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

January 1976 - March 1976

April 1976

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

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PACIFIC NORTHWEST LABORATORY
REPORT ON CONTROLLED THERMONUCLEAR
REACTOR TECHNOLOGY
JANUARY 1976 - MARCH 1976

ERDA RESEARCH AND DEVELOPMENT REPORT

April 1976

Battelle
Pacific Northwest Laboratories
Richland, Washington 99352

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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 January 1, 1976 through March 31, 1976. 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:

- Fusion Systems Engineering
- 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.

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REPORT ON CONTROLLED THERMONUCLEAR REACTOR TECHNOLOGY
JANUARY THROUGH MARCH 1976
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.

Scientists and engineers from PNL and Princeton Plasma Physics Laboratory (PPPL) are cooperating to evaluate a hybrid reactor based on the Two Component Torus (TCT) Concept and develop a conceptual design. Feasibility of reference design development must be assessed on production of fissile material, use of available technology and capital costs.

An information requirements document is being prepared to assure satisfactory economic and environmental comparisons of CTR designs.

The economic importance of the fusion-fission hybrid is being evaluated. Evaluation cases are being made which indicate that there is a role for the hybrid even with successful development of the pure CTR.

The effects of the primary plasma and associated radiations and emission upon the surfaces of the first wall are being studied. The measurements of radioactive recoil sputtering ratios were determined for several elements and alloys.

Radiation induced structural damage in potential CTR first wall materials is being investigated. Microstructural damage in ion bombarded molybdenum is being examined as a function of depth below the bombarded surface. Void nucleation is being studied in nickel irradiated with nickel and helium ions.

Penetrating light ions that produce displacement damage in materials allow a control over irradiation parameters not attainable with any neutron source. An ion irradiation

system is being developed to perform a variety of mechanical property experiments to find a correlation between the microstructure and mechanical properties of light ion and neutron irradiated materials.

Graphite cloth samples have been irradiated and visually examined for shrinkage and deterioration. The thinner samples appeared to shrink in the axial direction of the fiber with no visual deterioration.

Iron based alloys are being exposed to lightly contaminated helium and the effects on the mechanical and corrosion properties are being studied. Helium is also being injected into niobium and vanadium mechanical property specimens by the tritium trick method. The effect of helium on the vanadium alloy V-15 Cr-5 Ti is being determined from specimens charged by two different methods.

Suitable electrical insulators must be found to meet the varied requirements of the CTR designs. Selected samples of sputter-deposited SiO_2 insulators fabricated at PNL were evaluated for electrical resistivity and dielectric strength. The electric properties of sputter-deposited Al_2O_3 are also being evaluated. Insulators prepared by sputter deposition exhibit a wide range of properties that appear promising for various CTR applications.

Current technology indicates that the CTR should have a lower total environmental impact than fission power plants. The CTR design concepts have been analyzed and a summary topical report is being prepared. Reference reports presenting detailed technical data and analyses are in progress.

The transport of tritium in the atmosphere and food pathways are being studied by models formulated at PNL. Human and plant exposure to concentrated amounts of tritium must continue to be explored.

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.

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FUSION SYSTEMS ENGINEERING

In fusion systems engineering a coordinated effort between scientists and engineers from PPPL and PNL is underway to evaluate the Two Component Torus concept and develop a conceptual design for a fusion-fission hybrid.

An information requirements document is being prepared. The design, operation, and economic information that should be included in documents describing CTR design concepts is outlined to assure satisfactory economic and environmental comparisons of CTR designs. The first three fusion-fission hybrid evaluation cases of the ten proposed in the last quarterly report have been completed. The three cases are: 1) LMFBR introduced in 1992, no CTR, 2) CTR introduced in 2010, no LMFBR, and 3) neither LMFBR nor CTR. The results indicate that there is a role for the hybrid even with successful development of the pure CTR.

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SYSTEMS STUDIES

System studies focus on providing key, early information for planning and analyzing the fusion power program. The fusion-fission (hybrid) system has been identified as a concept of special interest at PNL since it offers near-term promise for demonstration of the fusion principle. Therefore, studies of useful application of the fusion-fission hybrid are continuing to provide a rational basis for evaluating the merits of this concept in the nation's energy economy. A cooperative effort between Princeton Plasma Physics Laboratory (PPPL) and PNL is underway to conduct a conceptual design of a hybrid based upon a Two Component Torus (TCT).⁽¹⁾ Standard economic analyses procedures and data bases are being established to assure compatibility of the estimates between fusion plants and competitive systems. Studies of the energy marketplace are being made directed towards estimating the competitiveness of CTR power systems and establishing target costs for CTRs. These studies seek to provide DCTR new and additional information, key to planning and analyzing the fusion power program.

TCT-Hybrid Conceptual Design Study

RT Perry, Jr., PNL, Dave Chapin, PPPL

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 rules are: 1) to optimize on production of fissile material, 2) to constrain the technology to that available to construct a machine in the early 1990s, and 3) to minimize the capital costs.

The TOKAMAK Fusion Test Reactor (TFTR)⁽²⁾ 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 conceptual design appears to be economically and technically attractive, a follow-on effort will continue leading to a reference design.

The neutronics survey calculations using the RSIC DLC-2F 100 group library folded to 30 groups were expanded to include more converter and blanket compositions. The cases

considered and the resulting energy multiplication, tritium and fissile production rates are summarized in Tables 1 through 6. The reactor model used is shown schematically in Figure 1 and was essentially the same for all calculations.

TABLE 1. Per Source Neutron Production Rates for Two Blanket Compositions

	% ²³⁵ U	% Pu		Mult.	Trit.	Net Fissile
Case			Carbon and Pin Lattice			
1	.3	0	One Lithium Zone 4.5 cm	4.45	.248	1.45
2	.3	.42		4.8	.253	1.44
3	.3	1		5.4	.261	1.44
4	.3	.42	Lithium as Coolant Depleted to 1% ⁶ Li	4.74	.397	1.34
5	.3	2.92		7.47	.459	1.32
6	.3	2.92		7.97	.127	1.62
7	.3	1	Convertor and Li Zone	4.24	1.28	.386
			HTGR Lattice			
8	.3	1	One Lithium Zone 4.5 cm	4.28	.337	1.1
9	.3	2.92		6.14	.353	.977
			Depleted Convertor			
10	1.35		Two Li Zones 1.5 & 10 cm. Depleted Convertor	5.2	.272	1.37
11	2.66			6.18	.409	1.41
12	9.82			8.65	.726	.785
13	17.9			9.52	.837	.646

TABLE 2. Per Source Neutron Production Rates for GCFR Blanket Lattice

Case	% ^{235}U	Pu	Mult.	Trit.	Net Fissile
1	13.92		Critical		
2	3		10.3	.33	1.54
3	6		12.3	.784	.857
4	10.6		18.7	1.46	.260
5		10.6	21.0	1.77	.45

GCFR - Lattice and Convertor are the same - Li in pins of Li_2O .

TABLE 3. Per Source Neutron Production Rates for a Molten Salt (U-Pu Cycle) Blanket
Converter: 55% UO₂, 12% SS, 33% He

Case No.	Salt Composition Mole %				Breeder Zone Volume %		Li ⁶ Atom % in Lithium	Tritons per Neutron T	Blanket Energy, MeV	M Energy Multiplication Factor	Net Fissile F	Conversion Ratio CR
	LiF	BeF ₂	UF ₄	PuF ₃	Salt	C						
A-1	50	44	6	--	15	80	7.4(nat'l)	.378	56.2	4.0	1.19	--
A-3	50	44	6	--	95	0	7.4	.534	59.1	4.2	1.23	--
A-4	50	44	5	1	95	0	7.4	.703	118.9	8.4	.88	2.84
A-7	50	44	5	1	95	0	0.5	.131	170.4	12.1	1.18	2.30
A-9	50	48	1	1	95	0	0.5	.403	477.9	33.9	-1.10	.70
A-10	50	48	1	1	95	0	2.0	.759	286.0	20.3	-.22	.89
A-11	50.5	48	0.5	1	95	0	2.0	.953	344.7	24.4	-.82	.67
A-13	50	48	1	1	95	0	3.0	.866	234.7	16.6	-.01	.99
A-14	50	48	1	1	95	0	6.0	1.021	163.5	11.6	.26	1.29

TABLE 4. Production Sensitivity to Converter Composition
Breeder Zone Salt of LiF (6% ⁶Li), 50%; BeF₂, 48%; UF₄, 1%; PuF₃, 1%

Run No.	Zone Thickness (cm)		Converter Materials	N _{U238} N _{all}	# Fast Fissions	Tritium T	Energy E (MeV)	Multiplication M	Fissile F	Conversion Ratio CR
	Converter	Breeder								
A-14	9	60	55% UO ₂ 12% SS 33% He	.265	.200	1.021	163.6	11.6	.263	1.29
A-15	9	60	55% UC 12% SS 33% He	.380	.242	1.070	177.7	12.6	.382	1.40
A-16	9	60	33% U-metal 25% SS 42% He	.430	.210	1.152	179.1	12.7	.152	1.15
A-17	9	60	40% U-metal 24% SS 36% He	.485	.240	1.152	186.1	13.2	.254	1.25
A-18	19	50	40% U-metal 24% SS 36% He	.485	.347	.815	160.7	11.4	1.018	2.40

