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Pacific Northwest Laboratory Report on Fusion Energy Research April 1977 - June 1977

July 1977

Prepared for the Energy Research and Development Administration under Contract EY-76-C-06-1830

Battelle
Pacific Northwest Laboratories

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NOTICE

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PACIFIC NORTHWEST LABORATORY REPORT ON FUSION ENERGY RESEARCH APRIL 1977 - JUNE 1977

July 1977

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PREFACE

This quarterly report on Fusion Energy Research consists of progress summaries of research conducted by the staff of Pacific Northwest Laboratories (PNL). This reporting period includes progress made from April 1, 1977 through June 30, 1977. 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 sections:

- Fusion Systems Engineering
- Materials Research and Radiation Environment Simulation
- Safety Analysis and 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.

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

PNL Report on Controlled Thermonuclear Reactor Technology, October through December 1975, BNWL-1939-2.

PNL Report on Controlled Thermonuclear Reactor Technology, January through March 1976, BNWL-1939-3.

PNL Report on Controlled Thermonuclear Reactor Technology, April through June 1976, BNWL-1939-4.

PNL Report on Fusion Energy Research, July through September 1976, BNWL-1939-5.

PNL Report on Fusion Energy Research, October through December 1976, BNWL-1939-6.

PNL Report on Fusion Energy Research, January through March 1977, BNWL-1939-7.

Subsequent quarterly reports in this series will be numbered with the prefix PNL.

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PACIFIC NORTHWEST LABORATORY
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APRIL THROUGH JUNE 1977

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.

Final reports are being prepared for two design and development studies for fusion-fission hybrid reactors based on the Two Component Torus (TCT). PNL cooperated with the Princeton Plasma Physics Laboratory on a conceptual design of a TCT-based hybrid reactor and with the University of Wisconsin in an evaluation of the fissile fuel producing capacity of an outside blanket for the Tokamak Engineering Test Reactor (TETR).

The development of economic data for fusion power plants continued in a study estimating the potential impact of a shortage of materials important in fusion plant construction. Estimates of the toal world requirements for these important materials are being prepared based on correlations of national consumptions of materials with indexes of industrial output. The estimates of world material requirements will be compared with estimates of potential world supplies, allowing estimation of long-run prices for commodities so designers can make better selections of power plant construction materials.

In studies developing heat transfer and fluid flow design tools for fusion reactor blankets, preconceptual design studies were initiated to identify the potential design limits of water cooling in the first wall of Tokamak Next Step (TNS) concepts. Thermal hydraulic and preliminary stress analyses were conducted to evaluate the Argonne National Laboratory (ANL) panel coil first wall design for the experimental power reactor and the PNL double wall design. It appears that the wall loading will be limited by thermal stresses in the stainless steel rather than by the heat transfer capability of the water coolant except for very low pressure water systems.

In surface effects research clean gold samples were irradiated in the University of California (D,Be) neutron source for a neutron sputtering experiment. Most of the work measuring fusion neutron sputtering yields is complete. Measurements of blistering thresholds for glass-impregnated stainless steel samples have been started using a new blistering chamber connected to PNL's 2-MeV Van de Graaff accelerator.

Light ion and neutron irradiation experiments have continued in studies of the effects of radiation on mechanical properties. The hardening response of 14 MeV neutron-irradiated nickel changed at high particle fluences (10^{16} to 10^{17} particles/cm^2) while the hardening response of 16 MeV proton-irradiated nickel did not, which may have been due to a difference in irradiation hardening mechanisms. The flux dependence of the damage microstructure and irradiation hardening of materials needs further study to clarify uncertainty about light ion and fusion neutron damage processes. Neutron irradiations of Ni, 316SS, and Nb wires and foils were completed.

In materials development studies the examinations of neutron-irradiated graphite cloths and fibers is nearing completion with the final report scheduled for release next quarter. Final data analysis is in progress for the fission-fusion correlation experiment in which relative atomic displacement rates in graphite are being determined with neutrons of different energies. Degassing measurements were taken of nuclear-grade graphite samples. Data suggest that degassing rates at elevated temperatures might not be much different from degassing rates for stainless steels.

Work has continued in studies developing acoustic emission (AE) techniques for determining the prebreakdown behavior and failure mechanisms in electric insulators with potential applications in fusion reactors. Scoping experiments with the high-vacuum dielectric breakdown apparatus were conducted. In other experiments analysis of AE signals recorded prior to complete breakdown of Al_2O_3 showed two different frequency spectra for dielectric breakdown at 300 and 450°K. It is proposed that the frequency component of the AE signals contains information related to the mechanism(s) of insulator failure.

PNL has prepared a draft Environmental Development Plan (EDP) to identify the key health, environmental, and safety issues associated with the development of magnetic fusion energy and to provide a schedule for research related to these issues. The plan outlines research needed to solve anticipated problems relevant to first generation magnetic fusion reactors, including consideration of materials availability, the health effects of magnetic fields, and the confinement of radioactive and toxic materials during normal operation and accident situations. In a related activity, the Regulatory Guides of the Nuclear Regulatory Commission, Division I, were examined in a review of existing fission reactor safety criteria and their applicability to fusion reactors.

PNL staff finished teaching the last quarter of a fusion technology course sequence that is included in the University of Washington graduate study program in nuclear engineering. The last quarter's work covered materials problems in a cross section of fusion reactor conceptual designs.

FUSION SYSTEMS ENGINEERING

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

In studies developing economic data for fusion power plants PNL is examining the potential impact of a shortage of materials important in fusion plant construction. The national consumptions of the materials characteristically used in fusion reactor construction were found to be best correlated with indexes of industrial output. Preliminary estimates of total world material requirements are being prepared for comparison to estimates of potential world supply. Ultimately, long-run estimates of commodity prices would enable designers to make better selections of fusion power plant construction materials.

In blanket and shield engineering studies experimental power reactor (EPR) blanket cooling studies are being performed to develop heat transfer and fluid flow design tools for fusion reactor blankets. High and low pressure design concepts for water-cooled TNS first walls were analyzed in preconceptual design studies initiated to identify potential design limits. The thermal hydraulic performance of the Argonne EPR panel coil first wall design and the PNL double wall design were analyzed in some detail. It was found that: 1) the PNL wall would require higher pressures ($\sim$6.8 atm) to operate in the 2 to 3 MWt/m^2 wall loading range; 2) nucleate boiling can be expected in normal operation at 0.6 MWt/m^2; 3) complete blockage of one flow channel in the ANL wall would not result in boiling in adjacent channels, but that the PNL wall would exceed the melting point under those conditions; 4) cyclic temperature variations of over 204°C and 121°C occur for the ANL and PNL walls, respectively, over the operational cycle at 0.6 MWt/m^2. Preliminary stress analyses of the ANL and PNL wall concepts indicated that both walls would have a very short life due to thermal fatigue, 25 and 50 hr, respectively. It appears that the wall loading will be limited by thermal stresses in the stainless steel rather than the heat transfer capability of the water coolant except for very low pressure water systems. Additional studies are in progress to determine the maximum thermal loads for acceptable wall life and alternate materials that would extend wall life.

Final reports are being prepared for two design and development studies for fusion-fission hybrid reactors based on the Two Component Torus (TCT). PNL cooperated with the Princeton Plasma Physics Laboratory on the conceptual design of a TCT-based hybrid reactor and with the University of Wisconsin to evaluate the fissile fuel producing capability of an outside blanket for the Tokamak Engineering Test Reactor (TETR).

