Materials Availability for Fusion Power Plant Construction

by
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September 1976

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PREFACE

Fusion reactor technology has developed far enough to expect laboratory demonstration of practical levels of fusion employing the D-T reaction to occur in the early 1980s. Following that demonstration, and depending upon the national priorities for energy from D-T fusion, construction and operation of experimental reactors and demonstration power reactors could occur before the end of this century. Operation of the first commercial power plants could then follow, starting about 2010.

Development and adoption of a new power system eventually will require a description of the environmental effects in an environmental statement providing a comparison to the effects of competitive systems. In anticipation of that statement, an environmental analysis (BNWL-2010) has been prepared for the ERDA Division of Magnetic Fusion Energy. That analysis estimates the environmental effects of constructing and operating D-T fusion reactors as an economically competitive source of electricity in the 21st century.

The analysis has four primary purposes:

1. To describe the general nature of the environmental effects,
2. To determine current ability to estimate the effects,
3. To determine methods for reducing the effects, and
4. To determine research necessary for increasing capability to define and reduce the effects.

Timely identification of needed research and methods for reducing effects will permit the performance of that research and the revision of conceptual fusion power plant designs before preparation of the program environmental statement. This would improve the quality of the environmental statements and could reduce the estimated adverse environmental effects due to fusion power plants.

The environmental analysis (BNWL-2010) concludes that the following assumed characteristics are the best set for the first operating fusion power plants:

• The D-T fusion reaction	• Standard electricity generation
• Large quantities of activation products	• Standard radioactive waste systems
• Kilogram quantities of tritium in the plant systems	• Large magnetic fields
• Massive reactor structures	• A self-contained fuel cycle
• Large lithium inventories	• Rural siting
• Large inventories of liquid metals and salts	

Using these characteristics a reference reactor was analyzed to determine the environmental effects by using available concepts of plant subsystems designs that control interactions with the environment or by assumption that best current technology would be used in subsystems design.

Because this analysis does not take into account advances in both fusion and waste control technology during the next thirty years, the estimated effects probably are significantly higher than the actual effects will be for the first fusion power plants. The estimated environmental effects should be interpreted only as being the probable upper limit for the actual effects.

Preparation of the fusion power plant environmental analysis required development and use of specially developed data and analysis methods not used in the preparation of current environmental statements for fossil and fission power plants. These data and analysis requirements are documented in a series of reference topical reports to make this information publicly available and to assure understanding of the basis for the conclusions made in the environmental analysis.

These reference topical reports summarize the state-of-the-art as applicable to preparation of environmental statements for fusion power plants. They present the data and analytical techniques used in the environmental analysis to estimate the interactions with the environment and the resultant environmental effects. This information then was analyzed for adequacy and the need was determined for additional research to assure satisfactory ability to prepare environmental statements for the fusion development program and experimental facilities in the early 1980s. Estimated environmental effects are presented in these reference documents only as necessary to illustrate use of the data and analytical techniques.

This report is one of those reference documents for the environmental analysis. The other documents in this series contain more details of the power plant concepts and the probable environmental effects of fusion power plants with the assumed characteristics listed above. These documents are available through the National Technical Information Service:

An Environmental Analysis of Fusion Power to Determine Related R&D Needs, BNWL-2010
Review of Fusion Research Program: Historical Summary and Program Projections, BNWL-2011
Fuel Procurement for First Generation Fusion Power Plants, BNWL-2012
Current Fusion Power Plant Design Concepts, BNWL-2013
Reference Commercial Fusion Power Plants, BNWL-2014
Siting Commercial Fusion Power Plants, BNWL-2015
Materials Availability for Fusion Power Plant Construction, BNWL-2016
Projected Thermodynamic Efficiencies of Fusion Power Plants, BNWL-2017
Tritium Source Terms for Fusion Power Plants, BNWL-2018
Management of Nontritium Radioactive Wastes from Fusion Power Plants, BNWL-2019
Methodology for Estimating Radiation Doses Due to Tritium and Radiocarbon Releases, BNWL-2020
Magnetic Field Considerations in Fusion Power Plant Environs, BNWL-2021
Biological Effects of Tritium Releases from Fusion Power Plants, BNWL-2022
Biological Effects of Activation Products and Other Chemicals Released from Fusion Power Plants, BNWL-2023
Safety Review of Conceptual Fusion Power Plants, BNWL-2024
An Investigation of the Transportation Requirements of Fusion Power Plants, BNWL-2025
Considerations of the Social Impact of Fusion Power, BNWL-2026
Environmental Impacts of Nonfusion Power Systems, BNWL-2027
Environmental Cost/Benefit Analysis for Fusion Power Plants, BNWL-2028
Biomagnetic Effects: A Consideration in Fusion Reactor Development, BNWL-1973
An Analysis of Tritium Releases to the Atmosphere by a CTR, BNWL-1938

SUMMARY

A preliminary assessment was made of the estimated total U.S. material usage with and without fusion power plants as well as the U.S. and foreign reserves and resources, and U.S. production capacity. The potential environmental impacts of fusion power plant material procurement were also reviewed including land alteration and resultant chemical releases. To provide a general measure for the impact of material procurement for fusion reactors, land requirements were estimated for mining and disposing of waste from mining.

The results of this preliminary assessment indicate the following trends:

- Construction of fusion power plants with their massive reactor systems might use tens of thousands of tons of metallic structural materials which might increase the total quantity of some materials used per unit of electrical capacity built.
- Current U.S. and world reserves of many fusion power plant materials are less than their expected U.S. cumulative uses to 2040. However, price increases and/or technological improvements would convert some resources into reserves. Reserve figures do not provide adequate information about material supply because they do not identify the material to be tapped with the next unit of investment. Thus, reserves cannot be used as the only basis for analyzing the availability of materials for fusion power plants. Information on resources that may become reserves in the future is also relevant.
- U.S. resources of beryllium, chromium, copper, lead, lithium, mercury and nickel are small compared to their possible domestic uses with fusion reactors. Therefore, some fusion power plant materials will probably come from foreign sources. However, this does not necessarily imply that they will not be available. The geographic distribution of some of these materials is so uneven that significant, temporary, price increases for some materials could result from foreign cartels.
- Reported world resources of beryllium, lead, and nickel are less than their expected U.S. cumulative uses to 2040. However, these data do not include large potential resources (for example, nickel in ocean nodules), and resource estimates based on crustal abundance of these metals exceed their expected U.S. cumulative uses to 2040.
- Production capacity at all stages of production is a major factor affecting materials prices in the immediate future. In the long-run capacity is expected to increase significantly in response to material usage for fusion power plant construction and other uses. Sufficient lead time (5 to 15 years) must be included when fusion power plant construction schedules are planned to allow for this construction. The use of materials in fusion power plants will influence the optimal rate of capital investment in mining, processing, and fabricating. Therefore, it is very important that the producing industries be made aware of the potential material usage so that they can plan for development of production capacities.

- The geochemically abundant elements: oxygen, silicon, aluminum, iron, calcium, magnesium sodium, potassium, titanium, hydrogen, manganese, and phosphorus account for 99.2% of the mass of the earth's crust. The remaining 76 geochemically scarce elements account for only 0.77% of the mass. The use of the geochemically abundant elements should be encouraged whenever their substitution for less abundant elements results in lower real costs discounted over the time of producing electricity from fusion power plants.
- About 0.16 km² (40 acres) of land might be altered as a result of the use of materials for constructing a 1000-MWe fusion power plant. Most of this land alteration would be the result of copper, molybdenum and nickel mining and milling operations.
- Materials will probably be available for the construction and operation of fusion power plants, if: 1) historical materials discovery rates continue, 2) improvements are made in the technology of mining, processing, fabricating, and recycling of materials, 3) we are able to accomplish more with less material resources, 4) per capita use of materials declines and 5) the uneven geographic distribution of reserves and resources is not sufficient to allow foreign monopolies or cartels among suppliers.

RESEARCH RECOMMENDATIONS

This report presents a preliminary estimate of the interaction between materials availability and use for fusion power plant construction and operation. Current knowledge of many aspects of this assessment was found to be very limited. For example, the available information on U.S. and world reserves and resources is limited. Currently estimated U.S. and world reserves and resources of many materials are less than expected U.S. cumulative use including fusion power plant uses. We expect some new resources to be discovered through additional exploration and some resources to become reserves through development of these new resources, through increased prices of these materials and through technological change. However, we do not have good predictions of these future changes. If few additions to reserves occur many materials may not be available for fusion power plants.

To improve the assessment of the materials availability for fusion power plants and of the impacts that the material procurement for fusion power plants have on the environment, we would need improved assessments and projections of: 1) material use rates, 2) the long-run costs of supply (potential for resource depletion), and 3) the associated environmental impacts for each material which is expected to be used for fusion power plant construction and operation. More knowledge of how much of the various materials exist in the earth would be helpful in assessing the availability of materials for fusion power plants. However, knowing where these materials are and in what quantities is only the first step towards determining the future costs of these materials. More information on future changes in the technology of mining, processing, fabricating, and recycling each material would also be needed to determine their long run supply curves. To determine the costs of supply from these long-run supply curves at a given future date, materials use rates at every point in time prior to and including this date would also

be needed. Finally, the environmental effects of all this future activity including the effects of future technologies would be needed to complete the improvements in this assessment of the effects of materials procurement for fusion power plants on the natural environment.

To determine whether the long-run supply prices for these materials are high enough to cause substitution of other materials in fusion power plant designs would require much more information on the comparative usefulness of various materials in these power plant designs. To determine whether use of materials in fusion power plants will have much effect on their use in other industries would require much more information on the future comparative usefulness of these materials in the other industries. In short, better assessment of the "availability" of materials and the environmental impacts of materials procurement for fusion power plants could usefully involve a much greater effort on each of the areas mentioned above than has been expended in this preliminary assessment.

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MATERIALS AVAILABILITY FOR FUSION POWER PLANT CONSTRUCTION

INTRODUCTION

Fusion power plants may have unique materials use characteristics for both the plant construction and the fuel cycle. This report presents the results of a preliminary assessment of the use and availability of construction materials for fusion power plants as well as the potential environmental impacts associated with the production of these materials.

The materials used to build fusion power plants are estimated by multiplying the normalized material use per unit power capacity by the estimated total fusion power plant capacity. Fusion power plant capacity is estimated by extending existing electrical use forecasts and assuming that fusion power plants will be able to produce electricity at a lower cost than fission or fossil plants. The fusion power plant estimated cumulative materials usages are then compared with total estimated cumulative use of each material without the fusion power plants as well as reserves and resources for each material.

Preliminary estimates indicate that fusion power plants may use larger quantities of construction materials than do fission or fossil fuel plants of the same megawatt electric (MWe) capacity. The conceptual fusion power plants have massive structures containing tens of thousands of tons of stainless steel, copper and lead. Also, large quantities of less commonly used materials may be used in fusion power plants, such as niobium, beryllium and titanium. The use of these materials may substantially affect the environment and may increase the probability of dramatic price increases for specific materials.

The material use estimates in this analysis should not be interpreted as the actual use for commercial fusion power plants. Because they are based on plant designs not optimized for minimum material use or electricity costs, future technological advances are expected to reduce substantially the material use per unit of generating capacity.

