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**Pacific Northwest Laboratory
Report on Controlled Thermonuclear
Reactor Technology**

October 1975 - December 1975

January 1976

**Prepared for the U.S. Energy
Research and Development Administration
under Contract E(45-1):1830**

MASTER

Battelle

Pacific Northwest Laboratories

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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Under Contract E(45-1)-1830

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$6.00; Microfiche \$2.25

PACIFIC NORTHWEST LABORATORY
REPORT ON CONTROLLED THERMONUCLEAR
REACTOR TECHNOLOGY

OCTOBER 1975 - December 1975

ERDA RESEARCH AND DEVELOPMENT REPORT

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January 1976

Battelle
Pacific Northwest Laboratories
Richland, Washington 99352

PREFACE

This quarterly report on Controlled Thermonuclear Reactor Technology consists of progress summaries of research conducted by the staff of Pacific Northwest Laboratories (PNL). This reporting period includes progress made from October 1, 1975 through December 31, 1975. The ERDA Division of Controlled Thermonuclear Research is a major sponsor of the work. However, fusion-related work sponsored by others is also included as appropriate.

The summaries are presented in four major categories of:

- System Design and Analysis
- Materials Research and Radiation Environment Simulation
- Environmental Effects
- Manpower Development

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.

Loren C. Schmid
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.
Report on Controlled Thermonuclear Reactor Technology, January through September 1975, BNWL-1939 1.

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REPORT ON CONTROLLED THERMONUCLEAR REACTOR TECHNOLOGY
OCTOBER THROUGH DECEMBER 1975
ERDA RESEARCH AND DEVELOPMENT REPORT

SUMMARY

The control of thermonuclear reactions using the relatively infinite supply of deuterium is looked toward as the ultimate source of high temperature energy. Success in the containment of fusion plasma has caused scientists to look beyond the scientific feasibility of obtaining more energy from fusion reactions than is supplied to the plasma. Scientists are now working to identify 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. Evaluations by PNL continue to emphasize research and development in engineering technology areas.

The PNL staff has been studying the economics and materials of the fusion-fission hybrid concept and materials, neutronics, environment and safety which may be applicable to all concepts. These studies are scoped to make efficient use of ERDA resources, and to complement and support the work at other laboratories.

The fusion-fission hybrid CTR may have less severe fusion operating conditions and may be introduced earlier than pure CTRs. The necessary economic characteristics for a competitive hybrid are being determined by economic modeling. Survey calculations are being made on three blanket configurations for a conceptual hybrid design based on a Two Component Torus (TCT) in a cooperative effort between Princeton Plasma Physics Laboratory (PPPL) and PNL. The TCT concept is used in the Tokamak Fusion Test Reactor concept for plasma heating and confinement and is being evaluated for the potential use in a reference design. Other studies are underway to provide background data in the design of a minimum thickness shield and a convertor region for the TCT hybrid.

The effect the plasma and associated radiation and emission will have upon the surfaces of the first wall are being studied. A variety of metal targets were prepared for neutron irradiation and were evaluated. Radioactive recoil sputtering ratios are summarized with complete results being prepared for separate publication. The development and testing of the ion blistering equipment is continuing with the design and installation of a special differential pumping stage.

Analysis of the molybdenum specimens irradiated for the initial BCC ion correlation experiment is completed and data from the participants have been compared. Micrographs will be provided by NRL for the measurement of void size and density to establish differences found in various measuring techniques. A report has been issued summarizing the mechanical property data needs for CTRs, the importance of ion simulation in determining mechanical properties, damage analysis and sample heating with light ions, and the size and surface considerations of test specimens.

Graphite cloth and fibers irradiated in EBR-II to $\sim 3 \times 10^{21} \text{ cm}^{-2}$ at $\sim 500^\circ\text{C}$ are being evaluated for radiation damage effects. Preliminary data indicate that fibers in the cloth samples have shrunk about 8% in the axial direction. Thermodynamic data indicate that carbon may not be compatible with some tritium breeder and neutron multiplier materials.

Helium effects are being studied on five alloys specified in CTR conceptual designs. Tests were designed to determine the effects of oxidation potential on low-level contaminant/metal interactions. Whether the trends in weight and yield strength changes continue after a specified time of exposure or whether they level off is not known. Niobium and vanadium are being studied for mechanical property effects after injection of helium by the tritium trick method.

An advanced state-of-the-art Acoustics Emission Event Energy Analyzer (AEEEA) has been developed and tested. Detailed analysis of the individual acoustic events may provide means for determining various mechanisms for dielectric failure of electrically stressed solid insulator materials. The generation of dc electrical resistivity data on BeO , Al_2O_3 and selected sputtered deposited samples of SiO_2 is continuing and evaluation of techniques to measure the ac resistivity of insulators is underway.

A search is continuing for superconductors for CTR applications from compounds that are candidates for advanced generation fusion devices.

The environmental analysis of the CTR is complete and a draft of the assessment is being reviewed. Studies of the effects of tritium on aquatic systems are continuing and an assessment of tritium releases from a CTR have been estimated. The biomagnetic effects have been assessed and the literature summarized in a special report.

Graduate courses on plasma technology, energy conversion and materials characteristics are being offered in the Nuclear Engineering curriculum at the Joint Center for Graduate Study at Richland, Washington.

SYSTEM DESIGN AND ANALYSIS

Fusion reactors are being considered as a future energy source. Their contribution to the U.S. power economy depends on their performance in comparison to competing systems. The fusion-fission hybrid CTR may have unique advantages from an earlier introduction date than pure CTRs and from less severe fusion operating conditions. The necessary economic characteristics for the competitive hybrid are being determined by economic modeling of the future electricity industry with and without the hybrid or other CTRs. The characteristics of the hybrid and the competitive power plants have been defined, and initial computer runs made for power systems not containing the LMFBF or the CTR.

PNL cross section sets and sample problems have been implemented on the PPPL computing facilities. Good agreement in results were obtained. Survey calculations on three blanket configurations for the TCT-hybrid have been completed. The results are being analyzed for guidance in setting up additional survey cases. Preliminary calculations relating maximum wall loading to allowed blanket power density have been made. The results will be used to guide blanket configuration selection for the survey calculations.

Valid technical bases are needed to establish adequate blanket and shield design methods. Improvements in the angular representation of neutron cross sections are being studied to determine the bias in calculated results to be expected from the use of current design methods. In order to achieve some degree of confidence in design values, some preliminary work is being performed on the comparison of calculated and measured values of some important neutronic parameters.

Ionization of atoms by low-energy ion bombardment is expected to be of importance in the development of fusion reactors. Ionization, particularly of impurity atoms and ions, may lead to the generation of plasma instabilities and provide an additional channel of energy loss. Work is presently in progress at BNW in which differential ionization cross sections are being measured for incident charged particles with energies in the region of interest to controlled thermonuclear fusion.

Technology developed for tritium production from lithium aluminate in fission reactors was classified because of its relation to the weapons program. The declassified and unclassified documentation is being reviewed to extract that information which is of value to fusion technology.

PLANNING AND ANALYSIS

The fusion-fission hybrid is a concept being considered in the designs of controlled thermonuclear reactors. To be viable for development, a new concept requires definition of the product characteristics (types, quantities and costs). The economic regimes effort attempts to determine the allowable cost for the hybrids for various competitive situations.

CTR Economic Regimes

DE Deonigi, RL Engel

The economic regimes program identifies the economic characteristics that a CTR must have to achieve a satisfactory return on research investment. The fusion-fission hybrid is being investigated in two complementary studies sponsored by the Division of Controlled Thermonuclear Research (DCTR) and the Electric Power Research Institute (EPRI). The analysis is being made by use of the computerized⁽¹⁾ Linear Programming (LP) model developed for forecasting the types of power plants built in the United States.

The approach is to determine the allowable cost for the hybrids for various competitive situations. A parametric treatment of two hybrid performance characteristics (fissile material production and electrical generation) is being used. Each possible competitive situation represents a case as summarized in Table 1. All cases include fossil and thermal converter nuclear power plants. By using the parametric treatment, the designer can analyze tradeoffs between capital cost, fissile material production, and electrical generation.

Uranium prices and separative work prices are important input to the LP model. Members of the EPRI fusion program committee were solicited to update values used for these important data. PNL's initial values and the revised values are shown in Tables 2 and 3.

A powerful feature of this LP model is the uranium price function. Uranium cost must be provided as a function of the amount used, not as a function of time. Thus the model in effect has a feedback loop on uranium cost. Similarly, fissile material price is inherent in the model, thus, does not require a price function of time. The price is set by availability and desirability of fissile material, as determined by the plant mix, which is the model decision variable.

TABLE 1. Parametric Hybrid Analysis Cases

System Characteristics		CASE									
		1	2	3	4	5	6	7	8	9	10
DT, Yr ^(a)											
Date of LMFBR Availability	20	1993	--	--	1993	1993	1993	1993	1993	--	1998
by Doubling Time	12	1999	--	--	1999	1999	1999	1999	1999	--	2004
	6	--	--	--	--	--	--	2003	--	--	--
Date of First CTR Availability		--	2010	--	2010	2020	2010	2010	2010	--	--
Date of First Hybrid Availability		1990	1990	1990	1990	2000	1990	1990	1990	2000	2000
Electrical System Growth Rate ^(b)		MH	MH	MH	MH	MH	MH	MH	Low	MH	MH
Enriched Uranium Cost Schedule ^(c)		EPRI	EPRI	EPRI	EPRI	EPRI	ERDA-A	EPRI	EPRI	EPRI	EPRI

- a. LMFBR performance based on designs used for Proposed Final Environmental State, WASH-1535.
b. Growth rate are keyed to ERDA (1975 version of WASH 1139) estimate through year 2000 with a slow decline in rate of growth thereafter. MH designates moderately high.
c. Cost of uranium and enrichment service based on comments by EPRI and ERDA fusion committee representatives. ERDA-A refers to the lower uranium costs assumed in the LMFBR environmental statement.

TABLE 2. Uranium Cost Function

Quantity					
Thousand Tons U ₃ O ₈		400	500	500	500
Final Year of Use		1988	1996	2004	2016
Constant 1975 Dollars/lb					
Initial		16	20	25	40
Revised		18	20	25	40
Current Dollars/lb					
Initial ^(a)		34	80	171	591
Revised ^(b)		50	100	232	938

- a. For average year of use.
b. For final year of use.

Another critical input to the LP model is the plant capital costs. The values used for capital cost are shown in Table 4. A capital increment of \$150/kW between LMFBR's and LWR's was used during the LMFBR introduction period, and a \$100/kW increment was used after the LMFBR was established in the market.

Fossil fuel cost data as aggregated from 1975 FPC reports is listed in Table 5. The model is formulated so nuclear energy competes with fossil in each National Electric Reliability Council (NERC) region.

