Fusion Power – An Assessment of Its Potential Impact in the USA

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The prospects for harnessing power through the fusion of light nuclei have by turns looked doubtful and hopeful since the first research was conducted some 20 years ago. When might fusion begin to make a significant contribution to electricty generation and what will be the economic and environmental consequences? Dr Kulcinski presents possible answers to these questions and also highlights difficulties that could arise in the cost and availability of refractory metals and alloying elements for construction of magnetically-confined plasma reactors.

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We are now hearing less of the phrase '. . . *if* thermonuclear fusion can be controlled . . .' and more and more scientific papers contain the statement '. . . *when* thermonuclear fusion power is controlled . . .'. Granted that such optimism is justified, what are the implications for society in the 21st century? Will such a source of power be cheaper, cleaner, safer and environmentally more acceptable than the more conventional fossil fuels or the relatively new fission fuels? This article attempts to address some of the above questions, at least with respect to how they might be answered in the USA. Such an assessment, by its nature, requires a great deal of speculation on the course that the world will take in the next 30 years. The author claims no special faculty for predicting that course and therefore cautions the reader that the scenario painted in this article represents a view from a single vantage point. Nevertheless, it can be projected, on the basis of past experience, and what is now known about plasma physics, what type of impact fusion power might make if we proceed in the direction that we are presently heading.*

The history of controlled thermonuclear research is not a very old one. It started in the early 1950s as classified research and was declassified in 1958. The initial optimism for producing large amounts of low-cost electrical power was shattered in the early 1960s when several formidable problems of plasma stability and confinement were encountered. For the next 5-10 years scientists went back to 'write the book' for a new field of science called plasma physics. The interest of all but the most dedicated tended to subside during this time while another form of nuclear energy, that released from the fissioning of uranium and plutonium, was developed into a commercial reality. Major advances by Russian and US scientists in the late 1960s rekindled those early dreams and by the early 1970s the quest for fusion power was joined not only by plasma physicists but by engineers, economists and environmentalists as well.

Despite progress made in the past few years, the basic problem of controlled thermonuclear reactors (CTRs) still remains, that is, to successfully contain a gas of charged particles (plasma) at ~100 000 000K long enough to release a favourable amount of energy. This containment must be accomplished while at the same time isolating the plasma from the solid structural components.

Table 1. Potential fusion reactions for controlled thermonuclear reactors

Reaction	energy/reaction – KeV Input*	Released
D + T → He-4 + n	10	17 600
D + D → He-3 + n / → T + p	50	~ 3300
D + He-3 → He-4 + p	100	18 300

* For reactor grade plasma

It was known from the earliest days of plasma physics that certain isotopes of hydrogen could be joined, or fused together, with a tremendous release of energy. Table 1 lists three of the most popular reactions of deuterium (D), tritium (T) and helium-3 (He-3). It should be noted that the D-T reaction requires the lowest energy-temperature (~10 KeV) for reactor operation and that it releases almost 1800 times as much energy as it takes to initiate it! The other reactions listed in Table 1, D-D and D-He-3, have certain advantages but they require higher ignition temperatures and return proportionally less of the energy required for their initiation. Therefore the D-T reaction is the most favoured and will be assumed to be the fuel for the 'fire' in CTRs considered here.

Six major points of the D-T reaction should be noted:

1. The products of the D-T reaction are *not* radioactive and therefore present no long-term disposal problems.
2. Tritium *is* radioactive and does not occur in nature; it must be bred in the reactor by neutronic reactions with lithium (Li). The real fuel for D-T system is deuterium and lithium, *not* deuterium and tritium.
3. The absorption of neutrons by structural components *will* produce radioactive isotopes which will have to be disposed of after the plant is closed down. The nature of these isotopes is somewhat different from that of fission reactors and represents a smaller, but not completely negligible problem.
4. Most of the energy (80%) from the reaction is carried away by the neutron. This kinetic energy must be converted to heat, and the heat to electricity.
5. The energy of the fusion neutrons is ~14 MeV compared to ~2 MeV for fission neutrons. The higher energy neutrons cause more and somewhat different types of damage in structural materials than is found in fission reactors. The higher energy neutrons also require more massive structures for complete thermalisation and removal of the neutrons.
6. Approximately four times as many neutrons must be produced per unit of energy in fusion reactors than in fission reactors. Roughly speaking, 20 MeV is released per fusion neutron and 80 MeV per fission neutron.

The confinement of the D, T ions can be accomplished in two ways: by magnetic fields, or by the inertial confinement of the atoms themselves. The magnetic approach is the most deeply studied and understood process while the latter has only become of interest in the last 5-10 years with the advent of laser-induced fusion.[1]

Simply stated, a magnetic field can contain a high temperature mixture of D, T ions in space because charged particles are constrained to rotate around the magnetic field lines. The magnetic fields are shaped so that the majority of charged particles are confined at distances of 50-100 cm from the nearest solid member of the reactor. The laser systems rely on a very different approach. A solid (frozen) pellet of D, T atoms is simultaneously irradiated from several directions with high intensity laser beams.

* This analysis will take as its basic premise that fusion feasibility can be demonstrated, that we can successfully build electrical generating stations powered by fusion reactions and that these power plants will be economically competitive. For technical details of fusion power the reader is referred to: D.J. Rose and M. Clark, Jr, *Plasma and controlled fusion* (New York, MIT Press, Wiley, 1961); R.F. Post, *Annual Review* of the Nuclear Society, Vol. 20, p. 509 (1970); *Proceedings* of the British Nuclear Energy Society, Conference on Nuclear Fusion Reactors, held at UKAEA Culham Laboratory, September 17-19, 1969; *Proceedings* of the International Working Sessions on Fusion Reactor Technology, June 28-July 2, 1971, CONF-710624; *Proceedings* of the Texas Symposium on the Technology of Controlled Thermonuclear Fusion Experiments and Engineering aspects of fusion reactors, Austin, Texas, November 1972, CONF-721111; International Conference on Nuclear Solutions to World Energy Problems, American Nuclear Society, Washington, DC, November 13-17, 1972. See papers by R. Hancox, p. 209, R.L. Hirsch, p. 216, F.L. Ribe, p. 226, G.L. Kulcinski, p. 240, A.P. Fraas, p. 261.

[1] J. Nuckolls, John Emmett, and Lowell Wood, *Physics Today*, August 1973, p. 46

The particle is rapidly heated to ignition and enough reactions take place before the pellet flies apart to result in a net energy output. The confinement here is then due mainly to the inertia of the fuel atoms.[1]

How long does the plasma need to be confined to produce more power than required to heat and contain it? Lawson[2] has found that for the D-T system operating above the ignition temperature (T_i) at moderate efficiencies (~33%), the product of the ion density (n) and confinement time (τ) must be

$$n\tau \sim 10^{14} \text{ sec cm}^{-3} \quad \text{at } T > T_i$$

The problem is currently to get n, τ, and T to the proper values so that the power output may equal the power input. Some devices currently operate at high plasma densities and temperatures and have relatively short confinement times; other devices work at long confinement times but at insufficient plasma densities or ion temperatures, and so forth.

How then does one go about building a reactor once the plasma has been contained? The steps are outlined in Figure 1 for a magnetically confined D-T plasma. First one starts with a reacting plasma which is emitting energy in the form of neutrons, charged particles and various forms of photons. The next step is to surround the plasma with a solid wall which absorbs the charged particles and photons as well as providing a vacuum for the plasma to ignite in a magnetically confined system. This wall will absorb about 20% of the energy from the plasma and must be cooled. Typical diameters of this first wall will be 5-10 metres for toroidal reactors such as the Tokamak.*

A third step is to surround the vacuum wall with a moderator to slow down the neutrons, a reflector to reduce the leakage of neutrons and a coolant to carry the heat away. This region should also contain a tritium breeding material so that the D-T reaction can be continued. One material that would satisfy all three of the above requirements is lithium. However, other moderators such as beryllium (Be), graphite, or even iron could be used and other

[2] J.D. Lawson, *Proceedings* of the Physical Society, Vol 70, 1957, p. 6

* The Tokamak (To – toroidal, ka – chamber, mak – magnetic) reactor consists of a metal torus surrounded by a large transformer which induces an axial current to flow through and heat the plasma. The torus is surrounded by solenoidal coils which produce a second magnetic field, stronger than that developed as a result of the plasma current. Thus the combined fields constitute a helical magnetic field which prevents leakage.

