



Minerals Resource Implications of a Tokamak Reactor Economy

E. Cameron, R.W. Conn, G.L. Kulcinski, and I. Sviatoslavsky

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Abstract

The mineral resource implications of an economy of tokamak-type fusion reactors are assessed based upon the recent conceptual reactor design study, NUWMAK, developed at the University of Wisconsin. For comparative purposes, various structural alloys of vanadium and steel are assumed to be usable in the NUWMAK design in place of the titanium alloy originally selected. In addition, the inner blanket core and magnet system of the conceptual reactor, HFCTR, developed at the Massachusetts Institute of Technology, are assumed to be interchangeable with the comparable components in NUWMAK. These variations permit a range of likely requirements to be assessed.

A comparison of present reactor design requirements with requirements based on earlier design studies shows that the drain on mineral resources due to development of a fusion economy will be less than originally expected.

The future availability of various required mineral derived materials will be first and foremost a function of the size and quality of U.S. and free world mineral resources, since these set limits on availability. Availability, however, is also a function of U.S. and free world extractive capacity and fabricating capacity. Additional considerations are the time factor in mineral development, the energy costs of metal production, and environmental impacts.

Free world extractive and fabricating industries can be expected to respond to future increases in demand for the materials required for fusion reactors. The response of the corresponding U. S. industries, however, is much less certain. Since World War II, the U.S. has become increasingly dependent

on foreign sources for most of the metals on the fusion list, and future increases in U.S. extractive and fabricating capacity for those metals cannot be assumed.

Requirements for various metals, carbon, and helium for a 300 GW_e fusion economy and a 1200 GW_e free world fusion economy are examined against U.S. and free world reserves at present prices and at three times (3X) present prices, and against present U.S. and free world production and consumption of those substances. Given conditions favorable to growth in U.S. extractive and fabricating capacity, the boron, iron, magnesium, zirconium, lead, lithium, helium and molybdenum needed for a 300 GW_e U.S. fusion economy could be available from domestic deposits at present prices. Manganese, vanadium, copper, aluminum, iron, and possibly niobium and nickel could be available at 3X present prices. For tin, chromium, tungsten, cobalt, and possibly nickel, heavy dependence on foreign sources is likely even at the higher price level. Requirements could place a heavy burden on world resources of tungsten, beryllium, and cobalt, but beryllium and tungsten could be eliminated by substituting lead to perform the design functions of both metals. The cobalt requirement arises from its use in steam generators and is not specific to fusion.

The present study indicates that future designs of fusion reactors should stress reduction in size and minimum use of the less abundant metals. This is particularly important if a free world fusion economy beyond 1200 GW_e is envisioned.

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I. Introduction

An energy source places a requirement on mineral resources for materials of construction. As research in controlled nuclear fusion progresses, efforts are being made to assess the form of fusion reactors and to identify technical issues as a guide to further research and development. A series of reactor studies has been published by the Fusion Reactor Study Group at the University of Wisconsin⁽¹⁻⁸⁾ based upon the tokamak concept. The first study published in 1973 is UWMAK-I.^(1,2) The most recent study, NUWMAK^(7,8), has been published in reports and papers during 1978 and 1979. The early reactor conceptual designs were pathfinding efforts, conservatively conceived in the process of developing knowledge, and an economy of such reactors would have placed great requirements on resources.⁽¹⁾ The most recent and more optimized NUWMAK study is based upon our current understanding of tokamak plasma physics and upon a much greater body of knowledge in the area of fusion technology. In this paper, we summarize the minerals resource requirements of a 300 GW_e economy of NUWMAK-type fusion reactors and assess the implications for five different primary materials of construction: three types of stainless steel, a titanium alloy and a vanadium alloy are included to provide perspective. Steel is the most likely near-term material of construction while titanium and vanadium alloys hold great promise for future applications. In addition, the blanket design and magnet system for the comparably sized conceptual High Field Compact Tokamak Reactor (HFCTR) developed at MIT^(9,10) are assumed to be substituted into the NUWMAK design to assess the influence of a different design approach to two important subsystems.

The paper is structured to provide both the context for the minerals resource assessment and the specific results on resource requirements and procurement of metals. Energy growth scenarios and the potential role of fusion reactors are discussed in Section II. An overview of tokamak reactors, the NUWMAK system and earlier design concepts are given in Section III. In Section IV, the specific materials requirements are given with some discussion of factors influencing requirements. The availability of materials for fusion reactors is discussed in Section V. Reserves and resources, both within the United States and worldwide, are considered at present and three times present prices. Also discussed are factors which determine availability, estimates of availability in light of assessed requirements, some environmental factors in the extraction of metals for fusion reactors, the sensitivity of the results to changes in the equilibrium fusion electric power contribution (from 100 to 1000 GW_e), and the influence of material substitutability to eliminate difficulties in availability, particularly for beryllium and tungsten. We close with a summary and conclusions in Section VI.

II. Energy Scenarios and Fusion

The 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 the world population increase is coupled to an increase in the average energy use per capita, the result will be a large increase in energy use above the present level. (The present value of 2 kW/capita is moving towards 3-4 kW/capita as the standard of living is raised in less developed nations.) It is probable that the total annual 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 ⁽¹¹⁾ (See Fig. 1). There is also a trend toward the use of more energy in the form of electricity. At present, electricity accounts for about 30% of total worldwide energy consumption. In the year 2000 the electrical fraction is projected to be about 40% worldwide (see also Fig. 1).

To estimate the fraction of the world and U.S. electrical markets that might be captured by fusion, it is obviously necessary to make 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 U.S. total and electrical generating demand⁽¹¹⁾ for the non-communist world will be used beginning in 2010. These predictions are summarized in Table 1.*
3. *The energy growth rates are assumed to follow the pattern given in Table 2.*

Figure 1

PROJECTED WORLDWIDE ENERGY RE- QUIREMENTS - NON COMMUNIST COUNTRIES

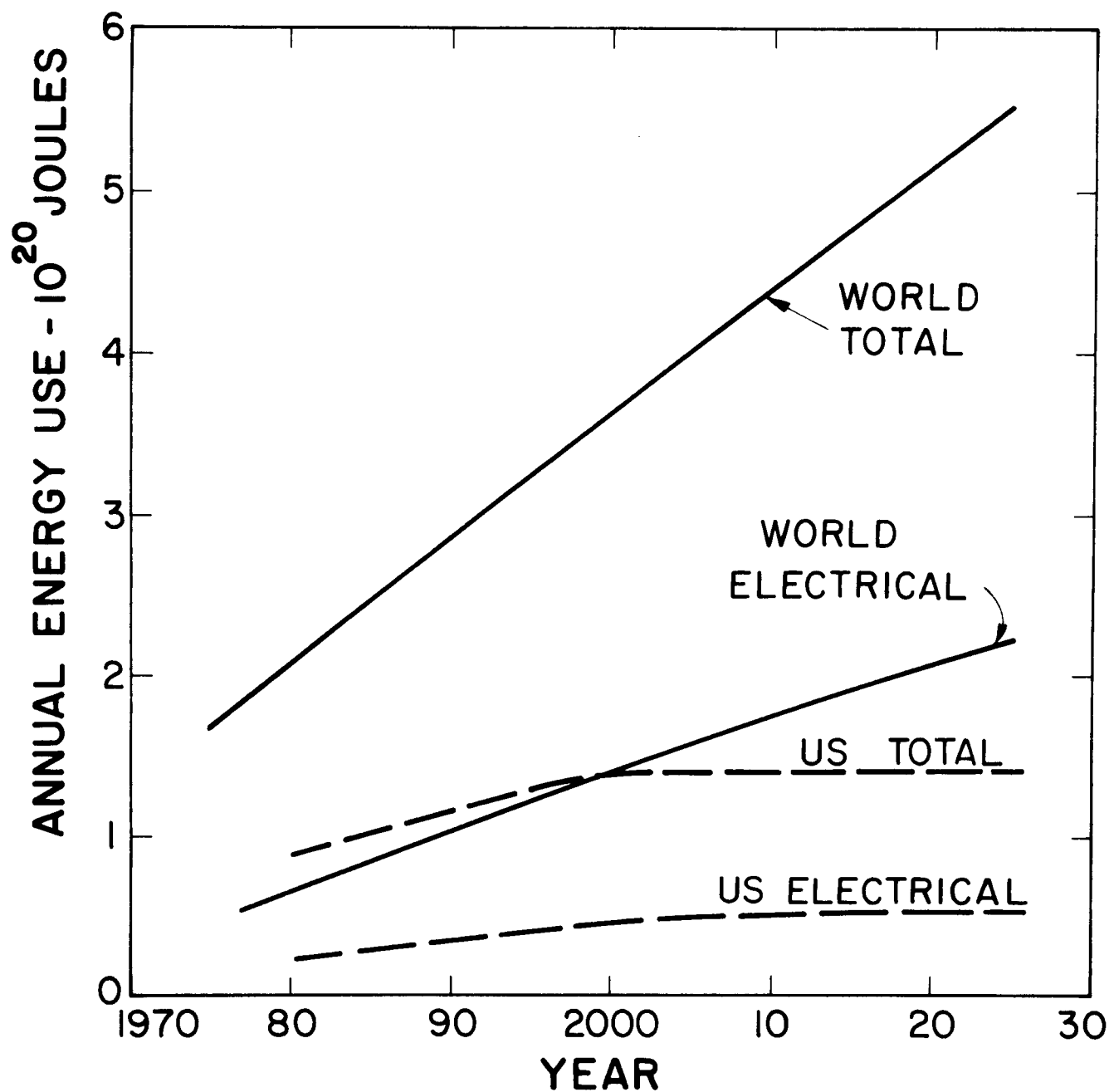


Table 1
OECD Predictions of Free World and U.S. Total
and Electrical Energy Demand⁽¹¹⁾ in 2010

	<u>World</u>	<u>U.S.</u>
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 2
Assumed Growth Rate Pattern for Total Energy and for Electricity (see Ref. 11)

	<u>Total Energy Growth Rate, %</u>		<u>Electrical Energy Growth Rate, %</u>	
	<u>World</u>	<u>U.S.</u>	<u>World</u>	<u>U.S.</u>
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	2.1	0.5
2010-2015	1.6	0	1.6	0.5
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

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⁽¹²⁾ as well as future projections⁽¹¹⁾ can be approximated by the curves shown in Fig. 2. As a high case, the fraction of new additions supplied by fission reactors increases from zero 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 is a reasonable assumption given the uncertainty over the future of the fission breeder reactor (particularly in the U.S.) and the fact that very few thermal fission reactors are likely to be built beyond the year 2030.*
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 reactor capacity as a function of time would follow the pattern given in Table 3. The projected electrical generating capacity, both total and from fusion alone, is given in Fig. 3. The fusion projections differ significantly from those in a scenario developed in 1973,⁽¹³⁾ prior to the Arab oil embargo and the downturn in energy growth curves. The fusion contribution to world electrical generating capacity was projected to reach 1000 GW_e by the year 2020.⁽¹³⁾ 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. 13); 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.

