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**Pacific Northwest Laboratory
Report on Fusion Energy
Research
July 1977 - September 1977**

October 1977

Prepared for the U.S. Department of Energy
under Contract EY-76-C-06-1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by

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PACIFIC NORTHWEST LABORATORY
REPORT ON FUSION ENERGY RESEARCH
JULY 1977 - SEPTEMBER 1977

October 1977

Prepared for
the U.S. Department of Energy
under Contract EY-76-C-06-1830

Pacific Northwest Laboratory
Richland, Washington 99352

PREFACE

This quarterly report on Fusion Energy Research consists of progress summaries of research conducted by the staff of the Pacific Northwest Laboratory (PNL). This reporting period includes progress made from July 1, 1977 through September 30, 1977. The Department of Energy (DOE) Division of Magnetic Fusion Energy is a major sponsor of the work. However, fusion-related work sponsored by others is also included as appropriate.

The summaries are presented in three major sections:

- Fusion Systems Engineering
- Materials Research and Radiation Environment Simulation
- Safety Analysis and Environmental Effects of Fusion Concepts

At the beginning of each section is a brief summary of the reports making up the section. The reports themselves have been kept relatively short and include preliminary results which ultimately are expected to be published elsewhere. Because of this, the reader is cautioned that the results may be modified before they are finalized. In some cases, reference is made to more complete reports that are available now.

D. A. Dingee
Fusion Programs Manager

Other Reports in the Series:

Annual Controlled Thermonuclear Reactor Technology Report-1971, BNWL-1604.
Annual Report on Controlled Thermonuclear Reactor Technology-1972, BNWL-1685.
Annual Report for 1973 on Controlled Thermonuclear Reactor Technology, BNWL-1823.
Annual Report for 1974 on Controlled Thermonuclear Reactor Technology, BNWL-1890.
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REPORT ON
FUSION ENERGY RESEARCH
JULY THROUGH SEPTEMBER 1977

SUMMARY

Controlled thermonuclear reactions are looked upon as the ultimate source of high-temperature energy. Success in the containment of fusion plasma has encouraged scientists to look beyond the confirmation of scientific feasibility to the identification of fusion reactor engineering problems that need solutions before demonstration plants can be built. Some fundamental and applied scientific problems could limit thermonuclear reactor development even after scientific feasibility is attained. Research at PNL continues to emphasize research in these development and technology areas.

The development of economic data for fusion power plants continued with completion of a critical materials analysis for fusion power plant construction materials. Projected world consumption of eleven critical materials was compared to estimates of reserves and resources to identify materials cost and availability expectations for the period during which fusion power plants would be built. Commodity price expectations are considered for aluminum, beryllium, chromium, copper, iron/steel, lead, lithium, mercury, molybdenum, nickel, and tin.

Final reports are being prepared for Experimental Power Reactor (EPR) blanket cooling studies, which have been developing heat transfer and fluid flow design tools for fusion reactor blanket engineering.

Work on several surface science studies has also been concluded, including the examination of plasma-wall interactions in Tokamak machines and measurements of fusion neutron sputtering yields.

Light ion and neutron irradiation experiments have continued in studies of the effects of radiation on mechanical properties. Light ion diagnostic capabilities were enhanced by several equipment improvements. Neutron-irradiated nickel foils are being examined with examination of proton-irradiated nickel foils to follow. PNL organized a radiation damage seminar and hosted a U.S.S.R. delegation interested in irradiation effects on fusion reactor materials.

In materials development studies a final report has been issued on the examination of neutron-irradiated cloths and fibers. The task to correlate relative atomic displacement rates in graphite irradiated with neutrons of different energies has been essentially completed, but another series of elastic modulus measurements will be required because of an unexpected slow annealing phenomenon with the irradiated samples.

Studies of electrical insulators with potential applications in fusion reactors continued with development of acoustic emission (AE) techniques and the acquisition of dielectric strength and resistivity data for insulator materials. Acoustic emission

measurements on electrically stressed BeO and Al_2O_3 have shown that acoustic signature analysis techniques can be used to distinguish mechanisms of dielectric failure in insulator materials. Electrical conductivities were measured for several insulator materials. Measurements determining the effect of porosity on the dielectric strength of MgAl_2O_4 showed that as little as 10% voids in the insulator can lower the dielectric breakdown strength of the insulator up to 50%.

PNL is providing program planning support to DMFE to assure that the needs of the safety and environment program are identified early enough to be addressed in a coordinated, timely manner. Reference reactor system designs are being reviewed for their safety and environmental impact. A review of relevant fission reactor safety was completed as a first step in establishing criteria for safe fusion reactor design and operation. The safety tradeoffs between different fusion design options are being analyzed. PNL coordinated a workshop, the Safety and Environmental Aspects of Fusion Power Plants, during this reporting period.

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FUSION SYSTEMS ENGINEERING

PNL's effort in Fusion System Engineering comprises research and development aimed at solving some of the major technical problems of bringing fusion power systems on-line to fulfill U.S. energy needs. It is necessary that attention be given early enough in the fusion program to properly identify and solve these engineering problems so that they do not limit the development and implementation of fusion reactors in commercial power production. Work reported this quarter includes a critical materials analysis for fusion power plants and studies to evaluate two design concepts for water-cooled Tokamak Next Step (TNS) first walls.

Economic data was developed to identify the fusion power plant construction materials for which a potential shortage would lead to large relative price increases. This critical materials analysis considered total world consumption of critical materials based on projected indexes of industrial production. The U.S. and world reserves and resources of eleven critical materials were compared with projected consumption data to make long-run estimates of commodity prices, which could be considered in designer selection of fusion power plant construction materials.

Heat transfer and fluid flow studies have been evaluating the performance of two reactor first wall designs: the Argonne Experimental Power Reactor (EPR) panel coil wall and the PNL double-wall designs. Preparation of final reports is underway for these EPR blanket cooling studies, which have included thermal hydraulic analyses, a survey of useful design computer codes, a consideration of helium cooling, and a consideration of first wall performance and materials.

SYSTEMS STUDIES

Systems studies focus on providing key technical and economic information for planning and analyzing the fusion power program. The Economic Regimes task is assisting in the development of economic data that will allow comparative analyses between fusion reactors and competing systems. Such analyses will be needed to determine the best opportunities for investing research and development funds for fusion power systems.

ECONOMIC REGIMES - CRITICAL MATERIALS ANALYSIS FOR FUSION POWER PLANTS

S. A. Rao, D. E. Deonigi

The economist's point of view is that materials are always available in the future, but possibly at a higher price required to recover or recycle low-grade ore. Thus, the reason for examining a list of fusion power plant construction materials is to identify the materials for which a potential shortage would lead to large relative price increases. Designers can then incorporate this information into their selection of materials for construction and testing. This quarter's effort has been to complete a critical materials analysis for fusion power plants.

COMPARISON OF U.S. AND WORLD SUPPLY/DEMAND FOR MATERIALS CRITICAL TO FUSION POWER PLANTS

A previous review⁽¹⁾ of materials requirements and availability for fusion power plants construction starting after 2010 compared estimated fusion power requirements with estimated U.S. consumption of world materials reserves and resources. However, such a comparison omits the problem that the U.S. is not the only consumer of these resources. To make world resource estimate information useful, it is necessary to compare world supplies with world demand. The methodology is reviewed here for the present critical materials analysis, which considers total world consumption as well as U.S. consumption. Figure 1 is a schematic description of the interrelationships of U.S. and world demand, supply, and price determination considered in the analysis.

An estimation of total world consumption must be based on some world growth scenario and a consumption rate estimated from an appropriate growth index, such as population, (used by Roberts⁽²⁾) industrial output, or gross national product. A scenario was developed by further extrapolation of available forecasts for the world through 2010, including a population growth rate about two-thirds the current pace and economic growth rates derived from long-term trends in industrialized countries augmented by rapid growth for the OPEC countries and a somewhat slower growth in the less developed countries. The consumption of materials characteristically used in fusion reactor construction was found to be best correlated with the index of industrial output as opposed to per capita consumption or other possible measures of consumption. Various mathematical formulations relating the consumption to the industrial production index were tested.

FIGURE 1. Interrelationships of U.S. and World Demand, Supply, and Price Determination

The following equation was used to estimate future consumption:

$$F_t = (a + bt)I_t$$

where

F_t = future material consumption at time 't'

I_t = forecast of industrial production index at time 't'

$(a + bt)$ = trend forecast of the ratio: consumption of material industrial production index

a, b = constants estimated in the equation

The above equations are used for the following eleven materials, which were identified by Hartley et al.⁽¹⁾ as potentially critical on the national level.

- Aluminum
- Beryllium
- Chromium
- Copper
- Iron/Steel
- Lead
- Lithium
- Mercury
- Molybdenum
- Nickel
- Tin

The cumulative consumption of each of these eleven materials between 1975-2010 was forecasted for both the U.S. and the rest of the world. These cumulative consumptions were compared against U.S. and world reserves and resources.

ESTIMATION OF INDUSTRIAL GROWTH

To establish the demand for raw materials, it is necessary to estimate the future levels of industrial activity that would consume these materials in each of the economies of the world. The population growth in each nation is one factor that will influence the growth rate for industrial and agricultural production. Population growth has been estimated to follow the forecasts from the Organization for Economic Cooperation and Development (OECD) and the United Nations (UN) up to 1985 and then to show a general decline in growth for the less developed areas of the world while maintaining the 1985 population growth rate for the currently industrialized nations, which have already achieved fairly low population growth rates. As most of the consumption will take place in these industrialized nations, special emphasis is placed on their part in world consumption. The rest of the world can be characterized in less detail by grouping nations with similar levels of economic growth rates. Table 1 lists the ten currently industrialized nations, five categories of nations grouped by level of economic development, and their annual population growth rates over the 1965 to 1975 period. Included in Table 1 are estimates of population growth rates provided by investigators who have made estimates through the year 2000.

Economic growth rates through 2000 have been forecasted by several investigators, but only the United Nations forecasts and the EXPLOR computer model⁽³⁾ utilize interlocking relationships between economies as a factor in providing forecasts. Table 2 is a summary of the GNP growth rates of the national economies predicted by the EXPLOR model through 1985.

