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**Pacific Northwest Laboratory
Report on Controlled
Thermonuclear Technology
April 1976 - June 1976**

July 1976

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

Battelle
Pacific Northwest Laboratories

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PACIFIC NORTHWEST LABORATORY
REPORT ON FUSION REACTOR TECHNOLOGY
APRIL 1976 - JUNE 1976

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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 April 1, 1976 through June 30, 1976. The ERDA Division of Magnetic Fusion Energy is a major sponsor of the work. However, fusion-related work sponsored by others is also included as appropriate.

The summaries are presented in four major categories of:

- Fusion Systems Engineering
- Material Research and Radiation Environment Simulation
- Environmental Effects of Fusion Concepts
- 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.

D. A. Dingee
Fusion Programs Manager

Other Reports in the Series:

- Annual Controlled Thermonuclear Reactor Technology Report-1971, BNWL-1604.
- Annual Report on Controlled Thermonuclear Reactor Technology-1972, BNWL-1685.
- Annual Report for 1973 on Controlled Thermonuclear Reactor Technology, BNWL-1823.
- Annual Report for 1974 on Controlled Thermonuclear Reactor Technology, BNWL-1890.
- Report on Controlled Thermonuclear Reactor Technology, January through September 1975, BNWL-1939 1.
- Report on Controlled Thermonuclear Reactor Technology, October through December 1975, BNWL-1939 2.
- Report on Controlled Thermonuclear Reactor Technology, January through March 1976, BNWL-1939 3.

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REPORT ON CONTROLLED THERMONUCLEAR REACTOR TECHNOLOGY

APRIL THROUGH JUNE 1976

ERDA RESEARCH AND DEVELOPMENT REPORT

SUMMARY

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

Research during the past quarter in the systems engineering area continued to review the role of the fusion-fission hybrid in the mix of future energy sources. Working in cooperation with the Princeton Plasma Physics Laboratory, PNL researchers have evaluated various blanket concepts suited to mid-1980's TGT-driven hybrids. A helium-cooled metallic uranium fuel concept is under study, which appears to have satisfactory engineering performance. In addition to engineering designs, studies have continued this quarter to identify economic performance goals of hybrids. A draft document describing design, operation, and economic information which should be included in systems designs has been forwarded to DMFE. The economic performance goals of hybrid devices were compared using hybrid introduction date (1990 or 2000) and the availability of pure fusion and LMFBRs as parameters. The dependence of cost on date of hybrid introduction is quite small if neither the LMFBR nor pure fusion are available, but with either LMFBR or pure fusion in place, the hybrid faces a "time window" for economic introduction.

PNL surface effects researchers in cooperation with the University of California (LA) Tokamak group have demonstrated that special processing of the containment system for MICROTOR can reduce carbon impurities by more than two orders of magnitude. This was achieved by vapor deposition of nickel and radio frequency discharge cleaning with 10 to 500 eV hydrogen. Fast neutron and ion sputtering experiments are continuing; the first fast neutron sputtering data from "clean" gold is under analysis; and other materials are in preparation. A new energy spectrum degrader has been placed on-line to provide polyenergetic helium ions for high dose-rate irradiations. Niobium blistering data at high dose-rates are being investigated.

In the area of radiation damage, the interlaboratory correlation experiments which compare the microstructural damage induced by various laboratory ion sources is nearly complete. In general the heavy ion sources produce comparable swelling for a fixed dpa, but the swelling rate from

protons is significantly higher. Experiments simulating helium-induced mechanical degradation via the tritium-trick method have indicated considerably reduced tensile properties of a 15Cr-5Ti vanadium alloy at high test temperatures and ~25 appm helium when compared with the pure metal. This technique appears to be a useful screening procedure to evaluate alloys for fusion applications. The study of microstructural damage to molybdenum induced by bombardment with 5 MeV Ni⁺⁺ and 7.5 MeV Ta⁺⁺⁺ ions has revealed a damage zone extending well below the calculated dose-depth profile. Diffusion of point defects during the initial stages of irradiation is the most probable explanation for the extended range of microstructural damage. In the area of radiation effects on mechanical properties, techniques for the fusion neutron irradiation of wire specimens have been demonstrated; D-T neutron irradiations of wire and foil samples of nickel and niobium are complete, and their tensile properties are being evaluated and compared with data from fission neutron irradiations. Post-irradiation examination of graphite cloth samples irradiated in EBR-II at about 500°C to a fluence of about $3 \times 10^{21} \text{ cm}^{-2}$ equivalent fission fluence has been completed. In general the data show shrinkage of both the fibers and cloth specimens; cloth surface area is reduced by about 50%. The carbon-14 labeled phenolic resin precursor has been received and is being used to prepare glassy carbon samples for neutron sputtering measurements. PNL irradiation capabilities have been recently enhanced by the installation and operation of a high-temperature, high-vacuum furnace at the dual beam facility. This will allow simultaneous bombardment of materials with heavy ions for bulk damage simulation and helium ions for the simulation of (n, α) helium production.

During the past quarter, ongoing studies of electrical insulators for fusion power applications were directed toward defining the appropriate technique for measuring electrical resistivity of insulators, the measurement of time dependence of the dielectric strength of Al₂O₃ using the acoustic emissions technique, and the preparation of a review and evaluation of the SCB-type glasses. The high-rate sputter-deposition technology was used to prepare insulator coatings to a 350 μm thickness and 80 cm^2 area, employing deposition rates of 0.3 $\mu\text{m}/\text{min}$; this rate is nearly ten times faster than conventional sputtering processes. The high voltage breakdown characteristics of the high-rate sputter specimens appear very favorable, and the microstructure was fine-grained, containing only traces of the sputter gas.

The environmental studies are indicating that fusion power plants should have a lower total environmental impact than fission power plants. A summary report has been drafted, which analyzes the environmental impact of fusion reactor concepts in order to define R&D needs. The report is slated for issue early in FY-1977 while numerous reference reports presenting the detailed technical data and analyses are currently being issued.

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.

FUSION SYSTEMS ENGINEERING

A coordinated effort between scientists and engineers from PNL and the Princeton Plasma Physics Laboratory is underway to evaluate the Two Component Torus (TCT) concept as the basis for a conceptual design of a fusion-fission hybrid. The gross physical characteristics of the blanket have been defined, using a helium-cooled convertor concept. Preliminary calculations indicate the feasibility of the cooling system in which hollow, metallic uranium slugs inside a stainless steel tube would be cooled with helium flowing on the outside and through the center of the hollow slugs.

A document outlining the design, operation, and economic information that should be included in documents describing fusion reactor design concepts has been prepared by PNL to assure satisfactory economic and environmental comparisons of fusion reactor designs. This information requirements document has been sent to the Division of Magnetic Fusion Energy for comments prior to issue.

The first 6 of 10 evaluation cases for the fusion-fission hybrids have been computer simulated. The results of the first six cases evaluate the cost effects of changing the availability date of the fusion-fission hybrids from 1990 to 2000 under three different situations: 1) LMFBR in 1993, but no pure fusion reactor, 2) pure fusion reactors in 2010, but no LMFBR, and 3) neither LMFBR nor pure fusion reactors. The allowable capitalized costs for introducing the fusion-fission hybrids were estimated for each situation and for three different benefits within each situation--a zero benefit, a \$10 billion benefit, and a \$20 billion benefit. Changing the availability date has little effect on allowable capitalized cost when neither the LMFBR nor the fusion reactors are available. When either the LMFBR or fusion reactors are available, the allowable capitalized cost that yields the same benefit is reduced 25 to 45 \$/kwt, representing a 5 to 10% reduction for the later availability date.

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SYSTEMS STUDIES

System studies focus on providing key, early information for planning and analyzing the fusion power program. One concept under study in the national fusion program is the fusion-fission (hybrid) system, which offers a possible near-term use of the fusion principle. The PNL studies 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 fusion power systems and establishing target costs for fusion reactors. These studies seek to provide DMFE with new and additional information essential to planning and analyzing the fusion power program.

TCT-Hybrid Conceptual Design Study

RT Perry, Jr., DT Aase

The objective of this study is to develop a conceptual design of a hybrid based on current TCT technology. If the concept appears promising, a reference design will be developed. The ground rules are: 1) to optimize on production of fissile material, consistent with the requirement that a tritium breeding ratio in excess of one is obtained, 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 conceptual design of the TCT-Hybrid has been developed to the point that the gross physical characteristics of the blanket may be defined. The blanket is envisioned to

consist of a convertor region of uranium metal or alloy followed by a region of molten salt containing ^6Li , fissile, and fertile material. The structural material is stainless steel and helium is the primary coolant.

The convertor itself is composed of hollow metallic uranium slugs inside a stainless steel tube. They are cooled with helium flowing on the outside and through the center of the hollow slug. The stainless steel tube acts as the pressure vessel. A schematic of a coolant channel is shown in Figure 1.

The influx of 14 MeV neutrons and subsequent fast fission in the convertor will result in large power densities. Before proceeding with the design it was necessary to know if it appeared feasible to cool a convertor in this configuration. To find out, a set of coupled differential equations were developed and solved analytically to describe the temperature profile in the fuel and clad and the temperature of the coolant at any point down the coolant channel.

In formulating the equations, Newton's law of cooling was used to describe the heat flow through the coolant film. The Fourier equation was used for heat transfer through the clad, and a heat balance was made to obtain an equation to describe the heat transfer in the fuel. It was assumed there was no heat loss through the walls of the coolant tube.

In developing the equations it was assumed that there was no mixing of the coolant at the end of a slug, that the heat transfer parameters such as the thermal conductivity and heat capacity were constants, and that the volumetric heat source in the fuel was constant. However, since the solution to the differential equations requires initial

FIGURE 1. Fuel Channel Schematic

values for the coolant temperatures, it would be a simpler matter to refine the calculations. This could be accomplished by dividing the coolant channel into sections and using the final coolant values from a section as the initial values for the following section in which any desired parameter could be changed.