Figure 2

ACTUAL AND ANTICIPATED PENETRATION OF ELECTRICAL GENERATING CAPACITY BY FISSION REACTORS

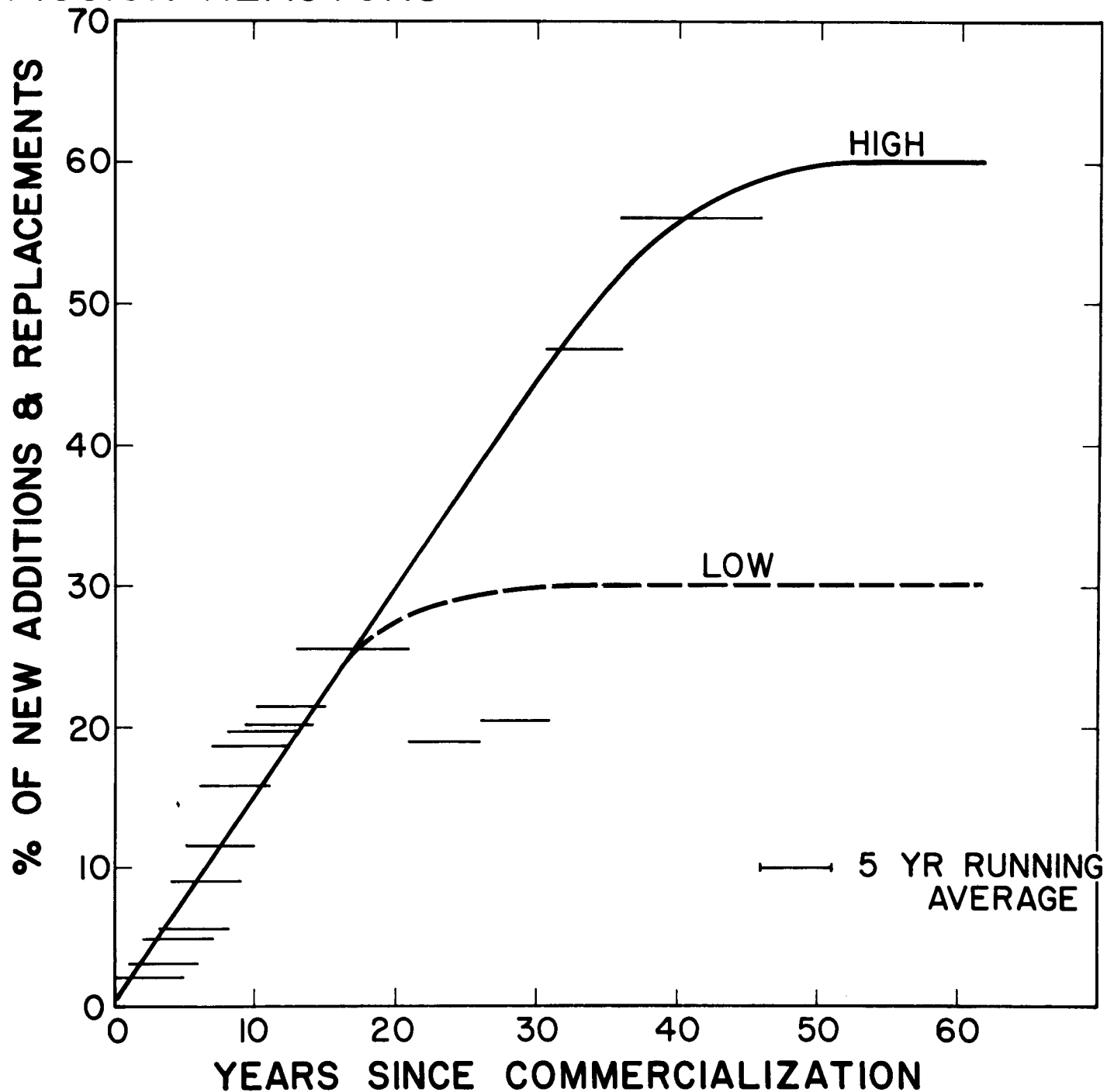


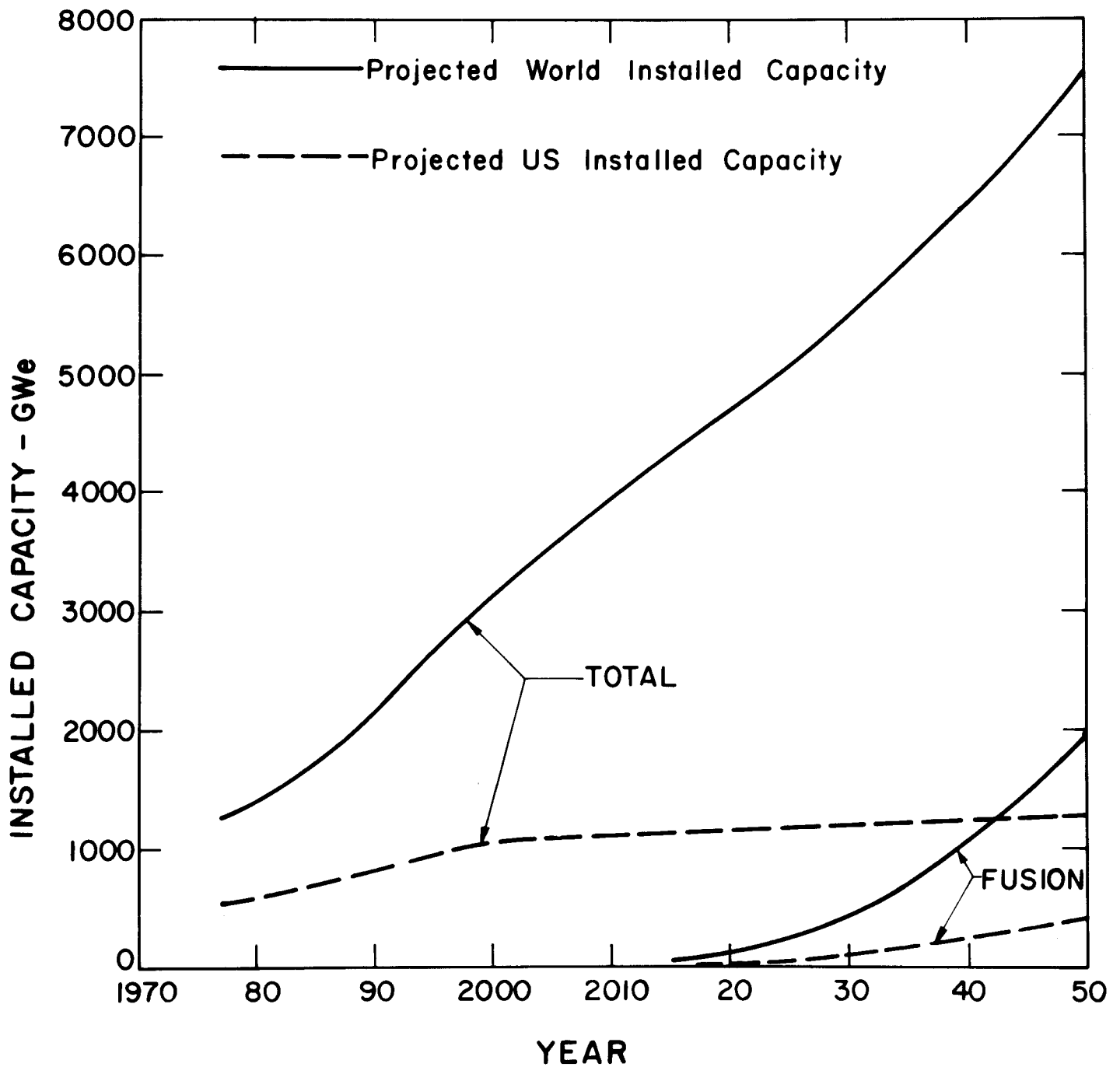
Table 3

Assumed Growth Pattern for Fusion Power in this Study

<u>Year</u>	<u>Generation Capacity in GW_e</u>	
	<u>Free World</u>	<u>U.S.</u>
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 3

PROJECTED WORLD-WIDE ELECTRICITY REQUIREMENTS - NON COMMUNIST COUNTRIES



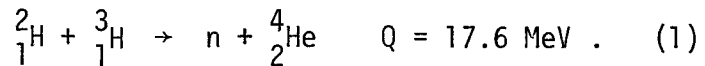
For the purposes of this paper, we have somewhat arbitrarily settled on 300 GW_e as the installed U.S. fusion capacity. The sensitivity of our results to changes in this level is tested by considering the installed capacity as 1000 GW_e. The high projection of fusion power penetration gives the time where these two levels are reached. For the U.S., one reaches 300 GW_e in 2042 and 1000 GW_e after 2070. For the free world (including the U.S.), the level of 300 GW_e is reached in 2027 and 1000 MW_e in 2040.