TABLE 1. Population Growth Rates Growth Rate Estimates
(Annual Percentage Rate)

Number	Country and Regions	Annual Percentage Population Growth Rate 1965-1975	EXPLOR Model ⁽³⁾		U.N. ⁽⁴⁾	Others ⁽²⁾
			1975-85	1985-2010		
1.	Belgium/Luxemburg	0.4	0.3	0.35	[0.6 to 1]	0.5
2.	France	0.8	0.7	0.6		0.5
3.	West Germany	0.5	-0.4	0.1		0.5
4.	Italy	0.7	0.4	0.5		0.5
5.	Netherlands	1.0	0.7	0.8		0.5
6.	United Kingdom	0.4	0.1	0.2		0.5
7.	Spain	1.0	1.0	0.9		0.5
8.	Canada	1.5	1.4	1.0		1.2
9.	United States	1.0	1.0	1.0		1.2
10.	Japan	1.2	1.0	0.5		0.5
11.	Other Developed Countries (Europe, Australia, New Zealand, South Africa)	1.1	1.2	1.0	[2.0 to 2.5]	1.3
12.	North Africa and Middle East	2.8	2.9	2.1		1.9
13.	Other Developing Countries (Africa, Oceania and Asia)	2.5	2.6	2.1		2.0
14.	Developing Countries (America)	2.8	2.8	2.1		1.7
15.	Centrally Planned Economies (Europe, USSR, Asia)	1.5	1.4	1.0		1.1

TABLE 2. Annual Percentage Growth Rates in GNP

Number	Country and Regions	Annual Percentage		U.N. ⁽⁴⁾	Others
		GNP Growth Rate 1965-1975	EXPLOR Model 1975-85 1985-2010		
1.	Belgium/Luxemburg	3.9	4.0	3.2	3.5 ⁽⁵⁾
2.	France	4.5	4.6	4.0	3.3 ⁽⁶⁾
3.	West Germany	3.1	4.1	3.5	3.5 ⁽⁵⁾
4.	Italy	3.9	4.5	4.2	5.0 3.5 ⁽⁵⁾
5.	Netherlands	4.2	4.4	3.8	3.5 ⁽⁵⁾
6.	United Kingdom	2.0	3.5	2.9	3.5 ⁽⁵⁾
7.	Spain	5.7	4.9	4.2	4.0 ⁽⁶⁾
8.	Canada	4.3	5.2	4.0	3.3 ⁽⁶⁾
9.	United States	2.7	4.7	3.0	3.3 3.2 ⁽⁶⁾
10.	Japan	8.7	6.2	5.1	4.9 5.0 ⁽⁶⁾ , 5.0 ⁽⁵⁾
11.	Other Developed Countries (Europe, Australia New Zealand, South Africa)	3.8	4.4	3.8	-- 3.5 ⁽⁵⁾
12.	North Africa & Middle East	7.3	7.4	6.9	7.5 --
13.	Other Developing Countries (Africa, Oceania and Asia)	4.6	3.9	3.2	6.7 --
14.	Developing Countries (America)	5.5	5.0	4.0	7.0 4.0 ⁽⁵⁾
15.	Centrally Planned Economies	6.6	5.1	3.8	5.0 4.0 ⁽⁵⁾

Comparison with other forecasts through year 2000 shows good agreement with the possible exception of the United Nations forecast, which was attempting to show expansion of the standards of living for the less developed areas, resulting in higher growth rates assigned to the "developing countries" and "other developing countries" of the model. The GNP growth rates used in EXPLOR for these countries currently require substantial transfers of wealth from the developed countries to the developing countries to achieve the levels of growth indicated for use in the U.N. report. Further, the growth rates of the developed economies are expected to be generally lower than their historical norms, in part due to lower population growth, some transfer of wealth to the OPEC countries (primarily included in the North Africa-Middle East region), and voluntary transfer of wealth to the less developed countries. The GNP growth forecasts are directly related to the industrial production of each country.

The forecasted industrial production indexes listed in Table 3 are based on considerations of the trade flow connection between each of the countries listed. By 2010 the industrialized countries will typically have at least four times the annual industrial output in 1970. It is primarily this growth that will be responsible for most of the demand for resources and not specifically the growth of fusion power plant construction.

ESTIMATION OF MATERIAL CONSUMPTION FROM PREVIOUS INDUSTRIAL OUTPUT INDEXES

Annual data on industrial output indexes of the 15 economic regions were taken from the EXPLOR model data base for the period 1965-1975. Annual data on materials consumption were tabulated from various sources, generally for the period 1965-1975. The quality of uniform data is always a problem in any effort that tries to put global data on a comparative basis. Table 4 shows the example of aluminum consumption by the 15 regions.

TABLE 3. Predicted Industrial Production Indexes
(1970 Index = 100)

Number	Country	Predicted Industrial Production Index by Year			
		1980	1990	2000	2010
1.	Belgium/Luxemburg	136	230	330	430
2.	France	153	305	459	614
3.	West Germany	131	277	427	579
4.	Italy	137	297	458	617
5.	Netherlands	148	265	381	507
6.	United Kingdom	122	214	306	401
7.	Spain	201	365	532	698
8.	Canada	179	333	486	641
9.	United States	155	259	363	468
10.	Japan	165	423	680	936
11.	Other Developed Countries (Europe, Australia, New Zealand, South Africa)	142	274	409	543
12.	North Africa & Middle East	210	750	1,295	1,842
13.	Other Developing Countries (Africa, Oceania and Asia)	160	270	405	544
14.	Developing Countries (America)	182	446	710	976
15.	Centrally Planned Economies (Europe, USSR, Asia)	209	455	698	948

Ratios of annual consumptions relative to the industrial production index are shown in Table 5. Such consumption data and consumption/production index ratios for each of the 11 materials were used as the basis for making forecasts of future consumption.

Using the methodology outlined here and discussed previously,⁽⁹⁾ annual rates of materials consumption were forecast for 1990 and 2010 for each of the 15 industrialized countries and regions of the world. Based on annual rates, cumulative consumptions for the period 1975-2010 were then calculated. Table 6 describes the annual and cumulative consumptions of aluminum for each of the 15 economic regions and their total. Similar information was developed for each of the 11 critical materials. Table 7 provides a summary of annual and cumulative consumption of each of these 11 materials for U.S. and the world. A brief look at the rate at which U.S. is consuming these materials relative to world consumption indicates the enormity of the problem. Table 8 indicates the importance of U.S. consumption relative to world consumption during 1975-2010: the ratio of U.S. to world cumulative consumption indicates that the U.S. would be a leading consumer of aluminum, beryllium, chromium, lithium and molybdenum.

TABLE 4. Aluminum Consumption, 1967-1974

Number	Country	Aluminum Consumption by Year, 10 ³ metric tons						
		1967	1968	1969	1970	1971	1972	1973 ⁽⁷⁾
1.	Belgium/Luxemburg	133.2	152.3	166.0	174.9	190.9	207.2	214.5
2.	France	294.0	293.5	367.1	413.3	377.4	411.0	450.1
3.	West Germany	416.8	539.5	642.3	669.8	684.4	741.6	855.7
4.	Italy	184.0	214.0	258.0	279.0	254.0	296.0	336.0
5.	Netherlands	26.4	31.4	53.4	52.6	59.2	79.2	94.3
6.	United Kingdom	355.8	387.7	387.7	404.2	325.6	409.9	491.5
7.	Spain	78.2	98.2	128.1	129.1	150.4	180.0	187.0
8.	Canada	178.9	193.0	217.4	220.0	292.2	302.6	331.8
9.	United States	3,119.2	3,597.1	3,706.2	3,488.1	3,916.1	4,277.6	5,076.7
10.	Japan	316.5	620.6	819.2	910.0	972.9	1,214.5	1,574.1
11.	Other Developed Countries (Europe, Australia, New Zealand, South Africa)	426.4	495.2	574.7	648.8	670.0	681.1	817.2
12.	North Africa & Middle East	64.3	85.1	103.3	123.6	134.0	165.0	192.0
13.	Other Developing Countries (Africa, Oceania and Asia)	133.0	144.5	133.7	182.0	213.0	213.8	252.7
14.	Developing Countries (America)	146.5	148.6	168.9	178.0	187.0	321.5	388.1
15.	Centrally Planned Economies (Europe, USSR, Asia)	1,718.1	1,835.6	1,925.8	1,992.0	2,133.2	2,282.0	2,397.3

**TABLE 5. Aluminum Consumption Relative to Industrial Production Index^(a)
(Metric Tons per Unit of Industrial Production Index)**

Number	Country	Annual Consumption, 10 ³ metric tons/Unit of Industrial Production Index ⁽⁹⁾						
		1967	1968	1969	1970	1971	1972	1973
1.	Belgium/Luxemburg	159	173	170	175	185	190	185
2.	France	365	350	388	413	363	367	375
3.	West Germany	560	646	682	670	671	700	757
4.	Italy	216	236	277	279	254	285	295
5.	Netherlands	36	38	58	53	56	71	80
6.	United Kingdom	394	408	394	404	326	402	443
7.	Spain	106	124	142	129	146	151	136
8.	Canada	209	210	223	220	276	286	270
9.	United States	3,953	4,381	4,309	3,488	3,912	3,961	4,303
10.	Japan	506	844	952	910	947	1,102	1,235
11.	Other Developed Countries (Europe, Australia, New Zealand, South Africa)	516	570	610	649	650	630	709
12.	North Africa & Middle East	90	106	113	124	122	137	142
13.	Other Developing Countries (Africa, Oceania and Asia)	172	171	143	182	203	190	206
14.	Developing Countries (America)	186	173	182	178	175	280	308
15.	Centrally Planned Economies (Europe, USSR, Asia)	2,231	2,160	2,093	1,992	1,957	1,934	1,858

(a) Aluminum consumption (in 1000 metric tons) is divided by industrial production index (base 1970 = 100) to give the ratios in this table.