This report contains three sections. The first section estimates the quantity of materials expected to be used for fusion power plant construction. Estimates are made of the amount of construction materials used per unit of electricity generation capacity at fusion power plants, the total generation capacity expected to be built in the United States through 2040, the portion of this generation capacity that would be provided by fusion power plants, and finally the total amounts of materials of interest that would be used in the United States with and without fusion power plants.

The second section investigates the "availability" of these construction materials. "Availability" is defined in this section and in the glossary. Both reserves and resources in the U.S. and the world are compared to the expected U.S. cumulative use to 2040 of selected materials with and without fusion power plants.

The last section estimates the general environmental effects of materials procurement for fusion power plants. A glossary defines the key terms used in this report.

MATERIAL USE FOR POWER PLANT CONSTRUCTION

Large quantities of materials may be used in fusion power plant construction and operation because of the large physical size of the conceptual fusion power plants and the supporting systems. The primary use of large quantities of minerals would be in the construction of these facilities. After plant operations begin a smaller quantity would be needed, primarily for replacement of the inner walls.

The total quantity of materials used for construction depends on the estimated types and numbers of fusion power plants to be built. The estimated material usage by fusion power plants that might be constructed as described in this section as well as the estimated number of fusion power plants which is based on electricity use forecasts presented in this section.

INDIVIDUAL FUSION POWER PLANT MATERIAL USAGE FORECASTS

In this study the amounts of material used per unit of power generation is based on the normalized usage for the six fusion power plant concepts for which sufficient data is available for material usage estimates. Although this report makes no attempt to evaluate the best way to use materials for any fusion power plant concept, it does identify some problems in materials availability. The originators of these conceptual fusion power plants are listed in Table 1.

TABLE 1. Originators of Conceptual and Reference Fusion Power Plant Designs

Magnetic Confinement Fusion Reactors

Tokamak	Brookhaven National Laboratory (BNL)
	Oak Ridge National Laboratory (ORNL)
	Princeton Plasma Physics Laboratory (PPPL)
	University of Wisconsin
Theta Pinch	Los Alamos Scientific Laboratory (LASL)
Mirror	Lawrence Livermore Laboratory (LLL)

This material "availability" analysis is made for a typical power plant on an individual material basis. Magnetic confinement designs are the only fusion power plant designs developed well enough to use in making material use estimates. Thus, materials used for the construction and operation of individual conceptual fusion power plants were estimated for the magnetic confinement design as shown in Tables 2 through 5. The normalized uses of construction materials for the fusion power plant design concepts for which material information is available are presented in Table 4. This materials information includes the entire power plant only for UWMAK-I and the PPPL Tokamak. Therefore, the materials usage estimates selected as a basis for this analysis are the maximum values shown in Table 4 for the UWMAK-I and PPPL power plants.

TABLE 2. Material Usage for Fusion Power Plant Construction*

Material Usage, Metric Tons												
Element	UWMAK-I (a)			UWMAK-II (b)			PPPL (c) Total	ORNL (d) Nuclear Island	Theta Pinch (e) Total	Mirror (f) Reactor and Converter (j)	BNL Blanket (g) Blanket and Shield	
	Nuclear Island (h)	Balance of Plant (i)	Total	Nuclear Island	Balance of Plant	Total						
Aluminum	347	445	792	4,766	20	4,786	17				2,488	
Boron	1,580		1,580	4,280		4,280					5,790	
Beryllium				985		985	875		50		189	
Carbon	446		446	4,890		4,890		1,100	680	233	3,138	
Chromium	5,490	6,199	11,689	5,825	3,605	9,430	1,658	36		7,506		
Copper	7,466	3,259	10,725	10,692	676	11,368	3,264	450	9,300	8,810		
Iron	18,872	95,924	114,796	29,229	78,527	107,756	11,921	6,424		24,770		
Helium	58	80	138	69	22	91	117	1	1,200			
Magnesium		3	3									
Potassium								10				
Lithium	1,700		1,700	980		980	598	460	1,600 (k)	83	60 (k)	
Manganese	607	608	1,215	937	355	1,292	164			751		
Molybdenum	579	22	601	917	92	1,009	288					
Sodium		17,826	17,826		9,816	9,816						
Niobium	101	39	140	145	7.5	153	102	1,000	3,600			
Nickel	4,221	4,484	8,705	6,480	2,480	8,960	1,647	28		4,504		
Lead	20,500		20,500	19,800		19,800		5,350		1,272		
Tin							34		300			
Tritium	52	20	72				17	642				
Yttrium		5	5		3	3						
Zirconium		100	100		100	100	1	1				
Concrete		680,000	680,000				32,000	20,000		38,200		

* In addition to the sources indicated in footnotes a-f, the following powerplant designs were consulted but did not include information on material requirements:

J. Williams, T. Merson, F. Finch, F. Schilling, and T. Frank, "A Conceptual Laser Controlled Thermonuclear Reactor Power Plant," CONF-740402-P1, Proceedings of the First Topical Meeting on the Technology of Controlled Nuclear Fusion, San Diego, CA, April 16-18, 1974. (The "Wetted Wall" concept.)

A. P. Fraas, "Conceptual Designs of a Series of Laser-Fusion Power Plants of 100 to 300 MW(e)," presented at the 9th Intersociety Energy Conversion Engineering Conference, San Francisco, CA, August 26-30, 1974. (The "Blascon" concept.)

J. Hovingh, J. Maniscalco, M. Peterson, and R. W. Werner, "The Preliminary Design of a Suppressed Ablation Laser-Induced Fusion Reactor," CONF-740402-P1, Proceedings of the First Topical Meeting on the Technology of Controlled Thermonuclear Fusion, San Diego, CA, April 16-18, 1974. (The "Suppressed Ablation" concept.)

(a) B. Badger et al. (22 authors), UWMAK-I, A Wisconsin Toroidal Fusion Reactor Design, Volume II, UWFD-68, University of Wisconsin, May 1975.(1) Net Plant Output is 1473 MWe.

(b) B. Badger et al., (30 authors), UWMAK-II, A Conceptual Tokamak Power Reactor Design, UWFD-112, University of Wisconsin, October 1975.(2)

(c) A Fusion Power Plant, R. G. Mills, Ed., MATT-1050, Princeton Plasma Physics Laboratory, 1974.(3) Does not include requirements for small components such as valves, pumps, electrical equipment. Net Plant Output is 2030 MWe.

(d) A. P. Fraas, Conceptual Design of the Blanket and Shield Region and Related Systems for a Full Scale Toroidal Fusion Reactor, ORNL-TM-3096, May 1973.(4) Major components only. Net Plant Output is 518 MWe.

(e) J. E. Draley, R. A. Krakowski, T. A. Coultas, and V. A. Maroni, An Engineering Design Study of a Reference Theta-Pinch Reactor (RTPR): Environmental Impact Study, LA-5336, ANL-8019 (Joint report), Vol. II, March, 1975.(5) Major elements only. Net plant output is 4100 MWe.

(f) R. W. Werner, G. A. Carlson, J. Hovingh, J. D. Lee, and M. A. Peterson, Progress Report #2 on the Design Considerations for a Low Power Experimental Mirror Fusion Reactor, UCRL-74054-2, September 1973.(6) As emphasized by the title, this design is for an experimental device of low power. Optimization for power production would be expected to introduce economics of scale reducing some of the material requirements per MWe. Covers blanket and shield, Cu for coils, 304 SS coil support structure and direct converter structure. Superconductor for coils not included. Net plant output is 170 MWe.

(g) J. R. Powell, Ed., "Preliminary Reference Design of a Fusion Reactor Exhibiting Very Low Residual Radioactivity," BNL-19565, Brookhaven National Laboratories, December 1974.(7) Net Plant Output is 1605 MWe.

(h) Only construction materials included here (differs from tabulation in source). Tabulation includes all material within toroidal magnets, plus divertor and vertical field coils, injectors, and entire primary coolants.

(i) Not including turbine, reheaters, control room, cooling towers and electrical switch gear. Not including tritium extraction equipment except yttrium.

(j) These requirements were not developed in the design document. Blanket and shield requirements were calculated from the spherical shell neutronics model; coil requirements and materials for coil support and for the direct converter structure were calculated from descriptions and dimensions, by G. A. Carlson.(6)

(k) Feedstock for ⁶Li enrichment included.

TABLE 3. Average Annual Material Replacement Estimates for Fusion Power Plants

Element	Average Annual Replacement Quantities, metric tons					
	UWMAK-I (a)	PPPL (b)	ORNL (c)	Theta Pinch (d)	Mirror (e)	BNL Blanket (f)
Aluminum	7.2					252
Beryllium				10		1
Carbon			110	140	11	174
Chromium	129	39			6.3	
Copper	7.2			2		
Iron	445	85			20	
Helium				1		
Lithium				16		5
Manganese	14				0.6	
Molybdenum	14					
Niobium			14	77		
Nickel	100	94			3.8	
Zirconium			0.1			

- (a) Due to 316 SS replacement. 32% due to biannual replacement of inner blanket; 68% due to replacement of remainder of blanket every 10 years.
(b) Due to Fe-16 replacement; one-fifth of blanket each year.
(c) Replace blanket every 10 years.
(d) Replace one-fifth of blanket modules each year.
(e) Blanket life is not estimated in the design. 304 SS structure and first wall loading are similar to UWMAK-I. This table is based upon replacement schedule postulated by rough analogy to UWMAK-I. Replacement of inner 30 cm of blanket every 2 years; replacement of outer 70 cm of blanket every 10 years; 30-year plant life.
(f) Replace one-third of blanket modules each year.

TABLE 4. Normalized Material Usage for Fusion Power Plant Construction*

Element	Metric Tons/MWe						Reference Envelope† Maximum	Typical LMFBF
	UWMAK-I (a) Total	PPPL (b) Total	ORNL (c) Nuclear Island	Theta Pinch (d) Total	Mirror (e) Reactor and Converter	BNL Blanket (f) Blanket and Shield		
Aluminum	0.54	0.008				1.55	1.6(f)	0.02
Boron	1.07					3.61	3.6(f)	
Beryllium		0.43		0.012		0.12	0.4(b)	
Carbon	0.30		2.12	0.17	1.4	1.96	2.1(c)	
Chromium	7.92	0.82	0.07		44		44(e)	0.4
Copper	7.27	1.61	0.87	2.27	52		53(e)	0.7
Iron	77.8	5.87	12.4		146		146(e)	34
Helium	0.09	0.06	0.002	0.29			0.3(d)	
Magnesium	0.002						0.002(a)	
Potassium			0.02				0.02(c)	
Lithium	1.15	0.29	0.89	0.39	0.49	0.04	1.2(a)	
Manganese	0.82	0.08			4.4		4.4(e)	
Molybdenum	0.41	0.14					0.4(a)	
Sodium	12.1						12.1(a)	
Niobium	0.09	0.05	1.93	0.88			1.9(c)	
Nickel	5.90	0.81	0.05		27		27(e)	0.3
Lead	13.9		10.3		7.5		13.9(a)	0.046
Tin		0.02		0.07			0.07(d)	
Titanium	0.05	0.008	1.24				1.24(c)	
Yttrium	0.003						0.003(a)	
Zirconium	0.07	0.0005	0.002				0.07(a)	
Concrete	461	15.8	38.6		225		461(a)	200

* See Footnotes to Table 2.

