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FUSION POWER AND THE ENVIRONMENT

J. P. Holdren, T. K. Fowler, and R. F. Post

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FUSION POWER AND THE ENVIRONMENT

J. P. Holdren, T. K. Fowler, and R. F. Post
Lawrence Livermore Laboratory
University of California
Livermore, California 94550

ABSTRACT

Environmental characteristics of conceptual fusion-reactor systems based on magnetic confinement are examined quantitatively, and some comparisons with fission systems are made. Fusion, like all other energy sources, will not be completely free of environmental liabilities, but the most obvious of these — tritium leakage and activation of structural materials by neutron bombardment — are susceptible to significant reduction by ingenuity in choice of materials and design. Large fusion reactors can probably be designed so that worst-case releases of radioactivity owing to accident or sabotage would produce no prompt fatalities in the public. A world energy economy relying heavily on fusion could make heavy demands on scarce nonfuel materials, a topic deserving further attention. Fusion's potential environmental advantages are not entirely "automatic" — converting them into practical reality will require emphasis on environmental characteristics throughout the process of reactor design and engineering. The central role of environmental impact in the long-term energy dilemma of civilization justifies the highest priority on this aspect of fusion.

1. INTRODUCTION

The attractiveness of controlled thermonuclear fusion as a future mainstay of civilization's energy supply is due largely to two characteristics: a fuel supply that is accessible, abundant, and cheap; and the potential for achieving a high degree of safety and low level of social and environmental impact. The latter aspects are actually in many respects the more important ones; for it is environmental and social constraints, far more than adequacy of fuel supplies, that threaten to limit civilization's rate of energy use in the next hundred years (1).

To embody the potential advantages of fusion in a practical and economic technology remains one of the great challenges of the twentieth century. A demonstration of scientific feasibility — that is, the laboratory achievement of a combination of fuel temperature, density, and duration of confinement that would lead, in a reactor, to net power production — has not yet been accomplished. There is reason to hope that such a demonstration will take place by 1980 or shortly thereafter. This event will have to be

followed by an intensive period of engineering development, lasting perhaps 10 to 15 years, in order to translate scientific feasibility into a power plant capable of delivering electricity to a utility grid. Some of the main pathways to scientific feasibility — and the intricacies of the technological development that subsequently will be required — have been described earlier in these proceedings by Fraas (2), and elsewhere by Post and Ribe (3).

In the present early stage of the development of fusion, it is not possible to be sure what a successful fusion reactor will look like in overall configuration, to say nothing of many engineering details. Nor is it possible, accordingly, to say with any confidence what a commercial fusion reactor will cost to build. This is an issue of some importance, because high construction costs could offset the economic advantage of cheap fuel (as advocates of nuclear fission and solar energy will recognize!); nevertheless, not much light can be shed on the cost question at the present state of knowledge. Despite the uncertainties, we believe it does make sense to look as carefully as we can at this stage at the environmental and safety characteristics of fusion. The motivation for doing so is to be able to identify potential problems early enough to take them into account in the main technological choices that are made. Fusion, like all energy technologies, will not be completely free of environmental consequences, but it should be possible to make the adverse impact relatively modest by designing with the advantages and liabilities of the fusion process clearly in mind from the beginning.

Environmental effects occur, in general, at many stages of the energy cycle, from exploring for fuel resources to management of final wastes. Without claiming to be completely comprehensive, we believe that the environmental characteristics of fusion important enough or unusual enough to deserve mention here fall into the following categories: (a) extraction and processing of the basic fuels; (b) routine emissions of radioactivity from fusion reactors; (c) production and handling of radioactive wastes; (d) non-routine releases of radioactivity, e.g., via accidents or hostile acts; (e) demands on nonfuel materials; (f) thermal discharges; and (g) use of nuclear materials for weapons.

We will discuss these issues in the context of some contemporary preliminary designs for fusion reactors, recognizing that future innovations could make some impacts smaller than those indicated here and, of course, that unforeseen problems could make some impacts larger. Our basic view is an optimistic one — we think fusion's inherent safety characteristics and freedom from long-lived radioactive "ashes" intrinsic to the process are enormous advantages that ingenious reactor designers will find better and better ways to exploit as the technology evolves. Some particularly innovative approaches that have already been suggested for minimizing the environmental impact of fusion will be mentioned as we proceed.

We shall limit our discussion here to fusion technologies based on magnetic confinement; we exclude laser-pellet fusion because magnetic confinement is the approach with which we are most familiar, on which by far the larger literature is available, and which we suspect at the moment offers the greater hope of early success. Many of the environmental characteristics of the two approaches would in any case be quite similar.

It is not our intent here to attempt a detailed comparison of the environmental characteristics of fusion and fission, but we will use the environmental impacts of fission technologies in some instances as a yardstick with which the technical community has some familiarity.