TABLE 3. Separative Work Costs

	Year			
	1980	1990	2000	2010
Constant 1975 Dollars				
Initial	85	85	85	85
Revised	76	75	70	65
Current Dollars				
Initial	120	234	461	907
Revised	106	205	405	800

TABLE 4. Fossil and Nuclear Capital Costs^(a)

	LWR and HTGR	LMFBR	Fossil				
			ECAR NPCC	WSCC SWPP	MARCA SERC	MAIN ERCOT	MAAC
1975	365		285	285	285	285	285
1980	598		496	503	509	518	494
1990	632	782	530	537	543	552	527
2000	640	740	540	546	552	561	536
2040	640	740	540	546	552	561	536

a. \$/kW 1975 Dollars

The first three cases summarized in Table 1 constitute the study being performed for EPRI. The computer calculations have been made for plutonium producing hybrids for all three cases. Since EPRI has the same outlook as the electric utilities, their benefit analysis includes the effect of taxes. DCTR does not include taxes when considering benefits. Therefore, the results of case 3 (no LMFBR and no CTR) were adjusted to remove the effect of taxes and Figure 1 shows the allowable capitalized cost (capital and capitalized operating cost over a 30 year life) for a range of benefits for hybrid designs producing 0.5 to 1.5 kilograms of plutonium per megawatt thermal per year. Fuel cycle costs are capitalized since cost data for the reference designs are not available. The results are presented as groups of curves, each group representing a different electrical to thermal ratio. Each curve represents a fixed benefit, where benefit is the reduction in total discounted system cost compared to a base case without the hybrid. The 0.40 MWe/MWt value depicts a hybrid system with a highly efficient conversion of thermal energy. The near zero 0.01 MWe/MWt value depicts a hybrid plant

TABLE 5. Fossil Fuel Cost by Region^(a)

Region	Cost ^(b) ¢/MBTU	Percent ^(c) of Supply	Region	Cost ^(b) ¢/MBTU	Percent ^(c) of Supply
ECAR	80	33.4	MAAC	99	31.7
	87	33.4		160	38.8
	163	33.2		206	29.5
WSCC	57	33.4	MAIN	80	34.5
	100	33.3		95	33.9
	220	33.3		180	31.6
MARCA	59	28.4	SERC	80	33.3
	86	39.0		100	33.3
	172	32.6		187	33.4
NPCC	125	44.4	ERCOT	25	33.7
	160	36.4		70	32.5
	204	19.2		180	33.8
SWPP	60	33.2			
	90	33.1			
	175	33.7			

a. 1975 dollars.

b. Derived from recent FPC data.

c. Supply function steps based on historical cost distribution from PNL power plant file.

which consumes nearly all of the electric energy produced. The -0.20 MWe/MWt depicts a hybrid plant requiring electrical energy from an outside source.

When benefits are zero, the hybrid cost is that which would barely penetrate the market and supply an alternate source of plutonium, in this case at over \$80/gram at year 2020. As benefits increase, the cost of fissile material drops, until at a benefit of 15 billion it is about \$62/gram at year 2020. Remember, this data represents the case without the LMFBR. For comparative purposes, if the LMFBR can be successfully introduced at the price shown in Table 4, the plutonium value is about \$58/gram and the benefit is \$20 billion.

The capitalized cost of present day LWR's is about \$250/kW(t). If this value is used as a reference for the hybrid, it could be concluded from Figure 1 that a hybrid that consumes electricity might barely be competitive. That is, a -0.20 MWe/MWt hybrid producing 1.5 kg/MWt would have to be built in the 300-350 \$/kW range, including fuel processing costs. However, a hybrid plant which generates enough electrical power for its own use could be competitive at 500-550 \$/kW(t) including fuel processing costs. The power producing hybrid could be built for a rather high cost and still be beneficial. In the absence of the LMFBR, such a hybrid producing 1.5 kg/MWt yields about \$4 billion

FIGURE 1. EPRI Core 3 - No LMFBR - Allowable Capital Cost for Hybrid - Adjusted for No Taxes

benefit if it could be built for \$1000/kW(t), including fuel processing. The power producing hybrid producing 1 kg/MWt would be competitive at just below \$900/kW(t).

Similar studies and analyses are being made for the other cases.

REACTOR SYSTEMS STUDIES

Reactor systems studies are focused on evaluation of fusion-fission (hybrid) concepts. The fusion-fission system has been identified as a concept of special interest at PNL since it offers the most immediate promise for demonstration of the fusion principle. A study is being completed on evaluating the technical feasibility of the various possible fusion-fission combinations. A cooperative effort between Princeton Plasma Physics Laboratory (PPPL) and PNL has been established to conduct a conceptual design of a hybrid based upon a Two Component Torus (TCT).⁽²⁾

TCT-Hybrid Conceptual Design Study

DT Aase, BR Leonard, Jr., RT Perry, Jr.

The objective of this study is to develop a conceptual design of a TCT-hybrid. If the concept appears promising, a reference design will be developed. The initial ground rules are: 1) to optimize on production of fissile material, 2) constrain the technology to that available to construct a machine in the early 1990s, and 3) minimize the capital costs.

The TOKAMAK Fusion Test Reactor (TFTR)⁽³⁾ will be the first fusion device, using magnetic plasma containment, to yield neutrons from the fusion process. The TFTR uses the TCT concept for plasma heating and containment. While the concept is expected to yield a near Lawson Plasma, it is not expected to extrapolate to a net exporter of electrical power. One potentially feasible way to commercially utilize this technology, however, is to design a hybrid device which uses the neutrons from the TCT device to breed fissile material for use in fission reactors and to produce some power directly. A coordinated effort between scientists and engineers from PPPL and PNL is underway to evaluate the potential of this concept and develop a conceptual design. If the conception design appears to be economically and technically attractive, a follow-on effort will continue leading to a reference design.

During this report period the preliminary blanket survey calculations were begun including the necessary groundwork for performing the computer calculations at PPPL.

The thirty group cross section set produced at PNL was placed on tape at PPPL. A sample problem that had been run at PNL was run on the PPPL IBM 360/91. The sample problem "a transport calculation for a spherical hybrid blanket" was run using the PPPL version of the ANISN Code with the 30 group cross sections from PNL.

The results (reaction rates and fluxes) from the sample calculation at PNL and PPPL were compared. Variances were found generally in the third decimal place. This indicates that the transport Codes and Computers at PNL and PPPL will produce essentially the same results.

The identical problem was run using the DLC-2 100 group library from RSIC. After summing the fluxes over various energy groups in order that the energy group boundaries would correspond to the 30 group fluxes from PNL, they were compared. In this comparison, large variations in the fluxes were noted, particularly in the thermal and epithermal regions. This is not too surprising considering the fact that the PNL 30 group cross sections are shielded. A more detailed comparison of various reaction rates is in progress which should give a better indication of the differences in results expected from shielded and infinite dilute cross sections.

The accuracy expected from the use of infinite dilute cross sections in hybrid problems is necessary at this point because infinite dilute cross sections will be used in a series of comparison runs. At this time, infinite dilute cross sections are not available for all elements.

To determine the neutronic performance expected from various blankets which will be run in survey calculations, a literature survey of all previous blanket calculations was made. The various designs were then ranked according to their neutronic performance, that is, on each blanket's ability to breed tritium, fissile fuel and power.

The results generally showed that blankets utilizing metal fuels were best, followed by carbides, then oxides and lastly salts. Uranium systems out-perform thorium systems and performance increased with enrichment.

Survey calculations were then begun. The physical size of the reactor chosen for the calculations was: plasma radius - 150 cm, vacuum wall at - 200 cm, blanket thickness - 72 cm, and shield thickness - 70 cm. For the actual calculations, a shield thickness of 28 cm was used. This thickness was employed merely to provide a boundary condition on the blanket.

The fuel for the first calculation was depleted UO_2 in both the convertor and fertile lattice. Depleted UO_2 was chosen for the first calculation on the basis that it would require the least extension of current technology and least expense.

To date three variations of the reference blanket have been calculated. The three variations are described in Figures 2, 3 and 4. The reaction rates of interest for the

Converter Vol %	Lattice Vol%	Shield
47% UO ₂	59.7% C	100%
21% SS	16.0% He	SS
32% Coolant He	14.4% UO ₂	
	9.9% SS	
Depleted U	Natural Li	Breeding Zone
0.3% ²³⁵ U	7.5% ⁶ Li	95% Li
	92.5% ⁷ Li	5% SS

FIGURE 2. Case I of TCT-Hybrid Blanket Survey Calculations

three cases are given in Tables 6, 7 and 8. No attempt has been made to optimize the performance nor to make tritium breeding ratios in excess of one. The results, which are currently being analyzed, are to be used as guide posts for future calculations of this size blanket.

The survey calculations will continue to determine the sensitivity of the reaction rates to:

- Converter region enrichment
- Fertile Material (²³²Th)
- Fissile and Fertile material form (i.e., metal, carbide and salt)
- Alternate combinations of coolant and moderator materials in converter and fertile regions
- Location of tritium breeding region.

FIGURE 3. Case II of TCT-Hybrid Blanket Survey Calculations

From these survey calculations, blanket configurations will be selected for more detailed study.

Of particular concern to establishing a minimum thickness shield and selecting blanket region thickness was the finding that the present preparation of neutron cross section "data sets" used in ANISN are inadequate for 14 MeV neutrons. Most important is that the forward peaking of the elastic scattering data is not properly handled so the penetration of high energy neutrons in the blanket and the shield are underestimated.

To minimize capital costs, the hybrid should be as compact as possible. Therefore, the majority of the PNL effort on this study to date has been working on the analysis methods required for doing the design. This is focused on getting the calculational tools, codes, cross sections, etc., in place to perform the neutronic calculations on

Convertor and Fast Blanket Lattice (Same Material)	Tritium Breed. Zone - 5 Vol%	Shield & Wall Z 3-10
Vol%		
47% UO_2	95% Li	100% SS
21% SS	5% SS	
32% He		
Z 4-6-7-8-9		
<u>Depleted U</u>	<u>Natural Li</u>	
0.3% ^{235}U	7.5% ^6Li	
	92.5% ^7Li	

FIGURE 4. Case III of TCT-Hybrid Blanket Survey Calculations

TABLE 6. Neutron Production Rates per Source for Case I Blanket Configuration

		Zone			Zone
^6Li (n, α)	0.0415	9	^{238}U (n,f)	0.2178	4
^7Li (n, α)	0.00028	9		0.0305	6
Total	0.04178			0.0066	7
^{235}U (n,f)	0.02989	4		0.0014	8
	0.02785	6			
	0.01470	7			
	0.00395	8			
Total	0.07639		+ Total	0.2563	
^{238}U (n, γ)	0.7148	4			= 0.3326 $\sim$ 66 MEV
	0.458	6			
	0.1958	7			
	0.0048	8			
Total	1.3734				

TABLE 7. Neutron Production Rates per Source for Case II Blanket Configuration

${}^6\text{Li}$ (n, α)T	0.318		${}^7\text{Li}$ (n, α)T	0.0177	Zone 7
	0.225			0.0083	8
	<u>0.073</u>			<u>0.0016</u>	9
Total	0.616	+	Total	0.0276	= 0.643
${}^{238}\text{U}$ (n,f)	0.215		${}^{235}\text{U}$ (n,f)	0.0192	4
	0.006			0.0006	5
	<u>0.101</u>			<u>0.0184</u>	6
Total	0.322	+	Total	0.0382	= 0.360 ~72 MEV
${}^{238}\text{U}$ (n, γ)	0.628				4
	0.025				5
	<u>0.633</u>				6
Total	1.286				

the shield and blanket configurations of interest. Since much of this work is generic to CTR blankets and shields, the results of this work for this report period are presented in the Blanket and Shield Technology section of this report.