An example of the results is shown in Figure 2. Here the peak fuel temperature as a function of distance down the coolant tube for three different volumetric heat sources is shown. In each case the coolant velocity is 1×10^6 ft/hr and the initial temperature of the inside and outside coolant channel is 200°F . The uranium slug has an outside and inside radius of 0.167 and 0.08 feet, respectively. The exit (30 ft) coolant temperatures are shown on the graph.

The preliminary results given here do indicate that this convertor concept appears feasible from the standpoint of cooling. Optimization of the design will follow once the exact neutron load on the first wall is finalized.

FIGURE 2. Maximum Fuel Temperature as a Function of Distance Down Coolant Channel

Preliminary Economic Analysis

JR Young

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

Economic and environmental information requirements have been provided in a document prepared for the Division of Magnetic Fusion Energy. This document describes the related types of design, operation, and economic information that should be included in each design study and establishes certain basic general rules and assumptions that should be used in the development of that information. Provision of such information in design studies will assure that the necessary data are available and that satisfactory comparisons of design concepts can be made.

A draft of the information requirements document has been distributed to the Division of Magnetic Fusion Energy for comments.

Fusion Reactor Economic Regimes

RL Engel, DE Deonigi

The economic regimes task is determining the capitalized cost that allows fusion-fission hybrid reactors to achieve initial introduction in the electric power system, then eventually provide a satisfactory return on the research investment. PNL is evaluating ten competitive scenarios which are summarized in Table 1. In all cases, it is assumed that the hybrid produces plutonium.

The computer simulation for the first six cases and case 10 were completed in this reporting period; however, case 10 results have not been thoroughly reviewed and are not included in this report. We are currently processing case 7 (low U-price schedule) and case 8 (low energy demand). We are obtaining the α mass balance data for the improved breeder for case 9.

The results of the first six cases evaluate the effect of changing the hybrids availability date from 2000 to 1990 under three different competitive scenarios:

Cases 1 and 4 with LMFBR in 1993, but no pure fusion reactor
 Cases 2 and 5 with pure fusion reactors in 2010, but no LMFBR
 Cases 3 and 6 with neither the LMFBR nor pure fusion reactors.

TABLE 1. Parametric Hybrid Analysis Case

System Characteristics	DT Yr(a)	Case									
		1	2	3	4	5	6	7	8	9	10
Date of LMFBR Avail- ability 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.

The allowable capitalized costs for a very high efficiency electric producer (0.40 Mwe/MWt) are presented in Figures 3, 4 and 5. Different allowable costs are presented in each figure:

- the zero benefit* cost (initial introduction),
- the cost that would yield \$10 billion benefit through the year 2040 with 7.5% discount rate, and
- the cost that would yield \$20 billion benefit over the time period through 2040, also with a 7.5% discount rate. The term benefit here is taken to be the reduction in the total U.S. electric generating system discount cost due to the availability of the hybrid.

* The zero benefit allowable cost is computed from the so-called reduced cost, a standard sensitivity analysis feature of the linear programming algorithm. The reduced cost for a variable that is excluded from the optimal solution is the amount of cost reduction required for that variable to come into the solution. By placing a high enough cost on the hybrid so that it is excluded from the optimum mix of energy systems, the zero benefit allowable cost for the hybrid can be determined by subtracting the assumed cost from the reduced cost that is calculated.

FIGURE 3. Hybrid Allowable Capitalized Cost With LMFBR but No Fusion Reactor

FIGURE 4. Hybrid Allowable Capitalized Cost With Fusion Reactors but Without LMFBR

FIGURE 5. Hybrid Allowable Capitalized Cost With Neither the LMFBR Nor Fusion Reactors

Note that there is only one curve for the hybrid zero benefit allowable cost, independent of the availability date. The value of plutonium and uranium is increasing with time, so that as the hybrid cost is gradually reduced, it will first enter the solution for an optimal energy mix after the year 2000, regardless of the date of its initial availability. The cost that allows the hybrid to be built when it is first available, 1990 or 2000, is slightly lower than the zero benefit cost, and could only be determined by extensive iterative calculations.

Table 2 summarizes the differences in allowable capitalized costs for the medium plutonium-producing hybrids (1 kg-Pu/MWt), according to benefit and year of introduction. These differences range from 5 to 45 \$/kWt, representing 1 to 10% reductions in allowable capitalized cost for the 10 year change to the later hybrid introduction date--1990 to 2000. The cost difference in changing the hybrid introduction date is quite small in the case with neither fusion nor the LMFBR, but is as high as \$60/kW for the highest plutonium-producing hybrid (1.5 kg-Pu/MWt) in the case with only the LMFBR at \$20 billion benefit. In those cases with either the LMFBR or pure fusion, the later hybrid introduction date reduces the "time window" when fissile material is of greatest value, thus requiring that the hybrid be introduced with lower cost to yield the same benefit.

TABLE 2. Allowable Capitalized Cost (\$/kWt) for Fission-Fusion Hybrids Producing 1 kg-Pu/MWt Annually

First Year of Availability	With LMFBR Without Fusion Reactors (Base Case)	w/o LMFBR With Fusion Reactors	w/o LMFBR w/o Fusion Reactors
\$10 Billion Benefits			
1990	510	625	685
2000	470	600	680
Cost Difference	40 \$/kWt	25 \$/kWt	5 \$/kWt
\$20 Billion Benefits			
1990	460	575	650
2000	415	535	645
Cost Difference	45 \$/kWt	40 \$/kWt	5 \$/kWt

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MATERIALS RESEARCH AND RADIATION ENVIRONMENT SIMULATION

Studies are continuing to determine the influence that primary plasmas and plasma emissions and radiations have on materials to be used in fusion reactors. Recent data from the joint experiments between PNL and the Tokamak group at UCLA have correlated tokamak cleaning procedures with plasma impurities as well as effects on surfaces. Results from the first fast neutron irradiations of "clean" surface gold are being analyzed to determine sputtering ratios. Refinements of the polyenergetic blistering apparatus have increased dose-rate capabilities. Preparations for low energy ion sputtering experiments are nearing completion.

The effect of test temperature on vanadium susceptibility to simulated radiation damage via helium-induced premature failure was investigated during the past quarter. Annealed specimens of the refractory metal show helium-induced decreases in uniform elongation in both constant and variable temperature tests. Vanadium exhibits very low uniform elongation values at high test temperatures and high helium concentrations. Similar decreases in elongation with increasing test temperature and constant helium concentration were found with cylindrical V-15%Cr-5%Ti alloy specimens in a continuing joint PNL-ANL study of the alloy. The preliminary indications are that this high-strength vanadium-base alloy is drastically more susceptible to helium embrittlement than the weaker, unalloyed vanadium.

A heavy ion tandem accelerator has been added to the accelerator laboratory which increases PNL's capability for research in radiation environment simulation. The accelerator expands the range of charged particle beams available for research at the laboratory and can be used as part of dual beam irradiation facility which allows simultaneous bombardment of a target from two particle accelerators. Performance testing of the new accelerator is underway, and the high-temperature, high-vacuum furnace for bombarding materials with dual beams of heavy ions and helium ions is complete.

Much of the work on the Body Centered Cubic (BCC) Ion Correlation Experiment has been completed, and a summary was presented at the workshop on Ion Correlation Experiments at Oak Ridge National Laboratory in June. The interlaboratory analysis of the Round Robin molybdenum specimen passed between the various laboratories has been completed. These analyses and the interlaboratory void measurements made from a common micrograph provide a basis for comparing electron microscopy data from the different laboratories. Studies on the depth dependence of damage in ion bombardment of molybdenum with Ni^{++} and Ta^{+++} ions have continued. Examination of specimens bombarded at 900°C with either 5 MeV Ni^{++} or 7.5 MeV Ta^{+++} ions revealed a disagreement in the depth dependence of the dislocation loop damage between calculated and experimental curves. Further investigation of the depth dependence of void swelling in nickel-bombarded

molybdenum was accomplished by examination of specimens from the Ion Correlation Experiment. At higher dose levels and higher temperature, swelling extended beyond anticipated values.

The ion irradiation chamber and components for radiation environment simulation and the preparation of specimens for mechanical properties testing have been designed and ordered. An ultra-high vacuum chamber for performing evaluated temperature postirradiation tests on wire specimens has been constructed, and techniques for irradiating and testing wire specimens irradiated with fusion neutrons have been successfully demonstrated. Testing of wire and foil samples of nickel and niobium irradiated at 20°C with D,T neutrons is complete. Evaluation of some tensile property similarities between D,T fusion neutron-irradiated nickel wire and fission neutron-irradiated nickel were complicated by different irradiation conditions.

Postirradiation examination at PNL of graphite cloth and graphite fiber samples irradiated in EBR-II to $\sim 3 \times 10^{21} \text{ cm}^{-2}$ EFF at $\sim 500^\circ\text{C}$ has been completed and some of these samples have been sent to McDonnell Douglas Company for degassing measurements. The carbon-14 labeled precursor for use in the preparation of glassy carbon samples for sputtering measurements has been received, and sample preparation is in progress.

Study is continuing on the effect of low contaminant level, high-pressure, high-temperature helium on the mechanical and corrosion properties of fusion reactor structural materials. Five near term alloys were exposed to lightly contaminated helium at 650°C and 300 psi in two autoclaves. Initial runs were disrupted by a large water/hydrogen/methane outgassing phenomenon which was subsequently suppressed. One alloy, a set of Croloy specimens, was found to dominate the rate of oxygen consumption in the O_2 autoclave and was removed to allow determination of oxygen uptake of the remaining alloys.

Three experimental techniques have been defined for measuring the electrical resistance of high-value electrical insulators. These techniques are a resistance bridge, time rate of charge of a precision capacitor, and a micro-microammeter technique. The time dependence of the dielectric strength of Al_2O_3 at room temperature was measured using an acoustic emission technique. The observed increase in acoustic event energy with increased time appears consistent with a mechanism for dielectric failure in porous materials. A review and evaluation of SCB type glasses was initiated.