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SYSTEMS STUDIES

Systems studies focus on providing key technical and economic 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 application of the fusion principle. The PNL studies of the 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 has been completed on the conceptual design of a hybrid based upon a Two Component Torus (TCT).[1] This concept utilizes intense neutral deuterium beams to drive a tritium Tokamak plasma, and it provides the basis upon which the Tokamak Fusion Test Reactor (TFTR)[2] has been designed. Another cooperative effort with the University of Wisconsin has been completed. This study has evaluated the plutonium breeding capability of perhaps a more near-term but smaller device--the Tokamak Engineering Test Reactor (TETR)[3] which is also based upon a TCT. Efforts for the past quarter have been in preparation of final reports.

The Economic Regimes task is assisting in the development of economic data that will allow comparative analyses between fusion reactors and competing systems. Such analyses will be needed to determine the best opportunities for investing research and development funds for fusion power systems.

ECONOMIC REGIMES

D. E. Deonigi

This quarter's effort on the Economic Regimes task has concentrated on a critical materials analysis for fusion power plants.

METHODOLOGY FOR FUSION PLANT CRITICAL MATERIALS ANALYSIS

General assessments of material requirements and availability for fusion power plant construction starting about the year 2000 have been reviewed by Kulcinski[4] and Hartley.[5] The two reports made comparisons between estimated fusion power requirements and materials reserve and resource estimates for the United States and the world. Hartley's report clearly identified the increased requirements for critical materials associated with fusion power relative to the total requirements of the U.S. economy. Only a few materials exhibited dramatic increases in the demand growth forecast. However, comparisons between the projected demand and current reserves of some critical materials indicated that consumption by other elements of the economy would consume known reserves well before year 2000. This should be expected as, generally, reserves are normally identified ten to twenty years prior to their use.

The economist's point of view is that materials are always available in the future, but possibly at a higher price required to recover or recycle low-grade ore. Thus, the reason for examining a list of potentially important materials in fusion plant construction is to estimate the potential impact of shortage on price. Designers can then incorporate this information into their selection of materials for construction and testing. Table 1 (Table 21 of Hartley's report) indicates that some of these materials have small reserves and are primarily imported; the United States must rely on World reserves for its future supply. However such a comparison omits the problem that the United States is not the only consumer of these resources in the world. To make the world resource estimate information useful it is necessary to estimate the world demand with world supplies, including the United States. To obtain this estimation, one must go through a process similar to that used by Roberts[6] where the estimates are made of expected growth in population, industrial output, and GNP of nations or groups of nations to represent the entire world as a basis for demand estimates. Relationships such as per capita consumption must be derived or consumption per unit of industrial output for each material potentially critical to fusion reactor construction. Based on the world growth scenario and the consumption rate correlations, a total world consumption can be estimated for each metal.

As most of the cumulative consumption will be in the currently industrialized countries over the period between now and year 2000, it is important that detailed analysis of these countries be included along with the less detailed representation of the developing countries of the world. Results from the computer model, EXPLOR,[7] used by Hartley to estimate U.S. consumption are available with representations of the industrialized countries and the rest of the world. These results will be used to make forecasts in the critical materials analysis. Such a scenario has been developed covering the period through year 2010, which includes a population growth pattern at about two-thirds of the current pace and the rate of economic growth derived from the historical long-term growth trends in industrialized countries augmented by a rapid growth scenario for the OPEC countries and a somewhat slower growth rate for the less developed countries.

TABLE 1. Critical Fusion Power Plant Materials Uses Versus Current Reserves and Resources

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

The consumption of the materials characteristically used in fusion reactor construction was found to be best correlated with the index of industrial output as opposed to per capita consumption or other possible measures of consumption. These correlations are currently being used to make preliminary estimates of total world requirements and to compare other forecasts where they exist. The next quarterly report for the Economic Regimes task will include these estimates compared with potential supplies.

Ultimately, comparisons between these correlations will allow estimation of long-run prices for commodities so designers can make better selections of materials for construction. The Solar Division of ERDA is currently making estimates of this nature for critical materials involved in the construction of solar technologies and, in particular, photovoltaic solar technologies.

BLANKET AND SHIELD ENGINEERING

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

HEAT TRANSFER AND FLUID FLOW

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

The objective of these studies is to develop design analysis tools and to scope experimental needs to investigate, define, and assess the heat transfer and fluid flow development requirements for the base technology of fusion reactors.

Low pressure water (1-2 atm) is being considered in nearly all Tokamak Next Step (TNS) concepts as a first wall coolant. Since TNS will not be required to produce electricity, low-temperature low-pressure water can be considered as a first wall coolant without compromising the performance of the plant. The extensive heat transfer-fluid flow and materials compatibility technology developed for water coolants make it desirable to seriously consider this option for TNS. Preconceptual design studies have been initiated at PNL to identify potential design limits for water-cooled TNS first walls. To do this, two specific design concepts, one high pressure and one low pressure, have been analyzed to evaluate their performance.

The thermal hydraulic performance of the Argonne Experimental Power Reactor (EPR) panel coil first wall and the PNL double wall designs has been analyzed in some detail. The developmental version of the computer code COBRA was used to study pressure drop and heat transfer characteristics, and the TRUTH code was applied to provide detailed material temperature distributions using COBRA output for boundary conditions. A channel length of 8 ft and a normal operating cycle of 15 sec off and 45 sec on were assumed. The following significant results were obtained from the thermal hydraulic analysis:

- Both wall designs are capable of operation in the 2-3 MWt/m^2 wall loading range. However, the PNL wall will require higher pressures to avoid boiling (∿100 psi or ∿6.8 atm).
- Nucleate boiling may be <u>expected</u> in normal operation at 0.6 MWt/m^2.
- The ANL wall is able to withstand the complete blockage of one flow channel without boiling in adjacent channels; the PNL wall exceeds the melting point under these conditions.
- Cyclic temperature variations of over 400°F (204°C) for the ANL wall and 250°F (121°C) in the PNL design occur over the operational cycle at 0.6 MWt/m^2.

The very high heat fluxes involved make subcooled nucleate boiling the dominant phenomena. Unfortunately, we do not have the capability at present to include this in transient thermal hydraulic analyses so its influence in flow stability and pressure drop cannot be studied in detail. Even if sub-cooled boiling effects could be analyzed in the one-dimensional channels, uncertainties would remain in manifold entrances and exits, bends, local restrictions, and other areas. If departure from nucleate boiling (DNB) occurred at a high heat flux, structural failure would almost certainly occur.

Preliminary stress analyses were completed on both the PNL double wall and the ANL panel coil concepts at 0.4 MWt/m^2 wall loading. The results indicated that both concepts would have very short life due to thermal fatigue, 50 hr and 25 hr, respectively. Except for very low pressure water systems, it appears that the wall loading will be limited by thermal stresses in the stainless steel wall rather than the heat transfer capability of the water coolant. Several additional studies are in progress using the same two geometries. Reduced thermal loads are being run to determine the maximum thermal load that will yield acceptable wall life. Secondarily, alternate wall materials are being substituted into the same two geometries to try to extend the wall life. Sintered Aluminum Product (SAP) and vanadium are being evaluated.

NUCLEAR DATA STANDARDS

B. R. Leonard, Jr.

The objective of this task is to participate in the development of current best-estimate nuclear data files for DMFE Technology programs. During this quarter the DMFE-sponsored Symposium on 10-40 MeV Nuclear Data was attended at Brookhaven National Laboratory (BNL). The principal investigator served as chairman of the working group on integral data and wrote the summary conclusions of that group for the symposium proceedings.

The principal investigator arranged a special meeting of the Cross-Section Evaluation Working Group's (CSEWG) Normalization and Standards Subcommittee. This meeting was held at BNL in conjunction with a CSEWG meeting. The primary purpose of the meeting was to review a NEANDC report on standards and discrepancies. Material for a Normalization and Standards critical review report was accumulated.