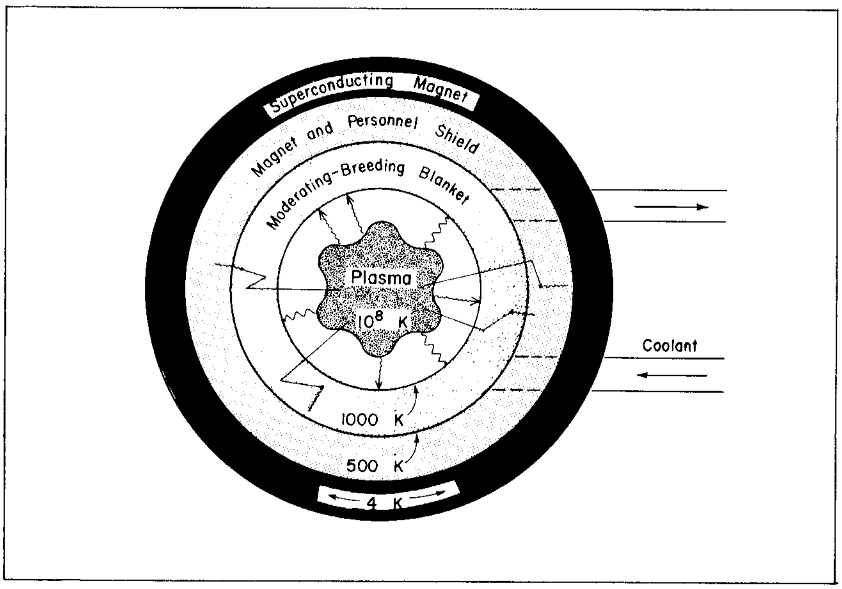

Figure 1. Schematic of controlled thermonuclear reactor based on D-T cycle

coolants such as liquid metals or helium would be satisfactory. Approximately one metre of blanket and first wall is required to absorb about 97% of the heat produced from the plasma. Unfortunately, some neutrons and gamma rays will escape and the magnets (or lasers) must be protected from these sources of irradiation. This protection is accomplished by surrounding the blanket with a shield which will complete the moderation of those neutrons which escape, and absorb the gamma rays emitted from the blanket. This shield will also serve as final radiation protection for personnel in the plant and might consist of various combinations of iron and lead to absorb the gamma rays and boron to absorb the neutrons.

Outside the shield will be located the magnets (or laser), fuelling equipment, heat exchangers, tritium removal devices and other equipment associated with the operation of the plant. It is expected that the sheer size of a fusion plant may be a problem from the standpoint of materials, construction and cost because the average energy density of a D-T reactor is one to two orders of magnitude smaller than in fission reactor cases.

US plan for commercial fusion reactors

A recent study conducted by the USAEC has revealed how the USA hopes to demonstrate commercial fusion reactors by the year 2000. The plans are summarised in Figure 2.[3] The first step is obviously to demonstrate that more power can be obtained from a plasma than goes into producing it; therefore feasibility experiments are required.

Research in this area is currently being conducted for the US government at four major laboratories*: Princeton Plasma Physics Laboratory (PPPL), Los Alamos Scientific Laboratory (LASL), Oak Ridge National Laboratory (ORNL) and Lawrence Livermore Laboratory (LLL). Several smaller, but equally important projects are being conducted at the University of Wisconsin, University of Texas and Massachusetts Institute of Technology. Each of these projects is studying one or more specific approaches to fusion.

* and a private industrial research laboratory, General Atomics.

[3] R.L. Hirsch, p. 216 in *Proceedings* of the International Conference on Nuclear Solutions to World Energy Problems, American Nuclear Society, Washington DC, 13-17 November 1972.

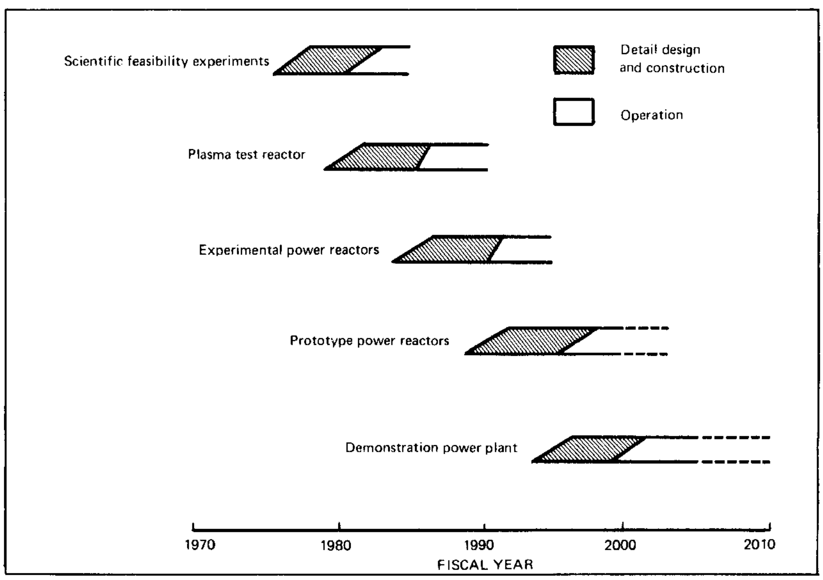

Figure 2. Bar chart indicating phasing of major steps in a fusion-reactor development programme

After fusion feasibility has been demonstrated in the late 1970s or early 1980s, a plasma test reactor would be built to test the validity of the plasma scaling laws. The next step would be to build a reactor which would demonstrate the breeding of tritium and test materials under severe radiation damage conditions. Such a facility would be built around 1990. In the mid-1990s a prototype reactor of several hundred MWe would be built which would probably produce electricity, although not economically. Finally, it is hoped that a reactor would be built around the year 2000 which would be in the thousand MWe range and demonstrate that fusion power can compete economically with other sources of power.

The money required to achieve the rather ambitious programme outlined above has not been officially established but estimates of $5-6000 million between 1974 and 2000 are probably reasonable. Recent estimates[4a] by the USAEC show that approximately $500 million have been spent on fusion research up to 1974 and that another $1·35 thousand million would be required for the fiscal years 1975-1979.

Penetration of fusion reactors into the US electrical generating market

Perhaps the best way to estimate this penetration factor is to use the method already established or predicted for fission reactors.[4b] Figure 3 shows what percentage of the installed electrical generating plants is anticipated to be nuclear in the time period from 1966 to 1986. Note that 20 years after the introduction of the first 'commercial' fission reactors, over 80% of the new additions will be nuclear plants. We will assume that fusion reactors will have the same penetration factor as fission plants.

[4a] D.L. Ray, 'The Nation's Energy Future', WASH-1281, December, 1973.

[4b] 'Nuclear Power 1973-2000,' WASH-1139(72) 1 December 1972.

