learning which low-activation materials can actually function in a fusion reactor will all take time and, perhaps, more money than rushing headlong toward a reactor for 1998. But if we are unwilling to pay the price of continued exploration now, we may shape fusion for decades to come with a premature poor choice.

What of the views that fission breeders or solar energy may have made fusion superfluous even before it has worked? With respect to fission breeders, it is clear that fusion has the theoretical potential to be better environmentally by such a large quantitative margin that the difference becomes qualitative. Whether that potential can be realized in practice is still far from certain, but it is too soon—and the role of environmental factors too important—to give up now. With respect to solar energy, too little is known of the economics and (for some forms of solar) ecological impacts of deployment on a truly large scale for a prudent society to abandon everything else.

In the pursuit of long-term energy options, then, resort to some substantial amount of diversity as a hedge against uncertainties as large as today's is justified, indeed essential. Part of the value of paying for diversity for a while, of course, is having the privilege, as information improves, of finally rejecting options that turn out to be unsuitable. That possibility cannot be ruled out for either of the nuclear sources. But for now, both the shape of fusion and the shape of the future are too dimly perceived to justify any course but pursuing fusion's promise with vigor, flexibility, and patience.

References and Notes

1. A. Lovins, British representative of Friends of the Earth, wrote that "fusion is a clever way to do something we don't really want to do, namely to find *yet another* complex, costly, large-scale, centralized, high-technology way to make electricity—all of which goes in the wrong direction" [*Foreign Affairs* **55**, 65 (October 1976)].
2. W. Häfele and C. Starr, *J. Br. Nucl. Energy Soc.* **13**, 131 (1974). Häfele was quoted more recently [*Umschau* **77** (No. 9), 259 (1977)] as saying, "alles, was der Fusionsreaktor einmal können soll, der Brüter schon heute kann" (everything that the fusion reactor is supposed to be able to do someday, the breeder can already do today).
3. A simpler version of Fig. 1 and a fuller exposition of its implications are given in P. Ehrlich, A. Ehrlich, J. Holdren, *Ecoscience* (Freeman, San Francisco, 1977).
4. J. Holdren, in *The Sustainable Society*, D. Pirages, Ed. (Praeger, New York, 1977).
5. Perhaps the best record of the evolution of this trend is to be found in the succession of Annual Reports of the President's Council on Environmental Quality, published by the Government Printing Office, Washington, D.C., starting in 1969.
6. That is, it will be nongrowing on the average. The rate may fluctuate and may grow for a time in some regions while remaining steady or falling in others. For example, see J. Holdren, *Bull. At. Sci.* **30** (No. 1), 26 (1975).
7. Fusion research and the details of emerging fusion technologies have been reviewed thoroughly. Accordingly, this article is designed mainly to update and elaborate on the aspects that are most relevant to an assessment in the context of the rationale outlined here. For more detail on fusion physics and technology, and for other perspectives, the reader should consult R. F. Post and F. L. Ribe, *Science* **186**, 397 (1974); R. F. Post, *Annu. Rev. Energy* **1**, 213 (1976); D. Rose and M. Feiertag, *Technol. Rev.* **79** (No. 2), 20 (1976); W. D. Metz, *Science* **192**, 1320 (1976); *ibid.* **193**, 38 (1976); and (*8, 10, 25*) in this article.
8. Much of the information on which the discussions under fuel supply, cost of energy, and environment are based was compiled as part of a comparison of fusion and fission breeder reactors carried out in 1974 to 1976 by a group of fusion and fission technologists from the Federal Republic of Germany, the United States, and the Soviet Union; the full results of that work are reported by W. Häfele, J. P. Holdren, G. Kessler, and G. L. Kulcinski, with contributions by A. M. Belostotsky, R. R. Grigoriants, D. K. Kurbatov, G. E. Shatalov, M. A. Styrikorich, and N. N. Vasiliev, in *Fusion and Fast Breeder Reactors*, D. Faude, M. Helm, W. Weisz, Eds. (International Institute for Applied Systems Analysis, Laxenburg, Austria, November 1976, revised July 1977).
9. Eight thermal terawatts (8×10^{12} watts) is the continuous average rate corresponding to an annual use of coal, oil, natural gas, hydropower, nuclear fission, geothermal energy, and purchased firewood totaling 265×10^{15} kJ (250×10^{15} Btu's) per year in 1975 [M. Kenward, *New Sci.* **71**, 181 (22 July 1976), reporting British Petroleum's annual review]. Nonmarket energy forms—dung, crop residues, and fuel wood gathered by individuals—may add another terawatt or so [A. Makhijani and A. Poole, *Energy and Agriculture in the Third World* (Ballinger, Cambridge, Mass., 1975)].