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MATERIALS RESEARCH AND RADIATION ENVIRONMENT SIMULATION

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

The PNL Surface Science group has been working on several experimental programs concerned with plasma-wall interactions in Tokamak plasma machines. This quarter a neutron sputtering experiment was performed using clean gold samples irradiated in the University of California (D,Be) neutron source. Most of the work is complete in measurements of fusion neutron sputtering yields, an ongoing project of several years. The new blistering chamber designed for studying the blistering effects of polyenergetic helium ions has been connected to PNL's 2-MeV Van de Graaff accelerator, and some measurements of blistering thresholds for glass-impregnated stainless steel samples have been started. A colutron ion source has been connected to the group's Scanning Auger system to allow introduction of ∿1-eV to 5-keV ions into the Auger chamber through a differential pumping system.

Mechanical properties studies at PNL have continued in an effort to correlate the microstructures and radiation hardening produced by light ions and fusion neutrons. Irradiation data from recent experiments suggest that the hardening responses of 16 MeV proton-irradiated nickel and 14 MeV neutron-irradiated nickel both change little at low particle fluences. At higher fluences (between 10^{16} and 10^{17} particles/cm^2) the hardening response of the neutron-irradiated nickel changed while the hardening response of the proton-irradiated nickel did not; this difference may be due to a difference in irradiation hardening mechanism or to experimental uncertainties. A similar difference was found between proton- and neutron-irradiated niobium. Although literature data indicate that 16 MeV protons impart a greater damage energy to target materials than an equal number of 14 MeV neutrons, the flux dependence of the damage microstructure and irradiation hardening of materials needs study to clarify uncertainties about light ion and fusion neutron damage processes. Neutron irradiations of Ni, 316 SS, and Nb wires and foils were completed at T(d,n) and Be(d,n) sources.

Material studies have continued to evaluate radiation damage and outgassing for carbons and graphites to determine if these are suitable for use as low-Z liner materials between the reactor first wall and the plasma. The examination of neutron-irradiated graphite cloths and fibers is nearing completion. The final report describing radiation damage in graphite cloth is scheduled for issue next quarter. Plans were made this quarter to irradiate graphite samples at temperatures up to 2000°C in the High Flux Isotope Reactor at Oak Ridge National Laboratory. Final data analysis is in progress for the fission-fusion correlation experiment in which relative atomic displacement rates in graphite are being determined with neutrons of different energies. Degassing measurements were taken of nuclear-grade graphite samples heated in-system to 400°C then heated inductively to between 800 and 2000°C. Degassing rates for samples previously degassed at 2000°C were $\leq 1 \times 10^{-11}$ torr-ℓ/sec-g at temperatures $\leq$ 1500°C. Data suggest that graphite degassing rates at elevated temperatures might not be much different from those for stainless steels. Further work will determine the conditions necessary for reducing graphite degassing to very low rates and investigate the effects of sample size and graphite type.

Work has continued in studies developing acoustic emission (AE) techniques for determining prebreakdown behavior and failure mechanisms in electrical insulators with potential applications in fusion reactors. Progress this reporting period concentrated on completion of the high-vacuum dielectric breakdown apparatus and the spectral analysis of AE signals to ascertain mechanism(s) of breakdown in ceramic insulators. Scoping experiments with the high-vacuum dielectric breakdown apparatus have been conducted at temperatures to 200°C and DC voltages of 5.5×10^4 V. The apparatus can allow dielectric breakdown measurements at a vacuum of $\sim 2.6 \times 10^{-5}$ Pa. In other experiments, the dielectric breakdown characteristics of Al_2O_3 were analyzed at 300 and 450°K. Spectral analysis of AE signals recorded prior to complete breakdown showed different frequency spectra for dielectric breakdown at the two temperatures. This data was consistent with the proposal that the frequency component of AE signals contains information related to mechanism(s) of insulator failure, in this case eletronic breakdown (300°K) and mixed electronic and thermal breakdown (450°K).

SURFACE SCIENCE RESEARCH RELATED TO FUSION TECHNOLOGY

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

SURFACE EFFECTS

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

The PNL Surface Science group has been working on several experimental programs concerned with plasma-wall interactions in Tokamak plasma machines. Measurements of fusion neutron sputtering yields have been a major project of the group for several years. Although most of the work has been completed and accepted for publication, a neutron sputtering experiment on clean gold samples was performed in June on the University of California (D,Be) source. Irradiations were made for 24, 36, and 48 hr. During this quarter three papers on earlier neutron sputtering work were accepted for publication by the Journal of Applied Physics (JAP) and an abridged version of the round robin report (neutron and proton sputtering experiments) was also accepted by the JAP.

The new blistering chamber connected to PNL's 2-MeV Van de Graff accelerator has been put into initial operation. Some measurements of blistering thresholds for specially prepared, glass-impregnated stainless steel samples has been started. Rotating sample experiments are nearly ready to begin.

A colutron ion source has been connected to our Scanning Auger system and the first ion beam was produced. This ion source will allow us to introduce $\sim$1-eV to 5-KeV ions into the Auger chamber through a differential pumping system.

During this quarter a paper on impurity flow in the UCLA Tokamaks was presented at the spring meeting of the American Physical Society. We were also represented at the American Chemical Society symposium on Surface Chemical Problems in Controlled Thermonuclear Reactors.

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

ALLOY DEVELOPMENT FOR IRRADIATION PERFORMANCE - MECHANICAL PROPERTIES

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

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

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

LIGHT ION/NEUTRON CORRELATION EXPERIMENT

The light ion/fusion neutron correlation experiment is expected to produce data which will allow a comparison between the damage efficiencies of 16 MeV p^+ and (D,T) and (D,Be) neutrons. Data for correlating (D,T) and (D,Be) neutron damage will also be produced.

16 MeV p^+ Irradiations

A series of irradiations at 10^{12} p^+/cm^2-sec and 35°C to fluences of 3 x 10^{16} p^+/cm^2, 6 x 10^{16} p^+/cm^2 and 1 x 10^{17} p^+/cm^2 have been completed. The change in yield strength for nickel and niobium for these irradiations are shown in Figures 1 and 2 along with the (D,T) neutron irradiation data. Also shown on these figures is the Lawrence Libermore Laboratory (LLL) data for (D,T) neutron-irradiated copper and niobium. At low fluences, the 16 MeV p^+ irradiated nickel and (D,T) neutron-irradiated copper behaved similarly. The similarity between the (D,T) neutron-irradiated nickel wire and the copper sheet at high fluences suggests that the (D,T) neutron-irradiated nickel would also behave similarly at low fluences.

A change in the hardening reponse of the 16 MeV p^+ irradiated nickel was not observed up to a fluence of 1.1 x 10^{17} p^+/cm^2 while a change in the hardening response has been observed at fluences exceeding 3 x 10^{16} n/cm^2 in copper and 6 x 10^{16} n/cm^2 in nickel as shown in Figure 1. If the change in hardening response with fluence is associated with the onset of cluster formation, a difference in the hardening mechanism of 16 MeV p^+ and 14 MeV neutrons may be suggested by this data. However, it is premature to conclude whether the difference is physical or experimental because of uncertainties in the beam current and profile. Experiments with improved beam monitoring capabilities and high fluences are planned for the next quarter.