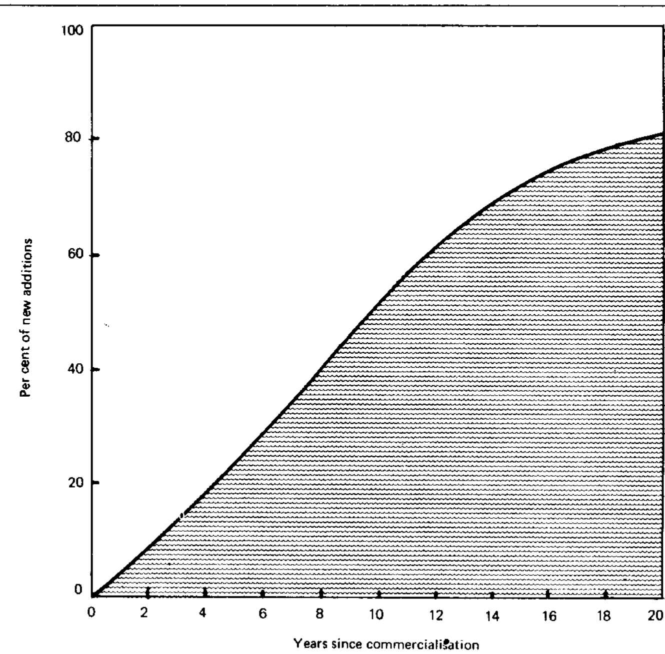

Figure 3. Projected penetration of fusion reactor into the US electrical generating market

One could transfer these figures to the case of fusion power by first noting what the projected mix of electrical generating stations might be in the years 2000-2020. We have chosen to use the Associated Universities (AUI) Report[5] to estimate these figures. Table 2 shows that by the year 2000 fission reactors are expected to account for ~51% of US electrical capacity, fossil fuelled plants ~45% and hydroelectric ~4%. The corresponding figures for the year 2020 are 60% nuclear fission reactors, ~38% fossil fuelled plants and ~2% hydroelectric. This information is plotted in Figure 4 and labelled Plan A. We shall now proceed to see how fusion might modify those figures assuming the total demand for electricity does not change

First, (Plan B in Table 2 and Figure 4) both fossil fuelled and fission reactor capacity could be proportionately reduced by the fraction of electrical generating capacity taken by the fusion reactors. Obviously, very little effect would be seen in the year 2000, but by 2010, fusion could account for almost 10% of the total generating capacity, fission reactors 49%, fossil fuelled plants 38% and hydroelectric 3%. By 2020, the CTR share could rise to 29% while fission reactors supply 40%, fossil fuelled plants 38% and hydroelectric 2%.

It is entirely possible that by the year 2000 the installation of CTRs may be predominantly in the place of fossil fuelled plants, both from the standpoint of air pollution and conservation of fossil fuels for other types of energy (eg automobiles, home heating, chemicals). If fusion plants were to be built entirely at the expense of fossil plants (Plan C in Table 2 and Figure 4), we would see that by the year 2020, 89% of the power would be generated by nuclear reactors (both fusion and fission), 9% by fossil fuels and 2% by hydroelectric. If Plan C were to take place, the fossil

[5] 'Reference Energy Systems and Resource Data for Use in the Assessment of Energy Technologies', AET-8, April 1972.

Table 2. Projected mix of electrical generating units (10^3MWe) [5]

Year	1977	2000	2010	2020
A. Base Plan				
Hydro	53	72	79	86
Gas Turbine and internal combustion	36	86	113	142
Gas-Steam	81	90	88	86
Oil-Steam	61	112	89	62
Coal-Steam	203	447	757	1070
LWR	90	407	432	443
LMFBR	0	422	926	1739
CTR				
Total	524	1636	2484	3628

Year	1977	2000	2010	2020
B. With fusion affecting fossil and fission systems proportionate to their new additions.				
	53	72	79	86
	36	86	110	118
	81	90	88	86
	61	112	89	62
	203	446	669	762
	90	407	425	429
	0	422	782	1022
	0	~1	242	1063
	524	1636	2484	3628

C. With fusion affecting fossil plants only				
Hydro	53	72	79	86
Gas turbine and internal combustion	36	86	100	37
Gas-steam	81	90	88	32
Oil-steam	61	112	89	33
Coal-steam	203	446	528	195
LWR	90	407	432	443
LMFBR	0	422	926	1739
CTR	0	~1	242	1063
Total	524	1636	2484	3628

D. With fusion affecting fission plants only				
	53	72	79	86
	36	86	113	142
	81	90	88	86
	61	112	89	62
	203	446	757	1070
	90	407	421	421
	0	422	695	698
	0	~1	242	1063
	524	1636	2484	3628

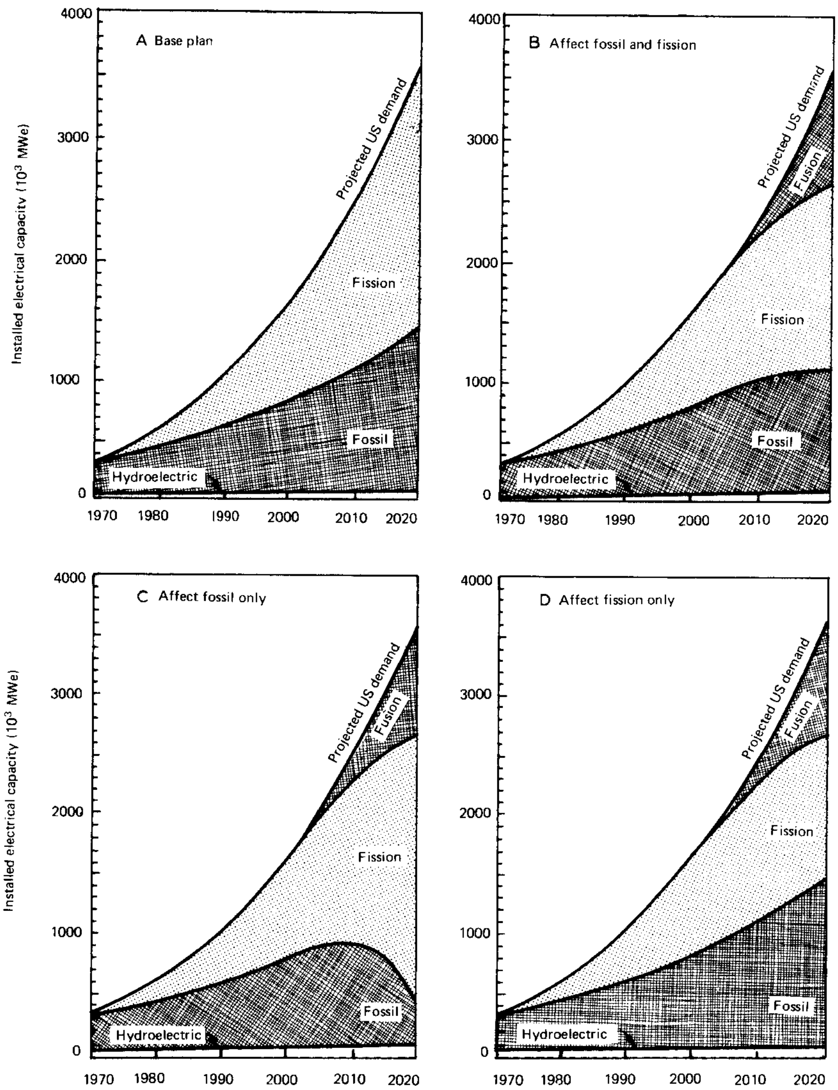

Figure 4. Projected mix of installed electrical capacity for various modes of fusion power introduction

fuel requirements for electrical generating capacity in 2020 would be about 78% of that anticipated for 1977 and 92% of that required in 1973.

The final option considered here, Plan D, assumes that fusion will enter the electrical generating market at the expense of fission plants only. All the previous figures are the same until the year 2010, where now 55% of the power is generated by nuclear reactions, 42% by fossil fuels and 3% by hydroelectric sources. By the year 2020, 60% of the total electrical generating capacity will be nuclear, with 49% of that supplied by fusion and 51% by fission.

The most important point to draw from this simple exercise is not the exact figures but the realisation that even *if* we can achieve controlled nuclear fusion by 1980, and even *if* we can successfully bring it to commercialisation by the year 2000, and even *if* we assume a rather optimistic penetration rate compared with other energy sources, fusion power will not account for more than 30% of the generating capacity in the USA in 2020, some 50 years from now. On the more positive side, replacing the fossil fuelled plants with CTRs would reduce the demand for those sources of energy in the year 2020 to approximately the present levels of consumption. Without fusion, the demand on fossil fuels in the USA in the year 2020 for generation of electricity will be as much as four times our present rate.

