Fusion vs Fission Energy

Energy, the Environment, and Thermonuclear Reactors

by John Holdren

The rapid increase of energy use, electrical and otherwise, has intensified a long-standing dichotomy: On the one hand, energy is the prime mover of technology and an essential ingredient in fashioning a decent standard of living; and on the other hand, it is a major ingredient of man's growing detrimental impact on his environment.

Thus the nature of the "energy crisis" depends on whom one asks. Industry and many branches of government apparently regard the present rates of growth of energy use as inviolable. They view the crisis as one of logistics—how to mobilize resources and technology quickly enough (in the face of growing opposition from environmentalists) to maintain these rates well into the future. To the environmentalists, the crisis is the possibility that the growth rates will indeed be maintained, accompanied by a degree of environmental deterioration barely hinted at today. And thoughtful observers of many persuasions are concerned about bringing the costs of pollution and depletion into the balance sheets—and about how the resulting increase in the price of energy will affect the poor.

Short and Long Term

Even a cursory examination of present and probable future energy technologies leads to two inescapable conclusions. First, technologies of the future (such as controlled fusion) will not solve the logistics problem of maintaining present growth rates over the next two decades. They simply cannot be brought to bear quickly enough in sufficient quantity. Second, even in the longer term, technology cannot completely resolve the dichotomy between mankind's demands for energy and the adverse environmental effects of providing it. No means of providing energy is free from environmental liabilities. Thus, the question of distinguishing *demands* (as for comfort heating of poorly insulated buildings and fuel for overpowered automobiles) from *needs* (as for mass transit, recycling plants, and renovating the urban environment) must be frankly addressed. Sooner or later, the necessity to stabilize energy consumption will have to be confronted. In the U.S., which now accounts for 35 percent of the world's annual energy use, it is likely to be sooner.

At the same time, no amount of progress in dealing with these economic and social issues will eliminate the question of how best to provide energy in the long term. There are a number of possibilities, but those that appear today to have the potential to meet the bulk of civilization's energy requirements far into the future—for thousands of centuries—are only three: nuclear fission with breeder reactors, nuclear fusion, and direct harnessing of solar energy. I will not dwell on solar energy here, except to note that it is obviously feasible technically and almost certainly the best option we have environmentally. The questions are, in what locations, what sizes, and indeed in what roles (office building energy systems or central station electricity generation) will solar energy prove economically interesting. Fusion reactors and breeder reactors, on the other hand, are relatively easy to compare directly because they fill the same well-defined role: central station generation, with economic and technical factors pointing to very large sizes.

Fuel Considerations

Basically, fission breeder reactors operate by using excess neutrons from fissions taking place in the reactor to transmute Uranium-238 and Thorium-232 (called *fertile* materials) into Plutonium-239 and Uranium-233 (*fissile*, or fissionable, materials). Breeding is made possible because each fission yields an average of more than two neutrons; one sustains the chain reaction by initiating

---

The most extensive work on the radiological aspects of fusion reactors has been done by Dr. Don Steiner of the Oak Ridge National Laboratory and Dr. J. D. Lee of the Lawrence Livermore Laboratory. Their publications are the source of many of the numbers in this article.

FUEL SUPPLIES IN THE LONG TERM

		energy in Q*
U.S. electricity generation, 1970		.015
U.S. energy consumption, 1970		.06
World energy consumption, 1970		.17
Hypothetical annual world energy consumption (10 billion people at 1970 U.S. per capita rate)		3
Initial world supply of fossil fuels		250
Lithium (D-T fusion)	known on land	670
	probable on land	8300
	sea	21 million
Uranium and thorium		5 million
Deuterium (D-D fusion)		7.5 billion

*One Q is a unit of energy equal to 10^{18} B.T.U. or 2.93×10^{14} kwht (kilowatt-hours, thermal).

RAW FUEL CONTRIBUTION TO PRICE OF ELECTRICITY (33% plant efficiency)

	cents/kwhe
Coal ($6/metric ton)	0.2
Uranium ($8/lb. of U_3O_8, 1.5% utilization)	0.02
Uranium ($100/lb. of U_3O_8, 70% utilization)	0.004
Lithium (2¢/gram)	0.0002
Deuterium (30¢/gram)	0.0008
Delivered cost of electricity to residential consumers, 1970	2.0

another fission, one replaces the fuel atom by transmuting a fertile atom, and any others can either make extra fuel (breeding) or be lost by escape from the reactor core or by non-productive absorption.

Of the possible fusion reactions, that of deuterium with tritium is the least difficult to achieve and will almost certainly be the one employed in the first successful fusion reactor. (Deuterium and tritium are the heavy isotopes of hydrogen.) In such a system the tritium, which is almost nonexistent in nature, would be regenerated by neutron-lithium reactions in a "blanket" surrounding the thermonuclear plasma. Thus the raw materials for D-T fusion are effectively deuterium, which is easily extracted from seawater, and lithium. Reactions fueled by deuterium alone exist, but they are more difficult to exploit.