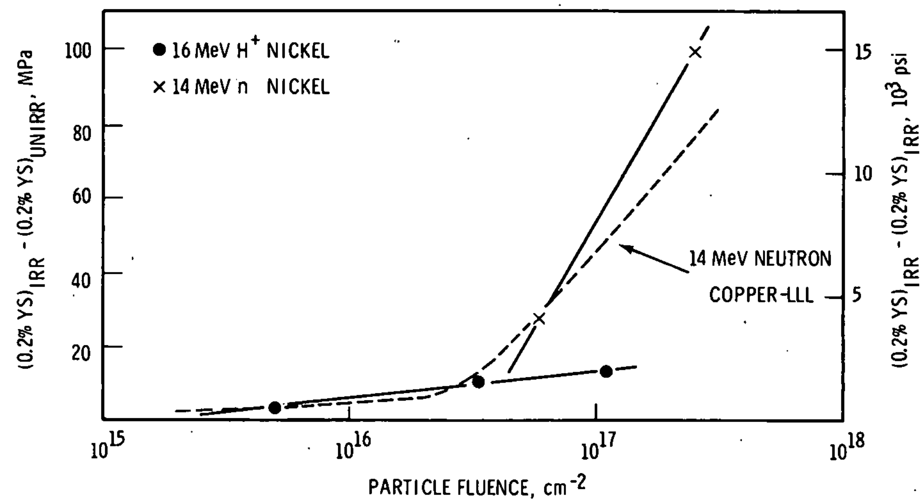


FIGURE 1. The ΔYS Versus Particle Fluence of MRC Marz Grade Nickel Irradiated at 25°C with 14 MeV Neutrons and 16 MeV Protons at a Flux of 10^{12} Particles/cm^2-sec.

The hardening response of 16 MeV p^+ irradiated niobium was also much less than that observed for 14 MeV neutrons, as shown in Figure 2. The close agreement between the (D,T) neutron-irradiated niobium wire (PNL) and sheet (LLL) indicates that the proton/neutron difference is either due to ion beam measuring errors or the displacement process.

The damage energy and displacement cross sections for 16 MeV p^+ and 14 MeV neutrons are compared for nickel, copper and niobium in Table 2. It can be seen from this data that the damage energy imparted to the target material per incident particle is greater for 16 MeV p^+ than it is for 14 MeV neutrons. A plot of the yield strength increase versus the damage energy would increase the difference between the proton and neutron data by shifting the proton results to higher damage energies relative to the neutron data for an equal number of particles.

Mitchell et al.[8] concluded that 16 MeV p^+ and 14 MeV neutrons produced very similar microstructures in copper at 20°C. However, the proton flux was 20 times greater than the neutron flux. The flux dependence of the damage microstructure and irradiation hardening of nickel, 316 SS and niobium will be studied as part of the 16 MeV proton/neutron correlation experiment which, it is hoped, will clarify many of the uncertainties that presently exist regarding the light ion and fusion neutron damage processes.

T(d,n) Irradiations

Irradiations of Ni, 316 SS, and Nb wires and Ni and Nb foils to 1×10^{17} n/cm^2 and 2×10^{17} n/cm^2 at 20°C have been completed. Also, Ni, 316 SS, and Nb wires and foils have been irradiated to 1×10^{17} n/cm^2 at 175°C. The yield strength evaluations of the specimens irradiated at 20°C will be performed next quarter while the elevated temperatures tests will be performed at a later time.

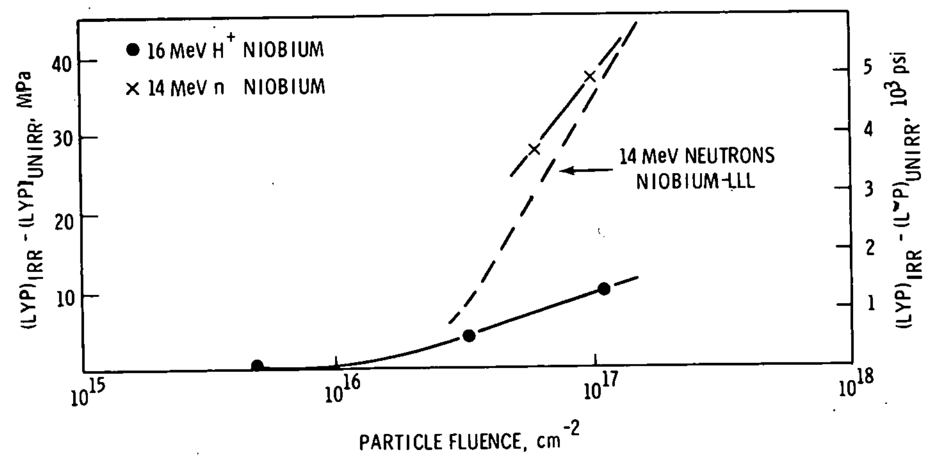


FIGURE 2. The ΔLYP Versus Particle Fluence of MRC Marz Grade Niobium Irradiated at 25°C with 14 MeV Neutrons and 16 MeV Protons at a Flux of 10^{12} Particles/cm^2-sec.

TABLE 2. Comparison of 16 MeV Proton/14 MeV Neutron Damage Parameters

Target Material	Damage Parameter	16 MeV Proton	14 MeV Neutron	Reference
Nickel	Damage Energy barn-keV	592	254	9
	Displacement, Cross Section, kilobarn	4.6 Coulomb Scattering Only	1.5	10
Copper	Defect Clusters 25-50A° 50-75A° 100-125A°	 2.1×10^{15} cm^{-3} 4.1×10^{14} cm^{-3} 5.2×10^{13} cm^{-3} $\phi = 10^{13}/cm^2$-sec	 1.7×10^{15} 5.8×10^{14} cm^{-3} 8.0×10^{13} cm^{-3} $\phi = 5 \times 10^{11}/cm^2$-sec	8
	Damage Energy barn-keV	589	267	9
Niobium	Damage Energy barn-keV	723 (636 @ T > 0.035)	266	9
		600	258	11
	Displacement Cross Section, kilobarn	4.0	2.5	10

Be(d,n) Irradiations

Irradiations of Ni, 316 SS, and Nb wire and foils to 5×10^{17} n/cm^2 and 1×10^{18} n/cm^2 at 20% have been completed. Bob Heinrich of Argonne National Laboratory assembled and analyzed the dosimetry foils with assistance on the short-lived foils from Curt Rowe of Lawrence Livermore Laboratory.

Proton irradiations at 10^{13} p^+/cm^2-sec to correlate with these irradiations are planned for the next quarter.

Transmission Electron Microscopy

Microstructure evaluation of the fusion neutron-irradiated foils has been initiated. Efforts will be concentrated on the (D,T) neutron-irradiated nickel and niobium since the yield strength data for these materials is the most reliable. Proton-irradiated foils will be examined after the questions regarding the proton-irradiated wires have been resolved.

Programs to identify and solve materials problems are essential to successful commercial fusion power development. The PNL materials technology program addresses areas where information will be needed for experimental and commercial reactors, including the behavior of graphites and electrical insulators in fusion reactor environments. Electrical insulator studies are examining the proposal that acoustic emission data generated during dielectric breakdown may contain information related to mechanism(s) of insulator failure.

EVALUATION OF CARBONS AND GRAPHITES FOR FUSION REACTOR APPLICATIONS

W. J. Gray, W. C. Morgan, G. L. 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 are: 1) radiation damage, 2) neutron, ion, and chemical sputtering, and 3) degassing.

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

- Radiation Damage in Graphite Cloth - evaluation of radiation damage effects in cloths and fibers since there are no previous data for these materials above about 1 x 10^{21} cm^{-2} EFF.[a]
- Radiation Damage at Very High Temperatures - evaluation of radiation damage effects at temperatures up to 2000°C since no data exist above ~1400°C.
- Fission-Fusion Correlation - experimental testing of the correlation between damage production rates in fission and fusion reactor spectra. This will allow more accurate projections of graphite performance in fusion reactors based on the extensive graphite data from fission reactor irradiations.
- Sputtering - measurement of neutron, ion, and chemical sputtering rates for carbon. This work is done in conjunction with other surface science research presented in this report.
- Degassing - measurement of degassing properties of large graphite samples under conditions appropriate to fusion reactor applications.