† Maximum quantities are from designs correspondingly labeled.

TABLE 5. Normalized Average Annual Material Replacement Estimates for Fusion Power Plants*

Element	Metric Tons/1000 MWe						Reference Envelope+ Maximum
	UWMAK-I (a)	PPPL (b)	ORNL (c)	Theta Pinch (d)	Mirror (e)	BNL Blanket (f)	
Aluminum	4.9					157	157(f)
Beryllium				2.4		0.6	2.4(d)
Carbon			212	34	66	108	212(c)
Chromium	87	19			37		87(a)
Copper	4.9			0.5			4.9(a)
Iron	302	42			118		302(a)
Helium				0.2			0.2(d)
Lithium				3.9		3	3.9(d)
Manganese	9.5						9.5(a)
Molybdenum	9.5				3.7		9.5(a)
Niobium			27	19			27(c)
Nickel	68	46			22		68(a)
Zirconium			0.3				0.3(c)

* See Footnotes to Table 2

+ Maximum quantities are from designs correspondingly labeled.

Material usage estimates for UWMAK-II are given in Table 2 for comparison only since this data was not available when this analysis was made. The estimated materials to be used for the LMFBR are included in Table 4 for comparison purposes.

ELECTRICITY USE FORECASTS

A large number of electricity-use forecasts have been prepared over the years and all were based, in some way, on historical experience. Some forecasts are based directly on the historical pattern of electricity use while others relate this electricity use to variables such as income or population. The available electricity forecasts have differences which are related to historical periods studied as well as various assumptions used in estimating future deviations from the patterns in those base periods. Of these forecasts, four that covered the range of currently credible future electrical use possibilities were selected for analysis. Since these forecasts did not go beyond the year 2000, they were extended to 2040 with methods which were as consistent as possible with the procedures originally used to generate the forecasts.

The electricity use forecasts are given in Table 6 and are illustrated in Figure 1. Compared to 1.5 trillion kW-hr (kilowatt hours) in 1970, these forecasts range from 3.4 to 9.7 trillion kW-hr in the year 2000 and from 5.6 to 73.3 trillion kW-hr by 2040. Forecasts I and II, which extend the high and low forecasts of the ERDA Assistant Administrator for Planning and Analysis,⁽⁸⁾ are similar to the LMFBR medium and low cases, respectively.⁽⁹⁾ Forecast III uses a relationship of electricity use to GNP given by Cochran⁽¹⁰⁾ in a recent critique of the LMFBR impact statements. Forecast IV extends the Zero Energy Growth (ZEG) Case found in the final report of the Ford Foundation's Energy Policy Project.⁽¹¹⁾

TABLE 6. U.S. Electricity Generated by Utilities in the U.S. Historical and Forecasted

	Forecast I	Forecast II (trillion kW-hr)	Forecast III	Forecast IV
1920			0.039	
1930			0.091	
1940			0.142	
1950			0.329	
1960			0.755	
1970			1.532	
1975	-	-	-	2.0
1980	3.08	2.79	2.43	-
1985	-	-	-	2.68
1990	5.62	4.56	3.49	-
2000	9.67	7.00	4.77	3.44
2010	16.57	10.50	6.38	3.89
2020	27.92	15.19	8.37	4.38
2030	45.63	21.37	10.76	4.94
2040	73.29	28.90	13.37	5.57

FIGURE 1. U.S. Electricity Use, Historical and Forecasts

Recent econometric literature indicates that the long-run income elasticity of demand for electricity is about 1.1.⁽¹²⁾ The following relationship was found to approximately replicate the ERDA-P&A forecasts for the 1970 to 2000 period:

$$\text{Electricity Use} = A (\text{GNP})^{1.1}$$

where A is not a constant. The value of A was found to follow an approximately linear trend from 1950 to 1970. The future values of A were taken from a linear extrapolation of this trend. While this is not a procedure that we would use to develop new electricity forecasts, it did approximately replicate the forecasts of ERDA-P&A. The above procedure was used to extend their high and low forecasts to 2040. It is recognized that the results may be little better than direct extrapolation of electricity use.

GNP forecasts for Forecasts I and II were made using the following assumptions: Forecast I uses the Bureau of Census' Series I population forecast to 2040,⁽¹³⁾ a 2.5% annual growth rate in GNP/worker⁽¹⁴⁾ and 45% of the population employed. Forecast II uses the Bureau of the Census' Series II population forecast,⁽¹³⁾ a 1.8% annual growth rate of GNP/worker⁽¹⁴⁾ and 45% of the population employed. The resulting GNP forecasts used are given in Table 7, while the population forecasts used are given in Table 8.

TABLE 7. U.S. GNP Forecasts

Forecast I	Forecast II (\$ billions 1958)	Forecast III 1958	Forecast IV
1920		139	
1930		181	
1940		230	
1950		355	
1960		488	
1970		722	
1975	-	-	1018
1980	1099	1006	-
1985	-	-	1434
1990	1600	1323	-
2000	2278	1697	2279
2010	3278	2165	3032
2020	4717	2712	3991
2030	6705	3364	5156
2040	9436	4050	6504

TABLE 8. U.S. Population Forecasts

Forecast I	Forecast II (\$ millions)	Forecast III 1958	Forecast IV
1920		106	
1930		123	
1940		133	
1950		151	
1960		179	
1970		205	
1975	-	-	-
1980	226	223	-
1985	-	-	236
1990	258	245	-
2000	287	262	265
2010	322	279	279
2020	362	294	294
2030	403	304	304
2040	449	312	312

Forecast III uses the following relationship attributed to Milton Searl in Cochran:⁽¹⁰⁾

$$\text{Electricity use} = 2.03 \text{ GNP} - 666$$

where

Electricity use is in billions of kW-hr

and

GNP is in billions of 1958 dollars

This relationship was estimated by Searl from 1947 to 1969 data. GNP forecasts for Forecast III were made by assuming a 2% annual growth rate in GNP/worker, the Bureau of the Census' Series II⁽¹³⁾ population forecast, and 45% of the population employed.

Historically, national income per person employed has grown at an annual rate of 1.9% from 1929 to 1969. Within this period the rate of growth varied from 1.4% during the 1929 to 1941 period to 2.5% during the 1953 to 1964 period.⁽¹⁴⁾ Thus, the GNP/worker growth rate used in Forecast I reflects the highest historical experience while Forecasts II and III use rates near the long-term historical average.

Forecast IV extends the ZEG case of the Ford Foundation's Energy Policy Project.⁽¹¹⁾ This case assumes total energy use will peak at 100 quadrillion Btus before 1990. The Census Bureau's Series E population forecast was used by the Ford Foundation while the similar and newer Series II⁽¹⁴⁾ was used to extend this work. In this energy forecast GNP/worker was expected to grow at 2.5% annually from 1975 to 1985 and 2.35% from 1985 to 2000. Therefore, a 2.25% annual growth rate from 2000 to 2040 is assumed here in extending their work. The Ford Foundation's ZEG case projects the percentage of total energy going to electricity to increase from 27% in 1975 to 30.5% in 1985 and 36.5% in 2000. An annual growth rate of 1.2% in the percentage of total energy going to electricity derived from these figures was used to bring this fraction to 58.5% by the year 2040. The constant conversion efficiency of 32.3% assumed in the Ford Foundation report⁽¹¹⁾ was also used here.

Other forecast results to the year 2000 are included for comparison. The Federal Power Commission in its 1970 National Power Survey⁽¹⁵⁾ forecasts U.S. electricity use of 3.07 trillion kW-hr in 1980 and 5.83 trillion kW-hr in 1990. A 1973 National Power Survey report extended these results to forecast 10.2 trillion kW-hr by the year 2000.⁽¹⁶⁾ These FPC forecasts are close to the Forecast I given here.

A recent survey of energy forecasts shows that electric energy consumption was expected to grow at the annual rate of 5.8% from 1970 to 1980 and 4.8% for the 1980 to 2000 period, while total energy use was expected to increase at 3.3%/year for the 1970-80 period.⁽¹⁷⁻¹⁹⁾ This would result in 2.7 trillion kW-hr in 1980 and 6.9 trillion kW-hr in 2000, which is close to the Forecast II presented here. Forecast II was arbitrarily selected as the case to be used as the base for other estimates in this report.

A recent set of state level electricity forecasts, based on econometric analyses of the demand for electricity, was produced by Tyrrell at ORNL.⁽²⁰⁾ He used estimates of the responses of electricity use to changes in the prices of electricity, natural gas, and appliances as well

as income and population size from an earlier ORNL study.⁽²¹⁾ He then combined these estimates with forecasts of these independent variables to produce a "base case" forecast of electricity use. Tyrrell tested the sensitivity of the results to these assumptions and found that the impacts of different electricity price and per capita income assumptions were the most significant. He also found that constant electricity prices would mean electricity use of 6.6 trillion kW-hr in 2000 compared to only 2.8 trillion kW-hr if electricity prices double and 4.3 trillion kW-hr in his base case. Tyrrell's base case is close to the Forecast III presented here.

In a more recent book⁽²²⁾ Uri used the same general procedures used in the earlier ORNL work but obtained different results. Uri's assumptions regarding the future course of electricity prices, population, and income are the same as Tyrrell's while his assumed rate of the natural gas price increase is less than Tyrrell's. Uri's commercial and industrial electricity use growth estimates are so far below Tyrrell's that his total electrical usage forecasts fall below Tyrrell's for all regions in spite of Uri's generally higher residential electricity forecasts. Uri expects the commercial sector to use less electricity in 1990 than in 1970 in most regions because of the high price elasticity he found in the commercial sector. For 1990 Uri forecasts electricity use to be 2.6 trillion kW-hr which is considered to be the lowest electricity forecast available and is less than Forecast IV.

Forecasts I through IV cover the range of possibilities that are considered most likely. This allows testing the sensitivity of the impacts of fusion power plants to changes in a wide variety of electrical use forecasts.

FUSION POWER PLANT CONSTRUCTION FORECAST

To evaluate the long-range role of fusion power plants a computer simulation system⁽²³⁾ was used to estimate the pattern of the electricity generation industry's long-range development on a multi-regional basis. The model simulates the industry's process of determining what types of plants to build and when to build them. The model finds the smallest present worth system cost, subject to many constraints which limit decisions. Linear programming was used and the system costs are those for both construction and operation.

This analysis consists of six cases covering the four electrical energy use forecasts described in the previous section; the six cases are summarized in Table 9. Cases 1 through 4 correspond to Forecasts I through IV presented in the previous section. In these cases it is assumed that a fusion power plant could be introduced in 2010 at an electricity cost of 3% less than the LMFBR. Case 5 represents Forecast II electric energy use with a 10% lower cost assumed for the fusion power plant while Case 6 represents the Forecast II electric energy use without any fusion power plants. The reference nuclear assumptions include new technologies according to the estimated dates of their first commercial use as shown in Table 10. Fusion power plants were introduced into the analysis assuming that construction of one plant was completed in 2010 with the building rate doubling every 2 years or as constrained by projected economic conditions.