To obtain adequate fissile material production rates, considerable neutron multiplication will be required in the TCT-Hybrid blanket. This will occur primarily in the convertor region by fissioning of fissile or fertile U isotopes. The fission event results in a considerable energy multiplication (200 MeV/fission). Approximately 80% of the fission energy is contained in the kinetic energy of fission products which is turned to sensible heat within a few microns of where the fission occurred. This can lead to very high power densities in the convertor region if high neutron multiplication and high wall loadings are combined. As a guide to the blanket survey calculations, Figure 5 was developed from a simple slab geometry. It relates allowed wall loading to allowed convertor region power density for various neutron multiplication factors. The neutron yield per fission was assumed to be three.

The average power density for various fission reactor lattices are also indicated on Figure 5. This work will be expanded to identify the allowed power density versus volume fraction fuel, coolant and structure for convertor region lattices of interest to the survey calculations.

TABLE 8. Neutron Production Rates per Source for Case III Blanket Configuration

${}^6\text{Li} (n,\alpha)\text{T}$	0.107	${}^7\text{Li} (n,\alpha)\text{T}$	0.011	<u>Zone</u> 5
Total	0.108			
${}^{235}\text{U} (n,f)$	0.0191	${}^{238}\text{U} (n,f)$	0.215	4
	0.0205		0.0970	5
	0.0112		0.025	6
	0.0047		0.0057	7
	<u>0.0009</u>		<u>0.0006</u>	8
Total	0.0564	+ Total	0.3423	= 0.39 ~80 MEV
${}^{238}\text{U} (n,\gamma)$	0.631			4
	0.697			6
	0.374			7
	0.150			8
	<u>0.028</u>			9
Total	1.880

FIGURE 5. Wall Loading Versus Allowable Converter Power Density

BLANKET AND SHIELD TECHNOLOGY

The objective of these studies is to develop valid technical bases for designing CTR blankets and shields. Research efforts are currently focused on improving the technology needed for design of fusion-fission systems. This includes: evaluation of nuclear cross sections to produce adequate descriptions of important reactions; modifying analytical procedures for condensing pointwise data to the multigroup values needed as input to design analysis codes; and assessing the accuracy of calculated values to aid in making realistic projections of the performance of fusion systems.

Theory/Experiment Analysis

MG Zimmerman, DF Newman

In the previous quarterly report⁽⁶⁾ we showed that the typical ways of handling cross section data in discrete ordinates transport codes, where the Legendre expansion is truncated at the P_3 term, is not adequate for D,T fusion neutron source spectra. Calculated reaction rates for ^{63}C (n,2n) ^{62}C and the ^{238}U fission rate using the P_3S_8 cross section representation and the ANISN code do not agree with experimental values. We showed that these disagreements could be reduced or eliminated by reducing the high energy (>10 MeV) self-scatter term in the cross sections. Other evidence was also presented which indicated the cause of the discrepancy to be related to the poor modeling of the high energy angular cross section of ^{238}U caused by truncating the cross sections at the P_3 Legendre terms.

The continuing discrepancy between calculated and measured results are probably caused by the substantial negative components of the differential scattering cross section in the forward direction. This can be seen from the data given in Figure 6 which shows the angular dependence of the 14 MeV cross section for ^{238}U modeled with different numbers of terms in the Legendre expansion. The existence of negative values for the differential cross section is nonphysical. The values given on ENDF/B-IV are a P_{20} representation. A low order angular model is desirable in design calculations to keep the cost of the computer runs within reason.

As shown in Figure 6, the P_9 representation does improve modeling of the forward directed peak relative to P_3 , but the P_9 representation also has substantial negative values at a more forward directed angle than the lower order Legendre representations. This could explain why the higher order Legendre model actually resulted in slightly less high energy flux calculated at several mean free paths from the source. We

FIGURE 6. Angular Dependence of the 14 MeV Cross Section for ^{238}U

believe that the Legendre order in the calculations will have to be increased to near P_{19} before the cross section is everywhere positive.

In addition to use of the current cross sections, the use of smaller angles to model the angular quadrature may improve the calculation. This could be done by increasing the quadrature order or by using an asymmetric quadrature so that more angular intervals were placed in the forward peak.

In addition to the ^{238}U system referred to above, two lithium systems are also being analyzed. These analyses consist of P_3S_8 ANISN calculations for experiments^(4,5) consisting of spherical lithium assemblies and point 14 MeV neutron sources.

There is a substantial disagreement between experiment and calculated U-235/U-238 fission ratios for this assembly (~30%). The P_3 representation for lithium at 14 MeV also has a significant negative component in the forward direction. The P_9 representation, however, has only a slight negative component. This is expected since, the angular dependence is a function of the mass of the nuclide (less dependence for lower mass). Therefore, expansions at, or slightly greater than P_9 may be adequate for light elements.

This study was undertaken with two separate but related objectives. The prime objective was to provide insight in design of a minimum thickness shield and the convertor region for the TCT hybrid (see the Reactor Systems Section this report). Knowledge of how well the penetration of 14 MeV neutrons in these regions can be predicted is needed to factor this into the design analysis. The other more general objective was to determine the bias to be expected in calculated results from the use of simpler models currently used for design analysis. In conducting a design analysis, it is generally necessary to use simplifying assumptions to study a variety of conceptual design possibilities and to keep the cost within reason (i.e., survey situations). A simple means of compensating for the principal deficiency of the P_3 description for uranium by decreasing the self-scatter cross section was reasonably successful.⁽⁶⁾ This type of correction might also be applied to the P_0 description for heavy atoms, for use as a survey tool. The original need to develop such a procedure for use in design analysis and to evaluate the expected bias is still relevant because calculated results, using standard P_3 or P_5 cross-section models, continue to show poor agreement with measured values.

Ionization of atoms by low-energy ion bombardment is expected to be of importance in the development of fusion reactors. Ionization, particularly of impurity atoms and ions, may lead to the generation of plasma instabilities and provide an additional channel of energy loss. The following report describes work presently in progress at BNW in which differential ionization cross sections are being measured for incident charged particles with energies in the region of interest to controlled thermonuclear fusion.

*Ionization in Low-Energy Ion-Atom Collisions**

TL Criswell, LH Toburen

The earliest investigations of ionization treated the process in its simplest form where only the total probability of ionization of the target was determined. Theoretical calculations, usually performed using the Born Approximation and applying hydrogenic wave functions for the target particle, were found to be in relatively good agreement with these measured values of the total ionization cross section for incident ion energies greater than approximately 100 keV. A more stringent test of theory has been comparison with cross sections that have been measured as a function of the energy and angle of ejection of the ionized electron (doubly differential cross sections). This comparison has revealed large discrepancies between calculated and measured differential cross sections. By improving the wave functions used in the theoretical calculations, excellent agreement can now be obtained between measured and calculated double-differential ionization cross sections for fast incident ions (proton energies of a few MeV and above). For incident proton energies from 50 keV to a few MeV there are still discrepancies for electron emission into small angles and below 50 keV there have been no data, theoretical or experimental. It is this low energy region (a few hundred eV to a 100 keV) that detailed information on the ionization process is needed most and where we have placed major emphasis on making cross section measurements.

Ionization cross sections, differential in ionized electron energy and emission angle, have recently been measured for both H^+ and H_2^+ ions for energies from 5 to 50 keV. These initial double-differential electron ejection cross section measurements for low energy ion impact have been carried out for ionization of argon. Argon was chosen as a target for our initial study since it can be analyzed theoretically with a reasonable degree of confidence using reliable wave function for initial-discrete and final-continuum states. In particular, the 3p to continuum-d ionization channel is sensitive

* Studies funded by Battelle Memorial Institute.
Report published in BMI Research Futures, December 1975. (7)

to the wave functions used and use of a full Hartree-Fock calculation for this channel leads to a more complete test of theory. A number of autoionization lines are observed which also provide information on the ionization process. Understanding the excitation functions for autoionization is particularly important as this effect contributes to a large fraction of the ionization produced in slow ion collisions.

A schematic drawing of the basic experimental system is shown in Figure 7. Protons and molecular hydrogen ions are produced in an r-f discharge in hydrogen gas. These ions are accelerated, focused and magnetically analyzed to provide the proper ion at the interaction region. The interaction region is formed by the intersection of the ion beam with a collimated gas beam. The gas beam has a density corresponding to a gas pressure of approximately 2×10^{-4} torr. The target gas is localized over an ion path length of about 2 cm with the rest of the chamber pumped to a vacuum of from 2 to 5×10^{-5} torr. At these pressures, single collision conditions will prevail in the interaction region.

The yield of ionized electrons was measured as a function of electron energy using a cylindrical mirror electrostatic energy analyzer (EEA). Effects due to stray electric and magnetic fields were minimized using standard techniques. The effective gas density in the interaction region was determined by measuring the yield of electrons due to ionization by 1 MeV protons and comparing the results to previous absolute cross section measurements made using a differentially pumped gas cell of known gas density distribution. This comparison yields an absolute calibration factor for each detector angle that accounts for all geometrical and instrumental effects. The resulting cross sections are accurate to $\pm 20\%$ for electron energies greater than 6 eV.

FIGURE 7. The Basic Experimental Apparatus: (A collimated proton (or H_2^+) beam passes through a diffuse target gas and is collected in a Faraday cup. The ejected electrons are electrostatically analyzed and detected by a channel-electron-multiplier. The data is analyzed and stored by an on-line computer.)

Direct and Autoionization

The general features of direct ionization and autoionization due to slow, heavy ion bombardment can be seen in a representative set of measured cross sections shown in Figure 8. Yields versus ejected electron energy are normally measured at 13 angles from 30 to 145°. The smooth continua are due to the direct ionization of loosely bound outer electrons. This direct ionization cross section rises rapidly to a maximum at an electron energy of approximately 3 eV and then goes approximately as the inverse of the ejected electron energy. The angular dependence of the emission cross sections exhibits a maximum in the forward direction. These features are generally understood and predictable in a qualitative way. The large structures below 16 eV electron energy are due to autoionization.

Though autoionization was first observed in 1926, an accurate description of autoionization following heavy particle bombardment has yet to be developed. The fundamental difficulty is the inability to predict the excitation probabilities to states leading to autoionization transitions.

FIGURE 8. Representative Set of Measured Cross Sections Showing the General Features of Direct Ionization and Autoionization Due to Slow, Heavy Ion Bombardment. (The continua is due to direct ionization. The large structures below 16 eV are due to autoionization.)