RADIATION DAMAGE IN GRAPHITE CLOTH

Graphite cloths and fibers have been irradiated to a maximum fluence of 1.0 x 10^{22} cm^{-2} EFF at 470°C in EBR-II. Results of examinations with optical and scanning electron microscopy, as well as measurements of density, surface area, and fiber length changes, were

[a] All fluences are quoted in terms of "Equivalent Fission Fluence for Damage in Graphite."[12]

reported last quarter.[13] Measurements of fiber diameter changes are nearing completion. Preliminary results for 11 different types of fibers indicate relatively small shrinkages of up to ∿ 6% for 7 types, shrinkages of 15 to 20% for 2 types, and expansions of ∿ 30% for 2 types. The final report for this task will be issued next quarter.

RADIATION DAMAGE AT VERY HIGH TEMPERATURES

Plans to irradiate graphite at temperatures up to ∿ 2000°C are in progress. Much of this quarter has been spent evaluating the relative merits of conducting the irradiations in the High Flux Isotope Reactor (HFIR) versus Oak Ridge Reactor, both at ORNL. In the interests of both time and money, HFIR is the best choice. Irradiation capsule design work has been resumed. The first capsule will be charged into HFIR during the first half of FY-1978 for a 1-cycle irradiation where a maximum neutron fluence of ∿ 2.4×10^{21} cm^{-2} EFF will be achieved. Graphite temperatures of ∿ 1900°C and ∿ 1500°C are planned.

FISSION-FUSION CORRELATION

Relative atomic displacement rates in graphite irradiated with neutrons of different energies are being determined by measuring relative changes in the elastic modulus of highly oriented pyrolytic graphite samples irradiated in three different neutron sources. The three sources are:

1) The Rotating Target Neutron Source at LLL with neutron energies of ∿ 15 MeV;

2) The D-Be source at Davis, California, operated at an average neutron energy of ∿ 5 MeV;

3) The Brookhaven Medical Research Reactor where average neutron energies are ∿ 1 MeV.

This task has taken much longer than anticipated because of an unexpected annealing phenomenon. That is, the elastic moduli of samples irradiated and then stored at room temperature have changed slowly over periods of several months, decreasing toward the original unirradiated values. All three irradiations have now been completed. Final data analysis is in progress, and task completion next quarter is anticipated.

SPUTTERING

No work was done on this task during this quarter.

DEGASSING

Degassing measurements using the apparatus described previously[14] are in progress. Only one type of nuclear-grade graphite and one sample size and geometry (3/4 in. dia x 1-in-long cylinder weighing ∿ 12 g) have been tested to date. Degassing was done in two stages: 1) both sample and system were heated at temperatures up to 400°C; then 2) the sample was heated inductively at temperatures between 800 and 2000°C while the system was maintained near room temperature.

Typical preliminary results for as-received samples are shown schematically in Figure 3.

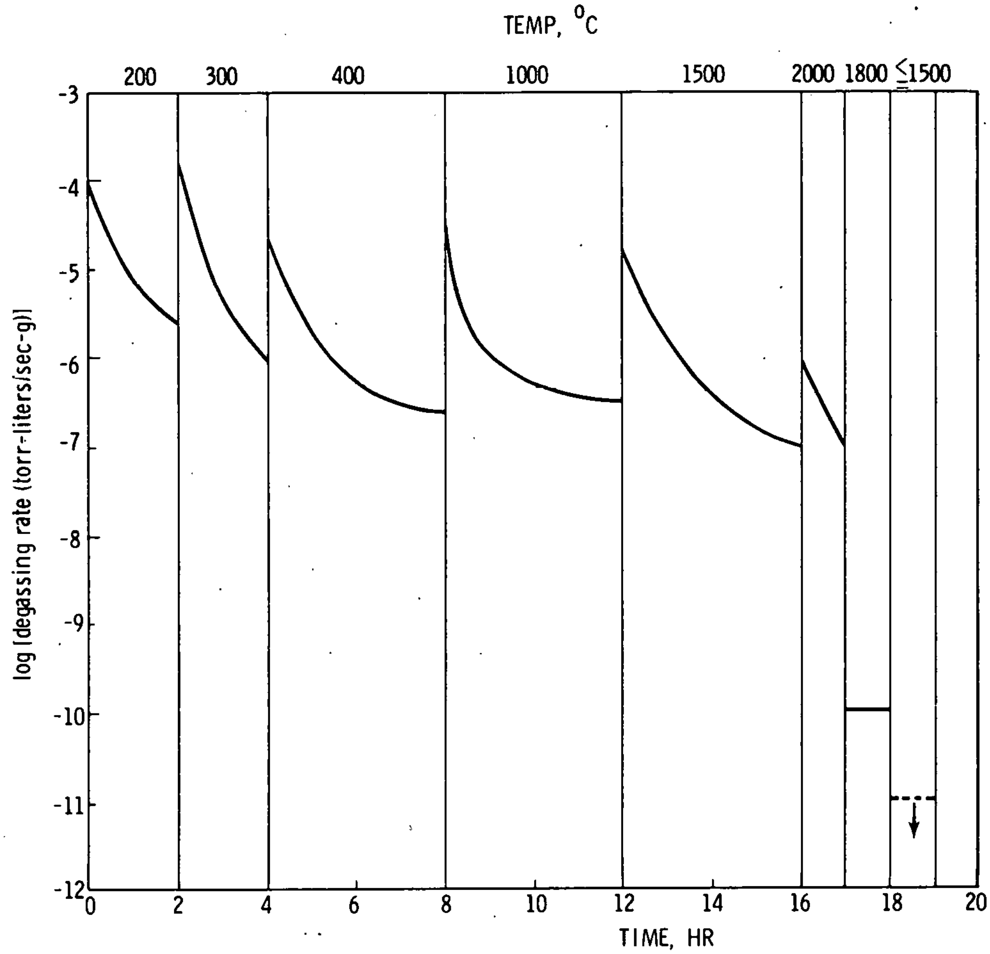


FIGURE 3. Schematic Representation of Typical Degassing Data for a Nuclear Grade Graphite

These data show that degassing rates for samples previously degassed at 2000°C were ∿ 1 x 10^{-10} torr liters/sec-g at 1800°C; no degassing was detected for temperatures ≤ 1500°C and the rates were, therefore, less than ∿ 1 x 10^{-11} torr-liters/sec-g. These rates were observed while the pressure was ∿ 1 x 10^{-6} torr. Total gas involved was ∿ 0.5 torr-liters/g up to 400°C and and additional ∿ 0.1 torr-liters/g up to 2000°C. Gas evolved from a sample previously degassed at 2000°C and then soaked in one atmosphere of dry nitrogen at room temperature for 24 hrs could not be accurately determined at 400°C because of the contribution from the system, but was on the order of ≤ 5 x 10^{-3} torr-liters/g. Additional gas evolved as the sample temperature was increased to 2000°C was ∿ 1 x 10^{-4} torr-liters/g.

The graphite degassing rates shown here need to be put in perspective by comparing them with values reported for other materials. So far this has been done only in a very cursory manner. Room temperature values for well degassed stainless steels of ∿ 10^{-14} torr-liters/sec-cm^2 are reported. Rates at elevated temperatures may be ∿ 10^{-11} torr-liters/sec-cm^2 or even higher depending on pretreatment. Thus, it appears possible that graphite degassing rates at elevated temperatures might be not much different from those for stainless steels. Additional, more definite, comparisons will be made in the future.