Though high-rate sputtering of SiO_2 and other related glasses has advanced to the stage where large-scale coatings for fusion reactor applications are feasible, target failures during the sputtering of Al_2O_3 and Y_2O_3 indicate that further research and development of these insulator coatings is necessary. Sputtering techniques have been used to form new materials that cannot be fabricated by conventional processes.

SURFACE SCIENCE RESEARCH RELATED TO FUSION REACTOR TECHNOLOGY

The surfaces of the primary plasma containment structure of the fusion reactors 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 fusion reactor blanket structures. Surface and near-surface damage will include sputtering and blistering. This will cause erosion and weakening of the fusion reactor walls and some of the sputtered heavy atoms entering the plasma may cause a loss in plasma energy.

Surface Effects

DL Styris, MT Thomas

Studies are continuing to determine the influence that primary plasmas and plasma radiations and emissions have on materials to be used in fusion reactors. A joint experimental effort of PNL surface scientists and R. Taylor's Tokamak group at the University of California in Los Angeles is underway to study the relationship between plasma impurities and the wall liner with emphasis on liner composition and vacuum processing. Recent experiments indicate that special processing of the containment walls of MICROTOR can reduce carbon impurities by more than two orders of magnitude. This was achieved by vapor deposition of nickel and radiofrequency discharge cleaning with 10 to 500 eV hydrogen. Resulting partial pressures of methane, which indicated relative amounts of carbon, were as low as 2×10^{-8} torr compared to 10^{-5} torr for an unconditioned chamber operating in a tokamak mode. Discharge cleaning with 500 eV Argon lowered the carbon impurity further, but resulted in Argon contamination when operation was in tokamak mode. Auger spectroscopy studies of materials used are in progress.

Existing fast neutron lattice dynamical sputtering data have been obtained from materials having near-surface to bulk metal atom density ratios less than unity; surface characterization and duplication of such material is difficult. The first fast neutron irradiations of "clean" surface gold have been completed, and the results are being analyzed to determine sputtering ratios from these surfaces. Similar experiments for different materials are in preparation.

Dose-rate capabilities in the polyenergetic helium ion blistering experiment were increased an order of magnitude with a new energy degrader design. Niobium blistering

thresholds using this higher dose rate are being investigated. Experiments to simulate prescribed ion spectra are being prepared.

Low energy (0 to 10 keV) ion sputtering experiments are being prepared to measure sputtering yields for helium and hydrogen ions at these energies. The experimental designs at the ion facilities have been completed, and most of the experimental apparatus components have been fabricated.

BULK RADIATION EFFECTS AND SIMULATION

Structural materials in fusion reactors will be subjected to bulk radiation damage from energetic neutrons coupled with cyclic temperatures and stresses. Materials research programs at PNL are directed toward understanding the effects of displacement damage combined with helium generation on the microstructure and mechanical properties of fusion candidate materials. The nature of displacement damage is being studied with heavy ion bombardment in a dual beam experiment for simultaneous heavy ion and helium bombardment near completion. The simulation of fusion neutron irradiation effects on the mechanical properties of materials is being evaluated in a correlation experiment between penetrating light ions and fusion neutrons. Also, the mechanical properties of fusion materials under dynamic irradiation conditions will be studied. The effects of helium formed during nuclear reactions between high energy fusion neutrons and the atoms in a structural material are being studied with specimens charged with helium by the decay of tritium to ^3He . The microstructure and short-time tensile properties, and creep properties of ^3He -charged niobium, vanadium, and V-15%Cr-15%Ti alloy are being studied.

Helium Effects in Fusion Reactor 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 fusion reactor 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 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).⁽³⁾ The helium charging method was described in a previous quarterly report⁽⁴⁾ and in Reference 5.

The majority of the tensile specimens currently utilized in this study are commercial purity niobium and vanadium in the annealed and cold-worked 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 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 annealed TEM specimens, along with the standard tensile specimens, are being used to study helium mobility 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 appm helium, and the short-time tensile properties of these metals were determined as a function of helium concentration at $\sim 1/2T_m$. 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 $\sim 1/2T_m$).

The effect of test temperature on vanadium susceptibility to helium-induced premature failure has been investigated this past quarter. The helium content for this series of tensile tests was kept at a level above that which induced embrittlement at 815°C. The specimens, containing a nominal helium concentration of 240 appm, were given a half-hour anneal at $1/2T_m$ (815°C) prior to testing in order to produce a consistent pre-test bubble distribution. The annealed specimens were then tested at temperatures ranging from 600 to 750°C.

The resultant elongations for the variable temperature tests and the constant temperature tests are presented in Figure 6. The elongations plotted in Figure 6 show that a helium-induced decrease in uniform elongation is present for both types of tests. The vanadium exhibits very low uniform elongation values at high test temperatures and at high helium concentrations. The uniform elongation values change from approximately 10% to less than 1% over a relatively short temperature or concentration range as the test temperature or helium concentration is increased. The total elongation remained approximately constant with helium content and with test temperature.

The changes in uniform elongation noted above were interpreted as being caused by a change in the controlling deformation mechanism. The high uniform elongation values result from "normal" matrix controlled deformation. The low uniform elongation values result from grain boundary controlled deformation. Grain boundary deformation is favored by the presence of helium bubbles on the grain boundaries, which decreases the load-carrying capacity of the grain boundary, or by high testing temperatures, which decrease the grain boundary strength relative to that of the matrix. Both of these potential causes of gross grain boundary deformation combine at high helium concentrations and high temperatures to cause a substantial decrease in uniform elongation.

FIGURE 6. Elongation of Annealed Vanadium as a Function of Helium Content and Test Temperature

The same trend of decreasing elongation with increasing test temperature (at a constant helium concentration) has been found in this quarter's work on cylindrical V-15%Cr-5%Ti alloy specimens tested as a continuation of the joint PNL-ANL study of this alloy.

The elongation results for specimens helium-charged by tritium decay to approximately 25 appm are shown in Figure 7 (the alloy rod stock was furnished by R. F. Mattas at ANL). The vanadium alloy test conditions cover essentially the same temperature range as the commercial purity results presented in Figure 6.

A comparison of the commercial purity vanadium and the vanadium alloy uniform elongation trends reveal a striking difference between the helium tolerance of the unalloyed material and the alloyed material. The commercial purity vanadium absorbed over 150 appm helium at 815°C before reduction in uniform elongation occurred. The vanadium alloy requires less than 25 appm helium for substantial reductions in uniform elongation at 815°C.

The susceptibility of the V-15%Cr-5%Ti alloy to helium embrittlement was originally studied because it was the highest strength vanadium-base alloy developed at ANL and thus an attractive alloy for fusion reactor applications.⁽⁶⁾ The results of this

FIGURE 7. Elongation of Tritium Tricked V-15Cr-5Ti Alloy Containing 25 appm Helium as a Function of Test Temperature.

preliminary alloy effects study indicate that, for fusion reactor applications, the gain in strength of this alloy over the pure metal was paid for by a drastic increase in susceptibility to helium embrittlement.

Radiation Environment Simulation--Heavy Ion Tandem Accelerator

LH Toburen, TL Criswell

A major milestone in the further development of PNL research capabilities for ion beam irradiation has been reached with the addition of a 2-MV heavy ion tandem accelerator to the PNL accelerator laboratory. The tandem accelerator, the existing 2-MV single-stage Van de Graaff accelerator, and a low energy ion accelerator now provide a range of charged particle beams from protons to heavy metallic ions such as gold and tantalum. The energy range of positive ion beams available extends from 0.005 to 4.0 MeV for protons and to as high as 8 to 10 MeV for multi-charged heavy ions. In addition, the unique design of the facility allows for simultaneous bombardment of a target using beams from both the 2-MV tandem and 2-MV single-stage Van de Graaff accelerators. Figure 8 shows the physical arrangement of the facility and the location of various ongoing research efforts.

Dual Beam Irradiation Facility with High-Temperature, High-Vacuum Furnace. Figure 9 shows the dual-beam irradiation facility located at the intersection of the beam lines from the tandem and Van de Graaff accelerators (also shown as element A in Figure 8). In this configuration, helium can be implanted to simulate the production of helium

- A. Dual beam irradiation facility--bulk radiation effects on materials (DPR and DMFE).
- B. Differential ionization cross-section measurements (DBER).
- C. Surface physics--blistering measurements (DMFE).
- D. Time-resolve radioluminescence studies--lifetime measurements of excited chemical species in liquid systems (DBER).
- E. Calorimetric measurements of energy defects in plastics (DBER).
- F. Differential ionization cross-section measurements (DBER and BI).
- G. Radiation biology--direct irradiation of cells by high LET radiation (DBER).
- H. Future station for low-energy heavy ion research.
- J. Neutron activation analysis (DBER and NASA).

FIGURE 8. Schematic Description of the Accelerator Facility Showing the Present Use of Various Experimental Stations

within the material through (n,α) reactions simultaneously with the bombardment by heavy ions which simulate bulk radiation damage. The high-temperature, high-vacuum furnace needed for bombarding materials with dual beams of helium ions and heavy ions is complete, and testing and alignment of the heavy ion beam with the specimen target is currently in progress. PNL will study a wide variety of materials using the furnace and dual beam capability; among these are pure molybdenum, nickel base alloys, and stainless steel alloys.

FIGURE 9. Dual Beam Irradiation Facility

Performance Testing of the Heavy Ion Tandem Accelerator. Performance testing of the new accelerator is now underway. Tests using a duoplasmatron negative ion injector have been successful in demonstrating design specifications of current, voltage, and beam stability for proton beams. Beam currents of 10 microamperes for 4-MeV protons were focused to the target with current stability of $\pm 10\%$ for an 8-hour period; energy

stability is better than ± 500 eV. The sputter-ion injector is presently being extensively tested for performance characteristics. The design specification of 0.5 microamperes of Ni^{++} at 6 MeV has been met, and PNL is now investigating the charge state ratios at various energies for the nickel beam. In addition to the work with nickel beams, an 8-MeV beam of Ta^{+++} has been accelerated; further investigation of the capabilities of the tandem for tantalum beams is underway.

