Fusion Power - One Answer to United States Energy Needs in the 21st Century

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I. Introduction - Why Do We Need Fusion?

The recent upheavals in world fossil energy markets and the current political resistance to fission reactors in the United States has placed this country in great peril. Strangely enough, this peril comes not from a lack of energy resources, but from a lack of willingness to adjust lifestyles to make use of the more abundant energy sources that we have in the United States. Gas and oil are clearly limited options and probably will play a decreasing role at the turn of the century. Coal is a viable option for the United States on paper, but environmental problems (acid rain, CO_2 "greenhouse" effects, land despoilment, etc.) and safety problems (mining and transportation accidents, increased lung disease, etc.) may limit its use. Furthermore, an increasing fraction of our coal will undoubtedly be used to produce liquid and gaseous hydrocarbons to replace our dwindling oil and gas resources. Fission reactors, based on thermal neutrons, cannot play a major role in United States energy policy much beyond the turn of the century because of domestic resource limitations and increased world demand for uranium outside the United States.

The fast breeder reactor can provide a large fraction of the United States and world energy needs in the 21st century. However, domestic political resistance to its near term development and public concern over the proliferation issues associated with a plutonium economy have effectively stopped the breeder program in the United States for the time being. Wind and solar electric could theoretically contribute to United States and world energy needs in the 21st century but their localized nature, intermittent operating characteristics, and inherently high materials intensity (and hence high cost) will probably keep them from contributing more than a few per cent of the total world energy needs by the turn of the century. Solar-thermal installations can be quite effective in some parts of the world but a recent study by the National Research Council [1] predicted that even with a vigorous solar program, no more than 4% of the total United States energy needs would be supplied by solar-thermal system in the year 2000. Geothermal, tidal, ocean thermal gradient schemes, biomass, etc., will undoubtedly be developed to some degree, but again, will probably provide only a small fraction of the United States energy needs.

Fortunately, the situation is not actually as bleak as painted above, especially in the United States. Scientists, roughly 30 years ago, discovered that nuclear fusion has the potential for freeing mankind from its fuel supply problems for centuries to come without most of the environmental and social problems presented by fossil fuels and nuclear fission. Recent success in theory and experiments have caused us to hear less of the phrase "... if thermonuclear fusion can be controlled ..." and more scientific papers now 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? We attempt in this article to address some of these questions, at least with respect to how they might be answered in the United States. Such an assessment, by its nature, requires speculation on the course that the United States and the world will take in the next 30 years.

The authors claim no special faculty for predicting that course and therefore caution the reader that the scenario painted in this article represents a view from a single vantage point. Nevertheless it is now possible to speculate, 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 organization of this paper is as follows: first we review where we have been and where we are going in DT fueled fusion power research. Next we examine the current view of how fast we could bring fusion into the United States and world economies. Once such a fusion economy is in place and in balance with other renewable energy sources, it is logical to ask, "What will the major impact of the economy be?". We limit our investigation in the above area to cost, fuel and material resources, risks, and environmental impact. Finally, our conclusions and recommendations will be summarized.

II. Where Have We Been and Where Are We Going in Fusion Research?

A. Introduction

Magnetic fusion energy has been under development since 1950 with the aim of tapping the energy of the stars by fusing hydrogen into helium. This requires that the hydrogen fuel be heated to 100,000,000°K under conditions where the product of gas density and characteristic energy retention time (the $n\tau$ product) exceeds 10^{14} cm^{-3}-s. Gases at these conditions are fully ionized plasmas.

In the decade of the seventies, plasmas have been confined by magnetic fields in straight or toroidal systems and brought to the point that the conditions required for a reactor have been essentially demonstrated. Specifically, in the toroidal system called tokamak [2], the temperature of the fuel ions has exceeded 90,000,000°K [3] and the $n\tau$ product has been as large as 2×10^{13} cm^{-3}-s [4]. Progress has also been made with linear approaches to magnetic fusion power such as the tandem mirror [5].

In parallel with the successes in physics, there have been extensive studies of fusion reactors, particularly based on the tokamak, and major efforts in fusion technology. Conceptual reactor designs have been developed to the point where the central features of fusion reactors have been uncovered. It is therefore possible to begin considering the impact of such reactors on a national energy economy.

For the purposes of this report, we will only introduce the essential concepts of nuclear fusion with emphasis on the tokamak and tandem mirror concepts in particular. We then summarize some of the major recent physics results. We will likewise briefly outline tokamak reactor studies completed over the past several years. Based upon this work, particularly the series of reactor studies carried out at the University of Wisconsin (UWMAK-I [6], UWMAK-II [7], UWMAK-III [8], and NUWMAK [9]), we explore the role of fusion power in connection with projected future energy scenarios and describe aspects relevant to fusion reactor deployment, specifically, potential reactor economics, comparative risks in utilizing fusion, and materials resource implications of a fusion economy. It is important to emphasize that these reactor designs may not be the optimum configuration for commercial power plants but only tools by which we can uncover those positive and negative features of fusion that we need to understand. Therefore we include some of the earlier studies along with the latest design.

B. Fusion Fuel Cycles

The most commonly used fuel in a fusion economy is deuterium, a stable hydrogen isotope which is found in a concentration of 0.0148% of the hydrogen atoms in ordinary water. The fuel cycles are:

Deuterium-Tritium Cycle

$$ {}^{2}_{1}H + {}^{3}_{1}H \rightarrow n + {}^{4}_{2}He \qquad Q = 17.6 \text{ MeV} \quad . \qquad (1)$$

Deuterium (${}^{2}_{1}H$ or D) and tritium (${}^{3}_{1}H$ or T) are the fuels most likely to be used in the earliest fusion reactors because they begin burning at the lowest temperature, approximately 60,000,000. This temperature has already been reached in experiments using ordinary hydrogen [2,3]. Tritium is radioactive and has a half-life of 12.35 years and it decays by emitting a low energy beta particle,

$$ {}^{3}_{1}H \rightarrow {}^{3}_{2}He + {}^{0}_{-1}\beta \qquad (2)$$

$$ t_{1/2} = 12.35y \quad . $$

Tritium can be produced by capture of the neutron produced in reaction eqn. (1) in both of the two isotopes of lithium, ${}^{6}Li$ and ${}^{7}Li$:

$$ n + {}^{6}Li \rightarrow {}^{3}_{1}H + {}^{4}_{2}He \qquad Q = 4.8 \text{ MeV} \qquad (3)$$

$$ n + {}^{7}Li \rightarrow {}^{3}_{1}H + {}^{4}_{2}He + n' \qquad Q = -2.87 \text{ MeV} \quad . \qquad (4)$$

The reaction with ${}^{6}Li$ is exothermic and will occur with neutrons of any energy. In particular, the reaction probability is highest with slow neutrons. The reaction with ${}^{7}Li$ is endothermic and will occur only when the incident neutron has an energy greater than the negative reaction Q value. However, this reaction yields another neutron, albeit of lower energy, which can react with ${}^{6}Li$. Thus, it is possible to produce, on the average, more than one triton per triton consumed, that is, to breed tritium. Therefore, the primary fuel resources of the DT cycle are deuterium and lithium.

Deuterium-Deuterium Cycle

$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow \begin{cases} \xrightarrow{50\%} {}^{1}_{1}H + {}^{3}_{1}H & Q = 4.04 \text{ MeV} \\ \xrightarrow{50\%} n + {}^{3}_{2}He & Q = 3.37 \text{ MeV} \end{cases} \qquad (5)$$

This cycle requires no breeding and the subsequent in-situ burning of both the tritium and helium-3 leads to a total average energy release per D-D reaction of approximately 22 MeV. The temperature required for burning is five times higher than for D-T but it may prove useful in early reactors, particularly if a small additional amount of tritium is added to the D-D mixture (lean burning of tritium).

Deuterium-Helium-3 Cycle

$$^{2}_{1}H + ^{3}_{2}He \rightarrow ^{1}_{1}H + ^{4}_{2}He \qquad Q = 18.35 \text{ MeV} \qquad (6)$$

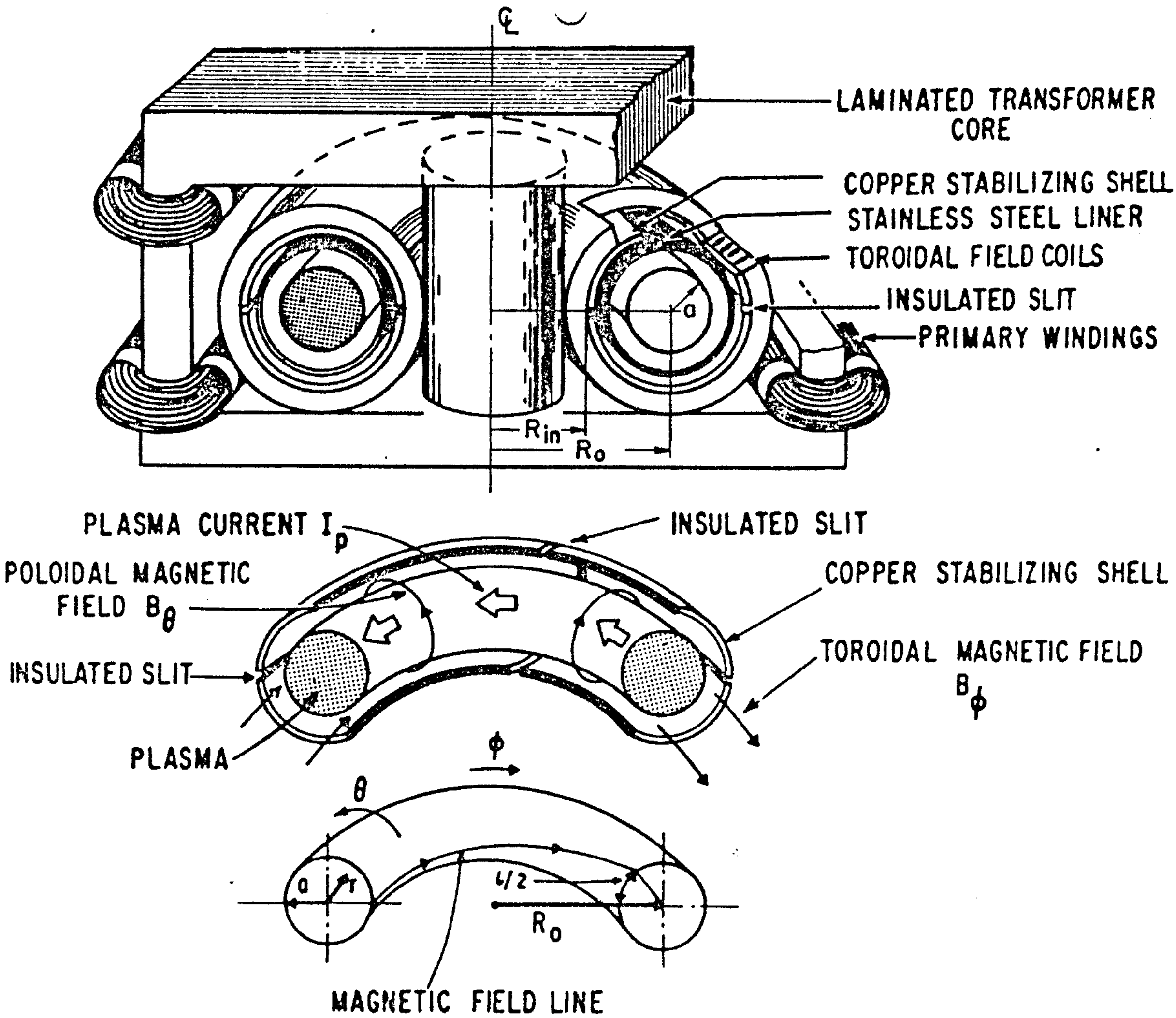
Helium-3 is stable but it unfortunately is very rare on earth. The likelihood of a self-sustaining economy based on this cycle is poor but the reaction is important because ^{3}He is produced via D-D reactions and because it is the natural product of tritium decay. We expect to burn the ^{3}He produced from these pathways in deuterium based reactors.

C. The Tokamak

The tokamak is a toroidal magnetic plasma confinement device which operates on the principle of an electric transformer with a one turn secondary. A time varying current in the primary windings establishes an electric field toroidally around the chamber which induces a toroidal current to flow in the plasma. A schematic picture of a tokamak is shown in Fig. II-1. A strong toroidal magnetic field is required for magnetohydrodynamic (MHD) stability of the plasma loop and a vertical field is required to stabilize whole-body plasma motion either horizontally or vertically. Thus, there are three key sets of magnets: large magnets which provide a strong toroidal field; induction magnets which constitute the primary windings of a transformer and induce the current to flow in the plasma, and magnets which extend toroidally around the device and provide a vertical field required for stability. Lines of magnetic force follow a helical path as shown in the figure and charged particles follow these field lines and are confined. Energy and particles are lost radially from the plasma because of transport resulting from collisions or from collective effects (wave-particle interactions and turbulence). The size of a tokamak is characterized by its major radius and the radius of the plasma. The technology is typically characterized by the value of plasma current, torodial magnetic field, and for reactors, the power and power density of the device.

We can immediately point to several important features of the tokamak as a reactor. It will have a pulsed burn cycle since one must eventually terminate the primary current and reset the transformer. The magnetic flux available in the core of the primary can potentially permit a burn time per pulse of more than 1000 seconds. The actual burn time will depend upon whether the plasma can be kept clean of impurities and whether the helium ash can be continuously removed. Proposals for continuous tokamaks have been made based upon the use of RF waves to drive the plasma current but these concepts require experimental verification [10].

Figure II-1



LAMINATED TRANSFORMER CORE
COPPER STABILIZING SHELL
STAINLESS STEEL LINER
TOROIDAL FIELD COILS
INSULATED SLIT
PRIMARY WINDINGS
a
R_{in}
R_o
PLASMA CURRENT I_p
INSULATED SLIT
POLOIDAL MAGNETIC FIELD B_θ
COPPER STABILIZING SHELL
INSULATED SLIT
TOROIDAL MAGNETIC FIELD B_ϕ
PLASMA
ϕ
θ
a
r
L/2
R_o
MAGNETIC FIELD LINE

A second feature derives from the stability requirement of a strong toroidal field. When combined with the poloidal field of the plasma current, the helical-shaped magnetic field lines shown in Fig. II-1 are produced. The toroidal and poloidal fields are related by

$$B_T = B_\theta qA \quad . \tag{7}$$

The toroidal field is B_T, B_θ is the poloidal field, and A is the aspect ratio of the plasma, i.e., the ratio of major radius R to plasma radius, a. The aspect ratio should be as small as possible to minimize the toroidal field strength. The safety factor q represents the number of times a field line encircles the device toroidally before closing on itself. For stability, q should be larger than 1 and is typically chosen between 2.5 and 3 in reactor designs.

Practical limitations on space near the center of the torus lead to values of machine aspect ratio between 3 and 5 when the major radius is about 5m. (The aspect ratio can be as low as 2.0 to 2.5 in reactors with larger major radii and in experiments.) It is found that B_T is approximately 10 B_θ which leads to the result that in both experiments and reactor designs, the value of B_T^0 at the plasma center is 3-6 Tesla (30-60 kG). Since B_T varies inversely with the major radius of the torus, the maximum field at the inner leg of the toroidal field (at R_{in} in Fig. II-1) is

$$B_T^{max} = \frac{R_0}{R_{in}} B_T^0 \quad . \tag{8}$$

The typical range of B_T^{max} is 7 to 12 T in reactor designs.

The small value of aspect ratio and the need for magnets to generate a vertical field imply that tokamaks are compact systems, particularly near the central region of the torus, and are complicated by the competition for space between the magnet system, the blanket and shield, the auxiliary heating system, and the vacuum exhaust system. A major focus of attention in reactor studies has thus been on the maintainabilty of the system, particularly since the lifetime of the structure near the plasma is expected to be less than the lifetime of the plant.

D. The Tandem Mirror

A tandem mirror, shown schematically in Figs. II-2 and II-3 consists of three major sections; two ordinary magnetic mirror machines at either end of a solenoid. A charged particle can be reflected as it approaches a region of higher magnetic field and this is the principle behind magnetic mirror confinement. In a single mirror cell (e.g., an isolated version of one end shown in Fig. II-2 and II-3) positive ions are confined. Electrons, which scatter more frequently than ions, preferentially escape from the mirror cell leaving

Figure II-2

Tandem Mirrors with Ambipolar Barriers at the Ends

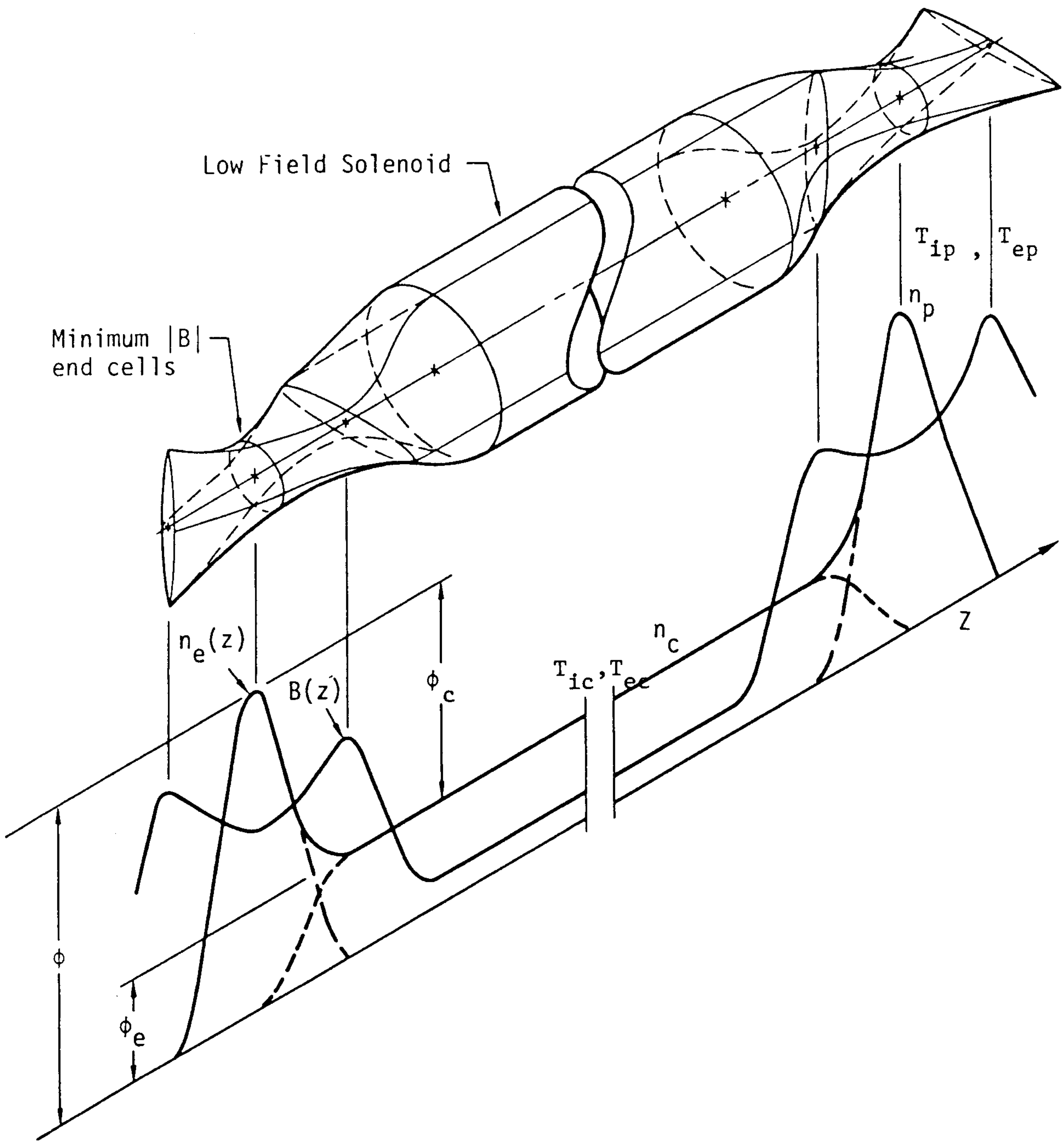
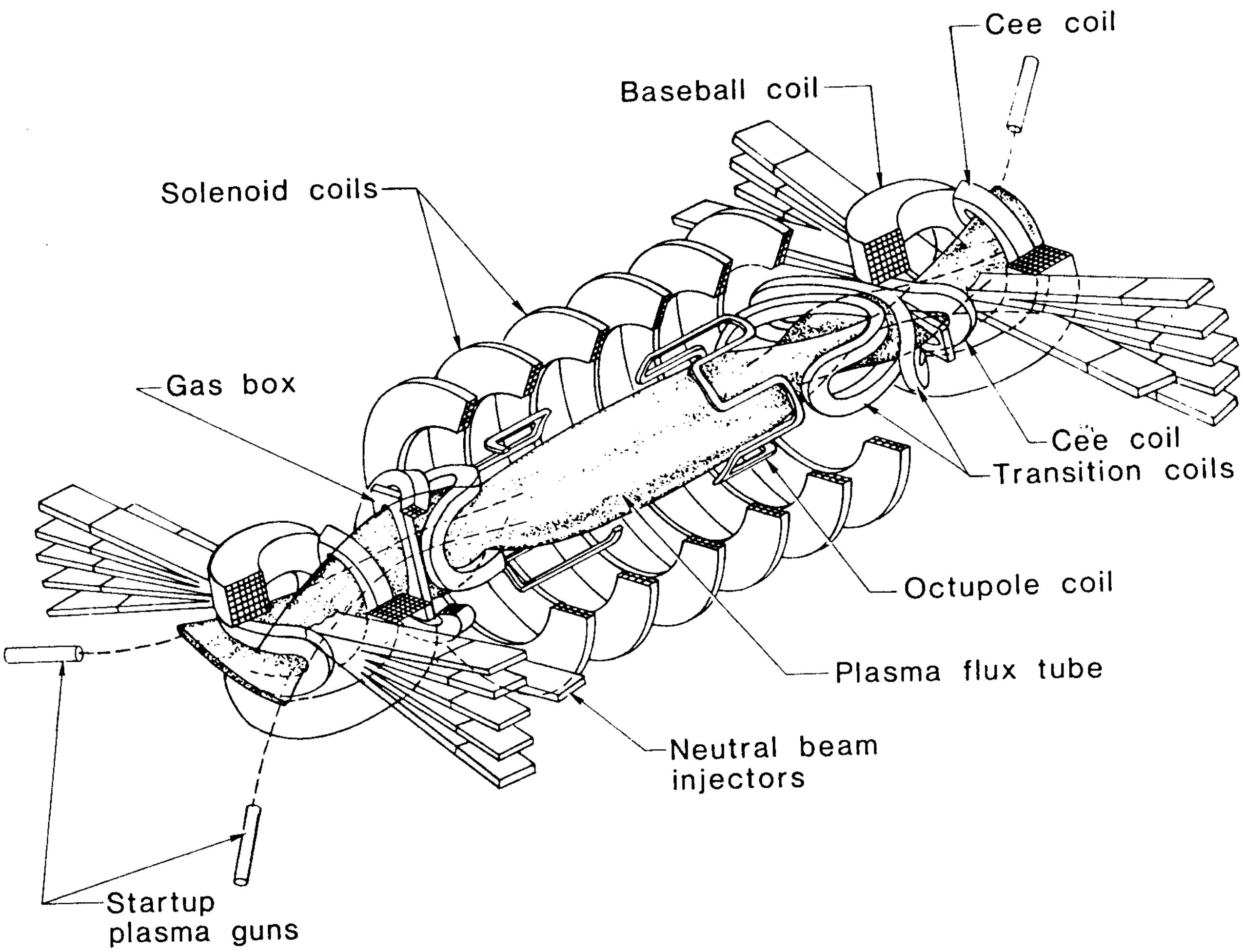


Figure II-3

Schematic Diagram of the TMX Device



it with a positive charge. A positive potential thus forms to equalize the currents of ions and electrons leaving the system.