TABLE 5. Per Source Neutron Production Rates for All Salt Blanket
(Converter and Breeder Zones)--Converter 95% Salt
(U-Pu) Cycle

Case No.	Salt Composition Mole %				Breeder Zone Volume %		Li ⁶ Atom % in Lithium	Tritons per Neutron T	Blanket Energy, MeV	M Energy Multiplication Factor	Net Fissile F	Conversion Ratio CR
	LiF	BeF ₂	UF ₄	PuF ₃	Salt	C						
B-5	50	48	1	1	95	0	7.4	1.504	140.5	10.0	-.80	.24
B-4	50	48	1	1	95	0	2.0	1.958	599.1	42.5	-3.81	.26
B-3	50.5	48	1	.5	95	0	2.0	.953	148.1	10.5	-.54	.54
B-2	50.5	48	1.25	.25	95	0	2.0	.713	63.8	4.5	.16	1.37

TABLE 6. Per Source Neutron Production Rates for All Salt Blanket
(Converter and Breeder Zones)--Converter 95% Salt
(U-Th) Cycle

Case No.	Salt Composition Mole %				Breeder Zone Volume %		Li ⁶ Atom % in Lithium	Tritons per Neutron T	Blanket Energy, MeV	M Energy Multiplication Factor	Net Fissile F	Conversion Ratio CR
	LiF	BeF ₂	UF ₄	PuF ₃	Salt	C						
C-1	71.7	16	12.3	--	40	55	7.4	.544	18.1	1.3	.630	--
C-2	71.7	15.8	12.3	0.2	40	55	7.4	.567	27.1	1.9	.612	12.5
C-3	71.7	15.8	12.3	0.2	40	55	2.0	.306	30.7	2.2	.863	12.7
C-5	75.9	20	2.6	1.5	40	55	2.0	6.90	2597	184	-9.93	.35
C-8	75.9	15.4	7.2	1.5	40	55	1.0	.640	391	27.7	.051	1.02
C-6	75.9	15.4	7.2	1.5	40	55	2.0	.756	267	18.9	.018	1.01
C-7	75.9	15.4	7.2	1.5	40	55	4.0	.864	175	12.4	.053	1.06

FIGURE 1. Hybrid Blanket Model

In Table 1, cases 1 through 6 have UO_2 pins in a carbon lattice, following a plate type convertor. In cases 1 through 3 the convertor is followed by a 4.5 cm lithium zone. In cases 4 through 6, lithium is used as coolant in place of He. Both the UO_2 convertor and pins are enriched to the percents shown. Case 7 represents a UO_2 plate type convertor followed by a 70 cm lithium zone.

Note that in each case enough neutrons are present to increase the tritium breeding ratio to 1, at the expense of reducing the net fissile production rates. The energy multiplication is quite low, since most of the energy is released as a result of fast fission in the convertor.

Cases 8 through 13 in Table 1 have a depleted UO_2 plate convertor and an HTGR lattice. Cases 10 through 13 are an attempt to reproduce the results of an earlier PNL study.⁽³⁾ Since the cross section set used does not contain self shielding factors, the ^{238}U cross section is much too high. The neutrons are absorbed in the ^{238}U and do not cause fission. In the PNL study, an enrichment of 1.35% resulted in an energy multiplication of 40. Here the multiplication was 5.2.

In Table 2, a GCFR blanket is used. The lithium is in pins in the form of Li_2O . The fissile and fertile fuel is UO_2 and PuO_2 .

The results of molten salt blankets are shown in Table 3. The convertors are plates of UO_2 .

In Table 4, the salt blanket is held constant and the convertors are changed.

In Table 5, the system is based on a U-Pu cycle and in Table 6 the system is based on a U-Th cycle. In both cases the convertor and blanket are salt.

The value of these studies is to show sensitivities only since the cross sections used are not shielded. These cases, as well as others will be run over again when the shielded cross sections are available.

Preliminary Economic Analysis

JR Young

Numerous design studies for CTR power plants are expected to be issued during the development program. These studies will provide the basis for economic and environmental analyses to determine necessary research and the most attractive designs. Use of past design studies for economic and environmental analyses has been difficult because of lack of information or inconsistent presentation of information.

An economic and environmental information requirements document is being prepared for the CTR program. This document will describe the related types of design, operation, and economic information that should be included in each design document and establish certain basic general rules and assumptions that should be used in the development of the information in the documents. Provision of the information described in this information document will assure that the necessary information is available and that satisfactory comparisons of design concepts can be made.

A first draft of the information requirements document has been prepared and currently is being reviewed internally prior to external distribution for comments. Issue is scheduled late in this fiscal year.

CTR Economic Regimes

RL Engel

The economic regimes program identifies the economic characteristics needed to achieve a satisfactory return on a research investment. PNL has proposed to evaluate the allowable capitalized cost for fusion-fission hybrid under ten competitive scenarios

as summarized in Table 7. The first three cases are based on availability dates and uranium cost suggested by an Electric Power Research Institute (EPRI) group. This analysis is utilizing a linear programming (LP) model that was developed for ERDA to forecast future power plants built in the U.S. The approach and detailed input assumptions were presented in the last quarterly report.

TABLE 7. Parametric Hybrid Analysis Cases

System Characteristics	DT, Yr(a)	1	2	3	4	5	6	7	8	9	10
Date of LMFBR Availability by Doubling Time (DT)	20 12 6	1993 1999 --	-- -- --	-- -- --	1993 1999 --	-- -- --	-- -- --	1993 1999 --	1993 1999 --	1993 1999 2003	1993 1999 --
Date of First CTR Availability		--	2010	--	--	2010	--	--	--	--	2010
Date of First Hybrid Availability		2000	2000	2000	1990	1990	1990	2000	2000	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	EPRI	ERDA-A	EPRI	EPRI	EPRI

- LMFBR performance based on designs used for Proposed Final Environmental Statement, WASH-1535.
- Growth rates 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.
- 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.

Only limited calculations have been performed awaiting final approval of the seven additional scenarios by the Division of Controlled Thermonuclear Research (DCTR). The government and the utilities place somewhat different values for the taxes and discount rates. One of the utility's objectives is to determine the economic advantages of advanced technologies including the effect of revenue and income taxes. A DCTR objective is to determine the economic benefit of CTR technology to the taxpayer who has a different discount rate and excludes tax payments. An improvement has been made to the LP model so that the optimization is performed on an objective function including taxes, thus simulating the utility decision process, but an auxiliary objective function excluding taxes is evaluated to measure system performance in terms of government objectives. In addition to differences in taxes, different discount rates were also used, 8.8% for the utility decision and 7.5% for the evaluation of government benefits (note: this is the same procedure used in the LMFBR Cost-Benefit study included in ERDA-1535).

Figure 2 presents the allowable capitalized cost for a fusion-fission hybrid producing electricity at the rate of 0.40 MWe/MWt as a function of annual plutonium production. Each curve is the allowable cost that will yield a particular benefit, ranging from 0 benefit to a 7.5% discounted benefit of \$40 billion. This represents allowable cost for scenario 2, CTR available in 2010 at a plant cost of \$770/MWe and without the LMFBFR. This hybrid with the electrical producing rate of 0.4 MWe/MWt has a break-even (0 benefit) allowable cost ranging from \$470/kWt to \$850/kWt when producing plutonium at the rate of from 0.25 kg/MWt to 1.5 kg/MWt, respectively. The allowable cost that would yield a 7.5% discounted benefit of \$40 billion ranges from \$380/MWt to \$600/MWt.

Figure 3 presents the allowable cost for a hybrid that consumes nearly all of the electric energy it produces, 0.01 MWe/MWt. These allowable costs are also for scenario 2, with CTR in 2010 and without the LMFBFR. The breakeven allowable cost for a hybrid with a 0.01 MWe/MWt electric generation rate has a breakeven (0 benefit) allowable cost ranging from \$80/kWt to \$450/kWt when producing plutonium at the rate of from 0.25 kg/MWt to 1.5 kg/MWt respectively. The allowable cost that would yield a 7.5% discounted benefit of \$40 billion range from \$40/kWt to \$230/kWt.

FIGURE 2. Allowable Cost for Fusion-Fission Hybrid Plants
Case 3 with CTR--Without LMFBFR; Electric Pro-
Production Rate = 0.040 MWe/MWt

FIGURE 3. Allowable Cost for Fusion-Fission Hybrid Plants
Case 3 with CTR--Without LMFBR; Electric Pro-
duction Rate = 0.01 MWe/MWt

Figure 4 presents the allowable capitalized cost for the 0.40 MWe/MWt electric producing hybrid that yields a 7.5% discounted benefit of \$40 billion for all three EPRI scenarios.