Effect of fusion on environment in the early 21st century

Fuel requirements and reserves

The earlier analysis revealed that the basic fuels for a D-T based fusion economy are deuterium and lithium. The procurement of deuterium from the oceans, where it occurs as one part in every 6500 parts of hydrogen, should be relatively easy and the water can be returned virtually unchanged to the oceans. The present cost of deuterium is 20c per gramme, and this amount, when burned with trituim, would contribute only 6×10^{-3} mill* per kWh to the electrical generating costs – an almost completely negligible cost. The amount of deuterium available is truly enormous and there is essentially no danger of ever running out of it. For example, if we were to extract the energy content from only 1% of all the deuterium available in the oceans, it would supply the total energy needs of the world in the year 2000 for almost 100 million years.[6]

It requires roughly 80 g of deuterium (in combination with tritium) to provide 1 MWe-yr of power assuming a 40% efficiency for converting heat into electricity. This means that in the year 2010, CTRs would require 19 tonnes of deuterium per year. This would most probably come from heavy water (D_2O) plants so that 96 tonnes of heavy water would be required per year in 2010. This number rises to 425 tonnes of D_2O in the year 2020. Such production rates are not uncommon even today. Canada's Bruce plant[7] currently produces 800 tonnes of heavy water per year so that it is conceivable that *one* plant could provide the entire deuterium requirements for the US CTR programme until the year 2020.

A slightly more limiting feature of the D-T fuel cycle is the availability of Li. It has been estimated that 'known and inferred' US reserves of Li at 2c/g is 6×10^6 tonnes[8] and 80% of this amount exists in heavy brines in Nevada and Canada. The energy content of natural Li is 25 MWthh/g[8] and therefore the 6×10^6 tonnes of Li could produce almost 6×10^9 MWe years of energy. Such an energy supply could furnish the total US electrical generating capacity for over 10 000 years at the 1977 rate. If that much energy is not sufficient, we could always extract Li from sea water. It has been estimated that this amount of Li could supply the total world electric generating capacity in 1977 for almost 300 000 years.[8]

Calculation of the total lithium requirements for fuel for our projected fusion economy reveals that the minimum yearly requirement for Li is 255 tonnes in 2010 and about 1100 tonnes in 2020.

It is also possible that future CTRs will use lithium, either in elemental form or in combination with other elements, as a coolant. We shall see later that typically, 1000 kg of lithium is required per MWe for cooling. Hence about 10^6 tonnes of lithium

* 1 mill = 0·001 US dollars

[6] W.C. Gough and B.J. Eastlund, *Scientific American*, Vol **224**, No. 2, p. 50 (1971).
[7] E. La Surf, Chalk River Laboratory, Canada, private communication.
[8] J.P. Holdren, UCID-15953, December 8 (1971).

Table 3. Cumulative land required to provide fuels for electrical generation

Strip Mining of coal	1977	square miles [a] 2000	2010	2020
Plan A[5]	100	7060	11 500	18 300
Plan B	100	7060	10 600	15 100
Plan C	100	7060	10 100	12 400
Plan D	100	7060	11 500	18 300
Lithium [b]	–	~0	0·35	1·5

a Cumulative from 1969
b To a depth of 30 feet, Li for cooling

would be required for this purpose until the year 2020, more than 100 times the cumulative amount required for producing tritium alone. However, even this amount is well within the known reserves of just one deposit in Silver Peak, Nevada.[9]

It is not sufficient merely to state that we have the reserves but we should also be sure that there is no environmental problem resulting from extraction of those reserves from the earth such as occurs in strip mining for coal. The volume of ore (or most probably brine) which must be processed can be estimated by noting that the lithium concentration in its ores is about 5% and in brines it is present at 40-300 parts per million.[9] Hence, if the lithium is obtained from brine, 5 x 10^9 gallons of liquid must be processed and reinserted into the ground, to produce the Li required up to the year 2020. All this Li could come from one 72 square mile deposit in Nevada without any appreciable upset in the environment. If the lithium is processed from ore and if the amount of gangue (for tunnels or overload) is three times the volume of ore removed, then approximately 40 x 10^6 cubic yards of earth must be disturbed. Assuming a mining depth for Li of 10 yards, this means that 1·5 square miles must be dug up to provide lithium for CTR cooling.

The significance of this last comparison can be more fully appreciated by noting how much land must be strip mined to produce coal for the coal fired electrical generating plants. Table 3 shows that depending on adoption of Plan A, B or C anywhere from 12 400 to 18 300 square miles of land could be used up in the production of coal by strip mining between 1968 and 2020. The higher figure is equal in area to the states of Vermont and New Hampshire. Note particularly that almost half the strip mining for coal will be done before the year 2000, when fusion might first be introduced assuming optimistic major scientific and technological advances, as well as generous funding. Nevertheless, it can also be seen that the introduction of fusion at that time could save almost 6000 square miles of land from strip mining by the year 2020. It is worth while to emphasise here that we are just talking about fuel procurement and we will treat structural metals in more detail later.*

Construction materials requirements

Resource requirements.† The situation with respect to the procurement of structural materials for CTRs is not so optimistic as for the procurement of fuels. The problem stems from two facts. First, more exotic and less abundant elements are required to harness fusion as opposed to those required in fossil fuelled and fission plants. Higher operating temperatures favour the use of refractory metals (V, Nb or Mo) or at the very least, high temperature, high strength iron alloys. If the CTR uses magnetic confinement of the plasma, the iron alloys should not be magnetic, which in turn requires significant amounts of alloying elements such as Ni or Mn to stabilise the austenitic (non-magnetic) phase of iron. Elements such as Cr are also required for corrosion resistance. The magnets themselves require enormous amounts of low electrical resistivity metals such as copper or aluminium and significant amounts of superconducting

[9] D.A. Brobst and W.P. Pratt, eds, 'United States Mineral Resources,' Geol. Survey Paper 820, Washington, US Government Printing Office, 1973.

*In summary, fuel availability is truly unlimited for fusion reactors and the procurement of this fuel would present a negligible impact on the environment. If lithium is used as a coolant as well as a breeder, then one might be limited to several hundred years of D-T fusion reactors if we rely on land based reserves and several thousands of years if the Li is extracted from the ocean.

† The elements are identified as they occur in the text of this section:

V	– vanadium	Be	– beryllium
Nb	– niobium	F	– flourine
Mo	– molybdenum	Zr	– zirconium
Cr	– chromium	Al	– aluminium
Ni	– nickel	B	– boron
Mn	– manganese	Cu	– copper
Ti	– titanium	Fe	– iron
Sn	– tin	K	– potassium
Ga	– gallium	He	– helium
Na	– sodium	Pb	– lead

materials. Currently, Nb-Ti alloys, Nb-Sn or V-Ga intermetallic compounds are the most suitable materials for the superconducting coils. Another problem arises if any scarce elements are used in the CTR coolants. For example, Li has already been shown to be a suitable coolant and Na will also be adequate. However, if more complex salts such as Li_2BeF_4 are used for coolants (for reasons which will not be outlined here) then the availability of Be and F becomes quite important.

The second major reason for large materials demands of CTRs is their sheer size, which is partly due to the fact that the energy generation density of fusion plants (1-10 MWth/m^3 of plasma) is much lower than that of fission plants (100 MWth/m^3 of core). The higher energy and larger number of neutrons also requires increased shielding to protect vital reactor components and personnel. This shielding is most often accomplished with boron to absorb neutrons after they have been slowed down and heavy elements such as lead to absorb gamma rays emitted from elements made radioactive on the absorption of neutrons.

Before we can proceed much further in this comparison and assess the materials requirements of CTRs, we must list the current estimates of various materials required in CTRs. Table 4 lists the range of structural materials required per MWe for four systems analysed thus far.[10–13] Representative values for Tokamak reactors were taken from studies at ORNL[10] PPPL,[11] and the University of Wisconsin.[12] The LASL study[13] of pulsed systems was also included. Such a consideration of many systems necessarily produces a wide range of values because of different design philosophies and the fact that some systems are constructed with Nb-Zr alloys while others prefer stainless steels. Nevertheless, using the worst case for all the materials ensures that we will not underestimate the materials requirement regardless of which

[10] A.P. Fraas, USAEC Report ORNL-TM-3096, May 1973.
[11] R.P. Mills, private communication.
[12] 'Tokamak Reactor Design,' Vol.I UW FDM-68, Nov. 1973, Vol.II, Aug. 1974
[13] S.C. Burnett, W.R. Ellis, T.A. Oliphant, and F.L. Ribe, LA-DC-72-234A, 1972

Table 4 Estimated maximum materials requirements for the "nuclear island" portion of future fusion reactors which rely on a magnetically confined D-T reaction