Further Capabilities Provided by the Heavy Ion Tandem Accelerator. In addition to providing special capabilities for the ongoing research in materials science, the new heavy ion accelerator will provide the capability to investigate collision phenomena which play an important role in thermonuclear plasma heating and confinement. Such processes as charge transfer, excitation, and ionization can be studied for heavy ions over a broad range of ion species and ion energies. With a slight modification of the inflection magnet chamber, either negative ion injector can be used independently as an intense source of low energy positive ions. Figure 10 shows the tandem accelerator ion injectors and the present inflection chamber. The ability to use beams either directly from these ion sources or indirectly from the accelerator provides the facility with a range of heavy ion energies spanning four orders of magnitude.

FIGURE 10. Dual Ion Injectors and Inflection Magnet

Structural Damage Characterization

JL Brimhall, ER Bradley

BCC Ion Correlation Experiment

The interlaboratory ion correlation experiment developed by PNL 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, a "Round Robin" specimen, was distributed to the laboratories for ion bombardment and analysis of the microstructure. In addition, a common electron microscope specimen and a common electron micrograph were analyzed by the participating laboratories to determine what constitutes meaningful differences in the experimental data.

Much of the work on the BCC Ion Correlation Experiment has been completed. A summary of this work was presented at the workshop on Ion Correlation Experiments at Oak Ridge National Laboratory in June. Figures 11 and 12 compare the dose dependence and temperature dependence of the swelling, respectively, for the various ion sources on a calculated dpa basis. The data from heavy metal ion bombardments agree quite well, although the swelling rate from 17 MeV Cu^{4+} ions is somewhat smaller. The swelling rate from protons is significantly higher than from heavy ions.

The results from the measurements on a common micrograph and the Round Robin specimen are given in Tables 3 and 4. The results from these experiments provide a basis for comparing experimental (TEM) results from different laboratories. A spread of $\pm 7\%$, about the average in the void size, and $\pm 35\%$, about the average in the void density, was found in the Round Robin examination. However, the spread in the void volume fraction was only $\pm 25\%$, because of compensating errors. These experiments represented good conditions, so agreement within an error band of this type is as good as can be expected.

Implanted Ion Effects

Studies on the depth dependence of damage in ion-bombarded molybdenum have continued during this reporting period. In the previous quarterly report the initial results of the depth dependence of damage in molybdenum bombarded* at 900°C with either 5 MeV Ni^{++} or 7.5 MeV Ta^{+++} ions were presented. Examination of these specimens to depths $> 3 \mu$ below the surface has been completed and the results evaluated in terms of the

* The ion bombardments described in this study were done at the High Voltage Engineering Corporation accelerator in Massachusetts.

FIGURE 11. Dose Dependence of Swelling in Mo Bombarded by Different Ions at 900°C

FIGURE 12. Temperature Dependence of Swelling in Mo Bombarded by Different Ions

TABLE 3. Void Measurements on a Common Micrograph

Site	Void Diameter (nm)	Number Measure	Void Density $N/m^3 \times 10^{-22}$	Void Volume Fraction (%)
1	8.4	--	5.86	2.2
2	7.9	1840	5.96	1.96
3	8.0	1664	5.85	2.07
4	7.8	--	5.10	1.63
5	8.2	1703	6.4	2.95
6	8.2	600	5.91	2.2
7	7.7	1850	5.57	1.68
8	7.8	700	6.04	2.04
Avg	8.0		5.84	2.00

TABLE 4. Data From "Round Robin" Specimen

Site	Size (nm)	Density (m ⁻³)	Volume Fraction (%)	Void Lattice (nm)
1	8.2	4.55×10^{22}	1.74	--
2	6.4	1.2×10^{23}	2.1	--
3	8.74	6.04×10^{22}	2.85	37.5
4	8.0	5.8×10^{22}	2.07	35.0
5	7.44	1.0×10^{23}	2.96	--
6	8.4	6.35×10^{22}	2.62	36.5
7	8.5	6.4×10^{22}	2.6	36.5
Avg	8.0	7.3×10^{22}	2.42	35.8

integrated dislocation loop area which is proportional to the retained defect concentrations. Figures 13 and 14, respectively, compare the integrated loop area with the calculated displacement damage curves for the nickel and tantalum ion irradiations. There are significant differences between the shapes of the experimental and calculated curves for both ions. Specifically, the experimental curves do not show a peak damage zone, and the damage does not drop off as swiftly as indicated by the calculated curves. Dislocation loop damage was actually observed to depths $>3 \mu$, but below 2.5μ the damage distribution was very heterogeneous, making quantitative analysis impractical.

FIGURE 13. Comparison of the Calculated and Experimental Depth Dependence of Damage in Molybdenum Bombarded with 5 MeV Ni⁺⁺ Ions (2×10^{16} ions/cm²)

FIGURE 14. Comparison of the Calculated and Experimental Depth Dependence of Damage in Molybdenum Bombarded with 7.5 MeV Ta⁺⁺⁺ Ions (3×10^{15} ions/cm²)

The disagreement between the experimental and calculated curves in the depth dependence of the dislocation loop damage as well as the conflicting evidence reported last quarter on the influence of the implanted nickel ions on void formation prompted further investigations and the depth dependence of void swelling in nickel-bombarded molybdenum. This was accomplished by examination of the entire damage zones of specimens from the Ion Correlation Experiment.

Void swelling as a function of depth for various nickel ion doses is shown in Figures 15 and 16 for bombardment at 900°C and 1000°C, respectively. These results show that only the low dose specimen bombarded at 900°C conforms to the shape of the displacement damage curve. At higher dose levels and at higher temperature, swelling extends beyond that anticipated from the calculated curves. Dislocation loop damage was observed to depths of $\sim 3 \mu$ for all specimens.

The low swelling values at 1μ below the surface in both of the high dose specimens is associated with the presence of rod-shaped precipitates in this region. Similar

FIGURE 15. The Depth Dependence of Void Swelling in Molybdenum Bombarded with 5 MeV Ni^{++} Ions at 900°C

FIGURE 16. The Depth Dependence of Void Swelling in Molybdenum Bombarded with 5 MeV Ni^{++} Ions at 1000°C

precipitates have been observed in molybdenum bombarded with nickel ions under a variety of conditions, and the experimental observations regarding these precipitates can be summarized as follows:

- The precipitates first form in the region $\sim 1 \mu$ below the bombarded surface.
- The appearance of the precipitates has a strong dose dependence but depends only slightly on dose rate as shown in Figure 17.
- The width of the zone containing the precipitates increases with increasing dose, increasing temperature, and decreasing dose rate.

The strong dose dependence and the fact that the precipitates first appear at a depth of $\sim 1 \mu$ suggest that the implanted nickel ions are promoting the precipitation. For a dose of 2×10^{16} ions/cm², ion range calculations show a maximum nickel concentration of 0.7% to occur at a depth of 1.1 μ . Since the solubility of nickel in molybdenum is less than 0.8% below 1200°C, it appears that precipitation occurs when the solubility limit is exceeded. However, the dose rate and temperature dependence indicate that diffusion may also be an important parameter in the precipitate formation.

FIGURE 17. The Dependence of Dose and Dose Rate on the Formation of Precipitates at a Depth of $\sim 1 \mu$ Below the Surface in Molybdenum Bombarded with 5 MeV Ni⁺⁺ Ions

Diffusion of point defects during the initial stages of irradiation is the most probable explanation for the extended range of the microstructural damage. Calculations on the depth dependence of the defect concentrations during ion bombardment have shown high concentrations of defects beyond the damage zone due to diffusion processes. However, the diffusion distance decreases rapidly with increasing sink density, and thus long-range diffusion is expected to be important only during the initial stages of irradiation before the microstructural damage fully develops.

Radiation Environment Simulation--Mechanical Properties

RH Jones, DL Styris, RP Marshall

The long term objective for this program is the development and application of a mechanical testing apparatus for use in ion beam irradiations which has sufficient flexibility to perform a variety of mechanical property experiments. The first application of this apparatus will be to determine the correlation between the properties of light ion- and neutron-irradiated materials and to evaluate the effects of the ion irradiation environment, damage gradients, and specimen size.

To date, an ion irradiation chamber has been designed and ordered with ultra-high vacuum capabilities, a high-purity helium gas loop for specimen cooling, and ion beam and specimen temperature monitors. A specially designed ultra-high vacuum chamber for performing elevated temperature post-irradiation tests on wire specimens has been constructed.

A successful demonstration of the techniques for the irradiation and tensile testing of wire specimens irradiated with fusion neutrons has been completed. A technique for simultaneously irradiating 20 wire specimens (10 nickel, 10 niobium, 1 foil of each), locating the irradiated zone, electropolishing a 0.13 mm dia by 5 mm long gage section, and tensile testing at 20°C has been developed. Six wire packets containing 10 wires of nickel, niobium, and 316 stainless steel plus nickel and niobium foils have been prepared for D,T and D,Be neutron irradiations at 20°C.

During this reporting period, PNL staff participated in the 8th ASTM International Symposium on Effects of Radiation on Structural Materials held on May 4-6, 1976, at St. Louis, Missouri in a task group on "The Measurement of Mechanical Properties During Ion Irradiation."

Irradiation and Testing Systems

These experiments require fabrication and assembly of two primary apparatus; the ultra-high vacuum (UHV) ion irradiation system necessary to control the irradiation environment and the UHV postirradiation test chamber necessary for high temperature testing in a controlled environment. The postirradiation system is complete and undergoing preliminary tests. It consists of a vacuum chamber, sample grips, sample positioners, infrared windows for radiation heating of the sample, and ion- as well as titanium-sublimation pumping capabilities.