Two such devices placed at the ends of a solenoidal section leads to the tandem mirror configuration with a potential distribution as shown in Fig. II-3. Ions now trapped in the solenoid are in an electrostatic potential valley with respect to the ends and are confined. The confinement time exceeds that in a single cell alone, thereby giving rise to a better overall power balance for the system.

Several key features of a tandem mirror as a reactor have been further improved by the introduction of the thermal barrier concept [5]. In a simple tandem mirror the plasma in the end cells must have high ion energy (0.5-1 MeV) to be reasonably well confined and this requires sustenance by the injection of intense, high energy neutral atom beams. In the thermal barrier concept this energy could be lowered to $\sim$ 500 keV or less. Confinement of the plasma pressure in the ends requires high magnetic fields (12-15 T) but such magnets are solonoidal and could be reasonably extrapolated beyond the present state of the art. Since no transformer is involved (as in a tokamak), operation is potentially steady-state. Analysis shows that these machines would typically be 50-100 m in length to achieve a ratio of fusion power out to injected power (a ratio called Q) of 10 or greater.

E. Current Status of Tokamak and Mirror Physics Results

A large number of tokamaks around the world have now been operated with remarkable success. Some of the outstanding results are summarized in Table II-1 for major United States tokamaks. The ion temperature in PLT has been measured with H or D. $n\tau$ values in both Alcator A and PLT are on the order of 10^{13} cm^{-3}-s. The high values of ion temperature have been achieved with external energetic neutral atom (beam) injection and the plasma has responded as predicted by theory. The scaling of $n\tau$ varies as n^2a^2 where a is the radius of the toroidal plasma and thus should continue to increase as machines are made larger and operate at high density.

Keeping tokamak plasmas clean to avoid excessive radiation of the input power is a key to long-range success. In recent years, tokamak plasmas have been made which have extreme cleanliness (effective plasma charge, Z, approaches one as would be indicative of an essentially pure hydrogenic plasma) for times that exceed several particle confinement times. Recently, high values of plasma pressure have been produced which equal or slightly exceed the pressure limit predicted theoretically. No outward sign of instability appeared and we do not yet know the upper pressure limit. These results are all significant enough that one can predict with considerable confidence that the next large tokamak, the D-T burning Tokamak Fusion Test Reactor (TFTR), will achieve its goal of plasma power breakeven (Q=1) and will begin to test the physics of burning plasmas.

The tandem mirror, though a relatively new concept, has been shown to operate approximately as predicted by theory in the tandem mirror experiment, TMX. The tandem mirror electrostatic potential configuration schematically

Table II-1

Design Parameters and "Typical" Plasma Properties for Major U.S. Tokamaks

Tokamak	a (cm)	$R_0 q$ (cm)	B_T[a] (kG)	I_p[a] (kA)	$T_e(0)$[b] (eV)	$T_i(0)$[b] (eV)	n_e[b] (cm^{-3})	τ_E[b] (ms)	$n_e \tau_E$ (Max. Poss.) ($cm^{-3} \cdot s$)
ST	13	109	50 (40)	130 (70)	2500	600	4×10^{13}	10	4×10^{11}
ATC[c]	17	90	20 (15)	100 (60)	1100	250	1.5×10^{13}	5	7.5×10^{10}
ORMAK	23	80	25	340 (170)	1500[d]	1800[d]	3×10^{13}	10	3×10^{11}
ALCATOR A	10	54	120 (80)	400 (200)	1200	800	7×10^{14}	20	1.4×10^{13}
DOUBLET II-A	14 x 40	66	10 (8)	320 (150)	400	200	2×10^{13}	4	1.2×10^{10}
PLT	45	130	45 (32)	1400 (550)	400[d]	7200	8×10^{13}	100	8×10^{12}
ISX	25	90	18 (12)	200 (230)	1500[d]	1400[d]	8×10^{13}	35	2.8×10^{12}
DOUBLET III	45 x 150	143	40 (20)	5000 (2000)	1000[e]	900[e]	6.7×10^{13}[e]	70[e]	4.7×10^{12}[e]
ALCATOR C	17	64	140 (100)	1000 (600)	2500	1500	6×10^{14}	30	1.8×10^{13}
PDX	45	145	24 (24)	500 (400)	2000[d]	2400[d]	1×10^{14}	70	7×10^{12}

[a]Design values (normal operating values in parentheses).

[b]Maximum obtained - not necessarily in same discharge.

[c]Before compression.

[d]With neutral beam heating.

[e]Self-consistent set at 1 MA and 24 kG.

shown in Fig. II-3 has been experimentally established [5]. The value of $\beta^2/2\mu_0$ has reached 20% in the central cell. Finally, confinement of electrons has been found to be better than in previous, single cell, mirror experiments.

Very recently, the Mirror Fusion Test Facility (MFTF) at Lawrence Livermore Laboratory has been modified to a larger tandem mirror experiment which should be in full operation in early 1985. The MFTF-B device (Fig. II-4) should achieve Q = 1 conditions with plasma confinement times of several seconds, a plasma density of 2 x 10^{13} particles per cm^3 and a mean ion temperature of 15 keV. A comparison of the main parameters of the major tandem mirror experiments around the world is given in Table II-2.

F. Tokamak Reactor Designs and the NUWMAK System

Tokamak conceptual reactor designs have been carried out to examine the technical problems presented by such machines and to assess the impact an economy of these reactors may have in areas like mineral resource requirements. For perspective, it is useful to examine four designs developed by the same group at the University of Wisconsin. These studies were conducted over a period of years as our understanding of fusion improved. The UWMAK-I design [6] was published in 1973, the UWMAK-II design [7] in 1975, the UWMAK-III design [8] in 1976, and the NUWMAK design [9] in 1979. Key parameters of these designs are summarized in Table II-3. One major feature which influences economics and minerals resource requirements is the overall size or power density of each device. Here, a major change has occurred as designs have been optimized, namely, the overall size has decreased sharply. It now appears that both UWMAK-III (5000 MW [thermal]) and NUWMAK (2300 MW [thermal]) are properly sized for their power output. The mineral resources required for an economy of NUWMAK reactors is greatly reduced compared to an economy of the earlier UWMAK-I and II systems.

The UWMAK-I system has a major radius of 13 m and a plasma radius of 5 m. The thermal power is 5000 MW and the electrical power is 1500 MW. The blanket and shield are constructed of 316 stainless steel and liquid lithium is the coolant. The superconducting magnets use NbTi superconductors embedded in copper and supported in a stainless steel structure. UWMAK-II has essentially the same physical dimensions and power parameters as UWMAK-I. It differs mainly in the blanket design where instead of using liquid lithium as both breeder and coolant, gaseous helium at 50 atm pressure is the coolant and the solid compound, lithium aluminate ($LiAlO_2$) is used as the breeder. For reasons of neutron transport, this design requires the use of a separate material to multiply the incident neutrons, because reactions with ^6Li are insufficient. Beryllium is neutronically ideal for this purpose. However, a resource study conducted in conjunction with UWMAK-II showed that this would not be feasible on a large scale [11] and has led us to avoid using beryllium in more recent work. UWMAK-III is smaller in physical size with a major radius of 8 m. It nevertheless is designed to generate the same thermal power. One goal of the study was to investigate the technical issues of using an advanced structural material (in the case, the molybdenum alloy TZM [99.4% Mo, 0.1% Zr, 0.5% Ti]). Liquid lithium is again the breeder and coolant. The

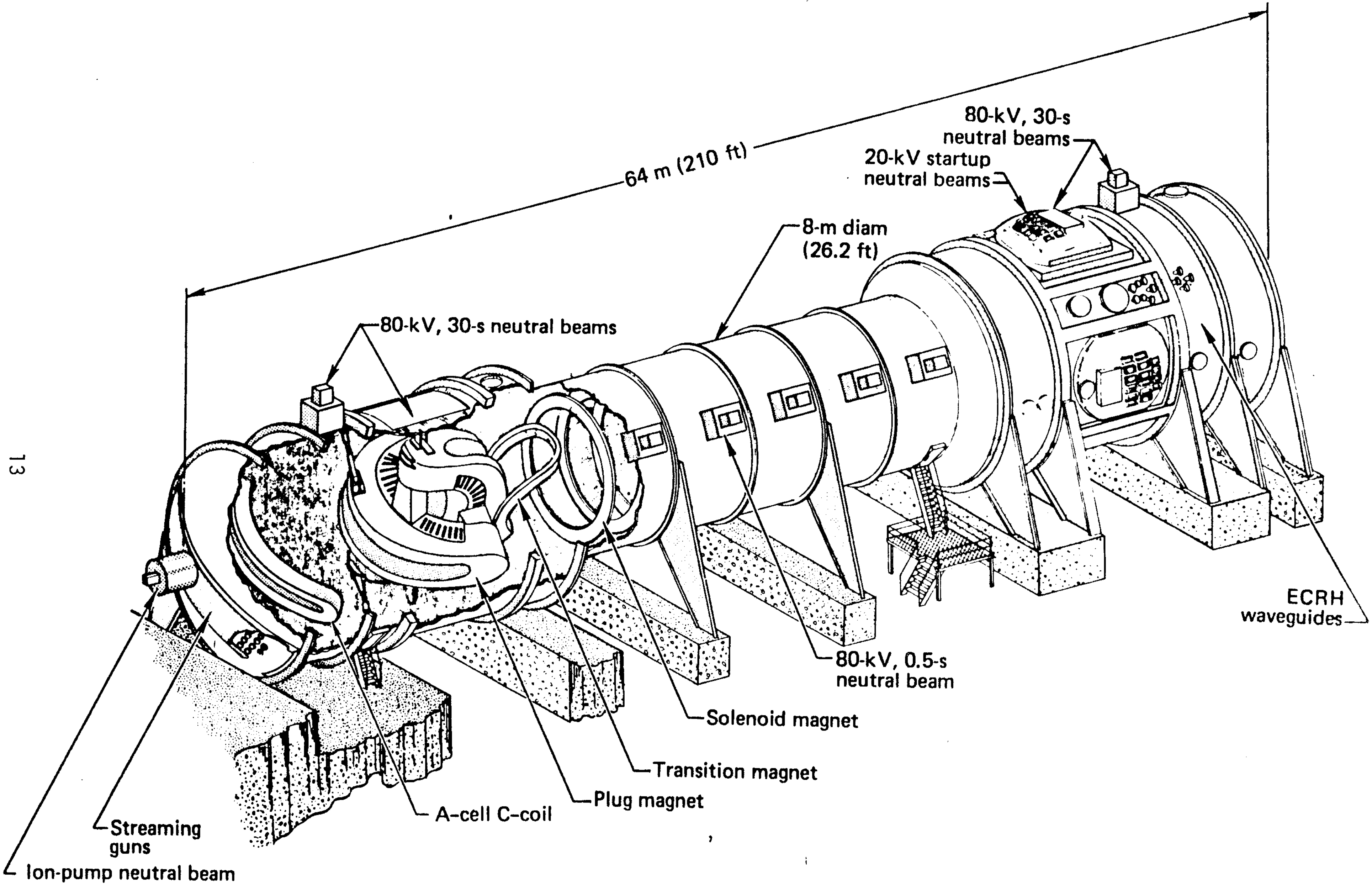


Figure II-4. MFTF tandem configuration.

Table II-2

Parameters of Major Tandem Mirror Experiments Around the World

	Gamma 6[1] JAPAN	TMX[1] USA	Phaedrus[1] USA	AMBAL[2] USSR	MFTF-B[2] USA
Plug					
B_0(kG)	4	10	3	12	20
B_{mirror} (kG)	10	20	6	---	40
R_p(cm)	4	10	7	12	48
$L_m$mirror - mirror (cm)	---	75	105	---	360
Heating method	Beam,RF,REB	Beam	Beam, ICRF	Beam	Beam/ECR
Heating power (MW)	0.5	9	0.6, 0.2	0.1	60/2
Duration (ms)	2.5	25	3	---	30 sec
n (cm^{-3})	5×10^{13}	5×10^{13}	5×10^{12}	3×10^{13}	5×10^{12}
W_i (keV)	0.4-10	26	2	20	375
T_e (eV)	20-2000	200	40	1000	90,000
$Q = Q_{DT}$					1
Solenoid					
B (kG)	1.5	0.5-2.0	0.5	2	15
$L_{plug-to-plug}$ (cm)	315	640	390	---	4000
R_p (cm)	2 x 20	30	30	30	30
n (cm^{-3})	1×10^{13}	1×10^{13}	5×10^{12}	1×10^{13}	2×10^{13}
W_i (eV)	---	80	200	500-1000	15,000
T_e (eV)	300	200	40	---	12,500
$n\tau$	2.5×10^{10}	2.5×10^{11}	10^{10}	---	5×10^{13}

1) in operation
2) under construction

Table II-3

University of Wisconsin Tokamak Conceptual Reactor Parameters

	UWMAK-1[6] (1973)	UWMAK-II[7] (1975)	UWMAK-III[8] (1976)	NUWMAK[9] (1979)
MACHINE PARAMETERS				
R(m)	13	13	8	5.2
a(m)	5	5	2.5	1.15
Plasma Height to Width b/a	1.0	1.0	2.0	1.6
Field at Plasma Center (T)	3.8	3.57	4.0	6.0
Max. Field at Magnet (T)	8.6	8.3	8.75	11.9
Fuel	DT	DT	DT	DT
PLASMA PARAMETERS				
Plasma Current (MA)	21	14.9	15.8	7.2
Safety Factor, q	1.75	2.3	2.5	1.09-2.6
Plasma Beta, β%	5	2.3	9	7
Aux. Heating Power (MW)	50	200	40	75-80
Type	Neutral Beam	Neutral Beam	RF	RF
Heating Time (s)	10	10	15	1
Burn Time (s)	5400	5400	1800	224
Dwell Time (s)	390	490	100	21
Duty Factor	0.93	0.80	0.95	0.91
POWER PARAMETERS				
Engineering Power Den. (W/cm^3)	0.4	0.3	1.1	1.1
DT Thermal Power (MW_t) (time averaged)	4650	4712	4735	2097
Net Electric Power (MW_t) (time averaged)	1473	1709	1985	660
Ave. Neutron Wall Load (MW/m^2)	1.25	1.16	2.5	4.34
Net Plant Eff. (%)	32	36	42	31

high allowable operating temperature for the structure (1000°C in Mo compared to 450-500°C in stainless steel) leads to a higher electrical power output (1985 MW_e net) and a net plant efficiency of 42%. The same superconductor is used in the magnets but the magnet structure is a high strength aluminum alloy instead of steel and the stabilizer is high purity aluminum instead of copper.

A cross section view of a recent conceptual design, NUWMAK, is shown in Fig. II-5. The plasma has an elliptically-shaped cross section and is surrounded by a blanket and shield. The blanket serves to absorb 99% of the neutron energy from each D-T reaction and to breed tritium. The shield is to minimize radiation leakage and heating of the superconducting magnets. The reactor itself has a major radius of 5.15 m and a plasma radius of 1.15 m. The diameter of the unit measured from the outside edge of the toroidal field magnets is 21 m. The time averaged DT thermal power is 2097 MW and the electrical output, after accounting for internal power requirements to operate the unit, is 660 MW_e. The power cycle is based upon a direct boiling water reactor cycle and the estimated net plant efficiency is 31%. The power density, defined as the thermal power divided by the plasma volume, is 9 MW/m^3 (more than ten times the value in UWMAK-I). The engineering power density, defined as the thermal power divided by the volume of the nuclear island (everything inside and including the transformer windings), is 1.1 MW/m^3 and the specific power, defined as the thermal power divided by the mass of the nuclear island, is 98 W/kg.

The structural material in the NUWMAK design is the titanium alloy, Ti-6Al-4V, the breeding material is the eutectic $Li_{62}Pb_{38}$, and the coolant is boiling water. The vertical section of blanket and shield nearest the device centerline (and referred to as the inner blanket/shield) is approximately 1.1 m thick. The outer blanket is somewhat thicker because space is more plentiful and design conditions can be relaxed. The main toroidal field (TF) coils use NbTi superconductor cooled with superfluid He at 1.8 K to produce a field at the plasma of 6 T and a peak field at the coil of 11.9 T. The primary superconducting transformer coils located outside the TF coils are referred to as ohmic heating (OH) magnets. There are several superconducting vertical field (VF) coils outside the TF magnets and four nonsuperconducting but cryogenic aluminum VF magnets inside them. This avoids the Gordian knot problem of interlocking rings and permits the four internal magnets to have demounting joints so that each coil can be removed in segments.

CROSS-SECTIONAL VIEW OF NUWMAK

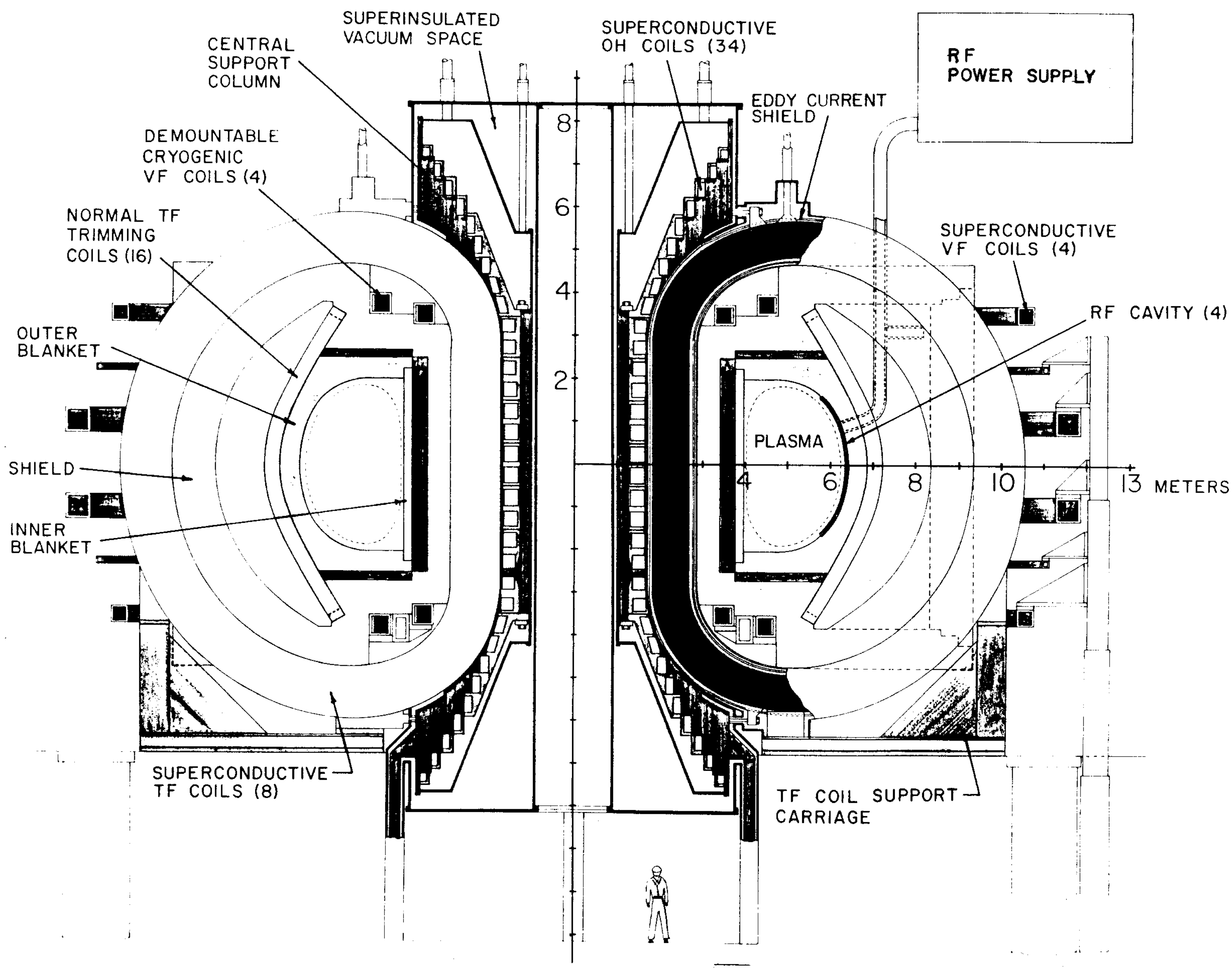


Figure II-5

III. Where Does Fusion Fit in Future Energy Scenarios?

The United Nations projected increase in world population from 4 billion now to 8 billion shortly after the turn of the century (and eventually to a "steady-state" value of 12 billion in the latter half of the 21st century) will clearly put pressure on world energy supplies. When this world population increase is coupled to the increase in the average energy use per capita desired by third world nations, the result will be a large increase in energy use above the present level. (The present world average is 2 kW/capita and is moving towards 3 kW/capita as the standard of living is raised in less developed nations.) It is probable that the total annual energy usage rate in the non-communist world will be 2 to 3 times the present level of 2×10^{20} Joules/year after the turn of the century [12] (See Fig. III-1).

There is a trend toward the use of more energy in the form of electricity. At present, electricity accounts for about 33% of total worldwide energy consumption up from the value of 15% in 1950. In the year 2000, the electrical fraction is projected to be about 40% worldwide (see also Fig. III-1).