		Millions of Metric Tonnes		
Element	**Metric ton required per installed MWe**	**Required for 1063 x 10^3 MWe**	**US Reserves(e)**	**World reserves (e)**
Aluminium	0.6(d)	0.6	13	3000
Boron	0·8(c)	0·8	33	66
Beryllium	0·12(b)	0·1	0·018(h)	0·38
Graphite	2(a)	2	10	large
Chromium	2(c)	2	~0	370
Copper	2(d)	2	74	310
Fluorine	1(b)	1	9	62
Iron	10(c)	11	8500(h)	180 000(h)
Helium	0·3(d)	0·3	1·2	1·2
Potassium	0·02(a)	0·02	42	30 000
Lithium	0·95(c)	1	6	180
Manganese	0·2(c)	0·2	0	590
Molybdenum	0·2(c)	0·2	2·5(h)	6·5(h)
Niobuim	0·8(d)	0·8	0·005(h)	7·8(h)
Nickel	1·5(c)	1·6	~0·14(h)	24(h)
Lead	11(c)	12	39	85(h)
Tin	0·2(b)	0·2	0·009	6(h)
Titanium	0·8(a)	0·9	23(f)	134(f)
Vanadium	0·5(a) (g)	0·5	0·1	26(h)
Zirconium	0·002(a)	0·002	0·06(h)	25

a Ref. 10
b Ref. 11
c Ref. 12
d Ref. 13
e Ref. 14 and except where noted at present prices.
f Ref. 9
g Use V as substitute for Nb structure
h Ref. 15

system eventually proves to be the most economic in electricity generation.

Table 4 shows that the major metallic structural requirements for CTRs range from 0·002 to 12 tonnes per MWe of installed capacity. Translating these figures into the amount of finished product required to provide 1063 x 10^3 MWe in 2020 reveals that the order of 0·002 to several million tonnes of some elements would be required by that time. The estimated US reserves of these elements is also listed in Table 4 along with comparable numbers for world reserves.[14,15] This information can be readily classified into three categories based on *current* reserves, (ie no allowance for depletion between now and 2020).

A. Those elements for which there appear to be abundant US reserves which could be used to meet CTR demands (Al, B, Cu, Fe, K, Mo, Ti, and Zr).
B. Those elements which could be supplied by US resources barring any great demand on these elements by other products before 2020 (F, graphite, He and Pb).
C. Those elements which could not be supplied by the US and reliance on foreign markets would be expected (Be, Mn, Cr, Ni, Sn, Ti, Nb, and V). However, these elements might not be able to be supplied even by world resources if other uses are found for the elements between now and 2020.

In category B, the exhaustion of helium from underground sources does not mean that the He would be lost; it will only be dispersed in the atmosphere and would have to be extracted at perhaps 100 times its present cost.[16] The use of Pb as a biological shield in CTRs could present problems if no future supplies were found. For example, approximately 1 200 000 tonnes of Pb were consumed in the USA in 1970, an amount equal to 100 CTRs at 1000 MWe rating. However, it is anticipated that large amounts of Pb could be processed at costs substantially above today's prices thus alleviating the problem of resources (but not economics).[15]

A more serious problem exists with those elements in category C. Three of the elements (Cr, Ni, Mn) are essential ingredients in austenitic (non-magnetic) stainless steel which, even if not used as the structural material of the CTR blanket, would probably be used as structural support and reinforcing for the magnets because of the low temperature strength and ductility of such steel. In the Wisconsin design[12] the blanket structural metal is less than 5% of the total steel required in the reactor. Tin would only be necessary if superconducting magnets capable of producing $>$ 125 kG were required. Niobium may be required in all fusion reactors which rely on superconducting magnets. Currently Nb-Ti alloys are the most promising superconducting materials for large magnets and hence could cause a large demand on the Nb reserves. It is estimated that about 0·3 tonne/MWe of Nb would be required in the magnet of a CTR regardless of what structural material was used in the blanket. If Nb were used as a blanket structure material then an additional 0·5 tonne/MWe would be required. The use of V as a substitute for Nb structural materials could also be made if the situation warrants this, but vanadium is also a metal which would have to be imported.

[14] First Annual Report of the Secretary of the Interior under the Mining and Mineral Policy Act of 1970 (P.L.91-631), March 1972

[15] E.N. Cameron, University of Wisconsin Report, UWFDM-68, Vol 2, 1974

[16] G.L. Kulcinski, University of Wisconsin Report UWFDM-83, August 1973

The projected average annual US requirement for Nb in CTRs for the period 2000-2020 is over three times the world consumption in 1970 and over 17 times that used in the USA during 1970!

Procurement of Mn, a vital component of not only austenitic stainless steels but also for ferritic structural steel, may be a severe problem. The requirement of 200 000 tonnes of Mn to build the projected CTRs up to 2020 is only a small fraction of the total world supply. However, it is almost certain that a large amount of this element will be used for other purposes in the next 50 years. It has been estimated[14] that the USA alone will use 10% of the world's known reserves of Mn between now and the year 2000 and probably another 10% of that value in the period 2000-2020 for non-CTR purposes. If the rest of the world continues to use seven times as much Mn as the USA does, then there could be a serious shortage of Mn in the early 21st century with obvious implications for fields other than fusion.

Finally, the use of Be either as a neutron multiplier (because of its high, n: 2n, cross section or as a component of an Li salt for cooling must be very closely examined. There are modest tonnage requirements for some CTRs (120 000 tonnes of Be for 10^6 MWe) but the reserves are quite limited, especially in the USA. For example, the above amount of Be corresponds to about 300 times the 1970 US consumption rate and five times the total projected cumulative US consumption between 1970 and 2000. Beryllium is not essential to most fusion reactors and it could be deleted without seriously affecting the breeding ratio. Pure lithium could also be used in place of Li_2BeF_4 salts. Therefore, unless large reserves of Be are found in the world, it is expected that Be will see only limited use of CTRs.

In summary the use of refractory metals Nb or V for high temperature structural materials in CTRs means that the USA will be essentially dependent on foreign sources for these elements. This dependence also will follow from the use of Nb-Ti or Nb_3Sn superconducting magnet materials. The unique requirement of non-magnetic low temperature high strength stainless steels will also place large demands on foreign suppliers for Cr, Ni and Mn. It appears to be very difficult to build a fusion economy on a system that uses large amounts of Be. On the brighter side, the USA has adequate reserves of Fe, Cu, Al, B, K, Mo and Zr to meet the projected needs.

Land despoilment. There will be a certain amount of land despoilment due to the procurement of the elements listed in Table 4. This will also occur for other types of power sources but it is worth demonstrating the level of disruption in view of similar effects for the procurement of fossil fuel. Table 5 lists the amount of ore which must be mined to get the CTR nuclear island materials for the period 2000-2020. Using the assumptions given in Table 5, about 60 square miles (160 km^2) need to be disrupted over the 20-year period prior to 2020 to provide the necessary ore. To put this figure in perspective, it is a factor of about 70 less than the land required *only* to provide strip mined coal for the equivalent electrical generating capacity.

Three of the required metals stand out as needing the largest

Table 5. Non-fuel ore requirement for projected CTRs from 2000 to 2020

Element	For 1063 x 10^3 MWe 10^6 tonnes	Approx. yeild of metal from ore[14]	Total ore requirements 10^6 tonnes
Aluminium	0·6	10	6
Beryllium	0·1	2	5
Chromium	2	5	40
Copper	3	0·9	220
Iron	13	45	29
Molybdenum	0·2	2	10
Niobium	0·8	2	50
Nickel	1	1	150
Lead	12	1·5	800
Tin	0·2	10	2
Vanadium *	0·5	5	10
			1351
		To account for overburden tunnels etc	x 4
			**5404 x 10^6 tonnes

*Substitute for Nb structural material.

**160 km^2 to a depth of 10 metres, assuming 0·3 m^3/tonne of ore.

Table 6. Financial requirements of importing metals to supply projected CTR capacity in the period 2000 – 2020.