The ion irradiation system being assembled is designed to minimize sample contamination. The system is bakeable and yields a base pressure of 5×10^{-10} torr. Helium, the sample coolant used in this system, is cycled through an all-stainless steel, bakeable helium pump chamber, then purified and recycled. Contaminants in the helium gas are monitored with a quadrupole mass analyzer. Oxygen contamination, a particular concern here, is minimized by vacuum processing and cryopumping. Vacuum pumping is achieved with a 60 l/sec ion pump and titanium sublimation. Assembly has begun and delivery of all major components has been made with the exception of the helium pumping system. This will not delay irradiation scheduling since initial experiments do not require extensive helium flow rates; helium will be vented to the atmosphere.

Initial ion irradiations will be made at the University of Washington's Van de Graaff facility. The model FN tandem, High Voltage Engineering Corporation machine used there will produce a maximum 18 MeV, 10 μ ampere proton beam with two stages of acceleration and a 24 MeV, 5 μ ampere proton beam with three stages. Energy variations can be expected to be about 1 keV through the deflection magnets and about 50 keV out of 15 MeV on the straight-through line. Beam focusing to approximately 1 mm spot size is possible. Because of proximity to PNL and the excellent facilities available to users of this Van de Graaff, it is felt that the University of Washington facility is ideal for shakedown of the ion-simulation systems and low dose rate experiments.

(D,T) Neutron Irradiation Results

A wire and foil packet containing 10 nickel and 10 niobium wires and a nickel and niobium foil has been irradiated with D,T neutrons at 20°C to a fluence of 2.45×10^{17} n/cm². The irradiation and dosimetry were performed by the Lawrence Livermore Laboratory while the disassembly and testing were performed by PNL. The position and profile of the neutron beam were determined from an autoradiograph obtained by placing the packet against a fluorescent screen and exposing Type 57 polaroid film. The wire positions were determined by superimposing an x-radiographic image of the packet on the autoradiograph. The beam profile was determined by scanning a negative of the autoradiograph with a photo densitometer. The uniform portion of the irradiated zone was

7.9 mm in the direction of the wire axis and 9.5 mm perpendicular to the wire axis. A 0.13 mm dia by 5 mm long gage section was produced by lacquering the wire ends and electropolishing. The gage section diameter was measured with a light microscope fitted with a micrometer eyepiece and operated in the transmitted light mode. This light mode produced the best edge resolution.

The tensile properties of the D,T fusion irradiated nickel wires tested at 20°C and a strain rate of $2 \times 10^{-2} \text{ min}^{-1}$ are given in Table 5. The unirradiated annealed nickel wire properties are also given for comparison. A yield strength increase of 15,400 psi and 12,400 psi was found for a D,T neutron fluence of $2.45 \times 10^{17} \text{ n/cm}^2$ based on the minimum area and average area yield strengths, respectively. The minimum area was calculated from the minimum diameter within the gage length while the average area was calculated from the average of six diameter measurements. Other property changes observed with irradiation include an increase in the work hardening rate at 1% plastic strain, an increase in the ultimate tensile strength, and a decrease in the total elongation.

TABLE 5. Tensile Properties of MRC Marz Grade Nickel Wire Irradiated with (D,T) Fusion Neutrons at 20°C

Specimen Number	Condition	0.2% YS, psi	0.2% YS, psi	(dσ/de)	Uts, psi	ε _T , %
		min area	avg area	1%, psi		
TNi-2	$2.45 \times 10^{17} \text{ n/cm}^2$ *	26,600	21,800	192,000	54,800	28
TNi-3	$2.45 \times 10^{17} \text{ n/cm}^2$	25,200	22,800	401,000	58,100	20
TNi-5	$2.45 \times 10^{17} \text{ n/cm}^2$	25,400	23,900	380,000	55,200	18
TNi-6	$2.45 \times 10^{17} \text{ n/cm}^2$	27,100	22,800	396,000	53,100	17
Average	$2.45 \times 10^{17} \text{ n/cm}^2$	26,100	22,800	342,000	55,100	21
Standard Deviation	$2.45 \times 10^{17} \text{ n/cm}^2$	943	848	100,000	2,100	5
Annealed Ni Wire	Unirradiated	10,700	10,400	241,000	48,000	29

* Dosimetry performed by Lawrence Livermore Laboratory

A comparison between the tensile properties of D,T fusion neutron-irradiated nickel wire and fission neutron-irradiated nickel is presented in Table 6. Differences in material purity, irradiation temperature, and neutron energy spectra complicate this comparison. Similarities in this data include an increase in both yield and ultimate strengths and a decrease in total elongation with irradiation. A discrepancy in the change in the work-hardening rate with irradiation was noted between the PNL results and the Makin⁽⁷⁾ and Laidler⁽¹¹⁾ results. Further tests on unirradiated nickel wire will be conducted to verify the PNL results.

TABLE 6. Comparison of the Tensile Properties of Fission and Fusion Neutron Irradiated Nickel Tested at 20°C

Material		Irradiation		0.2% YS	(dσ/dε), 1%	Uts	ε _T , %	Ref.
Source	Purity	Fluence n/cm ²	Temp.	psi	psi	psi		
MRC	99.99	0	20°C	10,700	241,000	48,000	29	PNL Rtns Wire Data
		2.5 x 10 ¹⁷ E = 14 MeV	20°C	22,800	342,000	55,300	21	
British Driver Co., Lt	99.83	0	20°C	35,800	297,000	58,200	34	
		5 x 10 ¹⁹ Slow Neutrons	20°C	61,200	51,000	62,400	23	7
		0	22°C	13,500	-	46,200	55	
	99.81	1.1 x 10 ²⁰ (total)	220-250°C	31,200	-	49,000	35	8
		0	20°C	17,800	-	45,400	28	
	Commercial	7 x 10 ¹⁹ (total)	70-100°C	30,500	-	48,300	17	9
	99.95	0	20°C	4,700	-	49,400	44	10
		1.4 x 10 ²⁰ fast	20°C	56,800	-	63,600	22	
		3.5 x 10 ²⁰ thermal						
Vacuum Melted electrolytic nickel	99.9	0	22°C	23,000	505,000*	52,000	35	11
		1 x 10 ¹⁹ in MTR	22°C	59,000	145,000*	67,000	21	

* Determined from published graph

The difference in the irradiated and unirradiated yield strengths ($\Delta\sigma_{ys}$) as a function of neutron fluence for nickel and copper is shown in Figure 18. It is apparent from this plot that quantitative comparisons between fusion and fission irradiated nickel is complicated by irradiation conditions. A comparison on a displacement per atom (dpa) basis is complicated by the lack of reported fission neutron energy spectra. The completion of future PNL experiments on (D,T)-, (D,Be)-, and p⁺-irradiated nickel wire at variable fluences, which is the basis of the ion/neutron correlation experiment, will produce more complete results for comparison to the published fission neutron-irradiated properties.

FIGURE 18. The Difference in the Irradiated and Unirradiated Yield Strengths as a Function of Neutron Fluence for Nickel and Copper

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 coolant compatibility.

Evaluation of Carbons and Graphites for Controlled Thermonuclear Reactor Applications

WJ Gray, WC Morgan, GL Tingey

Some fusion reactor concepts have proposed the use of a low-Z liner between the plasma and the first structural wall. A number of materials are being considered for the liner including graphite or graphite cloth. Among the more important data required before the choice of liner materials can be narrowed 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 fusion reactor conditions.

Radiation Damage in Graphite Cloth

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

* All fluences are quoted in terms of "Equivalent Fission Fluence for Damage in Graphite." (13)

subassembly was discharged in September 1975, after a fluence of about $3 \times 10^{21} \text{ cm}^{-2}$ EFF. The other two subassemblies will be discharged in July 1976, after fluences of about 6 and $9 \times 10^{21} \text{ cm}^{-2}$ EFF, respectively.

Postirradiation examination at PNL of samples from the first subassembly has been completed and some of the samples have been sent to McDonnell Douglas Company for degassing measurements. All the data are shown in Table 7 except for extensive optical and scanning electron microscopy, some of which has been discussed previously^(14,15) and will be published in entirety later.⁽¹⁶⁾

TABLE 7. Changes in Graphite Cloths and Fibers Irradiated to $\sim 3 \times 10^{21} \text{ cm}^{-2}$ EFF at $\sim 500^\circ\text{C}$ (a)

CLOTHS:

No.	Sample Type	Fiber Length Change (%)	Density Change (%)	Surface Area Change (%)
1	Thornel-50	$-8.0 \pm 0.6^{(b)}$	9.3	-67
2	GSGC-2	-8.6 ± 0.4	16.5	-49
3	WCA	-8.2 ± 0.5	14.7	-45
4	GSCC-2	-6.6 ± 0.5	18.0	-58

FIBERS:

No.	Sample Type	Equivalent Diameter Change (%)
1	Thornel-50	$+2.5 \pm 3.3^{(b)}$
2	GSGY-2	-10.5 ± 2.2
3	WYB-85-1/2	-3.2 ± 2.1
4	Type A	-4.8 ± 2.9
5	C-20	-9.5 ± 1.5

- a. Fibers in cloth samples 1 and 2 are the same as fiber samples 1 and 2. Fibers in cloth sample 3 are similar to fiber sample 3. No other direct comparison exists.
- b. Uncertainties are approximately at the 95% confidence level.

The changes in surface areas and equivalent fiber diameters shown in Table 7 have not been published previously.^(14,15) The cross sectional areas of the fibers, which are quite irregular in shape, were measured and converted to circles of equivalent area to determine the equivalent diameter changes shown. Although uncertainties in the diameter changes are rather large, Thornel-50 appears to have swelled slightly whereas the other types of fibers shrank. In a previous irradiation, Peggs⁽¹⁷⁾ found Thornel-50

fibers swelled ~50% in the radial direction after $1.5 \times 10^{21} \text{ cm}^{-2}$ EFF at 400 to 700°C. It is not presently known whether Thorne1-50 fibers first swell quite dramatically in the radial direction and then shrink when irradiated near 500°C or if temperature differences in the two irradiations are responsible for the different radial dimensional changes.