Comparison of Data

In Figure 9 we compare the data to theory keeping in mind that theoretical cross sections for low proton velocities are very difficult to calculate and of questionable reliability. The only manageable theory is the plasma-wave Born approximation (PWBA). However, at these low proton energies (5 to 50 keV), the validity of the Born approximation is undetermined. The PWBA is very dependent on the final state wave functions when the outgoing electron has low energy, as is the case here. The recent calculation by Manson⁽⁸⁾ using Hartree-Fock wave functions for these sensitive outgoing final states is the best theory available. Figure 9 shows a comparison of Manson's calculation to our results and to the 50 keV data of Crooks and Rudd.⁽⁹⁾ Agreement with theory is surprisingly good, particularly in the forward angle where not only the shape but also the magnitudes of theory and experiment are close. The comparison for large angles of emission is not so close. The magnitude on the whole disagrees by only a factor of two, but the shapes disagree significantly. During recent discussion between the authors and Manson, it was speculated that the source of disagreement may lie in the method of numerical integration used in the calculation. This comparison of data to theory is then indicating the direction for improvements in the existing theory of ionization by slow, heavy ions and marks a new lower bound for the general validity of the PWBA.

FIGURE 9. Comparison of Theory with Experiment. (This comparison reveals surprisingly good agreement for the forward angle, whereas the shape of the predicted cross sections at the back angle differs significantly. This comparison marks a new lower bound for the general validity of the plane-wave Born approximation.)

The cross sections for the production of autoionizing transitions due to heavy particle bombardment are not yet known either through theoretical calculation or experiment. Figure 10 shows a comparison of the autoionization lines of argon due to the bombardment by two different projectiles, H^+ and H_2^+ having equal total charge and velocity. The spectra have many peaks in common, but the relative intensities of these lines differ for the different projectiles and for different velocities of the same projectile. A clearer demonstration of the velocity dependence of the relative intensities is found in Figure 11. Note in particular the peak emerging at 7 eV as the H_2^+ energy increases while the peaks at 15 eV decrease. However, a detailed analysis of the data cannot be made for two reasons: First, the complex overlapping of the spectral lines do not allow for the determination of absolute intensities of individual lines; and second, the large number of excited states produced cannot be identified on the basis of ejected electron energy alone. However, three important trends can be seen in these spectra. First there is a strong dependence of the particular lines produced on the structure of the projectile. Second, an increasing fraction of the total number of ionized electrons is due to autoionization for decreasing projectile energies. Third, the fractional ionization due to autoionization appears to maximize at 10 keV for H_2^+ , and may be inferred to peak at an equal velocity for H^+ .

FIGURE 10. The Autoionization Spectrum of Argon Is Dependent on the Structure and Velocity of the Projectile. (Note that the autoionization electrons contribute a large fraction of the total number of ejected electrons.)

FIGURE 11. The Autoionization Cross Section Peaks at 10 keV. Since fusion reactors are anticipated to operate at this ion energy, the existence of this large energy loss mechanism might present an additional difficulty.

Conclusion

The direct ionization cross sections for 5 to 50 keV proton bombardment of Ar has been shown to disagree significantly with theory. The degree to which this disagreement can be reconciled is probably dependent on the accuracy of the numerical techniques used to determine and apply the final-continuum states of ionization.

The strong contribution of autoionization to the total ionization is the most striking result of this study. We have seen that as much as a quarter of the total energy lost to ionization goes into this channel for an incident 5 keV proton. If autoionization is equally important in other target atoms at low, ion energies, these results may have profound implications. For example, the peaking of the autoionization contribution at 10 keV for H_2^+ might have particular bearing on the fusion process since it is at just

this energy that ignition of the thermonuclear reaction needs to start. The presence of an additional ionization mechanism at 10 keV ion energy could have a great effect on the design of the reactor and necessitates further studies of ion-induced auto-ionization.

The hoped-for improvements in theory motivated by this and future experiments will be of importance to those modeling ionization mechanisms in fusion reactors.

TRITIUM TECHNOLOGY

Lithium or lithium compounds will be used for the breeding of tritium in early-generation fusion reactors. Lithium aluminate is used in some conceptual designs for tritium production but designers lack essential information regarding this method. Technology developed for tritium production in fission reactors was classified because of its relation to the weapons program. Work is continuing to identify, extract and document on an unclassified basis the information pertinent to fusion reactor technology.

Survey of Hanford Coproduct Literature

AB Johnson, Jr., TJ Kabele

Lithium aluminate has been the specified blanket material in some CTR conceptual designs.^(10,11) In the mid 1960's, tritium was produced on a relatively large scale in the Hanford N Reactor under the so-called Coproduct Program, using lithium aluminate and lithium silicate targets. Recently essentially all of the information was declassified. The purpose of this task is to review the declassified and unclassified documentation, to extract information which includes: the chemistry of lithium aluminate and lithium silicate production; target fabrication techniques; physical and chemical properties of unirradiated and irradiated targets; tritium and helium release characteristics from the irradiated targets; the neutronic aspects of tritium production in the solid targets.

Publication of two declassified reports is underway. The reports deal with tritium extraction from irradiated lithium aluminate targets.

A. B. Johnson, Jr., "Tritium Release from Lithium Silicate and Lithium Aluminate, In-Reactor and Out-of-Reactor," BNWL-CC-337, November 1965.

W. H. Yunker, W. O. Greenhalgh, J. R. Lundquist, et al., "Co-Product Extraction Studies on N Reactor PT-NR-57 Target Materials - Interim Report," BNWL-CC-558, April 15, 1966.

Approximately 20 classified and declassified reports from the Coproduct Program have been received from the library and information is being extracted on the topic indicated above.

The program goal is to complete the review of pertinent information and publish a formal report by July 1, 1976.

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MATERIALS RESEARCH AND RADIATION ENVIRONMENT SIMULATION

The effect the plasma-surface or radiation-surface interactions will have on the surfaces of the fusion reactor are being studied. The correlation and evaluation of the neutron sputtering and radioactive recoil emission results are nearly complete. Included in these analyses is an estimate of the effects these phenomena may have upon future CTRs. In addition, instrumentation is being tested for polychromatic ion blistering experiments.

An interlaboratory meeting was held to compare and summarize the results of an experiment to analyze the microstructure of ion bombarded molybdenum. A standard form for reporting the irradiation and experimental variables, as well as the data, is being reviewed. The effect of concurrent helium bombardment on void formation in ion bombarded nickel is being studied. There is some evidence of the strong effect of helium in promoting void nucleation.

A topical report has been issued which summarizes some of the mechanical property data needs for CTRs, the status of ion simulation for mechanical properties, damage analysis and sample heating with light ions, and sample size and surface considerations for ion irradiation mechanical property test specimens.

The first of three subassemblies containing graphite cloth and graphite fibers was discharged from EBR-II after a neutron fluence of about $3 \times 10^{21} \text{ cm}^{-2}$ at $\sim 500^\circ\text{C}$. Preliminary visual examinations indicate that fibers in each of the cloth samples have shrunk about 8% in the axial direction. Samples of stress-annealed pyrolytic graphite have been irradiated in the RTNS as part of a program to determine the correlation between damage production rates in fission and fusion reactor spectra. Thermodynamic data indicate that carbon may not be compatible with some tritium breeder and neutron multiplier materials.

Five alloys (321 SS, Incoloy, 316 SS, 347 SS and Croloy) were exposed to helium to characterize the degradation of near-term CTR structural materials. Tests were designed to determine the effects of oxidation potential on low level contaminant/metal interactions. Helium effects on the mechanical properties of niobium and vanadium were studied after injection of helium by the tritium trick method.

A technique for evaluating dielectric breakdown via the monitoring of acoustic emissions (A.E.) from electrically stressed solid insulator materials has been developed.

The data indicates that the acoustic emissions which emanate from a material in the presence of high voltage potentials are a precursor indication of impending catastrophic electrical breakdown. A detailed analysis of the individual acoustic events may provide a means for determining various mechanisms of dielectric failure. An advanced state-of-the-art Acoustics Emissions Event Energy Analyzer (AEEEA) has been developed and tested. The AEEEA is an instrument that will analyze individual sinusoidal acoustic emission burst (up to 36 kHz rate) in terms of energy and pulse width. This type of information may provide a further understanding of the mechanisms of electrical failure in insulators.

The generation of dc electrical resistivity data on BeO, Al_2O_3 and selected sputtered deposited samples of SiO_2 is continuing and evaluation of techniques to measure the ac resistivity of insulators is in progress.

The surfaces of the primary plasma containment structure of the CTRs will be exposed to high fluxes and fluences of energetic ions, photons, neutrons, neutral particles and electrons. These radiations will damage the surface and the near surface regions of the first wall structures. The fast neutrons will produce bulk damage and because of their penetration, they may adversely affect the surfaces in many ducts and cooling channels which are likely to be present in the CTR blanket structures. Surface and near surface damage will include sputtering and blistering. This will cause erosion and weakening of the CTR walls and some of the sputtered heavy atoms entering the plasma may cause a loss in plasma energy.

Surface Effects

OK Harling, MT Thomas, RL Brodzinski,
DL Styris, LA Rancitelli

The objective of this work is to determine the effects of the primary plasma and associated radiations and emission, upon the surfaces of the fusion reactor. The plasma contamination from impurities due to plasma-surface or radiation-surface interactions may weaken the first wall structures. Intense high energy neutron fields can produce radioactive species which are ejected from the surfaces of first wall structures.

Correlation and evaluation of neutron sputtering results and radioactive recoil sputtering ratios, was a major part of the effort during this quarter. Results from a total of 7 neutron irradiations and a large number of targets were integrated. Detailed summary publications of results to date are in advanced stages of preparation. Figure 12 shows an example of these results. This figure presents the radioactive recoil sputtering ratios for forward emission from a variety of metal targets irradiated normal to the surface with 14.8 MeV neutrons.

Development and testing of the ion blistering apparatus proceeded satisfactorily. A differential pumping stage to permit operation of the sample under UHV conditions and to decouple the irradiation chamber from the Van de Graaff vacuum, was designed, built and installed.

The Neutron Sputtering Round Robin Interim Reports from all participating laboratories were coordinated. The Round Robin experiment appears to be on schedule.

FIGURE 12: Summary of Neutron Sputtering Results

Several papers were presented on neutron sputtering, radioactive recoil emissions and the implications of these phenomena for CTR. Two of these papers were given at the 22nd National Vacuum Symposium in October and an invited paper was presented at the American Nuclear Society Winter Meeting in November.

STRUCTURAL DAMAGE CHARACTERIZATION

The objective of this work is to characterize radiation induced structural damage in potential CTR first wall materials. The investigation is specifically directed at determining the nature of displacement damage at high dose by heavy ion bombardment. The evaluation of the effect of parameters uniquely associated with ion bombardment is continuing to more thoroughly understand the ion simulation technique and make better correlation with neutron irradiation.