TABLE 9. Summary of Linear Programming Cases Solved

Case	Fusion Reactor Introduction	Electricity Use Forecast	Fusion Reactor Electricity Cost % of LMFBR	Fusion Reactors
1	2010	I	97	Reference
2	2010	II	97	Reference
3	2010	III	97	Reference
4	2010	IV	97	Reference
5	2010	II	90	Reference
6	--	II	--	Reference

TABLE 10. Nuclear Fuel Cycle Technology Developments

Reactor Type	Commercialization Availability Date	Fuel Cycle
LWR	1968	Uranium
	1976	Self-produced plutonium recycle
	1984	Full plutonium recycle
LMFBR	1992	Reference LMFBR (20 year doubling)
	1996	Reference LMFBR (12 year doubling)
HTGR	1980	²³³ U makeup without recycle
	1982	²³³ U makeup with full recycle
	1982	²³⁵ U makeup with self-produced recycle
	1984	Plutonium makeup
	1984	Plutonium makeup with recycle

Constant 1974 dollars were used as the basis for this analysis. The capital costs were based on the latest 1974 costs reported to ERDA by the utilities for fossil and thermal reactors.⁽²⁴⁾ Capital costs for the LMFBR were assumed to be \$100/kW higher than the LWR while the capital costs for the fusion power plant were selected so that the total power cost was approximately 3 to 10% less than the LMFBR. Fossil fuel costs were based on 1974 monthly summary reports.⁽²⁵⁾

The present value of total system costs from 1974 to 2040 discounted to 1974 at 8.8% was calculated for each case and the results are shown in Table 11. The benefits of fusion power plants for the Forecast II electric energy use (ERDA, P&A 1975 low forecast) are given by the difference in these present values of electricity production costs between Cases 2 and 5, and Case 6. Thus, the discounted benefits would be \$5 billion if the fusion power plant produces electricity at 10% less cost than the LMFBR or \$2 billion if it had a cost advantage of 3%.

TABLE 11. Total Estimated Present Value of Electricity Production Costs

Case	Trillion 1974 \$ Discounted at 8.8%	Case	Trillion 1974 \$ Discounted at 8.8%
1	1.181	4	0.267
2	0.740	5	0.737
3	0.434	6	0.742

The summaries of generating plants built in each decade by type are listed in Table 12 for Cases 1 through 6; the installed capacity by plant type is listed in Table 13 for Cases 1 through 6; and the electrical generation by plant type is listed in Table 14 for Cases 1 through 6. Tables 12 through 14 represent thermal plants built after 1970. Old fossil plants, hydro-electric, and internal combustion generators are excluded from the LP model. These generated an additional 482,000,000 MW-hr/yr in 1970, but will decline in importance as old plants are retired and replaced by new ones.

TABLE 12. Estimated Capacity Built (GWe) by Decade

	Light Water Reactor (LWR)	High Temperature Gas Reactor (HTGR)	Liquid Metal Fast Breeder Reactor (LMFBR)	Fusion Reactors	Fossil	Total
Case 1						
1970 - 79	71				233	306
1980 - 89	392	33			156	581
1990 - 99	506	90	30		247	873
2000 - 09	297	62	662		601	1622
2010 - 19	301	496	1017	621	877	2753
2020 - 29	262	839	241	2269	612	4223
2030 - 39	221	138	48	5946	630	6983
Case 2						
1970 - 79	71				192	263
1980 - 89	280	32			99	411
1990 - 99	376	51	31		128	586
2000 - 09	247	100	375		221	943
2010 - 19	200	273	493	62	271	1299
2020 - 29	201	305	170	835	251	1762
2030 - 39	200	76	47	1910	216	2449
Case 3						
1970 - 79	63	33			142	205.3
1980 - 89	148	21	.4		75	244.4
1990 - 99	219	43	30		66	358
2000 - 09	121	155	144		100	520
2010 - 19	106	136	199	62	111	614
2020 - 29	108	52	82	485	79	806
2030 - 39	106	38	49	753	96	1042
Case 4						
1970 - 79	63	.33			111	174.3
1980 - 89	125	14	.4		29	168.4
1990 - 99	148	25	5.6		34	212.6
2000 - 09	96	91	18		36	241
2010 - 19	84	9	83	37	36	249
2020 - 29	85	5	41	135	35	301
2030 - 39	83	10	17	220	22	346
Case 5						
1970 - 79	71				191	262
1980 - 89	282	32			97	411
1990 - 99	376	51	31		128	586
2000 - 09	252	98	376		218	944
2010 - 19	200	269	493	62	273	1297
2020 - 29	201	310	164	835	252	1762
2030 - 39	200	51	47	2010	143	2451
Case 6						
1970 - 79	71	.33			191	262.3
1980 - 89	282	32	.4		97	411.4
1990 - 99	377	51	30		127	585
2000 - 09	254	55	418		217	944
2010 - 19	202	45	787		265	1299
2020 - 29	202	317	923		318	1760
2030 - 39	202	296	1627		326	2451

TABLE 13. Estimated Installed Capacity (GWe) at Beginning of Year

Year	Light Water Reactor (LWR)	High Temperature Gas Reactor (HTGR)	Liquid Metal Fast Breeder Reactor (LMFBR)	Fusion Reactors	Fossil	Total
Case 1						
1980	74	.33			387	461.3
1990	426	33	.4		454	913.4
2000	929	123	30		636	1718
2010	1195	185	692		1004	3076
2020	1104	648	1709	62	1725	5247
2030	860	1397	1920	2331	2090	8598
2040	784	1473	1306	8277	2119	13959
Case 2						
1980	74	.33			345	419.3
1990	354	32	.4		355	741.4
2000	727	83	31		418	1259
2010	903	183	406		448	1940
2020	823	424	899	62	620	2828
2030	648	678	1038	897	743	4004
2040	601	654	710	2807	738	5510
Case 3						
1980	66	.33			296	362.3
1990	214	21	.4		282	517.4
2000	430	64	30		283	807
2010	488	219	174		241	1122
2020	446	334	373	62	277	1492
2030	335	343	425	547	290	1940
2040	320	226	330	1300	286	2462
Case 4						
1980	66	.33			265	331
1990	191	14	.4		205	411
2000	336	39	6		174	555
2010	369	130	24		99	622
2020	328	125	107	37	106	703
2030	265	105	142	172	107	791
2040	252	24	135	392	93	896
Case 5						
1980	74	.33			345	419.3
1990	356	32	.4		353	741.4
2000	729	83	31		416	1259
2010	910	181	407		443	1940
2020	828	418	900	62	619	2828
2030	653	677	1033	897	743	4003
2040	601	630	704	2907	668	5510
Case 6						
1980	74	.33			345	419.3
1990	356	32	.4		353	741.4
2000	730	83	30		415	1258
2010	913	138	448		441	1940
2020	833	151	1235		609	2828
2030	658	417	2128		800	4003
2040	606	658	3337		909	5510

TABLE 14. Estimated Annual Electric Generation by Plant Type

(Trillion Watt Hours)						
Year	Light Water Reactor (LWR)	High Temperature Gas Reactor (HTGR)	Liquid Metal Fast Breeder Reactor (LMFBR)	Fusion Reactors	Fossil	Total
Case 1						
1980	432	2			1822	2256
1990	2310	225	3		2222	4760
2000	4862	760	289		2948	8859
2010	5489	956	4464		4854	15763
2020	4435	3050	10416	565	8505	26971
2030	3307	6556	10275	14689	9640	44467
2040	3138	6217	6037	44166	9036	68594
Case 2						
1980	425	2			1585	2012
1990	1880	210	3		1697	3790
2000	3731	540	249		1860	6380
2010	4082	988	2674		2117	9861
2020	3313	2042	5576	460	3060	14451
2030	2506	3063	5626	5840	3511	20546
2040	2407	2646	3387	15456	3304	27200
Case 3						
1980	377	2			1318	1697
1990	1260	144	3		1330	2737
2000	2288	439	216		1235	4178
2010	2341	1137	1177		1109	5764
2020	1858	1588	2378	476	1386	7686
2030	1398	1356	2388	3517	1365	10024
2040	1374	940	1633	7173	1286	12372
Case 4						
1980	396	2			1175	1573
1990	1138	95	3		931	2167
2000	1836	279	38		728	2881
2010	1861	816	173		483	3333
2020	1505	733	704	250	565	3757
2030	1206	477	872	561	1152	4270
2040	1133	133	719	474	2381	4840
Case 5						
1980	425	2			1585	2012
1990	1892	210	3		1685	3790
2000	3742	541	249		1848	6380
2010	4107	972	2675		2097	9861
2020	3334	2018	5579	460	3058	14448
2030	2520	3060	5590	5860	3514	20544
2040	2409	2548	2248	15908	2987	27200
Case 6						
1980	426	2			1586	2014
1990	1892	210	3		1685	3790
2000	3745	548	242		1845	6380
2010	4125	784	2854		2089	9852
2020	3357	738	7377		2996	14468
2030	2542	1904	12260		3849	20555
2040	2427	2935	17589		4271	27222

ESTIMATED TOTAL MATERIAL USAGE (WITH AND WITHOUT FUSION POWER PLANTS)

To determine the impact of fusion power plant construction on materials availability, the quantity of materials that would be used if fusion power plants were not built was first estimated. Since the demand for most materials is derived from their use in another product, the final demand must be established for all commodities that use these materials in their production. (Final demand as used here and in all input/output analysis refers to the sales of products for final consumption and does not include inter-industry sales of commodities.) To accomplish this the EXPLOR MULTITRADE, an econometric model that embodies a comprehensive input/output analysis system, was used. EXPLOR MULTITRADE calculates the total output of all commodities necessary to produce the projected final demand; a brief description of the code and input data is presented in Appendix A.

For the purpose of this study, materials "critical" to the fusion power plant construction were assumed to be those where construction of 25 fusion power plants/year would require more than 1% of the present U.S. consumption of that material or where domestic reserves were considered to be very small compared to current use rates. Many basic materials are included in all EXPLOR MULTITRADE analyses. Table 15 shows the typical materials used in fusion power plant construction and the estimated quantities of each used per MWe of capacity built. These estimates were taken from the design that is expected to use the largest quantities (UWMAK-I or PPPL).

TABLE 15. Estimated Critical Material Usage for Constructing a Hypothetical Fusion Power Plant

<u>Material</u>	<u>Usage, (a) Metric Ton/MWe</u>	<u>Material</u>	<u>Usage, (a) Metric Ton/MWe</u>
Aluminum	0.54	Manganese	0.82
Beryllium	0.43	Molybdenum	0.41
Boron	1.07	Niobium	0.09
Chromium	7.92	Nickel	5.9
Copper	7.27	Lead	13.9
Iron	77.80	Sodium	12.1
Helium	0.09	Tin	0.02
Mercury	0.002	Titanium	0.05
Lithium	1.15	Zirconium	0.07

(a) The quantities were taken from the conceptual designs that are expected to use the largest amounts of materials (UWMAK-I or PPPL)

To determine domestic use of materials assuming no fusion power plants are built, but that the same electrical generation is produced by other nuclear plants, EXPLOR MULTITRADE computer runs were made for the years 2010, 2020, and 2040; projected domestic use of these materials for these years as well as for 1973 is shown in Table 16. The numbers represent order-of-magnitude estimates. The values in Table 16 were derived by assuming an overall GNP growth rate of approximately 3% between now and 2010, and a growth rate of approximately 2% thereafter. Total electricity consumption is assumed to be the same as that listed for Case II on Table 14.