TABLE 6. Forecasts of Aluminum Consumption

Number	Country	Annual Consumption, 10 ³ metric tons			Cumulative Consumption 10 ³ metric tons		
		1970	1990	2010	1975-1990	1990-2010	1975-2010
1.	Belgium/Luxemburg	175	410	769	4,388	11,790	16,178
2.	France	413	1,148	2,310	11,708	34,580	46,288
3.	West Germany	670	1,892	3,955	19,215	58,470	77,685
4.	Italy	279	799	1,661	8,085	24,600	32,685
5.	Netherlands	53	160	306	1,598	4,660	6,258
6.	United Kingdom	404	863	1,617	9,502	24,800	34,303
7.	Spain	129	487	932	4,620	14,190	18,810
8.	Canada	220	816	1,570	7,770	23,860	31,630
9.	United States	3,488	10,578	19,113	105,495	296,910	402,505
10.	Japan	910	3,984	8,815	36,705	127,990	164,695
11.	Other Developed Countries (Europe, Australia, New Zealand, South Africa)	645	4,771	9,454	40,620	142,250	182,870
12.	North Africa & Middle East	124	3,518	8,639	27,315	121,570	148,885
13.	Other Developing Countries (Africa, Oceania and Asia)	182	508	1,023	5,175	15,310	20,485
14.	Developing Countries (America)	178	4,616	10,101	35,955	147,170	183,125
15.	Centrally Planned Economies	1,992	9,133	19,030	83,438	281,630	365,068
	WORLD TOTAL	9,862	43,683	89,295	401,588	1,329,780	1,731,368

TABLE 7. Forecasts of the Consumption of 11 Critical Materials (1975-2010)

Metal	United States Consumption, 10 ⁶ metric tons				World Consumption, 10 ⁶ metric tons			
	Annual Consumption			Cumulative Consumption 1975-2010	Annual Consumption			Cumulative Consumption 1975-2010
	1970	1990	2010		1970	1990	2010	
Aluminum	3.5	11.0	19.0	402.0	9.9	44.0	89.0	1,731
Beryllium	0.0003	0.001	0.002	0.041	0.0004	0.0014	0.0025	0.052
Chromium	0.4	1.0	2.0	42.0	1.1	3.0	6.0	122
Copper	1.9	5.0	9.0	188.0	7.2	28	58	1,119
Iron/Steel	127	379	685	14,433	1,157	7,440	15,066	289,500
Lead	0.8	2.4	4.3	91	3.7	13	26	516
Lithium	0.002	0.006	0.01	0.2	0.005	0.015	0.028	0.586
Mercury	0.0015	0.0043	0.008	0.165	0.009	0.031	0.062	1.24
Molybdenum	0.034	0.082	0.149	3.2	0.091	0.243	0.479	9.7
Nickel	0.1	0.4	0.7	14.0	0.6	2.2	4.4	86.0
Tin	0.06	0.16	0.3	6.0	0.2	0.9	1.7	34.0

TABLE 8. Comparisons of U.S. to World Cumulative Consumption (1975-2010)

Metal	U.S. Cumulative Consumption, 10 ⁶ metric tons	World Cumulative Consumption, 10 ⁶ metric tons	Ratio (%) U.S./World Cumulative Consumption
Aluminum	402.0	1731	23
Beryllium	0.041	0.052	81
Chromium	42.0	122	34
Copper	188.0	1,119	17
Iron/Steel	14,433	289,500	5
Lead	91.0	516	18
Lithium	0.2	0.586	34
Mercury	0.165	1.24	13
Molybdenum	3.2	9.7	33
Nickel	14	86	16
Tin	6	34	18

COMPARISON OF U.S. AND WORLD CONSUMPTION TO EXISTING RESERVES AND RESOURCES

The terms "reserves" and "resources" have significantly different meanings and connotations, although they have been sometimes used interchangeably. As in earlier work, the following definitions distinguish between "reserves" and "resources":

- (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.
- (2) Resources include yet undiscovered mineral deposits as well as reserves and identified mineral deposits that cannot be profitably recovered at current prices using current technology. Resources are static since they are limited by the composition of the earth's crust, seas, and atmosphere. Resources estimates based on the average crustal concentration (crustal abundance) are the maximum expected.

Projection 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. The best available estimates of reserves and resources are published by the U.S. Bureau of Mines and the U.S. Geological Survey of the Department of Interior.^(6,7) These quantitative estimates of reserves and resources were used in further comparisons of the estimated cumulative consumption.

Table 9 indicates, separately for U.S. and the world, the cumulative consumption between 1975 and 2010, existing reserves and resources as of 1975, and ratios of consumption to existing reserves and resources. A ratio of less than unity, as in the case of lithium and molybdenum for the U.S., indicates no special concern about future prices from the general economic standpoint. Even on the world level lithium reserves and resources seem to be adequate to meet estimated consumption demands through 2010.

TABLE 9. U.S. and World Cumulative Consumption of Metals Relative to Current Reserves and Resources

Metal	U.S.					World				
	Cumulative Consumption 1975-2010, 10 ⁶ metric tons	Estimated ⁽¹⁰⁾ Reserves (1974), 10 ⁶ metric tons	Resources ⁽¹¹⁾ 10 ⁶ metric tons	Ratio of Cumulative Consumption to Reserves	Ratio of Cumulative Consumption to Resources	Cumulative Consumption 1975-2010, 10 ⁶ metric tons	Estimated ⁽¹⁰⁾ Reserves (1974), 10 ⁶ metric tons	Resources ⁽¹¹⁾ 10 ⁶ metric tons	Ratio of Cumulative Consumption to Reserves	Ratio of Cumulative Consumption to Resources
Aluminum	402	6.1	>1,000	66.0	0.4	1,731	2,400	>28,000	0.7	0.06
Beryllium	.042	.025	>.3	1.7	0.14	.052	.05	>.7	1.00	0.07
Chromium	42	0	>1.0	NA	42	122	460	>1,000	0.3	0.12
Copper	188	82	160	2.3	1.2	1,119	390	680	2.9	1.7
Iron/Steel	14,433	1,800	>30,000	8.0	0.5	289,500	88,000	>230,000	3.3	1.3
Lead	91	38	>50	2.4	1.8	516	140	>500	3.7	1.03
Lithium	.2	.36	>5.7	0.56	0.35	.586	1.1	9.1	0.53	0.06
Mercury	.165	.014	>.1	11.8	1.65	1.24	.16	>1.0	7.7	1.24
Molybdenum	3.2	3.6	500	0.9	0.01	9.7	5.0	>1,000	1.94	0.01
Nickel	14	.2	13	70	1.1	86	44	>75	2	1.2
Tin	6	.035	.2	171	30	34	9.1	34	3.7	1.0

On the other hand, a ratio of more than unity, especially in the case of aluminum (66.0) and mercury (11.8), indicates a huge disparity between existing reserves and estimated future consumption between 1975 and 2010.

The important result of comparing the U.S. and world position is to determine 1) if there is a potential for materials supply problems that would result in high relative prices for fusion plant construction materials and 2) if materials substitutions should be made because of high prices.

The following comments are in order with respect to each of the materials considered in this study:

Aluminum

Current estimated aluminum reserves (1975) are expected to be used up much before the year 2000. This indicates a general rise in prices that would encourage the search for reserves. Also, the U.S. will continue to be a large importer of bauxite and alumina from Surinam, Jamaica and Guinea. Aluminum price increases from a resource base will be small, but attention should be given to the influence of energy cost on the future price. Reserves and resources seem adequate on the world level.

Beryllium

Beryllium is an important element in some fusion power plant designs. United States consumption of beryllium between 1975 and 2010 is expected to be about 81% of the world consumption. Estimated U.S. reserves are only about 50% of its expected consumption. The difference is expected to be filled largely by imports from Brazil and other countries. As a result of dominant U.S. consumption, the world price of beryllium is expected to rise considerably by 2010.

Chromium

United States consumption of chromium is expected to be about one-third of world consumption from 1975 to 2010. Virtually all chromium consumed in the U.S. is made up of imported ores and alloys from the U.S.S.R., Turkey, Rhodesia, and South Africa. Because of the uncertainty of source, large stockpiles (representing nearly half of U.S. annual use) are maintained. However, the long-term price must be expected to rise considerably as with beryllium.

Copper

United States consumption of copper is about one-sixth of total world consumption. Consumption is expected to outpace existing reserves and resources, both in the U.S. and on the world level, giving rise to high prices that would encourage finding new resources. The United States will continue to import largely from Canada, Chile, and Yugoslavia. The price increase will be much greater than for aluminum; the UN model indicates a three-fold copper price increase by 2000.

Iron/Steel

United States consumption of iron/steel represents only about 5% of world consumption during 1975 to 2010. The ratio of U.S. consumption to U.S. reserves is about 8 to 1. World consumption is expected to be far greater than world reserves or resources. Because of this, world prices are expected to increase at about the same rate as copper.

Lead

Comparison of consumption to reserves and resources indicate that lead resources would be in short supply before 2010 for both the U.S. and the world.

Lead, along with copper and iron/steel, constitute important fusion power plant construction materials.⁽¹²⁾ An increased number of fusion power plants in construction could add to the existing imbalance between supply and demand for these commodities, thus raising future prices. The U.S. is in better shape than the world as a whole.

Lithium

Lithium consumption in the U.S. is expected to be about one-third of the world consumption between 1975 and 2010. Estimated world consumption is less than estimated world reserves and resources. Hence, reserves and resources seem adequate both at the U.S. and world level.

Mercury

United States consumption of mercury is about 1/12 of the world consumption from 1975 to 2010. Some fusion power plant designs use mercury in small amounts. Comparison with future reserves and resources indicate that both U.S. and world consumption outpace resources before 2000, thus giving rise to sharp increases in the price of mercury.

Molybdenum

United States molybdenum consumption, like lithium, is approximately one-third the world future consumption. United States reserves and resources seem adequate for U.S. use, but at the world level reserves are expected to be used up before 2000. The U.S. is an exporter of molybdenum and may continue exportation at high prices due to world demand.

Nickel

United States consumption of nickel is expected to be about one-sixth of world future consumption. U.S. reserves are far short of estimated consumption and are expected to run out before 2000. U.S. is a major importer of nickel from Canada.

As nickel is one of the important materials for some fusion power plant designs, increased use of nickel in U.S. could lead to a higher price for nickel. Further, since world consumption of nickel is also expected to be much greater than world supply, world price of nickel is expected to increase by a factor of 2 or 3.

Tin

United States consumption of tin is expected to outpace U.S. reserves and resources. The U.S. is a heavy importer of tin from Malaysia, Thailand, and the People's Republic of China. Continued imports of tin by the U.S. could cause the price to increase by a factor of 2 or 3. On the world level, resources seem adequate to meet world consumption.

BLANKET AND SHIELD ENGINEERING

Blanket and Shield Engineering studies focus on developing valid technical bases for reactor design and transferring the technology to industry capability. Experimental Power Reactor (EPR) blanket cooling studies were performed in studies to develop heat transfer and fluid flow design tools for fusion reactor blankets. PNL is also participating in the nuclear data community to define nuclear data needs and develop best-estimate nuclear data files for DMFE technology programs.

HEAT TRANSFER AND FLUID FLOW

D. T. Aase, C. W. Stewart, M. C. C. Bampton

The objective of these studies was to develop design analysis tools and to scope experimental needs to investigate, define, and assess the heat transfer and fluid flow development requirements for the base technology of fusion reactors. These studies have been reported in previous quarterly reports.^(9,13,14)

Preconceptual design studies were initiated at PNL to identify design limits for water cooling of the first wall in Tokamak Next Step (TNS) concepts. Two specific design concepts, the Argonne Experimental Power Reactor (EPR) panel coil first wall and the PNL double-wall designs, were analyzed to evaluate their performance. Efforts this quarter included studies to determine the maximum thermal load that would yield acceptable wall life in each concept and evaluations of sintered aluminum product (SAP) and vanadium as substitutes for stainless steel that might extend wall life.

Preparation of final reports has begun.