BCC Ion Correlation Experiment

JL Brimhall, ER Bradley

The interlaboratory ion correlation experiment developed to compare the microstructures of a standard material irradiated with various ions at different laboratories is under-way. Laboratories participating in the experiment are Pacific Northwest Laboratory, University of Wisconsin, Massachusetts Institute of Technology, Atomics International, Naval Research Laboratory, and Argonne National Laboratory/University of Cincinnati. For the experiment, molybdenum from a common source was distributed to the laboratories for ion bombardment and analysis of the microstructure.

Analysis of the molybdenum specimens irradiated by PNL for inclusion in the initial BCC ion correlation experiment is complete. The specimens were irradiated with 5 MeV Ni^{++} ions at temperatures of 800°, 900°, and 1000°C, to a total calculated dose of either 2 or 20 dpa. Two dose rates, $\sim 3 \times 10^{-3}$ dpa/sec, and $\sim 1 \times 10^{-2}$ dpa/sec, were used in the irradiations. At the high dose rate, specimens were irradiated at all of the various combinations of temperature and dose levels whereas at the low dose rate, specimens were not irradiated to a dose of 2 dpa at 800° or at 1000°C. The irradiation induced microstructures were examined by TEM at a nominal depth of 5000 Å below the bombarded surfaces.

Voids were observed in all of the irradiated specimens. The void parameters for the low and high dose rate specimens are given in Tables 9 and 10, respectively. These data can be summarized as follows:

- 1) At constant dose and dose rate, the void size increases with increasing irradiation temperature between 800° and 900°C and remains constant between 900° and 1000°C.
- 2) At constant dose and dose rate, the void density increases with increasing irradiation temperature. The low dose rate specimen irradiated at 1000°C is the only exception to this general trend.

- 3) With the exception of the low dose rate specimen irradiated at 1000°C, the void volume fraction increases with increasing temperature at constant dose and dose rate.
- 4) The void density appears to be saturated at a dose level of ~2 dpa.
- 5) The void volume fraction increases with increasing dose at constant temperature and dose rate.

The anomalous behavior exhibited by the low dose rate specimen irradiated at 1000°C is believed to be associated with the formation of rod- or ruler-shaped precipitates. These precipitates have not been identified but similar precipitates observed in other low dose rate experiments have been tentatively identified as Mo₂C. Work is continuing on positive identification of these precipitates as well as establishing the irradiation conditions under which they form.

The dislocation structures in the specimens consist of both loops and a dislocation network. In general, the loop size increases while both the loop and line density decreases with increasing irradiation temperature. However, the dislocation loop parameters depend upon the order in which the specimens are irradiated. This indicates that postirradiation annealing influences the observed dislocation structures, thereby preventing meaningful quantitative analysis of the data. The void parameters are not significantly affected by the postirradiation annealing as evidenced by the relatively good agreement in the void parameters between duplicate specimens (Tables 9 and 10).

TABLE 9. Void Parameters for Low Dose Rate Specimens -
Dose Rate ~3 x 10⁻³ dpa/sec

Temperature °C	Dose (a) dpa	Size $\bar{d}$ (Å)	Standard Deviation s (Å)	Void Density (cm ⁻³)	$\Delta V/V$ (%) (b)	Void Lattice Parameters (Å)
900	2	34	10	9.3×10^{16}	0.47	-
800	19	44	17	5.1×10^{16}	0.65	-
900	18	53	23	8.9×10^{16}	2.22	350
900	21	55	25	6.6×10^{16}	1.8	350
1000	21	53	20	2.1×10^{16}	0.45	380

a. Calculated at region of examination.

b. $\frac{\Delta V}{V}(\%) = 100 \left[\frac{\sum_i N_i \bar{d}_i^3}{\sum_i N_i} \right] \times \text{void density}.$

TABLE 10. Void Parameters for High Dose Rate Specimens -
Dose Rate $\sim 1 \times 10^{-2}$ dpa/sec

Temperature °C	Dose (a) dpa	Void Size (Å)	Standard Deviation s (Å)	Void Density (cm ⁻³)	$\Delta V/V(\%)$ (b)	Void Lattice Parameter (Å)
800	1.8	(c)				
800	2.0	(c)				
900	1.8	35	11	4.3×10^{16}	0.25	-
900	2.2	39	16	3.9×10^{16}	0.34	-
1000	1.9	36	12	8.7×10^{16}	0.48	
1000	1.9	40	17	1.1×10^{17}	0.96	400
800	18	(c)				
800	20	(c)				
900	22	63	20	5.4×10^{16}	1.9	340
900	18	66	23	4.5×10^{16}	1.8	
1000	22	65	25	7.6×10^{16}	3.2	400
1000	18	63	20	7.2×10^{16}	2.5	390

a. Calculated at region of examination.

b. $\frac{\Delta V}{V}(\%) = 100 \left[\frac{\sum_i N_i d_i^3}{\sum_i N_i} \right] \times \text{void density}.$

c. A low density of small voids $< 20^\circ \text{Å}$ was observed.

A meeting of the participants of the correlation experiment was held in Chicago, November 3, 1975, and the available data from the initial experiment were presented and compared. A summary of the results for the standard experimental temperature (900°C) are given in Table 11. Reasonable agreement exists in the void size and void density between the PNL and NRL data and also between the AI and the University of Wisconsin data. The first group shows a smaller void size and a higher void density than the second group. The differences between the two groups of data may be associated with the differences in dose rate. However, there are insufficient data to differentiate between dose rate effects and other possible effects such as the type and energy of the bombarding ion or the depth of observation in the foil. The University of Wisconsin will attempt to increase the dose rate of the 18 MeV Cu⁴⁺ ions and thereby establish data on those effects.

TABLE 11. Summary of the 900°C Data Presented at the BCC Ion Correlation Meeting

Site	Ion	Dose (dpa)	Dose Rate (dpa/sec)	Void Size (Å)	Void Density (cm ⁻³)	ΔV/V (%)	Void Lattice (Å)	Loop Size (Å)	Loop Density (cm ⁻³)	Total Line Density (cm/cm ⁻³)
PNL	5 MeV Ni ⁺⁺	2	3 x 10 ⁻³	34	9.3 x 10 ¹⁶	0.47	-	340	9.3 x 10 ¹³	3.8 x 10 ⁹
		20	3 x 10 ⁻³	54	~8 x 10 ¹⁶	2.0	350	350	1.8 x 10 ¹³	5.6 x 10 ⁹
NRL	3.2 MeV Mo ⁺	2	2.5 x 10 ⁻³	40	8.2 x 10 ¹⁶	0.34	-	(a)	(a)	6.8 x 10 ¹⁰
		20	2.5 x 10 ⁻³	80	5.8 x 10 ¹⁶	2.07	350	(a)	(a)	5.4 x 10 ¹⁰
U WIS	18.7 MeV Cu ⁴⁺	1.0	5 x 10 ⁻⁴	80	5 x 10 ¹⁵	0.13	-	(b)	(b)	5 x 10 ⁹
	17 MeV Cu ⁴⁺	2.1	4 x 10 ⁻⁴	100	5.1 x 10 ¹⁵	0.27	-	(a)	(a)	(a)
AI	0.5 MeV H ⁺	3	2 x 10 ⁻⁴	140	6 x 10 ¹⁵	1.2	Not Observed	(a)	(a)	(a)
PNL	5 MeV Ni	2	1 x 10 ⁻²	37	4 x 10 ¹⁶	0.3	-	165	3.8 x 10 ¹⁴	8.7 x 10 ⁹
		20	1 x 10 ⁻²	64	5 x 10 ¹⁶	1.85	340	270	2.6 x 10 ¹³	6 x 10 ⁹

a. Not reported.

b. None observed or very low density.

From the discussion at the meeting, a standard form for reporting the important irradiation and experimental variables, as well as the data, was developed. A data sheet which includes the variables and parameters discussed has been prepared and distributed to the participants for review and comments.

Two additional experiments were also planned at the meeting. In the first experiment, identical micrographs (provided by NRL) will be distributed to each of the participating sites for measurement of the void size and density. From these data, the variation in void parameters due solely to differences in the measuring techniques will be established. For the second experiment, each site will examine the same electron microscope specimen (also provided by NRL) and measure the void size and density. This experiment will indicate the amount of scatter to be expected in experimental data from different laboratories and will provide a basis for determining what constitutes meaningful differences in the data from the correlation program. Oak Ridge National Laboratory is also participating in these experiments.

*Effect of Helium on Void Nucleation**

JL Brimhall, EP Simonen

The effect of concurrent helium bombardment on void formation in ion bombarded nickel is presently under investigation. Nickel foils have been simultaneously bombarded with 5 MeV Ni⁺⁺ ions and 200 keV He⁺ ions under condition of constant Ni ion dose rate but

* Sponsored by the Division of Physical Research.

different He ion rates. The rate of helium deposition has been varied from 5.5×10^{-9} atom fraction/sec to 7×10^{-7} atom fraction/sec. The effect on the void parameters for a constant heavy ion dose and dose rate are given in Table 12.

TABLE 12. Void Parameters in Nickel Simultaneously Bombarded with Ni^{++} and He^+ Ions. (a)

Helium Deposition Rate (atom frac/sec)	Void dia (Å)	Void Concentration (cm^{-3})	Volume Fraction (%)
none	~200	$\sim 10^{12} - 10^{13}$	inhomogeneous distribution
5.5×10^{-9}	313	2.8×10^{13}	0.05
2.9×10^{-8}	214	1.5×10^{14}	0.08
1.5×10^{-7}	128	7×10^{14}	0.08
7×10^{-7}	60	2.7×10^{15}	0.04

a. Ni^{++} dose rate = 3×10^{-3} dpa/sec, Dose = 1 dpa, Temp = 575°C .

These preliminary results show a direct correlation between the void concentration and helium deposition rate. This is clear evidence of the strong effect of helium in promoting void nucleation. The volume fraction remains relatively constant because of the decrease in void size with the increase in void concentration. This work is continuing and the comparison of the effect of He under conditions of simultaneous injection and preinjection is currently being studied.

Radiation Simulation - Mechanical Properties

RH Jones, DL Styris, OK Harling,
RP Marshall

The first year of this program was devoted to reviewing the mechanical property data needs for CTR designs, the potential of ion simulation to fulfill these needs, and experimental planning. The first half of the second year has been devoted to apparatus design, construction, testing and sample preparation and testing techniques.

The following tasks were completed this quarter: 1) final draft of a topical report entitled: "Some Experimental Considerations Regarding Ion Beam Simulation of Neutron Irradiation for Mechanical Property Measurements;"⁽¹²⁾ 2) final design of ion irradiation chamber sent out for bid; 3) components for ion irradiation apparatus itemized and priced; 4) techniques for producing and measuring 0.127 mm (0.005 in.) diameter gauge

section in 0.254 mm (0.010 in.) diameter wire developed; 5) wire grips designed and built and strain gauge techniques developed; 6) grain size/annealing experiments of 0.127 mm (0.005 in.) and 0.254 mm (0.010 in.) diameter nickel wire completed; 7) preliminary tensile tests on nickel wire completed; 8) and nickel and niobium wire and foil packets assembled for delivery to Lawrence Livermore Laboratory for 14 MeV irradiation in the RTNS.