TABLE 16. Estimated Domestic Annual Use of Critical Materials
Assuming No Fusion Power Plants

	Metric Tons Used			
	1973	2010	2020	2040
Beryllium	383	4,960	6,000	9,170
Chromium	656,000	2,120,000	2,604,000	4,100,000
Copper	1,942,000	5,940,000	7,790,000	12,418,000
Iron Ore	92,500,000	376,000,000	474,000,000	737,600,000
Helium	2,500	10,800	14,500	22,900
Mercury	1,850	8,200	10,400	15,900
Lithium	3,600	11,700	15,400	23,700
Molybdenum	33,100	82,020	108,800	169,000
Nickel	285,000	798,000	989,000	1,543,000
Lead	1,758,000	10,357,000	13,436,000	21,297,000

Table 17 lists projected domestic usage for these same critical materials for the years 2010, 2020, and 2040 assuming introduction of fusion power plants at the rate shown in Case II above. Although only the first fusion power plant would be scheduled to be on line in 2010, more plants would be under construction at that time. Therefore, the figures in Table 17 include materials used not only for plants completed in the indicated year, but also for construction of plants to be completed later.

The actual projection of fusion power plant growth was done in a linear programming model⁽²³⁾ which minimized the discounted cost of building and operating thermal power plants subject to many decision limiting constraints as described in the previous section.

TABLE 17. Estimated Domestic Annual Use of Critical Materials
Assuming Introduction of Fusion Power Plants

Material	Metric Tons in 2010	% Change from non-Fusion Reactor Case	Metric Tons in 2020	% Change from non-Fusion Reactor Case	Metric Tons in 2040	% Change from non-Fusion Reactor Case
Beryllium	9,730	100.3	52,167	769	142,000	1,449
Chromium	2,207,000	4.2	3,450,000	32	6,540,000	60
Copper	6,080,000	2.4	8,230,000	6	13,700,000	10
Iron Ore	381,000,000	1.3	478,000,000	0.8	741,000,000	0.5
Helium	11,600	9.7	24,100	71	51,000	129
Mercury	8,300	0.2	10,700	3	16,400	3.2
Lithium	23,195	98	127,000	725	345,000	1,356
Molybdenum	86,600	5.6	152,000	40	295,000	75
Nickel	863,000	8.2	1,620,000	64	3,369,000	118
Lead	10,500,000	1.5	14,900,000	11	25,500,000	20

The materials use estimates in Tables 16 and 17 were summed for the period 1975 through 2040. The values for the intervening years were determined by interpolating between years that are shown. The total estimated domestic use of these materials between 1975 and 2040 appears in Table 18.

TABLE 18. Total Estimated Domestic Cumulative Use of Critical Materials (1975-2040)

<u>Material</u>	<u>Millions of Metric Tons Used</u>	
	<u>With Fusion Reactors</u>	<u>Without Fusion Reactors</u>
Beryllium	2.436	0.304
Chromium	181	141
Copper	439	412
Iron Ore	25000	25000
Helium	1.2	0.73
Mercury	54	54
Lithium	5.965	0.809
Molybdenum	8	6
Nickel	83	54
Lead	757	686

PROJECTED MATERIALS "AVAILABILITY"

THE MEANING OF "AVAILABILITY"

In assessing future materials availability one must first establish what is meant by the term "availability". First it should be noted that we are talking about the supply of these materials in the future. In economics, the supply of a commodity in a given time period is described by a price versus quantity relationship. Producers are willing to supply more of a commodity if they are offered a higher price. This is so because in the short run, production costs increase as output per unit time increases beyond normal operating levels of any fixed capacity. In the long run this capacity can be expanded. The prime cause of increasing supply prices of minerals over time is the mining of more accessible, higher grade ores first. We will return to this point in discussing the concept of "reserves". For now the important point is that the amount of a material that producers will supply is an increasing function of the price of this material.

Thus when people speak of a material being "available" the economist always asks "at what price?". The usual answer to this is "at a 'reasonable' price". This usually means that the price is not so much higher than present levels relative to other goods and services and people's incomes (in the case of final consumers) or revenues (in the case of an intermediate producer) that "many" people will reduce their purchases of this or items "very much" below what they would have bought at a lower or "more reasonable" price. Several points follow from this discussion:

- 1) People are willing to buy more of a commodity the lower its price compared to other goods and services. This inverse relationship between price and quantity is called a demand curve for the commodity.
- 2) People will buy more of a commodity if their incomes or revenues are higher and nothing else changes. Economists depict this as an upward shift in the demand curve.
- 3) When people speak of the future availability of an item they are really talking about how high its price is expected to be.
- 4) An interaction of supply and demand in markets for these items determines how high their prices are (in the absence of government controls).
- 5) This supply and demand interaction determines material use levels as well as their prices.

We have already discussed expected material use levels, so all that remains to be discussed is (A) whether these prices will increase enough as a result of the use of these materials for other purposes that these materials become "too expensive" relative to their substitutes to use them in fusion power plants and (B) whether the associated prices of these materials are expected to increase significantly as a result of the use of these materials in fusion power plants. If the answer to (A) is "no" then these materials will be judged as being "available" for use in fusion power plants. If the answer to (B) is "no" then the "availability" of these materials will be judged as being unaffected by the use of these materials in fusion power plants. It

should be clear that the answers to these two questions may be different depending on who answers them. The answers given here are those of the authors, but it is our view that most experts in the area of materials availability would agree with them.

This section of the report provides a preliminary assessment of the availability of raw materials which would ultimately be used in fusion power plants. These materials must go through several production stages before they are in the form to be used in fusion power plants. This report does not address productive capacity in these refining, manufacturing, and fabrication industries, because their capacity can be expanded if there is sufficient demand for their products and lead time. An assessment of manufacturing and fabrication technology can be found in Reference 26.

The availability of critical materials for fusion power plant construction was examined by reviewing U.S. and World reserves and resources, and comparing the quantities of materials expected to be used in the future with and without fusion power plants to these reserves and resources.

RESERVES AND RESOURCES

Reliability of the information on mineral resources is impaired by the inconsistent use of the terms "reserves" and "resources". These terms have significantly different meanings and connotations, but are sometimes used interchangeably. Reserves and resources as used in this report are defined as follows: 1) Reserves are the quantities of ore minerals located in identified deposits that can be developed profitably at current prices using current technology. Thus, they are dynamic and constantly changing as mineral prices and extraction technology change. Reserves are a function of man, as well as nature, and form the basis for the material supply system. 2) Resources are static since they are limited by the composition of the earth's crust, seas and atmosphere. Resources include undiscovered mineral deposits and reserves as well as identified mineral deposits that cannot be profitably recovered at current prices using current technology. Resource estimates based on the average crustal concentration (crustal abundance) are the maximum expected. Some resources can become reserves with higher prices or with the implementation of new technology.

Thus, reserves, which are identified by physically sampling the ore body, are constantly changing and usually increasing through price changes, discovery of new mineral deposits and the development of new technology. Projections of future reserves can be made using estimates or assumptions regarding future demands for these materials, technological change, and discovery rates. These future reserve estimates require assessment of the relative cost of extracting resources which are not yet discovered. As a result, good estimates are expensive and are not generally available.

Based on estimates of world resources and crustal abundance there are probably ample resources of minerals in the earth's crust which are expected to become reserves fast enough to allow use patterns of these materials to continue largely along present trends without significant relative price increases. Many areas of the world are only now being explored for

minerals and vast untapped resources are expected to exist in these areas. In addition, the mineral resources of the oceans which are close to being reserves are considerable, particularly for nickel, copper, manganese, and cobalt contained in nodules on the ocean floor.

Introductory chapters in USGS Professional Paper 820⁽²⁷⁾ provide some excellent discussion on the classification of resources as well as a comprehensive treatise on mineral resources. The U.S. Bureau of Mines, Commodity Data Summaries,⁽²⁸⁾ was also examined for this report as well as Mineral Yearbooks,⁽²⁹⁾ a survey of selected material resources by Prof. Cameron⁽³¹⁾ and this USGS Professional Paper.⁽²⁷⁾

Any attempt to assess the distant-future availability of materials using currently estimated reserves is fraught with risk. Resources are usually developed into reserves only to the extent that near-term exploitation of them seems likely. To do otherwise would entail premature exploration and development expenses. As a consequence, estimates of reserves are similar to inventories in other businesses; they do not necessarily decline over time in spite of sustained use of these reserves. World reserves of many minerals have actually grown at a rapid rate in the recent past (Table 19). For example, in 1950, world reserves of copper were 100 million metric tons while in 1970 they were 279 million metric tons. This represents a percentage increase of 179%. Even larger percentage increases in reserves have occurred. Since 1950 the reserves of phosphates have increased by 4430%. Nevertheless, estimates of reserves are used in the present analysis to infer where shortages, which cause price increases, might be expected for elements expected to be used in the construction of fusion power plants.

TABLE 19. Change in World Reserves^(a)

Ore	Reserves-1950 (1,000 Metric Tons)	Reserves-1970 (1,000 Metric Tons)	% Increase
Iron	19,000,000	251,000,000	1,321
Manganese	500,000	635,000	27
Chromite	100,000	775,000	675
Tungsten	1,903	1,328	-30
Copper	100,000	279,000	179
Lead	40,000	86,000	115
Zinc	70,000	113,000	61
Tin	6,000	6,600	10
Bauxite	1,400,000	5,300,000	279
Potash	5,000,000	118,000,000	2,360
Phosphates	26,000,000	1,178,000,000	4,430
Oil	75,000,000	455,000,000	507

(a) Source: Council on International Economic Policy, Executive Office of the President, Special Report, Critical Imported Materials (Washington, D.C.: U.S. Government Printing Office, December 1974).⁽³¹⁾

COMPARING MATERIALS USES TO RESERVES AND RESOURCES

The effect of fusion power plant construction on the projected availability of materials was determined by comparing the quantities of these materials expected to be used in the future to current estimate of U.S. and world reserves and resources; U.S. and world reserves of materials expected to be used in fusion power plant construction are presented in Table 20. Table 21 compares cumulative use with and without fusion power plant uses to U.S. and world reserves and resources for select elements. It is apparent from this comparison that if one were to look only at current U.S. reserves defined by present technology costs and prices, seven of the fusion power plant materials might be expected to become very expensive before 2010 as they become more scarce: beryllium, chromium, copper, iron, mercury, nickel and lead (Table 22). However, resources of these "critical" materials, although finite, are extremely large compared to reserves. Fusion power plant materials demands per se are not expected to contribute appreciably to these higher prices and hence to lack of "availability" except for beryllium and nickel where the change in consumption is expected to increase nearly 100% as a result of their use in fusion power plants.