NUCLEAR DATA STANDARDS

B. R. Leonard, Jr.

The objective of this task is to participate in the development of current best-estimate nuclear data files for DMFE technology programs. During this quarter, two presentations were attended at Oakridge National Laboratory (ORNL) in July. The first of these, presented by RSIC, was the status of the DMFE multigroup data library based on Evaluated Nuclear Data File (ENDF)/B-IV and distributed by RSIC. It was noted that the generic difficulty with this library continues to exist, i.e., all calculations with normally used codes cannot be used to obtain Doppler-broadened and self-shielded group cross sections in the resolved resonance region. In addition, benchmark calculations performed at several laboratories were noted to be in some error since the absorption cross sections of ENDF/B ^{12}C and ^{16}O had not been adjusted to the graphite and oxygen characteristic of the systems.

The second presentation was the status and planned measurements of the ORNL 14-MeV neutron source shielding experiments. After reviewing the planned measurements it was noted that no integral measurements, e.g., activation foil measurements, had been planned.

It was argued that unless such measurements were included the planned measurements would not be responsive to the needs of neutron dosimetry and radiation damage programs and of the proposed (d,Li) accelerator program. The status and plans of this program were later relayed to W. N. McElroy and D. G. Doran of the Hanford Engineering Development Laboratory to attempt to correct this deficiency.

MATERIALS RESEARCH AND RADIATION ENVIRONMENT SIMULATION

The various materials and components of a fusion reactor will be subjected to extreme environments, intense fluxes of high energy neutrons, alpha particles, and ionic species as well as internally generated products of neutron-induced reactions, such as helium. PNL is examining the effects of these environments on candidate fusion reactor materials, using reactor irradiations and simulation techniques to: 1) examine Tokamak plasma-wall interactions in surface science studies of blistering and neutron sputtering, 2) correlate changes in mechanical properties produced by light ions and fusion neutrons, 3) evaluate carbons and graphites for possible use as first-wall liner materials or as limiters in Tokamak devices, and 4) develop acoustic emissions (AE) techniques to determine prebreakdown behavior in stressed electrical insulators, as well as acquire dielectric strength and electrical resistivity data on potential fusion reactor insulator materials.

The PNL Surface Science group has concluded working on several experimental programs concerned with plasma-wall interactions in Tokamak plasma machines. Measurements of fusion neutron sputtering yields have been a major project of the group for several years.

Mechanical properties studies at PNL continued in efforts to correlate the microstructures and radiation hardening produced by light ions and fusion neutrons. Several improvements in the light ion beam diagnostic capabilities were completed this quarter, including 1) installation of a vacuum faraday cup, 2) installation of a quadrant collimator, 3) completion of a faraday cup current integrator, and 4) preparation of vanadium foils for faraday cup calibration. A new beam scanner and quadrapole magnet were also purchased. In neutron irradiation studies microstructural evaluation of T (d,n) neutron-irradiated nickel was initiated on foils irradiated to $1 \times 10^{17} \text{ n/cm}^2$ at 25°C . The examination of nickel foils irradiated with 16 MeV H^+ is planned for the near future.

A radiation damage seminar with emphasis on light ion and fusion neutron damage was organized by PNL and held at Battelle's Seattle Research Center. Dr. J. R. Beeler, Jr., was the key lecturer with D. G. Doran and J. O. Schiffgens of Westinghouse, Hanford Engineering Development Laboratory (HEDL) also contributing. The seminar was attended by Battelle and Westinghouse researchers working the field of radiation damage to materials. Dr. K. Zwilsky of U.S. ERDA also attended. The U.S.S.R. delegation interested in irradiation effects on fusion reactor materials was hosted by PNL July 29 to August 1, 1977. The purpose of the visit was to acquaint the members of the delegation with U.S. research capabilities in radiation damage. Potential joint research in this field was also discussed.

Materials studies have continued to evaluate radiation damage, sputtering, and degassing for carbons and graphites to determine if these are suitable for use as low-Z liner materials between the reactor first wall and the plasma. The irradiation of graphite cloths and fibers at 470°C to $1 \times 10^{22} \text{ cm}^{-2}$ Equivalent Fission Fluence has been

completed, and a final report has been issued. The task to correlate relative atomic displacement rates in graphite irradiated with neutrons of different energies has been essentially completed, but the final wrap-up has been frustrated by an unexpected and very slow annealing phenomenon which will require at least one more series of elastic modulus measurements. A glassy carbon sample labeled with ^{14}C was prepared for neutron and other sputtering experiments and used in blank runs with collectors in a vacuum system.

In materials studies of electrical insulators measurements on BeO and Al_2O_3 have shown that acoustic signature analysis techniques can be used to distinguish mechanisms of dielectric failure in insulator materials. Measurements determining the effect of porosity on the dielectric strength of MgAl_2O_4 have shown that the presence of as little as 10% voids in an insulator will lower dielectric breakdown strength of the insulator by up to 50%. The electrical conductivity of $\alpha\text{-Al}_2\text{O}_3$, BeO , fused SiO_2 , SiON_2 , Y_2O_3 (3 wt.% Al_2O_3), and MgAl_2O_4 were measured to 1275°K . MgAl_2O_4 has a lower electrical conductivity than any other oxide insulators. The MgAl_2O_4 also exhibits an anomalous inflection between 830°K and 1050°K .

SURFACE SCIENCE RESEARCH RELATED TO FUSION TECHNOLOGY

This work has been examining the effects of the fusion reactor environment on surface and near-surface regions of reactor structures and the influence of plasma-wall interactions on the plasma. Ions, neutral particles, neutrons, protons, and electrons from the plasma will interact with exposed surfaces to produce effects such as physical and chemical sputtering, desorption, blistering, and re-emission. Material that leaves the wall due to these effects may then enter the plasma and cause loss of plasma energy through bremsstrahlung or line radiation. Erosion will weaken structural integrity and may adversely influence surfaces exposed to coolant in the cooling channels.

SURFACE EFFECTS

M. T. Thomas, D. L. Styrus, D. R. Baer

The PNL Surface Science group has been working on several experimental programs concerned with plasma-wall interactions in Tokamak plasma machines. Measurements of fusion neutron sputtering yields have been a major project of the group for several years. Most of the sputtering work has been completed and accepted for publication. Surface effects work has been reported briefly in previous periodic progress reports and in more detail in journal publications listed in the progress reports. (13,14,15,16,17,18)

BULK RADIATION EFFECTS AND SIMULATION

Structural materials in magnetic fusion reactors will be subjected to bulk radiation damage from energetic neutrons coupled with cyclic temperatures and stresses. Irradiation-induced creep, fatigue, and embrittlement of materials are serious limitations on the design life of many fusion reactor components. An understanding of the specific effects of irradiation on creep, fatigue, and crack growth rates is necessary for the development and selection of alloys for these components; however, materials studies for fusion reactor applications are severely hampered by the lack of a high-flux, high-energy, large-volume irradiation facility. Charged particle irradiations of materials can help satisfy the flux and energy requirements for irradiation damage studies while lowering the necessary radiation levels (relative to neutronic irradiations) and offering the potential to control radiation parameters. A balanced program of light ion, fusion neutron, and fission neutron irradiation studies is underway to gain an understanding of the effects of a fusion neutron environment on the mechanical properties of materials.

ALLOY DEVELOPMENT FOR IRRADIATION PERFORMANCE - MECHANICAL PROPERTIES

R. H. Jones, D. L. Styris, E. R. Bradley

The irradiation behavior of fusion reactor materials is being studied with a variety of radiation sources because of the lack of a fusion neutron source with the appropriate flux and spectral characteristics. Fusion energy neutrons obtained from the T(d,n) and Be(d,n) reactions and 16 MeV protons (p) are three types of radiation currently being used by researchers studying fusion reactor materials. The 16 MeV p are of interest because 1) there is some evidence that the damage structure produced with 16 MeV p is similar to that produced by 14 MeV neutrons; 2) particle fluxes of $5 \times 10^{14}/\text{cm}^2\text{-sec}$ are possible, which are equal to fluxes expected in future fusion reactor first walls; and 3) 16 MeV p can penetrate a reasonably thick (~ 0.25 mm) specimen, thereby minimizing contamination from the bombarding ion and the chemical environment.

The near term objective of this program is to correlate the microstructures and radiation hardening produced by light ions and fusion neutrons. To accomplish this objective the microstructure and yield strength change of Ni, 316 SS, and Nb irradiated with 16 MeV p and (D,T) and D,Be) neutrons are being evaluated. The long term objective of this program is to study the creep, fatigue, and tensile properties of fusion candidate materials under simulated fusion reactor operation conditions.

LIGHT ION/NEUTRON CORRELATION EXPERIMENT

The light ion irradiation apparatus was modified to incorporate several improvements in the beam diagnostics: 1) a vacuum faraday cup was installed, 2) a specimen beam

collimator divided into quadrants was installed to allow comparative beam current measurements; 3) a faraday cup current integrator was built; 4) vanadium dosimeter foils for faraday cup calibration were prepared; 5) the number of thermocouples in the specimen array was increased. A beam scanner to aid the beam profiling and centering upstream from the light ion apparatus and a quadrupole magnet for focussing and steering the beam have been ordered. Beam focussing and steering with the switching magnet have been adequate for the low current (10^{12} p/cm²-s, ~ 200 nA/cm²) experiments, but the quadrupole magnet will be needed for higher current density experiments.

The vacuum faraday cup replaces a faraday cup which operated in the ambient helium gas without secondary electron suppression. The switch to a vacuum faraday cup was made because of uncertainties in calibrating and operating a faraday cup in a 1-atm pressure of helium gas. The vacuum faraday cup is isolated from the ambient gas by a 0.01-mm-thick Covar window. The cup is evacuated with the main vacuum system and then isolated and pumped on by a Varian 2ℓ/sec pump during irradiation. The secondary electrons are suppressed by a negative potential applied to a ring positioned between the window and the cup. The copper cup is bonded to the stainless steel body by a glass-to-metal seal. A sketch of the vacuum faraday cup is shown in Figure 2. The vacuum faraday cup has been tested with H⁺ beam currents up to 1.5 μA. The small appendage pump maintained a pressure of $\sim 10^{-5}$ Torr for an hour at 0.5 μA and for a short time at 1.5 μA. A suppression voltage of -120 V was adequate to suppress the secondary electrons from the window and cup. The quadrant collimator and increased number of specimen thermocouples will be used to monitor the beam position and profile close to the specimens. The faraday cup current integrator, designed and built by C. Ratcliffe of PNL's Energy Systems Engineering Section, will improve the particle fluence measurements, which can be very tedious when particle beam current irregularities occur.