The availability of the CTR does not eliminate the usefulness of hybrid plants since fissile material is still required in the LWRs built prior to the entry of the pure CTR.

The capitalized costs in Figures 2, 3 and 4 include plant cost, fuel cycle expense except purchase and sale of nuclear material, and interim capital replacements.

It can be written

$$C = P + \sum_{i=1}^L (1+r)^{-i} (F_i + R_i) \quad (1)$$

where

C = Capitalized cost

P = Plant cost

r = Discount rate (7.5% used in this analysis)

L = Plant lifetime (30 years in this analysis)

F_i = Fuel cycle expense for year i excluding nuclear material purchase or credits. Included in this category are costs for tritium, D_2O , fabrication costs, spent fuel reprocessing costs, and shipping costs.

R_i = Interim capital replacements, included here because some designs require large interim capital replacement due to deterioration of the first wall.

Not included as capitalized cost are plant operating and maintenance cost, cost or credit for electrical energy, nuclear fuel purchase and credits, taxes and insurance. These excluded items are included elsewhere in the model.

FIGURE 4. Allowable Costs for Fusion-Fission Hybrid that Yield \$40 Billion Benefit Discounted at 7.5%; Electric Production Rate = 0.40 MWe/MWh

As an alternate way of capitalizing the nonnuclear fuel cycle expense, a fuel cycle expense of \$1/kWt year is equivalent to a capital cost of \$9.8/kWt. When evaluating a hybrid design, the estimated plant cost should be increased by the sum of the discounted interim capital replacements in Equation (1) and by either the estimated fuel cycle expense (\$/MWt) multiplied by 9.8 or by the summation of discounted fuel cycle expense as expressed in Equation (1).

By using Figures 2 and 3, the designer can analyze tradeoffs between capital costs, national economic benefit, fissile material production, and electrical generation. The worthiness of a potential hybrid design may be evaluated.

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MATERIALS RESEARCH AND RADIATION ENVIRONMENT SIMULATION

In the surface effects studies data has been obtained on the lattice dynamical neutron sputtering ratio for niobium and gold. The ratios are on the order of 10^{-5} atoms/neutron. Sputtering ratios of this magnitude will not produce significant plasma impurities. The radioactive sputtering data indicate that considerable radioactivity will be ejected into the cooling channels of presently conceived tokamak power reactors.

The BCC correlation experiment is continuing. Comparison of the data gathered will indicate differences due to measuring techniques and will provide a basis for determining what constitutes meaningful differences in the data.

The effect of the implanted ion on the microstructure of ion bombarded molybdenum is currently being studied. Void nucleation in nickel has been examined in specimens bombarded simultaneously with He^+ and Ni^{++} ions.

The ion irradiation chamber and components have been ordered for the ion irradiation system with assembly and preliminary testing expected in the next quarter. Preliminary calculations on the effect of displacement rate gradient on ion irradiation creep measurements and thermal gradients resulting in an ion irradiation stress rupture experiment have been completed. Evaluation of specimen size and grain size effects on the tensile properties of MRC Marz grade nickel at 20°C have been completed. The results indicate that the yield and ultimate tensile strengths measured with the small ion irradiation specimen are representative of bulk properties.

Thin graphite cloth samples irradiated to a neutron fluence of about $3 \times 10^{21} \text{ cm}^{-2}$ at $\sim 500^\circ\text{C}$ shrank $\sim 8\%$ in the axial direction of the fiber, yet they accommodated this shrinkage with no visual deterioration. Thick cloth samples formed by three-dimensional weaves, on the other hand, have deteriorated and apparently have begun to tear themselves apart.

Elastic modulus changes produced in pyrolytic graphite samples irradiated in the RTNS correlate well with fluence; thus experimental correlation of the damage production rates between fission and fusion spectra seems assured.

The effect of low contaminant level, high pressure, high temperature helium on the mechanical and corrosion properties of CTR structural materials is being studied. Currently five near term alloys are being exposed to lightly contaminated helium at 650°C and 300 psi in two autoclaves.

The effect of helium on the refractory metals niobium and vanadium in the annealed and cold-worked states is being determined. Annealed refractory metals tolerated substantial helium concentrations under our test conditions before the uniform elongation was substantially reduced.

An evaluation of the electrical resistivity and dielectric breakdown behavior of selected samples of sputter-deposited SiO_2 was performed. In comparison to the fused SiO_2 target material (from which the sputtered SiO_2 material originated), the dc electrical resistivity of the sputtered SiO_2 samples (between 200 and 600°C) was less than for the fused SiO_2 target material. Above 600°C, the sputtered SiO_2 samples exhibited an erratic behavior whereas the fused SiO_2 did not. Although a reproducible value for the dielectric breakdown strength cannot be determined (due to microstructural considerations), the recorded prebreakdown acoustic emission behavior appears consistent with a thermal breakdown mechanism as reported for SiO_2 .

High temperature sputter deposition has produced good results in the preparation of insulator coatings. Electrical properties of high temperature deposited insulators need to be studied. It appears that insulators prepared by sputter deposition can be made into a wide range of properties, some of which may be ideal for various CTR applications.

SURFACE SCIENCE RESEARCH RELATED TO FUSION REACTOR TECHNOLOGY

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. Plasma contamination from impurities and resultant energy losses or possible lack of ignition may occur due to plasma-surface or radiation-surface interactions. Weakening of the first wall structures is also a possible result of such interactions. The intense high energy neutron fields, expected in a fusion reactor, can produce radioactive species which are ejected from the surfaces of first wall structures. These species may enter the vacuum system affecting the plasma or the cooling channels which after transport to other parts of the reactor could cause significant increases in the radiation hazard in normally low level zones.

Recent experimental results on neutron sputtering were summarized in a paper presented at the "Surface Effects in Controlled Thermonuclear Fusion Conference" in February (Table 8).⁽⁴⁾ In addition to the discussion of recent PNL results, we presented a brief review of the existing experimental measurements in this research area. In another paper at this Surface Science Conference we presented recent results of radioactive recoil emission yields and implications for future power producing fusion reactors.⁽⁵⁾ The most reliable measurements of neutron sputtering indicate that lattice dynamic neutron sputtering ratios are low in the range $\lesssim 5 \times 10^{-5}$ atoms/fast neutron for materials such as Nb and Au. Experiments to date have been done with targets in which the surface and the near surface regions have a reduced metal atom density when compared to the pure bulk materials. Experiments to determine the fast neutron sputtering ratios from "clean" surfaces are now in preparation at PNL.

TABLE 8. Summary of Neutron Sputtering Ratio Measurements by Neutron Activation Analysis

Target (a)	Number of Measurements and Collector Area Analyzed by Neutron Activation Analysis(b)		Total Neutron Dose on Targets (Neutrons) Σ Fluence x Area(c)	Best Estimates for S _n Atoms/Neutrons(d)		
	Forward	Backward		Forward	Backward	
<u>(d,t) Neutrons</u>						
<u>Gold</u>						
Annealed	8, 40 cm ²	8, 40 cm ²	1.4 x 10 ¹⁷		≈(1.9±0.5)10 ⁻⁵ ≈(1.3±0.4)10 ⁻⁵	
<u>Niobium</u>						
Single Crystal	2, 7.5 cm ²	2, 7.5 cm ²	2.0 x 10 ¹⁶	} Total 6.45 x 10 ¹⁷	≈2.8 x 10 ⁻⁵ ≈1.4 x 10 ⁻⁴	
Annealed	6, 17.5 cm ²	6, 17.5 cm ²	8.4 x 10 ¹⁶		≈1.7 x 10 ⁻⁵ ≈7.5 x 10 ⁻⁵	
Cold Worked	11, 45 cm ²	11, 29.7 cm ²	4.9 x 10 ¹⁷		≈1.1 x 10 ⁻⁵ ≈1.5 x 10 ⁻⁵	
Cold Worked Stressed in Tension	2, 10 cm ²		5.1 x 10 ¹⁶		≈4.9 x 10 ⁻⁵	
<u>(d,Be) Neutrons</u>						
<u>Gold</u>						
Annealed	4, 20 cm ²	4, 20 cm ²	5.6 x 10 ¹⁷		≈(1.9±0.6)10 ⁻⁶ ≈(1.8±0.6)10 ⁻⁶	
<u>Niobium</u>						
Annealed	1, 5 cm ²	1, 5 cm ²	1.1 x 10 ¹⁷	} Total 9.3 x 10 ¹⁷	≈4.7 x 10 ⁻⁵ ≈1.5 x 10 ⁻⁵	
Cold Worked	3, 10 cm ²	2, 5 cm ²	6.1 x 10 ¹⁷		≈2.5 x 10 ⁻⁵ ≈2.9 x 10 ⁻⁵	
Cold Worked		1, 5 cm ²	2.1 x 10 ¹⁷			≈7.5 x 10 ⁻⁶
Stressed in Compression						

- Column 1 lists the targets and various preparations.
- Columns 2 and 3 give the number of independent measurements and the total collector area analyzed.
- Column 4 gives the total neutron dose on the targets.
- The last two columns give the best estimates for the neutron sputtering ratios. Results were obtained with 14.8 MeV (d,t) neutrons at normal incidence and (d,Be) neutrons emitted in the forward direction from a thick Be target irradiated with 40 MeV deuterons. Sputtering ratios are upper limits in every case including Au as discussed in the text.