TABLE 20. U.S. and World Resources, Crustal Abundance, 1974 Reserves, 1974 Production and 1974 Consumption for Fusion Power Plant Construction Materials

Material	1974 Reserves (a)		Estimated Resources (b)		Million Metric Tons of Metal Recoverable Resources Based on Crustal Abundance (c,d)		1974 Production (a)		1974 U.S. Consumption
	U.S.	World	U.S.	World	U.S.	World	U.S.	World	
Aluminum	6.1	2,400	>1,000	>28,000	203,000	3,520,000	4.4	12.8	4.9
Beryllium	0.025	0.05	>0.3	>0.7	1.1	19	NA	0.00016	-
Boron	28	66	100	NA	-	-	1.1	2.1	0.2
Chromium	0.0	460	>1.0	>1,000	189	3,300	0.0	2.0	0.5
Copper	82	390	160	680	122	2,100	1.5	7.2	1.8
Helium	0.78	NA	4.7	NA	-	-	0.0043	0.005	-
Iron	1,800	88,000	>30,000	>230,000	118,000	2,030,000	76	800	91
Lead	38	140	>50	>500	32	550	0.62	3.4	0.8
Lithium	0.36	1.1	>5.7	9.1	54	930	<0.002	<0.003	<0.003
Manganese	0.0	5,500	340	5,600	2,450	42,000	0.0	23	0.8
Mercury	0.014	0.16	>0.1	>1.0	0.2	3.4	0.000051	0.0079	-
Molybdenum	3.6	5.0	500	>1,000	2.7	47	0.0052	0.0073	0.03
Nickel	0.2	44	13	75	150	2,600	0.015	0.69	0.2
Niobium (Colombium)	0.01	7.7	>0.1	18	49	850	0.0	0.011	0.001
Potassium	230	67,000	NA	>100,000	-	-	1.9	20.2	-
Sodium	200	24,000	NA	Very large	-	-	>17	>60	-
Tin	0.035	9.1	0.2	34	3.9	68	0.0	0.21	-
Titanium	<0.2	<6	380	<90,000	13,000	225,000	<0.016	<0.051	<0.2
Yttrium	0.0008	0.033	80	14,000	-	-	NA	>0.0002	-
Zirconium	5.5	NA	5	20	-	-	<0.054	<0.35	-

NA = Not available

- (a) = Data are from Reference 28: USBM Commodity Data Summaries, 1975.
 (b) = Estimates derived from data in USGS Professional Paper 820, 1973.(27)
 (c) = Data from Table 3, R. L. Erickson, Crustal Abundance of Elements, and Mineral Reserves and Resources in USGS PP820, pp. 22-23.(27)
 (d) = These estimates used to calculate resources are based upon currently recoverable resources and do not include resources whose feasibility of economic recovery is not established.

TABLE 21. Critical Fusion Power Plant Materials Uses Versus Current Reserves and Resources

Material	Total U.S. Use to 2040, Million Metric Tons		Ratio Cumulative Use (1975-2040) to 1974 Reserves				Ratio Cumulative Use (1975-2040) to Resources			
			U.S.		World		U.S.		World	
	Without Fusion Reactors	With Fusion Reactors	Without Fusion Reactors	With Fusion Reactors	Without Fusion Reactors	With Fusion Reactors	Without Fusion Reactors	With Fusion Reactors	Without Fusion Reactors	With Fusion Reactors
Beryllium	0.30	2.4	12	97	NA	NA	1.0	8.1	0.43	<3.5
Chromium	140	180	--	--	0.31	0.39	141	181	0.141	0.439
Copper	410	440	5.0	5.4	1.1	1.1	2.6	2.7	0.61	0.66
Iron	25000	25000	14	14	0.28	0.28	0.83	0.83	0.11	0.11
Helium	0.73	1.2	0.94	1.5	NA	NA	0.16	0.26	NA	NA
Mercury	0.48	0.48	34	34	3.0	3.0	>4.8	>4.8	>0.48	>0.48
Lithium	0.81	6.0	0.89	6.6	0.74	5.5	0.14	1.1	0.09	0.66
Molybdenum	6.0	8.0	1.7	2.2	1.2	1.6	0.01	0.016	0.006	0.008
Nickel	54	83	270	415	1.2	1.9	4.2	6.4	0.73	1.1
Lead	690	760	18	42	4.9	5.4	13.7	55.3	0.49	<1.5

TABLE 22. Dates of Depletion of 1974 U.S. Reserves of "Critical" Fusion Power Plant Materials, Assuming No Additions to Reserves

Material	U.S. Reserve Depletion Date	
	Without Fusion Reactors	With Fusion Reactors
Beryllium	Before 2010	Before 2010
Chromium	--All chromium currently imported--	
Copper	Before 2010	Before 2010
Iron	Before 2010	Before 2010
Helium	After 2040	2034
Mercury	Before 2010	Before 2010
Lithium	After 2040	2019
Molybdenum	2026	2023
Nickel	Before 2010	Before 2010
Lead	Before 2010	Before 2010

Table 23 presents the 1975 ratio of cutoff grade (lowest concentration profitably recoverable) to crustal abundance for several fusion reactor critical materials. The smaller this ratio the greater the expected chances that resources will continue to replenish reserves of this material as they are used. These data illustrate the range between concentrations of currently profitably mineable ore and crustal abundance. For example, the ratio of profitably mineable concentrations to crustal abundance of mercury is 11,200 while that for aluminum is only 2.2. This means that aluminum-bearing ore being mined today contains only 2.2 times more aluminum than the average concentration in the earth's crust, while mercury ore contains 11,200 times more mercury than crustal concentrations.

TABLE 23. Ratio of 1975 Cutoff Grade to Crustal Abundance for Selected Minerals

Element	Crustal (a) Abundance, g/metric tons	1975 Cutoff (b) Grade, g/metric tons	Ratio: (Cutoff Grade/ Crustal Abundance)
Mercury	0.089	1,000	11,200
Tungsten	1.1	4,500	4,000
Lead	12	40,000	3,300
Chromium	110	230,000	2,100
Molybdenum	1.3	2,000	1,540
Zinc	94	35,000	370
Lithium	21	5,000	240
Beryllium	1.3	200	154
Nickel	89	9,000	100
Copper	63	3,500	56
Iron	58,000	200,000	3.4
Aluminum	83,000	185,000	2.2

(a) Tan Lee and Chi Lung Yao, Abundance of Chemical Elements in the Earth's Crust and Its Major Tectonic Units: International Geology Review, Vol. 12, No. 7, 1970, p. 776-788, (32)

(b) The lowest concentration profitably recoverable in 1975.

CRITICAL MATERIALS FOR FUSION POWER PLANT CONSTRUCTION

This section summarizes the potential "availability" of critical fusion power plant construction materials (Table 24). As seen in this table, world resources are greater than expected U.S. cumulative use to 2040, while U.S. resources are less than expected U.S. cumulative use to 2040 for six out of the ten materials presented: beryllium, chromium, lead, lithium, mercury, and nickel. U.S. resources of copper, iron and molybdenum are expected to be greater than U.S. cumulative uses to 2040. Data on helium is insufficient to project availability.

TABLE 24. Summary of Material Availability for Select Fusion Power Plant Materials

Material	Projected Production Capacity(a)	Reserve and Resource Compared to US Cumulative Uses (1975 to 2040)(b)	Current Source of Material Supply(c)
Beryllium	2	2,4,6,7	2
Chromium	2	2,3,6,7	4
Copper	1	2,4,5,7	2
Helium	3	2	5
Iron	1	2,4,5,7	2
Lead	2	2,4,6,7	1
Lithium	2	2,4,6,7	1
Mercury	2	2,4,6,7	3
Molybdenum	2,3	2,4,5,7	1,5
Nickel	2	2,4,6,7	3

(a) Production Capacity Compared to Expected Use Rates

1. Planned production capacity greater than expected U.S. use rates with and without fusion power plant uses.
2. Additional production capacity development needed as a result of fusion power plant construction.
3. Production is a by-product of production of another material.

(b) Reserves and Resources Compared to Cumulative Use (1975-2040)

1. U.S. reserves greater than expected U.S. cumulative use
2. U.S. reserves less than expected U.S. cumulative use
3. World reserves greater than expected U.S. cumulative use.

(b) Continued

4. World reserves less than expected U.S. cumulative use
5. U.S. resource greater than expected U.S. cumulative use
6. U.S. resource less than expected U.S. cumulative use
7. World resource greater than expected U.S. cumulative use
8. World resource less than expected U.S. cumulative use

(c) Source of Material supply

1. Less than 10% dependent on foreign supply
2. Less than 50% dependent on foreign supply
3. Less than 75% dependent on foreign supply
4. Totally dependent on foreign supply
5. By-product of production of another material

The quantities of select metals used in the United States in 1974 and the percentage domestically produced is shown in Table 25 while the following paragraphs discuss expected future availability of individual materials.

TABLE 25. Quantities of Select Metals Used in the U.S. in 1974 and Percentage Domestically Produced(a)

<u>Metal</u>	<u>1000 Metric Tons</u>	<u>% Domestically Produced</u>
Raw Steel	132,000	60
Aluminum	5,700	10
Copper	2,000	90
Manganese	1,400	0
Lead	1,500	90
Zinc	1,200	50
Nickel	190	10
Chromium	510	0
Magnesium	120	50
Molybdenum	69	100
Tin	58	0
Titanium	25	0
Tungsten	15	50
Cobalt	8.6	0
Beryllium	0.19	100

(a) Source: Commodity Data Summaries, U.S. Bureau of Mines, 1976.(33)

- **CHROMIUM.** As shown in Table 21, world resources of chromium are greater than expected U.S. cumulative use, but U.S. resources are less than expected U.S. cumulative use, with or without fusion power plants. There are no U.S. resources of chromium at current prices and technology. Also, the one currently profitable source of this essential (18 to 33%) component of stainless steel, the mineral chromite, is not being mined in the United States. Greater than 1 million MT of chromium resources have been identified in the U.S., but they are not currently considered to be reserves and are not expected to become reserves in the foreseeable future. In 1973, 70% of U.S. chrome was imported while 20% came from strategic stockpile sales and 10% from secondary recovery. The import sources in 1973 were S. Africa, 31%; USSR, 21%; Rhodesia, 13%; Turkey, 11%; Philippines, 11%; and remaining 13% from a number of small producers. Because of the small number of producers, the potential exists for a cartel which could cause significant price increases for short periods. However, significant price increases due only to increasing world scarcity of chrome are not expected in the foreseeable future.
- **NICKEL.** Currently, world resources and reserves of nickel are less than expected U.S. cumulative use with fusion power plants and they are only somewhat greater than U.S. cumulative use without fusion power plants. As is true with chromium, this metal is consumed in large quantities in steel making. U.S. nickel production provides only 5 to 10% of the nickel consumed in the U.S. with secondary sources providing about 30%. The remaining 60 to 65% are imported primarily from Canada with small amounts from the Dominican Republic and Norway.

Domestic nickel reserves are very small (~180,000 MT nickel) while resources are estimated to be greater than 13 million MT. A large increase in nickel prices could transform much of these resources into reserves. Also, known world nickel resources are increasing rapidly with new laterite developments. Sea floor nodules probably contain several hundred million metric tons of nickel. Resolution of political and technological difficulties could result in large quantities of nickel, copper, cobalt and manganese reserves from these resources.