FIGURE 2. Vacuum Faraday Cup

The vanadium foil dosimetry will be performed by counting the ^{51}Cr isotope produced by the $^{51}\text{V}(p, \beta^-) ^{51}\text{Cr}$ reaction. Ned Wogman of PNL's Physical Science Department will perform the isotope counting.

MICROSTRUCTURAL ANALYSIS OF IRRADIATED MATERIALS

The microstructures of light ion- and fusion neutron-irradiated nickel and niobium are being evaluated by transmission electron microscopy (TEM) as part of the correlation experiment. The use of x-ray diffuse scattering for evaluating the small defect clusters is also being considered. Preliminary TEM examination of nickel foils irradiated to $1 \times 10^{17} \text{ n/cm}^2$ with T(d,n) neutrons revealed a moderate defect cluster density. Quantitative evaluation of neutron- and proton-irradiated nickel is in progress.

LIGHT ION AND FUSION NEUTRON DAMAGE SEMINAR

A seminar on the topic of displacement processes with special emphasis on light ion and fusion neutron damage was held on July 21 to 22, 1977. Dr. J. R. Beeler, Jr. was the key lecturer, with D. G. Doran and J. O. Schiffgens of Westinghouse, Hanford Engineering Development Laboratory (HEDL) giving short presentations. Dr. Beeler covered potentials; binary collision geometry; replacement sequences; effects of extant interstitials and vacancies; effects of surfaces, impurity atoms, dislocations, grain boundaries and temperature on isolated Frenkel pair production; and vacancy and interstitial clustering theory. Don Doren discussed Primary Knock-on Atom (PKA) spectra for light ions and fusion neutrons, and John Scheffgens presented a videotape showing three-dimensional displacement production. The film entitled "2.5 keV Cascades in Tungsten," produced by Lawrence Livermore Laboratories, was also shown.

U.S./U.S.S.R. FUSION REACTOR MATERIALS EXCHANGE

Battelle hosted the U.S.S.R. delegation on the dates of July 29-August 1, 1977. Technical discussions were held on the topics of light ion simulation of irradiation-enhanced creep, light ion and fusion neutron irradiation, hybrid fusion reactors, graphite studies for fusion, Body Centered Cubic (BCC) ion correlation, dual beam irradiation experiments, and helium blistering.

MATERIALS TECHNOLOGY

Programs to identify and solve materials problems are essential to successful commercial fusion power development. The PNL materials technology program addresses areas where information will be needed for experimental and commercial reactors, including the behavior of graphites and electrical insulators in fusion reactor environments.

EVALUATION OF CARBONS AND GRAPHITES FOR REACTOR APPLICATIONS

W. J. Gray, W. C. Morgan

Some fusion reactor concepts have proposed the use of a low-Z liner between the plasma and the first structural wall. A number of materials are being considered for the liner, including graphite or graphite cloth. Among the more important data required before the choice of liner materials can be narrowed are: (1) radiation damage; (2) neutron, ion, and chemical sputtering; and (3) degassing.

More recently there has been increasing interest in the use of graphite limiters in Tokamak devices. The above list of required data is also important for this application and, in addition, thermal shock characteristics must be considered.

To provide some of the necessary information on graphite, the following areas are being investigated:

- Radiation Damage in Graphite Cloth - evaluation of radiation damage effects in cloths and fibers since there are no previous data for these materials above about $1 \times 10^{21} \text{ cm}^{-2} \text{ EFF. (a)}$
- Radiation Damage at Very High Temperatures - evaluation of radiation damage effects at temperatures up to 2000°C since no data exist above $\sim 1400^{\circ}\text{C}$.
- Fission-Fusion Correlation - experimental testing of the correlation between damage production rates in fission and fusion reactor spectra. This will allow more accurate projections of graphite performance in fusion reactors based on the extensive graphite data from fission reactor irradiations. Additional data specific to fusion applications are required, and these must also be generated from fission reactor irradiations because no existing simulation techniques will suffice and no adequate 14-MeV neutron source is likely to be available prior to an operating fusion reactor.
- Sputtering - measurement of neutron, ion, and chemical sputtering rates for carbon. This work is being done in conjunction with other surface science research presented
- in this report.
- Degassing - measurement of degassing properties of large graphite samples under conditions appropriate to fusion reactor applications.

(a) All fluences are quoted in terms of "Equivalent Fission Fluence for Damage in Graphite."⁽¹⁹⁾

RADIATION DAMAGE IN GRAPHITE CLOTH

Graphite cloths and fibers have been irradiated to a maximum fluence of $1 \times 10^{22} \text{ cm}^{-2}$ EFF at 470°C in EBR-II. Results of examinations with optical and scanning electron microscopy, as well as measurements of density, surface area, and changes in fiber lengths and diameters were reported in the last two quarterly reports.^(9,13) The final report for this task has been issued as a topical report, BNWL-2390, and a condensed version has been submitted for publication in the Journal of Nuclear Materials.

RADIATION DAMAGE AT VERY HIGH TEMPERATURES

No work was done on this task during this quarter.

FISSION-FUSION CORRELATION

Relative atomic displacement rates in graphite irradiated with neutrons of different energies are being determined by measuring relative changes in the basal-plane elastic shear modulus, C_{44} , of highly oriented pyrolytic graphite samples irradiated in three different neutron sources. The three sources are:

- the (D,T) source at Lawrence Livermore Laboratory with a neutron energy of ~ 15 MeV.
- the (D,Be) source at the University of California at Davis operated at a peak neutron flux per unit lethargy of ~ 5.5 MeV.
- the Brookhaven Medical Research Reactor, which produces essentially a fission spectrum with a peak neutron flux per unit lethargy of ~ 1.5 MeV.

Figure 3 shows elastic modulus changes produced by neutrons of different energies. These data are plotted on the basis of fluence of neutrons with energy greater than 50 keV, which has been used quite successfully to correlate damage (atomic displacement rates) produced in different fission reactor spectra. However, the present data indicate that atomic displacement rates, which are proportioned to the change in elastic modulus, are higher for the two higher neutron energies by a factor of more than three. The atomic displacement cross sections recently developed by Morgan⁽²⁰⁾ produce better agreement between the modulus changes for the three irradiations, but even these require adjustment to provide good agreement. These adjustments have been made; however, an unexpected annealing phenomenon has led to some uncertainties that must be resolved before we publish the adjusted set of cross sections or data based on them.

The elastic moduli of samples irradiated and then stored at room temperature have decreased slowly back toward the unirradiated value over periods of many months. It is not yet clear how the time dependencies of these changes for the different sample sets are related. This must be resolved before data for the different sets can be placed on equal bases. Once this has been done, it will be a simple matter to readjust the atomic displacement cross sections to achieve agreement between modulus changes for the three irradiations.

FIGURE 3. Change of C_{44} Elastic Constant of Highly Oriented Pyrolytic Graphite Irradiated with Neutrons of Different Energies

SPUTTERING

A glass carbon sample labeled with ^{14}C has been prepared for use in neutron and other sputtering experiments. Blank runs where the labeled sample was placed in a vacuum system adjacent to collectors were made this quarter. Some transfer of ^{14}C from the sample to the collectors took place during pump-down and bake-out. In the actual neutron sputtering apparatus, the sample and collectors are maintained in separate chambers during pump-down and bake-out and only placed adjacent to each other during the time the neutron beam is on. A blank run in this apparatus will be required to determine if the ^{14}C transport in the ultra-high vacuum system is sufficiently low to allow completion of the neutron sputtering experiment.

DEGASSING

Two new and different capacitance manometer vacuum gauges were installed on the degassing apparatus and evaluated this quarter. It was hoped that these would lower the detection limit for degassing rates. Neither performed as well as the original gauge. Plans are to obtain a third new gauge for evaluation during the next quarter. In the meantime, degassing measurements using the original gauge have been resumed.

ELECTRICAL INSULATORS FOR FUSION REACTOR APPLICATIONS

J. E. Garnier, J. L. Bates, A. S. Rupaal

Current technology calls for the use of electrical insulators in various locations in controlled thermonuclear reactors. These insulators will be subjected to a variety of cyclic conditions and must function in the reactor's complex radiation environment. One of the more stringent requirements is the need for insulators which are electrically, thermally, and mechanically stable to intense neutron, particle, gamma, and beta radiation, e.g., $\sim 10^{16}$ nv and $\sim 10^{23}$ nvt. In some cases the insulator will be required to withstand very high electrical potentials (~ 100 kV/cm) and cyclic conditions at high temperatures.

One of the major goals of this program is to evaluate the dielectric breakdown behavior of ceramic insulators using acoustic emission (AE) techniques. These studies emphasize:

- development and understanding of acoustic emission information generated during the occurrence of electrical breakdown and the relationship of these data to material properties
- acquisition of dielectric strength and electrical resistivity data on potential fusion reactor insulator materials.

Progress in these areas is described with major efforts directed toward the use of acoustic signature analysis (ASA) techniques to determine mechanisms of dielectric failure in insulator materials and acquisition of electrical resistivity data on potential fusion reactor insulators.

SPECTRAL ANALYSIS OF ACOUSTIC EMISSION SIGNALS EMANATING FROM ELECTRICALLY STRESSED SOLID DIELECTRICS

It has been shown^(21, 22, 9) that the analysis of AE signals from an electrically stressed insulator can serve as a technique for determining pre-breakdown behavior and mechanisms of breakdown in solid insulators. In the previous quarterly report,⁽⁹⁾ it was proposed and demonstrated that frequency spectral analysis of acoustic emissions from electrically stressed solid dielectrics will contain information related to the mechanism(s) leading to failure of the insulator.

Experiments were conducted this quarter to experimentally verify the use of ASA techniques to determine the mechanism(s) of dielectric failure. The understanding gained from this experiment was then applied in experiments designed to determine the effects of porosity on the dielectric strength of MgAl_2O_4 . The following two sections discuss these experiments in greater detail.

Use of ASA Techniques To Determine Mechanism of Dielectric Failure

Acoustic signature analyses were conducted on polycrystalline samples of BeO and Al_2O_3 at temperatures of 300°K and 350°K and at varying applied dc electrical stresses. The purpose of these experiments were to further verify experimentally the hypothesis that the frequency spectrum of acoustic emissions resulting from internal localized discharges in an insulator contains information related to the operative mechanism(s) leading to failure of the insulator under an applied electrical stress.

It is known that the frequency component of AE signals will be dependent on sample

geometry, couplant, transducer, and source of AE generation. To produce system-independent AE spectral information, a helium gas jet spectral calibration is used.⁽²³⁾ If only the source of AE generation is changed, then a relative comparison of AE spectral information can be made by accounting only for the change in frequency characteristics of the transducer with temperature.