10. B. F. Gore and E. S. Murphy, *Current Fusion Power Plant Concepts* (BNWL-2013, Batelle Northwest Laboratories, Richland, Wash., 1976).
11. Estimates to one and even two significant figures have been published [R. G. Mills, Ed., *A Fusion Power Plant* (MATT 1050, Princeton Univ. Plasma Physics Laboratory, Princeton,

N.J., 1974); R. W. Conn *et al.*, in *Proceedings of the 6th IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research* (International Atomic Energy Agency, Vienna, 1976)], but the history of attempts to predict the costs of new technologies much closer to commercialization than fusion offers convincing evidence that these estimates are highly speculative.
12. G. H. Miley, *Fusion Energy Conversion* (American Nuclear Society, Hinsdale, Ill., 1976), chap. 2.
13. J. R. McNally, Jr., points out [in *Proceedings of the Review Meeting on Advanced Fuel Fusion* (EPRI ER-536-SR, Electric Power Research Institute, Palo Alto, Calif., 1977)] that ignition of D-D (assuming reinjection of product T and ^3He) requires an $n\tau$ at 10 keV only about ten times higher than that needed to ignite D-T, and that the power density of D-T at this temperature is also about ten times that of D-D. Ignition means that fusion power carried by charged particles, hence trapped in the plasma, exceeds power lost by radiation. At the more likely operating temperature for both D-T and D-D of 100 keV, ignition requires $n\tau = 5 \times 10^{14}$ cm^{-3} sec for D-T and 10^{15} cm^{-3} sec for D-D (with reinjection), and the power density of D-T at ignition at this temperature is only twice that of D-D.
14. For a range of views on costs of electric and nonelectric solar technologies, see M. Simmons *et al.*, *Report of the Resource Group on Solar Energy* (Committee on Nuclear and Alternative Energy Systems, National Academy of Sciences, Washington, D.C., 1977); W. G. Pollard, *Am. Sci.* **64**, 424 (1976); A. F. Hildebrandt and L. L. Vant-Hull, *Science* **197**, 1139 (1977); W. D. Metz, *ibid.*, p. 650.
15. A preliminary attempt to investigate the sensitivity of the timing of the need for inexhaustibles to a range of outcomes under these headings was made recently in the ERDA Inexhaustible Resources Planning Study [see *Proceedings of the Public Meeting to Review the Status of the Inexhaustible Energy Resources Study* (CONF-770715, National Technical Information Service, Springfield, Va., 1977)]. The "window" of times when substantial contributions from inexhaustibles would first be required in the United States was found to extend from about 2000 to about 2015.
16. J. Emmett, J. Nuckolls, L. Wood, *Sci. Am.* **230** (No. 6), 24 (1974).
17. J. D. Lawson, *Proc. Phys. Soc. B* **70**, 6 (1957). The result is approximate: by varying assumptions about energy conversion efficiencies and considering the injection of high-energy deuterons into a relatively cool tritium plasma, one can show the possibility of bare energy break-even at $n\tau = 10^{13}$ cm^{-3} sec or even a little less; on the other hand, a reactor probably will need to have $n\tau = 5 \times 10^{14}$ cm^{-3} sec or more to be economically interesting. See also (*12*) and (*25*).
18. There are two main classes of instabilities. Gross configurational, or magnetohydrodynamic, instabilities can cause very rapid loss of confinement and routinely did so in early devices, but they have now been brought substantially under control in the tokamak and mirror approaches. Microinstabilities are associated with details of charged-particle orbits and velocity distribution functions, and have the effect of enhancing loss of particles by diffusion across the confining magnetic fields of all devices and out the ends of open-ended devices. It is the proposition that these microinstabilities become less damaging as the confined plasma becomes bigger and hotter—that is, that the "scaling laws" of plasma confinement are favorable—that the next generation of bigger machines is intended to confirm definitely. See the references cited in (*7*) for detailed discussion.
19. *Nucl. News* **20** (No. 5), 29 (1977).
20. For a recent review of the status of tokamak physics and technology, see M. B. Gottlieb, in *Proceedings of the 2nd Topical Meeting on Technology of Controlled Fusion* (CONF-760935-P1, National Technical Information Service, Springfield, Va., 1976).