2. FUELS FOR FUSION

In principle, most of the nuclear isotopes near the lower end of the periodic table could combine in nuclear fusion reactions with a net release of energy. Indeed, such reactions in stellar interiors are thought to be the dominant processes in the evolution of stars. On the earth, however, we cannot hope to reproduce such conditions, and the list of fusion fuel candidates is much shorter, being confined to special isotopes of the elements at the bottom of the periodic table, such as hydrogen and helium. Even so, there is a richness of possibilities for fuel combinations for fusion power that is unmatched by any other energy source.

The primary fuel for fusion is deuterium — heavy hydrogen. Deuterium, a stable isotope of hydrogen, has the second simplest nucleus in the periodic table, consisting of one proton and one neutron bound together. Used as a fusion fuel, deuterium can react with itself or with other light isotopes. The four most important reactions involving deuterium are listed below, written in the same way as the formula for a chemical combustion reaction (such as the combination of hydrogen and oxygen to form water, with the release of chemical energy). The species involved are: p, protons (the nuclei of ordinary hydrogen); D, deuterons; T, tritons (tritium is an unstable, heavier isotope of hydrogen); ^3He , nuclei of helium-3 (a stable, light isotope of helium); and n, neutrons. The first two reactions listed are alternate possibilities for the D-D reaction and occur with roughly equal probability. The energy release from the reactions is given in two ways: (a) millions of electron volts (MeV), the electrical-equivalent energy imparted to the product nuclei, and (b) thermal kilowatt-hours per gram mass of the reacting nuclei (kWh/g). As a comparison, the chemical combustion reaction between hydrogen and oxygen that leads to water is also listed, with the same energy units.

These reactions, plus additional ones involving lithium and boron isotopes, are the building blocks of the fuel cycles for future fusion reactors. The last deuterium reaction listed, D- ^3He , is of particular interest, since its energy release is large and its reaction products are charged. In such

a case, there exists the possibility of a fusion reactor cycle involving direct conversion of fusion energy to electricity, potentially at very high efficiency. Note also that deuterium as a fuel has the unusual property that its "ashes" are themselves combustible (via the D-T and D-³He reactions), so that a fusion-reactor fuel cycle can be visualized in which deuterium is burned to completion; the end products are ordinary hydrogen and helium plus the release of 7 MeV per deuteron burned, that is, 96,000 kWh of energy per gram of deuterium fuel, or about four times the energy per gram released in the fission of uranium.

While there is reason to believe that the D-D-T-³He fuel cycle (hereafter referred to simply as D-D) will in time be employed, the first achievement of fusion power will probably depend mainly on the use of the D-T reaction. This is because the D-T reaction has the lowest "ignition temperature" (about 50 million degrees kinetic) of all the reactions and therefore is the least demanding in terms of heating and confinement. But since tritium exists only in trace quantities in nature (it is radioactive, with a half-life of 12.3 years), it must be "bred". Although there are several ways in which such breeding might be accomplished, the only one that has received serious study involves capture of the neutron reaction product of the D-T reaction in a "blanket" containing lithium surrounding the chamber. This capture process leads to tritium generation, with a potentially generous breeding ratio (BR = 1.1 to 2.0). Here the breeding ratio is the number of tritium nuclei produced per tritium nucleus consumed. The relevant reactions are:

The overall reactions for D-T fusion are therefore effectively

How much energy one obtains in practice from each gram of natural lithium (7.4% ⁶Li, 92.6% ⁷Li) must be determined from detailed neutronics calculations in which the geometry and composition of the lithium blanket (including degree of enrichment in ⁶Li) are specified. Such calculations indicate that a reasonable figure is 25,000 kWh per gram of natural (unenriched) Li at a T breeding ratio of 1 (appropriate for a steady-state fusion energy economy) and 13,000 kWh per gram of natural Li at a breeding ratio of 1.25 (appropriate for the transient when fusion-reactor capacity is growing rapidly) (4).

With this background, one can begin to investigate quantitatively the supplies of the main fusion fuels and the environmental impact of extracting them. The supply of deuterium in the oceans is about 5 x 10¹⁹ grams, which would yield about 5 x 10²⁴ kWh at 96,000 kWh per gram of D in the D-D fuel cycle (1). This is about 70 billion times the 1974 world energy use, and some 250 billion times the 1974 world energy use for electricity generation. Assuming a thermal-to-electric conversion efficiency of 40%, the 1974 U.S.

electricity demand (averaging about 200 million electrical kilowatts) could be supplied by D-D fusion reactors fed by a total of 5 kg of deuterium per hour. (The corresponding figure for coal would be about 65,000 metric tons per hour.) The required amount of deuterium could be produced by a small deuterium separation plant, the input to which was simply the amount of ordinary water that would flow through a pipe a few centimeters in diameter at ordinary pressures. At the cost of deuterium prevailing in the early 1970's - 30 to 40 cents per gram - the contribution of the fusion fuel to the price of electricity would be about 0.01 mills/kWh(e).