Further work will also be devoted to determining the minimum conditions necessary for reducing graphite degassing rates to very low values, and to investigating the effects of sample size and graphite type.

ELECTRICAL INSULATORS FOR FUSION REACTOR APPLICATIONS

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

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

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

1) Development and understanding of acoustic emission information generated during the occurrence of electrical breakdown and the relationship of these data to material properties.
2) Acquisition of dielectric strength and element resistivity data on potential fusion reactor insulator materials.

Progress in these areas is described below with major effort directed toward completion of the dielectric breakdown apparatus and the use of spectral analysis of AE signals to ascertain mechanism(s) of breakdown.

HIGH-VACUUM DIELECTRIC BREAKDOWN APPARATUS

The vacuum test chamber and internal dielectric breakdown testing apparatus has been completed and the system checked. As shown in Figure 4, the system consists of large vacuum cross chamber directly attached to a differential-ion (D/I) pump. A liquid nitrogen cooled sorption pump is used to lower the pressure below 10 microns at which the D/I pump can begin to operate. The interior components consist of a water-cooled support stand, heater, and sample holder.

A detailed schematic of the sample holder is shown in Figure 5. The sample temperature is determined by two type-K thermocouples embedded in the base at a location directly beneath the base sample electrode. Additional thermocouples are located on the AE transducer and near the upper sample electrode. The sample is held in position by means of a spring located at the edge of the sample. The AE transducer is coupled to the sample with a ceramic cement (Cermabond 503, Aremco Products, N.Y.).

Calibration of the frequency response of the AE transducer is made using a helium gas jet technique.[15] During the calibrations, the transducer is maintained at the operating

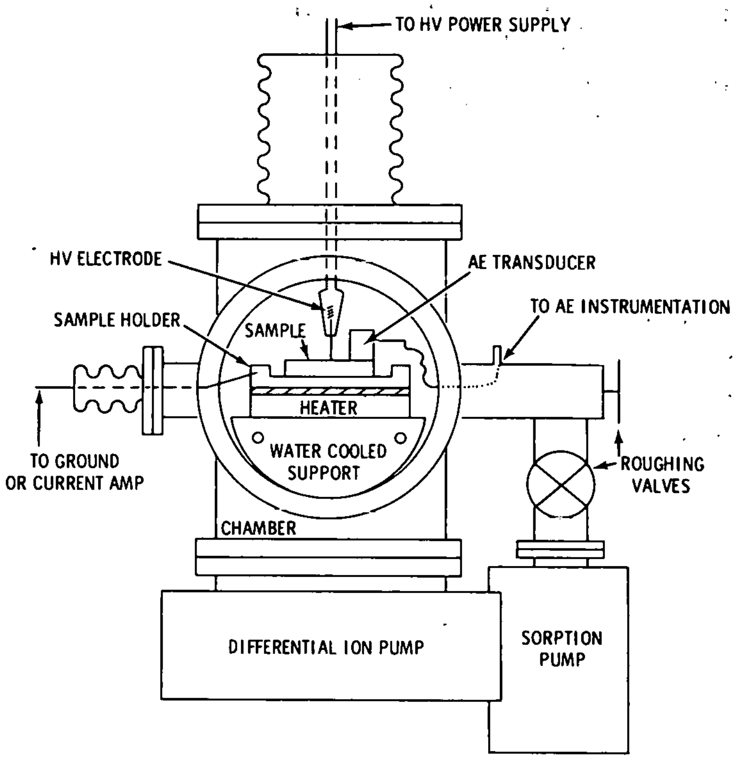


FIGURE 4. High-Vacuum Dielectric Breakdown System

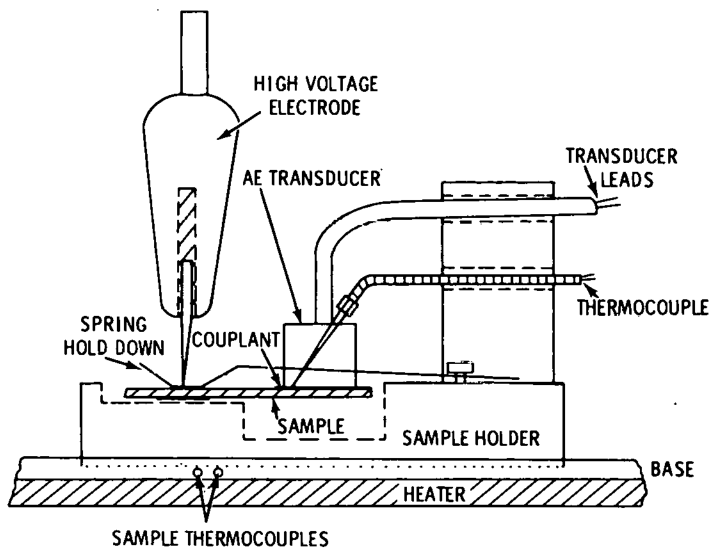


FIGURE 5. Sample Holder With Instrumented Sample

temperature of the subsequent experiment. Since the maximum operating temperature of the transducers is ∿100°C, the transducer is maintained at a temperature below the sample electrode by heating the electrode end only.

Scoping experiments have been conducted on this system at temperatures to 200°C and DC voltages to 5.5×10^4 V. The system with all internal components and the sample in place is capable of operating at a vacuum to $\sim 2.6 \times 10^{-5}$ Pa.

SPECTRAL ANALYSIS OF AE SIGNALS EMANATING FROM ELECTRICALLY STRESSED SOLID DIELECTRICS

It has been shown[16,17] that localized electrical discharges can occur in insulators at field strengths below that required for complete failure of the insulator. These localized discharges can occur at any region of enhanced electrical stress (i.e., voids, material inhomogeneities, etc.).[17] A portion of the energy disipated in these discharges will be converted into pressure waves (AE) which can be detected and analyzed. The remainder of the local discharge energy will be dissipated via heating of the surrounding discharge region.

During a local discharge, the associated localized temperature may rise to as high as 6000°K.[18] If the electrically stressed region is capable of repeated discharge, ultimate failure of the insulator can occur.

Although the localized current density in the discharge region may reach several thousand amperes during the discharge, the net current flow through the entire insulator will remain on the order of 10^{-14} to 10^{-6} A (depending on insulator resistance and applied voltage). The changes in current associated with the local discharge are several orders of magnitude less than the total current flow. This makes it exceedingly difficult to measure these small changes in current levels and to extract information concerning the breakdown mechanism(s). However, it has been shown[16,17] that monitoring acoustic emission signals from an electrically stressed insulator is a sensitive tool for distinguishing differences in pre-breakdown behavior.

IT IS PROPOSED THAT A FREQUENCY ANALYSIS OF ACOUSTIC EMISSIONS RESULTING FOR LOCALIZED DISCHARGES WILL CONTAIN INFORMATION RELATED TO THE OPERATIVE MECHANISM(S) LEADING TO FAILURE OF THE INSULATOR.

It is known that the frequency component of AE signals will be dependent on sample geometry, couplant, transducer, and source of AE generation. To produce system-independent AE spectral information, a helium gas jet spectral calibration is used.[15] If only the source of AE generation is changed, then a relative comparison of AE spectral information can be made by accounting only for the change in frequency characteristics of the transducer with temperature.

As determined by Britt[19] and shown in Figure 6, the dielectric strength of Lucalox increases with increasing temperature from 300°K to ∿400°K, which is characteristic of a material exhibiting electronic breakdown. At temperatures from ∿500°K and above, the dielectric strength of Lucalox decreases with increasing temperature. This is characteristic of thermal breakdown. At temperatures between ~300°K and ~500°K, the mechanism of failure in Lucalox was considered by Britt to be mixed (i.e. both electronic and thermal). To evaluate this hypothesis and for comparative purposes, the dielectric breakdown characteristic of Al_2O_3 (McDaniel ACL-112, 99.9% purity) were analyzed at 300°K and 450°K, Figure 6.