The topical report summarizes some of the mechanical property data needs for CTRs, the status of ion simulation for mechanical properties, damage analysis and sample heating with light ions, and sample size and surface considerations for ion irradiation mechanical property test specimens. It has been determined from annealing experiments that a stable grain size of 0.1 mm results from annealing temperatures above 400°C and times greater than 2 hours. A uniform grain size of 0.07 mm resulted from a 2-hour anneal at 600°C; however, this grain size would be unstable for irradiation temperatures above 400°C. Some tensile properties of 0.254 mm (0.010 in.) diameter nickel wire with a 0.127 mm (0.005 in.) gauge diameter are given in Table 13. These results demonstrate that the measurement of the yield strength of these small samples is reproducible. The variability in the ultimate tensile strength (UTS) and the total elongation is expected to decrease when more samples are tested because the scatter was caused by one sample. Further experiments are also required to determine the cause of the high yield strength values. Some possibilities are: 1) hydrogen absorption during electropolishing the gauge section; 2) oxygen, nitrogen contamination during annealing; 3) texture strengthening; 4) or size effects.

TABLE 13. Tensile Properties of 0.254 mm (0.010 in.) Diameter Nickel Wire with a 0.127 mm (0.005 in.) Gauge Diameter Annealed at 550°C

Sample Number	ys Load, gm	ys, psi avg dia	ys, psi min dia	$\left(\frac{d\sigma}{de}\right)$ 0.01, psi	UTS, psi	ϵ_T , %
A551	470	24,400	25,900	122,000	32,300	10
A552	500	23,100	24,900	110,000	37,900	19
A553	555	22,700	24,900	97,600	36,100	19
Average		23,400	25,200	110,000	35,400	16
% Difference		7	4	23	16	56

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: behavior of graphite and electrical insulators in fusion reactor environments, mechanical properties of candidate materials and helium embrittlement effects.

Evaluation of Carbons and Graphites for Controlled Thermonuclear Reactor Applications

WJ Gray, WC Morgan, GL Tingey

Many CTR concepts specify graphite in the blanket or shield regions. Some concepts^(13,14,15) have suggested the use of graphite or graphite cloth between the plasma and first structural wall. In some concepts, lithium and/or beryllium bearing compounds would be placed in the graphite region to improve the tritium breeding ratio. Location of the graphite inside the vacuum wall and adjacent to the plasma requires the assessment of several unknowns. Some of the areas currently being investigated include:

- Evaluation of radiation damage effects in cloths and fibers since no data currently exist for these materials above about 1×10^{21} EFF.*
- 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.
- Evaluation of lithium and/or beryllium bearing compounds for use within the graphite regions.
- 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.

Radiation Effects

Three different subassemblies containing specimens of graphite cloth and graphite fibers were charged into EBR-II in May 1975 for irradiation at about 500°C. The first subassembly was discharged in September 1975, after a fluence of about 3×10^{21} EFF. The other two subassemblies will be discharged about May 1976, after fluences of about 6 and 9×10^{21} EFF, respectively.

* All fluences are quoted in terms of "Equivalent Fission Fluence for Damage in Graphite."⁽¹⁶⁾

Only a preliminary visual postirradiation examination of specimens from the first sub-assembly has been made. Figure 13 shows photographs of one piece of cloth before and after irradiation. Little difference can be seen, except for some fraying around the edges, caused by handling. The magnification is slightly different in the two photographs, and when this is accounted for, the disc diameter is about 8% smaller after irradiation. This appears to indicate an 8% shrinkage of the fibers in the axial direction. Some of this apparent shrinkage could be due to increased curvature of the fibers but there is no evidence for this. It is not possible to determine from these photographs whether there are any dimensional changes in the radial direction of the fibers.

FIGURE 13. Carborundum Graphite Cloth, GSGC-2

Similar examinations of the other three types of cloth lead to much the same conclusions, except that the fibers in one of the materials appear to have become somewhat kinky. Detailed postirradiation examination of the cloths and fibers will begin January 1976, and will include measurements of density, surface area, and outgassing characteristics as well as more precise dimensional-change measurements.

The approximate 8% shrinkage of the fibers is to be compared with a shrinkage of about 1% for many nuclear graphites under the same conditions of temperature and fluence. While data at higher fluences and temperatures are needed, it seems probable from these preliminary data that allowance for a large amount of shrinkage will have to be made if graphite cloth is to be used as a curtain material in fusion reactors.

Damage Production Rates

Relative atomic displacement rates in different neutron spectra can be determined by irradiating samples of stress-annealed pyrolytic graphite in various high-energy neutron sources and by ultrasonically measuring the relative changes in elastic modulus. Modulus changes of samples irradiated to a maximum fluence of $\sim 10^{16}$ EFF in the RTNS at LLL, however, were not as large as expected. Therefore, a second set of samples is being irradiated to a maximum fluence of $\sim 10^{17}$ EFF in the RTNS. Because of a recent breakdown of the RTNS, however, modulus measurements on these samples will be delayed.

Possible Reactions

Abdou et al.⁽¹⁷⁾ found LiAlO_2 and Be to be the most promising solid breeder and multiplier materials, although Li_4SiO_4 , BeO , and Be_2C also appear to have potential. We have considered possible reactions of the above oxides with carbon using thermodynamic data from the JANAF tables.⁽¹⁸⁾ Li_2SiO_3 was considered because thermodynamic data for Li_4SiO_4 are not available. Although it seems unlikely that the conclusions would be significantly different, this should be verified.

A large number of reactions which produce CO or CO_2 were considered. (The lithium compounds also tend to dissociate slightly, which leads to loss of Li_2O vapor at the higher temperatures as pointed out by Abdou et al.).⁽¹⁷⁾ Arrhenius plots for those reactions found to give the highest gas pressures are shown in Figure 14. Even at temperatures of 1000°C or less, the equilibrium CO pressure is significant, and if the CO is allowed to escape, the reaction could proceed. Thus, a need for a study of the reaction kinetics is established, since thermodynamics show only that there will be problems if equilibrium is achieved.

FIGURE 14. Equilibrium CO Pressure for the Reactions Listed

Helium Compatibility with Fusion Reactor Materials

DG Atteridge, AB Johnson, Jr., RF Maness, DR Pratt, RE Westerman

The objective of this study is to determine the compatibility of state-of-the-art and advanced CTR materials with helium at high temperatures. Helium, one of the principle candidates for the primary coolant in fusion reactor conceptual designs,^(10,11,19) has many desirable characteristics. As a coolant for fusion reactors, helium:

- operates in a single-phase thermal hydraulic regime
- is nonflammable and nontoxic
- is not activated by the neutron flux
- does not interact with the magnetic field

- does not transport large volumes of radioactive corrosion products due to solubility effects, and
- offers the prospect of a direct power cycle using gas turbines.

The best attainable helium purity is not good enough to totally prevent contaminant/metal corrosion reactions at elevated temperatures. This study was initiated to determine the effect of low contaminant level, high pressure, high temperature helium on the mechanical and corrosion properties of near-term CTR structural materials. The program consists of exposing five alloys to helium at 650°C and 300 psi in two autoclaves. The oxidation potential of the helium in one autoclave was to be maintained at a relatively high level through the addition of 50 vppm O_2 , while the oxidation potential of the environment in a second autoclave was to be maintained at a relatively low oxidation level through the addition of 50 vppm H_2O .

The tests were designed to determine the effect of oxidation potential on low level contaminant/metal interactions. The low oxidation potential test essentially simulates a system where inleakage from the steam side of the heat exchanger contributes the major contaminant species; the high oxidation potential test simulates the effects of air contamination or oxygen additions for tritium recovery purposes.

The initial runs in both autoclaves indicate that, at least initially, the 50 ppm contaminant levels are "swamped out" by a large water/hydrogen outgassing phenomenon. The system outgassing lasted for the first several days under gas flow conditions when the gas test volume was completely replaced in the range of 1/2 to 2 hours. The effect occurred in both runs completed with H_2O additions and in the single run completed with O_2 additions. The high contaminant levels (up to 800 vppm H_2) that occurred in the ceramic autoclave system, in all startups in the metal PNL ATR Model loop, and in other contaminant studies in the literature, indicate this outgassing problem is relatively common.

Outgassing of residual hydrogen from the metal specimens and holders does not appear to explain the repeatability of the outgassing. Rather, the outgassing appears to result from moisture adsorption on the oxides on the specimens and holders, or from adsorption of moisture on the ceramic furnace tube. Similar outgassing in the ATR model loop occurred despite measures to minimize moisture adsorption in the loop. A study to determine system outgassing characteristics is currently underway.

These observations have implications to fusion reactor systems, where there are incentives to minimize hydrogen contamination of the tritium and to avoid swamping the tritium adsorption system in the helium primary coolant. To better define the outgassing phenomena, effort is underway to separate system and metal outgassing contributions

along with outgassing temperature dependence. It is anticipated that the observations will result in recommendations for fusion reactor startup procedures which minimize hydrogenous contaminants.

The specimens exposed in H₂O-contaminated helium have now accumulated 900 exposure hours during which tests were conducted to determine the effect of consecutive startups on the initial contamination levels. Continuation of the specimens' exposure in O₂ is being delayed until a practical low-contamination level startup procedure is developed. Unexposed specimens of all alloys present in the test will be added when the O₂ test is resumed.

Current results show definite trends between individual alloys. The four high-alloy steels are ranked below in order of increasing weight gain after exposure for 900 hours in H₂O-contaminated helium:

Increasing weight gain	↑	321 SS (Ti-stabilized)
		Incoloy 800
		347 SS (Nb/Ta-stabilized)
		316 SS

This general weight gain trend was present in both autoclaves. Weight losses occurred on Croloy specimens.

The yield strengths of the alloys decreased with increasing high temperature exposure. The yield strength decreases, after 900 hours in H₂O-contaminated helium, are:

Alloy	Percent Decreased in Yield Strength
321 SS (Ti-stabilized)	0
Incoloy	12
316 SS	15
347 SS (Nb/Ta-stabilized)	19
Croloy	30

Incoloy was the only alloy that showed a substantial decrease in notched toughness (~15% decrease after 900 hours in H₂O). The rest of the alloys had less than a 6% decrease in notched toughness. Trends in the change of yield strength will be obtained after longer exposures to determine whether the decreases in strength continue or whether they level off.

Helium Effects in CTR Materials Employing the Tritium Trick Method

DG Atteridge, AB Johnson, Jr., JF Remark, RE Westerman

The purpose of this program is to assess helium effects on the mechanical properties of CTR candidate structural materials. Helium induced mechanical degradation, resulting from helium formed during nuclear reactions between high energy fusion neutrons and matrix atoms, is expected to be one of the major controlling factors in first wall life. In this study, helium is injected into niobium and vanadium mechanical property specimens by tritium decay to ^3He (the so-called tritium trick).⁽²⁰⁾ The helium charging method was described in the previous quarterly report (BNWL-1939 1) and in reference 21.