Consumption of lithium in a fuel-cycle relying mainly on the D-T reaction would be 20 to 40 kg of natural lithium per hour to meet the total 1974 U.S. electricity demand. This corresponds to mining at most about 58,000 metric tons of pegmatite ore (0.60% Li) per year, or processing 1,100,000 metric tons per year of lithium-rich brines (300 ppm Li) from Nevada. Annual ore requirements for the different fusion fuel cycles are compared with those of fission and coal in Table I. Assumed energy contents for the table are: terrestrial lithium, 13,000 kWh/g (BR = 1.25); oceanic lithium, 25,000 kWh/g (by the time this Li is needed, the system is in steady state with BR = 1); uranium, 13,200 kWh/g in LMFBR (fissions 60% of natural U), 308 kWh/g in HTGR (fissions 1.4%), and LWR, 154 kWh/g (fissions 0.7%); coal 7.75 kWh/kg. At the 1970 price of lithium of about 2 cents per gram, its contribution to the price of electricity is at most 0.004 mills/kWh(e).

Table I. Ore requirements to produce 1974 U.S. electricity by various processes (5,6) [200,000 MW(e)-yr at assumed 40% efficiency, i.e., 500,000 MW(t)-yr].

Process	Ore (fuel ppm by weight)	Ore required, in million metric tons
D-D fusion	Sea water (32 ppm D)	1.4
D-T (Li) fusion	Pegmatite (6000 ppm Li)	0.06
	Silver Peak brine (300 ppm Li)	1.1
	Sea water (0.17 ppm Li)	1000
LMFBR fission	Colo. sandstone (2000 ppm U)	0.17
	Chattanooga shale (60 ppm U)	5.5
	Sea water (0.003 ppm U)	110,000
LWR fission	Colo. sandstone (2000 ppm U)	14
HTGR fission	Chattanooga shale (60 ppm U)	240
Coal-fired steam	Bituminous coal	570

Total supplies of lithium, while smaller than those of deuterium, are far more than adequate to justify development of D-T fusion as a major energy source. Meeting the 1974 U.S. electricity demand solely with D-T fusion would have required the consumption of about 340 metric tons of natural lithium metal (at 13,000 kWh/g) as fuel; this is on the order of 10% of the actual annual U.S. consumption of lithium for non-fuel purposes in the early 1970's, and about 15,000 times less than the known and inferred U.S. reserves of lithium in pegmatites and brines (5). With reserves of lithium so greatly

in excess of foreseeable needs, there has been little incentive to search for more. If an enormously increased level of energy use based largely on D-T fusion were to begin to deplete the lithium reserves, say, a few centuries from now, it is likely that new terrestrial deposits could be found. Moreover, since even a 100-fold increase in lithium price could be tolerated without serious impact on the cost of fusion energy, it is not unlikely that the vast lithium resource dissolved in sea water could be made available in the long term. The situation with respect to fuel supply for fusion, fission, and conventional fossil fuels is summarized in Table II.

Table II. Some fuel resources and consumption rates
(measured in trillions of GJ = 10^{12} J =
 0.948×10^{18} BTU ≈ 0.95 Q) (1).

	Energy (trillions of GJ)
<u>Fuel</u>	
World oil reserves, 1974	4
World ultimately recoverable gas, oil, coal	240
U.S. uranium to \$250/kg, used in LMFBR	700
U.S. lithium reserves (13,000 to 25,000 kWh/g)	250 to 500
Uranium in oceans, used in LMFBR	200,000
Lithium supply in oceans (25,000 kWh/g)	22,000,000
Deuterium supply in oceans	16,000,000,000
<u>Consumption rates</u>	
World energy use in 1974	0.25
U.S. energy used for electricity in 1974	0.02
Total annual energy for 8 billion people at 6 kW/persona	1.5

^aRate corresponds to Sweden in 1973.

Requirements of lithium for inventories in fusion reactors, as opposed to that actually consumed as fuel, must also be considered; this subject is taken up below along with the other materials requirements of fusion.

3. FUSION REACTOR CHARACTERISTICS

Discussion of environmental characteristics of the reactors themselves requires some knowledge of the basic arrangement of these devices. Figure 1 is a schematic diagram of the heart of a fusion reactor — a cross-section of the core and surrounding structure, based on magnetic containment according to present ideas. The fuel is assumed to be a mixture of equal volumes of deuterium and tritium, maintained as a fully ionized plasma at a temperature of more than 100 million kelvin. The region between the plasma and the wall of the vessel is evacuated to help insulate the plasma, and escape of the

Fig. 1. Cross-section of fusion reactor core.

fuel to the walls is inhibited by a strong magnetic field that effectively applies a constraining pressure against the plasma.

The 14-MeV neutrons produced by D-T reactions freely escape from the plasma and penetrate the walls to a depth of a meter or so. This inner wall region, known as the blanket, contains lithium. The neutrons react with the lithium to produce tritium, which is recovered and reinjected into the plasma where it is burned up as fuel. In this D-T system, the fusion energy is converted to heat which generates electricity in a thermal cycle, e.g., conventional steam or steam/metal-vapor combined cycle. (About 85% of the energy is carried away by the neutrons which deposit their energy as heat in the blanket. The remainder occurs as energetic helium ions that join the plasma.)

Fusion reactors with these general characteristics may take several different forms. Rather detailed engineering studies have been performed for reactors based on mirror confinement, on the theta-pinch concept, and on the Tokamak approach, and we rely on the results of these studies in what follows (2,3,7).