To estimate the fraction of the world and United States electrical markets that might be captured by fusion, it is necessary to make many assumptions and for this study, the following are made:

1. *The earliest that the first commercial fusion plant could be available is 2010.*

2. *The OECD "present trend" predictions of world and United States total and electrical generating demand [12] for the non-communist world will be used beginning in 2010. These predictions are summarized in Table III-1.*

3. *The energy growth rates are assumed to follow the pattern given in Table III-2.*

4. *The penetration rate of fusion into the electrical generation market will be based on the rate at which fission power has penetrated the electrical generating market. The historical data for the last 15 years [13] as well as future projections [12] can be approximated by the curves shown in Fig. III-2. As a high case, the fraction of new additions supplied by fission reactors is projected to increase from 0 to 60% during a 50-year period. For a low case, the new additions supplied by fission reactors levels at 30% after 30 years. The uncertainty in the penetration curve for fission reactors after a 30-year period is likely to be large and the high case may in fact represent an optimistic upper bound. However, to assess the potential impact of fusion on resource requirements, the high value is used in the analysis to follow. In fact, the high market capture rate for fusion may be a reasonable assumption given the uncertainty over the future of the fission breeder reactor (particularly in the United States) and the fact that very few thermal fission reactors are likely to be built beyond the turn of the century.*

Figure III-1

PROJECTED WORLDWIDE ENERGY REQUIREMENTS-NON COMMUNIST COUNTRIES

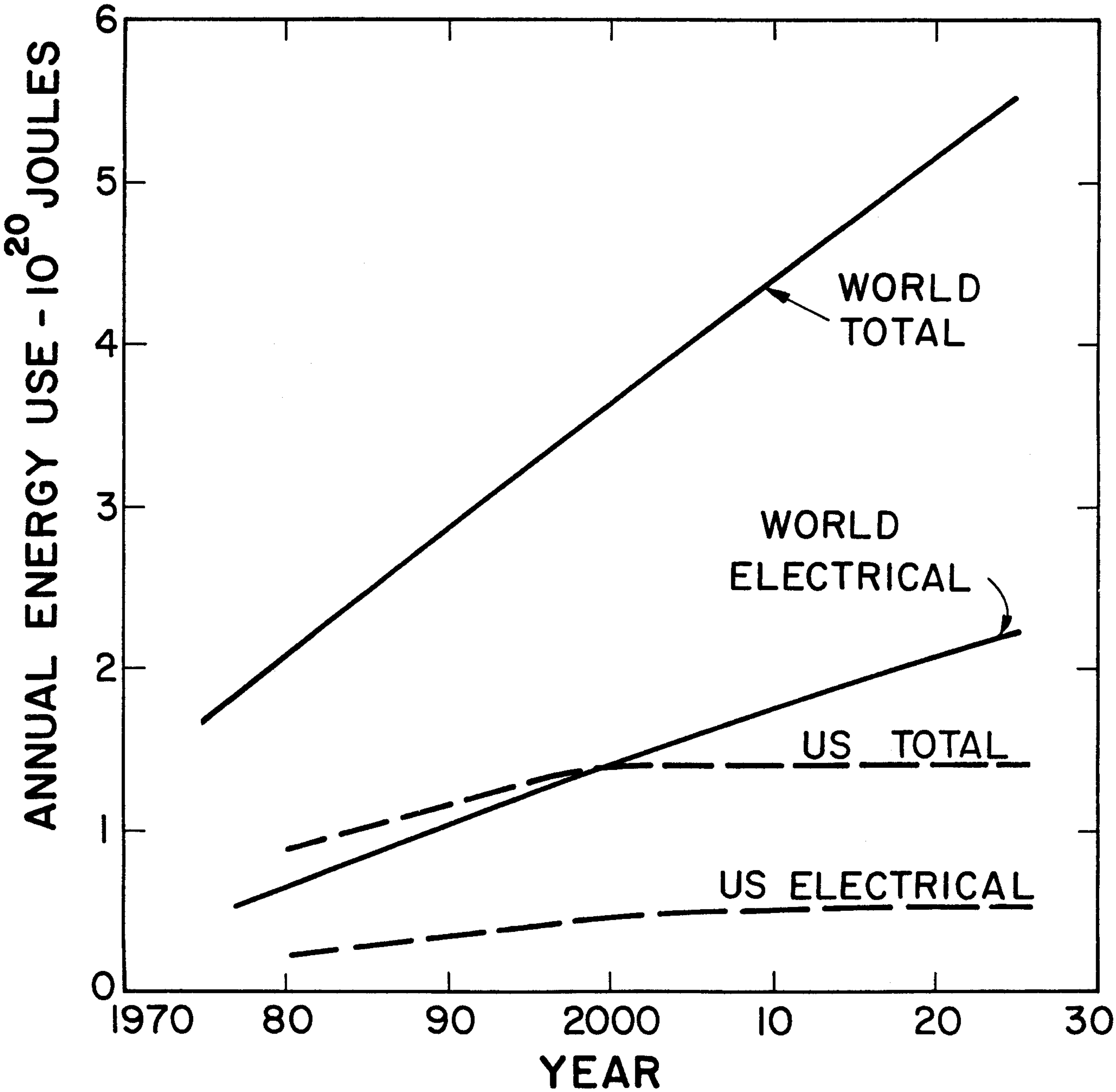


Table III-1

OECD Predictions of Free World and United States Total and Electrical Energy Demand [12] in 2010

	World	U.S.
Total annual energy demand (Joules/year)	4.85×10^{20}	1.47×10^{20}
Total energy required for electricity generation		
(Joules/year)	1.78×10^{20}	5.78×10^{19}
(TWh)	1.65×10^{4}	5.4×10^{3}
Installed electrical capacity (GW_e)	4×10^{3}	1.1×10^{3}

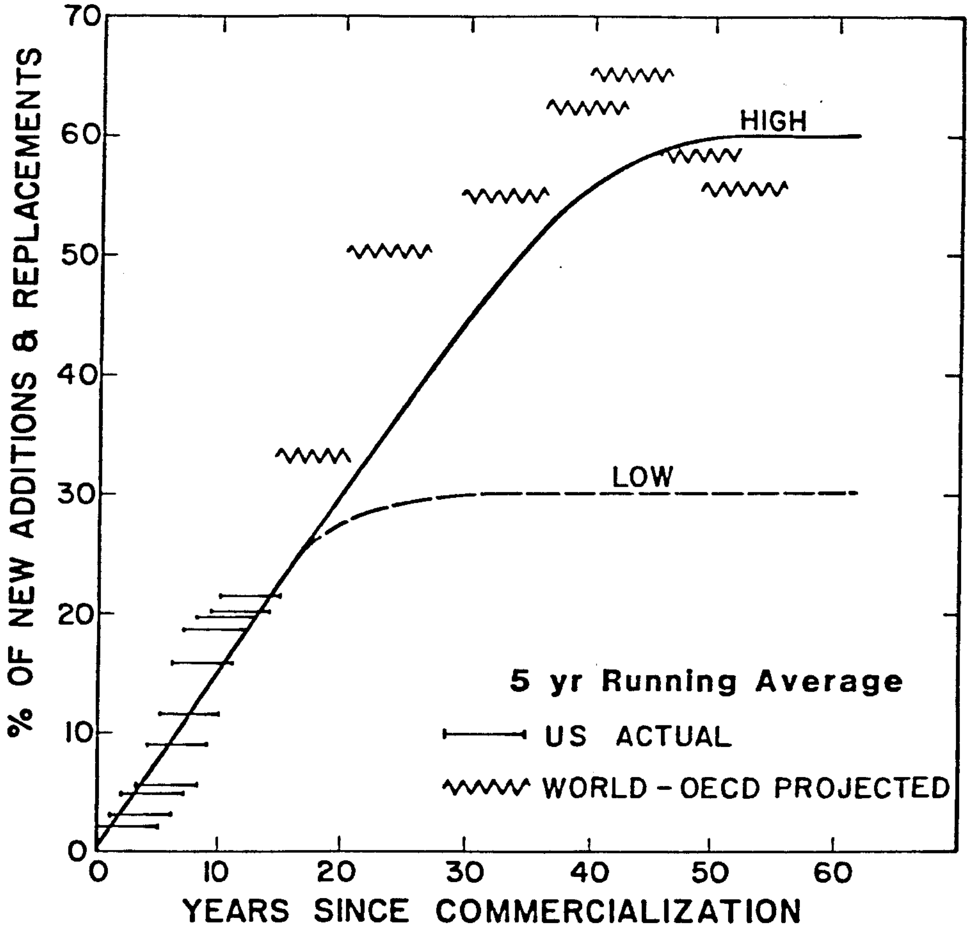
Table III-2

Assumed Growth Rate Pattern for Total Energy and that used for Production of Electricity [see Ref. 12]

	Total Energy Growth Rate, %		Electrical Energy Growth Rate, %	
	World	U.S.	World	U.S.
1975-1980	3.9	3.0	4.7	3.6
1980-1985	3.7	3.0	4.7	3.3
1985-1990	3.3	2.5	4.2	3.2
1990-1995	2.7	1.6	4.0	3.1
1995-2000	2.7	1.6	2.8	1.6
2000-2005	1.6	0	2.0	0.4
2005-2010	1.6	0	2.0	0.5
2010-2015	1.6	0	1.6	0.4
2015-2020	1.6	0	1.6	0.4
2020-2025	1.6	0	1.6	0.3
2025-thereafter	1.6	0	1.6	0.3

Figure III-2

ACTUAL AND ANTICIPATED PENETRATION OF ELECTRICAL GENERATING CAPACITY BY FISSION REACTORS



5. *The life of any electrical plant is 30 years. The new additions in any given year are the sum of those needed to match the growth rate and those built to match plant retirements.*

With these assumptions, one finds that the fusion reactor capacity as a function of time would follow the pattern given in Table III-3. The projected electrical generating capacity, both total and from fusion alone, is given in Fig. III-3. The fusion projections differ significantly from those in a scenario developed in 1973 [14], prior to the Arab oil embargo and the down turn in energy growth curves. It was projected in the earlier study that the fusion contribution to world electrical generating capacity would reach 1000 GW_e by the year 2020 [14]. In the present study, this number is reduced to 120 GW_e in 2020. The reduced capacity stems from three factors: the later anticipated commercialization date (2010 vs. 2000 in ref. 14); the lower penetration rate and a lower anticipated asymptotic value for the fraction of new additions by fusion plants, and the overall reduced energy growth scenario for the world as a whole.

In order to assess the potential impact of fusion in the 21st century, we have somewhat arbitrarily settled on 300 GW_e as the installed United States fusion capacity for a base point from which other installed capacities can be scaled. The sensitivity of our results to changes in this level is tested by considering the installed capacity as 1000 GW_e. As an illustration of the shortest time to reach each of these levels we have used the high penetration rate scenario. For the United States, one reaches 300 GW_e in 2042 and 1000 GW_e after 2070. For the free world (including the United States), the level of 300 GW_e is reached in 2027 and 1000 GW_e in 2040.

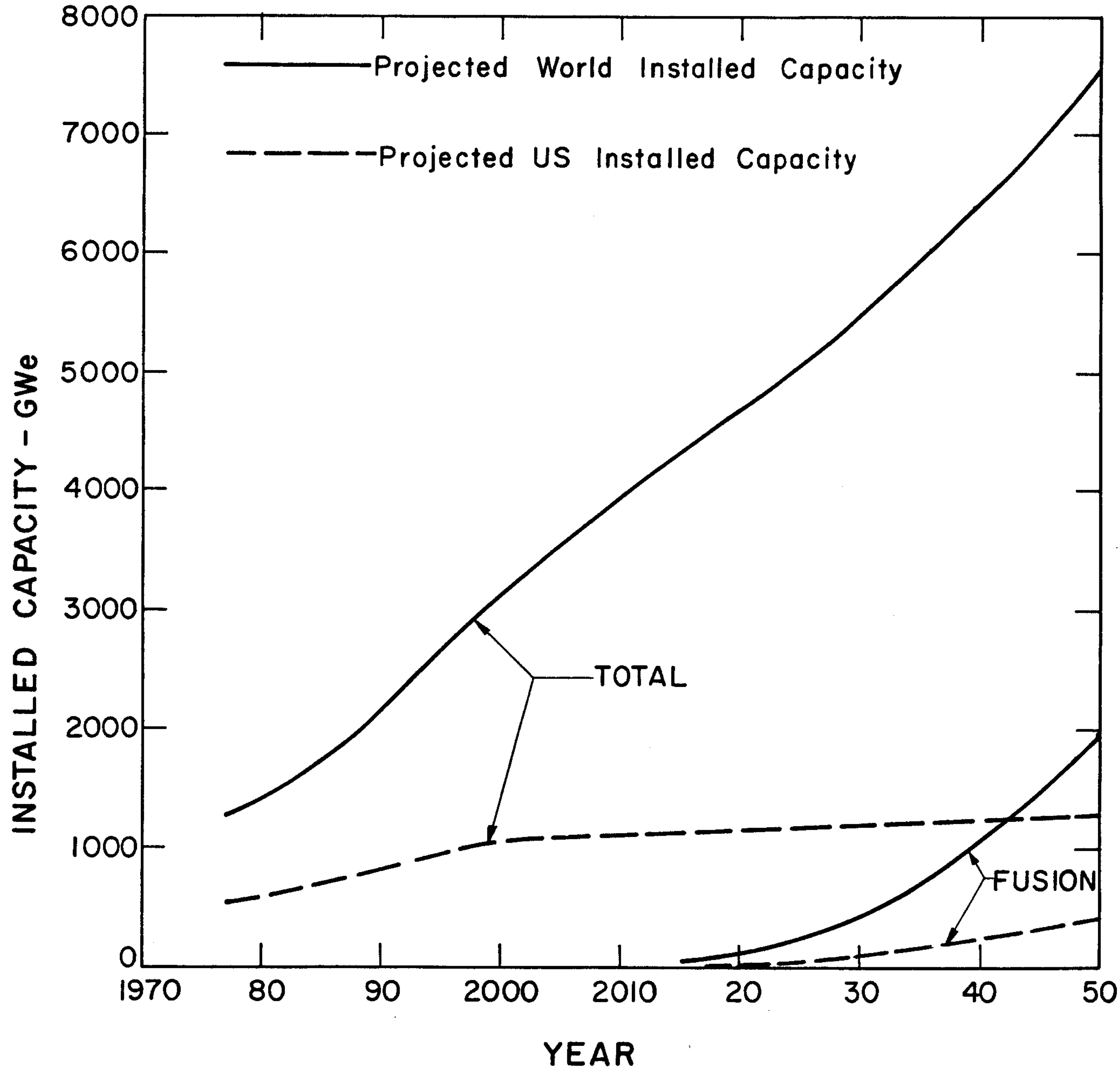
Table III-3

Assumed Growth Pattern for Fusion Power in this Study

Year	Generation Capacity/From Fusion (GW_e)	
	Non Communist World	U.S.
2010	1	1
2015	36	12
2020	118	38
2025	251	85
2030	443	129
2035	711	202
2040	1054	271
2045	1479	348
2050	1990	451

Figure III-3

PROJECTED WORLD-WIDE ELECTRICITY REQUIREMENTS - NON COMMUNIST COUNTRIES



IV. Major Impact of a Fusion Economy in the 21st Century

A. Costs

Because of the rapidly changing situation in world fossil fuel and uranium prices, it is difficult to accurately project future electrical generating costs even of our present coal and fission plants. It is also impossible to anticipate the effect of cartel formations in the mineral resource area or the effects of political instabilities on the non-fuel related costs of energy. Nevertheless, energy costs will play an ever increasing role in determining the standard of living of both developed and developing nations. We need, therefore, to have some qualitative idea of how a move toward fusion might affect at least the cost of electricity.

Consistent with the general nature of this article we approach the costs of fusion from a very generic standpoint. The costs can be conveniently divided into three categories; capital, fuel, and operation plus maintenance (O&M). In the past 6 years there have been at least six detailed cost analyses of large scale tokamak fusion reactor designs [6-10,15], all of which have shown that the O&M costs of fusion reactors will likely be minimal compared to the total costs. In fact, they will be comparable to O&M costs for fission reactors. The fuel costs have also been shown to be extremely small, a point we cover in a moment. One important conclusion from the past work is that fusion power plants will be considerably more capital intensive than fission reactors.

An illustration of this feature is shown in Fig. IV-1 where the relative costs of electricity are shown for coal, LWR's, LMFBR's and DT fusion plants. Whereas almost 40% of the total cost of electricity from coal-fired plants comes from the fuel, these fuel costs drop to roughly 20% of the electricity costs for LWR's, less than 10% for LMFBR's and less than 2% for fusion reactors. We shall see in a moment that this capital intensive feature of fusion has both its good and bad attributes.

Perhaps the best way to put the projected absolute costs of electricity from fusion into perspective is to compare one of the most recent studies (NUWMAK) to current projected costs of coal, LWR and LMFBR plants.

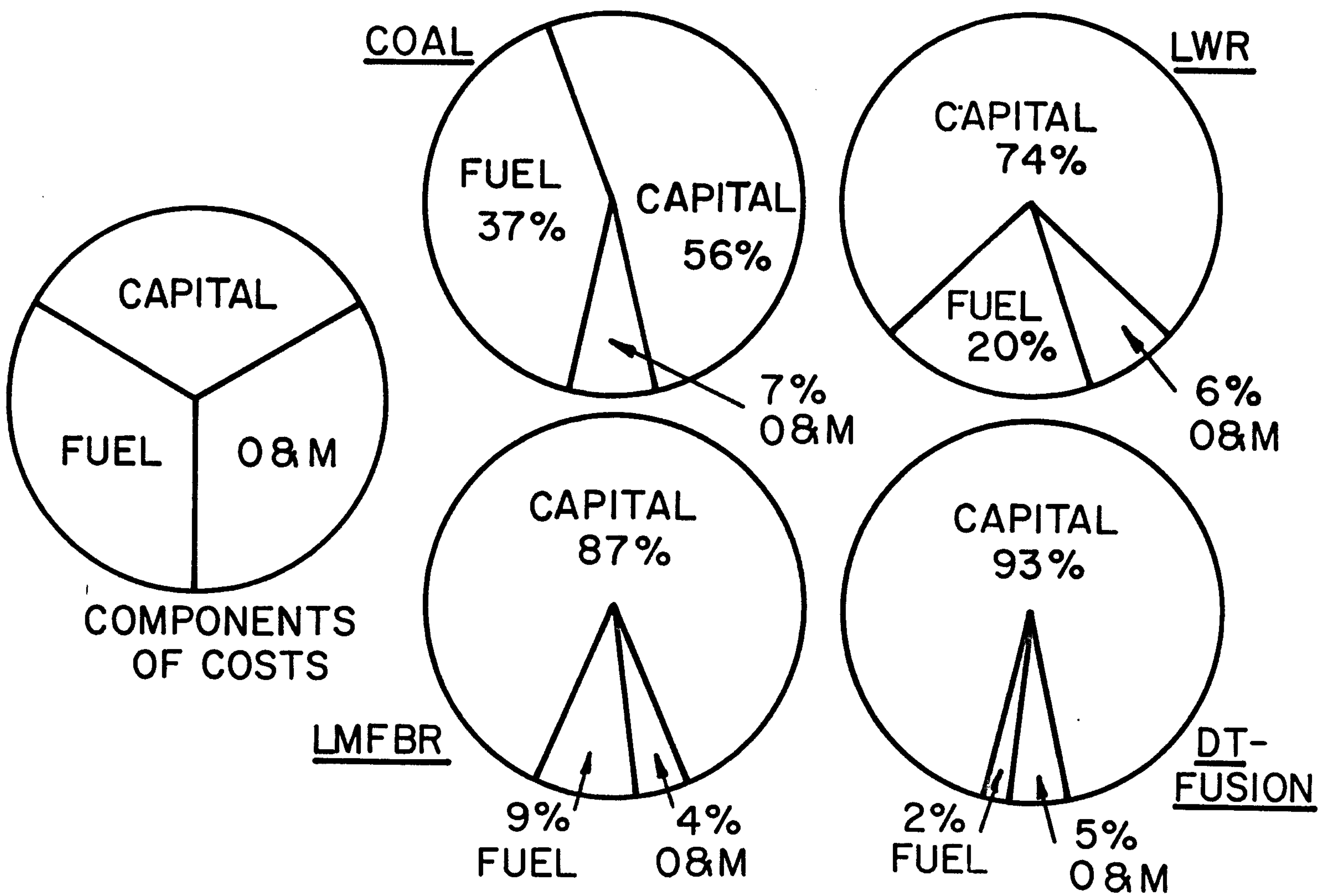
For cost comparisons, we consider the capital costs for the four systems assuming initial plant operation in 1990. Results of the estimates are summarized in Figure IV-2 (in 1990 dollars) [16,17]. This figure shows that coal plants have capital costs of ~ 1400 $\$/kW_e$ while LWR's have costs in the 1900 $\$/kW_e$ range. The LMFBR costs are speculative at this time but appear to be roughly 1.5 times LWR capital costs. Finally the costs of most recently designed fusion plants appear to be in the 3700 $\$/kW_e$ range.

The fuel costs for the four systems are given in Fig. IV-3. Here we see a complete reverse of the previous capital cost relationships with fusion now having the lowest costs and coal the highest.