III. Fusion Reactions and the Tokamak

A. Fusion Fuel Cycles

The basic fuel of a fusion economy is deuterium, a stable hydrogen isotope with a concentration of 0.0148% of the occurring hydrogen atoms within ordinary water. The fuel cycles are:

1. Deuterium-Tritium Cycle

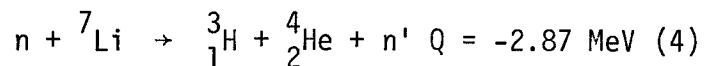
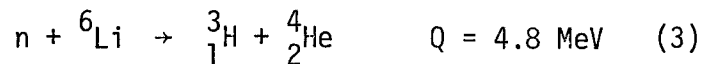


Deuterium (${}^2_1\text{H}$ or D) and tritium (${}^3_1\text{H}$ or T) are the most likely fuels to be used in the earliest fusion reactors because they begin burning at the lowest temperature, approximately 60×10^6 K. This temperature has already been reached in experiments using ordinary hydrogen.⁽¹⁴⁾

Tritium is radioactive and has a half-life of 12.35 years. It decays by emitting a low energy beta particle,



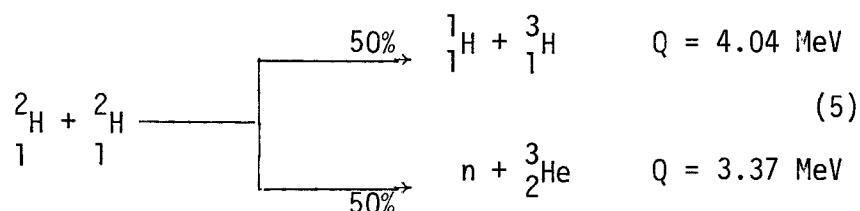
Tritium can be produced by capture of the neutron produced in reaction eqn. (1) in the two isotopes of lithium, ${}^6\text{Li}$ and ${}^7\text{Li}$:



The reaction with ${}^6\text{Li}$ is exothermic and will occur with neutrons of any energy. In particular, the reaction probability is highest with slow neutrons. The reaction with ${}^7\text{Li}$ 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 ${}^6\text{Li}$. Thus, it is possible to produce, on the average, more than one triton per triton consumed, that is, to breed tritium. All analyses show this to be a feasible process. Therefore, the primary fuel resources are deuterium and lithium.

2. Deuterium-Deuterium Cycle



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).

3. Deuterium-Helium-3 Cycle



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 ${}^3\text{He}$ is produced via D-D reactions and because it is the natural product of tritium decay. We expect to burn the ${}^3\text{He}$ produced from these pathways in deuterium based reactors.

B. The Tokamak

The tokamak is a toroidal magnetic plasma confinement device which operates on the principle of a DC electrical 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. 4. 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. 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, toroidal 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

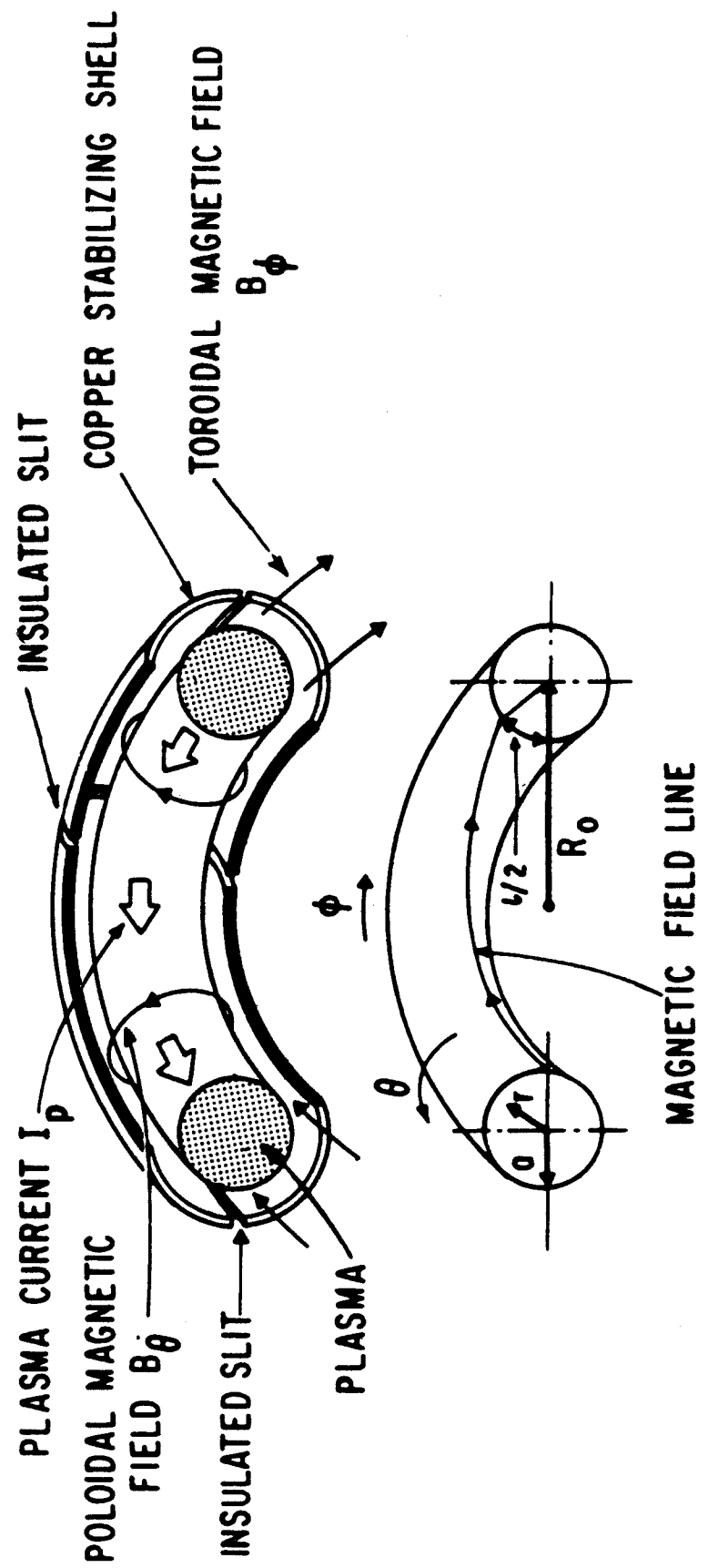
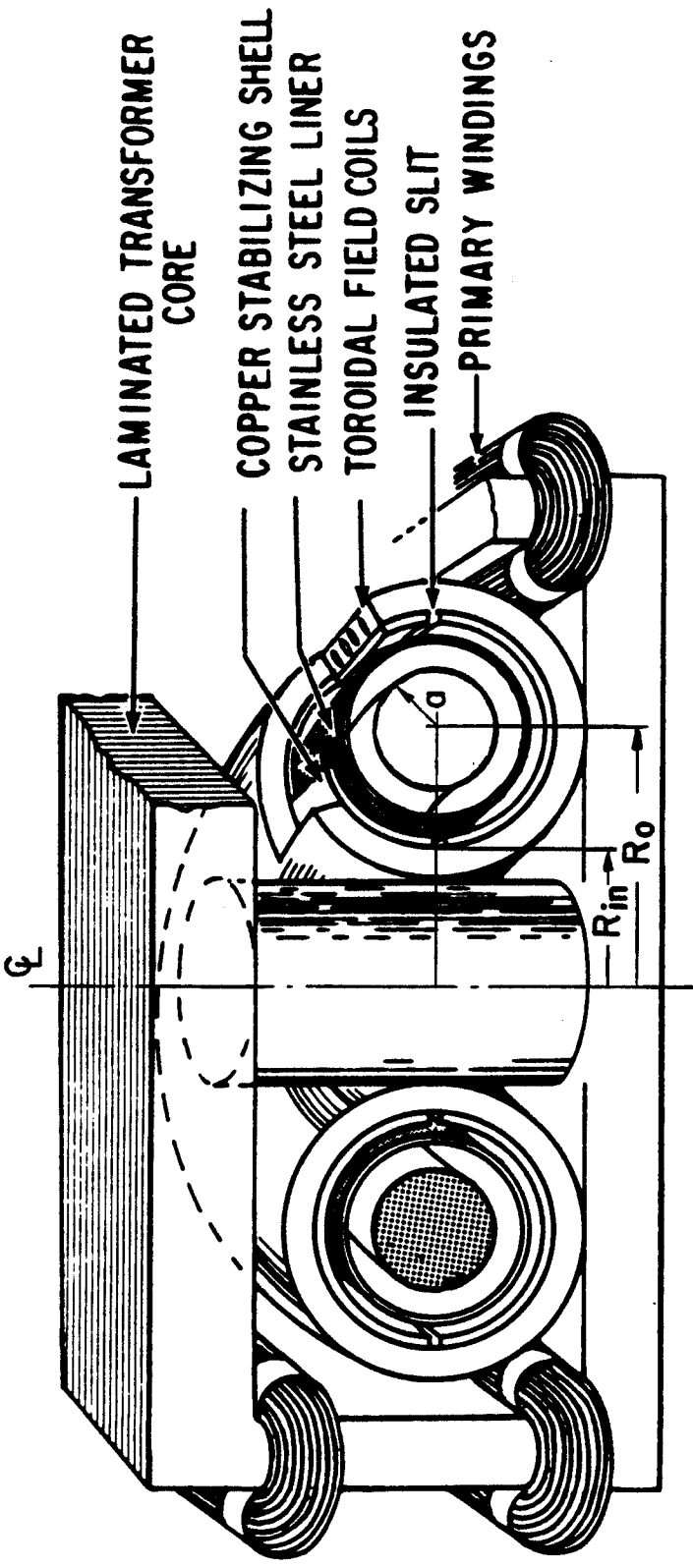


Fig. 4. Principal features of the tokamak magnetic confinement concept.

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 notions require experimental verification.