4. ROUTINE RELEASES OF RADIOACTIVITY

When one looks at the question of releases of radioactivity from fusion or fission reactors, it is important to distinguish between low-level releases in routine operation, on the one hand, and the much larger, sudden releases that might be associated with an accident, natural disaster, or sabotage, on the other. It is true of fission, and almost certainly will be true of fusion as well, that the routine releases of radioactivity can be held to very low levels (maximum doses to the public much smaller than the dose from natural background) with known technology and at moderate expense.

The only radioactive substance that could be released during routine operation of a fusion power plant is tritium. The size of the tritium inventory varies significantly among different designs, with most falling in the range of 10 to 100 megacuries (MCi) per 2500 MW(t) reactor [1000 MW(e) at 40% efficiency](7). On the assumption that the present standard for light-water cooled fission reactors (namely 5 millirem per year at the plant boundary) will apply in the case of fusion reactors, it will be necessary to restrict routine releases of tritium to 1 part in 10^6 or 10^7 of the inventory per day. This is tighter control over tritium than is exercised over this isotope in contemporary fission reactors, but the technology for accomplishing it is reasonably straightforward. Approaches employed in the various conceptual fusion-reactor designs include diffusion barriers (copper, aluminum, or ceramic coatings) on hot metal walls, trapping in yttrium trihydride or cold lithium tritide, and surrounding tritium zones with cold metal walls (8).

A particularly useful approach for minimizing routine leakage of tritium as well as the consequences of accidents is to make the fraction of the tritium inventory that is hot (say, above 100°C) as small as possible. One recent design employing this philosophy has a hot tritium inventory of only 15 to 30 g (0.15 to 0.30 MCi) per 2500 MW(t), compared to a total T inventory of about 5 kg (50 MCi) (9). Eighty percent of this total inventory is stored in isolated vaults around the plant periphery. One theta-pinch reactor design has a total tritium inventory of only about 120 g (1.2 MCi) per 2500 MW(t) (10).

5. PRODUCTION AND HANDLING OF RADIOACTIVE WASTES

A D-T fusion reactor will produce some long-lived radioactive isotopes, owing to bombardment of the reactor's structural materials by the 14 MeV neutrons produced in the D-T reactions. Like the radioactive wastes from nuclear fission, these isotopes will have to be isolated from the biosphere for long periods of time. Two aspects should make fusion's waste problem much less troublesome than fission's, however. First, the variety and quantity of radioisotopes produced in a fusion reactor are controllable to a significant extent by careful engineering -- that is, by choosing the materials for minimum neutron activation, consistent with other engineering requirements, and by designing the reactor to minimize the amount of structural material that comes into contact with neutrons. In fission, by contrast, most of the radioactive wastes are fission products, not activation products, so one is stuck with inventories determined only by the power level and the physics of the fission process itself. Second, the long-lived activation products one gets in fusion are mostly refractory metals. Because these materials have high melting points and are embedded in a solid matrix, they are relatively easy to keep out of the environment.

The amount of radioactivity one must actually deal with can be expressed as curies per thermal watt of reactor capacity as a function of time after shutdown, or as gross biological hazard potential (BHP), measured in cubic kilometers of air or water (also per watt) needed to dilute the curies present down to the maximum permissible concentrations (MPCs) specified in Federal regulations for public exposure. The BHP, then, is a measure incorporating both the quantity of any given isotope and much of what is known about that isotope's toxicity.

Figure 2 presents a comparison of total activities of conceptual Tokamak and theta-pinch (RTPR) reactors with the activity of the fission products for a fission reactor (3). In the case of the fusion reactors, the following alternative structural alloys are assumed: (a) niobium (99% Nb, 1% Zr) and (b) vanadium (80% V, 20% Ti). The choice of a vanadium structure reduces the curies per watt by about an order of magnitude. Figure 3 compares the relative biological hazard potentials of the radioactivity from fusion and fission reactors. For times after shutdown of less than 1 year, the niobium fusion reactors have radioactive BHP's roughly equal to that of the fission products, but much less than that of the plutonium fuel of a reference liquid-metal fast breeder reactor (LMFBR) (3). For the vanadium fusion reactors, the BHP's are one to two orders of magnitude less than for the fission case. At times greater than 1 year (times of waste storage), the fusion BHP is one to two orders of magnitude less than that of the fission products in the niobium case, and is negligible in the vanadium case. This property of vanadium — a low burden of long-lived activation products — makes it an attractive candidate as a structural material for fusion reactors.

Several novel concepts that could reduce further the long-lived radioactivity of fusion reactors have been explored in a preliminary way. One such idea is to replace the liquid lithium coolant/breeding-blanket of a conventional Tokamak reactor design with a blanket cooled by helium and breeding tritium in a solid lithium-aluminum alloy embedded in a sintered aluminum product (SAP) structure (9). (The SAP is 89.5 wt% aluminum metal with a 10.5 wt% Al_2O_3 dispersoid.) The blanket radioactivity of this system is only a factor of three below that of the reference Tokamak design (stainless steel structure) at shutdown, but five orders of magnitude lower at

Fig. 2. Total induced activity for fusion and fission reactor plants as functions of time after shutdown. Abbreviations: T, operating time; I_w , 14-MeV neutron wall loading.