The surface area changes are quite large and, in fact, exceed by a large margin changes calculated from radial and axial changes of fiber dimensions. Evidently some very fine porosity not visible at 30,000X has been eliminated. Similarly, calculated density changes for samples 1 and 2 are not matched by measured density changes although the differences are in opposite directions in the two cases.

Sputtering Measurements

The carbon-14 labeled phenolic resin precursor, which will be used to prepare glassy carbon samples for the sputtering measurements, has been received, and sample preparation is in progress. Neutron sputtering measurements on these samples by the surface science group are expected to begin late in the next quarter with ion and chemical sputtering measurements to follow.

Helium Compatibility with Fusion Reactor Materials

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

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. (18,19,20) Helium operates in a single-phase thermal hydraulic regime, is non-flammable 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.

This study was initiated to determine the effect of low contaminant level, high pressure, high temperature helium on the mechanical and corrosion properties of potential fusion reactor structural materials--the best attainable helium purity is not good enough to totally prevent contaminant/metal corrosion reactions at elevated temperatures. The program 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 to simulate the effects of air contamination or oxygen additions for tritium recovery purposes. 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 to simulate a system where in-leakage from the steam side of the heat exchanger contributes the major contaminant species.

The exposed alloys consisted of three stainless steels (316, 321, 347), a high nickel alloy (Incoloy 800), and a ferritic alloy (2.25% Cr - 1% Mo Croloy). The 321 and 347 stainless steels are both basically 316 SS with minor alloying additions and were included in the study because minor alloying elements are known to influence oxidation resistance and mechanical properties in high-temperature, high-impurity atmospheres. The titanium in 321 SS and the niobium and tantalum in 347 SS are expected to substantially change both the oxidation rate and the type of oxide morphology which occurs on a given alloy in low-impurity helium. The Incoloy 800 alloy was added to study the effect of high nickel content, and the Croloy alloy was included in order to determine the feasibility of using ferritic components in an impure helium atmosphere.

In the initial runs the intentionally-added 50 vppm contaminant levels were "swamped out" by a large water/hydrogen/methane outgassing phenomenon in both autoclaves at the low gas flow rates used. The water vapor apparently comes from the outgassing of the absorbed water in the ceramic furnace tubes and the metal specimen and specimen holder surfaces. The hydrogen probably comes from the reduction of water by chromium and iron during the formation of their respective oxides, while the methane probably arises from decarburization reactions on the surface of the Croloy specimens.

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 hours. Contaminant levels up to 800 vppm hydrogen and 125 vppm methane occurred during these initial runs. This outgassing phenomenon was suppressed during the second startup of the O_2 autoclave by a combination of step heating and high test gas flow rate. It was found during a third startup that the outgassing of methane and hydrogen could also be suppressed under low flow rates and high O_2 concentrations (up to 400 vppm O_2). The results of these latter runs indicate that the hydrogen and methane outgassing can be completely suppressed (<1 vppm) by either a high gas flow rate and low oxygen concentration or a low gas flow rate and a high oxygen concentration if the exit gas remains oxidizing.

It was also found that the rate of oxygen consumption in the O_2 autoclave was completely dominated by the presence of the Croloy specimens even though they were only one-fifth of the specimens in the autoclave. No oxygen was found in the exit gas until the O_2

input rate was greater than the oxidation rate of Croloy at 650°C in air. Thus the limiting oxidation rate of Croloy in 300 psi helium at 650°C was found to be essentially that of Croloy in one atmosphere air at 650°C.

The Croloy specimens were subsequently removed from the O₂ autoclave to allow determination of oxygen uptake of the remaining alloys. It was found that the atmosphere remained oxidizing during startup of the remaining four alloys at the 50 vppm O₂ concentration and low flow rate conditions used in the initial startup. It was also found that there was essentially no hydrogen or methane outgassing during heatup.

*Electrical Insulators for Fusion
Reactor Applications*

JL Bates, JE Garnier

Various fusion reactor concepts require the use of electrical insulators in a variety of critical locations. The electrical insulator requirements will vary among reactor designs and within each reactor. One of the more stringent requirements is the 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. There is currently no known available insulator material(s) capable of meeting these requirements. The objective of this program is to define and develop experimental techniques which will allow the study and evaluation of the electrical and related properties of potential electrical insulators for fusion applications. The ultimate goal is to find or develop suitable electrical insulators which meet the varied requirements for fusion reactor designs.

Work in this quarter has been directed toward the defining of techniques for measuring electrical resistivity of insulators, the measurement of the time dependence of the dielectric strength of Al₂O₃ using acoustic emissions, and the preparation of a review and evaluation of the SCB-type glasses.

Techniques for Measurement of Electrical Resistivity

The electrical behavior of insulators, metal oxides in particular, is usually strongly dependent upon temperature and composition. When the resistivity is high, conduction may occur by both electronic and ionic processes. The selection of an oxide for a particular application is usually dependent on the magnitude of its electrical conductivity.

In oxide insulators, such as Al_2O_3 and BeO , which exhibit large bandgap energies and small deviations from stoichiometry, the electrical conductivity tends to be extrinsically controlled unless the measurements are made on very high purity specimens at high temperatures. Even if high purity specimens are prepared, the problem of preventing contamination with impurities in situ at high temperatures remains. When the electrical behavior of materials with high resistance are investigated care must be exercised to avoid leakage paths arising from either surface or gas-phase conduction. The effects of gas-phase and surface conduction may be either eliminated or minimized using a guarded circuit and isolating the gas phase at the electrodes. This is accomplished by maintaining the guard electrode at the same potential as the center electrode.

Three circuits have been designed to measure the sample resistance for dc, $\pm$ dc, and high $\pm$ dc, ac, and pulsed voltage potentials (Figures 19, 20, and 21, respectively). Common to all three figures is the sample geometry and guarded electrode arrangement. A sample guard at ground potential surrounds the center electrode which is at virtual (e.g., ± 0 volts) ground. In Figures 19 and 20, the high potential is supplied by a dc voltage source internal to the measuring instrument (shown as a dashed line). The sample resistance, R_x , is determined by a precision bridge network (Figure 19) or by the time rate of charge of a precision capacitor (Figure 20).

FIGURE 19: Megohm Bridge Arrangement: dc Voltage Potentials

$$R_x = \left[\frac{R_1 \cdot 1}{R_2 \cdot fC} \right] \bar{N}$$

FIGURE 20. Teraohmmeter Arrangement: $\pm$ dc Voltage Potentials

FIGURE 21. Micro Microammeter Arrangement: $\pm$ dc, ac, and Pulsed dc Potentials

The experimental arrangements described in Figures 19 and 20 can measure dc sample resistances up to 1000 volts applied dc potential. To evaluate the electrical resistivity of insulators at high dc voltage potentials, ac potentials, and/or pulsed voltages, an experimental arrangement as shown in Figure 21 is proposed. A micro microammeter is used to measure the current flow through the sample during the application of an external high voltage potential. The output from the micro microammeter is then recorded on a transient waveform recorder. A high voltage divider (1000:1) is used to drop the applied voltage potential. At 20 kV applied voltage potential this results in a voltage of 20 volts, which is conveniently recorded on a transient waveform recorder. The sample resistance may be determined from the simultaneous recording of applied voltage and current flow.

Time Dependence of the Dielectric Strength of Al_2O_3 Using Acoustic Emission Techniques

The time dependence of the dielectric strength of Al_2O_3 was measured at room temperature using an acoustic emission technique.* The output of the AEEEA (acoustic emission event energy analyzer) was recorded as a function of time using a transient waveform recorder. The information recorded was transmitted to an oscilloscope and filmed directly as acoustic event energy versus time as shown in Figure 22. A negative electrical potential of 10 kV dc was maintained across a 0.025 cm-thick sample of Al_2O_3 until failure occurred. For initial times (10 to 30 seconds) the recorded A.E. event energy was less than $2V^2$ -msec at an acoustic event frequency of 0.5 counts/second. At times between 380 to 400 seconds, however, the A.E. event energy exhibited several events at energies greater than $2V^2$ -msec but less than $6V^2$ -msec. The acoustic event frequency during this time interval had increased to 3.5 counts/second. Prior to complete failure (puncture) of the specimen at times between 600 to 620 seconds, the A.E. event energy had increased to $9V^2$ -msec during several events with the acoustic event frequency increasing to 11 counts/second.

The process by which internal discharges may initiate breakdown depends, to a degree, on the material in which they occur. If the dielectric material contains gas-filled voids of varying shapes, sizes, and volumes, the electrical stress in cavity will be greater than the electric stress in the material to an extent determined by the ratio of permitivities and by the shape of the cavity.⁽²¹⁾ For instance, the electrical stress in a spherical cavity may be as much as 3/2 as large as the electrical stress in the material. The higher electric stress combined with the lower dielectric strength of the gas will lead to an electrical discharge in the cavity. After an initial discharge occurs at constant applied voltage, further discharges can only occur by charge leakage through the material to re-charge the sites already discharged.

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

FIGURE 22. Pre-dielectric Breakdown--Acoustic Emission Characteristics of Polycrystalline Al_2O_3 Showing Effects of Time at an Electrical Stress of $\sim 75\%$ of that for Total Breakdown

As repeated discharges occur, the inside cavity surface will be eroded. If the erosion causes an increase in electrical stress by changing the shape of the cavity, then the rate of erosion will increase rapidly with the discharges becoming more concentrated and forming further changes in the shape of the cavity. When the overall cavity attains critical size or length, the discharge channels can propagate more easily through the remaining material, causing failure. The mechanism suggests that the energy liberated increases with the length of the channel over which the discharge occurs. This would be consistent with the observed increase in A.E. event energy at longer times.