The tensile specimens currently utilized in this study are commercial purity niobium and vanadium in the annealed and coldworked conditions. Tritium is charged into the metal at 450°C and the helium is allowed to accumulate by tritium decay at room temperature. The remaining tritium is removed by hot vacuum extraction after the desired helium concentration is achieved. The usual test conditions consist of a 30-minute soak at test temperature ($\leq$ one-half the melting point) prior to tensile test initiation.

The ^3He is born interstitially, because the recoil energy associated with tritium decay is insufficient to knock a matrix atom from its lattice site. The interstitial helium migrates through the lattice and interacts with structural defects in the matrix. Post-test TEM of selected specimens has revealed helium bubbles in the matrix, decorating dislocations, and at grain boundaries. High temperature anneal TEM specimens, along with the tensile specimens, are being used to study helium stability at high temperatures.

The adverse effects of helium on the ductility of annealed commercial purity niobium was reported earlier.⁽²²⁾ Niobium from the same melt, having ~35% cold work, was also charged with helium to investigate interactions between helium and the dislocations resulting from cold working. Changes in ductility with helium concentration are shown in Figure 15 compared with previous results for annealed niobium. The ductilities of coldworked specimens were lower than annealed specimens. The ductility of the cold-worked specimens was much less influenced by the presence of helium than the ductility of the annealed specimens.

Preliminary results regarding effects of helium on the ductility of annealed vanadium are shown in Figure 16. The uniform elongation remained relatively unchanged up to 170 appm helium and then decreased sharply between 170 and 270 appm helium. The sharp drop may correspond to a similar feature in the uniform elongation curve for annealed niobium (Figure 15), although the drop for niobium occurred at a higher helium concentration.

FIGURE 15. Decrease in Ductility with Increasing Helium Concentration-- Annealed and Coldworked Niobium, Tested at 1020°C

FIGURE 16. Ductility Changes with Increasing Helium Concentration-- Annealed Vanadium, Tested at 815°C

Other major accomplishments during this quarter are:

- 25 niobium and vanadium tensile specimens were machined.
- 3 zero-helium annealed niobium specimens were sent to LLL for initial creep parameter determinations in the first step of the joint PNL-LLL helium-effects creep study.
- 5 niobium specimens have been charged with tritium and are accumulating helium for the PNL-LLL creep study.
- Thin foil V-15Cr-5Ti tensile specimens charged with helium at PNL by the tritium trick, were tested at ANL. The results demonstrated that the tritium-charged helium gives essentially the same magnitude of helium embrittlement as helium charged by bombardment, at helium concentrations of 25 to 35 appm helium.

The successful production of engineering size tensile specimens containing up to 500 appm He implanted by tritium decay illustrates the feasibility and usefulness of this helium charging technique in bulk property helium effects studies. The present experimental results indicate that the presence of over 100 appm He does not significantly affect the short-time tensile properties of commercially pure annealed vanadium or niobium at $\sim 1/2 T_m$. This 100 appm helium concentration relates to over 2 years helium accumulation for either material in a first wall application.

Electrical Insulators for Controlled Thermonuclear Reactor Applications

JL Bates, JE Garnier

The various CTR concepts require the use of electrical insulators in various critical locations (e.g., first wall, implosion and compression coils of the Theta-Pinch Reactor; insulator baffles and neutral beam injector of the Tokamak Reactor; beam injector of the Mirror Reactor). Although the insulator requirements will vary among reactor designs and within each reactor, there is a need for a high temperature (800 to 1300°C) insulator which is electrically, thermally, and mechanically stable to the intense neutron, particle, gamma, and beta radiation, e.g., $\sim 10^{16}$ nv and $\sim 10^{23}$ nvt. The insulator will, in some uses, be required to withstand very high electrical potentials (>100 kV/cm) under cyclic thermal and irradiation conditions at these high temperatures. The objective of this program is to study and evaluate the electrical and related properties of potential electrical insulators for CTR application. The ultimate goal is to find or develop suitable electrical insulators which meet the varied requirements for CTR designs.

Work in this quarter has been directed towards the evaluation and continued development of a new technique for determining the modes of failure in and absolute value of the dielectric breakdown strength of insulators using acoustic emissions. Generation of dc electrical resistivity data on BeO and Al_2O_3 and selected samples of sputtered deposited SiO_2 is continuing. The evaluation of selected instrumentation for ac resistivity measurements is in progress.

Dielectric Breakdown Measurements

A new technique for determining the dielectric breakdown strength of insulator materials has been developed.⁽²³⁾ This technique consists of the monitoring of acoustic emissions (A.E.) from electrically stressed solid dielectric insulators.

Acoustic emissions are generated by energy released from dynamic processes occurring inside a material. When an electrical field is applied to a material, localized electrical discharges can occur at regions of enhanced electrical stress even though the average electrical field is below that required for complete breakdown. The occurrence and energy dissipated in these events can be difficult to detect by the usual methods of current and voltage monitoring, especially when high voltages are present. However, if a portion of energy released during these discharges is converted into mechanical energy, this would appear as pressure waves (A.E.) propagating through the sample medium. These pressure waves can be detected by a transducer that converts the mechanical waves into voltage pulses which can be detected⁽²⁴⁾ by standard A.E. techniques.* An analysis of these waves could then provide information on the processes involved which destroy the insulating capacity of the material.

Typical room temperature results obtained for polycrystalline samples of Al_2O_3 and BeO (99.9 and 99.5 purity, respectively) are shown in Figure 17 where the total cumulative A.E. event count and A.E. energy count are plotted versus applied voltage potential. The applied voltage was incremented in steps of 1 kV at 2 minute intervals. The threshold settings on the respective emission analyzers were adjusted above the level of background noise such that no false A.E. was detected over a prior period of 1 hour. An increasing number of event counts with increasing voltage potential occurs for both Al_2O_3 and BeO. The total A.E. energy count curve, however, increases faster than the event count curve, indicating an increase in acoustic emission energy as the voltage is increased. This may be attributed to the breakdown processes within the material transferring higher energy to the surrounding material medium with increasing voltage. Similar acoustic behavior was also observed on a sample of Al_2O_3 at a fixed high voltage potential with time as a variable.

* P. H. Hutton, J. F. Dawson and J. R. Skorpik, Personal Communication, PNL (May 1975).

FIGURE 17. Total A.E. Event and Event Energy Count Versus Applied dc Voltage

The acoustic behavior of Al_2O_3 is significantly different than of BeO . A larger number of prebreakdown A.E. counts occurs for Al_2O_3 than for BeO . However, the A.E. energy per event is less for Al_2O_3 than for BeO as evidenced by the differences in the signal patterns of typical acoustic events. The pattern of the acoustic data is consistent with the reported differences in the room temperature dc breakdown behavior for polycrystalline Al_2O_3 and BeO , which are intrinsic (electronic) and mainly thermal breakdown, respectively.⁽²⁵⁾ Thus, the characteristics of the acoustic signals may provide a means for readily distinguishing between various breakdown mechanisms in electrical insulators.

An Acoustic Emission Event Energy Analyzer (AEEEA) instrument was developed, constructed, and tested in this quarter.⁽²⁶⁾ The AEEEA is an instrument that will quantize sinusoidal bursts, such as those generated by acoustic emission transducers, in terms of energy ($\text{V}^2 \cdot \text{millisec}$) and pulse width (millisec). Figure 18a and 18b illustrate the type of information (energy and event width, respectively) that can be obtained. The capability to determine the energy per acoustic event will allow for a further elucidation of the observed differences in the A.E. energy count curves (obtained with the use of less informative A.E. instrumentation) as discussed previously.

Acoustic
Emission
Event
(2.0 V/cm)

Energy
Output =
 $6.1 \text{ V}^2 \cdot \text{msec}$

0.1 msec/cm →

FIGURE 18a. Acoustic Emission Event and AEEEA Energy Measurement

Acoustic
Emission
Event
(2.0 V/cm)

Event
Width =
0.33 msec

0.1 msec/cm →

FIGURE 18b. Acoustic Emission Event and AEEEA Event Width Measurement

Present work is directed towards the generation of room temperature dielectric breakdown data on the following insulators: polycrystalline-BeO, Al_2O_3 and $\text{Y}_2\text{O}_3\text{-Al}_2\text{O}_3$; single crystal - magnesium aluminate spinel ($\text{MgO: Al}_2\text{O}_3$; (111) orientation), white sapphire (Al_2O_3 - 90 degree orientation), and yttrium aluminum garnet ($\text{Y}_3\text{Al}_5\text{O}_{12}$; (111) orientation), and selected samples of sputtered deposited SiO_2 . In addition, adaption of the experimental system to allow the monitoring of A.E. under different applied high voltage potentials (<40 kV), e.g., ramp dc and burst dc is continuing.

Electrical Resistivity Measurements

The efforts in this quarter have been directed towards generation of dc electrical resistivity data on BeO, Al₂O₃ and selected samples of sputtered SiO₂, and evaluation of techniques to determine the ac resistivity of insulators.

Modifications to the experimental system were made to evaluate the potential use of a lock-in amplifier (Princeton Applied Research: model 124A with preamplifier model 117) used in conjunction with a current preamplifier to measure small changes in sample current with sample sinusoidal voltage potential variation. The currents in these sample insulators can vary from approximately 10^{-13} amp (20°C 100 V_{rms}) to 10^{-7} amp (1000°C, 10 V_{rms}). Due to the small currents and level of background noise involved, it is difficult to accurately determine changes in sample current, phase angle, etc. with changes in applied voltage potential.

Sputter-Deposition of Materials for CTR Application

R Wang, MA Bayne, RD Nelson

The objective of this program is to develop sputter-deposition technology to produce thick insulating coatings and explore the physical properties obtainable in such sputtered deposits. Progress during this quarter showed that structurally modified ceramics such as Al₂O₃ and SiO₂ can be prepared by a choice of different substrate temperature and heat treatment. High-temperature deposition is promising on a technique for preparing Al₂O₃ coatings.

Results Summary

Fine-grained α -Al₂O₃ coating (~20 μ m thick) was prepared by sputtering onto a hot Nb substrate (800°C). This coating was well bonded to the substrate. Structural characterization of four SiO₂ deposits by x-ray diffraction showed that sputtering onto room temperature substrate resulted in structurally modified SiO₂ deposits. After heat treating at 850°C, structure of the SiO₂ deposit approached that of the target SiO₂.

Technical Progress

This quarter's efforts were divided into two areas: 1) sputter-deposition of Al₂O₃ coatings and 2) characterization of SiO₂ deposits. Supported plasma rf deposition of Al₂O₃ was attempted with a 5-in. target made by a stack of thin Al₂O₃ plates. This target geometry did not yield satisfactory results since considerable arcing occurred during the deposition when the Al₂O₃ plates cracked.