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. 4 are produced. The toroidal and poloidal fields are related by

$$B_T = B_\theta qA . \quad (7)$$

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 $10 B_\theta$ 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. 4) is

$$B_T^{\max} = \frac{R_o}{R_{in}} B_T^0 . \quad (8)$$

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

IV. Tokamak Reactor Design and Material Requirements

A. Reactor Designs and NUWMAK

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. The UWMAK-I design^(1,2) was published in 1973, the UWMAK-II design^(3,4) in 1975, the UWMAK-III design^(5,6) in 1976, and the NUWMAK design^(7,8) in 1979. Key parameters of these designs are summarized in Table 4. One major feature which influences mineral 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 unit size has decreased sharply. As an illustration, the cross section of UWMAK-I, an early design, is compared to that of UWMAK-III and NUWMAK in Fig. 5. It appears now 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 UWMAK-I 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 superconductor 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

Table 4

Tokamak Conceptual Reactor Parameters

	UWMAK-I ^(1,2) (1973)	UWMAK-II ^(3,4) (1975)	UWMAK-III ^(5,6) (1976)	NUWMAK ^(7,8) (1978)	HFCTR ^(9,10) (1978)
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MACHINE PARAMETERS

R(m)	13	13	8	5.2	6.0
a(m)	5	5	2.5	1.15	1.2
Plasma Height to Width b/a	1.0	1.0	2.0	1.6	1.5
Field at Plasma Center (T)	3.8	3.57	4.0	6.0	7.4
Max. Field at Magnet (T)	8.6	8.3	8.75	11.9	13.1
Fuel	DT	DT	DT	DT	DT

POWER PARAMETERS

Plasma Power Den. (W/cm ³)	0.78	0.78	2.3	9.3	7.7
Thermal Power (MW _t)	5000	5000	5000	2097	2470
Electric Power (MW _t)	1495	1716	1985	660	775
Neutron Wall Load MW/m ²	1.25	1.16	2.5	4.34	3.4
Plant Eff. (%)	N/S	N/S	41.9	31.5 net	31
Plasma Current (MA)	21	14.9	15.8	7.2	6.7
Safety Factor, q	1.75	2.3	2.5	1.09-2.6	3.0
Plasma Beta, β%	5	2.3	9	7	4
Aux. Heating Power (MW)	50	200	40	75-80	100
Type	Neutral Beam	Neutral Beam	RF	RF	Neutral Beam
Heating Time (s)	10	10	15s htg. by RF	1	5
Burn Time (s)	5400	5400	1800	224	500
Dwell Time (s)	390	490	100	21	20
Duty Factor	0.93	0.80	0.95	0.91	0.85

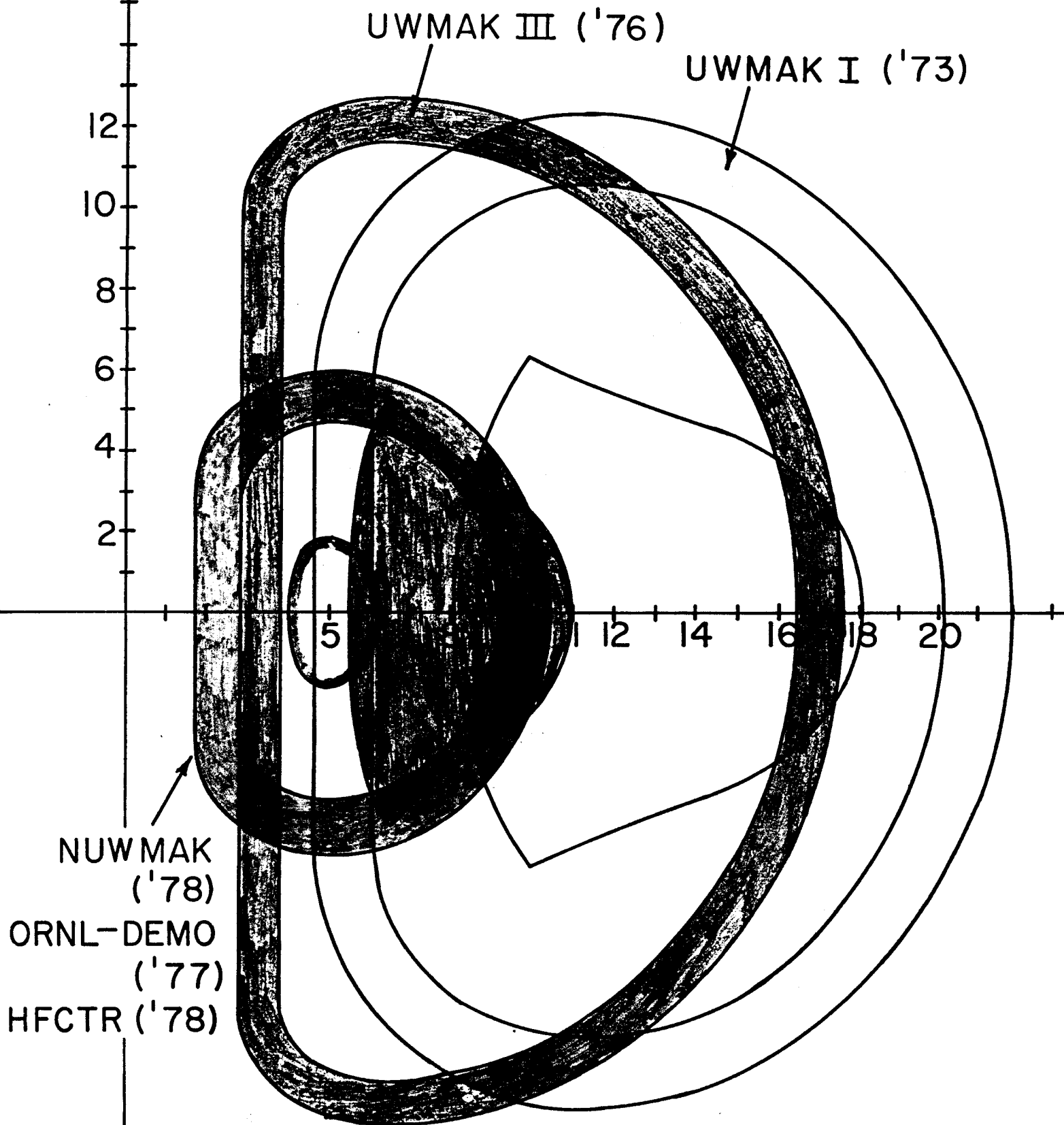
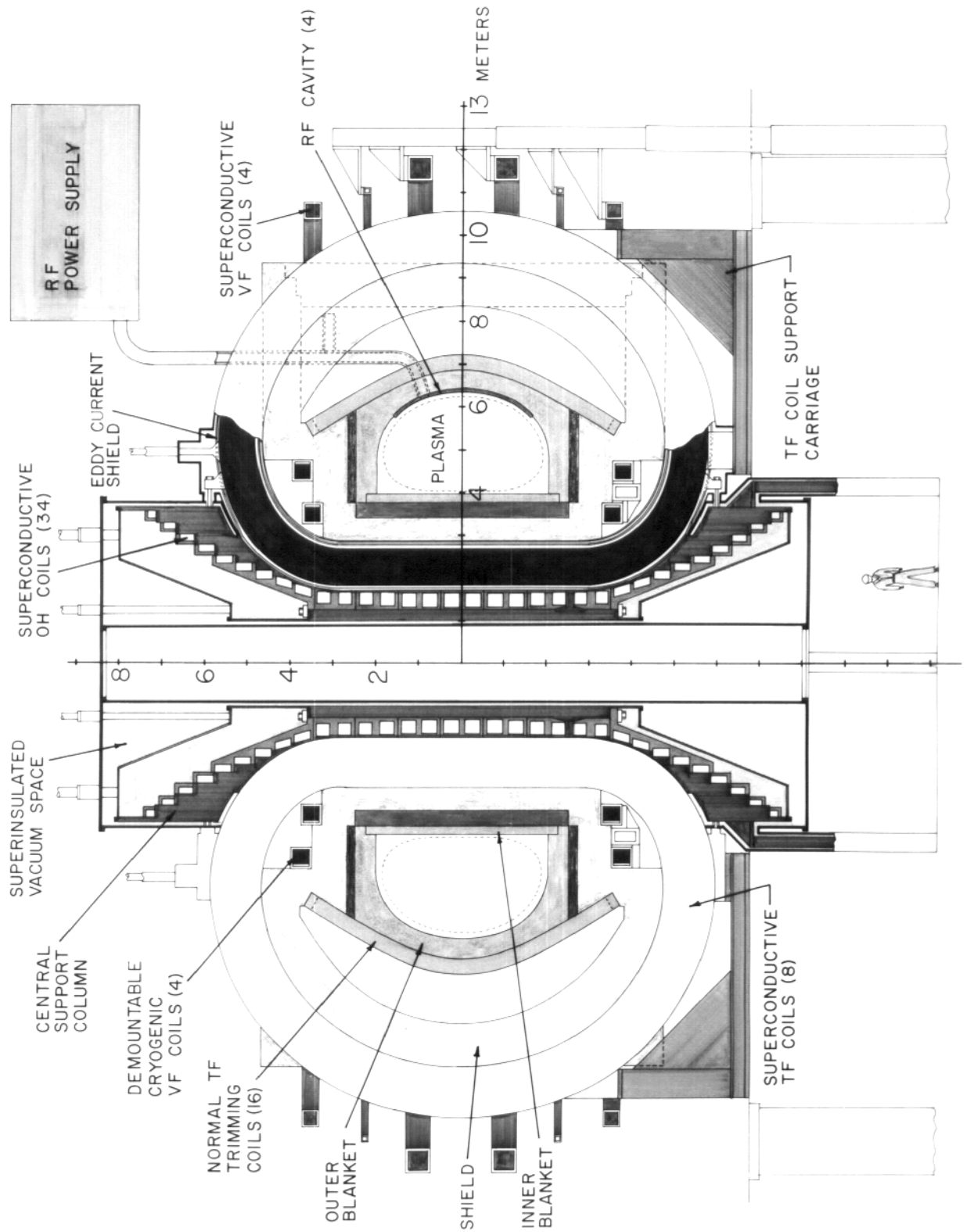


Fig. 5.

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, it is necessary in this design to use a separate material to multiply the incident neutron because reactions with ^6Li are insufficient. Beryllium is ideal neutronically for this purpose. However, a resource study conducted in conjunction with UWMAK-II showed that this would not be feasible on a large scale⁽¹⁵⁾ 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 this case, the molybdenum alloy TZM (99.4% Mo, 0.1% Zr, 0.5% Ti)). Liquid lithium is again the breeder and coolant and the high allowable operating temperature for the structure (1000°C in Mo compared to 450-500°C in stainless steel) leads to a larger 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.