SCB Glass Insulators for Fusion Reactors

A review and evaluation of SCB-type glasses as related to fusion reactor needs, requirements, and applications has been initiated with particular reference to those glasses developed by Atomics International. Work in this quarter has been directed toward compilation of data from Atomics International, Los Alamos Scientific Laboratory, Lawrence Livermore Laboratory, Argonne National Laboratory, and PNL.

*High Rate Sputter-Deposition of Materials
for Fusion Reactor Applications*

R Wang

The current status of high-rate sputter-deposition of insulator coatings is reviewed in two major areas: 1) development of the sputtering technology and 2) characteristics of the deposited insulators.

Development of the Sputter-Deposition Technology

The sputter-deposition process has been developed to prepare insulator coatings 350 μm thick and 80 cm^2 in area with deposition rates up to 0.3 $\mu\text{m}/\text{min}$. This rate is nearly ten times faster than rates for conventional sputtering processes. Insulator coatings of Al_2O_3 , Y_2O_3 , AlN , and SiO_2 have been successfully prepared with thicknesses from 125 to 350 μm on 10 cm diameter substrates at 25°C.

The technology for high rate sputtering of SiO_2 and other related glasses has advanced to the stage where large-scale coatings for fusion reactor applications are feasible. For other materials, however, further research and development is necessary. For example, the high rf power density (30 to 80 x/cm^2) caused target failures during the sputtering of Al_2O_3 and Y_2O_3 when the target size was greater than 5 cm in diameter.

For technical and economic reasons, high-rate sputter-deposition with small target sizes (<5 cm diameter) was employed to produce Al_2O_3 specimens for study of the characteristics of the deposited insulators. Routinely, it was possible to produce small diameter samples (2 to 5 cm) with thick coatings (~ 0.1 mm) and low macroscopic defects at substrate temperatures between 20 and 800°C.

Characteristics of the Deposited Insulators

Electrical Properties. The results of electrical measurements showed that the resistivities of SiO_2 deposits between 200 and 700°C were only one magnitude less than the averaged values for SiO_2 reported in the literature. At 700°C, the resistivity of the SiO_2 deposits was 10^7 ohm-cm. Resistivity measurements at temperatures greater than 800°C were erratic because the trapped krypton in SiO_2 started to form small bubbles. We have found that SiO_2 deposited at 600°C contains only trace amounts of krypton, and these deposits will therefore be studied at high temperature.

Room temperature dielectric breakdown tests on both SiO_2 and Al_2O_3 deposits also indicated promising properties. The breakdown voltage for a 175 μm thick SiO_2 deposit was 7×10^5 V/cm, which was close to the measured 8×10^5 V/cm for a polycrystalline Al_2O_3 .

at similar thickness. The dielectric breakdown voltage of a 350 μm -thick, sputtered amorphous- Al_2O_3 deposit was between 4.2 and 6.4×10^5 v/cm, which was significantly better than the measured 3.1×10^5 v/cm of a polycrystalline Al_2O_3 at the same thickness.

Structure and Microstructure. The high-rate sputter deposition process is unique for preparation of thick oxide coatings with a large, controllable variation of structures and microstructures. By adjusting the sputtering parameters, especially the substrate temperature, one can form a series of new materials that cannot be fabricated by conventional processes. For example, amorphous- Al_2O_3 , α - Al_2O_3 , and γ - Al_2O_3 were obtained by properly selecting the sputtering rate, the substrate temperature, and temperature of heat treatment.

The structure of the SiO_2 deposits made at 25°C consisted of short-range ordering different from that of fused SiO_2 . This modified short-range structure may be due to the ion bombardment and atom-by-atom recombination processes occurring during sputter deposition. Recently, using X-ray fluorescence analysis, we found that a high concentration of krypton (the sputtering gas) existed in the modified structure. For these reasons, it would be most interesting to study the radiation effects of sputtered insulators, since they may be actually more resistant to radiation damage.

Depositions made at temperatures greater than 500°C are desirable to produce stable insulator coatings. For a 20 μm thick α - Al_2O_3 deposited onto a niobium substrate at 800°C , excellent adhesion between the α - Al_2O_3 and the niobium substrate was found on cooling from 800 to 25°C and during quenching from 25 to -195°C . There was no evidence of debonding during thermal cycling of the coating three times from 1000°C to 800°C within 10 seconds. The sputtered Al_2O_3 coating had a fine grain size and contained only traces of the sputtering gas. It may also have improved resistance to radiation damage compared to conventional α - Al_2O_3 .

Fusion Reactor Applications

The full potential of the sputtering of insulating materials has neither been determined nor developed. Therefore, the process of high-rate sputtering still remains as a unique, and relatively simple method of preparing thick coatings with various structures and microstructures useful for improving the understanding of ceramic materials. For example, amorphous Al_2O_3 , α - Al_2O_3 , and γ - Al_2O_3 were all formed by sputtering at various substrate temperatures and heat treatments. Good bonding between the coating and substrate was obtained by depositing on a hot substrate. Insulator coatings made by sputter-deposition may still be important for fusion reactor applications, depending upon the requirements for specific electrical properties of the insulator coating in future reactor designs.

ENVIRONMENTAL EFFECTS OF FUSION CONCEPTS

The identification of fusion reactor environmental impacts early enough in the development program would permit a maximum emphasis on research and reactor designs to minimize those impacts. The fusion reactor 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 fusion power plant 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 fusion reactors 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 is currently being prepared for issue in early FY-1977 as a summary topical report supported by numerous reference reports presenting the detailed technical data and analyses.

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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 fusion reactor concepts are useful in guiding the engineering of systems for future fusion reactor designs which minimize environmental effects. The environmental impacts have been estimated.

Fusion Reactor Environmental Effects

JR Young

The environmental analysis for the fusion reactor development program currently is being prepared for issue in FY-1977. The analysis was made to determine the possible environmental effects of the first commercial fusion 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 fusion reactor 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 fusion reactor has potential for substantially lower total environmental effects than current fossil or fission power plants or than the estimated effects of fast breeder reactors.

When the analysis is issued in FY-1977, data currently being developed at ORNL for the permeation of tritium at low pressures will be available. Preliminary data has been promising, and it is expected that subsequent data will show low enough permeation rates that the loss of tritium by diffusion through reactor and cooling system structures will not be a significant problem.

During the course of putting together the environmental analysis, PNL identified numerous deficiencies in the technology needed for making a complete analysis. The research necessary for obtaining this information includes numerous small efforts to provide missing data and analysis techniques unique to fusion reactor evaluations. Nine of these research efforts have continued at PNL during this reporting period. 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 environmental analysis will summarize the total body of information developed and gathered at PNL, which includes much previously unsummarized background on fusion concepts and technical analyses. The details, the unique data and individual analyses used during preparation of the larger environmental analysis, are being published as a series of reference topical reports.

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. A special course on "Fusion Power Conversion and Materials Technology" was presented during this reporting period.

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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 at 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" was presented.

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

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REFERENCES

1. D. L. Jassby, "Beam-Driven Tokamak Fusion-Fission Hybrid Reactors." ERDA-4, presented at the DCTR Fusion-Fission Energy Systems Review Meeting, ERDA Division of Controlled Thermonuclear Research, December 3-4, 1974.
2. TCT Two Component Torus Joint Conceptual Design Study, Vol. I-III. Plasma Physics Laboratory, Princeton, NJ and Nuclear Energy Systems Division, Westinghouse Corporation, Pittsburgh, PA, 1974.
3. W. V. Green, "Tritium Effects and Some Possible Fatigue Effects in Pulsed Reaction." WASH-1206, presented at the Fusion First Wall Materials Conference, p. 57, April 1972.
4. Pacific Northwest Laboratory Report on Controlled Thermonuclear Reactor Technology, January 1975-September 1975. BNWL-1939 1, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, October 1975.
5. J. F. Remark, A. B. Johnson, Jr., Harry Farrar, IV, and D. G. Atteridge, "Helium Charging of Metals by Tritium Decay." Nucl. Tech. 29(3):369-377, June 1976.
6. A. T. Santhanum, A. Taylor and S. D. Harkness, "Charged-Particle Simulation Studies of Vanadium and Vanadium Alloys," Defects and Defect Clusters in BCC Metals and Their Alloys. National Bureau of Standards, Gaithersburg, MD. p. 302, 1973.
7. M. J. Makin, "The Effect of Neutron Irradiation on the Mechanical Properties of Copper and Nickel." J. Inst. of Metals. 86:449, 1957-58.
8. Sh. Sh. Ubragimov, "The Influence of Impurities on the Behavior of the Mechanical Properties of Iron and Nickel Exposed to Neutron Bombardment." Phy. Met. and Metalloy. 27(6):130, 1969.
9. Sh. Sh. Ubragimov, "The Effect of Plastic Deformation on the Behavior of Metals Under Neutron Bombardment." Phy. Met. and Metalloy. 22(2):176-178, 1966.
10. J. P. Andre, A. Silvent, F. Feirieux, J. Frenkel, J. Lemaire, P. Morgand and G. Sainfort, "Radiation Embrittlement of Nickel. Mechanical Properties in Extension and Creep Tests." Presented at the 10^e Colloque de Metallurgie, Saclay, France, p. 199, 1966.
11. J. J. Laidler, Yielding Behavior in Neutron-Irradiated Nickel. HW-78178, p. 17, July 1963.
12. J. B. Mitchell, R. A. Konynenburg, C. J. Echer and D. M. Parkin, "DT Fusion Neutron Radiation Strengthening of Copper and Niobium." UCRL-77357 Rev. 1, presented at the International Conference on Radiation Effects and Tritium Technology for Fusion Reactors, Gatlinburg, TN, October 1-3, 1975.
13. "ASTM Recommended Practice E525," Book of ASTM Standards, Part 45. American Society for Testing Materials.
14. Pacific Northwest Laboratory Report on Controlled Thermonuclear Reactor Technology, October 1975-December 1975. BNWL-1939 2, p. 39, January 1976.
15. Pacific Northwest Laboratory Report on Controlled Thermonuclear Reactor Technology, January 1976-March 1976. BNWL-1939 3, p. 31, April 1976.