- IRON ORE. U.S. reserves are less than expected U.S. cumulative use to 2040 with or without fusion power plants, but U.S. and world resources are greater than expected U.S. cumulative use. Significant long-term iron ore price increases are not expected even if nationalization of U.S.-owned iron ore production facilities in foreign countries occurs. Only about 30% of the iron ore used in the U.S. each year is imported. Delays in adding to production capacity could cause temporary shortages and high prices of iron as the use of this material for fusion power plants is added to other uses.
- ALUMINUM. U.S. reserves of the currently used aluminum ore, bauxite, are much less than current annual U.S. consumption. Domestic resources are greater than 1 trillion MT of aluminum which is considerably larger than expected U.S. cumulative consumption. Conversion to use of domestic resources such as clays, shales and other lower grade sources of aluminum would reduce reliance on imports.
- MERCURY. Currently, there is no mercury mined in the U.S. Although there are large U.S. resources (greater than 0.1 million MT), they are still less than expected domestic uses of mercury with or without fusion power plants. World reserves are less than expected U.S. cumulative use to 2040 while world resources are greater than expected U.S. consumption.
- LEAD. U.S. and world reserves are less than expected U.S. cumulative use to 2040. World reported resources are less than expected U.S. cumulative use to 2040. Significant lead time should be expected for expansion of production capacity.
- COPPER. U.S. and world reserves are less than expected U.S. cumulative use to 2040 with or without fusion power plants. Also U.S. resources are less than expected U.S. cumulative use, and world resources are greater than expected U.S. cumulative use to 2040. Significant lead time for expansion of production capacity should be expected.
- MOLYBDENUM. U.S. and world reserves are less than expected U.S. cumulative use to 2040 with or without fusion power plants. U.S. and world resources are very large compared to U.S. cumulative use of molybdenum.
- HELIUM. U.S. reserves and resources of helium are less than their expected U.S. cumulative use to 2040. No reliable data are available on world reserves or resources of helium. Natural gas is the primary source of helium.
- BERYLLIUM. Information on beryllium reserves and resources is very incomplete and unreliable. Data on world reserves of beryllium are essentially nonexistent while data on world resources are very conservative. The world cumulative use of beryllium to 2040 is expected to be greater than the world resources currently reported in the literature.

- NIOBIUM. U.S. reserves and resources are negligible. Most of the niobium used in the U.S. is currently imported from Brazil. World resources (greater than 18 million MT) are expected to be larger than U.S. cumulative use to 2040 with or without fusion power plants.
- MANGANESE. The U.S. has no reserves of manganese, and hence imports all of this metal which is used in the steel industry. However, world reserves are very large compared to U.S. expected cumulative use to 2040.
- LITHIUM. Fusion power plants are expected to use relatively large amounts of lithium compared to current U.S. production, but small when compared to the total U.S. resources. Further, significant price increases would not cause the substitution of other materials for lithium in fusion power plants because of the high energy content of Liase fusion fuel. For more detail on lithium supply see BNWL-2012.⁽³⁴⁾
- Additional information on select materials can be found in Appendix B.

Long lead times are involved in the exploration and development of reserves and the construction of production capacity. For example, to develop reserves takes from 8 to 20 years (in general) from the time of initial exploration, mine development takes up to 8 years, and construction of final production and fabrication facilities could take up to 5 years. Thus, the total lead time could be as long as 16 to 30 years.

Industrial capacity must be increased faster than currently planned to produce fusion power plant materials and elements including stainless steels, nickel-base alloys, boron, beryllium, chromium, helium, lithium, molybdenum, niobium, lead, tantalum, vanadium, and yttrium.

Other factors that could affect material availability but which were not extensively reviewed in this report are: geologic environment, geographic distribution and political influences. The uneven distribution of the geologic environments for various mineral deposits is the basic element in the structure of the mineral industry. The inequality of the geographic distribution of mineral deposits has had an affect on the political and economic availability of many materials (Table 26). These inequalities of distribution of minerals are complicated by the effects of various political climates. Wars, nationalism, cartels, demands for more control, high taxation, expropriation etc. lead to the need for industry to have diversified sources of raw materials.

POTENTIAL ENVIRONMENTAL IMPACTS OF MATERIALS PROCUREMENT FOR FUSION POWER PLANTS

Procurement of materials will result in environmental impacts from the mining, milling, and processing operations. Mining operations change the land and water use by releasing chemicals and other materials. Milling and processing operations have impacts on land occupancy and from releases of chemicals to water and air. These environmental impacts are discussed in the following subsections.

TABLE 26. Percentage Distribution of 1967 World Mineral Production for Select Materials

<u>Material</u>	<u>North America</u>	<u>South America</u>	<u>Europe</u>	<u>Africa</u>	<u>Asia</u>	<u>Oceania</u>	<u>Communist</u>
Aluminum	27.8	20.1	30.8	5.2	6.6	9.5	16.2
Chromium	0.6	0.1	40.1	30.9	28.3	--	38.8
Copper	29.9	17.1	20.2	23.8	7.2	1.8	19.3
Iron	20.7	9.5	48.2	6.0	12.5	3.0	34.4
Lead	26.8	8.0	36.3	6.5	9.4	13.1	26.3
Magnesium	52.6	--	43.4	--	4.0	--	22.3
Mercury	19.7	1.3	66.2	0.1	12.7	--	27.4
Molybdenum	76.7	8.9	11.2	--	3.2	--	13.1
Nickel	60.2	0.2	22.7	1.5	1.4	14.0	28.1

Land Alteration by Mining

Land is altered in several ways by mining. Strip mining completely alters the surface since it removes and replaces overburden. All vegetation is destroyed and mobile life forms are either displaced or destroyed. However, proper restoration practices could return land to its former condition after completion of the mining at some expense.

Underground mining requires that the ground surface be occupied by buildings, facilities, waste piles, and waste ponds. All life forms on these surface lands are displaced and destroyed, and much of the land is rendered less productive for other purposes because of the installation of permanent structures or because of the nature of the waste materials placed on the land. Further, the land may be altered by the subsidence that may occur as abandoned mining shafts cave in. This subsidence temporarily alters the surface conditions, possibly causing severe damage to structures and pollution of water bodies until the land surface is stabilized.

Chemical Release

Chemicals and other materials may be released to water bodies as a result of erosion of waste piles and loosened earth or as a result of dissolution of minerals exposed by mining operations. Often the land can no longer support profitable agricultural activities or lumber production for a long period after mining ceases. An adverse aesthetic impact could result from the presence of waste piles, structures, or barren ground in contrast to former forest, desert, or agricultural lands.

Proper design of waste piles, strip mines, and other surface locations that are subject to washing by rainwater will generally prevent washing of these materials into nearby bodies of water. Similarly, proper control of mine waters will minimize the amounts of dissolved materials entering nearby water bodies. Of course, these precautions increase mining costs.

During milling operations land is occupied by the process buildings, waste piles, and waste ponds. This land may become less productive because the chemicals in the water inhibit plant

growth. Chemical releases can be prevented from having adverse impacts through use of modern waste control technology, although this is accompanied by increased costs and land use for waste storage.

Processing operations to convert the concentrated ore into pure metals and fabricated equipment also use land and release chemicals. These impacts are quite similar to those for milling operations except that less land is used for waste disposal because there is no need to dispose of large quantities of gangue materials. Milling and processing operations may have significant adverse impacts due to heat releases, noise, and odors. These impacts can be kept insignificant through remote location of operations and use of current control technology at moderate cost.

Summary of Estimated Environmental Impacts

Information is not readily available on the average impacts due to procurement of most materials. Surveys have not been made to determine the average quantities of land alteration and chemical releases per ton of material produced. As a result, the actual impacts cannot be specified accurately. The amount of land required for the mining and disposing of the waste materials from mining was used as a general measure of the impact of material procurement. Generally, this land usage represents a majority of the known impacts, particularly if the chemicals and heat are released according to appropriate standards. The alteration of land for mining usually is much larger than for milling and processing.

As estimate of the amount of land altered for construction of a 1000-MWe fusion power plant is presented in Table 27. This estimate is based on the assumption that the average mining conditions are:

- strip mining to a depth of 25 meters,
- an ore and waste (overburden) average density of 3.0 kg/liter,
- as much land needed for handling and storing the overburden as is needed for the strip mine,
- ore concentrations equal to those of currently profitably mineable ores,
- restoration of 50% of the altered land to its original condition, and
- current mine stripping ratios (waste volume/ore volume).

The quantities of the materials used in the fusion power plant construction are based on the estimates for the UWMak-I tokamak.

This analysis indicates that about 0.16 km² (40 acres) of land probably would be altered as a result of construction of 1000-MWe fusion reactor power plant. Most of this land alteration is due to mining of copper, molybdenum and nickel. The actual land alteration appears to be primarily dependent on the quantities of these materials used and the mining conditions.

TABLE 27. Estimated Land Alterations for Mining of Materials for Fusion Power Plants

Material	Estimated Conc. of Metal in Resource, %	Estimated Metric Tons of Ore/MT of Metal	Assumed Stripping Ratio	Metric Tons Waste + Ore/MT Metal	Metric Tons Metal/MWe	Metric Tons + Waste Ore/MWe	Land Alteration (a) M ² /MWe	Land Alteration km ² /1,000 MWe
Aluminum	19.0	5.3	1.0	11	0.54	6		
Boron	6.0	17	1.0	34	1.07	36		
Chromium	6.8	15	1.0	30	7.92	238		
Copper	0.3	333	2.0	1,000	7.27	7,270		
Helium	--	--	--	--	--	--		
Iron	30.3	3.3	2.0	10	77.8	778		
Lead	3.0	33	0.5	50	13.9	695		
Lithium	0.5	200	1.0	400	1.15	460		
Manganese	30.0	3.3	1.0	66	0.82	54		
Mercury	0.1	1,000	1.0	2,000	0.002	4		
Molybdenum	0.12	830	2.0	2,500	0.41	1,025		
Nickel	1.0	100	1.0	200	5.9	1,180		
Niobium	0.2	480	2.0	1,440	0.09	130		
Sodium	22.0	4.6	0.1	5.1	12.1	62		
Titanium	1.2	83	1.1	174	0.05	9		
Yttrium	1.0	100	1.1	210	0.003	1		
Zirconium	0.2	500	0.1	550	0.07	39		
						11,987	160	0.16 (0.06 mi ²)

(a) Based on density of 3.0 kg/l, mining depth of 25 meters plus an equal amount of land needed to handle overburden and 50% reclamation.

APPENDIX A

APPENDIX A

DESCRIPTION OF THE EXPLOR-MULTITRADE PROGRAM

Input/output analysis answers the basic question: At what level of output will each industry in the economy operate to produce the total product of all industries? The commodity produced in some industries (e.g., the primary metals) becomes input to other industries, expressed in input/output analysis as a fixed proportion per unit of output of each industry. Therefore, the output level of primary metals is given by the input of these metals to other industries which is in turn dependent on the output level of all the industries in the economy. Since other industries provide input to the primary metals industry, their output is dependent on the input mix and the output level of the primary metals industry. Because of this interdependence, any projected output levels for all industries are consistent with all input levels in the economy. Input/output analyses will only predict a level of metals output that is consistent in the input/output sense with the rest of the economy.