In February, PNL organized and held the Second International Workshop on Neutron Sputtering. Major activities in this workshop included the presentation of results from a standardized neutron sputtering experiment which had been completed since the First Neutron Sputtering Workshop. The seven laboratories involved in the "Round Robin" experiment were: Lawrence Livermore Laboratory, Argonne National Laboratory, McMaster University (Canada), Oak Ridge National Laboratory, Hahn-Meitner Institute (Germany), Max-Planck Institute (Germany), and PNL. The participating research groups presented their data on neutron sputtering ratios from standard samples and discussed results as well as needs for coordinated ongoing activities. An agreement was reached for joint publication of the results of the standardized or "Round Robin" experiment. Joint conclusions were reached which would be included in the joint publication. Finally, a timetable with assignment of responsibilities was agreed upon. The observation of micrometer chunks, although at low yields, continues to be a discrepancy between the various research groups.

Initial results were obtained for helium ion bombardment of Nb surfaces using continuous He ion energy distributions in the range ~ 0 to 0.9 MeV. A reduced threshold for blistering was observed compared with irradiations using monoenergetic ions. Work is in progress to determine the quantitative differences in blistering thresholds using continuous simulated CTR spectra and monoenergetic ion irradiations.

Joint experiments with PNL surface scientists and R. Taylor's Tokamak group at the University of California, Los Angeles, were initiated to study the effects of various wall liners and temperatures on the plasma impurities.

A Soviet surface science team, Drs. V. Gusev and Y. Martinenko, visited PNL as a part of the official US-USSR protocol for exchange of CTR information. Possibilities were discussed for joint experiments on in-situ evaluation of impurities in Tokamaks using surface probes and a preliminary proposal was submitted to DCTR and the Russian committee to enter into feasible joint experiments.

STRUCTURAL DAMAGE CHARACTERIZATION

This work characterizes radiation induced structural damage in potential CTR first wall materials. The investigation is specifically directed at determining the nature of displacement damage at high doses by heavy ion bombardment. Currently, the effect of parameters uniquely associated with ion bombardment are being evaluated 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 continuing. 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.

Each laboratory is currently analyzing the void microstructure in a common electron microscope specimen. Comparison of the data gathered will establish the variation in void parameters that are due to differences in experimental techniques. The results will indicate the amount of scatter to be expected in experimental data from the different laboratories and will provide a basis for determining what constitutes meaningful differences in the data. At present the specimen has not been examined by all of the participating laboratories.

Effect of the Implanted Ion on the Microstructure of Bombarded Molybdenum

ER Bradley

High purity molybdenum discs have been bombarded at 900°C with either 5 MeV Ni^{++} ions or 7.5 MeV Ta^{+++} ions. The irradiation induced microstructures are being examined as a function of depth below the bombarded surfaces and the results compared with the calculated displacement damage curves for the respective ions.

The prominent feature of the bombarded microstructures in both the nickel and tantalum bombarded specimens is the presence of a high density of small dislocation loops. The dislocation loop parameters from the various regions examined are listed in Table 9 for the nickel bombarded specimens and in Table 10 for the tantalum bombarded specimens.

TABLE 9. Dislocation Loop Parameters in Molybdenum Bombarded with 5 MeV Ni⁺⁺ Ions at 900°C

Sample Number	Surface removed (μ)	Dose (dpa)	Dose Rate (dpa/sec)	Nickel Concentrations (%)	loop size (nm)	loop Density (m^{-3})
A-45	0.27	7	1.2×10^{-2}	0	9.0	6.6×10^{22}
A-44	0.52	10	1.5×10^{-2}	0	9.5	
A-50	0.49	10	1.4×10^{-2}	0	9.0	8.0×10^{22}
A-46	0.75	16	2.5×10^{-2}	.13	12.5	3.6×10^{22}
A-47	1.05	15	2.3×10^{-2}	.70	11.0	3.4×10^{22}
A-43	1.64	*	*	0	10.0	2.8×10^{22}

* Beyond calculated damage zone.

TABLE 10. Dislocation Loop Parameters in Molybdenum Bombarded with 7.5 MeV Ta⁺⁺⁺ Ions at 900°C

Sample Number	Surface Removed (μ)	Dose (dpa)	Dose Rate (dpa/sec)	Tantalum Concentration (%)	loop size (nm)	loop Density (m^{-3})
A-53	0.28	10	1.3×10^{-2}	0.01	8.0	7.2×10^{22}
A-55	0.46	12	1.4×10^{-2}	0.05	9.0	5.2×10^{22}
A-54	0.92	2	2.0×10^{-3}	0.05	8.0	7.0×10^{22}

The data show that the depth dependence of the microstructural damage does not directly correspond to the calculated displacement damage curves. This is especially evident at depths beyond the calculated peak damage zone where the microstructural damage does not drop as sharply as would be indicated by the calculated curves.

Additional surface removals and microscope examinations on specimens A-43 and A-54 show that significant microstructural damage exists at depths of approximately 1 μ beyond the maximum range of the calculated displacement damage curves for both the nickel and tantalum ions. This large discrepancy between the calculated and the observed damage range indicates that either the ion penetrations used in the damage calculations were underestimated or that appreciable defect migration occurred during irradiation. Calculations are planned to estimate the extent of defect migration under these irradiation conditions.

The influence of the implanted ions on the microstructures was studied by examining the microstructure at the peak damage zone, where a substantial fraction of the implanted ions come to rest, and midway between the surface and the peak damage zone where the implanted ion concentration is negligible. The irradiation conditions were adjusted to produce equivalent dose and dose rates at the respective regions of examination.

Comparison of the microstructures in tantalum bombarded molybdenum at depths of 0.3 and 0.5 μ below the surface shows that the implanted tantalum ions have no effect on the irradiation induced microstructure. The microstructures in both specimens consist of a high density of small dislocation loops and no differences in the loop size or density were observed. Voids were not observed in either specimen.

Conflicting evidence as to the effect of the implanted nickel ion was observed. In regions bombarded to ~ 10 dpa at $\sim 1.4 \times 10^{-2}$ dpa/sec, small voids were observed at 0.85 μ below the surface while voids were not observed at 0.5 μ below the surface. This would indicate that the implanted nickel ions ($\sim 0.14\%$) promote void formation during ion bombardment of molybdenum. However, voids were not observed near the peak damage zone in the specimens bombarded at a higher dose rate even though the nickel concentrations were higher (Table 9).

*Effect of Helium on Void Nucleation**

JL Brimhall, EP Simonen

The void nucleation is currently being studied in nickel that has been bombarded simultaneously with Ni^{++} ions and He^+ ions. Last quarter the void density was reported to be directly proportional to the helium current under condition of constant dose rate due to Ni^{++} ions. The void parameters have now been evaluated as a function of time in nickel that was bombarded under conditions of constant nickel ion and helium ion current. The results are shown in Table 11.

* Work supported by Division of Physical Research.

TABLE 11. Void Parameters in Nickel Bombarded with Ni^{++} and He^+ Ions

Dose Rate = 6×10^{-3} dpa/sec

He Deposition Rate = 1.4×10^{-7} at frac/sec

Temp. = 575°C

Time (sec)	Dose (dpa)	Void size (nm)	density (voids/m ³)	$\Delta V/V$ (%)
7	0.06	4.1	7.0×10^{18}	0.0025
14	0.16	9.3	2.0×10^{18}	0.008
58	0.27	8.2	1.7×10^{19}	0.054
228	2.2	18.9	8.0×10^{18}	0.32

The void density saturates rather early in the irradiation and there is no consistent change thereafter. The low value of 2×10^{18} voids/m³ after 14 sec can partly be explained by the lower helium content in this specimen. The large surface removal placed it near the end of the helium zone. The swelling increased monotonically with dose due to increase in void size. The results indicate that the nucleation period is quite short and most of the subsequent swelling results from void growth. Studies on nickel irradiated under identical conditions except for no helium revealed no voids until the highest dose levels. In this case the void distribution was very inhomogenous.

Mechanical Properties

RH Jones, DL Styris, OK Harling, RP Marshall

The use of penetrating light ions to produce displacement damage in materials offers a degree of control over irradiation parameters not attainable with any neutron source. The long term objective for the ion irradiation for mechanical property measurements program is the development of an ion irradiation system with sufficient flexibility to perform a variety of mechanical property experiments while the short term objective is a correlation between the microstructure and mechanical properties of light ion and neutron irradiated materials. Also, the effect of the ion irradiation environment, damage gradients and specimen size are being evaluated.