A cross section view of the most recent conceptual design, NUWMAK, is shown in Fig. 6. 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

Fig. 6. CROSS-SECTIONAL VIEW OF
NUWMAK



edge of the toroidal field magnets is 21 m. The thermal power is 2300 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 33%. The power density, defined as the thermal power divided by the plasma volume, is 10 MW/m³ (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 0.37 MW/m³ and the specific power, defined as the thermal power divided by the mass of the nuclear island, is 97.5 W/kg.

The original structural material in the NUWMAK design is the titanium alloy, Ti-6Al-4V, the breeding material is the eutectic Li₆₂Pb₃₈, 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.

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 maintainability of the system, particularly since the lifetime of the structure near the plasma is expected to be less than the lifetime of the plant.

B. Mineral Resource Requirements

The NUWMAK conceptual tokamak will be used as a model fusion reactor. For purposes of comparison, the resource requirements for a 300 GWe economy of UWMAK-I, II, III or NUWMAK-type reactors will be considered. Further, it will be assumed for the purposes here that NUWMAK can be constructed of alternative structural materials without major changes in design. The alternate 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. The base of analysis is broadened still further by assuming that the blanket, shield, and toroidal field magnet design from the recent High Field Compact Tokamak Reactor^(9,10) (HFCTR) can be substituted into NUWMAK. The HFCTR is of comparable physical dimension. The blanket structural material is the molybdenum alloy TZM, and the breeder material is static liquid lithium; the coolant is the molten salt, FLIBE ($2\text{LiF} \cdot \text{BeF}_2$). The lithium is slowly circulated for tritium recovery and the beryllium in the salt serves as a neutron multiplier. The magnets for HFCTR are substantially different from those in NUWMAK. The superconductor is Nb_3Sn rather than NbTi and the maximum field is 13.1 T. Forces on the magnets are greater requiring larger amounts of magnet structure. Thus, by contrasting NUWMAK and HFCTR requirements, one can determine if high magnetic field tokamaks place a different and perhaps greater burden on mineral resource requirements. For reference, the composition of the various structural alloys we have discussed are summarized in Table 5.

Table 5

Composition of Structural Alloys

<u>Typical Alloys</u>	<u>Typical Primary Constituents</u>
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

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 is given in Appendix A. The total requirements in tonnes per MW_e are summarized for all systems in Table 6. The requirements for UWMAK-III and all forms of NUWMAK including the HFCTR subsystems 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 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.
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-II 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.

Table 6
Total Estimated Material Requirements of Tokamak Reactors
(Tonnes/MW_e)

	UMIAK-I 316 Stainless Structure	UMIAK-II 316 Stainless Structure	UMIAK-III Mo Structure	UMIAK Ti-6Al-4V Structure	UMIAK V-20Ti Structure	UMIAK 316 Stainless Steel Structure	UMIAK Tenelon Structure	NUMIAK HT-9 Structure	HFCTR (HIT) Mo Structure
Li [*]	1.15	0.57	0.24	0.19	0.18	0.13	0.12	0.12	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
Zr	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	0.5037	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.

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 ($2\text{LiF}\cdot\text{BeF}_2$), 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.

V. Availability of Materials for Thermonuclear Reactors

A. Factors Determining Availability

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

1. The size and quality of U.S. and world mineral resources;
2. U. S. 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 in the above list 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. We discuss these various factors before turning in Section B to a discussion of availability of the various metals, carbon, and helium.

1. Size and Quality of U.S. and Free World Resources

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 tonnages of ore and contained metal can be calculated within acceptable limits of accuracy, and have been judged to be minable 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 7, 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 U.S. 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.

Table 7

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

Metal	Maximum Requirement (3) 300 GWe Economy	U.S. Production		U.S. Consumption	World Production (1978)	Reserves at Present Prices		Reserves at 3 Times Present Prices (1)		Principal Present Sources
		From Domestic Ores & Scrap	Total Production			U.S.	World	U.S.	World	
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	740	10,000	No data	720,000	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., Bolivia, Thailand
Molybdenum	26-6 (N)	60	60-0	30-0	98-0	4,500	9,300	No data	No data	U.S.A., Canada, Chile
Cobalt	21-0 (H)	0-3	0-3	8-5	30-8	None	72,600	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 (UNMAK-1)	0-9	<0-02	<0-05	<0-05	<0-4	~3	~38	No data	No data	Malaysia, Australia
Helium	70									U.S.A.
Fluorine	153 (H)		200	1,132	2,310	>2,500	>51,240	7300,000	>200,000	Mexico, France, S. Africa, Spain

* Information on U.S. and World production and consumption are from the U.S. Bureau of Mines. (26)

Information on reserves is partly from the U.S. Bureau of Mines, (26) partly from Brobst and Pratt, (36) and partly from other miscellaneous sources.

(1) Includes reserves at present prices.

(2) Reserves in non-Communist countries only.

(3) From stainless steel scrap.

(4) Primary

^NMaximum requirement of UNMAK. ^HMaximum requirement for HFCTR (M.I.T.).

2. U. S. and Free World Extractive Capacity

Data for total extractive capacity of the U.S. and free world mining and metallurgical industry are not readily obtained but working capacities are indicated, for any year, by data for metal production. Data for 1978 are given in Table 7. For the U.S., 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 U.S. 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.

The magnitude of U.S. extractive capacity for various metals in the twenty-first century is impossible to predict. The record since World War II shows a trend toward growing dependence on foreign sources for metals as a group. There are few bright pages in this record. Political and social developments in the United States in the last 10 years offer little prospect of a reversal in the trend. Costs of meeting environmental and other state and federal regulations now constitute a heavy burden on domestic mining industries, and competition with mining industries abroad is proving more difficult for some. Exploration that is needed to discover new metal deposits in the United States, in order to offset depletion of

present reserves, is being steadily restricted by massive withdrawals of land from the public domain. All these factors contribute to the trend toward greater dependence on foreign sources. Only recently is there evidence, at the national level, of concern with this problem.

The figures for U.S. reserves at 3X present prices suggest that certain metals currently imported could be procured from domestic resources in amounts sufficient for fusion purposes. However, guarantee of prices permitting adequate returns on investments would be necessary to stimulate domestic production.

3. U.S. and World Fabricating Capacity

As a general index of U.S. fabricating capacity (working capacity), we use the figures for U.S. consumption of various metals and helium given in Table 7. 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 U.S. productive and fabricating capacity would be necessary to meet the demands of fusion.

Figures for total world consumption of metals (primary plus secondary metal) are not available but the figures for world production of metals (new metal) given in Table 7 are a partial index of consumption. 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.

For the world one must assume that fabricating capacity will be sensitive to demand. The past record is reassuring on this point. The same assumption for future fabricating capacity within the United States, however, would be risky. History indicates that smelting, refining, and fabricating capacity tend to shift, over the longer term, to countries that possess the necessary mineral raw materials, particularly those that have the supplies of energy necessary to process them. Such shifts are already under way in certain U.S. ferroalloy industries and in the aluminum

industry.⁽¹⁶⁾ As measured by consumption of metals, U.S. fabricating capacity grew almost steadily from 1948 to 1974, but there has been no growth since 1974.

4. The Time Factor in Mineral Availability

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 mills for extraction of valuable minerals from the ores, 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 factor of lead time must be considered in all planning for future mineral supply. It means that steps to increase production cannot be deferred until shortages develop. Shortages must be anticipated long in advance and appropriate programs undertaken. In the usual case, the most critical link in the chain is the first, namely, the period of exploration and discovery. There is no advance assurance of success. This fact sets a premium on the encouragement of exploration as long as possible in advance of needs.

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 regulatory 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.

5. 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 U.S. primary minerals industry has been made by Battelle-Columbus Laboratories for the U.S. Bureau of Mines.⁽¹⁷⁾ Pertinent results are summarized by H. H. Kellogg⁽¹⁸⁾ together with his own observations. Energy requirements for most of the metals of Table 6 are given in Table 8. For each metal, the figure given includes energy consumed in mining, beneficiation, 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.

Table 8

Energy Requirements for Fusion Metals⁽¹⁾
 (10⁶ 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
Ferrovandium	490
Nickel cathode	144
Tungsten powder	350
Tin ingot	190
Molybdenic oxide	150
Sodium metal	92

B. Availability of Various Materials for Fusion Reactors

In succeeding sections, the availability of each of the materials required for various fusion reactors is assessed. The data presented in Table 7 are the first basis of assessment. In forecasting availability, however, depletion of existing resources prior to and during the development of a fusion economy is taken into account, together with prospects for additions to known reserves and apparent trends in the development of world extractive and fabricating capacity.

1. Lithium

The size of lithium reserves and resources is of prime importance in view of the prospective use of lithium as a source of tritium for the fusion process. Information on lithium, however, is incomplete and uneven in quality, and the availability of lithium for fuel is further clouded by possible changes in the scale of use of lithium for other purposes. Lithium resources and requirements by the year 2000 were reviewed at a symposium held in 1976. At a second symposium held in 1977, the results of a study by the lithium subpanel of CONAES were reported.⁽¹⁹⁾ Estimates given in Table 7 are based largely on this report plus a report by Erikson⁽²⁰⁾ on brines in salars of Western Bolivia.

Known lithium resources in the world are contained mostly in two classes of deposits, pegmatite deposits and brine deposits. The largest known reserves of Li in pegmatite deposits are in the tin-spodumene belt (Kings Mountain district) of North Carolina and in the Manono-Kitole district of Zaire, the former a principal source of the United States and world supply, the latter apparently about to be brought into production. The only productive brine deposit at present is that of Clayton Valley, Nevada, but

development of the much larger brine deposits of the Atacama Desert in northern Chile is under way. All these are included in the figure in Table 7 for world resources of Li. Reserves in Clayton Valley and North Carolina constitute U.S. reserves, since by-product Li will no longer be available from the brine of Searles Lake, California.