When the operation and maintenance costs of 6, 4, 4, and 5 mills per kWh for coal fired systems, LWR's, LMFBR's and fusion reactors respectively, are

Figure IV-1

BUSBAR COST OF ELECTRICITY



Fusion - NUWMAK, 1978
Source for LWR and Coal - Rossin, Science 1978
LMFBR - Kennedy - AIF Forum, Feb. 1979

Figure IV-2

CAPITAL COSTS OF ELECTRICITY PRODUCING POWER PLANTS

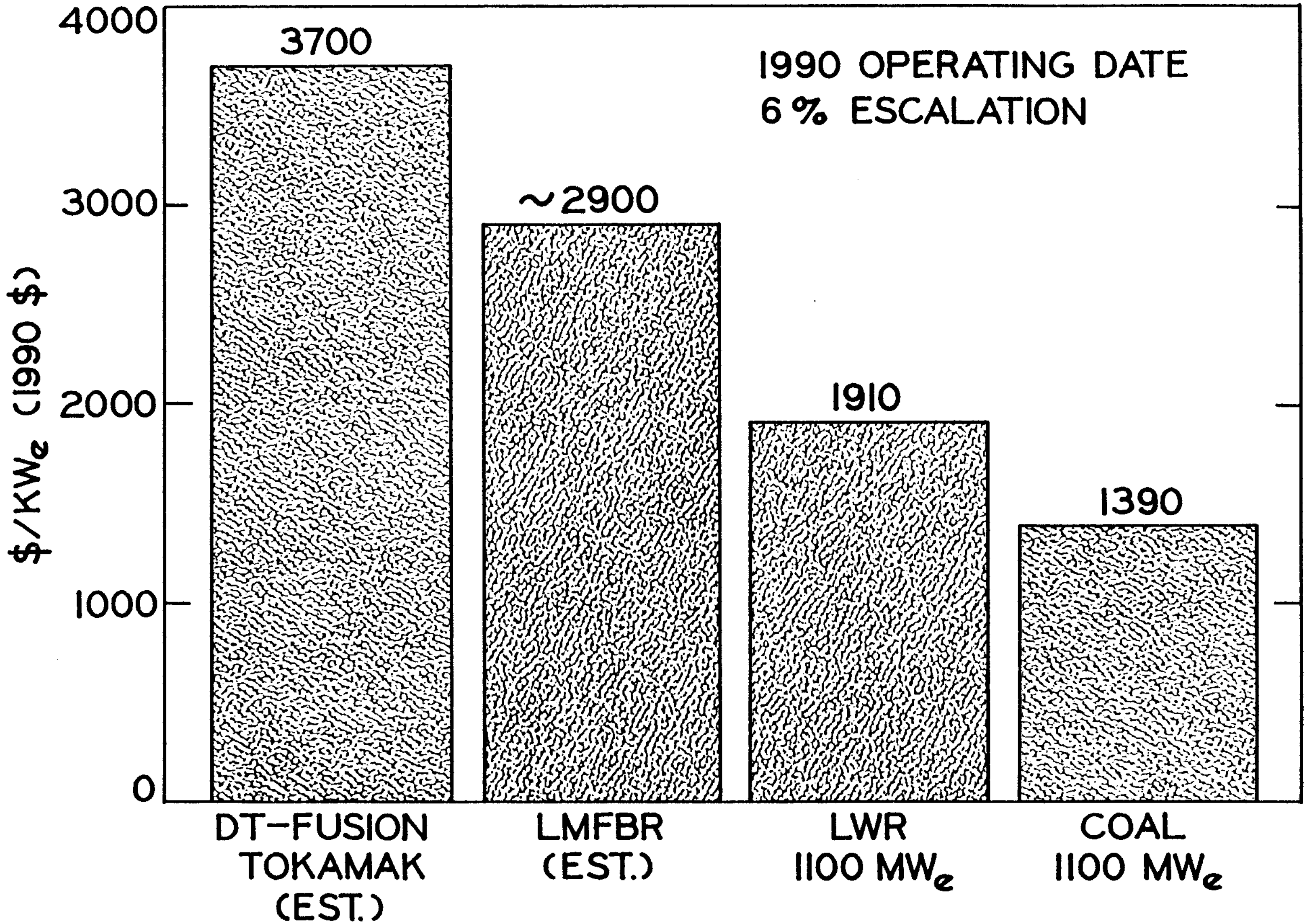
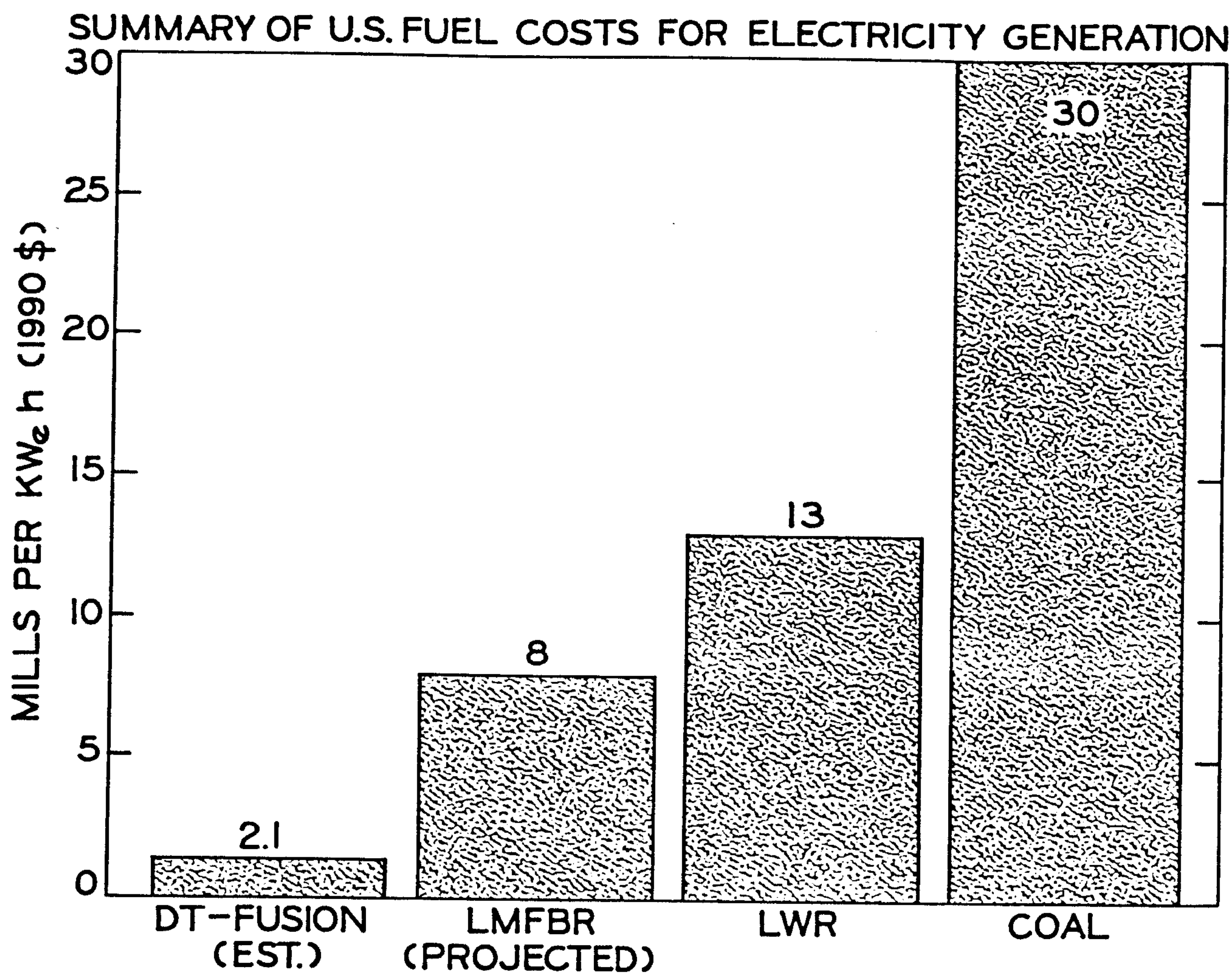


Figure IV-3


SUMMARY OF U.S. FUEL COSTS FOR ELECTRICITY GENERATION
MILLS PER KWe h (1990 $)
30
25
20
15
10
5
0
2.1
8
13
30
DT-FUSION (EST.)
LMFBR (PROJECTED)
LWR
COAL

added to the previous costs, the total busbar cost of electricity can be calculated. (See Fig. IV-4.)

As would be expected, the LWR's are somewhat cheaper than coal-fired plants and LMFBR's might be a bit more expensive. The fusion costs of 117 mills per kWh are only 18% higher than the LMFBR and at this early stage of fusion reactor design, such a relatively small difference is encouraging.

The data in Fig. IV-4 may be a bit misleading because they are based on current costs of fuel (with a modest amount of escalation) and do not reflect the expected depletion of U resources at the turn of the century. When this happens, the breeder would become the only fission option. Further- more, since the electricity costs for the breeder are rather insensitive to the cost of U, the LMFBR costs should rise at a lower rate than those for LWR's. Mine safety requirements, environmental equipment on coal plants, and land use restrictions will also have a big effect on increasing coal prices. Since the cost of electricity from coal plants is so sensitive to fuel costs, it is expected that future increases in electricity costs from such plants will be faster than the general rate of inflation.* For fusion, exactly the opposite situation exists. Because electricity from fusion reactors is insensitive to the fuel costs (Fig. IV-3) even increases far above the inflation rate will have little effect on total electrical costs.

Perhaps the best way to illustrate this point is to calculate the 30-year levelized cost of electricity from the four sources considered. This will bring out the advantages of a capital intensive system (like fusion and the LMFBR) in an economy which has rampant increases in fuel costs. We consider the case where the fuel costs increase up to 8% faster than the general infla- ation rate after the plant starts up.

The calculated 30-year levelized costs are given in Fig. IV-5 and it can be seen that if the escalation rate of fuel exceeds 4% above the general inflation rate, fusion reactors will become in fact more economical than coal-fired plants and the differential between fusion and the LMFBR will be significantly reduced. (Remember that the LWR's probably cannot compete with fusion in the early 21st century because of dwindling U resources.) Hence, while the high capital costs of fusion may present an early problem of investment funds, this feature may turn out to be a big advantage if fossil fuels keep rising faster than inflation.

In summary, while current estimates of electrical costs from fusion power plants are somewhat higher than its potential competitors in the early 21st century, the difference is not overwhelming. In fact, the long range economic picture is rather promising for fusion. Its relative insensitivity to fuel prices gives it a welcome insulation from the rapid fluctuations in the

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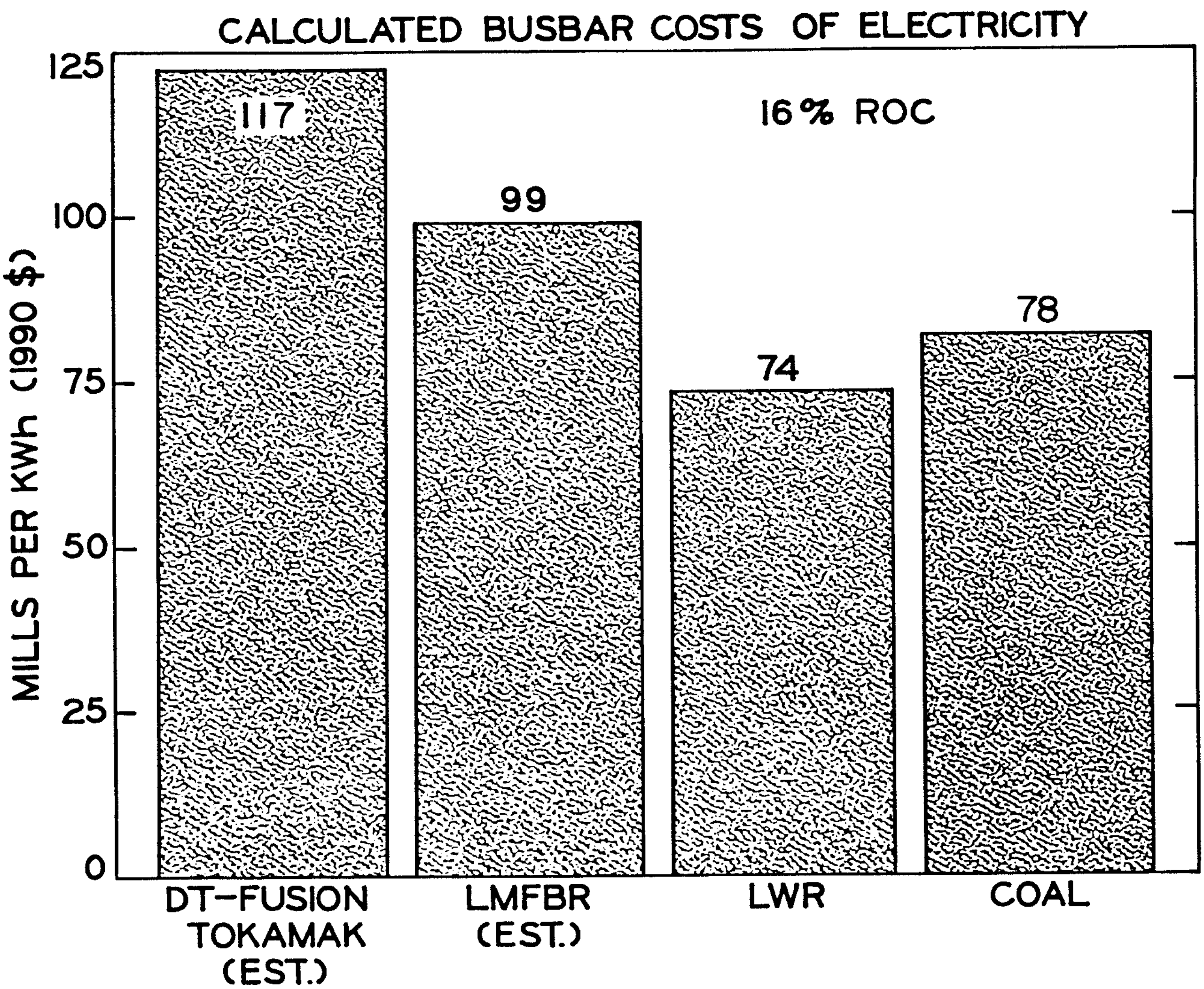
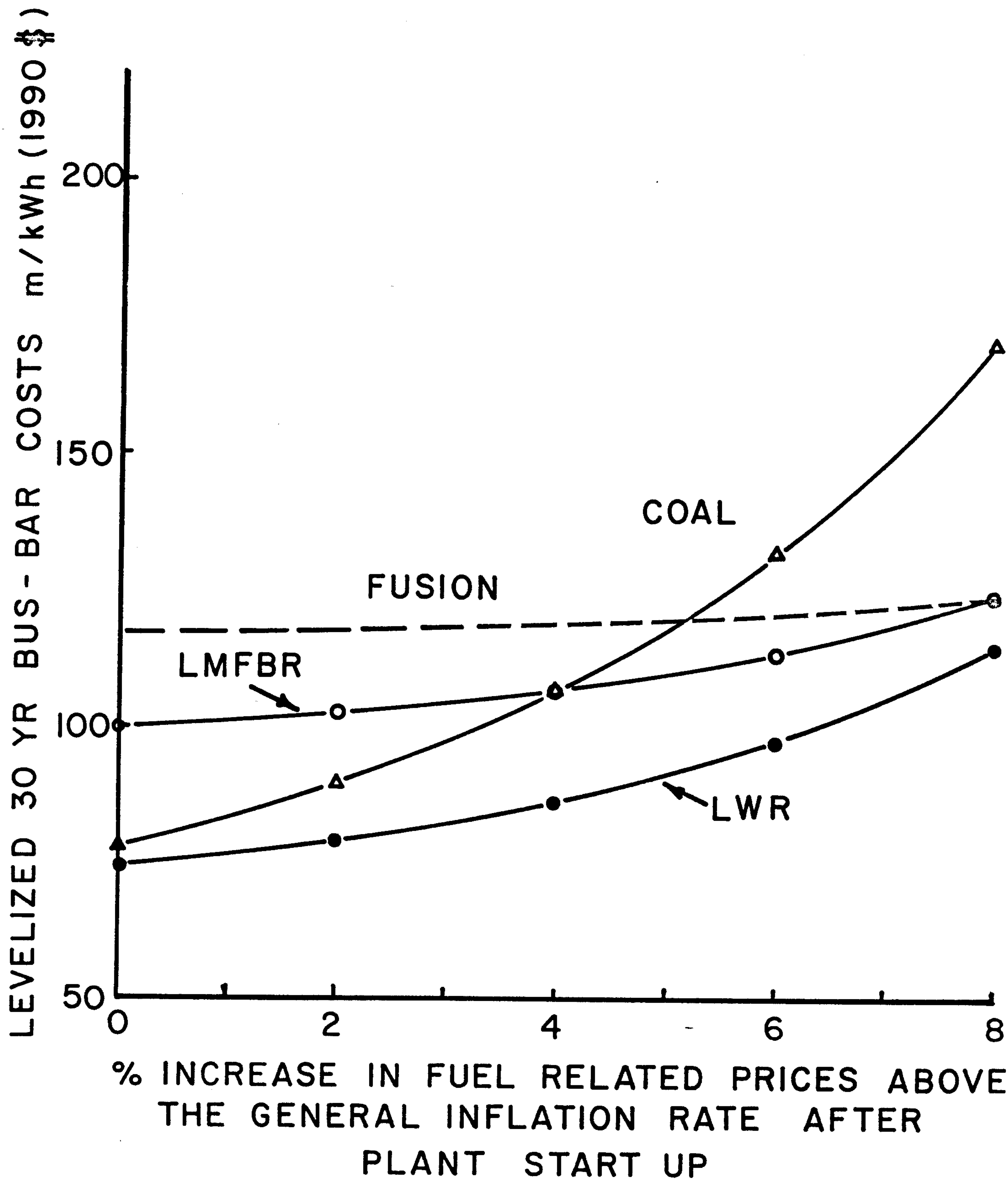
*Coal prices have doubled since 1973 while inflation during that period was 60%. Coal prices have risen ~ 50% in the period from 1976 to 1979 while the consumer price index has increased only 30%.

Figure IV-4



CALCULATED BUSBAR COSTS OF ELECTRICITY
16% ROC
MILLS PER KWh (1990 $)
125
100
75
50
25
0
117
99
74
78
DT-FUSION TOKAMAK (EST.)
LMFBR (EST.)
LWR
COAL

Figure IV-5


LEVELIZED 30 YR BUS-BAR COSTS m/kWh (1990 $)
200
150
100
50
COAL
FUSION
LMFBR
LWR
0
2
4
6
8
% INCREASE IN FUEL RELATED PRICES ABOVE THE GENERAL INFLATION RATE AFTER PLANT START UP

domestic and world markets. Continued updating of the financial side of fusion reactors is important to bring out this potential advantage.

B. Mineral Resource Requirements and Substitutability Factors

Because of the relatively low power density in fusion reactor systems, they tend to require more materials than their fossil or fission reactor counterparts. Therefore it is instructive to examine the potential impact of a large scale move to a fusion economy with respect to the demand for minerals. We will use more recent tokamak reactor designs to illustate the general features of this issue, and the reader can easily extrapolate the results to other reactor designs once their materials inventories have been stated.

1. Mineral Resource Requirements of Tokamak Reactors

The resource requirements for a 300 GW_e economy of the UWMAK, NUWMAK, and HFCTR*-type reactors have been considered [11]. It has been assumed for the purposes here that NUWMAK can be constructed of alternative structural materials without major changes in design to permit a broadly based survey. The alternative alloys are 316 stainless steel (the primary structural alloy of the fusion program at this time), Tenelon stainless steel (a nonmagnetic steel without nickel or molybdenum), HT-9 (a ferritic steel), and the vanadium alloy, V-20 Ti. The vanadium alloy is assumed to be used throughout the power cycle. For reference, the compositions of the various structural alloys we have considered are summarized in Table IV-1.

The material requirements have been determined for an entire NUWMAK reactor system including the nuclear island (blanket, shield, magnets, vacuum systems, etc.) and the balance of plant (heat exchangers, turbines, pumps, buildings, etc.). A breakdown of requirements for the nuclear island and balance of plant for NUWMAK with various structural materials has been made [11]. The total requirements in tonnes per MW_e are summarized for all systems in Table IV-2. The requirements for UWMAK-III and all forms of NUWMAK are substantially less than requirements posed by UWMAK-I and II for the materials Cr, Cu, Fe, Pb, Si, Mn, Mo, and Ni. Increased amounts of Al, B, C, Mo, W, V, and Co are required by NUWMAK but the overall effect is a significant decrease in the total bill of materials. Requirements are comparable for UWMAK-III and HFCTR and the various forms of NUWMAK except in the following cases:

1. Chromium: Substantially more chromium is required for the HFCTR because of the extra steel structure required for very high toroidal field magnets.

2. Copper: Substantially more copper is required in HFCTR again because of its use in larger quantities as a stabilizer in high field magnets.

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*HFCTR - High Field Controlled Thermonuclear Reactor designed by MIT.

Table IV-1

Composition of Structural Alloys

Typical Alloys	Typical Primary Constituents
Ti-6Al-4V	90% Ti, 6% Al, 4% V
316 Stainless Steel	65% Fe, 11% Ni, 18% Cr, 1.5% Mo, 2% Mn, 0.8% C
Tenelon	69% Fe, 17% Cr, 14.5% Mn, 0.3% Si, 0.045% P, 0.03% S, 0.08% C
HT-9	85.25% Fe, 11.5% Cr, 1% Mo, 0.5% Ni, 0.5% W, 0.5% Mn, 0.3% V, 0.2% C
V-20Ti	80% V, 20% Ti

Table IV-2

Total Estimated Material Requirements of Tokamak Reactors [11]
(Tonnes/MW_e)

	UWMAK-I 316 Stainless Structure	UWMAK-II 316 Stainless Structure	UWMAK-III Mo Structure	NUWMAK Ti-6Al-4V Structure	NUWMAK V-20Ti Structure	NUWMAK 316 Stainless Steel Structure	NUWMAK Tenelon Structure	NUWMAK HT-9 Structure	HFCTR (MIT) Mo Structure
Li*	1.15	0.57	0.24	0.18	0.18	0.18	0.18	0.18	0.54
Al	0.54	1.34	2.42	2.363	2.282	2.282	2.282	2.282	0.40
B	1.07	2.50	0.47	2.254	2.254	2.254	2.254	2.254	
C	0.30	1.47	8.95	1.104	1.104	1.104	1.104	1.104	0.36
Cr	7.92	8.44	1.08	0.350	0.260	0.5993	0.5872	0.4515	5.14
Nb	0.10	0.10	.06	0.0756	0.0756	0.0756	0.0756	0.0756	0.09
Cu	7.27	6.54	0.98	1.195	1.195	1.195	1.1865	1.195	5.71
He	0.09	0.05	0.06	0.21	0.21	0.21	0.21		0.233
Fe	77.82	53.88	60.28	59.926	53.163	53.163	53.163	57.679	76.08
Pb	13.90	11.6	1.82	2.858	2.858	2.858	2.858	2.858	
Mn	0.82	0.46	0.46	0.0535	0.0339	0.0813	0.0813	0.0813	0.55
F									0.51
Sn									0.024
Mo	0.40	0.29	4.08	0.0686	0.0296	0.0885	0.0686	0.0579	5.21
Ni	5.91	3.18	0.67	0.328	0.328	0.5087	0.328	0.3322	3.79
Na	11.99	5.74	1.0						
Ti	0.05	0.07	0.05	1.2991	1.107	0.0535	0.0535	0.0535	0.08
Y	0.003	0.0017	?<.001						
Zr	0.07	0.058	0.01	0.0317	0.0317	0.0317	0.0014	0.0014	0.006
He				0.21	0.21	0.21	0.21		0.233
Be	--	0.25	--				Initial inventory only →		0.09
Co	--	--	0.003	0.0682	0.0682	0.0682	0.0682	0.0682	0.07
Mg				0.0083	0.0083	0.0083	0.0083	0.0083	0.002
V				0.1182	4.2945	0.0652	0.0652	0.0377	
W				1.0506	1.0506	1.0506	1.0506	1.0551	

* Includes burnup during 30 y life of plant.