Given these possibilities, it quickly becomes apparent that both fission breeders and fusion reactors meet the requirements for long-term energy sources that the fuel be abundant. This point is illustrated in the table (top left), where current and projected energy consumption figures are compared with the energy content available in the fission and fusion fuels.

It is also clear that raw fuel costs will be very low with either option, as shown at the left. Even in today's light water reactors, only 1 or 2 percent of the energy potentially available in the uranium is extracted, and the cost of the raw uranium oxide accounts for only 1 percent of the delivered cost to residential consumers of nuclear-generated electricity. Enrichment, fabrication into fuel elements, and eventual reprocessing make the total fuel costs about 0.2¢ per kwhe (kilowatt-hour, electrical) in a light water reactor, but none of these expenses depend on the cost of raw uranium. This fact undercuts the Atomic Energy Commission's argument that we need the breeder reactor in order to hold the price of nuclear electricity down as high-grade uranium becomes scarce.

At this point, of course, it is not at all clear what construction costs for a reliable breeder will be. They could easily be high enough to offset the cheapness of the

Comparison between the breeder and the fusion reactor boils down to environmental aspects.

raw fuel. The same is true for fusion reactors: It is difficult to predict costs when no one yet knows what the successful device will look like. Even if the fuel were free (and .0008¢/kwhe is close to that), the electricity could be expensive.

Evidently, then, the breeder and the fusion reactor cannot meaningfully be distinguished at this point in time in respect to either abundance of fuel or to cost of the electricity. The comparison therefore boils down to environmental aspects. To focus on this issue, the table below lists the principal environmental liabilities of the breeder reactor—with no pretense of ranking by importance. For purposes of this discussion, "breeder reactor" will refer hereafter to the plutonium fueled liquid-metal fast breeder, which dominates the U. S. research program in this field. In evaluating a potential fusion system against the list in the table below, I will concentrate on the D-T reaction both because it is the easiest to achieve and because it is the worst case environmentally.

ENVIRONMENTAL LIABILITIES OF BREEDER REACTOR

Operation
- Routine emissions
- Thermal pollution
- Accidents
  - nuclear excursion
  - loss of coolant

Fuel Management
- Mining and refining
  - defacing landscape
  - workers' health
  - radioactive tailings
- Transportation
  - escape of spent fuel or concentrated waste
  - escape of plutonium
  - diversion of plutonium for clandestine purposes
- Emissions in reprocessing
- Storage of concentrated wastes

Fuel Management

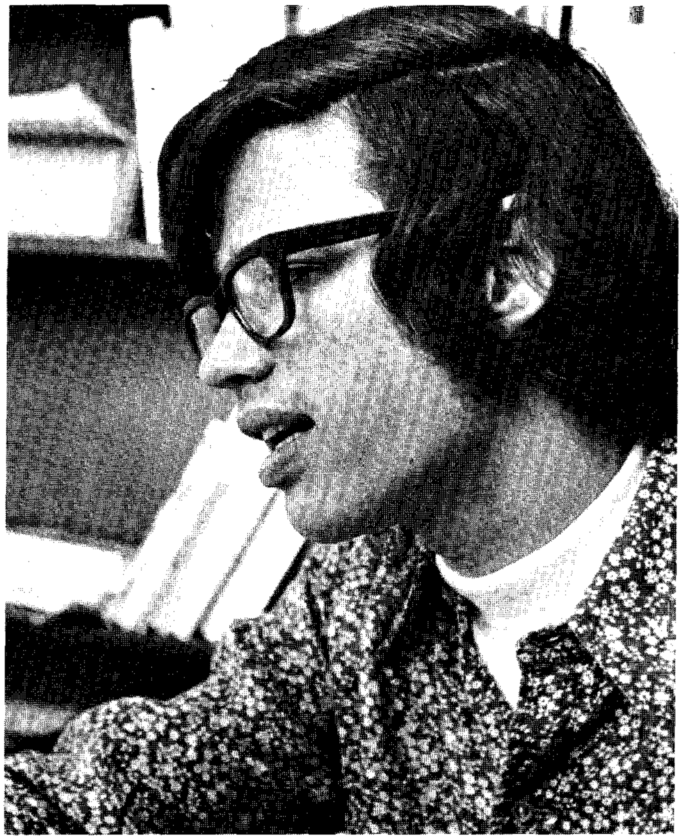
Deuterium is obtained from sea water by isotope separation, and water depleted of deuterium can be returned to its source without ill effect. The lithium from which tritium will be "bred" by neutron bombardment is now obtained principally from heavy brines found in Nevada and California. Eventually lithium may also be extracted from the oceans. Both deuterium and lithium are non-radioactive.