Fig. 3. Relative biological hazard potentials of induced activities in fusion and fission reactor plants after shutdown. The plutonium fuel is included in the fission case. Abbreviations are as given for Fig. 2.

1 month after shutdown and four orders of magnitude lower 10 years after shutdown. The principal long-lived isotope produced in the SAP system is aluminum-26 (half-life 730,000 years). Its specific activity is so low (10^{-6} Ci aluminum-26 per gram of aluminum structure) that the structure could be buried and the aluminum allowed to come to equilibrium with aluminum dissolved in groundwater, and the result would be an aluminum-26 concentration 10 times smaller than the MPC (9). One liability of this design is the requirement for relatively scarce beryllium as a neutron multiplier to maintain a breeding ratio above 1.

Another concept for reducing the radioactivity burden is the use of woven graphite "curtains" between the fusion plasma and the load-bearing structure and breeding blanket (11). Such curtains can be used to modify the neutron spectrum in a way that reduces the production of long-lived activation products, while also reducing sputtering of wall material (increasing wall lifetime and thus reducing the total quantity of structural material that must be reprocessed or disposed of). One set of calculations indicated a reduction of a factor of 10 in radioactivity at 1 week after shutdown, when graphite curtains were added to a Tokamak design with vanadium structure and lithium coolant (11). This gain comes at the expense of an increase in very short-lived activity (Ci/W up a factor of 3 at shutdown) and a reduction in breeding ratio (1.29 to 1.06).

Fusion reactions more difficult to achieve than D-T — such as D-D and D-³He — would produce somewhat fewer and less energetic neutrons. These

reactions offer long-term promise for further reduction in the production of long-lived radioisotopes by fusion — by a factor of 2, according to one preliminary analysis (12), but perhaps by more in a "two-component" system in which the He is maintained at a higher temperature than the D.

Still another approach to minimizing neutron activation is to do away entirely with the solid wall between the fusion plasma and the lithium blanket. This concept implies very high plasma density and short confinement time (pulsed systems), wherein a good vacuum surrounding the plasma is not needed. One idea in this category is a high-density Z-pinch produced in the center of a vortex of liquid lithium (13). This idea is at a very early stage of development.

6. NONROUTINE RELEASES OF RADIOACTIVITY

One must be concerned, in addition to the evaluation of routine consequences of low-level reactor emissions and waste-handling practices, with events of low probability but potentially serious consequences. Such events include accidents owing to human error and/or mechanical malfunction internal to the nuclear operation, externally generated accidents (aircraft impact, natural disasters), and aggressive acts such as sabotage or acts of war. Estimation of the risk associated with such possibilities has two main parts: (a) the evaluation of the inventories of radioactive material potentially available for release, together with their physical behavior and biological effects once in the environment; and (b) the analysis of accident modes in a way that can assign probabilities to events releasing different fractions of the radioactive inventories.

The data shown in Figs. 2 and 3, for times shortly after shutdown, are relevant to the question of inventories. One must try to determine, however, what part of these inventories is volatile at temperatures that could be encountered in an accident. In fusion reactors, the principal volatile hazard is clearly tritium. In fission reactors, the volatile hazard is dominated in the first several days after shutdown by radioiodine, and thereafter by other isotopes such as noble gases and such fractions of the radio-cesium, tellurium, and other isotopes as may have been volatile under the conditions governing the release. The BHP's associated with volatile isotopes in nominal fusion and fission reactors at various times after shutdown are given in Table III (the fission data are from Ref. 14). We have assumed that a variety of accidents could release in volatile form 10% of the alkali metals present (most seriously, cesium in the fission reactor). Significant quantities of radioactive sodium are present for fusion only in the aluminum-blanket design, for which the volatile tritium inventory is about two orders of magnitude lower than that shown. The tritium inventory assumed for the fusion reactor in Table III is 100 MCi per 2500 Mw(t), near the high end of the published range of values for different designs. There is reason to believe, then, that the very substantial advantage of fusion over fission with respect to volatile hazard potential, as reflected in Table III, can be further enlarged.

The BHP measures how much air is required to dilute the material present to the MPC, but it is possible to say something more about the physical likelihood that the required dilution would actually take place if a release

Table III. Biological hazard potential (1000 km³ of air) represented by volatile inventories in nominal fusion and fission reactors [2500 MW(t)]. (Results rounded to 2 significant figures.)