16. W. J. Gray, "Neutron Irradiation Effects on Graphite Cloth." Accepted for presentation at the Second ANS Topical Meeting on Technology of Controlled Nuclear Fusion, Richland, WA, September 21-23, 1976.
17. I. D. Peggs, "Changes in Properties of Carbon Fibers During Fast Neutron Irradiation," Nature Phys. Sci. 235:112, 1972.
18. R. W. Conn et al., "Major Design Features of the Conceptual D-T Tokamak Power Reactor, UWMAK-II," IAEA-CN-33/G1-2, presented at the Fifth IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo, Japan, November 11-15, 1974. Also designated as University of Wisconsin Fusion Design Memo, UWFDM-114.
19. R. G. Mills, Ed., A Fusion Power Plant. MATT-1050, Princeton University Plasma Physics Laboratory, Princeton, NJ, August 1974.
20. J. Powell, F. T. Miles, A. Aronson and W. F. Winsche, Studies of Fusion Reactor Blankets with Minimum Radioactive Inventory and with Tritium Breeding in Solid Lithium Compounds: A Preliminary Report. BNL-18236, Brookhaven National Laboratory, Brookhaven, NY, June 1973.
21. H. C. Hall and R. M. Russek, "Discharge Inception and Extinction in Dielectric Voids," Proc. Instr. Elect. Engrs. 101:47, 1954.

PUBLICATIONS AND PRESENTATIONS

Publications

J. E. Garnier, A. S. Rupaal and J. L. Bates, "Application of Acoustic Emission to Evaluation of Dielectric Breakdown in Insulator Materials." Ceramic Bulletin, 55 (5): 533-34, 1976.

J. F. Remark, A. B. Johnson, Jr., Harry Farrar, IV, and D. G. Atteridge, "Helium Charging of Metals by Tritium Decay." Nucl. Tech. 29 (3): 369-377, June 1976.

Reports Published

W. J. Gray, W. C. Morgan and G. L. Tingey, Potential for Graphite Use Adjacent to the Plasma in Nuclear Fusion Reactors. BNWL-2078, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, June 1976.

Reports to be Published

J. A. Strand, W. L. Templeton and P. A. Olson, "Fixation and Long-Term Accumulation of Tritium from Tritiated Water in an Experimental Aquatic Environment." Proceedings of the International Conference on Radiation Effects and Tritium Technology for Fusion Reactors, October 1-3, 1975, Gatlinburg, TN (to be published).

M. T. Thomas, O. K. Harling, R. L. Brodzinski and L. A. Rancitelli, "(D,T) Neutron Radioactive Sputtering Yield." Presented at the 22nd National Vacuum Symposium, American Vacuum Society, Philadelphia, PA, October 28-31, 1975 (to be published by Jour. of Vacuum Science and Technology).

M. T. Thomas, O. K. Harling, R. L. Brodzinski and L. A. Rancitelli, "Neutron Sputtering from Metal Foils." Presented at the 22nd National Vacuum Symposium, American Vacuum Society, Philadelphia, PA, October 28-31, 1975 (to be published by Jour. of Vacuum Science and Technology).

O. K. Harling, M. T. Thomas, R. L. Brodzinski and L. A. Rancitelli, "(D,T) Neutron Sputtering and Radioactive Recoil Ejection from the Surfaces of Fusion Reactors." Invited paper presented at ANS Winter Meeting, San Francisco, CA, November 16-21, 1975.

T. J. Kabele, A. B. Johnson, Jr. and L. K. Mudge, "Definition of Source Terms for Tritium Evolution from CTR Systems." Presented at the International Conference on Radiation Effects and Tritium Technology for Fusion Reactors, Gatlinburg, TN, October 1-3, 1975 (to be published).

E. P. Simonen and J. L. Brimhall, "Kinetic Stability Against Void Coarsening in Molybdenum." Presented at the International Conference on Radiation Effects for Fusion Reactors, Gatlinburg, TN, October 1-3, 1975 (to be published).

J. S. Allison, "CTR Fabrication Technology." Presented at the ASM Materials Science Symposium, Cincinnati, OH, November 11-13, 1975 (to be published).

D. G. Atteridge, L. A. Charlot, A. B. Johnson, Jr., J. F. Remark and R. E. Westerman, "Effects of Helium Implantation by Tritium Decay on the High Temperature Mechanical Properties of Niobium." Presented at the International Conference on Radiation Effects and Tritium Technology for Fusion Reactors, Gatlinburg, TN, October 1-3, 1975 (to be published).

E. R. Bradley and J. L. Brimhall, "The Effect of the Free Surface on Void Formation in Ion Bombarded Molybdenum." Presented at the International Conference on Radiation Effects for Fusion Reactors, Gatlinburg, TN, October 1-3, 1975 (to be published).

J. L. Brimhall, "Ion Bombardment Simulation: A Review Related to CTR Radiation Damage." Presented at the International Conference on Radiation Effects for Fusion Reactors, Gatlinburg, TN, October 1-3, 1975 (to be published).

D. L. Styris and O. K. Harling, "Niobium Irradiations With Polychromatic He^+ Ions of 0-1.5 MeV." Presented at the Second International Conference on Surface Effects in Controlled Thermonuclear Fusion, San Francisco, CA, February 16-20, 1976 (to be published by J. of Nuclear Materials).

M. T. Thomas, O. K. Harling, R. L. Brodzinski and L. A. Rancitelli, "Fusion Neutron Induced Radioactive Emissions From Surfaces." Presented at the Second International Conference on Surface Effects in Controlled Thermonuclear Fusion, San Francisco, CA, February 16-20, 1976 (to be published by J. of Nuclear Materials).

O. K. Harling, M. T. Thomas, R. L. Brodzinski and L. A. Rancitelli, "Recent Neutron Sputtering Results and the Status of Neutron Sputtering." Presented at the Second International Conference on Surface Effects in Controlled Thermonuclear Fusion, San Francisco, CA, February 16-20, 1976 (to be published by J. of Nuclear Materials).

Presentations Given

J. E. Garnier and J. L. Bates, "Dielectric Breakdown in Electrical Insulators Using Acoustic Emissions." Presented at the American Ceramic Society Symposium, Cincinnati, OH, May 3-5, 1976.

R. H. Jones, D. L. Styris and R. P. Marshall, "The Measurement of Mechanical Properties During Ion Irradiation." Presented at the Eighth ASTM International Symposium on Effects of Radiation on Structural Materials, St. Louis, MO, May 4-6, 1976.

J. L. Brimhall, "BCC Ion Correlation Experiment." Presented at Workshop on Ion Correlation Experiments, Oak Ridge National Laboratory, Oak Ridge, TN, June 8-9, 1976.

D. A. Baker, G. R. Hoenes and J. K. Soldat, "Food - An Interactive Code to Calculate Internal Radiation Doses from Contaminated Food Products." BNWL-SA-5523, Proceedings of the EPA Conference on Environmental Modeling and Simulation, Cincinnati, OH, April 20-22, 1976.

Presentations to be Given

W. J. Gray, "Neutron Irradiation Effects on Graphite Cloth." Accepted for presentation at the Second ANS Topical Meeting on Technology of Controlled Nuclear Fusion, Richland, WA, September 21-23, 1976.

W. C. Morgan, E. M. Woodruff and W. J. Gray, "Irradiation Behavior of Graphite at Very High Temperatures." Accepted for Presentation at the Second ANS Topical Meeting on Technology of Controlled Nuclear Fusion, Richland, WA, September 21-23, 1976.

E. R. Bradley, "Comparison of Ion Irradiation Damage in Three Grades of Unalloyed Molybdenum." Accepted for presentation at the Second ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, WA, September 21-23, 1976.

R. F. Mattas and H. Wiedersich (ANL); D. T. Atteridge, A. B. Johnson, Jr., and J. F. Remark (PNL), "Embrittlement of V-15 Cr-5 Ti Containing Helium Introduced by Both Tritium Decay and Ion Bombardment." Accepted for presentation at the Second ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, WA, September 21-23, 1976.

R. H. Jones and D. L. Styris, "Some Considerations of Temperature, Displacement Rate Gradients, and Specimen Dimensions on Penetrating Ion Irradiation Experiments." Accepted for presentation at the Second ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, WA, September 21-23, 1976.

R. Wang, "Sputter Deposited Electrical Insulators for CTR Applications." Accepted for presentation at the Second ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, WA, September 21-23, 1976.

J. L. Bates and J. E. Garnier, "Dielectric Breakdown of CTR Electrical Insulators Using Acoustic Emission Techniques." Accepted for presentation at the Second ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, WA, September 21-23, 1976.

J. R. Young, "Potential Environmental Effects of Fusion Power Plants." Invited paper, Second ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, WA, September 21-23, 1976.

A. B. Johnson, Jr., and T. J. Kabele, "Tritium Containment in Fusion Reactors." Invited paper, Second ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, WA, September 21-23, 1976.

J. D. Kaser, A. K. Postma, and D. J. Bradley, "Management of Radioactive Wastes from Fusion Reactors." Accepted for presentation at the Second ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, WA, September 21-23, 1976.

R. J. Taylor (UCLA); O. K. Harling, D. L. Styris, and M. T. Thomas, "Containment Wall Processing and Impurity Generation in MICROTOR." Accepted for presentation at the Second ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, WA, September 21-23, 1976.

B. R. Leonard and U. P. Jenquin, "The Quality of Fissile Fuel Bred in a Fusion Reactor Blanket." Accepted for presentation at the Second ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, WA, September 21-23, 1976.

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