In a study by Britt,⁽²⁴⁾ the mechanism of dielectric failure in polycrystalline samples of BeO was considered to be a thermal failure mechanism at temperatures ranging from 290°K up to 700°K. If the frequency spectra of AE generated in electrically stressed samples of BeO contain information related to the operative mechanism of failure, then the spectral content of the AE signals at 300°K and 350°K should be the same. This is in contrast to previous experiments⁽⁹⁾ on Al₂O₃ at 300°K and 450°K where it was shown that the AE spectrum is different at the different temperatures because the mechanisms for dielectric failure are also different at those temperatures.

Figure 4 is a plot of the corrected AE frequency spectrum for polycrystalline BeO at 300°K and 350°K between 100 kHz and 400 kHz. Results below 100 kHz are not shown as the low frequency cutoff of the AE signal conditioner used in these experiments was set to attenuate any frequency below 100 kHz. Comparison of results shows no definitive difference between the AE signal amplitude obtained at 300 K and 350 K, except that some peaks in the frequency regions 120-160 kHz, 200 to 240 kHz, and 320 to 360 kHz have become slightly less predominant. This is consistent with previous comments that the BeO exhibits a thermal breakdown mechanism from temperatures ranging from 293 to 700°K.

FIGURE 4. The Corrected AE Frequency Spectrum for Polycrystalline BeO Undergoing Breakdown at 300°K and 350°K

Figure 5 is a comparison of AE signal amplitude versus frequency from AE signals obtained on samples of polycrystalline BeO and Al₂O₃. As Al₂O₃ is known to undergo electrical (avalanche) breakdown and BeO thermal failure at 300°K, the differences between AE signal amplitude can only arise as a result of different mechanisms leading to dielectric failure.

FIGURE 5. Comparison of Corrected AE Frequency Spectra for Polycrystalline BeO and Al₂O₃ at 300°K

From the above analysis, the conclusions can be made that if the breakdown mechanism is thermal then the higher frequencies are enhanced. No significant change in the frequency spectrum with temperature is expected if the dielectric breakdown mechanism remains unchanged.

Effect of Porosity on the Dielectric Strength of Polycrystalline Magnesium-Aluminate Spinel

The failure of an insulator under an electrical stress is of considerable importance. Current published values for commercial insulators show that the same material will exhibit a wide range of dielectric strengths, depending on its environment and mode of use. Even when conditions of application and field distribution are the same, the breakdown strength is found to spread over a wide range of values.⁽²⁵⁾ In practical insulators it is difficult to produce a block of dielectric which is a continuous, homogeneous solid. In addition to fabricated voids in the material, the formation of additional defects (i.e., thermal or fatigue cracks, voids, second phases, etc.) are possible under certain operating conditions, especially in the fusion reactor environment. The presence of these internal defects will cause regions of enhanced electrical stress leading to failure of the insulator at lower field strengths than found in the pure material. The process by which this can occur depends on the material and the presence and distribution of these defects. For example, if the dielectric material contains gas-filled voids of varying shapes and volumes, the electrical stress in the cavity will

be greater than the electric stress in the material to an extent determined by the ratio of permittivities and by the shape of the cavity. The higher electric stress combined with the lower dielectric strength of the gas will lead to an electrical discharge in the cavity. The process of internal discharge can then lead to an erosion of the cavity, which, if continued, will lead to the formation of a discharge channel, causing failure.⁽²¹⁾

A literature survey⁽²⁶⁻²⁹⁾ conducted this quarter revealed a sparsity of effort on the effect of porosity on the dielectric strength of insulators. Polycrystalline samples of MgAl_2O_4 with varying percentages of porosity were prepared. A technique was developed to fabricate MgAl_2O_4 with the same pore size and shape and same grain size. Only the number of pores (pore volume) is varied.

Dielectric breakdown measurements were performed on these samples of MgAl_2O_4 . The ultimate dc dielectric strength is plotted against volume percent porosity, Figure 6. As the percentage porosity increased, the dielectric strength decreased. This is consistent with results observed for lead zirconate titanate ceramics⁽²⁶⁾ and for polycrystalline MgO .⁽²⁹⁾ Thus, it appears that the pressure of 10% voids in a ceramic can lead to decreases in the dielectric strength by as much as 50%. Consideration of void formation in insulation ceramics must be taken into account in their design and application.

FIGURE 6. Effect of Porosity on the Dielectric Strength of MgAl_2O_4 at 300°K

ELECTRICAL CONDUCTIVITY OF OXIDE INSULATORS

The electrical conductivity of a number of potential oxide insulators for fusion reactors were measured from near room temperature to 1270°K. Measurements were made in air, purified argon, and 3% oxygen in argon.

Measurements were made using a three-contact, guarded electrode technique. The resistance was measured with a dc potential and a time rate of charge of a precision capacitor.⁽³⁰⁾ Applied potentials up to 1000 volts were applied; however, most data were obtained at 1 and 10 volts. Data were obtained 1 minute and 10 minutes after application of the direct current. A comparison of these data obtained at different times gives some qualitative evaluation of ionic-electric conduction. The advanced capacitor measurements indicate resistance with accuracies approaching $\pm 10\%$ at 10^{16} ohms and $\pm 0.5\%$ at 10^{14} ohms. The lower resistances 10^6 to 10^{10} ohms were compared to results from a dc megohm bridge and determination of resistances by direct measurement of current and voltage. The argon was passed over zirconium metal at 1073°K and through a molecular sieve to a dewpoint of 225°K. The 3% oxygen in argon was a mixture of the above gas and commercially bottled oxygen added in appropriate volume.

The electrical conductivities of sintered, commercial Al_2O_3 , single crystal Al_2O_3 , sintered BeO , fused SiO_2 , hot-pressed, commercial Si_2ON_2 , hot-pressed Y_2O_3 containing 3 wt% Al_2O_3 , single crystal MgAl_2O_4 , and high-purity sintered MgAl_2O_4 were determined.

Results of Electrical Conductivity Measurements

Al_2O_3 : The electrical conductivity for sintered commercial 98% TD Al_2O_3 in air from a commercial supplier of alumina is shown in Figure 7. The conductivity is higher than that measured for single-crystal $\alpha\text{-Al}_2\text{O}_3$ ⁽³¹⁾ with a lower activation energy. A break is also observed in the $\log \sigma$ versus T^{-1} curve near 500°K, typical of possible impurity conduction. The data are consistent with other electrical conductivities for high-purity commercial aluminum oxides.⁽³²⁾

FIGURE 7. Electrical Conductivity of Commercially Sintered Al_2O_3 Compared to the Conductivity Previously Measured for Single Crystal Al_2O_3

The conductivity values measured after 10 minutes of applied potential are only slightly lower at the higher temperatures than that measured after 1 minute. However, below 500⁰K, the 10-minute values are significantly lower, suggesting possible ionic conduction.

BeO: The electrical conductivity of sintered BeO in air, shown in Figure 8, is slightly lower than values for sibling samples measured previously during the development of the measurement technique.⁽³⁰⁾ The data correspond also to some of the lowest values reported for BeO in this temperature region.⁽³²⁾ The conductivity obtained at 1 and 10 minutes of applied current above 575⁰K are identical and only at the break in the curve below 575⁰K are the 10-minute values lower than those obtained after 1 minute.

FIGURE 8. Electrical Conductivity of Sintered BeO

Fused SiO₂: The electrical conductivity of fused silica was measured in air, Figure 9. This was the silica target material used in the RF sputtering of SiO₂.⁽³³⁾ The absolute electrical conductivity values for SiO₂ are consistent with reported data for alkali-free vitreous silica.

Si₂ON₂: The electrical conductivity of a commercial hot-pressed silicon oxynitride was measured in both air and argon, Figure 10. The log σ versus T^{-1} is not linear but slightly S-shaped. The 10-minute measurements above 550⁰K give a significantly lower electrical conductivity in both air or argon.

FIGURE 9. Electrical Conductivity of Fused SiO₂ Compared to Previous SiO₂ Target and Sputter-Deposited SiO₂

FIGURE 10. Electrical Conductivity of Commercial Hot-Pressed Si₂ON₂ (Type B)

No electrical conductivity data for silicon oxynitride were available to compare with these data. The electrical conductivity values are substantially higher than the good electrically resisting oxides, but the conductivity may be sufficiently low for some fusion reactor uses. However, further studies as a function of microstructure and composition will be required, since the composition and structure vary substantially with fabrication methods.

Y₂O₃ With 3 wt% Al₂O₃: The electrical conductivities of three samples of hot-pressed Y₂O₃ were measured in air and argon, Figures 11 and 12. The electrical conductivity in air (sample 1) shows a typical log versus T⁻¹ curve above 550°K after heating to 1250°K, Figure 11. The data obtained at 1 and 10 minutes of applied voltage were identical above 550°K. Below 550°K, the data obtained at 10 minutes were lower and deviated from linearity.

In argon, the conductivity (samples 2 and 4) during the initial heatings above 870°K exhibits anomalous deviations from linearity, Figure 13. The conductivity values for sample 2 were approximately an order of magnitude higher than samples 1 and 4 on the first heating. However, after heating to 1250°K in argon, these anomalous changes were not observed and the conductivity decreased, approaching that of the other samples. In addition, the conductivity values after heating to 1000°K for the three samples were essentially the same in air and argon below 800°K. Sample 4, however, changed after heating, Figure 12. These results suggest that some residual stresses, structures, or other properties are introduced during hot pressing and are apparently changed on heating to 1250°K.

The electrical conductivity values agree very well with the lowest conductivity data reported for high-purity (99.99%) Y₂O₃,⁽³²⁾ August 8.

MgAl₂O₄: The electrical conductivity of high-purity single crystals and sintered (95% TD) MgAl₂O₄ was measured in air, 3% air in argon, and argon, Figure 14. The electrical conductivity of the single crystal is lower by approximately an order of magnitude than the polycrystalline sintered MgAl₂O₄. The electrical conductivity of the MgAl₂O₄ appears to be as low as or lower than any oxide electrical insulators.⁽³²⁾ The electrical conductivity for the single crystal is the same in air, 3% oxygen in argon, and argon except in the narrow temperature range between 830 and 1050°K. In this temperature range, the conductivities are characterized by unusual inflections in the log versus T⁻¹ curve, resulting in a maximum and a minimum, Figure 15. An inflection is also observed in the sintered MgAl₂O₄ but to a lesser degree, and no minimums or maximums are observed.

Only in this region does the conductivity vary with atmosphere and with the length of time the direct current is applied.

- 1) The conductivity obtained after applying the current 10 minutes is always lower (by much as an order of magnitude) than the conductivity obtained after 1 minute.
- 2) The maximum and minimum occur at lower temperatures for measurements made at 10 minutes than for those measured at 1 minute after application of the direct current.
- 3) The conductivity in air and 3% air-97% argon is essentially the same, while the conductivity in argon is higher.
- 4) The maximums and minimums occur at higher temperatures in argon than in the higher oxygen pressures.
- 5) These anomalies occur both on heating and cooling and are reproducible. Further experimentation and characterization are required to determine the causes of these phenomena.