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 second year has been devoted to design and construction of the ion irradiation system and post irradiation evaluation chamber, specimen preparation and testing methodology, and ion and fusion neutron irradiations and testing of Ni, 316 SS, Nb and Mo at 20°C.

The following tasks were completed this quarter: 1) ordered ion irradiation chamber, vacuum components, helium coolant pump and post evaluation chamber and components; 2) determined tensile properties and grain size of MRC Marz grade nickel as a function of annealing temperature (350 to 550°C) and specimen diameter (0.127 to 3.175 mm) at 20°C; 3) evaluated specimen preparation techniques and initiated tensile tests on 0.127 mm gauge diameter 316 SS and MRC Marz grade niobium; 4) obtained 0.25 mm diameter 316 SS from 7.62 mm diameter stock of Westinghouse heat no. 86210 on which extensive fission neutron data exists; 5) participated in workshop on "The Measurement of Mechanical Properties During Ion Irradiation" and met with Task Group "A" of ASTM Committee E10.08 at PNL on January 29-30, 1976; 6) completed preliminary calculations on the effect of displacement rate gradients on ion irradiation creep measurements and calculated thermal gradients in an ion irradiation stress rupture experiment.

Tensile Properties as a Function of Grain Size and Specimen Diameter

The geometry and dimensions of the mechanical property test specimen for ion irradiation experiments were determined from heat removal and damage gradient considerations as an upper limit and size effects and handling difficulties as a lower limit. Based on these considerations, a cylindrical specimen with a 0.127 mm gauge diameter and 6 mm gauge length was selected. The relationship between the mechanical property data obtained with these small specimens to that obtained with bulk specimens is being determined in the PNL-DCTR program. The tensile properties of MRC Marz grade nickel have been determined at 20°C as a function of annealing temperature and specimen diameter (Figures 5 and 6). The average grain diameters ranged from 0.02 to 0.10 mm for annealing temperatures of 350 to 550°C. The yield strength dependence on annealing temperature reflects this change in grain diameter. The yield and ultimate strengths of nickel obtained with the ion irradiation test specimen are within 30% of those obtained with bulk specimens as shown in Figure 6, however, the total elongation and strain hardening at 1% plastic strain were significantly lower. The increase in both total elongation and strain hardening with increasing specimen diameter may be explained by the number of grains per diameter which ranges from about 2 for the ion irradiation test specimen to approximately 30 for the 3.175 mm diameter specimens.

FIGURE 5. Tensile Properties of 0.127 mm MRC Marz Grade Nickel at 20°C Versus Annealing Temperature

FIGURE 6. Tensile Properties of MRC Marz Grade Nickel at 20°C Following a 2 hr Anneal at 550°C Versus Specimen Diameter

The study of post irradiation tensile properties has certain advantages for ion-neutron correlation experiments such as: 1) yield strength changes are expected for materials irradiated at practical 14 MeV neutron fluences of 10^{17} to 10^{18} n/cm²; 2) specimens can be positioned to obtain maximum flux; 3) low irradiation costs because multiple specimens may be irradiated; 4) strength and ductility changes, which are both important properties for CTR design, will be measured; 5) tensile data obtained with ion irradiation test specimens may be related to bulk behavior although this has not been fully demonstrated at this time.

However, the main advantages of ion irradiation over any neutron source are the degree of control and flexibility of irradiation parameters for a dynamic (in-situ) irradiation experiment. The effect of features which are unique to the ion irradiation environment are being considered in the selection of experimental tests for the PNL-DCTR program. Vacuum or reactive gas environment and radiation induced gradients are two such ion irradiation environment features which are being examined carefully. Thermal gradients which would result during third stage creep of an ion irradiation stress rupture experiment and the effect of displacement rate gradients on ion irradiation creep measurements are both being analyzed and the results of preliminary calculations of displacement rate gradient effects are presented briefly in the following text.

The Effect of Displacement Rate Gradients on Ion Irradiation Creep

The calculated effect of a linear displacement rate gradient which varies by a factor of 2 from front to back side of the specimen on the creep rate is shown in Figure 7. The ratio $\langle \dot{\epsilon}_{i,j} \rangle_{av} / \langle \dot{\epsilon}_{i,0} \rangle_{av}$ is the average strain rate of i laminar elements at time j divided by the average strain rate of the i elements at time zero. A major consideration of this calculation was that a stress gradient developed with time because of the strain continuity requirement between the laminar elements and the variable strain rate associated with the displacement rate gradient. A stress gradient of 20% developed in 3000s with the starting conditions specified in Figure 7. The details of the calculational procedure and assumptions will be given in a future publication.

The significance of these preliminary calculations is to demonstrate that the strain rates measured by ion irradiation creep experiments may not be seriously affected by displacement rate gradients while the effect of a stress gradient must be considered.

FIGURE 7. The Effect of a Displacement Rate Gradient on the Irradiation Enhanced Creep Rate in Nickel

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, coolant compatibility and helium embrittlement effects.

Evaluation of Carbons and Graphites for Controlled Thermonuclear Reactor Applications

WJ Gray, WC Morgan, GL Tingey

Some CTR concepts including those for an Experimental Power Reactor (EPR)⁽⁶⁻¹⁰⁾ have proposed the use of a low-Z liner between the plasma and the first structural wall. A number of materials are being considered for the liner including graphite or graphite cloth. Among the more important data required before the choice of liner materials can be narrowed include: 1) radiation damage, 2) sputtering, and 3) degassing.

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

- Evaluation of radiation damage effects in cloths and fibers since there are no previous data for these materials above about $1 \times 10^{21} \text{ cm}^{-2} \text{ EFF.}^*$
- 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.
- 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.
- Measurement of degassing properties of large graphite samples under conditions appropriate to CTR conditions.

* All fluences are quoted in terms of "Equivalent Fission Fluence for Damage in Graphite."⁽¹¹⁾

Radiation Damage

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.

Table 12 lists data for the first set of samples and shows that neutron irradiation causes considerable shrinkage in thin cloth samples, yet they have accommodated this shrinkage with no visual deterioration. On the other hand, two types of thick cloth samples formed by three-dimensional weaves, one orthogonal and the other angle interlock, have suffered some deterioration. It has not been possible to perform dimensional-change measurements on these samples, but one gets the impression that they are beginning to tear themselves apart probably because the three-dimensional weave does not provide enough freedom to accommodate the axial shrinkage of the fibers. This does not necessarily mean, however, that three-dimensional weaves in general will be unsuitable. Perhaps a more forgiving type of weave can be developed.

TABLE 12. Changes in Density and Fiber Lengths for Thin Cloth Samples Irradiated to $\sim 3 \times 10^{21}$ cm⁻² EFF at $\sim 500^\circ\text{C}$

Sample	Length Change (%)	Density Change (%)
GSCC-2	-6.6	18.0
GSGC-2	-8.6	16.5
WCA	-8.2	14.7
Thornel-50	-8.0	9.3

The density changes shown in Table 12 exceed the axial length changes for all the cloths except, perhaps, for Thornel-50. This implies that the fibers shrank in the radial direction also. Efforts to confirm this by direct measurements are currently in progress.

Damage Production Rates

Elastic modulus changes produced in stress-annealed pyrolytic graphite samples by irradiation in the RTNS at LLL to fluences in the range 1.6×10^{15} to 1.1×10^{17} cm⁻² EFF correlate very well with fluence; the largest change was $\Delta E/E_0 = 6.60$. This indicates that the method is sound and that irradiation of other samples in two additional neutron sources (the Hanford N-reactor and the D-Be source at Davis, California) will yield an accurate experimental correlation of the damage production rates between fission and fusion spectra. The latter two irradiations are planned about July 1976.

Neutron Sputtering Measurements

A sample of glassy carbon prepared from a phenolic resin precursor labeled with carbon-14 will be used for the neutron sputtering measurements. Many months of work with a company that deals in carbon-14 labeled organic compounds has finally culminated in the development of a technique for the preparation of a suitable resin in the very small batch size (~ 0.1 g) required, and the labeled batch has now been ordered. Preparation of the labeled sample should be completed by April 1976 and sputtering measurements by the surface science group will begin shortly thereafter.

Degassing

The degassing equipment has been assembled and is currently being checked. Measurements on relatively small samples will begin about April 1976 prior to work with larger samples.

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 has many desirable characteristics as a coolant for fusion reactors and is one of the principle candidates for the primary coolant in fusion reactor conceptual designs.^(12,13,14) 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, however, 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 CTR structural materials. The program currently consists of exposing five near term alloys to lightly contaminated helium at 650°C and 300 psi in two autoclaves.

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

The intentionally added 50 vppm contaminant levels were "swamped out" by a large water/hydrogen/methane outgassing phenomenon in the initial runs in both autoclaves. The system outgassing lasted for the first several days under gas flow conditions where the test gas volume was completely replaced within 10 to 20 hr. Contaminant levels up to 800 vppm hydrogen and 125 vppm methane occurred during these initial runs. This outgassing phenomenon was suppressed during the second start up of the O₂ autoclave by a combination of step heating and high test gas flow rate.