The core of the EXPLOR-MULTITRADE model is a commodity-by-commodity input/output accounting system. The system begins with historic inter-industry flow matrices where an element in the i^{th} row and the j^{th} column represent the dollar value of an input of the i^{th} commodity to the production of the j^{th} commodity. These inter-industry flow matrices are converted to technical coefficient matrices by dividing each column by the constant dollar value of the output of the commodity corresponding to that column. Time trend analyses of the technological makeup of the economy, modified by expert opinion, are then used to estimate the shifts which will occur in these matrices in the future.

With the projected matrix of technical coefficients and exogenous forecasts of the components of final demand, prices, profits, and additional components of value added, EXPLOR-MULTITRADE iterates to a consistent solution for the entire economy of a country. The computer program attempts to get as close as possible to estimated prices and profits for all commodities subject to the many economic constraints embodied in the code. In effect, the program gives credance to the best estimates of the forecaster but forces the results to be compatible within themselves. A benefit to using a computer code such as this is that wild projections of material use without the necessary final demand will not be allowed. Final demand in input/output analysis refers to all sales of a commodity which are not used as input to the production process of any industry. This includes private expenditure, exports net of imports, capital expenditure, government expenditure, investment in dwellings, and changes in inventory.

The technical coefficients were aggregated from 129 sector detail technical coefficients supplied by the Bureau of Labor Statistics to 80 sector detail and were projected for future years. Further aggregation was done to make room for the critical materials that are examined in this assessment. Coefficients were developed for the critical materials which were not discernible from the BLS data due to the level of aggregation. These coefficients are shown in Table A.1 along with the SIC classification of the sectors which use the materials as inputs in

production. The coefficients in Table A.1 were developed from time series data in the Bureau of Mines documents; Minerals in the U.S. Economy⁽³⁵⁾ and Commodity Data Summaries 1974: Appendix I to Mining and Mineral Policy.⁽³⁶⁾ Coefficients for iron ore, copper ore, lithium, and lead were already in the earlier data base.

TABLE A.1. Technical Coefficients Representing Sales of Critical Materials to Other EXPLOR Sectors

EXPLOR SECTOR	SIC Classification	Beryllium	Chromium	Helium	Mercury	Molybdenum	Nickel
9	29						0.00120
10	491 and part 493			0.00002			
11	492 and part 493					0.00113	
27	324-329		0.00398				
29	281,286,287,289 (except 28195)		0.00115		0.00025	0.00035	0.00303
32	285				0.00110		
39	(3331,2,4,9), 334,28195, (3351,2,6,7), 336,3392			0.00010			
40	341,3491		0.00258	0.00012			0.00374
43	342,347,348,349, except 3491		0.00049				
44	351		0.01055				
48	(354-356)					0.00081	0.00126
52	361,362						0.00625
53	363		0.00215				0.00600
54	364	0.00435					
56	367	0.00082				0.00034	
57	369				0.00202		
58	381,382,384,387			0.00025	0.00070		
59	383,385,386			0.00014			
61	371		0.00083				0.00112
62	372	0.00021		0.00009		0.00134	0.00186
63	19			0.00077			
64	374,375,379,373						0.00249
69	(60-67),70,72,73, 75,76,(78-82)			0.00001			
78	part of 491 and 493			0.00002			
79	part of 491 and 493			0.00002			
80	part of 491 and 493			0.00002			

APPENDIX B

APPENDIX B

SUPPLY OF SELECTED MATERIALS

The information in this appendix discusses the sources for selected materials used domestically.⁽²⁶⁾

ALUMINUM

Domestic production of bauxite, the current raw material used for production of aluminum, is the source of only 10 to 15% of U.S. bauxite consumption. Even this small fraction has been waning⁽²⁸⁾ due to the substantial increase in imports of alumina, as well as bauxite, in the past 5 years. Major U.S. sources of bauxite are Jamaica, Surinam, Dominican Republic, and Guyana, while Australia, Jamaica, and Suriname provide the U.S. with alumina. Although these sources are considered stable, cartelization could temporarily raise prices dramatically. Given high enough aluminum prices and low cost energy, abundant low-grade U.S. resources (such as the Georgia kaolins) could become reserves.

Domestic production of primary and secondary aluminum typically provides more than 90% of the aluminum consumed annually in the U.S. The majority of aluminum that is imported comes from Canada. Domestic primary aluminum capacity is estimated to be 32% of total world capacity, and from 1972 to 1974 the U.S. accounted for 34 to 35% of estimated world production.

COPPER

The copper industry has historically been marked by large recurrent fluctuations in the price of its output. Because of this, the domestic copper industry (mines, smelters, refineries) has less capacity than if the price of copper had stabilized at its highest levels and more capacity than if it had stabilized at its lowest levels. The U.S. is a net importer of copper in ore, blister, and refined forms. Domestic mine production is slightly less than smelter capacity, which in turn is slightly less than refinery capacity, which in turn is slightly less than domestic consumption. Nevertheless, the domestic refining industry is typically the source of 90% or more of the domestic copper used while domestic mines are typically the source of about 75% of domestic consumption.⁽²⁸⁾ About 20% of the copper used domestically comes from the domestic secondary copper industry which salvages used copper from Canada, Peru, and Chile. From 1972 to 1974, domestic mines accounted for 20 to 22% of the world mine production of copper. This pattern is not expected to change in the foreseeable future.

FLUORINE

The use of fluorine in the manufacture of industrial chemicals comprises about 1/3 of the total market for fluorspar, which is the primary raw material.⁽³⁷⁾ Although flibe is not now a significant product of this industry, its manufacture would very conveniently fit chemical plant

operations.⁽³⁸⁾ Beryllium fluoride is an intermediate product in the manufacture of beryllium metal, and lithium fluoride is widely used as a flux. Thus, fluorine use is directly related to the beryllium and lithium industries.

From 1970 to 1974, domestic production of fluorspar decreased from about 20 to 15% of domestic use.⁽²⁸⁾ Thus, the domestic fluorine industry is getting a growing fraction of its primary raw material from foreign sources, principally from Mexico, but also from Spain and Italy. These sources of supply presently appear stable, but cartel action is a possibility. Domestic fluorine production as a by-product of phosphate processing is fostered by environmental regulations. Increased costs resulting from depletion of the highest quality fluorspar deposits and from these environmental regulations could result in fluorine production from phosphate rock treatment providing all of the fluorine used in the U.S. by the year 2000.

IRON

Currently, imports (chiefly from Canada and Venezuela) account for roughly 1/3 of the iron ore consumed by the domestic iron and steel industry.⁽²⁸⁾ The U.S. is also a net importer of iron and steel products, with imports exceeding exports by about 3 to 5 times from 1970 to 1974. However, shipments from domestic mills provided about 92% of the domestic iron and steel used from 1973 to 1974; this is an increase from about 85% from 1971 to 1972.

MERCURY

The fusion power plant use of mercury in vacuum pumps is small relative to the available projections of domestic use of mercury for other purposes. Worldwide mercury consumption is presently projected to grow at a compound annual rate of 2.2% through the end of this century.⁽³⁹⁾ Growth in domestic use of mercury is expected to be slower than this.⁽²⁸⁾ Environmental pressures have recently reduced the growth in domestic mercury consumption, and annual consumption through the early 1970s remained between 50 and 60 thousand flasks, down from the 70 to 100 thousand flasks/year level of the mid and late 1960s.

Domestic primary production of mercury in the past 5 years has decreased markedly in the face of falling prices for mercury since the late 1960s. In 1970, domestic primary and secondary production accounted for 44 and 13% of domestic consumption, respectively; in 1974 domestic primary production provided 3% of the mercury used domestically and secondary production provided 15%.⁽²⁸⁾ Even if, for example, one company achieves their stated goal of bringing on line in 1976 a primary plant capable of producing about 1/3 of current U.S. annual use, the U.S. will continue to rely heavily on foreign sources, barring a large upturn in price or technological improvements. (Environmental regulations have increased the cost of producing mercury in the U.S. with current technology.) Canada is the major source of mercury for the U.S., while Algeria, Mexico, and Spain are also important sources.

MANGANESE

The U.S. steel industry imports all of the manganese ore it uses from Brazil, Gabon, South Africa, and Zaire. Imports of ferro-manganese from South Africa, France, and India have been steadily increasing in proportion to domestic production of ferro-manganese from imported ore.⁽²⁹⁾ Nearly all of the manganese used in fusion power plants and otherwise is expected to be employed in making steel. Development of deep-sea nodule resources could greatly increase manganese reserves.

TIN

Domestic mine production of tin is miniscule, and domestic smelting of principally imported ore provides less than 10% of the domestically consumed tin; the domestic secondary industry provides roughly another 1/4 of domestic use. Thus, the U.S. imports most of the tin it uses. Malaysia and Thailand are the major sources of primary tin for the U.S.⁽²⁹⁾ The development of substitutes for tin in several applications has resulted in about constant domestic use of tin for several years. By virtue of control exercised by the International Tin Council, tin prices are not expected to increase dramatically in the near future. The amount of tin expected to be used in fusion power plants is small compared to other uses.

TITANIUM AND ZIRCONIUM

Almost all of the ore from which titanium is made (rutile) is imported from Australia. However, ilmenite (a potential titanium ore) is produced domestically in amounts sufficient to provide for 70 to 80% of domestic uses given higher titanium prices or new technology. The U.S. is also a net importer of titanium metal (sponge), primarily from Japan, the Soviet Union, and the United Kingdom. Sponge imports typically supply about 1/4 of domestic uses. Domestic industry provides virtually all of the mill products used domestically.

Roughly half of the zircon used in the U.S. is provided by Australia with the balance produced domestically. However, the U.S. is a net exporter of zirconium metal.

Domestic industrial production of both metals is expected to grow at a rapid rate. Foreign ore imports will probably continue for the foreseeable future. The use of these metals in fusion power plants is small compared to other uses of these materials and compared to the use of other materials in fusion power plants.

GLOSSARY

GLOSSARY

- Resource - includes undiscovered mineral deposits and reserves as well as identified mineral deposits that cannot be profitably recovered at current prices using current technology (see "Reserves and Resources" for additional details).
- Reserves - quantities of ore minerals located in identified deposits that can be developed profitably at current prices using current technology (see "Reserves and Resources" for additional details).
- Availability - a material is said to be "available" when its price is not so high relative to other goods and services and to peoples' incomes that "many" people will choose not to buy "very much" of it. This availability is determined by an interaction between the supply of and the demand for each material (see "The Meaning of Availability" for further details).
- Geochemically abundant elements - those elements that are present in the earth's crust in quantities equal to or greater than 0.1% of the whole mass. Twelve elements account for 99.23% of the mass of the crust.
- Geochemically scarce elements - those elements that are present in the earth's crust in quantities less than 0.1% of the whole mass. Seventy-six elements account for a mere 0.77% of the mass.
- Critical materials - those materials where construction of 25 fusion power plants/year would require more than 1% of the present consumption of that material or where domestic reserves were considered to be very small compared to current use rates.

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10 J. R. Young
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1 Technical Publications (BH)
5 Technical Information