	Element	Required from foreign sources – 10^6 tonne	1970 cost $/tonne 14	Total cost ($$10^9$)
	Beryllium	0·1	$132000	13·2
	Chromium	2	~3000	6
Definitely	Manganese	0·2	1320	1·3
must be	Niobium	0·8	3630	2·9
imported	Nickel	1·5	2816	4·2
even now	Tin	0·2	3828	0·77
	Titanium	0·9	2904	2·6
	Vanadium	0·5	9614	4·7
				~36[a]
Quite	Aluminium	0·6	638	0·38
probably	Copper	2	3630	7·3
imported	Fluorine	1	113	0·11
for economic	Iron	13	136	1·8
reasons	Lead	12	352	4·3
before 2000.				
				~14[a]

[a] rounded off

amount of ore to be processed per plant. These are in increasing order: Ni, Cu, and Pb. Obviously, if all other things were equal, one would like to substitute other elements with higher ore yields for these materials.

Balance of payments problems. One consequence of relying on foreign sources for raw materials lies with the balance of payments problem created by the purchase of the elements. The effect of importing these elements (Be, Mn, Cr, Ni, Sn, Ti, Nb and V) at constant (1970) prices to provide 1063 x 10^3 MWe of CTR capacity is approximately $36 000 million (Table 6). Other elements such as A1, Cu, F, Fe and Pb may also have to be imported after the year 2000 because of price considerations even though the USA may have sufficient reserves to cover the demand in the event of a national emergency. If these elements are imported, then the total costs are almost $50 000 million. Certainly, some of these problems would also be encountered by building other electrical generating stations, especially with Cr, Mn, Ni, Al, Cu, and Fe, but the costs for imported elements in the fossil systems would be lower by perhaps a factor of three or more.

Such large balance of payments charges will require serious study for other reasons such as international politics and national security. The switch to an energy source which requires large amounts of rare materials may be, at least from the US standpoint, somewhat unattractive.

Electrical distribution requirements

There are two areas to consider here: the actual land used by the power plant itself (which includes building, cooling arrangements, fuel storage and exclusion areas), and the transmission line requirements. It is expected that the actual site usage for CTRs will be very much like that for fission plants. Recent estimates of the land requirements for electrical generating stations are given in Table 7. It can be seen that if Plan B in our scenario were to take effect, by the year 2020, 342 square miles would be saved by the introduction of CTRs. This saving will rise to ~950 square miles for Plan C where fusion plants were envisaged to take the place of newly installed fossil fuelled plants (mainly coal).

Another area in which land saving might be effected by the introduction of fusion is that of transmission requirements. If fusion reactors, which have no chemical emissions, no potential for a nuclear accident, and minimal radioactivity problems, can be sited inside big cities, substantial savings can be made in the area of land required for transmission of electricity to the load centres.

For example, it has been estimated[5] that 19 square miles of land will be required per 1000 MWe for transmission line rights of way in 1990. Presumably, this could be reduced to 10 square miles/1000 MWe if the plants were located in the cities. Placing all the CTRs in the cities for the years 2000-2020 would then save over 9000 square miles of land for transmission lines. Other benefits might accrue from urban siting of plants such as use of waste heat for residential and industrial heating, industrial processing or sewage distillation.

Table 7. Land requirements for power plant sites[5]

	Square Miles/ 1000 MWe	Comment
Coal	1·60	on-site coal storage and ash disposal
Oil	0·40	on-site fuel storage
Gas	0·24	
Fission	0·47	exclusion area required
CTR	0·47	assumed to be same as fission for this study

Emissions to the biosphere

Conventional chemical pollutants. Fusion reactors do not emit chemical pollutants such as SO_2, NO_x, or CO. Therefore the introduction of fusion into the economy should have a beneficial effect on the quality of the air around electrical generating plants. Table 8 lists the projected emissions from electrical generating plants in 1973 and the year 2020. We have also included the effect of introducing fusion according to our previous Plans A, B, and C and have included the effects of more stringent air quality standards.[5]

Table 8. Effect of fusion on the air pollutants emitted during the generation of electricity in the year 2020 (units: 10^9 lb/year)

Pollutant	Plan A[a]	Plan B	Plan C	Est. 1973
CO_2	10 850	7950	2200	2750
CO	1·75	1·25	0·32	0·34
SO_2	55·2	40·1	11·0	25
NO_x	32·4	24·5	6·3	9·4
Particulates	8·97	6·45	1·7	7·5
Hydrocarbons	0·71	0·54	0·16	0·28
Aldehydes	0·099	0·04	0·018	0·029

[a] Base Plan, ref. 5

Table 9. Effect of various rates of CTR penetration into the electrical generating market on the overall pollution of the air from all sources in the USA in 2020 (units: 10^9 lb/year)

	Plan A[a]	Plan B	Plan C	Est. 1973
CO_2	30 400	27 800	22 000	10 900
CO	53	53	52	180
SO_2	87	72	43	49
NO_x	81	73	55	38
Particulates	44	46	36	22
Hydrocarbons	19	19	19	31
Aldehydes	1·1	1	1	0·41

[a] Base Plan, ref. 5.

The effect of fusion on the amount of CO_2, CO, SO_2, NO_X, particulates, hydrocarbons and aldehydes is rather dramatic with Plan C. Without exception, the total pollutants emitted by the electrical generating stations in 2020 were actually less than they were expected to be in 1973! It is hard to put a dollar value on this reduction in pollution because the cost in human life and property damage is still uncertain. However, lest we deceive ourselves, we must recognise that when the pollutants from all forms of energy (eg, cars, planes,) is added up, the impact of fusion is less evident (Table 9). Therefore, those who look forward to fusion to produce a pristine environment may be disappointed with the differences between Plans A and C in Table 9, because fusion can only make a fractional impact on a part of the economy, which in turn only emits a *fraction* of the total pollutants.

Potential hazards from fusion power

Conventional sources. Probably the largest amount of stored energy in a CTR lies in the coolant system. It was mentioned previously that either high pressure gases, such as helium, or liquid metals like lithium are the most likely coolants. A quick investigation will show that the most serious problem comes from the possibility of a liquid lithium fire and the amount of heat that could be released in such a reaction.

Liquid metal fires require oxygen and are even more spectacular in the presence of water as any chemistry student knows. If we were to imagine the maximum possible conventional accident that a CTR plant could sustain, we might then envision a rupture of the entire CTR confinement vessel which results in all of the lithium (for cooling and breeding) flowing out into the reactor building. Coupled with this release of Li might be the rupture of cooling water pipes (if allowed in the building) or addition of air and water into the building by means of a severe storm. If all the Li were to burn up in a 1000 MWe plant (~1000 tonnes of Li) then the energy released would be equivalent to that released by burning about a million gallons of fuel oil. This amount of energy would not be released instantaneously and it would take perhaps hours or days for all the Li to burn up. If it took a day, this would be the equivalent of the amount of thermal energy released inside the boilers of a 1000 MWe oil fired plant in the same time period. Certainly, severe damage might be incurred inside the plant, but there is little potential for damage to the surrounding populace.

Another accident that might be envisaged is the release of the energy in the superconducting magnets operating at about 100 kG. The complete failure (transition from superconducting state to normal resistive state) of the magnets could release energy equivalent to that in about 1500 gallons of fuel oil.[17] Again such an accident would be hard on the reactor and surrounding building, but would not pose any severe problem for the public.

Finally, if all the fuel in a 1000 MWe fusion reactor were to burn up instantaneously (a process that present-day scientists would dearly love to happen) then the energy equivalent of ~4000 gallons of fuel oil would be released. Such an amount of energy could hardly affect the large CTR plants we have been discussing.

Radioactive effluents. The only radioactive effluent from CTRs during normal operation should be tritium (half-life about 12·3 years). An analysis of a proposed CTR has been conducted by Daley and Greenberg.[18] They have concluded that leak rates as small as 6 curies per day can be maintained in 1000 MWe CTR plants. This number is also consistent with a value of 10 curies/day for a 1500 MWe plant.[12] Such a leak rate amounts to about 2 megacuries of tritium released per year for all the CTRs in the year 2020. Table 10 was prepared to compare the release rates to those expected from fission reactor and fossil fuelled plants.

Martin *et al*[19] have calculated that the average 1000 MWe coal fired plant releases about 48 millicuries per year of radium-226, radium-228 and thorium-232 isotopes. Hence, all the fossil plants now release about 8 curies per year and this is expected to increase to about 50 curies per year in 2020. The release of tritium and krypton-85 from fission reactors (and reprocessing facilities) is presently about 17 megacuries/year.[5] This is expected to rise to 36 megacuries per year for tritium and 270 megacuries per year for Kr-85 in 2020.