The stainless steel alloys included in this study are 316 SS, 321 SS, and 347 SS. In general their yield strength, ultimate strength, total elongation and notched toughness ratio decreased with increasing exposure time. Their mechanical properties were found to be essentially independent of test atmosphere for the initial short time exposure, as illustrated by 316 SS in Figure 8. It was also found that the mechanical properties of the stainless steel alloys tend to approach each other as the exposure time increases (Figure 9).

The Incoloy 800 and Croloy yield strength, ultimate strength and elongation were found to be less than those for the stainless steels. The Croloy had the highest notch toughness ratio of all the alloys while the Incoloy 800 had the lowest.

Exposure of all alloys are continuing and the longer time exposure corrosion rates and mechanical property results will be reported in subsequent reports. The current short-time exposure mechanical property results do not rule out any of the test alloys from high-temperature helium-cooled heat exchanges use. The previously reported hot gas corrosion rate of the Croloy does, however, indicate potential structural integrity and radioactive particle transport problems.

FIGURE 8. 316 SS Room Temperature Mechanical Properties After Exposure at 650°C

FIGURE 9. Comparison of the Room Temperature Mechanical Properties of 2 1/4 Cr-1 Mo Steel and Incoloy 800 with Stainless Steel Alloys After Exposure at 650°C

Helium Effects in CTR Materials by 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).⁽¹⁵⁾ The helium charging method was described in a previous quarterly report⁽¹⁶⁾ and in reference 17.

The majority of 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-min 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 helium then 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 standard tensile specimens, are being used to study helium stability at high temperatures.

The major emphasis of this program is currently centered on determining the effect of helium on the refractory metals niobium and vanadium in both the annealed and cold-worked states. Standard engineering size specimens of these materials have been charged with up to 500 ppm He, and the short time tensile properties of these metals were determined as a function of helium concentration at $\sim 1/2 T_m$. It was found that the annealed refractory metals could tolerate substantial helium concentrations under these test conditions before the uniform elongation was substantially reduced (~ 250 ppm He for Nb and ~ 150 ppm He for V at $\sim 1/2 T_m$). Both additional Nb and V specimens are currently accumulating helium by tritium decay in order to further define the exact composition range and the change in elongation characteristics that accompany this rapid drop in uniform elongation found over a relatively narrow change in helium concentration.

The first Nb control specimen in the joint PNL-LLL Nb creep study directed toward determining the effect of tritium charged helium on high temperature creep was tested this quarter. The testing of the helium charged Nb specimens will begin during the next quarter.

Three V-15Cr-5Ti alloy thin foil specimens typically used in ion bombardment experiments were helium charged by tritium decay and tested at elevated temperatures in a joint PNL-ANL program to study the effect of helium charging method and specimen configuration on mechanical property response. The thin foil mechanical property specimens were machined by ANL, helium charged to approximately 35 ppm by the tritium trick at PNL and subsequently tested at ANL.⁽¹⁸⁾ The tritium tricked specimen test conditions were chosen so that the test results would be comparable to earlier work done at ANL on ion bombarded helium-charged specimens of this alloy.⁽¹⁹⁾

The V-15Cr-5Ti alloy control test results for both the tritium tricked and ion bombarded specimens are shown in Figure 10. The properties of the controls agree relatively well, although the results do exhibit substantial discrepancy in total elongation.

The helium charged results are shown in Figure 11. Both types of helium charging methods result in dramatic decreases in elongation at relatively low helium concentrations (25 to 35 appm He). The wide discrepancy between the elongations for the helium charged specimens found at 700°C is believed to be due mainly to the presence of different bubble distributions from the different maximum temperatures experienced by the 700°C specimens. The tritium trick 700°C specimen reached a temperature of 740°C during tritium outgassing prior to tensile testing while maximum temperature the ion bombarded specimen experienced was the 700°C test temperature. Thus the increased helium diffusion time/rate for the tritium tricked 700°C specimen may explain the 700°C elongation differences between the two charging methods.

The extra high-temperature soak of all the tritium tricked specimens during tritium outgassing may explain the consistently low elongation values exhibited at all test temperatures. These discrepancies may, however, also be a function of helium content or a function of charging method. Further testing of both types of specimens is proceeding in order to define the extent and reasons for the elongation discrepancies and for the other mechanical property deviations found between the two charging methods.

Cylindrical gauge length V-15Cr-5Ti specimens are currently being machined from material furnished by ANL. Work is continuing on the characterization of the helium bubble distributions present in tritium trick helium charged specimens after testing and after high temperature anneals. Both Nb and V specimens designated for furthering the understanding of helium degradation in refractory metals are currently accumulating helium.

FIGURE 10. Elevated Temperature Tensile Test Results for V-15Cr-5Ti Alloy Control Specimens

FIGURE 11. Elevated Temperature Tensile Test Results for V-15Cr-5Ti Alloy Containing Helium

Electrical Insulators for Controlled Thermonuclear Reactor Applications

JL Bates, JE Garnier

Various CTR concepts require the use of electrical insulators in a variety of critical locations. 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 applications. 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 an evaluation of the electrical properties of selected samples of sputter-deposited SiO_2 insulators.

Evaluation of the Electrical Properties of Sputter-Deposited SiO_2

The evaluation of selected samples of sputter-deposited SiO_2 fabricated at PNL by the Metallurgy Research Section consisted of the following:

A. Electrical Resistivity

- To determine the change in the electrical resistivity of selected sputter-deposited SiO_2 samples as a function of temperature.
- To compare the measured electrical resistivity of selected sputter-deposited SiO_2 samples with the measured electrical resistivity of fused SiO_2 target material from which the sputtered SiO_2 material originated.

B. Dielectric Strength

- To compare the measured room temperature dielectric strength of sputter-deposited and fused SiO_2 materials with the range of dielectric strength for SiO_2 as reported in the literature.
- Compare prebreakdown behavior of sputter-deposited SiO_2 , fused SiO_2 and polycrystalline Al_2O_3 as a means of qualitatively interpreting the mechanism(s) leading to failure in a particular sample.

Experimental Apparatus

The electrical resistivity was measured using a three probe, guarded ring technique. A teraohmmeter measured the sample resistance from 10^6 ohms ($\pm 0.25\%$) to 10^{16} ohms ($\pm 10\%$)

while a meg. ohm bridge measured resistances from 10^3 ohms ($\pm 1\%$) to overlapping resistances up to 10^{14} ohms ($\pm 10\%$). The specimens were heated by a resistance furnace. The ambient sample temperatures were maintained to within $\pm 1^\circ\text{C}$ over the range from 200 to 1100°C . The measurements were performed in argon gas at 1 atm with an oxygen partial pressure of $\sim 10^{-10}$ atm.

The dielectric strength was measured at room temperature (20°C) using an acoustic emission technique.* Change in location of the AE monitoring transducer was required since the sputter-deposited SiO_2 samples were too small to allow direct attachment of the acoustic transducer. The SiO_2 samples were placed between point-plane electrodes and the monitoring transducer epoxied to the outside of the test container wall. The dielectric transformer oil surrounding the samples was used as an acoustic waveguide by which the generated acoustic emissions within the sample were transmitted to the transducer. This reduced the sensitivity of the acoustic signal detection and may have caused a further attenuation of the acoustic signal to occur. The sensitivity was minimized by increasing the signal amplifier gain and polycrystalline Al_2O_3 was tested under the same conditions as the SiO_2 samples for acoustic signal comparison.

Data Calculation

A. Electrical Resistivity

The electrical resistivity was determined from the measured sample resistances from the following formula:

$$\rho = \frac{1}{\sigma} = \frac{A}{t} \cdot R_V \text{ (ohm-cm)} \quad (1)$$

where

ρ = resistivity (ohm-cm)

σ = conductivity (ohm-cm) $^{-1}$

R_V = measured volume resistance (ohm)

t = measured sample thickness (cm)

A = effective cross sectioned electrode area (cm^2)

The value of R_V used was that value recorded at a time of 1 min after the voltage had been applied across the sample. This recorded value of resistance is greater than the extrapolated instantaneous value but 5 to 10% less than the value of resistance measured at a time of 5 min. The percentage difference between R_V at 1 and 5 min intervals was found to decrease with increasing temperature. This behavior is typical of ionic

* Refer to previous PNL Quarterly Reports on CTR Technology, BNWL-1939-1 and BNWL-1939-2 for details.

conductors where the current is time and temperature dependent. Since only percentage changes were observed on all SiO₂ samples the value of R_v at 1 min was used. No corrections were made for the effects of sample porosity (which would also change A and t) on the magnitude of the measured electrical conductivity. The samples as-received were considered to be nominally 100% dense.