	Time after shutdown			
	0	12 hours	24 hours	7 days
<u>Fusion</u>				
T as HTO	500	500	500	500
Na-24 ^a	120	69	40	0
<u>Fission</u>				
I-131	580,000	560,000	530,000	320,000
I-132 to 135	420,000	210,000	130,000	900
Kr-85	0.3	27	31	31
Kr-85m	140	21	3	0
Xe-133	370	350	330	150
Cs-134 ^a	2800	2800	2800	2800
Cs-137 ^a	1100	1100	1100	1100

^aSee text.

occurred. In this respect, note that tritium behaves at best like hydrogen gas, diffusing rapidly into the atmosphere, and at worst (as HTO) like water, mixing with atmospheric water vapor and surface water and being excreted from the body with a physiological half-life of about 10 days. (We have assumed the worst case for the calculations presented here, namely that all the tritium is released as HTO.) Tritium is not preferentially concentrated in food chains, or bound to soil. Because of the short mixing times and enormous dilution that result, the dose to members of the public a few months after even a massive tritium release is extremely small. By contrast, most of any fission-product cesium and iodine released in a fission-reactor accident are deposited over a relatively small surface area (tens to hundreds of km²) downwind of the release and are concentrated and held in food chains (16). The long-half-life cesium is particularly tightly bound to soil, remaining for many years in the first few centimeters (where it not only delivers a direct gamma dose to humans in the vicinity but also is readily taken up by plants).

Detailed calculations of the public-health costs of the largest hypothetical accidents require modelling of plume behavior under various meteorological conditions, coupled with estimates of population density in the exposed area and models of the consequences of radiation doses received. A number of such studies have been performed over the years for hypothetical fission-reactor accidents, and include or imply estimates of prompt fatalities ranging from zero under favorable circumstances to 20,000 or more under the most adverse circumstances (17-20). "Prompt fatalities" are those

occurring in the first month or so after the event is a direct result of acute radiation exposure. Total damages from a major release of radioisotopes would also include prompt nonfatal injuries, delayed incidence of cancer, production of genetic defects, destruction of crops, and withdrawal of land from habitation and food production.

As a first cut at comparing maximum hypothetical accidents in fusion systems to those in fission reactors, one of us has applied the basic methodology employed in fission-accident studies to estimate the worst-case prompt fatalities from the release of the entire tritium inventory of a 2500 MW(t) fusion reactor, all as HTO (21). These results are summarized in Fig. 4. Under the most adverse meteorological conditions and with a tritium inventory of 100 MCi (reflecting no attempt at minimization of this quantity by design), the area over which any prompt fatalities would be expected is less than 1 km².^{*} If intelligent design can hold the tritium inventory to

Fig. 4. Acute radiation doses in worst-case tritium accidents: ground level, short-duration release, all at HTO; no thermal plume rise; Pasquill F (very stable) atmosphere, mean wind = 2 m/s; includes skin absorption and breathing rate corresponding to excited population. Whether real circumstances could generate this event is extremely doubtful.

^{*}The calculation accounts for both inhalation and skin absorption. It is assumed that prompt fatalities begin to occur in the most susceptible members of the population where the whole-body dose in the first 4 days exceeds 200 mrem.

10 MCi for a large plant, no off-site prompt fatalities at all are expected even in the worst combination of circumstances (100% release as HTO at ground level, no thermal plume rise, Pasquill F stability conditions, no evacuation prior to plume passage). Such an accident could still be a significant event in terms of property damage and health effects other than prompt fatalities, but the quantitative difference in comparison with the fission worst case is so enormous that it can be considered a qualitative one.

It is not enough, of course, to ask what is inside a reactor and what could happen if this material escaped; one must also consider the probability that any substantial part of the material will get out. Now, a major earthquake or a direct hit by a Boeing 747 are the sorts of dangerous external impacts that could happen to either kind of reactor, and the containment problems in this respect are similar for both fission and fusion. As for the violence of the sequel to a damaging external event, or the chance of the containment being ruptured from within, much depends on how much energy is stored inside and on what pathways exist for its rapid release. Table IV shows the stored energy in various forms in a conceptual Tokamak fusion reactor (liquid-lithium coolant) and in a liquid-sodium-cooled fast-breeder fission reactor (LMFBR).

Table IV. Stored energy in nominal fusion and fission reactors [2500 MW(t)]. (GJ, rounded to 1 significant figure.)

	Fusion	Fission (LMFBR)
Nuclear energy in fuel	100 ^a	100,000,000
Thermal energy in fuel	2	40
Chemical energy in coolant	60,000	10,000
Energy in magnet	200	--

^aIn the plasma at any one time.

Instantaneous release of a large fraction of the total nuclear energy of the fuel is not possible in either the fusion reactor or the LMFBR. In the fusion reactor, any malfunction tends to quench the reaction by loss of confinement. Even if all the fuel could somehow react in a few seconds (a phenomenon for which present understanding includes no mechanism), the resulting energy release could be absorbed in the lithium blanket without any destructive results. The case of the LMFBR is more troublesome, in that the possibility of a nuclear energy release too sudden and severe to be contained has not been convincingly excluded. The range of competent opinion about the maximum possible conversion of nuclear energy to mechanical work in an LMFBR accident ranges from 150 MJ (22), which can certainly be contained, to more than 2000 MJ (23), which perhaps cannot be.