21. The instability is the drift cyclotron loss cone (DCLC) mode. Its suppression by a technique called "warm plasma stabilization" is described by F. H. Coensgen *et al.*, in *Proceedings of the 6th International Conference on Plasma Physics and Controlled Nuclear Fusion Research* (CN-35/C1, International Atomic Energy Agency, Vienna, 1976).
22. W. C. Condit *et al.*, in *Proceedings of the 2nd Topical Meeting on the Technology of Controlled Nuclear Fusion* (CONF-760935-P1, National Technical Information Service, Springfield, Va., 1976).
23. The idea was independently conceived at about the same time in the Soviet Union and the United States [G. I. Dimov, V. V. Zakaidakov, M. E. Kishinevsky, *Fiz. Plazmy* **2**, 597 (1976); T. K. Fowler and B. G. Logan, *Comments on Plasma Phys. Controlled Fusion* **2** (No. 6), 167 (1977)].
24. For some of the possible weapons linkages see Energy Research and Development Administration, *Final Report of the Special Laser-Fusion Advisory Panel* (ERDA-28, National Technical Information Service, Springfield, Va., 1975); Atomic Energy Commission, *AEC Laser and Electron Beam Programs FY1976–FY1980* (WASH-1363, Government Printing Office, Washington, D.C., 1974); W. D. Metz, *Science* **194**, 166 (1976).
25. R. J. DeBellis and Z. A. Sabri, Eds., *Fusion Power: Status and Options* (ER-510-SR, Electric Power Research Institute, Palo Alto, Calif., 1977).
26. R. W. Conn and G. L. Kulcinski, *Science* **193**, 630 (1976); D. J. Rose and M. Feiertag, *Technol. Rev.* **79** (No. 2), 20 (1976).
27. C. P. Ashworth, in *Proceedings of the Review Meeting on Advanced Fuel Fusion* (EPRI ER-536-SR, Electric Power Research Institute, Palo Alto, Calif., 1977).
28. A concise introduction to the ion-beam approach is given in W. D. Metz, *Science* **194**, 307 (1976).
29. Energy Research and Development Administration, *Fusion Power by Magnetic Confinement Program Plan* (ERDA 76/110/1, National Technical Information Service, Springfield, Va., 1976).
30. A. Weinberg observed in a panel discussion at the 23rd annual meeting of the American Nuclear Society in New York in June 1977 that "the fact is that nowhere in the world has anybody put 100 kg of plutonium into a reactor and taken 120 kg out. And that experiment, I think, should be done" [*Nucl. News* **20** (No. 10), 34 (1977)].
31. The abbreviated treatment here relies heavily on recent, more exhaustive reviews. In addition to (*8*), see J. P. Holdren [in *Proceedings of the EPRI Executive Seminar on Controlled Fusion* (Electric Power Research Institute, Palo Alto, Calif., in press)]; J. R. Young [*An Environmental Analysis of Fusion Power to Determine Related R & D Needs* (BNWL-2010, Batelle Northwest Laboratories, Richland, Wash., 1976)]; D. Steiner [*Nucl. Sci. Eng.* **58**, 107 (1975)]; and J. P. Holdren, T. K. Fowler, R. F. Post [in *Energy and the Environment: Cost-Benefit Analysis*, F. Karam and K. Z. Morgan, Eds. (Pergamon, New York, 1976)]. Environmental aspects of solar options are not considered systematically here, but see J. P. Holdren [in *Distributed Energy Technologies of California*, M. Christensen, M. Simmons, P. Craig, Eds. (LBL-6831, Lawrence Berkeley Laboratory, Berkeley, Calif., 1977), vol. 2].
32. Tritium (half-life, 12.3 years) is significant radiologically only as an internal emitter, because its soft β particle (maximum energy, 18 keV) cannot penetrate the skin. The oxide (HTO, tritiated water) is considered about 200 times more dangerous than the elemental form, as the latter is not retained in the body; the dose per curie of tritium ingested as the oxide is about 70 rem. An excellent detailed review of the radiological aspects of tritium is given in P. S. Rohwer and W. H. Wilcox [*Nucl. Safety* **17**, 216 (1976)].
33. Nuclear Regulatory Commission, *Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants* [WASH 1400 (NUREG-75/014), National Technical Information Service, Springfield, Va., 1976].
34. T. R. Galloway, *Tritium Control in a Mirror-Fusion Central Power Station* (UCRL-78586, Lawrence Livermore Laboratory, Livermore, Calif., 1976).
35. J. P. Holdren, *Safety and Environmental Aspects of Fusion Reactors* (UCRL-78759. Lawrence Livermore Laboratory, Livermore, Calif., 1976).