The figure for U.S. reserves at 3X present prices includes resources known to exist in Great Salt Lake, additional Li present in Clayton Valley brines not economically recoverable at present prices, and probable additions, through further exploration, to tonnages of ore known in the Kings Mountain district. A 50 percent discount, possibly excessive, has been applied to the gross resource figures to allow for losses in extractive processes. The brines of the Salton Sea Basin, California, are estimated to contain⁽²¹⁾ 1,000,000 tonnes of Li, but in view of severe technological problems of extraction are not included. The brines of the Smackover Formation of Arkansas and Texas are also excluded. The figure for world reserves at 3X present prices expresses the likelihood that additional reserves will be disclosed by deeper drilling in Zaire⁽²²⁾ and that additional reserves in lithium-bearing brine deposits will be defined in western South America,⁽²⁰⁾ the United States, and possibly other parts of the world unexplored for Li. A substantial part of these resources may ultimately be found to qualify as reserves at present prices. Known reserves of Li are so large relative to current demand that there has been little incentive to explore for lithium in recent years.

Despite large reserves and resources relative to current demand, and the favorable prospects for new discoveries, there has been concern about the future availability of Li for fusion. Lithium is under consideration

for use in electric cars powered by lithium-anode batteries. Assuming that in the year 2000 12 to 16 percent of all vehicles are powered by lithium-air-water batteries, Cooper and others⁽²³⁾ estimate that between 234,000 and 425,000 tons of Li would be required. U.S. reserves at present prices would not support the necessary rate of production; Vine⁽²⁴⁾ estimates the probable yield by the year 2000 at 230,000 tons. Conventional uses, batteries not included, may demand as much as 300,000 tons between now and 2000. The need for tapping the deposits included under reserves at 3X present prices is evident.

In considering the use of lithium for energy applications, it should be noted that lithium's contribution to energy supply will be far greater if it is used as a fusion fuel than if it is used in batteries for energy storage. In terms of energy yield, lithium would be economic as a fuel at nearly 10 times the present price of 3.5 cents per gram.

2. Aluminum

The United States produces more aluminum than any other country in the world but is dependent on foreign sources for more than 90 percent of its supplies of raw materials, bauxite ($\text{Al}_2\text{O}_3 \cdot n\text{H}_2\text{O}$) and aluminum oxide. Chances of discovery of additional domestic deposits of bauxite are negligible. However, at 3X present prices, or somewhat below, large known resources of aluminous materials would come into the economic range. The figure given in Table 7 for reserves at 3X present prices includes only Al estimated to be present in the high-alumina clays of Georgia and South Carolina. There are other large resources of aluminous materials (alunite, anorthosite) that could also be brought into production. Dawsonite [$\text{NaAl}(\text{OH})_2\text{CO}_3$] in the oil shales of the Green River formation is another potential source of aluminum.

Despite the high level of domestic metal production, production has fallen behind domestic demand in recent years, and increase in imports of Al metal seems likely in the future. This is a consequence of the lack of domestic reserves of bauxite. New smelting and refining capacity is being established mostly in countries such as Australia, Guinea, and Brazil that have large reserves of bauxite. The growing deficiency in U.S. aluminum-producing capacity is not likely to be arrested unless recourse to domestic resources of aluminous materials becomes economically feasible. The rising costs of energy in the United States are an unfavorable development, since as indicated in Table 8 aluminum production is energy-intensive. The figure in Table 8 for Btu/ton applies to Al produced from bauxite. The energy cost could be significantly higher for production of Al from high-alumina clays.

As indicated in Table 7, world reserves of Al at present prices are more than 5 billion m.t. Projection of the growth curve for Al production for 1964-1978 suggests that as much as 1.5 billion tons will be produced from 1979 to 2010 but large reserves will still remain. Additions to present reserves can be anticipated.

3. Boron

The United States produces nearly 50 percent of annual world supply of boron and has the second largest reserves of boron in the world. Additional large resources in the western states would become available at 3X present prices. Annual U.S. consumption of boron rose 37 percent from 1974 to 1978. If this remarkable rate of growth continues, about 4,800,000 tons will have been consumed by the end of the year 2000. U.S. reserves and resources of boron, however, are adequate to sustain the

necessary rate of production, and the fusion requirement, spread over a period of 30 years, would not be an unacceptable additional burden on resources. Substantial additions to present boron-producing capacity would obviously be required. Moreover, capacity for producing boron carbide would have to be increased enormously, since only a small percentage of current production consists of metal and fabricated products.

4. Chromium

The United States, like Japan and the major industrial nations of Western Europe, depends entirely on imports for its supply of chromium. There are no reserves in the United States. World reserves are very large relative to foreseeable demand, but 99 percent of world reserves are located in Zimbabwe-Rhodesia and the Republic of South Africa.⁽²⁵⁾ Much of the remainder is in the U.S.S.R. and in Turkey.

At 3X present prices, chromite, the ore of chromium, would become available from the Stillwater Complex, Montana. Resources there are sufficient to supply the indicated U.S. requirements for nuclear fusion. Such prices are only likely, however, if sources abroad are cut off. In that case, demand for chromium for fusion purposes would have to compete with other demands for chromium. The metal has become an essential material for a number of important industrial applications, and competition would be severe.

The United States has low-grade resources of chromium from which chromite might be extracted, though probably at high cost. At present, however, there is no economic incentive for the industrial research and development that would be required to make chromium available from such resources.

5. Niobium

Since niobium is an indispensable component of the superconducting magnets necessary in reactors, the size and distribution of niobium reserves and resources are of critical importance.

Niobium resembles chromium, in that the United States depends for its supply completely on imports of ores and the base alloy ferrocolumbium. The United States produces no niobium from domestic deposits. There are no domestic reserves. Reserves indicated at 3X present prices are in the Powderhorn area, Colorado. They would be adequate for fusion requirements only in the absence of competing demands.

World reserves of niobium are large. Of the reserves indicated, 8,000,000 tons are in Brazil, nearly 600,000 tons in Canada, the remainder mostly in countries of Africa. Nearly all of the world demand outside the Communist sphere is supplied from Brazil (78 percent) and Canada (17 percent). Resources that would be available at 3X present prices are even larger; the figure of 20×10^6 m.t. given in Table 7 is conservative. Significant additional resources in Canada are included. Prices at the higher level would bring only modest U.S. resources into the category of reserves.

In summary, world reserves of niobium are more than adequate to supply world needs, including possible requirements, for many decades. The existence of large resources in Canada, available at 3X present prices, gives the United States insurance against any possible disruption of the flow of niobium raw materials from sources outside North America.

6. Copper

The United States mines more copper annually than any other nation, and reserves of copper, as reported by the U.S. Bureau of Mines⁽²⁶⁾, are at an all time record high. Despite this, total domestic production, mine

production plus scrap metal, is less than annual consumption, and has been so for more than ten years. There are several reasons: competition from foreign copper, limitations on the rates at which copper can be produced from domestic deposits, fluctuating and periodically depressed prices, and insufficient domestic capacity for smelting and refining. Measures for environmental protection have involved heavy costs for the American copper industry.

The problem of availability of copper was reviewed by a panel under the auspices of the National Academy of Sciences.⁽²⁷⁾ It was concluded that United States self-sufficiency in the production of primary copper is unlikely. This conclusion is supported by statistics of the copper industry through 1978. U.S. mine production peaked in 1970 at 1,720,000 tonnes but during 1971-78 averaged only 1,563,000 tonnes.

Assuming the 1971-78 rate of production is maintained, nearly one-half of U.S. copper reserves at present prices will be depleted by 2010, and most of the remainder will be gone by 2040. It is expected, however, that depletion will be offset, at least to some extent, by discovery of additional deposits, and additional copper from deepsea nodule deposits may become available. The amount of copper required for a 300 GW_e fusion economy is not large, particularly if spread over 30 years. Given conditions more favorable to the growth of the U.S. copper mining industry, it is conceivable that the demand could be met during 2010-2040 from domestic deposits. It is probably not prudent to rely on free world reserves outside the U.S. From 1964 to 1978, world consumption of new copper increased by 64 per cent. If this rate of increase continues, about 400,000,000 tonnes will be consumed between 1979 and 2010. Some of this depletion will be offset by discovery of new reserves and the rate of increase in world consumption appears to have slowed since 1972. In any event the potential availability of copper from U.S. and free world resources should be re-evaluated from time-to-time and the potential for substituting aluminum for copper, as was done in the UWMAK-III design, should be further explored.

7. Iron

The known requirement for iron is far larger than that for any other metal, but spread over a period of twenty years it would be small relative to the scale of United States and world production. As indicated in Table 7, U.S. reserves at present prices are adequate to satisfy demand for many decades, and world reserves are extremely large.

The United States produces virtually all the pig iron consumed by the American steel industry but imports about 30 percent of the iron ore used in pig iron production. Half of the imports are from Canada, another 25 percent from Venezuela. United States mine production capacity could be expanded to take care of any deficiencies in supplies from abroad.

Steel production capacity is a somewhat different matter. The American steel industry has been plagued by problems of plant obsolescence, generation of necessary capital, costs of meeting environmental standards, competition from imports, and pressure from government to hold down prices of steel in the face of rising costs of production. The consequences of the interplay of these factors during the remainder of the century are impossible to predict.

8. Lead

The amount of lead required for a 300 gigawatt fusion economy is second only to the requirement for iron. The requirement is, however, much less severe if spread over a period of 30 years. The amount is actually less than twice U.S. annual production of newly mined lead (1978 - 481,000 m.t.), the remainder of U.S. production being recycled metal. The United States for many years has not produced enough lead from domestic sources to satisfy demand, but that situation could change during the remainder of the century. Gasoline additives, now being phased out, account for 15 percent of total

demand, storage batteries 51 percent. If the present batteries are replaced by a new generation of batteries not requiring lead, consumption of lead could be correspondingly reduced.

The United States has substantial reserves of lead, as indicated in Table 7, but mine capacity and smelting and refining capacity are deficient relative to consumption. The threatened imposition of severe environmental standards on lead smelters and refineries is causing concern about the future of the lead-producing industry in the United States. World reserves of lead may not sustain world demand through 2040, but development of large additional reserves is likely.

9. Manganese

The requirement for manganese for a 300 gigawatt economy, spread over a period of 30 years, is so small relative to the scale of U.S. and world consumption and world reserves that there can be little concern about availability. The United States produces no manganese ore, but low grade domestic resources could supply the necessary amounts at 3X present prices.