Unfortunately, tritium is radioactive. Since it is a fuel rather than a waste product, it does not need to be shipped to remote storage sites, but some shipping would be involved in supplying new fusion reactors with their initial inventories of this substance. In a stable fusion-energy economy, no tritium would have to be shipped. "Reprocessing," in the sense of regenerating tritium from lithium, would take place on-site.

Thermal Pollution

Discharge of waste heat to the environment is a liability common to all forms of thermal electricity generation, and its biological and climatic effects have been widely discussed. A more general problem is that virtually all the electricity itself, as well as the energy wasted in generation, eventually appears in the environment as heat. This phenomenon already influences the climate of metropolitan areas and may ultimately be important on a larger scale.

First-generation fusion reactors will probably operate at thermal efficiencies between 40 and 50 percent, offering little or no improvement over the fossil and fission plants likely to be operating in the same time period. This is because most of the energy of the D-T reaction is carried by the neutrons and must therefore be converted in a more or less conventional thermal cycle. When the D-D reaction becomes exploitable, this situation may change. Here, most of the energy is carried by charged reaction



John Holdren

products, opening the possibility of direct conversion of this kinetic energy to electricity. Experimental and theoretical work on direct conversion at the University of California's Lawrence Livermore Laboratory suggests that plant efficiencies of perhaps 80 percent may eventually be possible. This would yield a sixfold reduction from today's best plants in respect to waste heat at the site per unit of electricity generated, and a twofold reduction of total thermal load per unit of electricity.

Tritium

A more bothersome issue is the inventory of tritium that would be associated with a D-T fusion reactor. Tritium decays to Helium-3, which is stable, with a half-life of 12.3 years. The accompanying radiation is a low-energy beta particle (electron), which is stopped by 7 millimeters of air and cannot penetrate the skin. The most serious aspect of the tritium problem is the tendency of tritium to replace one of the hydrogen atoms in a water molecule, forming HTO and giving tritium access from the inside to many of the cells of the body.

PRINCIPAL VOLATILE ISOTOPES IN 2500 Mwt FISSION AND FUSION REACTORS

	fission (iodine-131)	**D-T fusion (tritium)**
Activity, curies	8×10^{7}	3×10^{7}
MPC, curies/meter^3	10^{-10} (respirated)	2×10^{-5} (T_2)
	1.4×10^{-13} (on crops)	2×10^{-7} (HTO)
Relative hazard, meter^3	8×10^{17}—6×10^{20}	1.5×10^{12}—1.5×10^{14}

Preliminary engineering studies indicate that a 2,500 Mwt (megawatts, thermal) fusion reactor—1,000 megawatts, electrical, at 40 percent thermal efficiency—would require a tritium inventory of about 3 kilograms, or 30 million curies. (A curie of radioactivity equals 37 billion disintegrations per second of a radioactive material.) The table above compares this amount in quantity and in biological hazard with the dominant volatile fission product (Iodine-131) in a breeder reactor of the same size. Relative biological hazard can be thought of as the volume of air that could be contaminated to the maximum permissible concentration (MPC) if all the material escaped.

It is evident from the table that the potential hazard associated with the tritium in a fusion reactor is much smaller—by a factor of 10,000 to 1 million—than that associated with the Iodine-131 in a breeder reactor. At the same time, the tritium hazard is far from negligible. The sudden loss of only a thousandth of the tritium inventory under atmospheric inversion conditions would constitute an accident with serious public health implications. The application to fusion reactors of the Atomic

Breeder reactors and fusion reactors will both permit mankind to exploit nearly inexhaustible supplies of inexpensive fuel, but the costs are still uncertain.

Energy Commission's new emission standards for light water fission reactors would mean that routine releases could not exceed one part in ten million of the tritium inventory a day. Meeting this requirement will necessitate great care (and perhaps expense), but it can be done.

Accidents

It is not enough, of course, to ask what is inside the reactor—one should also try to examine the odds that the material will get out. Today, the possibility that a fission reactor might suffer a major accident leading to loss of containment is the subject of considerable speculation. Neither operating experience nor theoretical analysis is yet adequate to the task of assigning a numerical probability to such an event. However, the results of recent investigations into the performance of emergency core cooling systems for light water reactors suggest to some competent observers that the odds may be worse than had been supposed. Breeder reactors will certainly be even trickier to handle in this respect, owing to their higher power densities and operating temperatures.