The pathway for chemical energy release is a lithium fire in the case of the fusion reactor, a sodium fire for the LMFBR. This may actually be the largest hazard for both systems. A form of stored energy unique to the

fusion system is the energy in the magnetic fields confining the fusion plasma. Magnets will have to be designed to avoid too rapid release of this energy in the event of a malfunction, but this is a relatively straightforward matter ⁽²⁾).

Another accident pathway that must be considered is internal melting, owing to buildup of the heat of radioactive decay following malfunction of a reactor's cooling system — the loss-of-coolant accident so widely discussed for today's light-water-cooled fission reactors. The energy associated with this radioactive afterheat in the first hour after the malfunction is likely to be some 10 to 30 times smaller in a fusion reactor than in a fission reactor — and so could be handled by simple and reliable (entirely passive) measures. A more detailed look at afterheat for different fusion designs is provided in Fig. 5 (3).

Fig. 5. Relative afterheat powers for fusion and fission power plants as functions of time after shutdown. Abbreviations are as given for Fig. 2.

7. DEMANDS FOR STRUCTURAL MATERIALS

While the basic fusion fuels — deuterium and lithium — are abundant, construction of the fusion reactors themselves will compete for scarce resources. In this regard, fusion does not appear to have significant advantages over alternative technologies and may even pose problems. Examples of materials inventories in a major fusion power economy are given in Table V (from Ref. 24, where the origins of some of the more exotic requirements are discussed). The total fusion-generating capacity assumed is 1 million MW, which is about 2.5 times the present U.S. capacity. All the materials listed are not needed for every design, and many of the inventory figures given are uncertain by large factors. In steady state, the inventories shown would have to be replaced at rates on the order of 2.5 to 5% per year (corresponding to reactor life-times of 20 to 40 years), faster for wall materials subject to rapid deterioration under neutron bombardment. The extent to which

Table V. Materials requirements for 10^6 MW(e)
of fusion generating capacity (24).

Element	Material quantity (million metric tons)		
	Inventory for 10^6 MW(e)	1970 U.S. reserves	1970 world reserves
Al	0.6	13	3009
B	0.8	33	66
Be	0.12	0.018	0.38
C	2	10	large
Cr	2	~0	370
Cu	2	74	310
F	1	9	62
Fe	10	8500	180,000
He	0.3	1.2	1.2
K	0.02	42	30,000
Li	1	6	180
Mn	0.2	0	590
Mo	0.2	2.5	6.5
Nb	0.8	0.005	7.8
Ni	1.5	0.14	24
Pb	11	39	85
Sn	0.2	0.009	6
Ti	0.8	23	134
V	0.5	0.1	26
Zr	0.002	0.06	25

such replacement can be supported by recycling will vary from one material to another, and should be more carefully investigated. The reserves listed in Table V for the various materials reflect for the most part the amount of material whose location is now known and which could be made available at or near present prices.

As the table shows, use of fusion may imply potential problems of materials supply if the more exotic structural materials — niobium and vanadium — are relied upon, and if total electricity generation reaches levels many times today's. Consider, e.g., a 10 or 50 million MW(e) fusion economy, instead of the 1 million MW(e) assumed. No one can now say at what cost and, accordingly, with what impact on the price of fusion energy, these quantities of materials could be made available. As an alternative, though, the potential for using very abundant materials such as aluminum appears good.

If helium supply becomes a problem, there are several possibilities: one is tapping helium in the atmosphere, at some higher cost; another is using cryogenic aluminum coils running at the temperature of liquid neon.

There is also a more general materials problem associated with fusion or any of the other long-term, large-scale energy sources: a civilization with energy available in these quantities is likely to generate very high materials demands beyond those arising from the energy technology itself; the extraction and processing of these may generate serious environmental stresses even if the energy use itself does not.

8. THERMAL DISCHARGES

Discharges of heat to the environment occur when energy in other forms is converted to electricity, and also whenever and wherever the electricity is put to use. This situation is of course not unique to fusion (or, for that matter, electricity), but, in consequence of the laws of thermodynamics, is characteristic of all energy conversion and application. One can distinguish two basic kinds of problems associated with these releases of heat: (a) the local effects at the power plant itself, in terms of aquatic life if the waste heat is discharged to natural bodies of water, and in terms of microclimate whether the heat is discharged to water or to the atmosphere; and (b) the regional and global climatic effects that may eventually result from large-scale alterations of the heat balance at the earth's surface.

Fusion's effects in the first category should not be worse than those of fossil-fueled and fission-power plants, because the conversion efficiencies will be similar — probably in the range of 35 to 45% for first-generation D-T systems. Advanced fusion-fuel cycles, in which a larger fraction of the reaction energy is carried off by charged particles, offer the hope of eventual direct conversion to electricity at plant efficiencies as high as 70 or 80% (25). This would greatly decrease the local thermal impact, which varies as $(1 - \eta)/\eta$ for fixed electrical output produced at efficiency η .