If the frequency content of the acoustic emissions generated in the electrically stressed samples of Al_2O_3 contain information related to the operative mechanism(s) leading to failure, then the spectral content of the AE signals obtained at 300°K and 450°K should be different.

The spectral analysis of AE signals recorded prior to complete breakdown for the same sample of Al_2O_3 at 300°K and 450°K are illustrated in Figures 7 and 8, respectively. Large peaks are observed at 300°K in the frequency spectrum at 90 KHz, 140 KHz, and 190 KHz, with several smaller but well-defined peaks at frequencies between 240 KHz and 360 KHz, Figure 7. On the other hand, the frequency spectrum at 450°K, Figure 8, also shows peaks in the vicinity of 90 KHz, 140 KHz, and 190 KHz, but no well-defined peaks at frequencies above 200 KHz. In addition, there appears an additional well-defined peak of lower frequency at 30 KHz.

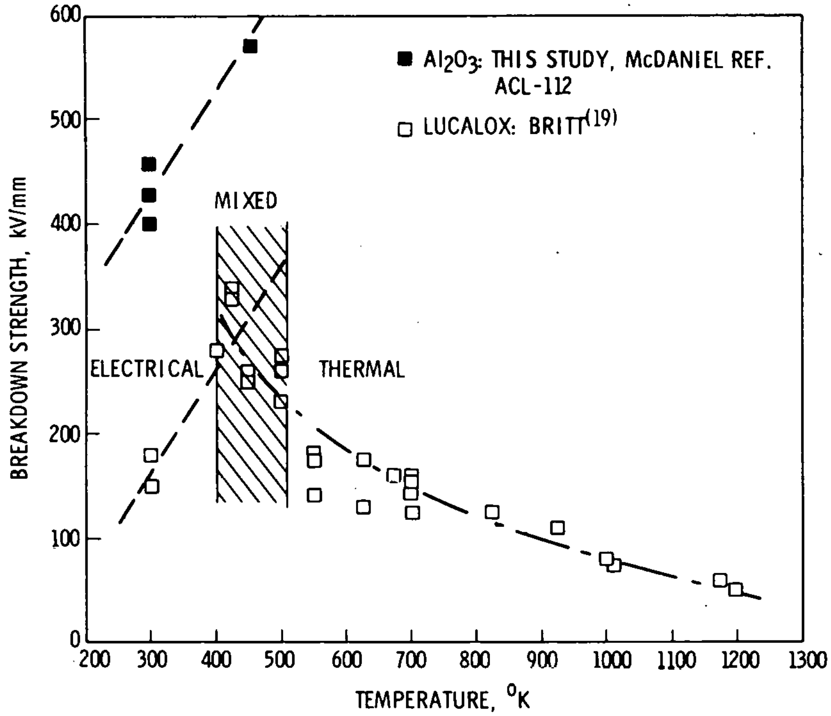
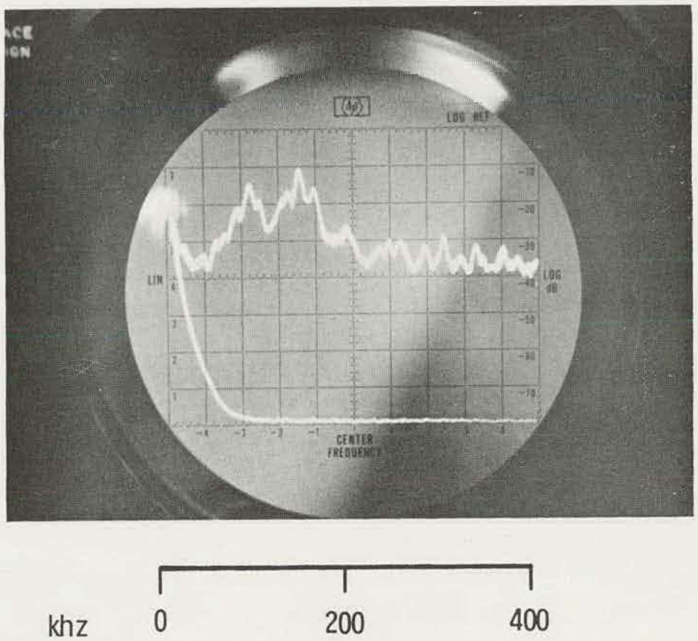
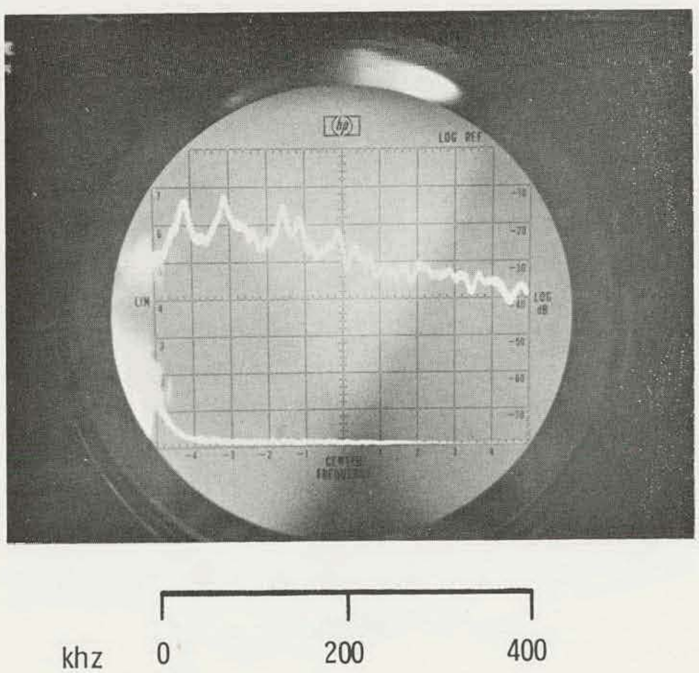


FIGURE 6. Breakdown Strength (kV/mm) Versus Temperature (°K) for Lucalox[19] and Al_2O_3 (This Study).



Band Width: 6 kHz
Span: 0-400 kHz
Log Reference
Level: -10 db

FIGURE 7. AE Spectrum [AE Signal Amplitude (db) versus Frequency (kHz)] of Prebreakdown Signal on Sample of Al_2O_3 at 300°K Stressed to 48 kV/mm.



Band Width: 6 kHz
Span: 0-400 kHz
Log Reference
Level: -10 db

FIGURE 8. AE Spectrum [AE Signal Amplitude (db) versus Frequency (kHz)] of Prebreakdown Signal on Same Sample as Figure 7 at 450°K Stressed to 57 kV/mm.

To produce system-independent AE spectral information[15] the spectral information in Figures 7 and 8 are corrected for the effects of transducer, sample, and couplant using the following relationship:

db(corrected) = db(AE signal) - db(calibration)

where

db(calibration = db(helium gas jet, standard transducer) - db(helium gas jet, system)

The results of db(corrected) determined at corresponding frequences of db(AE signal) and db(calibrations) are shown in Figure 9.

If the spectral content of an AE signal emanating from an insulator undergoing electronic breakdown contains higher frequencies, and if that of an insulator undergoing thermal breakdown contains lower frequencies, then an insulator that undergoes mixed breakdown (i.e., both electrical and thermal) should exhibit pronounced low and high frequencies. This would be consistent with the observed differences in the AE spectra of Al_2O_3 in the region of electronic breakdown (300°K, Figure 7) and mixed breakdown (450°K, Figure 8).