3. Graphite: Graphite requirements are substantially higher in UWMAK-III because of a unique blanket design which calls for graphite to be used inside the vacuum vessel to moderate neutrons before they reach the structure. The lifetime of this graphite is only one year so the large requirement reflects the makeup requirements throughout plant life if no recycle is assumed.

4. Molybdenum-Vanadium: The Mo requirements in UWMAK-III and HFCTR and the V requirements in NUWMAK are large only when an alloy of these materials is used as the primary structural alloy for the reactor.

5. Beryllium: The requirement in UWMAK-II and the HFCTR relates to the use of beryllium as a neutron multiplier. Lead is a ready substitute in the UWMAK-II design. The molten salt FLIBE ($2LiF \cdot BeF_2$), used as a coolant in HFCTR would have to be replaced or an alternate blanket design adopted.

6. Tungsten: The tungsten requirement in NUWMAK is related to its use as a neutron shielding material. While it is best from a neutronics viewpoint, lead is a ready substitute if tungsten requirements are excessive (albeit at a somewhat increased shield thickness).

The availability of mineral-derived materials for any purpose is a function primarily of three factors:

1. The size and quality of United States and world mineral resources;

2. United States and world extractive capacity, i.e., capacity for mining, smelting, and refining or other processing required for extracting metals or minerals from their ores;

3. United States and world capacity for fabricating materials into forms suitable for use.

The first item sets fundamental limits on the amount of material that can become available. The second and third determine, within the limits set by the size and quality of resources, the amount of material that can actually be furnished by industry, in usable forms, within a given period. In forecasting future availability, two other factors, lead time and the energy cost of metals production, must also be taken into account.

At any given time, resources of metals and other minerals are divisible into two classes, reserves and other resources. Reserves of a metal are tonnages of that metal contained in mineral deposits that have already been discovered, have been explored and sampled sufficiently so that tonnage of ore and contained metal can be calculated within acceptable limits of accuracy, and have been judged to be mineable within the present economic, social, and political framework of society. Reserves, therefore, are amounts of metals actually available to man under current conditions. Other resources are a very different matter. In part they consist of metals contained in mineral deposits that have already been found but for one reason or another are not really available at present. They may be too low in metal content to be economic, they may present extractive problems as yet unresolved, they may be in areas where mining is forbidden for social or environmental reasons, or they may be insufficiently explored and sampled, so that tonnages of metals present are still uncertain. The earth's crust, however, is still only partly explored, hence the inventory of mineral resources is incomplete. There certainly are other resources still to be found by exploration in the future. Many estimates of other resources therefore include estimates of undiscovered resources, the estimates being made on geological grounds. These have some value but must be used with caution.

In Table IV-3, estimates of resources of metals and of helium are given. For each metal, two figures are given, one for reserves at present prices, the other for reserves at 3X present prices. The latter, of course, are not reserves at present but could become reserves with an increase in price. Estimates of reserves at present prices are based on a large amount of information. The estimates are approximations, because they include some materials that do not conform strictly to the definition of reserves given above. They indicate, however, the magnitude of United States and world reserves of metals with sufficient accuracy for present purposes. The figures for reserves at 3X present prices include only tonnages estimated to be present in deposits already discovered and explored and sampled to some extent. However, the data from which these figures are derived are uneven in amount and quality, and figures given for some metals involve a factor of personal judgment. In general, they should be taken to indicate only orders of magnitude which might be available at the higher prices.

Data for total extractive capacity of the United States and free world mining and metallurgical industry are not readily obtained but working capacity is indicated, for any year, by data for metal production. Data for 1978 are given in Table IV-3. For the United States, data are given for production from domestic ores and scrap and for total production (which includes production from imported ores and concentrates). For any metal, comparison of the two indicates the degree to which United States production is supplied from domestic sources. For the world, production figures are only for production from newly mined ore. Production from scrap metal is not included. There is substantial production of iron, copper, aluminum, lead, chromium, and nickel from scrap. Exact figures are not available. Data for total world consumption (newly mined metal plus scrap) are not available. Over any short period, however, world production and consumption of newly mined metal are roughly equal.

As a general index of United States fabricating capacity (working capacity), we use the figures for United States consumption of various metals and helium given in Table IV-3. The material demands of nuclear fusion will presumably be additional to demands for other purposes. The figures in the table suggest for each metal (and for helium) whether major or minor adjustments in United States productive and fabricating capacity would be necessary to meet the demands of fusion. It is evident from figures for successive years that world fabricating capacity has grown enormously. Much of this growth has taken place outside the United States, especially in the last ten years.

Table IV-3

Materials Requirements and Estimates of Reserves* [11]
(Units of 1000 Tonnes)

Metal	Maximum Requirement 300 GWe Economy	U.S. Production: From Domestic Ores & Scrap	U.S. Production: Total Production	U.S. Consumption	World Production (1978)	Reserves at Present Prices: U.S.	Reserves at Present Prices: World	Reserves at 3 Times Present Prices[1]: U.S.	Reserves at 3 Times Present Prices[1]: World	Principal Present Sources
Aluminum	709[H]	960	4,350	5,380	13,860	8,500	5,450,000	~5,000,000	Very Large	Australia, Guinea, Jamaica
Boron	676[N]	207	207	118	390	~28,500	~124,000	Very Large		U.S.A., Turkey
Carbon	331[N]									
Chromium	1543[N]	43[3]	43[3]	~534	3,180	None	11,000,000	7,300	20,000,000	S. Africa, U.S.S.R., Albania
Niobium	27[H]	0	3	3	11	None	10,000[2]	~60	>20,000	Brazil, Canada, Malaysia
Copper	358[H]	1,780	1,785	2,250	7,620	107,000	~500,000	No data	No data	U.S.A., Chile, Zambia, Zaire
Iron (pig)	22,824[H]	52,000	79,000	79,800	485,600	>10,000,000	100,000,000	>20,000,000	Very Large	(Iron Ore) U.S.A., Canada, Venezuela
Lead	857[N]	1,026	1,090	1,440	3,506	26,000	157,000	>40,000	>500,000	Canada, Mexico, Peru
Lithium	163[H]	~6	~6	3.9	NA	450-600	2,000	2,500	>10,000	U.S.A.
Titanium (in rutile and anatase)	390[N]	NA	15	17	46	1,360	60,700	Large	Very Large	Australia
Manganese	164[H]	Small	~110	1,280	10,190	None	>14,000,000	>30,000	>20,000,000	Gabon, Brazil, S. Africa, Australia, U.S.S.R.
Tin	7.2[H]	Small	23	49[4]	247	?40	10,000	No data	?20,000	S.E. Asia, Malaysia, U.S.A.
Magnesium	2.5[N]	~100	~100	~100	140	Inexhaustible				
Vanadium	1288[N]	5.3	5.3	7.2	32	113	>10,000	600	>20,000	U.S.A., S. Africa, U.S.S.R.
Nickel	1137[H]	47	79	210	588	180	54,000	12,700	136,000	Canada, New Caledonia, U.S.S.R.
Zirconium	9.5[N]	NA	NA	<3	<6	3,550	18,000	No data	Very Large	U.S.A., Australia
Tungsten	315[N]	4.1	10.2	9.3	43.0	125	1,990	No data	No data	China, U.S.A., Boliva, Thailand
Molybdenum	26.6[N]	60	60.0	30.0	98.0	4,500	9,300	?7,000	No data	U.S.A., Canada, Chile
Cobalt	21.0[H]	0.3	0.3	8.5	30.8	None	?2,600	No data	No data	Zaire, New Caledonia, Australia
Beryllium	27.0[H]	<0.1	<0.2	<0.1	<0.3	28	No data	55	No data	U.S.A., Brazil, S. Africa
Yttrium (UWMAK-1)	0.9	<0.02	<0.05	<.05	<0.4	~3	~38	No data	No data	Malaysia, Australia
Helium	70				See Text					U.S.A.
Fluorine	153[H]		200	1,132	2,310	>2,500	>51,240	?300,000	>200,000	Mexico, France, S. Africa, Spain

*Information on U.S. and World production and consumption are from the U.S. Bureau of Mines. Information on reserves is partly from the U.S. Bureau of Mines, partly from Brobst and Pratt, and partly from other miscellaneous sources. (See Ref. 11 for references.)

[1] Includes reserves at present prices.

[2] Reserves in non-Communist countries only.

[3] From stainless steet scrap.

[4] Primary

[N] Maximum requirement of NUWMAK. [H] Maximum requirement for HFCTR (M.I.T.)

Time is an important factor in the availability of mineral raw materials. Mining and metallurgical developments required to add significantly to the amounts of metals annually available to society are large undertakings that cannot be accomplished overnight. Any major addition involves a chain of events that begins with exploration for new mineral deposits and the delineation of reserves in deposits that may be discovered. It continues with economic and engineering evaluation, the construction of a mine, the construction of smelters and refineries, and finally the construction of fabricating plants. The part of the chain from exploration through mine and mill construction will require from 5 to 25 years. This is the lead time for new mineral production.

The time factor in mineral exploration and development has a bearing on the roles of government and private industry in the development of mineral resources. American mineral industry has a remarkable record of successful exploration and, given a favorable economic and social framework, can be relied upon to do an effective job in future years. There are, however, certain constraints on private exploration quite apart from those presently imposed for regularity purposes. Money invested in mineral exploration yields no return, even if exploration is successful, until the mineral deposits found are brought into production. Exploration must necessarily cease when reserves adequate to meet demand for a limited period of years have been found. If additional exploration is required, for reasons of national policy, support may have to be provided by government. Of the metals that may be involved in nuclear fusion, lithium and vanadium may be cases in point if availability from domestic sources is considered essential.

Finally, we consider energy requirements of metals production. The end of the era of cheap energy means that the availability of metals, and their costs, will be influenced more than in the past by the amount of energy required for their production. A comprehensive study of energy use patterns of the United States primary minerals industry has been made by Battelle-Columbus Laboratories for the United States Bureau of Mines [18]. Pertinent results are summarized by H. H. Kellogg [19] together with his own observations. Energy requirements for most of the metals of Table IV-1 are given in Table IV-4. For each metal, the figure given includes energy consumed in mining, geneficiation, and various steps of chemical or metallurgical processing, together with energy for transportation and the energy equivalent of major supplies and reagents. The chief conclusion to be drawn is that, from the standpoint of energy consumption, stainless steels are to be preferred over titanium and vanadium alloys as main structural materials.

2. Energy Payback Times for Fusion Reactors

A convenient measure of the attractiveness of any type of electric power plant is the time that the plant must run in order to pay back the energy invested in the plant and the fuel. Obviously if the payback time is longer than the life of the plant, then it will be unattractive and uneconomic. In order to do a proper accounting of the energy invested in a plant one must consider both the fuel cycle and the construction of the plant itself. Furthermore, one must be careful to include the energy invested in the mines

Table IV-4

Energy Requirements for Fusion Metals [11]

(10^6 Btu/tonne)

Aluminum	244
Ferrochrome, low carbon	129
Ferrochrome, high carbon	61
Copper, refined	112
Iron (steel slabs, grey iron and steel casings)	24.9
Lithium hydroxide	400
Titanium sponge	410
Ferromanganese	50
Magnesium ingot	358
Ferrovanadium	490
Nickel cathode	144
Tungsten powder	350
Tin ingot	190
Molybdic oxide	150
Sodium metal	92

that produce the fuels and materials for construction, as well as the energy invested in the factories that make the equipment for the power plant itself. This approach can involve an endless chain of contributions, so it has been customary to develop an energy to cost ratio for industrial equipment and then to use this value times the direct cost of plant to obtain an energy input value. In 1975, Rombough and Koen [20] developed a weighted average of energy/cost ratios for various parts of the industrial sector, new constructions and utilities. They found a value of 75,530 BTU per 1963$ to be appropriate. Aside from adjusting this value for inflation on items where exact values are not known, one could use the actual energy costs for specific pieces of equipment developed by Rotty et al. [21], Chapman and Mortimer [22], Rombough and Koen [20], and Wright and Syrett [23].

We have applied the above information to NUWMAK and have calculated that the energy payback time is approximately 3.6 years. This compares favorably to 1.8-2.9 years for fission reactors [20-23] and 2.1 to 2.5 years for coal plants [22]. Such an analysis at this state of fusion reactor development is encouraging.

3. Influence of Substitutability on Resource Requirements

Substitution of one element for another with little or no loss in functional capability is one way to avoid an anticipated resource crisis. Several elements have been identified in the NUWMAK study as resource problems for an economy of these reactors, specifically tungsten, beryllium, copper and cobalt. Tungsten and beryllium are not essential for fusion reactor design. Tungsten is used in the inboard shield in NUWMAK because of its superior neutron shielding properties and because it is desirable to have the thinnest inner blanket and shield possible. However, lead is a ready and practical substitute. The major radius of the reactor would probably be increased by 10 cm (from 5.15 m to 5.25 m) to permit additional shielding space. Otherwise, the design will remain essentially unchanged and tungsten as a resource issue would not occur.

Beryllium is another case illustrating the same phenomenon. It is used to increase the number of neutrons available for breeding in the blanket and is favored for this purpose because it has a low threshold energy for the (n,2n) nuclear reaction. Lead is again a suitable substitute because, although heavy, it has properties similar to light nuclei. In particular, lead has low neutron absorption and high (n,2n) reaction probabilities. The threshold energy for (n,2n) reactions is higher than for beryllium but this creates no great problem. Thus, although beryllium is used in the blanket designs for UWMAK-II and HFCTR, practical alternatives exist. An example is the NUWMAK blanket where a Li-Pb mixture is used.

Copper reserves may not be adequate but aluminum is a ready substitute. Copper is used as the stabilizer in superconducting magnets but designs have been developed using aluminum for the stabilizer and aluminum alloy for the magnet structure (see the UWMAK-III [8]). In addition, the large tokamak, T-15, to be constructed by the Soviet Union, will employ aluminum as the stabilizer. World aluminum reserves at present prices are at least 10 times those for copper and would thus relieve this potential difficulty.

The cobalt resource issue is independent of fusion since cobalt is used in the steam generator alloy, an item in all power plants regardless of the heat source. Cobalt use should be monitored and substitutes examined if and when a resource shortage emerges.

Lithium resources are large enough for more than a millennium at any predicted level of future energy requirement when it is used primarily to breed tritium in fusion devices. The deuterium-deuterium cycle is surely to be in use before this question becomes an issue. One can argue therefore that deuterium will be substituted for lithium on a time scale to relieve any doubts regarding lithium resources. In some designs, lithium is also used in liquid form as a coolant. A much larger initial lithium inventory is then required per reactor since it now resides not only in the fusion blanket but everywhere in the primary heat transfer loop. Questions of availability and procurement discussed earlier become more important if the potential competition for lithium from battery applications becomes serious. One can minimize this problem by designing fusion blankets which have a minimum lithium (and thus tritium) inventory. Design solutions include the use of static lithium, stationary solid lithium compounds (as in UWMAK-II), or static liquid compounds such as the Li-Pb mixture employed in NUWMAK.

In summary, the elements identified as potential resource difficulties in an economy of fusion reactors are ones for which more abundant substitutes are available and, in some cases, have been used in design. The concept of material substitution as an approach around critical resource limitations has been discussed in a broader context by Kahn, Brown, and Martel [24]. Nevertheless, future developments in fusion reactor design should aim at reducing the size of reactors (increasing their power density) and stressing the use of more abundant metals.

4. Conclusions Relating to Resources

The present survey indicates that, given the elimination of beryllium, tungsten, and cobalt from the list of required elements, metals needed for a 300 GW_e United States fusion economy could be provided from domestic sources at prices ranging from present prices to 3X present prices. The one exception is chromium. Whether these metals will actually be domestically available depends not only on prices but also on United States capacities for mining, smelting, refining and fabricating. As indicated in a previous section, the record of the past ten years is not encouraging in this respect. If the trends of this period continue, increasing dependence of the United States on foreign sources is likely not only for new supplies of metal but for semi-finished and finished metal products.

World reserves of the various metals needed for fusion, apart from beryllium, tungsten and possibly cobalt and copper, are adequate to sustain substantially increased production and the added requirements of a total world fusion economy of 1200 GW_e would not change the pattern of availability. Thus far, world mining, smelting, refining and fabricating capacities have been responsive to demand.

The development of a free world fusion economy in terms of present reactor designs would obviously invoke a significant burden on United States and free world resources of some of the metals specified. Particularly if development of a world fusion economy beyond a level of 1200 GW_e is envisioned, future design development should aim at reducing the size of reactors and should stress the use of the more abundant metals.

It should be emphasized that forecasting availability of mineral-derived materials twenty to forty years in the future is fraught with many uncertainties. Periodic monitoring of availability and revision of forecasts is therefore essential. Lithium is a case in point. Its availability depends on the future interplay of success in exploration, success in developing new or improved techniques of extraction, and technology changes that may greatly alter the scale of use. The present assessment is therefore not a firm one; its main function is to call attention to those materials that are likely to be available in ample amounts as opposed to those that could present more or less difficult problems of procurement. At a stage when thermonuclear designs are steadily evolving and materials alternatives present themselves, it may direct attention to designs that involve a minimum of problems of materials procurement.

C. Risks

The generation of electricity by any form of energy involves risk. This risk is not always localized in time or location and in fact, recent analyses show that the risks of energy production may range throughout the entire society. Dr. Herbert Inhaber, in his recent (Sept. 1979) [25] report on the "Risk of Energy Production" defines risk studies in two different ways. "Risk evaluation" may be approximately defined as that which considers physical and biological risk. "Risk assessment" considers physical and biological risks as well as social, psychological, aesthetic and related risks. As a society we are relatively well equipped for "risk evaluation" but "risk assessment" involves judgements which could vary significantly from person to person. In this study we will try to confine our remarks to "risk evaluation" since fusion is not developed enough to attempt "risk assessment". Furthermore, a total and thorough "risk evaluation" is beyond the scope of this paper. We are thus forced to limit our discussion to a few of the more tractable areas such as material resource acquisitions and radioactivity inventories.

1. Risks Associated with the Procurement of Fuels for Power Reactors

The mining, refining and transporting of fuels is a hazardous business. News of large numbers of workers killed in deep coal mining activities around the world is a frequent occurrence. However, deaths and injuries on oil platform disasters which occur one or two at a time (and in fact make up the majority of the overall risks) are less "newsworthy" and escape the public eye. It is therefore informative to compare the potential risks of procuring fuel for three forms of energy likely to be used in the United States in the 21st century; coal, fission energy from uranium, and fusion energy from the DT cycle. First we will determine how much fuel is required, then we will examine the records for risk associated with procuring the fuel.

The amount of fuel required to generate 1 GW_e-year of energy is given in Table IV-5. It can be seen that roughly 79 times as much coal bearing minerals need to be handled as the ore for a LWR. The major impact of fusion is the requirement of approximately 700 tonnes of Li ore per GW_e-y and roughly 3000 tonnes of H_2O to be processed for the deuterium. The ratio of solid materials mined for coal to fusion is ~ 9,000 to 1.

The mining and transportation of such large amounts of material is hazardous whether associated with underground or surface mines. Using data from a recent study on coal and uranium procurement [27], plus making pessimistic estimates for mining deaths in the Li industry*, will illustrate that point. Table IV-6 shows that on the average, about two miners will lose their lives mining the coal for 1 GW_e-y of energy if it comes from underground mines. Procuring the same amount of coal from surface mines is 6 times safer but can still result in roughly one death per 3 GW_e-y.

Transporting that coal from the mine to the utility is also very hazardous, and furthermore, roughly half of the victims are from the general public (e.g., at railroad crossings). When the accidental deaths from mining and transportation of coal are added together, we find that just getting the coal into the furnace will cost the lives of 2 to 4 individuals per GW_e-y.

The situation for the procurement of U is at least a factor of 20 better than for coal, but it is still non-negligible (~ 0.2 accidental death per GW_e-y). Because a steady state LMFBR economy requires so much less U, the occupational deaths associated with mining and transportation are truly small. For example, if all the present electrical energy in the United States generated by nuclear plants in 1979 (~ 30 GW_e-y) were in LMFBR's, there would be less than 1 occupational accidental death every three years associated with the procurement of fuel.

Finally, the extremely small amount of lithium required for a DT fusion reactor (~ 7 tonnes per GW_e-y) represents a truly negligible risk of accidental death. For example, if all the non-communist world's electrical energy in 1979 were provided by DT fusion reactors (~ 700 GW_e-y) then there would be the probability of less than one occupational death per year procuring the fuel. This should be compared with the number of 1800 to 2800 deaths if all the world's electrical energy were produced by coal. Such a relatively simple comparison truly illustrates one of fusion's strong points.

2. Amount of Non-Fuel Materials Required for Electrical Generating Plants

As we saw previously, an electrical power plant uses large amounts of materials other than fuels; e.g., structural members, heat exchangers, electrical switching and transmission equipment, cooling towers, shielding,

*That is, assuming that the mining of Li is as hazardous as the mining of coal.

Table IV-5

Amount of Fuel Required to Generate 1000 MWe-y of Energy

Energy System	Fuel	Tonnes of Fuel "Burned"	Additional Tonnes of Fuel for Inventory(a)	Total Tonnes Fuel	Yield from Ore Wt %	Total Tonnes Mined
Coal [26]	Coal	3,000,000	8,000(b)	3,008,000	50(c)	~ 6,000,000
Light Water Reactor [26]	U	1.2	170(d)	171(d)	0.2	86,000
LMFBR [26]	U	1.0	3(e)	~ 4	0.1(f)	4,000
DT Fusion	Li	0.4	6(g)	~ 7	0.1	700
	D	0.1	~ 0	~ 0.1	3×10^{-3} (H_2O)	~ 3,000 (H_2O)

(a) Prorated over a 30 year reactor life, 1000 MWe plant.

(b) A 30 day supply.

(c) Assume 50-50 split between surface and underground mining.

(d) Includes depleted U and assumes no recycle; this fuel could be used in subsequent LMFBR reactors.

(e) Includes fuel in reprocessing as well as core material prorated over 30 years.

(f) Assume only 0.1% available when breeder is commerical.

(g) Some of this Li could be used in subsequent reactors.

Table IV-6

Accidental Deaths Associated with the Fuels Procurement

for 1 GW_e-y of Energy - Recent Data

Activity	Deep Mines	Surface Mines
Coal [27]		
Mining	1.7	0.3
Transportation	2.3	2.3
Total	4.0	2.6
Fission (LWR) [27]		
Mining	0.2	(0.05)
Trans. + Const.	0.01	0.01
Total	0.2	(<0.06)
Fission (LMFBR)		
Mining	0.01	(0.002)
Trans. + Const.	0.0005	0.0005
Total	0.01	(0.003)
DT Fusion (est.)		
Li Mining	No Deep Mines Used	(0.00004)[(a)]
Transportation		(0.00009)[(b)]
Total	?	(0.0001)

[(a)]Assume open pit mining of pegmatite lithium deposits is as hazardous as surface mining of coal.