10. Tin

Small amounts of tin are produced as a byproduct of molybdenum mining in Colorado, but the U.S. is almost totally dependent on recycled scrap (20 percent) and imports (80 percent) for its supply. About 85 percent of the world's reserves of tin are in a belt that extends from eastern Siberia through East Asia into Indonesia. Modest reserves are in Brazil, Bolivia, Zaire, Australia, and Nigeria. U.S. reserves, measured, indicated, and inferred, were estimated by Sainsbury and Reed⁽²⁸⁾ at about 41,000 tons.

The total requirement for 300 GW_e (HFCTR reactor) is small relative to world reserves and world annual production. So long as access to world supplies is open, tin should present no problem of procurement. A large share of world reserves will be depleted by 2010 but substantial additions to reserves at present or 3X present prices can be expected.

11. Molybdenum

The United States accounts for about 60 percent of total world production of Mo and has nearly 45 percent of total world reserves of the metal. U.S. reserves are large relative to the current rate of production, but at that rate about one-third of present reserves will be depleted by the end of the century. Furthermore, demand for the metal has been increasing at an annual average rate of about 4 percent, and continued increase is forecast for the future.

A substantial part of U.S. molybdenum production is a by-product of copper mining and fluctuates with conditions in the copper industry. Prospects for development of new reserves are mixed. Substantial success has attended exploration in recent years, but development is complicated by environmental problems and by land withdrawals and other Federal actions that are hindering both exploration and development. Development of the second largest known Mo orebody in the world at Quartz Hill, Ketchikan District, Alaska may be prevented owing to its inclusion in a national monument.

The availability of Mo for fusion purposes is thus a function of four things: (1) rate of increase in demand for other purposes; (2) rate of discovery of new deposits; (3) rate of development of new production capacity; and (4) the health of the domestic copper industry. The demand for fusion purposes, spread over 30 years, is not large, but the molybdenum supply situation will need to be monitored periodically in anticipation of needs for fusion.

12. Nickel

The United States has been heavily dependent on foreign sources for nickel for many decades. During 1974-78, U.S. production of newly mined nickel ranged from 10,600 and 14,300 tons annually. Reserves in the only

productive district (Riddle, Oregon) will be virtually exhausted by the end of the century. The remainder of total production shown in Table 7 is from recycled scrap.

Large resources of nickel that would be economic at 3X present prices are known in the Duluth Complex of northern Minnesota, and these account for most of the tonnage at 3X present prices indicated in Table 7. One company has a substantial program of research and development in progress in a portion of the known deposits in the Complex. At present, however, there is no schedule for production from the deposits. Future development will depend not only on prices of nickel and copper but also on the resolution of environmental problems.

During the past 15 years an alternative to the conventional sources of nickel has emerged through recognition of the presence of large tonnages of nickel in deposits of "manganese nodules" on the deep sea floors. A belt south of the Hawaiian Islands is particularly rich in such deposits. The development of necessary technology is well advanced, but actual mining will not take place until legal and political problems are resolved. The establishment of a deep sea mining industry will require very large capital investments, and these are not likely to be made until mining companies can have assurance of tenure of the deposits under conditions that will permit a satisfactory return on investment. The successive international conferences on the law of the sea have thus far failed to resolve the problem.

Outside the United States there are large reserves of nickel both in sulfide deposits and in lateritic deposits in the tropical belt. Canada has large reserves and currently supplies nearly 60 percent of U.S. imports.

13. Titanium

The requirement for titanium given in Table 6 is sharply influenced by design. A design employing 90Ti-6Al-4V would require an amount of Ti nearly 10 times present annual world consumption of titanium metal. Given adequate reserves, a marked expansion in the U.S. and world capacity for metal production would be required.

The reserve situation is good. At the present time, the preferred raw materials for titanium metal production are the TiO_2 minerals, rutile and anatase. U.S. reserves (rutile) are modest, but world reserves and resources are large, much larger than indicated by the reserve figures of Table 7. The reason is that known reserves are so large relative to demand that there is no incentive to explore extensive deposits of rutile-bearing beach sands along certain of the coastlines of the world, notably along the east coast of Africa. Beyond these reserves there are enormous reserves of the mineral ilmenite (FeTiO_3), from which TiO_2 and Ti metal can be extracted. Most of the world's production of titanium minerals (ca. 4,400,000 tonnes per year) is consumed in the manufacture of paint. World resources of ilmenite, however, are adequate for more than 100 years, and there are still other alternative sources of titanium.

14. Zirconium

The principal ore mineral of zirconium is zircon (ZrSiO_4), which is a by-product of the mining of beach sand deposits for the titanium minerals ilmenite and rutile. Most of the zircon produced is used in refractories, abrasives, and chemicals, and probably less than 2,000 tons of metal are consumed in the U.S. per year. Reserves and resources of zircon are very large, and large future additions to reserves are likely. Fulfilling the NUWMAK requirement of 9,500 tons should present no problem.

15. Beryllium

The NUWMAK reactor design calls for no beryllium but the M.I.T. design calls for 27,000 tons for a 300 GW_e fusion economy. This is nearly equal to total U.S. reserves of Be and about 9 times total world production. In terms of present production rates, the M.I.T. requirement is large even if spread over a period of 20 years.

The size of United States and world resources of beryllium is very uncertain. The only published estimate of beryllium resources is by W. R. Griffiths⁽²⁹⁾ and is reproduced here as Table 9. As indicated, there are two classes of beryllium deposits, pegmatitic and non-pegmatitic deposits. Past world production has come largely from the mineral beryl ($\text{Be}_3\text{Al}_2\text{Si}_2\text{O}_{18}$, 4 to 5 percent Be), mined from pegmatite deposits. Such deposits are generally small. Single deposits yielding more than 100 tons of beryl are uncommon. Non-pegmatitic deposits are a diverse group. One deposit, at Spor Mountain, Utah, is estimated to contain 28,000 tons of Be, the only reserves and the only deposit currently being mined in the United States. Other known U.S. resources of beryllium that might become available at 3X present prices consist of a few hundred tons of Be in pegmatite deposits plus about 32,000 tons of Be in non-pegmatitic deposits in Alaska, Utah, and Nevada. The pegmatites of the Kings Mountain district of North and South Carolina, currently being mined for lithium, are estimated⁽³⁰⁾ to contain 40,000 tons Be, but the average beryl content is only about 0.5 percent, the beryl is difficult to recover, costs of producing beryl would be very high, and rate of production would be limited by the rate of mining for lithium. This resource is therefore not included in Table 7. Table 9⁽²⁹⁾ includes a figure of 250,000 tons for resources in undiscovered non-pegmatitic deposits. There is no concrete basis for this figure. It expresses a hope, based on the fact that exploration for beryllium in the United States is

Table 9

Estimated Resources of Beryllium, in Short Tons of Metal

	<u>In Known Deposits</u>		<u>In Undiscovered Deposits</u>	
	Pegmatitic	Non-pegmatitic	Pegmatitic	Non-pegmatitic
United States	300	60,000	600	250,000
Other Countries	600	32,000	4,500	400,000

incomplete, that additional non-pegmatite deposits of beryllium will be found.

In the authors' opinion, the following statement with regard to world resources⁽³¹⁾ is still applicable:

"For world resources and reserves, little concrete information is available. Estimates of a few thousand tons contained Be are based on past production and the likelihood of discovering additional deposits in productive pegmatite districts. World reserves and resources in non-pegmatitic deposits cannot be estimated.

"The world's beryllium reserves and resources are thus very inadequately known. The small annual demand for beryllium has discouraged the exploration and sampling necessary to define reserves. Decades of experience with pegmatite deposits, however, indicate that such deposits will not sustain production significantly higher than in the past. The chief hope for expanded production lies in the discovery of major non-pegmatite deposits. Recognized only in recent years, these have not been as intensively sought as pegmatite deposits. Enough work has been done, however, by industry, government, and academia, to indicate that such deposits are uncommon, at least in the United States, and that large deposits will be difficult to find. In view of this, designers of thermonuclear reactors would be well advised to minimize requirements for beryllium."

A more optimistic view has been taken by Bass.⁽³²⁾ In any event, if at any time the use of beryllium in substantial amounts in thermonuclear reactors is found to be unavoidable, an intensive program of exploration for new deposits should be undertaken without delay. Even with good luck, 10 years or more might be required for discovery of deposits and the development of processes of extraction. The deposit at Spor Mountain, Utah, was discovered in 1959, but did not come into production until 1969.

16. Cobalt

In a previous report, considering a requirement of 68,000 tons for a 1000 GWe fusion economy, we stated that supplying the metal could be a severe problem, since that figure is more than twice the current annual world production of Co. All cobalt currently produced is a by-product of copper, copper-nickel, or nickel production, and major increases in Co production therefore require that markets for much larger amounts of copper and nickel must be found if the price of cobalt is to be kept anywhere near present levels. This will be true of whatever Co may be produced from the deep-sea "manganese nodules".

There are no U.S. reserves of cobalt. Reserves of cobalt outside the U.S. are large relative to world annual consumption of cobalt, and additions to reserves are likely in the future. As implied in the preceding paragraph, however, size of reserves is not as important as the dependence of rate of production on the scale of Ni and Cu production. About 40 percent of world production in 1978 was from Zaire and Zambia, but this may change with further development of cobalt-bearing lateritic nickel deposits in other countries of the world.

The requirement for a 300 GWe fusion economy is much less severe, especially if the demand is spread over a period of 30 years. The supply situation for Co should be monitored, however, if it continues on the list of raw materials required for fusion.

17. Magnesium

Magnesium can be produced from sea water and from abundant rock materials. Reserves and resources are for all practical purposes inexhaustible.

18. Vanadium

The requirement and the supply problem for vanadium is very much a function of design. The vanadium requirement for the design in which the V-20Ti alloy is the main structural material is 42 times total production in the non-Communist world in 1978. World annual production would have to be doubled for a twenty-year period to meet just the U.S. requirement for fusion.