The above figures might be put into a little more perspective by noting that tritium is produced at the rate of 4 megacuries per year in the upper atmosphere by cosmic ray action on nitrogen.[20] Since this has been happening for some time, there is an equilibrium inventory of about 70 megacuries in the stratosphere from that source. Furtheremore, the amount of tritium in the atmosphere due to nuclear weapons testing is about 700 megacuries, excluding the recent French and Chinese tests.

17 'Fusion Power,' WASH-1239, February 1973

18 J.E. Draley and S. Greenberg, to be published in *Proceedings* of the Texas symposium on the technology of controlled thermonuclear fusion experiments and engineering aspects of fusion reactors, Austin, Texas, November 1972

19 J.E. Martin, E.D. Harward, D.T. Oakley, J.M. Smith, and P.H. Bedrosian, Paper SM-146/19 in IAEA symposium on safety of nuclear power plants, Vienna, 1971

20 D.G. Jacobs, 'Sources of tritium and its behavior upon release to the environment,' TID-24635, USAEC, 1968

The data in Table 10 show that the present gaseous radioactivity already in the atmosphere may be considerably larger than that released in the year 2020 and comparable to the total inventory of radioactivity over the period 2000-2020 if radioactive decay is taken into account. The introduction of fusion into the electrical generating market 2000-2020 has a relatively minor (~15%) effect of radioactivity due to man-made sources if Plan B is followed and has essentially no effect if Plan C is maintained. The implication of Plan D is that the total radioactivity released in the year 2020 could be reduced by ~40% if CTRs are introduced at the expense of fission reactors. However, lest we lost our perspective, the radiation levels from these effluents are negligible when compared to those arising from cosmic rays, ultraviolet rays, natural radioactive elements, X-ray machines, weapons testing, etc.

A comparison of total radioactivity in curies is not the best way of calculating the biological impact of emission from power plants. It is more instructive to take account of the MPC (maximum permissible concentration) for each isotope released. The bottom half of Table 10 contains the information on how many cubic kilometres of air are required to dilute specific radioactive emissions to acceptable standards.[21] It is seen from this table that whereas radioactive emissions (measured in curies) from coal fired plants are negligible when compared to nuclear facilities, they could amount to 1-8% of the total biological hazard potential (BHP) of all power plants in the time period 1973-2020. The introduction of fusion at the expense of coal-fired plants (Plan C) would not increase the total BHP and in fact would reduce it by 2%. On the other hand, if fusion is introduced at the expense of

[21] 25 FR 10914, Part 20, December 1968

Table 10. Projected gaseous radioactivity released into the atmosphere in the year 2020 due to the generation of electricity and that present from selected sources

Source	Isotope	Plan A	Plan B	Plan C	Plan D	Est. 1973
			Megacuries			
Fossil fuel[a]	(Ra-228 Th-232)	0.00005	0.00004	0.00001	0.00005	0.000008
Fission reactors	Tritium	36[b]	23	36	18	0·6
	Kr-85	270[b]	220	270	140	16
CTRs	Tritium	0	2	2	2	0
Weapons Testing[c]	Tritium	40	40	40	40	700
Cosmic rays[d]	Tritium	70	70	70	70	70
Total (rounded)		*420*	*360*	*420*	*270*	*790*
			10^3 (km)^3 of air required to dilute to MPC			
Fossil fuel	(Ra-228 Th-232)	50	40	9	50	8
Fission reactors	Tritium	180	115	180	90	3
	Kr-85	900	730	900	460	53
CTRs	Tritium	0	10	10	10	0
Weapons testing[c]	Tritium	200	200	200	200	3500
Cosmic rays	Tritium	350	350	350	350	350
Total (rounded)		*1680*	*1450*	*1650*	*1160*	*3900*

a Ref. 20
b Ref. 5
c Already present assuing no addition from 1968 onward and allowing for natural decay.
d Equilibrium value.

fission reactors (Plans B and D) then reductions in the year 2020 of 20 to 45% in BHP could be achieved. Again, it is noted that the presence of tritium from weapons testing is a dominating feature of the present picture.

Radioactivity inventory. The two major considerations in this category are:

- The release of radioisotopes in the event of an accident;
- the long-term storage of radioisotopes.

It is very difficult, and sometimes misleading, to discuss the release of radioisotopes during accidents because such an analysis automatically assumes that all the safety devices on a reactor will fail at the same time. This is an unrealistic assumption and must be recognised as such before we can assess the maximum possible damage that could be done by the release of all radioisotopes in a reactor.

Table 11 lists the major isotopes produced by the fuel of a fission reactor and in the first wall and blanket region of a CTR. Data on four different CTR structural materials are given: 316 stainless steel, a Nb-1Zr alloy, a V-20Ti alloy and aluminium.[22,23] Information is given for the number of curies generated per kWth

[22] W.F. Vogelsang, G.L. Kulcinski, R.G. Lott, and T. Sung, to be published, Transactions American Nuclear Society.

[23] J.F. Powell, F.T. Miles, A. Aronso , W.E. Winsche and P. Bezler, Brookhaven National Laboratory Report, BNL-18439, November 1973

[24] D. Steiner and A.P. Fraas, *Nuclear Safety*, Vol. 13, 1972 No. 5, p. 353

[25] T.J. Burnett, *Health Physics*, vol 18, 1970, p. 73

Table 11 Major long-lived radioactive isotopes in various CTR first wall materials in fuels of advanced fission reactors[a]

System	Isotope	Half-life	Activity (curie/kWth)	Maximum permissible concentration (microcurie/cm^3)	Biological hazard potential (km^3 of air/kWth)
Fusion-all	H-3	12·3 y	60	2×10^{-7}	0·30
	V-49	331 d	0·67	1×10^{-10}	6·7
316 Stainless Steel First	Fe-55	2·94 y	140	3×10^{-8}	4·6
Wall Only[b]	Co-58	72 d	29	2×10^{-9}	14·5
	Ni-57	36 h	1·1	1×10^{-10}	11
	Mn-54	310 d	24	1×10^{-9}	24
	Co-60	5·25 y	4·7	3×10^{-10}	15·6
Total					~77
Nb-1Zr[b]	Nb-92m	10·1 d	152	1×10^{-10}	1520
	Nb-95m	3·75 d	50	1×10^{-10}	500
	Nb-95	35 d	43	3×10^{-9}	14
	Sr-89	51 d	38	3×10^{-10}	126
Total					~2200
V-20Ti[b]	Sc-48	1·81 d	12·1	5×10^{-9}	2·5
	Ca-45	165 d	2·6	1×10^{-9}	2·6
	Sc-46	84 d	1·87	8×10^{-10}	2·3
Total					7·5
A1[c]	Na-24	1·5 h	630	4×10^{-8}	15·8
	A1-26	$7{\cdot}5 \times 10^{5}$ y	0·004	1×10^{-10}	0·04
Total					~15·8
Fission	1·131[d]	8·04 d	31·6	1×10^{-10}	330
	Pu-239[e]	24 100 y	0·06	6×10^{-14}	1000
	all Pu isotopes		18·2		8300
	Sr-90[e]	25 y	0·64	3×10^{-11}	21
	Cs-137[e]	33 y	0·94	5×10^{-10}	2
all other fission products		>1 d	–	–	18 000

a Neglect all isotopes with half lives <12 h
b Ref. 22 for 10-year exposure
c Ref. 23
d Ref. 24
e Ref. 25

and for the biological hazard potential (BHP) of various isotopes in terms of the volume of air (km^3) required to dilute the isotopes to the maximum permissible concentration (MPC).

After 10 years of operating CTRs with 316 stainless steel, Nb-1Zr, Al or V-20Ti as structural material, the total BHP of the reactor is greater than that of the entire tritium inventory by one to three orders of magnitude. This observation is particularly striking for systems using Nb-1Zr alloys.