[(b)]Assume transportation of Li is as hazardous as transportation of U.

auxiliary equipment, buildings, and so forth. In addition to these on-site requirements, a considerable amount of steel and other construction material is needed just to procure and transport the fuels to the point of use; e.g., for excavation equipment, mine and smelter construction, locomotives, railroad cars, etc. The reader should remember that to produce a tonne of raw steel requires 1.7 tonnes of iron ore and 1.5 tonnes of coal to smelt the ore. These extra mining activities must be added to those required for the fuel itself. Finally, the fabrication of finished components and the construction of the power plant itself involves risks which can be readily quantified from recent statistics on deaths (or accidents) per man-hour of work involved.

It is necessary to also point out that the risks of procuring fuel and non-fuel material are not limited to those in the specific occupation of energy production. The public suffers from the emissions from smelters (roughly 10 tonnes of SO_2 is emitted for every 1000 tonnes of Al produced) [25]. The public is exposed to higher risks associated with increased truck and train traffic, and they have even been exposed to catastrophic accidents associated with the procurement of fossil fuels. A few of the more notable recent events were the killing of 116 school children in Aberfan, Wales in 1966 during a slag pile slide and the loss of 118 people who drowned in Saunders, West Virginia in 1972 when a coal refuse dam collapsed.

Since it is not within the scope of this paper to develop the models for risk evaluation we rely heavily on the most recent (1979) report by H. Inhaber [25]. We will use, without modification, his values for coal and LWR systems and we will extrapolate to the LMFBR system. The risk values for fusion will be based on the NUWMAK reactor [9] and where possible, construction and transportation risks for fusion plants will be ratioed to those of fission reactors.

The state-of-the-art in risk evaluation will not allow a precise risk value to be assigned to every element procured for a power plant (i.e., Cr, Mn, Ni, Fe, Nb, Sn, V, Mo, Al, Cu, etc.). Therefore the non-fuel risks associated with production of steel and cement will be applied to all metal and concrete requirements, respectively. Further studies of the individual industries should be performed to obtain a more exact value.

The inventory of non-fuel materials required for four future large scale facilities is given in Table IV-7 and displayed graphically in Fig. IV-6. The materials inventory is broken up into:

a. Gathering and Handling of Fuels. (This includes the mining equipment and facilities.)

b. Transportation. (This includes truck and train related materials.)

c. Electricity Production. (This includes the facility itself.)

The materials are further subdivided into three other categories.

Table IV-7

Non Fuel Materials Required for Electricity Generation - Tonnes/GWe-y*

Component	Gathering & Handling of Fuels				Transportation				Electricity Production				Total			
	Coal	LWR	LMFBR[a]	CTR	Coal	LWR[c]	LMFBR[c]	CTR[c]	Coal	LWR	LMFBR	CTR	Coal	LWR	LMFBR	CTR
Construction-Metals																
Structural	490	39	1.8	---	29	---	---	---	740	1,250	1,250	2,150	1,260	1,290	1,250	2,150
Piping	160	14	0.7	---	---	---	---	---	90	120	120	160	250	130	120	160
Major Equip.	660	265	12.3	---	870	---	---	---	880	250	250	90	2,410	520	260	90
Other Equip.	---	77	3.6	---	58	---	---	---	360	230	230	30	420	310	230	30
Coolant	---	---	---	---	---	---	---	---	---	---	150[e]	---	---		150	---
Sub Total	1310	396	18	0.2[b]	957	---	---	---	2,080	1,850	~2,000	2,430	4,340	2,250	~2,010	2,430
Construction-Concrete	---	333	16	---	---	---	---	---	6,820	12,400	12,400	19,000	6,820	12,700	12,400	19,000
Operation-Maintenance	---	---	---	---	---	---	---	---	247,000 (Lime)	20[d]	20[d]	<<20	247,000 (Lime)	20	20	<<20
Total	1310	729	34	0.2	957	---	---	---	256,000	14,300	14,400	21,400	258,000	15,000	14,500	21,400

(a) Reduced by amount of U required

(b) Reduced by amount of Li required

(c) Included in Gathering and Handling of Fuels

(d) Waste Management

(e) Sodium

*Values for coal and LWR's obtained from Ref. 25.

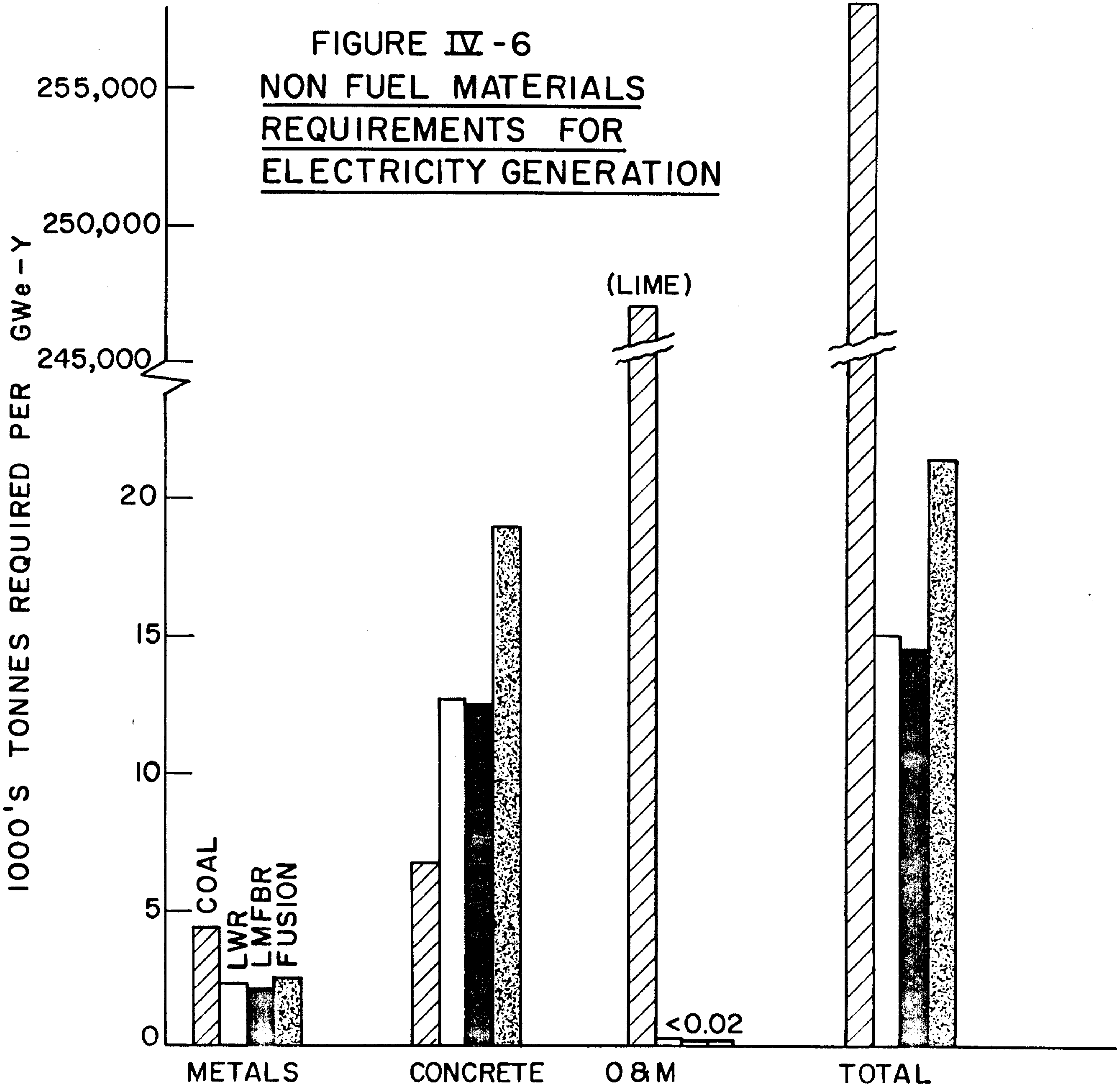


FIGURE IV -6
NON FUEL MATERIALS REQUIREMENTS FOR ELECTRICITY GENERATION

a. Construction metals, including structural components, piping, major equipment such as excavators, trains, boilers, etc., other equipment, and coolants such as Na for the LMFBR.

b. Construction Concrete.

c. Operation and Maintenance which includes waste treatment.

The numbers are given in tonnes required per GW_e-y of electricity generation averaged over the lifetime of the plant. For example if a 1000 MWe plant ran continuously for 1 year then it would generate 1 GW_e-y of energy. If the plant runs at only 60% of its potential capacity for the year then it would generate only 0.6 GW_e-y per year of operation. The total inventory of materials is then divided by the total GWe-y's of energy generated over the lifetime of the plant to obtain the tonnes per GW_e-y value.

A few words about Table IV-7 are in order before we discuss the results. First, the amount of material required to mine U for the LMFBR was calculated from the LWR values, appropriately reduced by the fuel requirements (see Table IV-5). A similar reduction was applied to the fusion system for the mining of Li.

The transportation values of Inhaber [25] were used for coal and the reduction factors of roughly 20 and 100 for the LMFBR and CTR systems compared to the LWR's were also applied.

The power plant materials requirements for the LMFBR were assumed to be the same as for the LWR system except that ~ 150 tonnes of Na were added per GW_e-y for the coolant [28]. The values for fusion were obtained from the NUWMAK report. The radioactive waste handling requirements for the LMFBR were assumed to be roughly the same as for the LWR. Since there is no requirement for shielded chemical facilities to dissolve the radioactive wastes from a fusion plant, the material required for the disposal of the wastes should be much smaller for fusion than required for a fission reactor. No exact value is available at this time.

There are six interesting conclusions from Table IV-7.

a. The requirement to handle and transport large amounts of fuel for the coal scenario means that roughly as much metal is required for that activity as to build LWR, LMFBR, and CTR plants themselves. This explains why the total metal requirements for coal-fired plants per GW_e-y of energy generated is twice the other systems.

b. There is a substantial metallic and concrete requirement for the procurement of U for LWR's although only 1/3 the amount of metallic components are required in LWR's as for the coal plants. The reduced U requirements of the LMFBR's and almost negligible fuel requirements of the fusion reactors means that the fuel related metals required for LMFBR and CTR systems are only 1% and 0.02% of those for the coal system, respectively.

c. The lower engineering power density in fusion reactors themselves is translated into higher amounts of metallic components per GW_e-y. The amount is ~ 20% higher than for fission reactors and may even be somewhat higher once detailed designs appear.

d. The fusion reactor also places rather high demands on concrete because of the difficulty in shielding 14 MeV neutrons, and the somewhat larger buildings required on site. The concrete requirements are three times those of the fossil plant and 50% higher than fission reactors.

e. Future coal-fired plants will have an enormous demand for lime (CaO) to neutralize acidic wastes. The requirement of ~ 250,000 tonnes per GW_e year will in itself place a substantial load on mining and train transportation systems (for example, roughly 25 trains, each consisting of 100 cars would be required to transport the lime for just one GW_e-y). The corresponding waste disposal volume for fission and fusion reactors is negligible in comparison.

f. From an overall metallic materials requirement standpoint, the entire coal system requires the highest amount, followed by fusion and fission reactors in that order. Adding metallic requirements to concrete requirements one finds that fusion requires roughly twice as much material as coal plants and ~ 40% more than fission plants. Finally when all materials are added together, coal units require ~ 12 times more material to be transported than fusion plants and 17 times more than fission reactors.

3. Risks Associated with Procuring Both Fuel and Non-Fuel Materials for Electrical Power Plants

Now that the materials requirements for the various electrical generating plants are established we can proceed with an estimate of the risks associated with each system. These risks could be stated in several ways:

a. Occupational and Public Deaths,

b. Occupational and Public Injuries Due to Accident or Disease,

c. Man-days Lost Due to Accidents or Disease,

d. Property Damage Due to Emissions or Accidents, etc.

Several previous studies have addressed the above categories for the main energy sources of the future and for the purposes of this study we will only consider public and occupational related deaths. We do this not to diminish the importance of injuries or lost work days, but because records on cause of death are more "unambiguous" and perhaps are better understood by the public. We also consider here the deaths associated with emission from mining, smelting, transportation and production systems.

Again we will follow the approach set out by H. Inhaber [25] and will use his numbers for coal and LWR's. The values for LMFBR's will be ratioed where appropriate and we will estimate the fusion numbers on the basis of materials handled. We will make no distinction between the various materials in fusion plants compared to fission or coal plants.

The risk comparison between the four energy sources is given in Table IV-8 and shown graphically in Fig. IV-7. Only the predicted occupational and public related deaths are listed. The data is further broken up into those deaths which are related to accidents (mine cave-ins, falling off of construction platforms, train-auto collisions, etc.) and those related to disease (i.e., from black lung, radon exposure, SO_2, NO_x and particulate emissions, etc.). The method for determining the deaths related to coal and light water fission reactors is described in the Inhaber report [25] and again we have ratioed the values for the LMFBR in the fuel handling and transportation area by the relative amounts of U that has to be mined. The values for fusion are further reduced from the LWR data because of the small fuel procurement requirements and because there is no need for shipping fuel outside the plant for reprocessing. The risks for the fusion plant construction are assumed to be higher because of the larger amount of construction materials to be handled and the risk to the public due to radioactivity emissions was assumed to be at least as low as for fission reactors. In fact, the risks due to emissions from fusion related facilities will probably be less than fission reactors because there is inherently only one volatile isotope, tritium. However, there are other potentially volatile isotopes in the coolants and until a complete safety and accident analysis can be performed on a real design, we will use the conservative assumption that fusion plants will present no more of a hazard to the public than the lowest estimates for fission reactors. Finally, ranges of values are quoted following Inhaber's assessment of the maximum and minimum possible effects. When the lower value was less than 0.001 death per GW_e-y, it was not reported.

There are five major points from Table IV-8 and Fig. IV-7:

a. By far the most hazardous form of energy generation is coal. Roughly 100 times more deaths per GW_e-y are associated with it than for the nearest "competitor", LWR's. Fusion appears to have a factor 7 to 25 times lower risk associated with it compared to fission reactors.

b. Most of the death related risks associated with generating electricity by the four methods studied here come from the generating plant itself or the materials required to build the plant. This fraction ranges from 80 to 100% of the total for fusion and the LMFBR, 80-90% for coal, and 20 to 60% for the LWR's.

c. The general public is subjected to most of the deaths from coal plants. The risk of death is roughly equally divided between the workers and public for the LMFBR and fusion and only in the LWR systems do the workers take most of the risks.

Table IV-8

Risks Associated with Electrical Energy Production - per GW_e-y

Event	Gathering & Handling of Fuels				Transportation				Electricity Production				Total			
	Coal	LWR	LMFBR[c]	Fusion[e]	Coal	LWR	LMFBR	Fusion	Coal	LWR[b]	LMFBR[b]	Fusion	Coal	LWR[b,d]	LMFBR[b,d]	Fusion
Occupational Deaths																
Accidental	0.7-1.5	0.08-0.57	0.004-0.03	0.001 -0.006	1.6-5	0.003-0.12	Negl.	Negl.	0.013-0.09	0.013-0.017	0.013-0.017	0.02-0.03[f]	2.3-6.6	0.96 -0.60	0.017-0.05	0.021-0.032
Disease	0 -3.5	0.022-0.6	0.001-0.03	0.0002-0.006	---	<0.004	Negl.	Negl.	---	0.11	0.11	---	0-3.5	0.136-0.71	0.11 -0.14	<0.006
Sub Total	0.7-5	0.1 -1.2	0.005-0.06	0.001 -0.012	1.6-5	0.007-0.016	Negl.	Negl.	0.013-0.09	0.12-0.13	0.12 -0.13	0.02-0.03	2.3-10.1	0.23 -1.31	0.13 -0.19	<0.03-0.04
Public Deaths																
Accidental	Negl.	Negl.	Negl.	Negl.	0.8-1.9	0.012	Negl.	Negl.	Negl.	Negl.	Negl.	Negl.	0.8-1.9	0.012	Negl.	Negl.
Disease	1.4-14	<0.0002	Negl.	Negl.	---	<0.0002	Negl.	Negl.	32-95[a]	0.03 -0.23[d]	0.03-0.23[d]	<0.03[g]	33 -109	0.03 -0.23	0.03 -0.23	<0.03
Sub Total	1.4-14	<0.0002	Negl.	Negl.	0.8-1.9	0.012	Negl.	Negl.	32-95	0.03 -0.23	0.03-0.23	0.03	34 -111	0.04 -0.24	0.03 -0.23	<0.03
Total Deaths	2.1-19	0.1 -1.2	0.005-0.06	0.001-0.012	2.4-6.9	0.019-0.028	Negl.	Negl.	32-95	0.15 -0.36	0.15-0.36	<0.05-0.06	36 -121	0.27 -1.55	0.16 -0.42	<0.06-0.07

(a) Includes only SO_2 related deaths; further study is needed on NO_x and particulate related deaths.

(b) Including waste management.

(c) Reduced from LWR values by a factor of 20 to reflect lower U requirements.

(d) Includes catastrophic accident possibility.

(e) Reduced from LWR values by a factor of 100 to reflect lower mass of Li ore (Brine) handled.

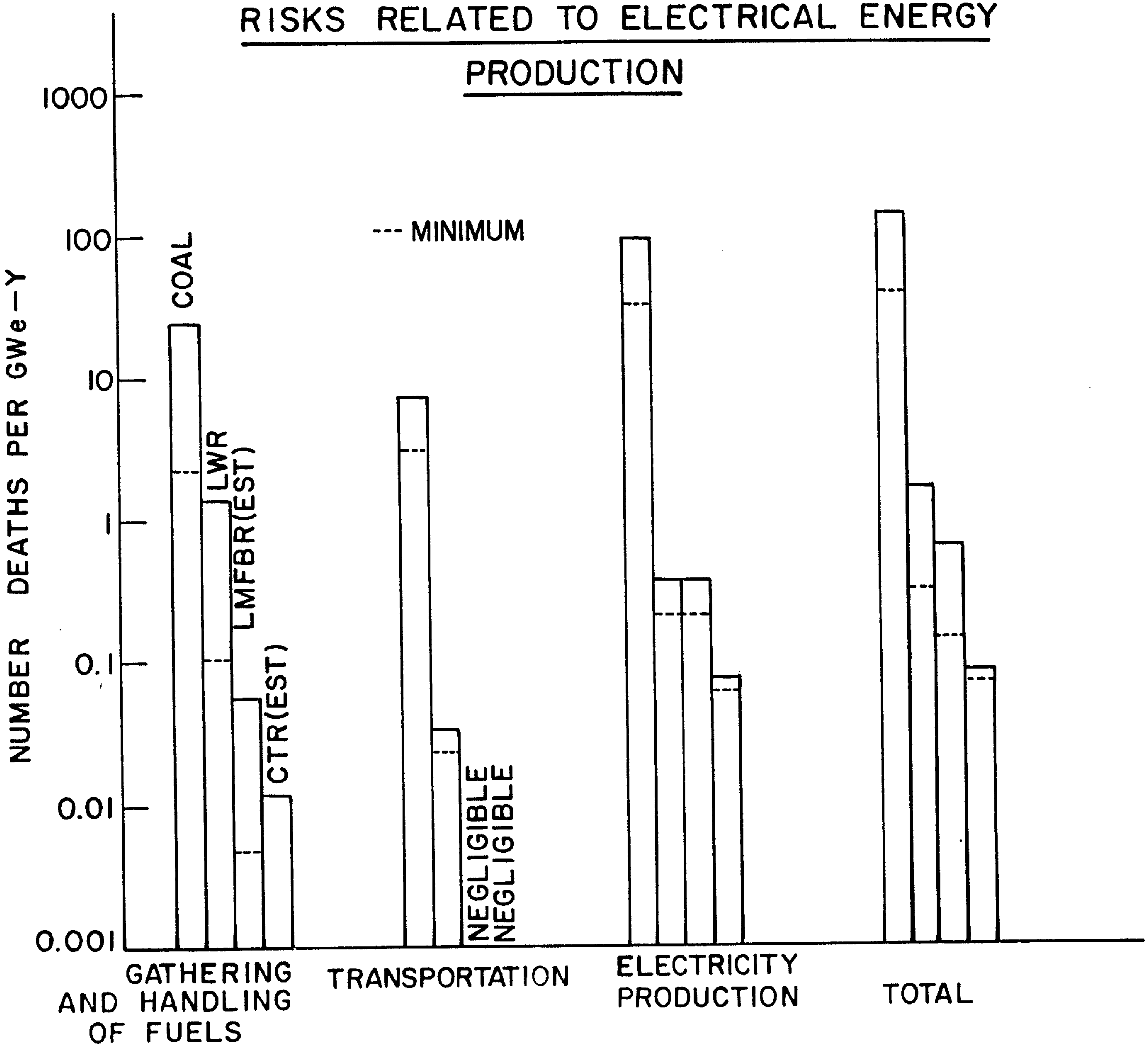
(f) 1.5 times LWR value to reflect increased materials required for plant.

(g) Value unknown but should be less than 10% of fission reactor because the biological hazard inventory of volatile radioisotope is 10-100 times less than fission reactor.

Negl. = considerably less than 0.001 per GW_e-y

FIGURE IV-7

RISKS RELATED TO ELECTRICAL ENERGY PRODUCTION



d. The contribution of routine emissions to the death related risks for fusion is unknown. If the emissions can be kept to 10 curies or less per day of only tritium, then the total death rate (occupational and public) would be < 0.03 per GW_e-y, roughly the same as the hazard of building the plant itself.

e. Because of the low fuel and transportation requirements of fusion, it appears that practically all of the hazards from this form of energy come from the construction of the plant itself and the procurement of construction materials. It appears that this minimum risk associated with fusion is ~ 0.03 deaths per GW_e-year, roughly 1000-4000 times safer than coal systems, 10 to 50 times safer than LWR's and 5-15 times safer than LMFBR's.

As a final note it is instructive to calculate the occupational and public deaths that might be related to a 300 GW_e fusion economy and compare those numbers to what they might be if coal, LWR's, or LMFBR's were used to generate the same amount of energy. The numbers in Table IV-9 show that generating electricity for 300 GW_e of installed capacity (roughly 60% of the 1979 United States capacity) would cause in the neighborhood of 10,000 deaths or more if it were done with coal plants, a few hundred if done with LWR's, less than 100 if by LMFBR's and probably less than 15 if produced by fusion.

Lest we lose perspective, it should be noted that the risk of death, either in the public or industrial sector, is not exclusive to electrical power plants. For example, we see in Table IV-10 that in 1979 alone there were almost 56,000 deaths in the transportation area alone [29].