The design of a small scale sputtering unit has been completed. This unit can use targets and substrates up to 3 inches in diameter. A substrate shutter and a substrate heater enable us to maintain a clean substrate surface and to reach temperatures to 800°C. Thus, for the first time, an Al_2O_3 coating (nearly 20 μm) was prepared on a Nb substrate held at 800°C. The Al_2O_3 deposit was well bonded to the Nb substrate. Microscopic examination of the coating at 800X showed no cracks or voids. The Al_2O_3 deposit has a white-gray appearance probably because no oxygen was introduced into the sputtering gas. X-ray diffraction results showed it is fine-grained $\alpha\text{-Al}_2\text{O}_3$ with grain size estimated between 0.5 and 2 μm . After heat treatment in air at 800°C for 3 hours, the Al_2O_3 deposit turned to nearly white. Attempts to produce fine grained $\gamma\text{-Al}_2\text{O}_3$ between 500 to 700°C by sputtering are underway.

Structural characterization of SiO_2 deposits by x-ray diffraction showed interesting results. A comparison of the x-ray diffraction patterns of four sputtered SiO_2 deposits and the fused SiO_2 target is given in Figure 19. All the SiO_2 deposits made to a room temperature substrate are amorphous. Compared with the diffraction pattern of the fused SiO_2 target, the SiO_2 deposits have broader diffraction peaks located at higher 2θ angles. The diffraction study indicates that some kind of structural modifications occurred in sputter-deposited SiO_2 at the atomic level. Thus, these SiO_2 deposits may exhibit different electrical properties and radiation effects compared to the fused SiO_2 . Since the diffraction pattern of a heat treated SiO_2 closely resembles the diffraction pattern of the target SiO_2 , sputter-deposition to a hot substrate may produce a SiO_2 deposit resembling the target SiO_2 .

Structural and microstructural characterization of Al_2O_3 and SiO_2 deposits will be continued for the next quarter with emphasis on the determination of the stoichiometry of the deposit.

FIGURE 19. X-ray Diffraction Patterns of High-Rate Sputter-Deposited SiO_2 (A, B, C, D) and the SiO_2 Target

*Superconductors for CTR Applications**

SD Dahlgren, R Wang

High-rate sputter deposition has been used successfully to produce high critical temperature (T_c), high critical current density (J_c) A-15 phase superconductors of compounds that are candidates for advanced generation fusion devices. A-15 compounds having very high critical magnetic fields will be needed for the advanced machines. The work has been largely research oriented, but the results show that it is feasible to produce tape, tubular, and possibly multifilamentary conductors. For example, 1/2-in. dia tubes were coated with up to 55 μm of Nb-Al-Ge superconductor for electrical power transmission line test samples. Additional work was conducted to coat microwave cavities with Nb_3Al superconductor which had a high critical temperature of 16.8°K. Furthermore, current density samples of Nb_3Al recently were prepared for J_c tests at Oak Ridge National Laboratory. Other work is being conducted to find higher T_c materials among the candidates Nb_3Ge and Nb_3Si , and extensive research was conducted to investigate the phase stability conditions for the A-15 phase in these two binary systems. Techniques for raising J_c by controlling microstructural grain size also are being investigated.

* Funded by the Division of Physical Research.

ENVIRONMENTAL EFFECTS

The identification of CTR environmental impacts early enough in the development program would permit a maximum emphasis on research and reactor designs to minimize those impacts. The CTR design concepts were analyzed to determine the probable interactions with the environment and the resultant environmental effects. Although results based on current technology indicate that the CTR should have a lower total environmental impact than fission power plants, adverse impacts may result from an increase in construction material usage, the presence of large magnetic fields, and increased employee radiation doses. Since commercial CTRs are not expected to operate for 40-50 years, future technical advances should lower these impacts. A draft document describing the analysis has been completed and distributed for comments by DCTR and a review committee prior to issue.

Results of studies on aquatic organisms have demonstrated that the response to tritium is not significant due to continued isotropic discrimination and rapid turnover rates. However, low levels of irradiation in fish reduce the serum proteins that are associated with antibody synthesis which lowers the natural immunity to disease. Any tritium routinely or accidentally released to the air during operation of a CTR would subsequently be removed by atmospheric processes. Concentration values at the surface water and ground-level were computed at a local, regional and global scale with concentrations estimated for routine and accidental releases during CTR operation.

Controlled Thermonuclear Reactor Environmental Analysis

JR Young

The first draft of the environmental analysis of the CTR development program has been completed and distributed for comments from DCTR and a national review committee. An objective of the review is to determine if the analysis should be directed toward an environmental assessment.

The analysis was made to estimate the possible environmental effects of the CTR power plants after acceptance for commercial use. CTR design concepts being developed were described and analyzed to determine the general types of interaction with the environment. The effects of these interactions were estimated by use of current technology. The analysis shows that the CTR has potential for lower total environmental effects than current fossil or fission power plants or than the estimated effects of fast breeder reactors. Since commercial CTRs are not expected to operate until the year 2010, future technical advances should result in even lower impacts.

Many years of development will be necessary before the designs of the first commercial CTRs are known and actual environmental effects can be estimated. During this development, methods may be identified that will reduce or eliminate some of the potentially adverse effects. The analysis focuses attention on areas which need study before designs can be engineered and on areas where alternate designs may be developed to prevent adverse impacts.

*SUBLETHAL EFFECTS OF TRITIUM IN AQUATIC SYSTEMS**

Research in the areas of tritium accumulation and effects in biological systems have been summarized in two reports released during the last quarter.^(27,28) Information on tritium in the environment is of interest because of increased application of nuclear energy, since greater quantities of potentially harmful radionuclides are available for release to the environment. This may be particularly true for advanced reactor designs such as CTR where radionuclides, principally tritium, are available in both gaseous and liquid effluents in quantities significantly greater than for present PWR and BWR designs.

A two part program has been developed to deal with both accumulation and incorporation of tritium, and the effects of tritium in aquatic systems.

Accumulation and Incorporation of Tritium in Aquatic Systems

JA Strand, WL Templeton, PA Olson

The objective of these investigations was to follow the uptake of tritium in the tissue-free-water and tissue-bound fractions of aquatic organisms in a simulated freshwater ecosystem. Tritium as tritiated water was introduced continuously for 8 months in replacement waters at a concentration of 1 $\mu\text{Ci/liter}$. At termination of the uptake phase of the experiment, additional data were sought on elimination of tritium from the ecosystem. Freshwater fish, clams, and crayfish served as principal test organisms as they represent sources of food utilized by man.

Results

The experimental results indicated that living organisms discriminated against tritium as opposed to protium in biosynthetic reactions. Early accumulation of tritium was found to be largely attributed to the more mobile HTO form, while final accumulation may have been influenced by the uptake of tritiated compounds as in the diet. Such results suggested that tritium may increase above the second trophic level of food chains in a classical way; however because of demonstrated continued isotopic discrimination and rapid turnover rates, this response should not be significant.

* Funded by the Division of Biomedical and Environmental Research, USERDA.

The objective of these studies was to yield definitive information on the effects of radiation on the expression of the primary immune process in a representative teleost. The primary immune process contributes substantially to immune competence in higher animals and is, therefore, a useful indicator of the degree of susceptibility or resistance of an animal to disease-causing microorganisms. In these studies, antibody synthesis in response to the fish pathogen, Flexibacter columnaris, was applied to investigate the effect of tritium irradiation (0, 0.04, 0.4, 4.0, 40.0 rads administered during the first 20 days of embryogenesis) on primary immune responsiveness in juvenile rainbow trout, Salmo gairdneri. Both serum agglutination assay and acrylamide gel electrophoresis were performed following vaccination.

Results

Specific antibodies to the pathogen, F. columnaris, increased rapidly in both control and tritium irradiated fish following vaccination. However, during the 9th and 11th weeks following vaccination, control fish demonstrated higher antibody concentrations, indicating suppression of the primary immune response in tritium irradiated fish. Antibody levels in irradiated fish were suppressed 50% of control levels at 40.0 rads during the 9th week, and 50% of control levels at 4.0 rads during the 11th week. Acrylamide gel electrophoresis demonstrated that three serum proteins were associated with antibody synthesis; and that these proteins were significantly reduced in irradiated vaccinated fish. These results suggest that the reduction of the serum proteins associated with antibody synthesis lowers the natural immunity to disease in fish that are subjected to low levels of irradiation.

An Analysis of Tritium Releases to the Atmosphere by a CTR

DS Renné, WF Sandusky, MT Dana

Removal by atmospheric processes of routinely and accidentally released tritium from a controlled thermonuclear reactor (CTR) has been investigated.⁽²⁹⁾ Based on previous studies, the assumed form of the tritium for this analysis was HTO, or tritiated water vapor. Assuming a CTR operation in Morris, Illinois, surface water and ground-level air concentration values of tritium were computed for three space (or time) scales: local (50 Km of a plant), regional (up to 1000 Km of the plant), and global.

Results of this analysis show that within 50 Km of the plant atmospheric concentrations of tritium will be the limiting factor for routine releases. On the regional and global scale, surface water concentrations tend to become the limiting factor. However, both air and surface water tritium concentrations are estimated to be below existing standards during normal commercial CTR operations.

An analysis for an accidental release of tritium shows surface water concentrations in the vicinity of the plant to be quite high after a rainfall. The analysis indicates that up to 0.1 kg of tritium could be released without concentrations in the environment exceeding currently accepted standards.

The model of worldwide atmospheric tritium transport was incorporated into a draft chapter entitled, "Transport in the Geosphere" for a forthcoming NCPR Task Group report on tritium sources and behavior by JK Soldat and DA Baker.

MANPOWER DEVELOPMENT

To develop a better understanding of fusion technology, graduate courses have been developed on plasma technology, energy conversion and materials characteristics. These courses will be a routine offering in the Nuclear Engineering curriculum at the Joint Center for Graduate Study at Richland, Washington.

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*Educational Development**

BF Gore, AB Johnson, Jr., HB Liemohn, LC Schmid

A graduate course sequence on fusion technology with a balanced emphasis of plasma and engineering aspects has been approved for addition to the Nuclear Engineering curriculum of the University of Washington at the Joint Center for Graduate Study. The Center is operated in Richland, WA, by Oregon State University, Washington State University and the University of Washington.

The sequence will be given routinely in three quarters starting with the 1976-77 academic year. The first quarter will cover fusion plasma engineering and is to include an introduction to plasma theory and its application to controlled thermonuclear fusion. In the second quarter, main emphasis will be on blanket technology and environmental aspects. The last quarter covers candidate materials problems of principal fusion reactor conceptual designs such as first walls, coolant systems, blankets, shields, magnets, and heat exchangers.

In preparation of this sequence, an overview course covering plasma technology, energy conversion aspects, and materials characteristics was presented Spring quarter, 1975, as a special course in Nuclear Engineering. A two quarter course, an introduction to plasma theory (fall quarter) and plasma and controlled fusion (winter quarter), is being taught during the 1975-76 academic year.

* Effort funded as part of the Joint Center for Graduate Study Program.

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