B. Dielectric Strength

The dc dielectric strength of a material may be defined to be that electrical stress which a material will support until total failure. The dc breakdown strength can be calculated from the formula:

$$\text{dc dielectric strength} = \frac{\text{applied dc voltage}}{\text{thickness}} = \text{kV/cm} \quad (2)$$

where the thickness is considered to be the width of the sample in cm at the point of total failure (puncture).

In contrast to the electrical conductivity of a material, which is dependent mainly on the type and number of electronic charge carriers, the dielectric strength of a material may exhibit a first order dependence on microstructure (e.g., grain boundaries, porosity, pore distribution). In the vicinity of a microstructural defect(s) a region of enhanced electrical stress can occur which, if high enough, leads to a localized electrical discharge. If the local discharging continues, a discharge channel forms that propagates through the material and causes total failure. Thus, complete reproducibility of sample conditions among samples or materials cannot be achieved (e.g., location of microstructural defects, etc.).

In comparing the calculated results of Equation (2) among samples or between materials, meaningful results will only be achieved in terms of comparative norms and standard deviations determined from a sufficient number of independent measurements. On the other hand, analysis and comparison of prebreakdown information may yield an understanding of the mechanism(s) which lead to or initiated catastrophic failure in a particular sample and/or material. This may be achieved by interpreting, in a qualitative sense, the observed characteristic acoustic behavior that insulators will generate when exposed to a voltage stress.⁽²⁰⁾

Results

A. Electrical Conductivity

The dc electrical conductivity of three samples: fused SiO₂ target material (0.127 cm thick); 0.009 cm thick sputter-deposited SiO₂; and 0.018 cm thick sputter-deposited SiO₂ is shown in Figure 12 plotted as log conductivity versus reciprocal temperature. Typical "best literature" data⁽²¹⁾ for SiO₂ is represented by the heavy solid line.

FIGURE 12. Log Electrical Conductivity Versus Temperature: Samples of Sputtered Deposited and Fused SiO_2

The error bars represent an estimate of the errors associated with changes in the calculated value of conductivity due to variations on A and t (Equation 1) from thermal expansion effects and from instrument error.

The electrical conductivity curves may be separated into two regions based on temperature.

- Region I: 200 to 600°C. The electrical conductivities of the sputter-deposited SiO_2 samples are higher than the fused SiO_2 target material by 1 and 2 orders of magnitude at 200°C and by 1/2 and 1 orders of magnitude at 600°C for the

0.008 cm and 0.018 cm thick SiO_2 samples, respectively. The best literature data are higher by 1 to 1/4 order of magnitude than the fused SiO_2 target.

- Region II: 600°C and higher. At temperatures above 600°C, both sputter-deposited SiO_2 specimens exhibited an erratic electrical conductivity. The electrical conductivity deviated from a linear dependence on temperature and the change in measured sample resistivity, R_V , at 5 min approached differences up to 50% or greater of that obtained at 1 min. This behavior may be due to sample outgassing or sample fracture occurring at elevated temperatures.

The fused SiO_2 target sample did not exhibit these erratic variations in its measured resistance. The behavior of the sample was the same from 200 to 1100°C. However, a slight increase in the sample conductivity occurred during cooling from high temperatures when compared with the data obtained on heating. The cause of this is not known.

Upon removal and inspection of the sputter-deposited SiO_2 samples, signs of bubble formation and blistering were observed as seen in the photographs (Figure 13). The 0.018 cm thick sputtered SiO_2 (electrical resistivity) sample, for example, had fractured and bowed in locations which were unrestrained by the pressure of the guard tube, the center electrode, and the lower base electrode. The edges at the fractures showed further signs of deformation. Another 0.018 cm thick sputtered SiO_2 sample (same lot) deformed into a corn-flake appearance upon only the process of firing on the platinum electrodes in air. A 0.007 cm thick sputtered SiO_2 (different fused SiO_2 target used) sample showed signs of bowing and bubble formation after firing of the platinum electrodes in air. Measurements of the electrical conductivity were not possible on the latter two samples.

B. Dielectric Breakdown

A dc voltage that was incremented in steps of 1 kV each minute until total failure, was applied to samples of fused and sputtered SiO_2 and polycrystalline Al_2O_3 . Using an acoustic emission technique, ⁽²⁰⁾ the cumulative total AE event count and AE energy count were recorded on a dual channel x-y timebase recorder. Using Equation (2), the overall electrical stress, kV/cm, was calculated at each voltage level for each sample. These results are shown on Figures 14 and 15 where total AE event count and total AE energy count, respectively, are plotted versus electrical stress. Common features of both figures are:

- Significant difference in the AE behavior between the SiO_2 and Al_2O_3 samples is apparent. The SiO_2 samples exhibit large bursts of AE events and AE energy count prior to complete breakdown. The energy associated with the bursts increased with increasing voltage stress until complete failure. The Al_2O_3

0.018 cm SPUTTER-DEPOSITED SiO_2
AFTER ELECTRICAL RESISTIVITY
MEASUREMENTS

0.018 cm SPUTTER-DEPOSITED SiO_2
AFTER FIRING IN AIR AT 1000°C
FOR 1 hr

0.008 cm SPUTTERED-DEPOSITED
 SiO_2 AFTER FIRING IN AIR
AT 1000°C FOR 1 hr

FIGURE 13. Sputter-Deposited SiO_2 Samples--Appearance

FIGURE 14. Acoustic Emission Event Count Versus dc Voltage Stress (kV/cm): Sputter-Deposited and Fused SiO₂ and Polycrystalline Al₂O₃

FIGURE 15. Acoustic Emission Energy Count Versus dc Voltage Stress (kV/cm): Sputter-Deposited and Fused SiO₂, and Polycrystalline Al₂O₃

sample, on the other hand, shows a large number of AE events with a reduced AE event energy per event at voltage stresses far below that required for complete breakdown. The observed differences in acoustic behavior may be consistent with the reported differences in mechanisms for breakdown in SiO_2 and Al_2O_3 . These mechanisms are considered to be ion-induced, thermal breakdown⁽²²⁾ for SiO_2 in comparison to Al_2O_3 , which is known to exhibit an electrical breakdown at room temperatures.⁽²³⁾

- The values for dielectric strength obtained from the limited number of sputter-deposited and fused SiO_2 samples measured were found to lie within the reported spread for SiO_2 .⁽²¹⁾ No significance can be ascribed to the measured values at this time because insufficient data is available to determine any meaningful statistical spread.

Sputter Deposition of Materials for CTR Applications

R Wang

The objective of this program is to develop a sputter-deposition technology to produce insulator coatings, and explore the physical properties obtainable in such sputtered deposits. Progress was made during this quarter in the following areas:

- The thermal stability of an Al_2O_3 coating on Nb.
- Evaluation of the electric properties of thick Al_2O_3 and SiO_2 .
- Preparation of high temperature sputtered SiO_2 samples.

Thermal Stability of an Al_2O_3 Coating on Nb

Excellent thermal stability was found for a 20 μm thick Al_2O_3 coating sputter deposited on a 2.5 cm diameter Nb substrate at 800°C. The structure of the coating was fine grained $\alpha\text{-Al}_2\text{O}_3$ (Figure 16a) and had no visible cracks revealed at 200X magnification (Figure 16b). Furthermore, the coating remained crack-free after the sample was quenched from 25 to -195°C and back to 25°C (Figure 16c). A specimen of 1 x 0.5 cm was also subjected to three thermal cycles in vacuum between 1000 to 800°C with a cooling rate about 20°C/sec and did not show visible signs of cracking (Figure 16d). This high thermal stability of Al_2O_3 coating on Nb may be attributed to the strong interfacial bonding between the Al_2O_3 and Nb. This sample demonstrated that sputtered insulator coatings deposited at high temperature may be advantageous in applications where thermal cycling is involved.

a.

b.

c.

d.

FIGURE 16. Micrographs of a Sputtered Al_2O_3 Coating on Nb Deposited at 800°C
a) As Deposited, SEM-1000X, b) As Deposited SEM-200X, c) Thermal Shocked to -195°C , No Visible Cracks, Scratches Are Due to Handling. SEM-400X. d) Thermal Cycled Between 800 to 1000°C , No Visible Cracks, Lines Are Scratch Traces, Optical-400X.

Electrical Properties of Al_2O_3 and SiO_2

Preliminary electrical resistivity and dielectric breakdown measurements were made on selected samples of Al_2O_3 and SiO_2 deposited at 25°C . The dielectric breakdown characteristics of sputtered insulators were determined using an acoustic emission

technique.* The electrical stress necessary for an electrical failure at room temperature for a 350 μm thick sputtered Al_2O_3 was 6.4×10^5 V/cm. The electrical stress at failure for a 175 μm thick SiO_2 deposit was 7×10^5 V/cm. The electrical stresses at the point of failure of reference materials of 99% pure polycrystalline Al_2O_3 , and fused SiO_2 target material tested at the same temperature but different thickness were compared. The sputter deposited insulators performed as well or better than the reference materials. Since the number of samples tested is small, sputter-deposited insulators cannot be compared to insulators prepared by conventional techniques. The data we have can only be used to speculate that the breakdown characteristics of sputtered insulators may be closely related to the unique microstructures, i.e. high density and absence of grain boundary, resulting in a high dielectric strength of these few samples. This phenomenon is an area for future investigations.