D. Environmental Impact of Fusion

There have been many studies on the environmental impact of coal and nuclear power stations but relatively few attempts to incorporate fusion. The changing nature of fusion reactor design has made detailed comparisons difficult so in this paper we approach the environmental effects from a more global viewpoint. We highlight some of the more intrinsic properties of fusion while leaving the treatment of more novel ideas (i.e., advanced fuels, advanced confinement schemes) to a time when they have been proven to be viable.

One can conveniently classify the environmental impacts of electrical generating plants into three categories.

a. Land (use for fuel, structural and siting requirements plus long term impacts after it is no longer of use to the power facility).

b. Water (use for mining and heat disposal purposes plus degradation of water quality).

c. Climatic effects (health effects of emissions have been covered previously, here we mean the effects of SO_2, NO_x, CO_2, etc. on the weather).

Table IV-9

Number of Deaths per Year That Might Be Related to a 300 GW_e Installed Capacity of Various Forms of Energy*

Source	Occupational Deaths	Public Deaths	Total Deaths, y^{-1}
Coal	500 - 2100	7000 - 23000	7500 - 25000
LWR	50 - 280	8 - 50	60 - 330
LMFBR	30 - 40	6 - 50	40 - 90
Fusion	6 - 8	< 6	< 15

*300 GW_e at 70% capacity factor = 210 GW_e-y.

Table IV-10

Transportation Related Deaths in the U.S. in 1979 [29]

Area	Number
Highways	51,083
Water Recreation	1,400
General Aviation	1,311
Rail-Auto Collisions	878
Railroads	614
Commercial Aviation	353
Commerical Shipping	181
Pipelines	38
Total	55,858

1. Land Use Impact

The most obvious area to consider here is the land required to site the reactor, turbines, cooling towers, fuel storage, waste products, etc. However, this area is quite small in some cases when compared to the land disturbed to procure the fuels and structural materials. Table IV-11 summarizes land area requirements per GW_e-y of energy (assuming a 30-year life at 70% capacity factor).

The first thing to notice is that the land area required to site the nuclear facilities is about 2 times less than the amount required for a coal-fired plant because of fuel and waste product storage areas. The second point is that there is ~ 4 orders of magnitude difference between coal and fusion plants when the land disturbed to procure the fuels is considered.

Next the land required for transportation of the fuels and the electricity must be considered. For coal, this means that the land necessary for the railroad right-of-way must be considered, appropriately ratioed by the fraction of traffic in coal trains. In the case of nuclear systems it must include the land required for high voltage lines from the plant to the load center. Unfortunately, there are no values available at this time and future studies are necessary to add this information.

The obvious conclusion with respect to land usage is that the nuclear systems all represent a tremendous improvement over the coal cycle and that the breeder and fusion systems have a significant advantage over the light water reactor system.

Table IV-11

Land Use Requirements for Large Scale Power Plants

(km^2 per GW_e-y)

System	Production Site	Fuel Procurement and Waste (surface)	Transportation	Total
Coal	0.035(30)	40(27)	(Not Available)	>40
LWR	0.015(30)	1(27)	Negl.	~1
LMFBR	~ 0.015	~ 0.05	Negl.	~0.07
DT Fusion	~ 0.015	~ 0.008	Negl.	~0.02

Negl. = negligible

2. Water Use

There are three major requirements for water when considering power plants; the water used during the mining process, the water required to restore the land after both the fuel and non-fuel related minerals are extracted, and the water required to dispose of the waste heat. The first and the last quantities are more easily calculated, e.g., for a 1 GW_e power plant the cooling water requirements are listed below in Table IV-12 for various fuels.

The water requirements for heat disposal in the coal system are slightly less than for the nuclear systems because roughly 30% of the waste heat can "go up the stack" and because the thermal efficiency is higher than the LWR and projected fusion plants. Consequently, coal systems require ~70% less cooling water than LWR or fusion systems and 50% less than the LMFBR. When dry cooling towers are used (as they will most probably be at the turn of the century) this difference falls to less than 20%. Therefore, it appears that future fusion operating plants will not be a particular burden to water supplies, at least not much more than any other electrical power station.

A somewhat different picture emerges when we consider the water required to mine the fuels and treat the wastes from electrical power plants. Here we see that roughly nine times more water is required in coal systems outside of the plant than to dispose waste heat via dry cooling towers. LWR fission reactors also require a substantial amount of H_2O in the fuel process but the reduced U requirements in the LMFBR system are more easily accommodated. While there are no data on fusion fuel cycles, it is anticipated that because of the small amount of Li and deuterium required, that less than 10,000 m^3 of water are required per GW_e-y.

Finally, water related reclamation activities as applied to strip mines can be enormous. It takes roughly 0.05-4 m^3 of water/tonne of coal to restore the surface of a strip mine, and this could amount to as much as 12 million m^3/GW_e-y for a coal plant. Obviously, the impact on future water supplies can be large in this respect and it is particularly true in areas where water is not always abundant (i.e., Wyoming).

3. Radioactive Inventories in Fission and Fusion Plants

This topic has been the subject of many comparisons in the past with one of the most complete tabulations published by IIASA [28]. We cover only the highlights of that study augmented by results recently calculated for the present paper.

There are two main sources of radioactivity in a fusion plant; that associated with the fuel (tritium), and that associated with the energy transport and conversion system (we must also include the pellet debris for inertial confinement fusion). On the fission side one could conveniently break the sources of radioactivity into that from the fuel (fission products) and that from the coolant and structural components. At this point, we encounter our first main difference between the two energy sources, namely

Table IV-12

Water Requirements for Electric Power Producing Stations $-m^3/GW_e\text{-}y$

System	System Eff. %	Once Through	Cooling Ponds	Evaporation Cooling Tower	Dry Cooling Tower	Fuel & Waste Management [31]
LWR	32	1.9×10^9	59×10^6	38×10^6	380,000	670,000
Fusion	~32	$\sim 1.9 \times 10^9$	$\sim 59 \times 10^6$	$\sim 38 \times 10^6$	~380,000	<10,000
LMFBR	~38	$\sim 1.6 \times 10^9$	$\sim 50 \times 10^6$	$\sim 32 \times 10^6$	~320,000	30,000
Coal	38	1.1×10^9	35×10^6	23×10^6	310,000	2,700,000[a]

(a) Not including the 0.05 to 4 m^3 of water per tonne of coal required for reclamation of the land area from western surface mines [32]. This would amount to an extra 150,000 - 12,000,000 m^3 per GW_e-y for coal.

that the magnitude of the radioactive inventory or hazard potential associated with a fusion plant is largest in the components around the fuel whereas in fission both the major hazard potential and radioactive inventory is in the fuel.

Aside from this rather simple observation, a quantitative comparison between fusion and fission can either be based on curies or the biological hazard potential of the various isotopes released into air or water (see Fig. IV-8). Curies do not account for the type of decay or the biological lifetime. The BHP unit is of more use to us even though the units are not as familiar. Basically, those units are the total amount of air or water required to reduce a given isotope to the maximum permissible concentration for the general public. Since this quantity depends on the curies level, it also varies with time. To illustrate where the fusion community currently stands with respect to fission reactors we will quote the BHP at three times that might be of interest to the general public. These times are 1 day after shutdown, a time which is commensurate with an accidental release of radioisotopes; 1 year after shutdown, a time which might be consistent with disassembly of a reactor or reprocessing of the wastes for long term burial; and 1000 years, probably the longest time that current generations could project into the future for storing wastes.

To make the comparison we use a 1000 MW_e DT stainless steel tokamak fusion reactor and a 1000 MW_e stainless steel LMFBR. We have assumed a 10 kg tritium inventory (5 kg in storage) per 1000 MW_{th}[a] and 620 kg Pu inventory per 1000 MW_{th}-YR. The magnitude of tritium in the active system depends very much on how fast the vacuum pumps can be recycled and the fractional burnup in the plasma. Presently we anticipate burnups of a few per cent and recycle times a few hours. Any reduction in burnup or extension in recycle time could increase the inventory.

The choice of a steel structure for fusion requires some explanation. It is often heard that fusion designers have the flexibility to choose any structural material they want to and they can choose a material that has isotopes with shorter half-lifes than those in steel. There are two replies to that statement. First, very few metallurgists and radiation damage experts would support the choice of the more exotic structural materials like Mo, Nb, V or even Al. Indeed, when hard choices have been made in the past few years for 14 near term magnetic fusion reactor designs in six different laboratories in the United States, 13 out of the 14 designs have used steel as the structural elements. In the inertial confinement field, out of the 8 most recent designs, half of them have been with steel.

The second reply to the question of structural material choice is that for short times after shutdown, it doesn't make much difference which material is chosen and this will be demonstrated in a minute.

a) If Pb-Li alloys are used for breeding, then the active tritium inventory in the reactor can be reduced from 5 kg per 1000 MW_{th} to ~3 kg per 1000 MW_{th}.

Figure IV-8

Methods of Determining Radiological Hazard

UNIT	DEFINITION	FEATURE
CURIE	3.7×10^{10} DPS	DOES NOT ACCOUNT FOR TYPE OF DECAY OR BIOLOGICAL LIFETIME
BIOLOGICAL HAZARD POTENTIAL (BHP)	$\left(\dfrac{\text{CURIES}}{\text{MAX. PERMIS. CURIES IN AIR OR } H_2O} \right)$	INCLUDES SEVERITY OF EMITTED RADIATION AND BIOLOGICAL RESIDENCE TIME

The choice of coolants is rather obvious although with respect to Li in fusion, it contributes very little in the way of radioactivity. Replacing Li with other nonactivating coolants would have virtually no effect on the inventory of radioisotopes.

There are several ways to compare the radioactive inventory of the two nuclear systems but for the purposes of this paper we will separate the fuel inventory from that of the structural components.

Figure IV-9 shows the BHP hazard of the fuel inventories at the three times stated earlier. The first point is that at 1 day after shutdown the fission products are 10,000 times more hazardous for an air release than the loss of all the fuel in a DT fusion reactor. Secondly, if one just considered the volatile fission products it is found that they are still 100 times more than the BHP for the tritium.

One year after shutdown the BHP of the fusion fuel has not changed substantially while that of the LMFBR fuel has dropped because of reprocessing. The volatile component has dropped by 2 orders of magnitude to 2-3 km^3 of air per kW_{th}. Finally, after 1000 years, there would be no trace of the T_2, the volatile FP have decayed to $\sim 10^{-6}$ km^3/kW_{th} but the residual actinides plus fission products keep the overall BHP high for fission reactors.

A similar plot has been made for the structural material and is shown in Fig. IV-10. Here we see that in fact, per unit of energy produced, the radioactivity in a steel fusion reactor is 6-7 times that of the core + Na coolant in an LMFBR. The situation does not change much in one year and after 1000 years the fusion structure is still potentially 100 times more hazardous than the structures of an LMFBR.

It is worthwhile to see how the substitution of other structural materials might change the results of Fig. IV-10. In Fig. IV-11 the BHP values for Mo, Nb, V, Ti and Al are compared to the steel values. From these numbers one can see that all of the above-mentioned alloys have BHP's equal to or greater than the LMFBR materials shortly after shutdown. This changes somewhat after one year with Nb and Mo alloys looking better. After 1000 years the radioactivity in the V and Ti alloys has essentially disappeared, while that of Al, Mo, and Nb alloys is actually higher than that for steel.

The sum of the BHP for the two systems is shown in the Fig. IV-12. We have shown the 1 day BHP in terms of air release consistent with an accidental release and the 1000 year BHP in terms of water release consistent with a leaching in the ground storage area. The point is amply made here that in both cases the BHP of fusion systems is far less than that in the fission reactor. This is even true for the volatile components and if we use other structural elements than 316 SS.

The overall conclusion is that, as far as potential radioactive hazards are concerned, fusion represents a less hazardous energy source. However, the fusion community must also realize that while it has a factor of 10 or 100 edge over fission, these are still large amounts of radioactivity to be contained and even release of only 1% of the tritium inventory would equal all of the gaseous (Kr, Xe) radioactivity released in the 3 Mile Island incident.

Figure IV-9

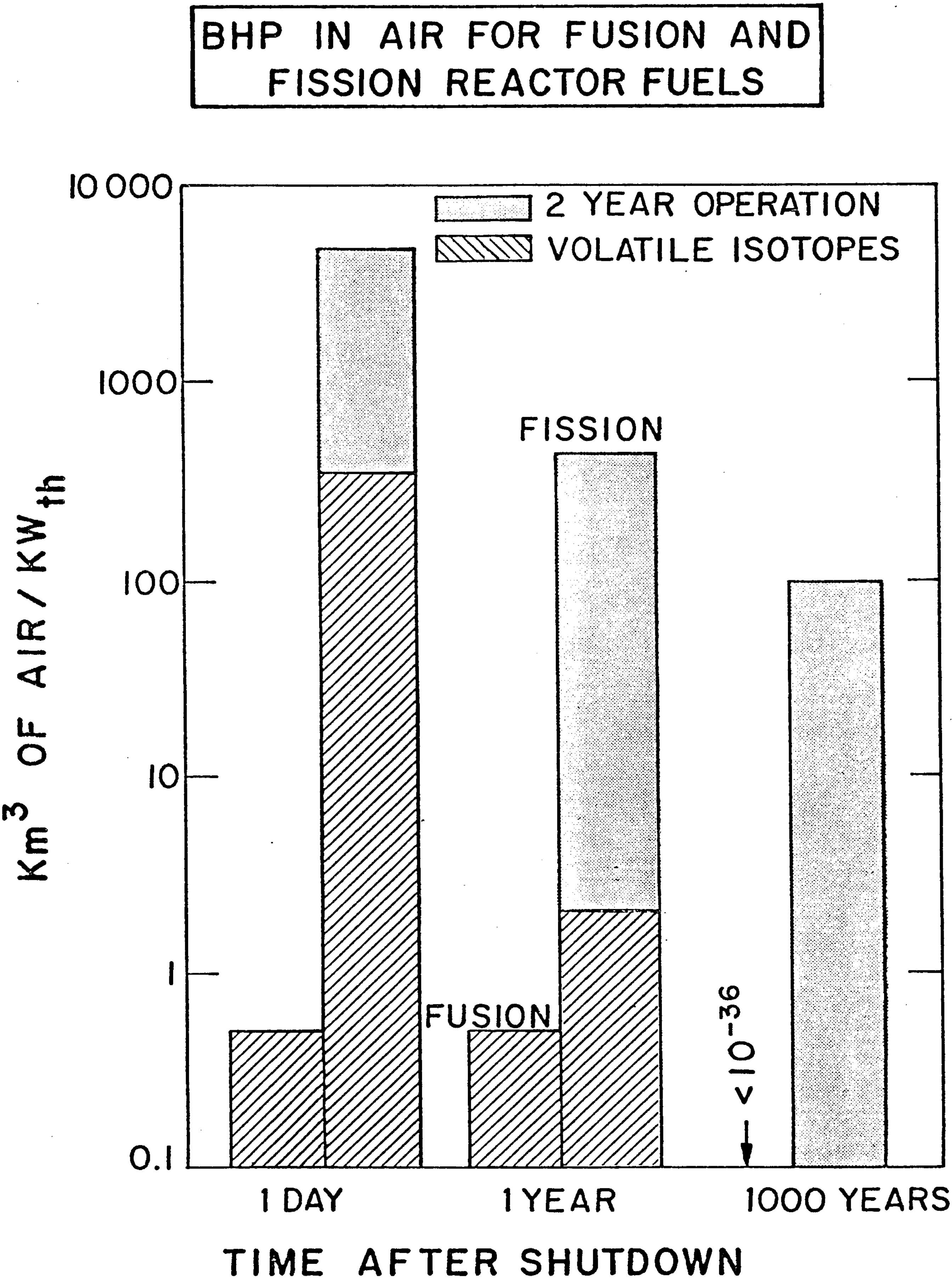

BHP IN AIR FOR FUSION AND FISSION REACTOR FUELS
2 YEAR OPERATION
VOLATILE ISOTOPES
10 000
1000
100
10
1
0.1
Km^3 OF AIR / KW_{th}
FISSION
FUSION
< 10^{-36}
1 DAY
1 YEAR
1000 YEARS
TIME AFTER SHUTDOWN

Figure IV-10

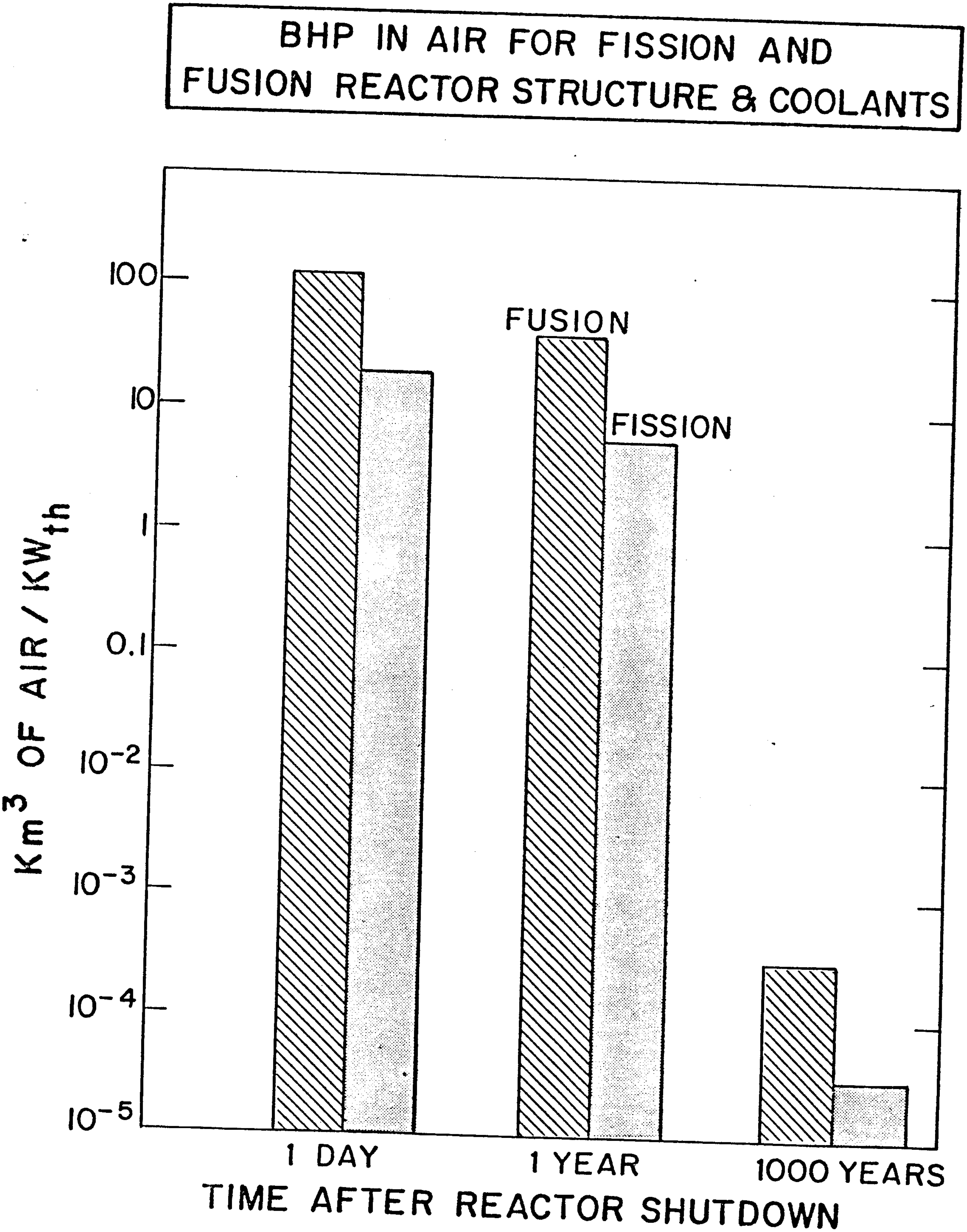
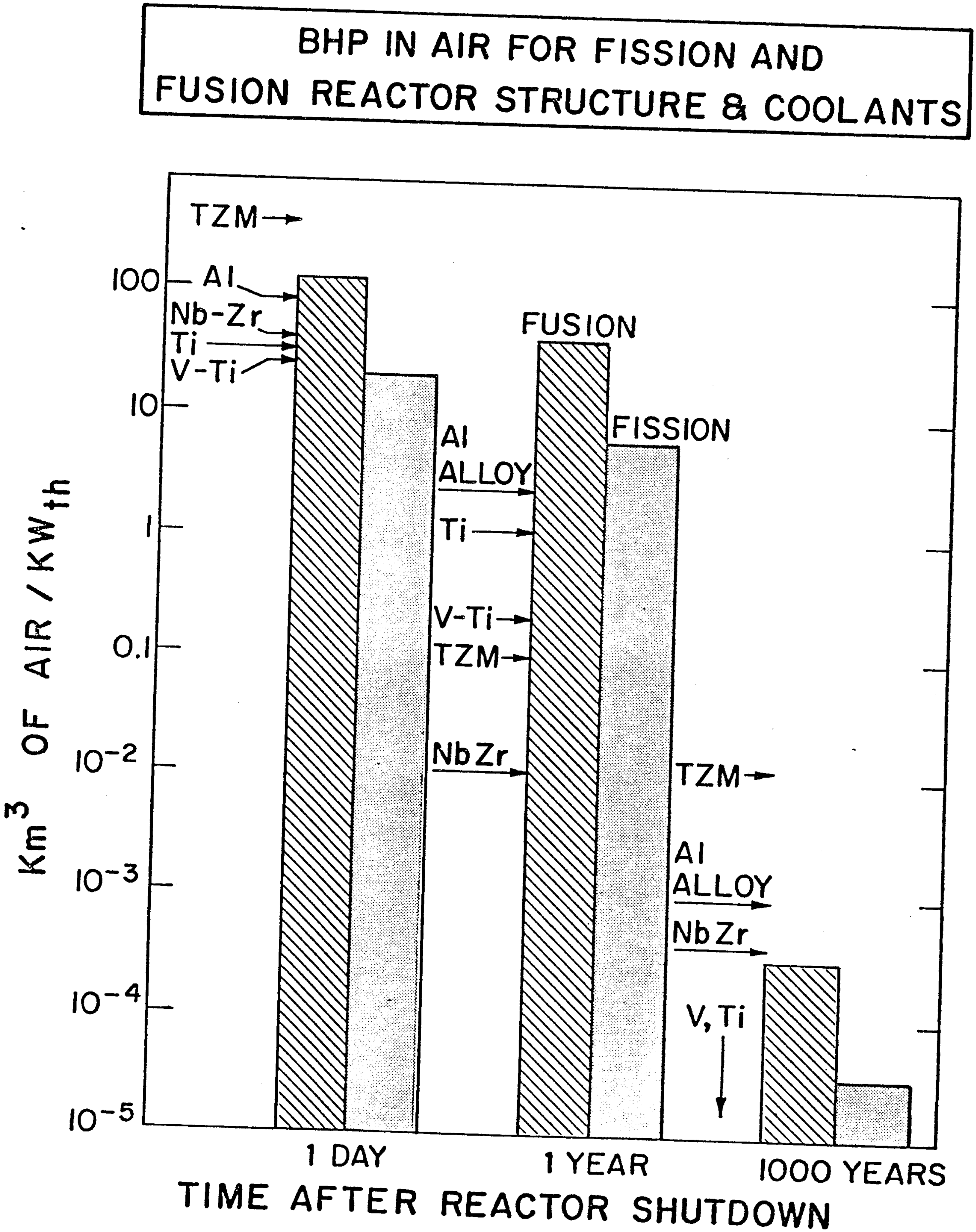