FIGURE 11. Electrical Conductivity of $Y_2O_3 + 3 \text{ wt}\% Al_2O_3$ Showing Variations Between Samples Compared with Literature Values for Y_2O_3

FIGURE 12. Electrical Conductivity of $\text{Y}_2\text{O}_3 + 3 \text{ wt\% Al}_2\text{O}_3$ Showing Anomalies Above 800°K (1 minute of applied current) and Thermal Cycling

FIGURE 13. Electrical Conductivity of $\text{Y}_2\text{O}_3 + 3 \text{ wt\% Al}_2\text{O}_3$ (Sample 4) Showing Variations on Thermal Cycling at 1- and 10-minute Applied Potential

FIGURE 14. Electrical Conductivity of Single-Crystal and Polycrystalline MgAl_2O_4

FIGURE 15. Electrical Conductivity of MgAl_2O_4 Showing Anomalous Curvatures as Functions of Atmosphere and Measurement Time

SAFETY AND ENVIRONMENTAL PROGRAM PLANNING FOR MAGNETIC FUSION

PNL is working to support DMFE's safety and environment program in a variety of functions. Reference reactor system designs are being reviewed for their safety and environmental impact, and potential hazards are identified. Communications are being encouraged between American laboratories engaged in fusion safety and reactor design. This effort to establish communications was manifested in the PNL coordination of the Workshop on the Safety and Environmental Aspects of Fusion Power Plants in September. Criteria for safe fusion reactor design and operation are being established. A review was completed of relevant fission reactor safety criteria as a first step in this process. Analyses are being performed of various aspects of fusion safety and the safety tradeoffs of different design options. PNL is providing program planning support to DMFE to assure that the needs of the safety and environment program are identified early enough to be addressed in a coordinated, timely manner.

FUSION SYSTEMS SAFETY ANALYSIS

In fusion systems safety analysis, PNL is working to assure the timely availability of information which will be required when safety analysis reports and environmental impact statements are prepared for DMFE's fusion power development program. The identification of fusion safety and environmental impacts early enough in the development program would permit maximum emphasis on research and reactor designs to minimize those impacts.

FUSION REACTOR SAFETY CRITERIA

S. H. Bush, H. J. Willenberg

A review of existing fusion reactor safety criteria has been performed to evaluate their applicability to fusion reactors. The technical, philosophical, economic and political basis for their adoption has been reviewed so that a basis can be formulated for establishment of fusion reactor safety criteria. This review was completed during the current quarter and is summarized here.

While major accidents in fusion systems should have less severe radioactive release implications than would similar accidents in fission systems, they may result in substantial releases. One method of minimizing such releases would be through utilization of safety criteria developed for fission reactors, which could reduce both the probability of accidents and their consequences. Examples of such safety criteria are included in the Code of Federal Regulations (10 CRF), Regulatory Guides, Nuclear Regulatory Commission Branch Technical Positions (BTC), and similar documents.

All of these fission-related safety criteria have been reviewed for their safety significance (if any) when related to fusion systems and for the financial impact of implementation. In essence, the philosophy has been to apply as many criteria as possible even if their safety significance is limited with regard to fusion systems on the basis that these criteria could improve maintenance and reflect good engineering practices. Such an approach may lead to overkill, but it should indicate the breadth and scope of existing safety criteria.

Many of the judgments are highly subjective concerning the relative safety implications of a specific regulation, guide, or BTC. Even so, it is hoped that the information provided is a first step in the development of definitive fusion safety criteria.

With regard to costs, substantial use has been made of an article from Power Engineering (May 1977); similar criteria have been applied to safety guides and regulations not covered in this article.

Table 10 lists Regulatory Guides, relevant regulations, and other sources pertinent to fission safety. Each of these sources have been examined to establish how it might be relevant to a fusion system. With regard to containments or confinements, it was assumed that items pertinent to fission containments could be relevant to fusion confinements (or containments). The second portion of the table, Degree of Safety Relevance, is somewhat more difficult to understand. The five columns, Design Bases Accident, ALARA, Minimize Maintenance Time, Good Engineering Practice, and Not Relevant are used in the following context:

- Criteria that could minimize or mitigate the consequences of design basis accidents such as pressure boundary failure, increased power, or breaching of containments leading to major releases of energy and radioactivity should be checked here.
- Criteria that lead to minimization of routine releases of radioactivity or to limiting the exposure of plant personnel are checked under ALARA (As Low As Reasonably Achievable).
- If an item has minimal safety significance with regard to fusion systems, it may be classified as desirable because it minimizes maintenance time or because such application is considered to be good engineering practice.
- Finally, when the item is considered to be not relevant to fusion systems, the item is so indicated.

Decisions concerning safety relevance to fusion systems and confinements such as yes, indirect, and no are subjective judgments that may be changed in the future.

TABLE 10. Relevance of Regulatory Guides to Fusion Systems and Their Containment (Division 1 only)

No.	Topic	To Fusion System			To Confinement or Containment			Design Basis Accident	ALARA	Min. Maint. Time	Good Engr. Practice	Not Rel.	Cost Implication
		Yes	Indirect	No	Yes	Indirect	No						
1.1	NPSH			X								X	
1.2	Thermal Shock			X								X	
1.3	BWR-P.P. Release			X								X	
1.4	LOCA PWR F.P. Release			X								X	
1.5	Steam Line Break BWRs			X								X	
1.6	Onsite Power Independence		X					X					[m]
1.7	Combustible Gas Control			X							X		[Rm]
1.8	Personnel Training	X						X					[m]
1.9	Diesel Generators	X						X					[Rm]
1.10	Cadweld Splices				X						X		[m]
1.11	Inst. Lines thru Cont.					X			X				(m)
1.12	Seismic Inst.	X							X				[m]
1.13	Spent Fuel Storage			X								X	
1.14	Pump Flywheel Integrity	X			X								(Rm)
1.15	Re-bar Testing												[m]
1.16	Report LER								X				[m]
1.17	Sabotage Protection	X						X					[Rm]
1.18	Concrete Containments					X							[Rm]
1.19	NDE Containment Welds					X					X		[m]

Key to Definition

m = Minor financial impact

Rm = Relatively minor impact Rm>m

RM = Relatively major impact

M = Major impact M>RM

() = Westinghouse assumption as to impact

[] = PNL assumption as to impact

TABLE 10. Relevance of Regulatory Guides to Fusion Systems and Their Containment (Division 1 only) (Cont'd)

No.	Topic	To Fusion System			To Confinement or Containment			Design Basis Accident	ALARA	Min. Maint. Time	Good Engr. Practice	Not Rel.	Cost Implication
		Yes	Indirect	No	Yes	Indirect	No						
1.20	Internals Vibration Assess.			X								X	
1.21	Radwaste	X							X				(m)
1.22	Testing Protection System	X											(Rm)
1.23	Meteorology	X							X				[m]
1.24	Radwaste Gas Storage	X							X				(Rm)
1.25	Fuel Handling Accident		X						X				(m)
1.26	Quality Group Classification	X							X				(Rm)
1.27	Ultimate Heat Sink		X					X					[Rm]
1.28	Q.A. Design	X								X			(m)
1.29	Seismic Clarification	X						X					(Rm)
1.30	Q.A. Electrical	X						X					(m)
1.31	Control S.S. Welding	X						X					(Rm)
1.32	Safety Related Electric	X						X					(Rm)
1.33	Q.A.	X		X								X	
1.34	Electroslag Weld					X					X		(Rm)
1.35	ISI UngROUTED Tendons										X		(m)
1.36	Thermal Insulation Aust.S.S.	X								X			[m]
1.37	Q.A. Cleaning		X								X		[RM]
1.38	Handling		X								X		[RM]
1.39	Housekeeping		X								X		[RM]
1.40	Motor Qualification		X							X			(m)
1.41	Testing Onsite Power	X						X					[m]
1.43	S.S. Cladding			X								X	
1.44	Sensitized S.S.	X									X		(m)
1.45	RCPB Leak Detection	X								X			(m)
1.46	Pipe Whip	X						X					(RM)
1.47	Inoperable Status Indication		X					X					(RM)
1.48	Seismic Design	X						X					(Rm)
1.49	Power Levels			X								X	

TABLE 10. Relevance of Regulatory Guides to Fusion Systems and Their Containment (Division 1 only) (Cont'd)

No.	Topic	To Fusion System			To Confinement or Containment			Design Basis Accident	ALARA	Min. Maint. Time	Good Engr. Practice	Not Rel.	Cost Implication
		Yes	Indirect	No	Yes	Indirect	No						
1.50	Welding Preheat	X								X			[m]
1.52	Cleanup (Atmosphere)	X									X		(m)
1.53	Single Failure Criterion	X									X		(Rm)
1.54	Q.A. Coatings		X					X					(Rm)
1.55	Concrete Placement			X								X	
1.56	Water Purity		X								X		[Rm]
1.57	Containment Components					X							(m)
1.58	Personnel Qualifications	X									X		[Rm]
1.59	Design Basis Flood	X						X					[RM]
1.60	Seismic Spectra	X						X					[RM]
1.61	Seismic Damping Values	X						X					(m)
1.62	Man. Initiation Prot.Action			X								X	
1.63	Elect. Penetrations										X		[Rm]
1.64	Design Q.A.	X							X				[RM]
1.65	Closure Studs	X						X					[m]
1.66	NDE Tubular	X									X		[Rm]
1.67	Overpressure Prot.			X					X				[Rm]
1.68	Preop. & Startup		X									X	
1.69	Concrete Rad. Shields		X							X			(Rm)
1.71	Welder Qualification	X									X		[m]
1.72	Spray/Pond Piping			X				X					[m]
1.73	Elec. Valve Oper. Qual.	X									X		(m)
1.74	Q.A. Definitions	X								X			[m]
1.75	Physical Independence Elect.		X					X					(RM)
1.76	Design Tornado	X									X		[Rm]
1.77	Control Rod Ejection		X					X					[Rm]
1.78	Control Room Habitability		X					X					[Rm]
1.79	Preop. Tests ECCS		X						X				(m)

TABLE 10. Relevance of Regulatory Guides to Fusion Systems and Their Containment (Division 1 only) (Cont'd)