The effects of the conversion to heat of all the energy used by society are today still restricted to urban regions, but they could become regional and even global as civilization's energy flows become a more significant fraction of the natural flows governing climate (26). Since the total heat release (conversion losses plus heat dissipation at end-use) for fixed electrical output varies as $1/\eta$, advanced fusion systems with $\eta = 0.80$ would buy only a factor of 2 over conventional systems with $\eta = 0.40$. If fusion should prove to be cheap enough and benign enough in its other environmental impacts, moreover, it might encourage particularly rapid growth of energy consumption that will hasten the day when significant disruption of climate by heat dissipation is possible.

9. MISUSE OF NUCLEAR MATERIALS

There has been considerable concern about the possible misuse of nuclear materials, both as regards the proliferation of nuclear weapons among nations and the possible theft of nuclear materials by terrorists, gangsters, and malcontents. In this respect, fission and fusion reactors are very different.

With respect to fissile materials from nuclear fission fuel cycles, it is at least doubtful that the detection of diversion or theft (which is all that the Non-Proliferation Treaty and associated IAEA safeguards can accomplish) will deter either nations or subnational groups. For countries that do not sign the treaty, or that subsequently decide to abrogate it openly, the deterrent is meaningless. Countries that breach the treaty clandestinely and are caught receive only international censure, a price that many nations have paid before in what they perceived to be their national self-interest. Terrorists and blackmailers are unlikely to be deterred by detection of the loss, especially inasmuch as it is likely to follow the event by several months; in that case official confirmation of the theft may well suit their purposes. Nor will a small country or a criminal group be much troubled by the fact that the efficiency and predictability of bombs made from reactor-quality plutonium are not up to the standards of the major nuclear powers. Finally, there is plutonium's potential for use as a non-explosive, radiological terror weapon. This is much easier than making a bomb (and, because of the properties of plutonium, vastly more effective than using tritium for the same purpose). Nonetheless, making fission bombs is in itself relatively straightforward, and the requisite knowledge is widespread (27).

Since in a fusion reactor tritium would be generated, circulated, and burned within the fusion plant, its availability outside the plant would be minimal. Tritium is enormously less dangerous than plutonium as a radiological weapon, moreover, and the construction of fusion bombs is much more difficult than is the case with fission bombs. The problem of making a fusion bomb taxed the ingenuity and technical sophistication of a great industrial nation, France, for 8 years after she achieved a fission explosion. Evidently, making a fusion bomb is a formidable task, even given a fission bomb for a trigger. Without a fission trigger, the task is vastly more difficult. (Safeguard experts Willrich and Taylor wrote on this point in 1974: "No successful development has yet been announced, and we have no reason to believe it has taken place.") (27). The irrelevance for this purpose of most approaches to fusion reactors need not be belabored for anyone familiar with controlled-fusion research. For the exceptions — and more generally — the following point is critical: any group or nation sophisticated enough to design and fabricate a workable fusion explosive, with or without a fission trigger, will be sophisticated enough to produce any fusion fuels it needs without having a fusion reactor. No corresponding statement can be made for fission explosives. Their proliferation has been limited by lack of nuclear materials and reluctance to commit the necessary resources more than by lack of knowledge or technical sophistication. In short, the existence of nuclear fission reactors makes fission explosives accessible in principle to groups that otherwise would not have such access; the existence of fusion reactors will not give access to fusion explosives to groups that otherwise could not have it.

10. CONCLUSION

Fusion has significant potential environmental advantages over the nuclear fission alternative. These include a much less hazardous volatile radioactive inventory, less long-lived waste, less vulnerability to loss-of-coolant accidents and other internally generated accidents, no fissionable

materials to steal, and the potential for less waste heat through higher efficiency. These potential advantages, however, are not entirely "automatic" — to convert them into practical reality will require an emphasis on environmental characteristics throughout the process of fusion reactor design and engineering. To assume, on the contrary, that environmental characteristics will take care of themselves could easily result in reactor designs in which some of the principal reasons for preferring fusion in the first place (such as low burden of long-lived wastes) have been sacrificed in the pursuit of other engineering and economic criteria.

In our view, the central role of environmental impact in the long-term energy dilemma of civilization justifies the highest priority on realizing the full potential of fusion for low environmental disruption. Doing so will take time, money, and ingenuity, but it is surely worth it.

Even so, there are deeper difficulties in the future of industrial society that we should not expect fusion to solve. First, any attempt to increase energy consumption without limit will run into difficulties getting rid of the heat that is produced when energy is used — this is the ultimate pollutant. Second, although a prosperous future requires energy, it also requires some other ingredients that energy by itself cannot provide: other raw materials, better social organization and cooperation, and much help from the already beleaguered processes of the biosphere. Finally, one may ask whether the advent of a completely clean, cheap, and unlimited energy source (which neither fusion nor even solar quite is), accompanied by equally benign materials technologies, would be entirely a blessing. If we used these tools to render the world into a global Los Angeles, how many of us would be pleased with the result? To ask such questions is not by any means to suggest that controlled fusion should not be sought; it is merely to warn that the potential for misuse exists, and to suggest that there is much merit in thinking about these problems before the tools are actually in hand. It is essential, in other words, to ask not only how soon and how much energy will be available from new sources, but what kind of world we want to make with it.

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