BHP IN AIR FOR FISSION AND
FUSION REACTOR STRUCTURE & COOLANTS
100
10
1
0.1
10^-2
10^-3
10^-4
10^-5
Km^3 OF AIR / KW_th
FUSION
FISSION
1 DAY
1 YEAR
1000 YEARS
TIME AFTER REACTOR SHUTDOWN

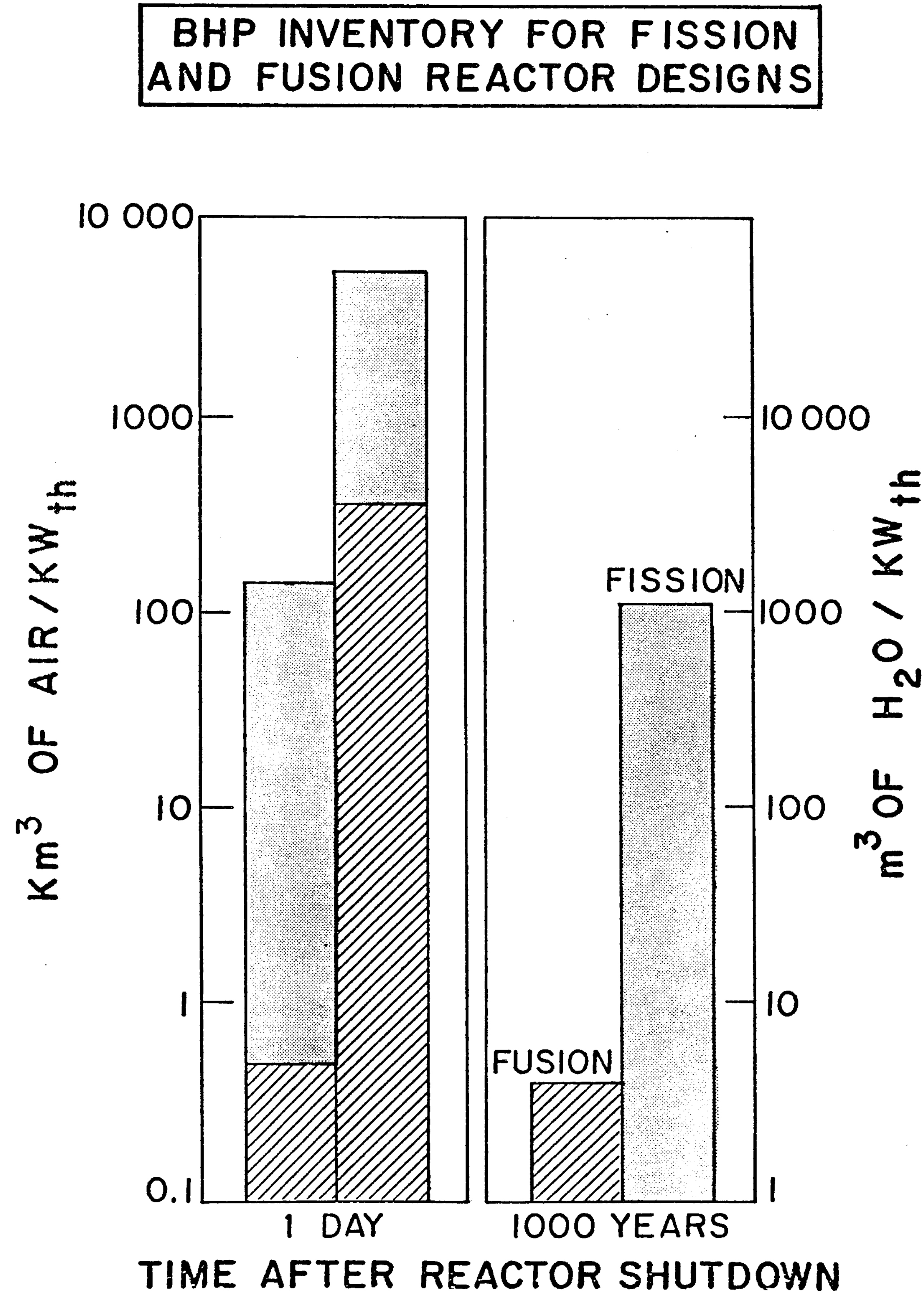
Figure IV-11



BHP IN AIR FOR FISSION AND
FUSION REACTOR STRUCTURE & COOLANTS
Km3 OF AIR / KWth
100
10
1
0.1
10-2
10-3
10-4
10-5
TZM
Al
Nb-Zr
Ti
V-Ti
FUSION
FISSION
Al
ALLOY
Ti
V-Ti
TZM
NbZr
TZM
Al
ALLOY
NbZr
V, Ti
1 DAY
1 YEAR
1000 YEARS
TIME AFTER REACTOR SHUTDOWN

Figure IV-12

Note: Cross-hatched regions represent volatile isotope contributions.



4. Emissions Associated with the Production of Electricity

During the course of procuring fuels, structural materials and operation of any power plant there can be significant emissions of harmful substances to the air and water. The major types of emissions will be listed here and some attempt made to put them into perspective on a unit of energy basis.

a. Air Emissions

A study prepared for the Environmental Protection Agency has investigated the full range of chemicals and radioactivity emitted into the atmosphere for the LWR and coal-fired systems [26]. A more recent study has also looked at the fuel cycle emissions for the LMFBR and fusion reactor [28], and we will try to summarize that work here.

Table IV-13 lists the emissions associated with the production of 1 GW_e-y of energy. The sources are broken up into the fuel procurement and preparation area, the operation of the electric plant, and the reprocessing of the fuel. The data for preparation of the initial LMFBR fuel elements are derived from the LWR values, appropriately reduced by the amount of LMFBR fuel used (~5% of the LWR case). Unfortunately there are no data on the non-radioactive emissions for the procurement or reprocessing of the fusion fuel but the numbers are probably quite small and in the latter case contained within the power plant itself.

The radioactive emissions are, as might be expected, higher for the LWR than all the other systems. Most of this comes from the release of Kr, Xe, and tritium during reprocessing of the fuels. The radioactive releases from the LMFBR fuel cycle are anticipated to be a factor of 20 below those of the LWR (normalized on a MW_e-y basis) and, if fusion plants can meet the tritium release level of 10 curie per day, the radioactivity from the fusion plants could be roughly 1% of the LWR values.

The emission of non-radioactive substances such as SO_2, SO_x, NO_x, NO_3, CO, etc., are of great concern to society. It is not surprising that the major "offenders" in this regard are the coal-fired plants but there is also some nitrogen oxide and sulfur oxide pollution associated with the procurement of uranium. Table IV-13 reveals that over 50,000 tonnes of SO_2 could be emitted per GW_e-year from coal plants if no efforts were made to remove it from stack gases. Likewise over 25,000 tonnes of nitrogen oxide are also emitted per GW_e-y along with over 1500 tonnes of CO.

We have seen previously that such high levels of pollutants can have severe health effects, especially to the elderly. However, here we are concerned about the environmental effects such as acid rain. This phenomenon results when the sulfuric acid and nitric acids formed from the SO_2 and NO_x emissions are washed from the upper atmosphere and end up in the rivers and lakes. The lowering of the pH can impair the egg producing ability of fish, sharply reduce the plankton supply, and increase the levels of Hg and other harmful metals in lakes by dissolving them from the sediments where they are normally insoluble. Scientists in Scandinavia estimate that acid rain has

Table IV-13

Summary of Gaseous Effluents Emitted GW_e-y [26], [28], [33]

Effluent	Fuel Procurement and Preparation				Electric Plant Operation				Reprocessing				Total			
	Coal	LWR	LMFBR	Fusion	Coal	LWR	LMFBR	Fusion	Coal	LWR	LMFBR	Fusion	Coal	LWR	LMFBR	Fusion
Radioactive-Ci																
Rn^{222}	---	56.7	~3	---	---	---	---	---	---	---	---	---	---	56.7	~3	---
Th & Ra Isotopes	---	0.0452	~0.002	---	0.013	---	---	---	---	---	---	---	0.013	~0.045	~0.002	---
U	---	0.0487	~0.002	---	---	---	---	---	---	---	---	---	---	~0.049	~0.002	---
Tritium	---	---	---	---	---	50	350	~3700(est)	---	20,580	3000	?	---	20,030	3350	3700
I^{131} + Isotopes	---	---	---	---	---	0.8	0.01	---	---	0.06	0.003	---	---	0.86	0.013	---
Kr + Xe Isotopes	---	---	---	---	---	7000	0.43	---	---	373,000	16,000	---	---	380,000	16,000	---
Other F.P.	---	---	---	---	---	---	---	---	---	0.918	---	---	---	0.918	---	---
Transuranics	---	---		---	---	---	---	---	---	0.0037	0.005	---	---	0.004	0.005	---
C-14	---	---	---	---	---	---	---	---	---	---	50	---	---	---	50	---
Total (rounded)	---	57	~3	---	0.013	7000	350	~3700(est)	---	394,000	19,000	Small	0.013	401,000	19,400	~3700
NonRadioactive-tonnes																
NO_x	260	23.0	~1		27,300	---	---	---	---	7.4	~0.3		27,600	30	~1	
NO_3	---	23.0	~1		---	---	---	---	---	---	---		---	23	1	
NH_3	---	10	~0.5		---	---	---	---	---	---	---		---	10	0.5	
SO_2	20	0.226	~0.01		57,600	---	---	---	---	---	---		57,600	0.226	0.01	
SO_x	---	22.4	~1	NA	---	---	---	---	---	---	---	NA	---	22.4	~	NA
Fluorides	---	1.19	~0.05		---	---	---	---	---	---	---		---	1.19	~0.05	
Particulates	120	---	---		15,000	---	---	---	---	---	---		15,100	---	---	
CO	140	---	---		1,516	---	---	---	---	---	---		1,656	---	---	
Hydrocarbon	40	---	---		454	---	---	---	---	---	---		494	---	---	
Aldehydes	---	---	---		7.6	---	---	---	---	---	---		7.6	---	---	
Total (rounded)	580	79	~3.6	NA	101,900	Small	Small	Small	---	7.4	~0.3	NA	102,500	87	~4	NA

NA - not available

recently caused a 15% reduction in timber growth and the structural damage in the United States is estimated at 2 billion dollars per year. Obviously, the lack of such problems with fusion, and to some extent with fission is an important and positive feature.

Another serious problem that the building of fusion reactors would avoid is the emission of large amounts of CO_2 during the production of electricity. A typical coal plant produces ~10^7 tonnes of CO_2 per GW_e-y. The current CO_2 content in the atmosphere is 700 x 10^9 tonnes. The rate of addition of CO_2 is currently ~2 x 10^9 tonnes per year. If the use of carbon based fuels continued to grow at only 5% per year, the CO_2 content of the atmosphere could double by the year 2035 even accounting for some absorption of CO_2 in the environment. While the exact effects of such an increase in CO_2 content of the upper atmosphere are not known, it is fairly certain that substantial temperature increases (~5-10°C) could take place at the polar ice caps [27]. Such an event would greatly affect the level of the oceans and could even cause permanent climatic changes with dramatic effects on food production. Hence the use of both fission and fusion to replace coal plants would greatly reduce this problem and therefore have a much less harmful impact on the environment.

b. Emission to Water Systems

As with the land use and air emission considerations, it is important to recognize that the total impact of power plants must include the fuel cycle outside the plant as well as the plant itself. The release of acids into streams around mines, smelters, and fuel preparation facilities is just as important as releases of chemicals and radioactivity from the power plant. We have relied on the Teknekron study [26] for data on coal and LWR systems and the IIASA Report [28] for the LMFBR system. The results are given in Table IV-14.

The major problems with the normal releases into the water are:

1. The tritium from the fusion and fission reactors.

2. The acid wastes from coal mining.

The tritium release values for LWR's are quite well-established and the values for the LMFBR are taken from reference [28]. The values for fusion are estimated to be ~10 curie/day, typical of most designs, but obviously no experience is available.

The more than 30,000 tonnes of acid released during the mining of coal for 1 GW_e-y is a major environmental problem for small streams around the mines and it certainly aggravates an already serious problem of acid rain run-off into lakes and rivers. There are also some acid release problems associated with the mining of and preparation of U but these amount to ~10 tonnes per GW_e-y versus tens of thousands of tonnes in the case of coal. There is, at this point, no identifiable source of acid discharge in the DT fuel cycle

Table IV-14

Summary of Water Effluents from Power Plants - per GW_e-y

Effluents	Fuel Procurement and Preparation				Plant Operation				Waste				Total			
	Coal[a]	LWR	LMFBR	Fusion	Coal	LWR	LMFBR	Fusion	Coal	LWR	LMFBR	Fusion	Coal	LWR	LMFBR	Fusion
Radioactive-Ci																
U	---	0.29	0.03	---	---	---	---	---	---	---	---	---	---	0.29	0.03	---
Ra^{226}	---	0.30	0.03	---	---	---	---	---	---	---	---	---	---	0.30	0.03	---
Th isotopes	---	3.23	0.32	---	---	---	---	---	---	---	---	---	---	3.23	0.32	---
H^3	---	---	---	---	---	450	350	3700[b]	---	3340	8000	?	---	3340	---	3700[b]
Ru^{106}	---	---	---	---	---	---	---	---	---	3.67	---	---	---	3.67	---	---
α emitting Pu isotopes	---	---	0.0002	---	---	---	> 2	---	---	---	---	---	---	---	0.0002	---
Pu^{241}	---	---	0.0005	---	---	---	---	---	---	---	---	---	---	---	0.0005	---
NonRadioactive-tonne																
NaCl	---	24.4	2.44	NA	---	---	---	---	NA	---	---	---	---	24.4	2.44	NA
Ca^+	---	7.91	0.79	NA	---	---	---	---	NA	---	---	---	---	7.91	0.79	NA
$SO_4^=$	---	7.91	0.79	NA	---	---	---	---	NA	0.415	~0.4	---	---	8.32	1.19	NA
Fe	---	0.52	0.05	NA	---	---	---	---	NA	---	---	---	---	0.52	0.05	NA
NO_3^-	---	3.96	0.40	NA	---	---	---	---	NA	0.176	~0.2	---	---	4.14	0.6	NA
CaF_2	---	33.8	3.38	NA	---	---	---	---	NA	---	---	---	---	33.8	2.38	NA
Dissolved solids	31,700	---	---	NA	4270	7180	?	?	NA	---	---	---	35,970	7180	---	NA
Na^+	---	---	---	NA	---	---	---	---	NA	5.03	~5	---	---	5.03	~5	NA
Cl^-	---	---	---	NA	---	---	---	---	NA	0.23	~0.2	---	---	0.23	~0.2	NA
Acid	33,200	---	---	NA	02.5	---	---	---	NA	---	---	---	33,300	---	---	NA
Suspended solids	59,700	---	---	NA	497	---	---	---	NA	---	---	---	60,200	---	---	NA
Organics	---	---	---	NA	66.2	---	---	---	NA	---	---	---	66.2	---	---	NA
BOD	---	---	---	NA	2.4	---	---	---	NA	---	---	---	2.4	---	---	NA
Cl_2	---	---	---	NA	26.3	---	---	---	NA	---	---	---	26.3	---	---	NA
Phosphates	---	---	---	NA	41.7	---	---	---	NA	---	---	---	41.7	---	---	NA
Boron	---	---	---	NA	331	---	---	---	NA	---	---	---	331	---	---	NA
Chromates	---	---	---	NA	2.4	---	---	---	NA	---	---	---	2.4	---	---	NA

(a) Open pit mining.

(b) Tritium would be released to either air or water, but probably not both.

(i.e., from Li mining or deuterium extraction) but a proper detailed accounting of the production of non-fuel related construction materials might reveal some more information along these lines.

In summary, the major advantage of fusion in this regard is the lack of any substantial acid release into the water. Releases of radioactive tritium will probably be on the same order of magnitude as for fission plants.

V. Conclusions

Although many conclusions become apparent after reviewing the preceding information, eleven points stand out and should be emphasized:

(1) *The optimism about the successful demonstration of net energy from magnetic fusion is real and supported by a firm base of theory and experimental facilities. It is only a question of 5 to 10 years before fusion will be elevated from its present status of an "exotic" future energy source to one which will be seriously considered alongside the breeder and the extensive use of coal as the means to generate electricity during the 21st century.*

(2) *The introduction rate of fusion reactors into the U.S. and world economies could take place as early as 2010 but it will be the year 2020 to 2030 before 5% of the world's or the U.S. electrical generating capacity could be in fusion power plants.*

(3) *Fusion reactors are characterized by high capital and low fuel costs. At the present time the* capital *costs of fusion reactors are estimated to be 25% higher than the LMFBR and 2.7 times higher than coal fired units. However, the fuel costs for coal are almost 4 times those of the breeder and 15 times those of fusion. This means that under normal circumstances, the busbar costs of electricity from fusion are only 50% and 20% higher than from coal or the breeder respectively. However, if the fuel prices rise faster than inflation (as has been the case for coal and U since 1973), then the levelized cost of electricity from fusion reactors can be cheaper than either coal or LMFBR plants. The increase in the inflation rate above the normal value at which the fusion electricity costs equal those from coal and the LMFBR is 4% and 6% respectively.*

(4) *The minerals resource picture for fusion, which looked bleak in the early reactor designs, has now become more promising. It appears that with the exception of Cr, all the materials resources required for a 300* GW_e *economy could be obtained from domestic resources at present, or up to 3 times present prices. World reserves are sufficient to support a 1200* GW_e *economy with the exception of Be, W and possibly Co and Cu. It is possible to substitute Pb for the neutronic properties of Be or the shielding properties desired from W. Aluminum could be substituted for Cu and Co is a problem for all systems which require high strength, high temperature alloys for electricity generation.*

(5) *One of the biggest assets of a fusion economy is the extremely small amount of fuel needed to generate energy. Not only is this a factor in the cost of fusion electricity, but it is also important in assessing the overall risk of fusion plants. Mining and transporting large amounts of material to the power plant are known to be extremely hazardous professions. Conservative estimates reveal that to procure the fuel for 100* GW_e*-y of energy will cost the lives of*

to procure the fuel for 100 GW_e-y of energy will cost the lives of 200-400 workers in the coal industry, ~ 20 workers in the uranium industry for LWR's and ~ 1 worker for the LMFBR. The corresponding number for fusion is estimated to be a maximum of 0.1 worker per 100 GW_e-y.

(6) *Contrary to early studies which showed that the lower power density of fusion reactors leads to excessively high non-fuel materials requirements, this study comes up with a different conclusion. The difference lies in considering the whole cycle of materials procurement including those materials required to mine and transport fuel to the reactors. When the non-reactor structural material (e.g., locomotives, railroad cars, excavating equipment, mine shafts, etc.) are included, one finds that coal plants require almost 80% more metallic elements, such as steel, than fusion plants. Coal plants also require enormous amounts of lime to treat wastes and this causes large demand on materials for transportation and handling.*

On the other hand, current fusion reactor designs seem to require more concrete. They require anywhere from 50 to 250% more concrete than fission reactors or coal plants. Future examinations should investigate this area more fully.

(7) *When the risks associated with the procurement of fuels, the building of power plants and the effects of plant emissions are put together, one finds that fusion is safer than the coal and fission systems by factors of more than 10 to 1000 per GW_e-y of energy generated. The major reductions in accidental deaths compared to coal fired plants come from reduced mining and transportation accidents while the reduction in disease related deaths comes from the lack of harmful emissions to the atmosphere.*

(8) *Because of the greatly reduced requirement for fuels, even compared to the LWR case, the land usage required to generate a unit of energy from fusion reactors is a factor of 10,000 lower than for coal and 100 lower than for LWR fission reactors. It appears that the major impact on land usage for fusion plants will be to procure the concrete, a problem we already must live with for the general construction industry.*

(9) *The use of water for fusion power plants also looks to be considerably less (by a factor of 7) than for coal plants and about the same for the LMFBR. It is important to recognize that in the case of coal and LWR systems much more water is required per GW_e-y to mine the fuels than to cool the plant using dry cooling towers. The lower water requirements to procure fusion fuel tends to offset the higher thermal efficiency of LMFBR's so that the total water commitments are about the same for both systems.*

(10) *A lack of harmful emissions to the air is perhaps one of the greatest advantages of fusion compared to coal plants. The SO_2 and*

acid rain phenomenon which is alarming citizens all over the world. Similarly, the lack of CO_2 emissions means that fusion does not contribute to potential climatic changes due to the trapping of infrared radiation by the increased CO_2 in the atmosphere. Finally, because there is no obvious operation, such as fuel reprocessing, in the fusion systems that would routinely release large amounts of radioactivity, the total radioactive inventory in the atmosphere would be reduced by fusion. The release of Kr, Xe, and other volatile isotopes during fuel dissolution is completely avoided in the DT fusion cycle and only one volatile isotope, tritium, needs to be contained during fuel handling processes.

(11) *The lack of significant emissions of harmful substances to the water, both during the operation of the plant or during the procurement of fuel, is another major advantage of fusion. There are no large mine tailings to be acid leached over time nor will there be the problem of containing hundreds to thousands of tonnes of sludge from the combustion products of coal fired plants.*

As a final note, it appears that the generation of electricity from fusion reactors would represent a dramatic improvement in the level of risk to humans and the environment when compared to coal plants. Because of the reduced fuel requirements there is also a significant improvement when fusion is compared with the LWR system. The difference between DT fusion and the LMFBR is smaller, but still in favor of fusion. However, in the latter comparison the proliferation issue and long term waste issues may turn the tide heavily in favor of fusion. With the cost issue looking reasonably promising, it appears that the major barriers to the extensive use of fusion power is only a matter of time; the time required to finish the final "chapters" in the physics area and the time to build and test hardware for the reactors. It is comforting to know that such an energy source exists and that in the lifetime of the present generation of young people, a significant fraction of our energy could be supplied by a fusion economy.

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