A crude comparison of the hypothetical accident potential of breeder reactors and fusion reactors may be made by examining the magnitudes of the various forms of energy stored in these devices. Estimates are given in the table below. These figures are not the whole story, of course. One must also know whether the energy can be released suddenly. A fusion reactor will certainly be safe against a nuclear excursion (i.e., runaway), since any malfunction tends to quench the reaction by loss of confinement, loss of temperature, or both. Rather sudden releases of the magnetic and chemical energy in a fusion system are possible in principle, but there is no question that a structure sturdy enough to withstand the maximum event can be provided. In a breeder reactor, by contrast, excursions too extreme to be contained—involving sudden rearrangement of the nuclear core after extensive melting—cannot yet be ruled out.

STORED ENERGY IN 2500 Mwt FISSION AND FUSION REACTORS

	fission (breeder)	fusion
Nuclear	5x10^{18} joules	5x10^{11} joules
Chemical	5x10^{11} joules (sodium)	5x10^{11} joules (lithium)
Magnetic (1 ton TNT=4x10^{9} joules)	0	5x10^{10} joules

Long-lived Radioactivity

Tritium is not the only radiological problem of fusion reactors. Each D-T reaction produces energetic neutrons, and these particles bombard the vacuum wall separating the fusion plasma from the other components of the reactor. Unfortunately, neutron bombardment can transmute stable elements into unstable ones. Thus radioactivity is induced in the vacuum wall, the nature of the new isotopes depending on what the wall is made of. Moreover, the intense neutron flux erodes the structural integrity of materials, so that the entire wall will probably have to be replaced as often as every two or three years.

One does not have a wide choice of wall material, since it must meet many stringent requirements—operating temperature, resistance to corrosion, ability to withstand bombardment by plasma ions as well as by neutrons, and so on. From most points of view, niobium seems the ideal choice for this application, and almost all early engineering studies have assumed it will be used. However, some of the isotopes of niobium induced by neutron bombardment are so long-lived and so hazardous as to represent a waste-disposal problem only a hundredfold smaller than that associated with fission reactors. The table above right gives

LONG-LIVED ISOTOPES (2500 Mwt reactors)

	half-life (years)	generation rate (curies/yr)	accumulated activity after 1000 yr (curies)	relative hazard after 1000 yrs*
FUSION				
niobium-93m	13.6	2.2×10^7	4.3×10^8	1.1×10^{16}
niobium-94	20,000	7.3×10^3	7.3×10^6	7.3×10^{14}
FISSION				
strontium-90	28	1.7×10^6	6.8×10^7	6.8×10^{17}
cesium-137	30	2.3×10^6	10^8	2.0×10^{16}

*relative hazard=curies/MPC

the comparison. In view of this situation, it now seems likely that vanadium will be used instead of niobium in fusion reactors. Although use of this substance will entail some loss of thermal efficiency, it would reduce the long-lived waste burden by an additional factor of approximately 1,000—or 100,000 times less than that for fission reactors.

Afterheat

Another potential problem associated with the radioactive materials in fission and fusion reactors is afterheat—the energy released by radioactive decay of the accumulated isotopes even after the reactor itself has been shut down. This phenomenon is what makes an effective emergency cooling system absolutely essential in a fission reactor, even assuming that the reactor would be shut down at once if the main coolant were lost. The afterheat associated with the niobium in a fusion reactor would be small compared to that in a breeder reactor—so small that loss of coolant is unlikely to be a major problem. If vanadium is used instead of niobium, the afterheat will be smaller still.

ENVIRONMENTAL ASSETS OF FUSION

- volatile radioactivity 10^4—10^6 lower than breeder
- long lived waste 10^2—10^5 lower than breeder
- afterheat 20-30 lower than breeder
- nuclear excursion impossible; maximum internal energy release can be contained
- grinding up earth's crust to obtain fuel unnecessary
- potential reduction in thermal pollution

Advanced Fusion Reactors

Although it is sometimes assumed that eventual success with the more difficult reactions (such as D-D and D-He^3) will eliminate the sort of problems described here, this is not the case. The D-D reaction produces both neutrons and tritium, and one cannot have D-He^3 reactions without D-D taking place too. Present evidence suggests that advanced reactors might get by with tritium inventories ten times smaller than those assumed here, and with neutron activation five times smaller. These are substantial improvements, but they do not eliminate the radiological hazards entirely.

Conclusion

Breeder reactors and fusion reactors will both permit mankind to exploit nearly inexhaustible supplies of inexpensive fuel, but the total system costs for both approaches are still uncertain. Present comparisons between them must therefore hinge mainly on environmental factors. The advantages of fusion are summarized in the table at the left. These assets are well worth striving for and, indeed, worth a good deal more research money than is currently being applied to the task. Nevertheless, fusion will not reduce the environmental impact of electricity generation to zero. Neither do any other alternatives available to us. Perhaps one moral of this story is the old dictum of economics, now being advertised as a law of ecology: There is no such thing as a free lunch.