36. J. W. Davis and G. L. Kulcinski, *Assessment of Titanium for Use in the 1st Wall/Blanket Structure of Fusion Power Reactors* (EPRI ER-386, Electric Power Research Institute, Palo Alto, Calif., 1977).
37. R. W. Conn, G. L. Kulcinski, H. Avci, M. El-Maghrabi, *Nucl. Technol.* **26**, 125 (1975).
38. G. Hopkins, *Fusion Reactor Studies: Potential of Low Z Materials for the First Wall* (EPRI 115-2, Electric Power Research Institute, Palo Alto, Calif., 1975).
39. C. W. Hartman *et al.*, *A Conceptual Fusion Reactor Based on the High Plasma Density Z-Pinch* (UCRL-78655, Lawrence Livermore Laboratory, Livermore, Calif., 1976).
40. For one of the more comprehensive attempts to analyze fusion-reactor safety to date, see D. Okrent *et al.*, *Nucl. Eng. Des.* **39**, 215, 1976.
41. H. G. Yeh, *Considerations of Coil Protection and Electrical Connecting Schemes in Large Superconducting Toroidal Magnet Systems* (ORNL TM-0543, National Technical Information Service, Springfield, Va., 1976).
42. B. F. Gore and P. L. Hendrickson, *Fuel Procurement for First Generation Fusion Power Plants* (BNWL-2012, Battelle Pacific Northwest Laboratories, Richland, Wash., 1976).
43. A good discussion of ecological effects of end use of energy is given by J. Harte *et al.*, *Energy and the Fate of Ecosystems* (Resource Group on Ecosystem Impacts, Committee on Nuclear and Alternative Energy Systems, National Academy of Sciences, Washington, D.C., 1978).
44. For eloquent and forceful, if still controversial, views on scale and other aspects of compatibility, see A. B. Lovins, *Soft Energy Paths* (Ballinger, Cambridge, Mass., 1977).
45. The succeeding material in this paragraph is based largely on B. J. Eastlund, *Enhanced Energy Utilization from a Controlled Thermonuclear Fusion Reactor* (EPRI ER-248, Electric Power Research Institute, Palo Alto, Calif., 1976); L. A. Booth, *Fusion Energy Applied to Synthetic Fuel Production* (CONF-770593, Department of Energy, Washington, D.C., 1977); G. H. Miley (*12*).
46. The interested reader, however, will find discussions of the "fusion torch," fusion space propulsion, and other esoteric applications in (*12*).
47. The best review article on these concepts is L. Lidsky, *Nucl. Fusion* **15**, 151 (1975).
48. J. P. Holdren, in *DCTR Fusion-Fission Energy Systems Review Meeting*, L. Bogart, Ed. (ERDA-4, National Technical Information Service, Springfield, Va. 1974), pp. 209–216.
49. Whether either of these hypothetical advantages is real depends on whether substantially proliferation-resistant fuel cycles exist and on whether converter fission reactors are safer than breeders; both propositions are controversial [see also J. P. Holdren, in (*50*), pp. 267–272].
50. C. Taylor, Ed., *Proceedings of the U.S.-U.S.S.R. Symposium on Fusion-Fission Reactors* (CONF-760733, National Technical Information Service, Springfield, Va., 1976).
51. T. A. Kunasz, in *Industrial Minerals and Rocks* (American Institute of Mining Engineers, New York, revised ed., 1975).
52. National Commission on Materials Policy, *Material Needs and the Environment Today and Tomorrow* (Government Printing Office, Washington, D.C., 1973).
53. R. C. Weast, Ed., *Handbook of Chemistry and Physics* (Chemical Rubber Co., Cleveland, Ohio, ed. 55, 1974).
54. Energy Research and Development Administration, *Report of the Liquid Metal Fast Breeder Reactor Program Review Group* (Report ERDA-1, Washington, D.C., 1975).
55. Concentrations are from E. Wenk, Jr. [*Sci. Am.* **221** (No. 3), 166 (1969)]. Considering seawater "probable" ore seems unobjectionable for ^{11}B, at a concentration by mass only eight times smaller than that of the deuterium, which is routinely extracted today. Lithium, at a concentration 200 times smaller than that of deuterium, is more problematical, but extension of the technology already used to extract lithium from heavier brines should be possible, given time. Whether uranium, which is another 50 times more dilute in seawater, is a usable ore is more speculative.
56. I thank T. K. Fowler and K. Anderson for helpful comments.