No.	Topic	To Fusion System			To Confinement or Containment			Design Basis Accident	ALARA	Min. Maint. Time	Good Engr. Practice	Not Rel.	Cost Implication
		Yes	Indirect	No	Yes	Indirect	No						
1.80	Preop. Tests Inst. Air		X								X		[m]
1.81	Shared Electrical	X						X					[Rm]
1.82	ECCS Sumps			X								X	
1.83	ISI S.G.'s	X							X				(RM)
1.84	ASME III Code Cases	X									X		(m)
1.85	ASME Code Cases	X									X		(m)
1.86	Termination Oper. Licenses		X						X				[Rm]
1.87	Code Cases	X						X					[RM]
1.88	Q.A. Records	X									X		[Rm]
1.89	Class I.E. Qualification	X						X					(RM)
1.90	ISI Concrete				X						X		[Rm]
1.91	Explosions Near Plant	X						X					[m]
1.92	Seismic Analysis	X						X					(m)
1.93	Electric Power Availability	X						X					[Rm]
1.94	Q.A. Concrete				X						X		[Rm]
1.95	Chlorine Release - Protect.	X									X		[Rm]
1.96	MSIV Design			X								X	
1.97	Inst. to follow Accident		X					X					[RM]
1.98	Offgas Release		X						X				[Rm]
1.99	Rad Damage		X						X				(M)
1.100	Seismic Qualification	X						X					(M)
1.101	Emergency Plans	X						X					[Rm]
1.102	Flood Protection	X						X					[Rm]
1.103	Post-Tensional					X					X		[m]
1.104	Cranes		X								X		(m)
1.105	Inst. Setpoints	X						X					(Rm)
1.106	Motor Thermal Overload	X									X		[m]
1.107	Cement Grout			X							X		[m]

TABLE 10. Relevance of Regulatory Guides to Fusion Systems and Their Containment (Division 1 only) (Cont'd)

No.	Topic	To Fusion System			To Containment or Confinement			Design Basis Accident	ALARA	Min. Maint. Time	Good Engrn. Practice	Not Rel.	Cost Implication
		Yes	Indirect	No	Yes	Indirect	No						
1.108	Diesel Generator Tests	X						X					[RM]
1.109	Routine Release Doses	X							X				(m)
1.110	Radwaste Cost Benefit		X						X				(m)
1.111	Transport Rad.Effluents		X						X				(m)
1.112	Radioactive Release		X						X				(m)
1.113	Aquatic - App. I	X							X				(m)
1.114	Operator at Controls	X						X					[Rm]
1.115	Turbine Missiles	X						X					(Rm)
1.116	Q.A. Mechanical	X						X					(RM)
1.117	Tornado Design	X						X					(m)
45 1.118	Testing Electrical	X						X					(Rm)
1.119	Surv. New Fuel			X								X	
1.120	Fire Protection	X						X					(Rm)
1.121	S.G. Plugging	X							X				(RM)
1.122	Seismic Equipment	X						X					(Rm)
1.123	Q.A. Procurement	X									X		(RM)
1.124	Design Loads		X					X					(M)
1.125	Hydraulic Structures		X								X		[Rm]
1.126	Fuel Densificaton			X								X	
1.127	Inspection Water Control Structures			X								X	
1.128	Storage Materials		X					X					[Rm]
1.129	Storage Batteries		X					X					[Rm]

TABLE 10. Relevance of Regulatory Guides to Fusion Systems and Their Containment (Division 1 only) (Cont'd)

Item	Relevant Fusion			To Confinement			Design Basis Accident	ALARA	Min. Maint. Time	Good Engnr. Practice	Not Rel.	Cost Implications
	Yes	Indirect	No	Yes	Indirect	No						
10 CFR 21	X							X				(m)
10 CFR 50, APP.A (GDC'S)	X						X					(RM)
10 CFR 50, APP.B (QA)	X						X					(Rm)
10 CFR 50, APP.G (LEFM)		X								X		(m)
10 CFR 50.55(a) Codes	X						X					(RM)
10 CFR 50, APP.I	X							X				(RM)
10 CFR 50.55(a), (g)	X							X				(Rm)
10 CFR 100 (Seismic)	X						X					(M)
ALARA	X							X				(Rm)
ECCS		X									X	
10 CFR 50.55(c)(Reporting Deficiencies)		X									X	
ATWS	X						X					(RM)
Pipe Whip	X									X		(M)
Single Failure Criteria	X						X					(Rm)
Reference System Interfaces	X									X		(Rm)
Standard Technical Specs.		X					X					(Rm)
Branch Technical Position	X						X					(Rm)
NEPA	X						X					(m)
Env. Qual. Ratchet	X							X				(M)
Waste Proc. and Fuel Cycle	X							X				(M)

WORKSHOP ON THE SAFETY AND ENVIRONMENTAL ASPECTS OF FUSION POWER PLANTS

H. J. Willenberg

The workshop on the Safety and Environmental Aspects of Fusion Power Plants was held in Seattle, Washington, on 14-15 September 1977. The objectives were to establish a dialogue between fusion reactor designers and safety and environmental researchers, and to identify the primary environment and safety concerns which might be unique to fusion power plants. The participants included representatives from all the major fusion laboratories in the United States. Their expertise included design of Tokamak, mirror, and inertially-confined fusion reactors; fission reactor safety; physics and engineering aspects of safety and environments; and biological sciences. This diversity of disciplines provided an effective forum for discussion of the major safety and environmental issues which might be associated with fusion power plants, and potential design solutions to these problems. The workshop was jointly sponsored by the United States Energy Research and Development Administration, Division of Magnetic Fusion Energy and the Electric Power Research Institute. It was coordinated by Battelle, Pacific Northwest Laboratories (PNL).

The list of topics discussed at the workshop is shown in Figure 16.

<u>Session 1.</u>	RADIATION EXPOSURE
	A. Tritium
	B. Activation Products
	1. Blanket and Structures
	2. Corrosion Products
	3. Air
<u>Session 2.</u>
ACCIDENTS
	A. Liquid Metal Spills
	B. Magnet Safety
	C. Power-Flow Mismatch
	D. Hydrogen and Tritium Accidents
	E. Plasma Disturbances
	F. External Hazards
<u>Session 3.</u>
ENVIRONMENT
	A. Tritium
	B. Magnetic Fields
	C. Natural Resources
	D. Radioactive Waste
<u>Session 4.</u>
PLANT SAFETY
	A. Safety Criteria
	B. Safety Instrumentation
	C. Maintenance and Operation Requirements
SUMMARY, CONCLUSIONS, and RECOMMENDATIONS |

FIGURE 16. Safety and Environment Workshop Discussion Topics

A fifteen-minute overview of each topic was presented by one of the participants, followed by an open discussion directed toward identifying what the key safety and environmental issues are and what kinds of design solutions are available to mitigate the hazards that might be associated with these issues. For each topic, the discussion was centered on these four questions:

- What is the safety and environmental significance of the topic?
- Is current technology adequate to ensure that the degree of hazard is within acceptable levels?
- What design solutions are available to mitigate the effects?
- Where should future research and development be concentrated?

The discussion in the first session focused on radiation exposure within a fusion plant during normal operating conditions. It was generally agreed that tritium leakage represents the greatest potential for routine plant exposure. The Tritium Systems Test Assembly was described, and its role in demonstrating tritium handling capabilities in reactor-like environments was explained. Evidence was cited for tritium permeation rate scaling linearly with pressure rather than as the square root of pressure for very low partial pressures.

Neutron activation of blanket and structural materials may result in very high radioactivity levels. Careful choice of materials can greatly reduce the radioactive waste storage problems, and possibly even permit contact maintenance after about a one week cool-down period. It was suggested that an active materials technology program can permit the use of low activation materials rather than stainless steel by the time commercial reactors are built.

The experience of the fission reactor industry with activated corrosion products was described, and application of this knowledge to fusion reactors was discussed. Activated corrosion product transport may considerably affect reactor maintenance early in the fusion program. Activation of building air, particularly argon, may also limit reactor accessibility, even for the first D-T physics experiments. Proper shielding should reduce this hazard for commercial reactors.

The second session dealt with hazards resulting from major accidents. The accidents with the greatest potential for release of energy or hazardous materials appear to be liquid metal spills, superconducting magnet failures, loss-of-flow/loss-of-coolant type accidents, and hydrogen explosions. An analogy was drawn between liquid sodium-concrete fires analyzed for fast breeder reactors and liquid lithium-concrete fires which might be possible with fusion reactors. Much of the liquid sodium technology should also apply to liquid lithium, so that engineered safety features which are effective for liquid metal fast breeder reactors should be effective for liquid-cooled fusion reactors.

Superconducting magnet safety experience is very limited. Superconducting magnets built to date have been much smaller and simpler than those required for Tokamaks, have very little operating time, and have experienced high failure rates to date. An active research program is in progress to identify magnet faults and design safety systems. Electrical breakdown and magnet quench probably have the greatest potential for severe consequences.

Loss-of-flow/loss-of-coolant type accidents were discussed in this session. This appears to be a more serious hazard for the divertor in a lithium-cooled Tokamak than for the blanket. Under worst-case conditions the first wall or divertor might melt, leading to serious consequences. In either case, however, melting would result in plasma quench, terminating the rapid heating of the coolant.

The third session dealt with the impact of fusion power on the environment outside the power plant. A considerable body of information exists in the literature on atmospheric and ecological transport of tritium. The integrated dose to the public as a result of even large accidental tritium releases seems small. A number of unknowns still exist, however, in the characterization of routine long-term tritium releases. The biological effects of magnetic fields are very poorly understood at the present time. No chronic effects have been positively identified, and only minor acute effects have been reported. An integrated research program is under way to determine the biological significance of magnetic fields. Current conceptual designs of commercial fusion power plants would utilize substantial fractions of the world's resources of certain materials. The case for analysis of alternate materials was well presented, and no material was identified which would represent a problem compared to world reserves when proper design considerations were made. The same argument for alternate blanket materials was made with respect to environmental considerations of radioactive waste disposal. Blanket material choices result in decay times ranging from weeks to millenia.

The final session was devoted primarily to relating the fission reactor safety research experience to fusion reactor safety. A review of fission reactor safety criteria that should apply to fusion (assuming the NRC-type licensing will be required for commercial fusion reactors) was presented. It was felt that emphasis should be placed on accessibility at the design stage and that lower inventories of radioactive elements and less severe design basis accidents should permit relaxation of some criteria when compared to those for fission reactors. An overview was given of some considerations which will apply to safety instrumentation in fusion reactors. The session concluded with a description of maintenance and operation requirements for the Tokamak Fusion Test Reactor and discussion of its relevance to more advanced reactors.

The most significant results of the workshop were to provide perspective on the relevant safety and environmental issues, on how significant they might be, and on what design solutions are available. Communications were promoted between fusion reactor designers and safety and environmental analysts, and the functions of each in developing safe, reliable fusion power plants were discussed. Although a large number of issues were discussed, nothing was really identified as a problem for which careful design could not provide adequate protection.

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