Preliminary resistivity measurements of two SiO_2 deposits prepared at 25°C showed resistivities near 10^7 ohm-cm at 700°C. Between 200 and 700°C the resistivities were to 1 to 2 orders of magnitude lower than the averaged values for fused SiO_2 reported in the literature. However, the results from resistivity measurements at temperature greater than 600°C were erratic. This may be due to Kr (sputtering gas) release from the samples since a fairly large amount of Kr was trapped in SiO_2 deposits made at a substrate temperature of 25°C. Deposition at 600°C did not result in trapping of sputtering gas in SiO_2 , and therefore such samples will be characterized at temperatures greater than 800°C.

High Temperature Sputtered SiO_2 Film

Ten specifically prepared substrates were received from LASL to be coated with a 5 μm SiO_2 at 600°C for dielectric breakdown tests. These substrates were made by coating two thin layers of Pt and Ti films on 0.3 cm SiO_2 . Two sputtered SiO_2 samples were prepared for this investigation.

Summary

High temperature sputter deposition has produced good results in the preparation of insulator coatings. Sputtered Al_2O_3 coatings at 800°C on Nb demonstrated excellent thermal stability within temperature range 1000 to -195°C.

Electrical properties of Al_2O_3 and SiO_2 were obtained from a few samples sputtered at 25°C. The measured resistivities of deposited SiO_2 were within the range of scattered values reported in literature. The data obtained from the preliminary dielectric

* Refer to "Electrical Insulators for CTR Applications."

breakdown tests showed encouraging properties of 25°C deposited insulators. By controlling the substrate temperature, a wide range of insulators can be fabricated. Electrical properties of high temperature deposited insulators need to be studied. It appears that insulators prepared by sputter deposition can be made into a wide range of properties, some of which may be ideal for various CTR applications.

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ENVIRONMENTAL EFFECTS OF FUSION CONCEPTS

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 have been 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 and increased employee radiation doses. Since commercial CTRs are not expected to operate for 40 to 50 years, future technical advances should lower these impacts. A draft document describing the analysis has been reviewed by the national fusion laboratories and appropriate ERDA administrators. The analysis will be issued in early FY-1977 as a summary topical report supported by numerous reference reports presenting the detailed technical data and analyses.

Work is continuing on the model for the transport of tritium in the atmosphere over long periods of time. The computer code called FOOD has been revised to include a new specific activity approach for movement of tritium through food pathways.

ENVIRONMENTAL EFFECTS ANALYSES

A correlation exists between the acceptance of a new technology and the environmental effects incurred by that technology. Therefore, the extrapolation of known data plus the generation of data from existing technologies as they could apply to CTR concepts are useful in guiding the engineering of systems for future CTR designs. The environmental impacts that can be assumed have been analyzed and studies are continuing in areas of plant and animal exposure to tritium.

Controlled Thermonuclear Reactor Environmental Analysis

JR Young

The first draft of the environmental analysis for the CTR development program has been reviewed by the national review committee, and the analysis currently is being prepared for issue later this year.

The analysis was made to determine the possible environmental effects of the first commercial CTR power plants, the research necessary to assure adequate ability to describe those effects, and the power plant designs that would result in minimum adverse environmental impacts. The CTR design concepts being developed were analyzed to determine the interactions with the environment and the resultant impacts. A conservative (or pessimistic) approach was used by assuming that only current technology would be used for designing the plant subsystems that control releases to the environment. Yet, the analysis still shows that the CTR has potential for substantially lower total environmental effects than current fossil or fission power plants or than the estimated effects of fast breeder reactors.

Performance of the environmental analysis has identified numerous deficiencies in the technology needed for making such analyses. The research efforts necessary for obtaining this information include numerous small efforts to provide missing data and analysis techniques unique to CTR evaluations. Nine of these small research efforts have been initiated during this quarter. These efforts will increase analysis capability for electricity demand forecasting, power plant thermal efficiencies and the environmental effects due to tritium and carbon-14 releases. Topical reports will be issued for each of these research efforts as they are completed.

The primary conclusions from the national review of the environmental analysis are that it correctly summarizes the probable environmental effects of the first commercial CTR

power plants and that it should be issued as a topical report that has the primary purpose of defining the research necessary to assure adequate ability to estimate the environmental effects of CTRs.

When the analysis is issued early in FY-1977, data currently being developed for the permeation of tritium at low pressures will be available. These data are expected to show low enough permeation rates that the loss of tritium by diffusion through reactor and cooling system structures will be insignificant.

The draft environmental analysis includes much background information and technical analyses that had not been previously summarized in the form desirable for an environmental analysis. In order to reduce the size of the environmental analysis, this information will be published as a series of reference topical reports.

Measuring Tritium in Food Pathways

JK Soldat, DA Baker

A revised model for the computer code called FOOD which calculates doses from the ingestion of vegetables and animal products contaminated from radioactive fallout was submitted for presentation at a forthcoming EPA-sponsored conference on Environmental Modeling and Simulation in Cincinnati, Ohio. Included in the revision is a new specific activity approach for movement of tritium through food pathways.

The computer program FOOD is designed to calculate radiation doses to man from ingestion of foods, such as produce, milk, eggs and meat contaminated by radionuclides. These radionuclides may be deposited on vegetation and the ground by water used for irrigation or directly from the air. A total of 14 food categories may be selected with corresponding consumption rates, growing periods and irrigation rates or atmospheric deposition assigned by the user. At present, doses to the total body, and six internal organs from 190 radionuclides may be calculated. Dose summaries are displayed at the local terminal. Additional details on percent contribution to dose by nuclide and by food type are available from an auxiliary high-speed printer. This latter output also includes estimated radionuclide concentrations in soil, plants and animal products.

The program is designed to be compatible with files of releases and dose factors which are used by a program, ARRRG, which calculates doses to man from ingestion of drinking water and aquatic foods and from aquatic recreation.

Tritium and Carbon-14 Model

The concentration of tritium or carbon-14 in environmental media (soil, plants and animal products) is assumed to have the same specific activity (pCi of nuclide per kg of soluble element) as the contaminating medium (air or water). The fractional content of hydrogen or carbon in a plant or animal product is then used to compute the concentration of tritium or carbon-14 in the food product under consideration. Hydrogen content in both the water and the nonwater (dry) portion of the food product is used to calculate the tritium concentration. It is assumed that plants obtain all their carbon from airborne carbon dioxide and that animals obtain all their carbon through ingestion of plants.

When carbon-14 is present only in the water used for irrigation it is difficult to model the transfer of this nuclide to vegetation, because plants acquire most of their carbon from the air. At this time we have not yet determined the transfer of carbon from the water to the air or soil. We have therefore conservatively assumed that plants obtain all their carbon from the irrigation water. Such an assumption could lead to plant concentrations which are high by about an order of magnitude or more. To date no operating nuclear facilities have been identified which specify releases of carbon-14 in their liquid effluents. However, this pathway could exist from migration of carbon-14 into ground water from long-term storage of nuclear wastes.

Global Model of Tritium Transported in the Atmosphere

TJ Bander, DS Renné

A global model for the dispersal of HTO, tritiated water vapor, which follows the hydrologic cycle has been formulated. Dividing the Earth's surface into 10° latitude belts, balance equations based on the amount of precipitable water vapor in the atmosphere and the amount of surface water in each latitude belt are obtained. The general form of the balance equation is:

$$\frac{dX_i}{dt} = \sum_{j=1}^{36} a_{ij} X_j + b_i$$

X_i is the amount of HTO in the atmosphere or surface water in a latitude belt. The coefficients a_{ij} are constants which depend on the amount of precipitation and evaporation in each latitude belt and also the net flow of water vapor and surface water between adjacent latitude belts. The b_i are essentially the source terms of HTO.

The main assumption which allows the balance equations to be written in the above linear form is that the amount of precipitable water vapor and surface water remain constant in each latitude belt. This assumption is fairly good when time periods of a year or longer are considered. The solutions of the homogeneous system of equations, $b_i = 0$, determine the eigenvalues and eigenvectors of the system, which are measures of the turnover time for the water vapor and surface water in each latitude belt. The particular solutions can be determined from the homogeneous solutions by the method of variation of constants and this solution represents the steady state values of HTO in each latitude belt.

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, Washington, 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.

Approval of the above-described three-course sequence was not granted in time for the 1975-76 academic year. Consequently, development of the course sequence is continuing during 1975-76 through the presentation of previously approved courses and special topics.

During Fall and Winter quarters the courses "Introduction to Plasma Theory, and Plasmas and Controlled Fusion" were presented. During Spring quarter, the special course, "Fusion Power Conversion and Materials Technology" will be presented.

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

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