An interesting comparison can be drawn between fusion and fission. It can be seen in Table 11 that fusion systems have BHP values of one to four orders of magnitude lower than fission reactors. The most critical isotopes in the time period shortly after reactor shutdown are iodine-131 and caesium-137. It is important to note that iodine (I) or caesium (Cs) are volatile elements and could conceivably escape the reactor in the event of a severe accident while most of the radioactivity in fusion systems is in the form of non-volatile metallic elements. Stated another way, the 0·94 Ci/kWth of Cs-137 in Table 11 would probably present more of a hazard than the 152 Ci/kWth of Nb-92m. This is because the Nb is tightly bound in the metallic structure with a very low vapour pressure at reactor temperatures, whereas the Cs-137 is in a vapour state at typical fuel element temperatures.

A brief analysis of Table 11 reveals that the replacement of fission reactors with fusion reactors will lower the BHP of our total electrical generating system in almost direct proportion to the CTR fraction. Hence, fusion can reduce future potential hazards from large-scale release of radioactivity in the unlikely event of a severe nuclear accident.

The long-term storage problem of fission reactor fuel stems from the actinides, of which plutonium 239 is the predominant example, and the strontium-90 and Cs-137 isotopes. Because of their long half-lives and low MPC it can be seen in Table 12 that 100 years after the generation of the waste the BHP fission fuel has only dropped by one order of magnitude but that of fusion has dropped by three to seven orders of magnitude for the case of 316 stainless steel and Nb alloys respectively. There are essentially no long-term storage problems with CTRs constructed of vanadium.

Thus the introduction of fusion into the economy after the year 2000 will tend to reduce both the BHP in the event of serious fission power plant accidents and will also reduce the long-term storage requirements for radioactive wastes, especially if vanadium aluminium and stainless steel are used.

Costs of fusion power

Absolute values for the cost of electricity from different types of energy sources are very difficult to obtain because of variations in local economic or climatic conditions (ie fossil plants at the source of fuel versus fossil plants in the centre of a city). However, there are some inherent features that are worth noting about each of these plants.

First of all, the cost of generating electricity from fossil plants depends quite heavily on the fuel costs which can amount to ~40% of the total costs. The corresponding figure in fission

Table 12. Long-term radioactive wastes from fusion and fission systems after 100 years decay

System	Isotope	Half-life	Activity curie/kWth	Maximum permissible concentration microcurie/cm^3	Biological hazard potential km^3 of air/kWth
Fusion					
316 Stainless steel	Co-60	5·25 years	8.7×10^{-6}	3×10^{-10}	3×10^{-5}
	Ni-63	85 years	1.3×10^{-4}	2×10^{-9}	6.6×10^{-5}
Nb-1Zr	Nb-94	50 000 years	0·008	1×10^{-10}	0·8
	Zr-93	5 000 000 years	0·006	4×10^{-9}	0·0015
V-20Ti					Negligible
Al	Al-26	75 000 years	0·004	1×10^{-10}	0·04
Fission	Pu-239	24 100 years	0·06	6×10^{-14}	1000
	Sr-90	25 years	0·04	3×10^{-11}	1·3
	Cs-137	33 years	0·115	5×10^{-10}	0·23

reactors is ~20% and we have seen that fuel costs for fusion reactors are much less than 1% of the total cost of electricity.

The second point is that because fusion reactors are so capital intensive and have relatively low energy densities and depend on rather expensive reactor materials, one can get an idea (within a factor of ~3) of capital costs of this type of power plant by simply calculating the fabricated cost of the materials in the reactor. Past estimates have shown that the fabricated materials costs for fusion reactors are of the order of $250/kWe.[17,27,28]

Some representative values of known electrical generating costs are given in Table 13 for a coal fired plant and a light water fission reactor and these are compared to estimated fusion reactor costs.[28,29]

Although the make-up of the electrical generating costs varies dramatically from one system to another, the total cost of electricity does not vary significantly with the three forms of energy. One factor which may invalidate the information in Table 13 is the cost of environmental protection and long-term radioactive waste disposal. When such costs are properly assessed in relation to fossil, fission *and* fusion systems it is felt that the fusion reactor may look better economically.

In summary, it appears that fusion will be able to generate electricity at about the same cost as fission and fossil fuel plants. However, it must be recognised that it is far too early to make any more quantitative statements.

[26] *Steam electric plant construction costs and annual production expenses*, US Power Commission Report No. 197, 1972

[27] *Electrical World*, Vol. 180 No. 9, 1973, p. 39

[28] J. Young, University of Wisconsin Report UWFDM-68, Vol. 2, 1974

[29] R.G. Mills, *Princeton Fusion Reactor Design*, to be published, 1974

Table 13. Comparison of known electrical generating costs from fossil-fueled and fission reactors to projected costs for fusion reacotrs

	Coal[a]	Fisson[b]	Fusion[d, e]
Capital investment $/kWe[c]	120-220	120-220	600-800
Cost of Electricity mills/kWe-h [c]			
Plant investment	4-10	6-15	10-17
Operation maintenance	1-3	1-2	1-2
Fuel	3-5	2-3	<0.01
Total	8-18	9-20	11-19

a Reference 26, placed on line in 1972
b Reference 27, placed on line in 1970-1972
c in 1974 dollars
d Reference 28
e Reference 29

Summary

We will need to develop other sources of energy between now and the year 2000 while fusion technology is being perfected. It appears that 2000 is the earliest date at which we will be able to operate commercial fusion power plants. Given an optimistic penetration of fusion into the electrical generating market, it is possible that 10% of our electrical generating capacity in the year 2010 could be supplied by CTRs. This could rise to almost 30% by the year 2020, still below the percentage generated by fission reactors which may account for 40% of the installed capacity.

The fuel requirements for fusion represent its biggest advantage. Both the amount and method of procuring the fuel will represent a negligible impact on the environment. The development of fusion power will considerably relieve the pressure on the environment from the standpoint of strip mining of coal and the depletion of our vital fossil fuels. Because the fuel cost is essentially zero and supplies virtually unlimited, we will have to concentrate on minimising the impact on the environment due to structural materials procurement.

Some serious problems for magnetically confined plasma reactors could arise because of the need for refractory metals and relatively expensive alloying elements in iron-based alloys. Deficiencies of Nb, V, Cr, Mn, and Ni in the USA could increase its dependence on foreign suppliers for these metals, thus trading her present problem of fossil fuel dependence for one of structural materials dependence in the future.

Fusion reactors could considerably reduce the land requirements for electrical power stations both at the power plant site and because their inherent safety may allow them to be placed closer to, if not inside, large cities. This advantage of fusion will become more important as our land reserves dwindle and a premium is placed on utility land.

The introduction of fusion power, which has no chemical emissions, will greatly reduce the air pollutants from power plants beyond the year 2000. However, when viewed in total, fusion can make only small percentage improvements in air quality because of the large contributions of other energy consuming sectors of the economy.

Fusion reactors can significantly reduce the radioactive emission of power plants to the environment, especially when one views this problem with respect to biological hazard potentials. However, because neutrons are a natural by-product of the D-T reaction, there will be large amounts of radioactive isotopes generated during the production of fusion power. These isotopes generate as much activity in curies as do those resulting from fission, but they are chemically more stable and do not have the low maximum permissible concentration levels characteristic of the actinides, strontium-90, iodine-131 or caesium-137. There will be large amounts of tritium in D-T fusion reactors and it must be contained with leakage rates not exceeding 10^{-6} per day.

Another advantage of fusion power is that the half-lives of the CTR generated isotopes, with the exception of Nb, are quite a bit shorter than the half-lives of the important fission fuel isotopes.

This means that the long-term radioactive storage problems can be significantly reduced by fusion power.

Finally, the cost of generating electricity by fusion does not appear to be significantly higher or lower than that typical of present-day fossil or fission plants. This conclusion could be modified if changes are made in our methods of assessing environmental damage. It would be expected that the corresponding increase in CTR electrical generating costs would be far less than for fossil or fission fuelled systems.

If the state of the art advances sufficiently to allow us to tame fusion reactions which emitted no neutrons, it would change many of the conclusions of this article. A similar revision would be in order if we could attain laser induced reactions or successfully achieve direct conversion of the kinetic energy of the charged particles emitted in fusion reactors to electricity.

All of these are exciting possibilities but we must be careful that we do not get so fixed on the potential of future developments that we forget to utilise those energy sources at our disposal. Only vigorous effort on our part will ensure that we reach the year 2000 with enough inertia and technical knowledge to take advantage of this potential new source of power.