Efforts next quarter will be directed towards generation and analysis of AE frequency spectra information on other insulators. An extension of AE experiments on Al_2O_3 to temperature above 450°K will be made.

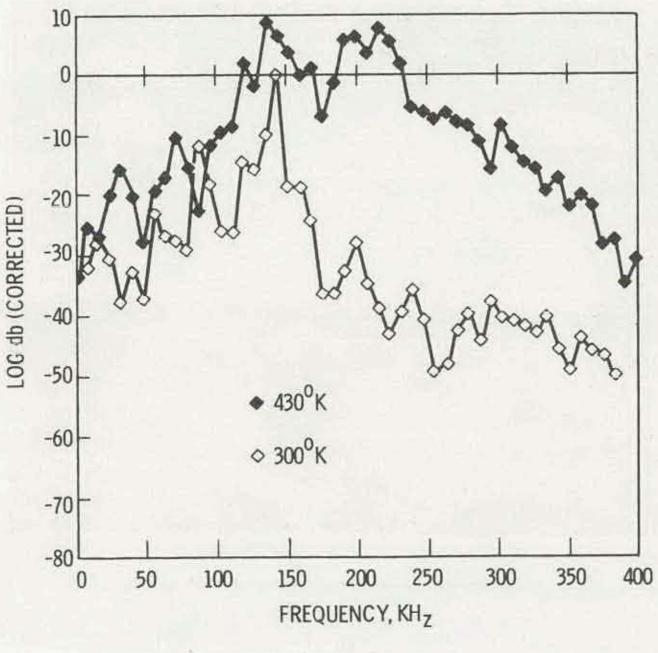


FIGURE 9. The Corrected Spectrums for Al_2O_3 Undergoing Breakdown at 300 and 430°K.

SAFETY AND ENVIRONMENTAL PROGRAM PLANNING FOR MAGNETIC FUSION

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

PNL has prepared a draft Environmental Development Plan (EDP) to identify the key health, environmental, and safety issues associated with the development of magnetic fusion energy and to provide a schedule for research related to these issues. The EDP describes the present status of magnetic fusion energy technology and identifies areas of environmental, health, and safety concern. This plan encourages research to solve anticipated problems relevant to first generation magnetic fusion reactors, including consideration of materials availability, the health effects of magnetic fields, and the confinement of radioactive and toxic materials during normal operation and accident situations.

Existing fission reactor safety criteria are being reviewed to evaluate their applicability to fusion reactors. The Regulatory Guides of the Nuclear Regulatory Commission, Division I, were reviewed this quarter and classified according to applicability to fusion systems or reactor confinement.

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FUSION SYSTEMS SAFETY ANALYSIS

The development program leading toward practical fusion power will involve construction and operation of a number of experimental reactors. This will require an understanding of the normal and accident behavior of the reactor systems in order to assure the safety of the operating staff and the public. Potential safety concerns in such facilities and in the support activities (e.g., transportation, waste disposal, etc.) need to be addressed early in the program to allow timely development of necessary data and the predictive methods. PNL's fusion systems safety analysis task is identifying the key needs and providing a plan for obtaining this information. This task will also review existing and evolving safety criteria which may be applicable to fusion reactors.

FUSION SAFETY PROGRAM PLANNING

H. J. Willenberg, F. P. Hungate

A draft Environmental Development Plan (EDP) has been prepared to identify the key health, environment, and safety issues associated with development of magnetic fusion energy, and to provide a schedule for performing research related to these issues. This EDP for magnetic fusion energy (MFE) briefly describes the present status of MFE technology and identifies potential areas of concern relevant to the health of workers and the natural and man-made environment. It also addresses socioeconomic and safety implications. This plan encourages research to solve anticipated problems in a timely fashion so that design and operational decisions can be made with reasonably relevant data on which to base such decisions.

The principal concern is radiation exposure resulting directly and indirectly from the deuterium-tritium fusion reaction to be used in early fusion devices. Later fusion cycles may be able to rely on other than radioactive fuels with reactions producing less activated materials, but containment and heating problems preclude their early use. Potentials for personnel and environmental exposure to tritium and neutron-activated materials necessitate special consideration in the selection of materials and development of techniques to minimize escape of these radioactive materials and to ameliorate the consequences of contamination events. As always, accidents represent the greatest potential for exposure of operating personnel, the environment, and the public.

The presence of magnetic fields up to 500 gauss in occupied areas of magnetic fusion reactors (MFRs) raises the question of possible health consequences. Work has already been initiated to determine whether health effects from magnetic fields are to be expected and to provide a basis for MFR design criteria. Other potentially hazardous materials include the alkali metals, beryllium, and mercury. It is anticipated that adequate designs and operating techniques will be developed to make potential health, environment, and safety (HE&S) effects from these materials nominal under normal operating conditions. Possible accident situations require understanding the behavior and effects of these materials when released into the environment.

MFRs will require large amounts of special materials whose price and availability must be considered. Of these, helium, required for magnet cooling and possibly for heat transfer, appears to be the most critical. Consideration of steps to stockpile helium from currently rich sources is in order. Other scarce materials, such as beryllium, will warrant special attention as they become more specifically identified for use in MFRs.

This EDP addresses only HE&S issues relevant to first generation MFRs. Significant prospects beyound the first generation include using fusion reactions not requiring or producing large quantities of radioactive materials and using the products of fusion for direct energy conversion. These prospects for the future development of fusion reactors capable of producing cleaner energy should in themselves encourage rapid progress in fusion technology.

FUSION REACTOR SAFETY CRITERIA

H. J. Willenberg, S. H. Bush

A review is being performed of existing fission reactor safety criteria to evaluate their applicability to fusion reactors. The technical, philosophical, economic and political basis for their adoption will be reviewed so that a basis can be formed for establishment of fusion reactor safety criteria. The applicable fission criteria have been identified this quarter.

The Regulatory Guides of the Nuclear Regulatory Commission, Division I, were reviewed during the quarter. Each guide was evaluated regarding its applicability, either directly or indirectly, to the fusion system itself or to reactor confinement or containment. This classification, together with progress reported in the last quarterly progress report(completes the review process. Identification of the basis for establishment of the existing criteria was initiated.

MANPOWER DEVELOPMENT

To promote a better understanding of fusion technology, PNL participates in educational programs offered through the Joint Center for Graduate Study in Richland, Washington. PNL staff finished teaching a course sequence for the three quarters of the 1976-77 academic year as a part of the University of Washington's graduate study program in Nuclear Engineering. The last quarter, finished in June, covered materials problems encountered in a cross section of fusion reactor conceptual designs.

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EDUCATIONAL DEVELOPMENT

B. F. Gore, A. B. Johnson, Jr., H. B. Liemohn, F. P. Hungate

A graduate course sequence on fusion technology with a balanced emphasis of plasma and engineering aspects was approved for the Nuclear Engineering Curriculum of the University of Washington at the Joint Center for Graduate Study.[a] The Center is operated in Richland, Washington, by Oregon State University, Washington State University, and the University of Washington.

The sequence is being given routinely in three quarters starting with the 1976-77 academic year. The first quarter covered fusion plasma engineering and included an introduction to plasma theory and its application to controlled thermonuclear fusion. The second quarter emphasized blanket technology and environmental aspects. The last quarter, finished in June, covered materials problems encountered in a cross section of fusion reactor conceptual designs. This included discussions of first walls, coolant systems, blanket, shields, magnets, and heat exchangers.

(a) Effort funded as part of the Joint Center for Graduate Study Program

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D. R. Baer, M. T. Thomas and R. J. Taylor, "Auger Electron Spectroscopy of Samples Removed from Microtor and Macrotor." Presented at the spring meeting of the American Physical Society, Washington D.C., April 25-28, 1977.

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