Estimates of world reserves are imperfect and incomplete. The U.S. Bureau of Mines estimates⁽²⁶⁾ Free World Reserves at 2,550,000 metric tons, of which about 1,800,000 tons is in South Africa. The figure for South African reserves is a very conservative one; Van Rensburg and Pretorius⁽³³⁾ estimate South African reserves at nearly 12,800,000 m.t., and this figure is based on firm data for the deposits in the Bushveld Complex. Much less firm is our estimate for reserves at 3X present prices. The reason is that the economics of production of vanadium from low-grade sources of various types is speculative.

It seems unlikely that the higher requirement for V could be met from U.S. reserves, even at 3X present prices. Allowing for depletion of reserves during the remainder of the century, meeting even the lower requirement from U.S. reserves would depend on success in developing new reserves. Otherwise, recourse would be to the reserves at 3X present prices.

19. Tungsten

With a requirement of 315,200 tons for the NUWMAK reactor, tungsten could present a difficult problem of procurement. The amount is more than

twice U.S. reserves at present prices⁽³⁴⁾ and 16 percent of total world reserves.⁽²⁶⁾ The United States produces only about 40 percent of its normal requirements. In recent years the rest has been met from imports and releases from the government stockpile. Fusion would place an added burden on U.S. and world supply. Even if use were spread over a period of 30 years the annual requirement (10,5000 m.t.) would be 2-1/2 times 1978 U.S. production, and the total requirement for a free world fusion economy at the 1200 GW_e level would be nearly 30 times free world annual production.

World consumption of tungsten for conventional uses is rising. Even at the 1978 rate of production, over one-half U.S. present reserves, and nearly one-half of world reserves, would be used up by the year 2000. Other U.S. identified sources are estimated by Hobbs and Elliott to be about three times reserves at present prices, but the rates and prices at which these might become available are unknown.

A substantial share of world production comes from China, which supplies its own needs, part of the demand from the Soviet bloc, and part of Free World demand. The scale of Chinese production is uncertain. Production for 1975 is estimated by Thurber⁽³⁵⁾ at 8.6 to 9 thousand metric tons. Hobbs and Elliott estimate that southeastern China contains 60 percent of world reserves (1.2 million m.t.). Second largest reserves are in Canada (215,000 tons). Much of the remaining reserves are in Australia, Turkey, Korea, Bolivia, and U.S.S.R.

China is thus a major factor in both present and future supply of tungsten. If industrialization of China is speeded up, internal needs for tungsten will rise, and much less might be available for export.

In summary, the availability of tungsten in large amounts beyond the year 2000 is far from certain. Efforts to minimize the tungsten requirement are desirable and possible (discussed in Part E of this section).

20. Fluorine

For many years the United States has been dependent on imports for more than 75 percent of the 550,000 to 730,000 tons of fluorine consumed annually in the United States. Most of the U.S. and world production of fluorine comes from deposits of fluorspar (CaF_2 , F = 48 percent), but about 33 percent of domestic production is recovered as a by-product of the processing of phosphate rock for fertilizer. U.S. reserves of fluorspar at present prices are only about 5X annual consumption, and at current rates of production will be largely depleted by the year 2000. Deposits of fluorspar newly discovered in East Tennessee may add to domestic reserves, but the size and economic viability of these deposits will be known only when exploration is further advanced.

The largest U.S. resources consist of fluorine in phosphate rock, averaging about 3 percent fluorine. U.S. reserves of phosphate rock are variously estimated at 10 billion tons, and other resources at more than 15 billion tons. U.S. production of phosphate in 1978 was 44,000,000 tonnes, containing about 1.4 million tonnes of fluorine, but only a small part of this, 34,000 tonnes, was recovered. Increase in price of fluorine would favor a large increase in production of F from phosphate rock, perhaps to an amount equal to U.S. annual imports. (37)

World reserves of fluorspar as estimated by the U.S. Bureau of Mines (1979) are about 60 times current world production. The U.S.B.M. assigned

78,000,000 tons (27 percent of world reserves) to South Africa and 39,000,000 tons (13 percent) to Mexico. However, Van Rensburg and Pretorius⁽³³⁾ estimate South African reserves at 200,000,000 tons. World resources of F in phosphate rock are enormous.

Spread over 30 years, the fusion requirement for F should present no problem. Cutoff of supplies from abroad or excessive world prices for fluorspar could stimulate U.S. production of F from phosphate to a level of self-sufficiency.

21. Yttrium

U.S. and world demand for yttrium has been so small that there has been little incentive toward establishing the size of resources. Known world reserves, however, are ample. The metal should not be a problem of procurement.

22. Helium

Helium resources consist of helium in the earth's atmosphere and helium contained in natural gas. The cost of recovering He from air is estimated at \$2000/MCF (thousand cubic feet) as compared with a cost (U.S. Bureau of Mines plant at Keyes, Oklahoma) of \$11/MCF from natural gas. Reserves of He therefore consist only of amounts contained in the gas fields of the U.S.

Four categories of He resources in natural gas are recognized, as follows:

- (1) Depleting - in gas fields currently in production
- (2) Non-depleting - in gas fields not currently in production
- (3) Stored
- (4) Undiscovered

Helium resources as estimated by the U.S. Bureau of Mines, January 1, 1977, are given in Table 10. The He requirement for 300 GW_e of installed fusion capacity is 63×10^3 tonnes, equivalent to 12 BCF (billion cu. ft.).

The subject of the availability has recently been reviewed by the General Accounting Office (GAO). The Helium Act of 1960 established a Federal Helium Conservation Plan. The act authorized the Secretary of the Interior to purchase He from private producers for Federal agency consumption and for future Government use. About 37 BCF of He have been stored under this program. The private sector has stored only 1.6 BCF. About 2.7 BCF are lost annually from existing private facilities.

The Federal conservation program is at a standstill although GAO argues that a new conservation policy is needed. GAO estimates that nuclear fusion reactors, superconducting transmission lines, and magnetic energy storage could require up to 5 MCF per year by 2030. Meanwhile, much of the present underground domestic reserves of He will have been lost.

Table 10
Domestic Helium Resources in Natural Gas
(billions of cubic feet)

<u>Category</u>	<u>Reserves</u>	<u>Resources Exclusive of Reserves</u>	<u>Total Resources</u>
Depleting	81	55	136
Non-depleting	65	19	84
Stored	39	--	39
Undiscovered	<u>--</u>	<u>455</u>	<u>455</u>
	185	529	714

C. Sensitivity to Size of Power Economy

The assessment of availability of various metals and helium for a 300 GW_e economy falls into three categories. The first consists of those elements which could be available from domestic deposits; namely, boron, iron, titanium, magnesium, zirconium and possibly helium and molybdenum, at present prices, and lithium, lead manganese, vanadium (if not used as a major structural component), copper, aluminum, fluorine, and possibly niobium at 3X present prices. The second category consists of metals for which heavy U.S. dependence on foreign sources is likely, regardless of price; namely tin, chromium, tungsten, and cobalt. The final category consists of metals that may not be available in adequate amounts either from the U.S. or world resources. Beryllium (HFCTR reactor) certainly belongs here, and so also may tungsten and cobalt.

If growth of a U.S. fusion economy to a level of 300 GW_e is part of the growth of a free world fusion economy to 1200 GW_e, copper, tin, and molybdenum may be added to the list of metals unavailable in adequate amounts. Aluminum has been shown to be a substitute for copper in superconducting magnets (the UWMAC-III study), and this design option may be needed if copper becomes scarce.

With a 1000 GW_e U.S. economy and a 4000 GW_e free world economy, the burden on free world resources of some of the metals considered here would be very heavy. Li (from an inventory, not a burnup standpoint), Sn, Cr, Mo, and Cu are likely to be in short supply. Boron reserves at present prices, taking into account the growth of U.S. and world consumption

by 2010, could be exhausted. U.S. lead reserves at present prices could be inadequate, especially if lead is substituted for tungsten in the shield designs. Tungsten and beryllium supplies would be likewise inadequate. Unless material requirements for fusion reactors can be substantially reduced, the availability of metals may set limits on the use of fusion as an energy source.

D. 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 study^(5,6)). In addition, the large tokamak, T-15, to be constructed by the Soviet Union, will employ aluminum as the stabilizer. Aluminum reserves at present prices are at least 10 times those for copper and could 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.

The maximum requirement for lithium (HFCTR) is 163,000 tonnes for a 300 GW_e fusion economy. Only a small part of this, however, would be required in breeding tritium (500 MW_e yrs/tonne Li), and the remainder would be recycled. Taking this into account 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. The design solution is to use static lithium (as in the HFCTR), 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, Born, and Martel.⁽³⁸⁾ 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.

E. Some Environmental Factors

Mining involves removal of material from the ground. Disturbance of the environment is an inevitable consequence of nearly all mining operations. A very rough calculation of the amount of material that would have to be mined for the extraction of the metals for the NUWMAK reactor yields a total of 300 million tonnes to support a 300 GW_e generating capacity for a period of twenty years. In one year, 1973, coal-burning power plants with a generating capacity of 311 gigawatts consumed 387 million tons of coal, the mining of which required removal of at least five times that amount of material. The overall effect of replacement of coal-based generating capacity by fusion power would be an enormous decrease in environmental damage, even without taking into consideration the air pollution caused by a large amount of coal burning.

The environmental impacts of coal mining are especially severe because oxidation of sulfur present in coals and associated strata releases acids into the drainage of coal-producing areas. In addition, coal mining is one of the world's most hazardous occupations, both because serious accidents are common and because of the problem of pneumoconiosis. The mining of the ores of aluminum, chromium, niobium, iron, lithium (in part), titanium, vanadium, tungsten and zirconium yields inert materials that do not cause chemical pollution. Environmental damage consists of disturbance of the surface at mine and plant sites, damage involved in disposal of wastes, and atmospheric pollution around smelters. The ores of copper, molybdenum, lead, nickel, and cobalt (in part), on the other hand, are sulfide ores, and special measures are needed to control pollution of streams by acid-forming

wastes. Control is required of atmospheric pollution at smelters. To the extent that these metals are used in construction of other types of generating plants, however, those plants cause similar environmental impacts.

VI. Conclusions and Summary

The present survey indicates that, given the elimination of beryllium, tungsten, and cobalt from the list of required metals, metals needed for a 300 GW_e U.S. 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 U.S. 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 semifinished 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 U.S. 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 reduction in 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 technologic 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.

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