MEETING REPORTS

FUSION REACTOR MATERIALS—A REVIEW OF THE SECOND INTERNATIONAL CONFERENCE, CHICAGO, ILLINOIS, APRIL 13–17, 1986

The objective of the Second International Conference on Fusion Reactor Materials was to provide an international forum for the exchange of new information and the furtherance of understanding of the science and technology of materials proposed for use in fusion reactors. To highlight this objective, the conference selected as its theme "Developing Improved Fusion Options Through Materials Research." This conference represented a merging of the three U.S. topical meetings on fusion reactor materials (Miami, Florida, January 1979; Seattle, Washington, August 1981; and Albuquerque, New Mexico, September 1983) and the First International Conference on Fusion Reactor Materials (Tokyo, December 1984). Conference sponsors were the Argonne National Laboratory and the U.S. Department of Energy with minor sponsorship from the American Nuclear Society and the Nuclear Metallurgy Committee of the American Institute of Mining, Metallurgical, and Petroleum Engineers and American Society for Metals. The technical program consisted of 254 technical papers, of which 59 were oral and the balance posterboard presentations. Conference proceedings will be published as a special supplement to the *Journal of Nuclear Materials*. Therefore, this paper is intended to serve as an overview of the conference, summarizing the highlights of the program prior to publication of the full proceedings.

KEYNOTE AND PLENARY SESSION

The keynote address was given by John F. Clark, head of the Office of Fusion Energy, U.S. Department of Energy. Clark's theme was "Fusion in Perspective," and he essentially reviewed the progress fusion research has made in the past decade and the challenges that lie ahead, particularly with regard to the budget limitations. The realities of a diminishing budget have caused a rethinking in the national fusion program and a reordering of the priorities. Key to this new strategy is the need for international collaboration, which is particularly beneficial because it develops between countries understandings that go beyond technology. In addition, it is beneficial to participant countries in tight budget situations. With this thought in mind, Clark described two new fusion experiments, both tokamaks. One is an ignition experiment designed to study the physics of burning plasmas, and the other is an engineering test reactor that would involve international collaboration. The need for international collaboration was echoed by a number of other presentations that described the Reagan-Gorbachev summit agreement and the current effort to develop a cooperative program based on the successes of international materials efforts. Rounding out this session was a discussion of the curreent U.S. technical planning activity and the progress in materials research over the past decade. The technical planning activity essentially is divided into three areas: plasma science, fusion technology, and fusion systems. This study, which covers a large portion of the U.S. fusion technical community, is trying to develop a detailed program strategy that could be used for the next 20 years. In the area of materials research, substantial progress has been made in the past decade in understanding the mechanical behavior of materials in the chemical and neutron environment of a fusion reactor. This understanding has led to the selection of candidate materials for potential use in fusion reactors along with the development of optimized materials, particularly low-activation materials.

LOW-ACTIVATION MATERIALS

The U.S. magnetic fusion program has adopted as a major objective the development of structural materials with low long-term activation, which would help make fusion power environmentally acceptable to both the public and utilities. Seventeen papers were presented on this topic describing work performed in the United States, England, and Japan. These papers essentially covered three potential low-activation alloy classes, austenitic steels, ferritic steels, and vanadium alloys. In the austenitic and ferritic steels, initial efforts are aimed at reducing or eliminating those alloying elements that create long-term radioactive isotopes (e.g., niobium, molybdenum, and nickel. In the case of the austenitic steels, the immediate objective is to replace the major alloying constituent nickel with manganese. Early results indicate that it may be more difficult to attain an equivalent radiation resistance in this material than in a primary candidate alloy. In the ferritic steels, the effort has been directed toward removing the molybdenum and replacing it with tungsten or vanadium. Preliminary results indicate that there is some loss in the unirradiated mechanical properties, but further alloy development may offset these losses. The candidate vanadium alloys under investigation are intrinsically low activation and as a result the major thrust in development is to remove impurity elements, particularly niobium, and to develop an understanding of how vanadium alloys respond to radiation damage. Preliminary results indicate that there is a wide variation in the responses of alloys and that further research needs to be performed before any conclusions can be drawn.

STRUCTURAL MATERIALS

Forty-eight papers were presented covering unirradiated and irradiated properties of candidate fusion reactor structural materials and their fabrication. Studies on the unirradiated properties of the structural materials were primarily directed toward developing correlations for test techniques such as the miniature disk bend. The disk-bend test has been one of many techniques used to develop data on small-volume specimens. Papers presented on these techniques indicate good progress in developing correlations to mechanical properties for the ferritic steels and copper alloys. Most of the papers covered the effects of irradiation on the properties of a variety of materials ranging from ferritic steels to copper alloys. Experimental results included swelling, irradiation creep, fatigue, and ductile-to-brittle transition temperature (DBTT). Swelling results presented included irradiations up to 100 displacements per atom (dpa) for the ferritic steels and indicate very low swelling rates on the order of $<0.2\%$. In a study on the irradiation creep of materials, it was found that there appears to be a correlation between the reduction of irradiation creep on high-swelling (5 to 10%) materials and changes in the failure modes. It was suggested that creep correlations developed from fast reactor data could lead to an overprediction of the creep strain. It was also found that increasing helium concentrations reduces the fatigue life on irradiated HT-9 specimens irradiated at 55°C, but these fatigue lives were greater than the fatigue life of Type 316 stainless steel. Depending on conditions, irradiation can cause a shift of more than 100°C in the DBTT of ferritic steels. Experiments in fast and thermal reactors indicate that the shift in the DBTT saturates at higher doses than previously thought, and maybe >15 dpa.

TRITIUM BREEDER MATERIALS

Twenty-two papers were presented on tritium breeding materials; they covered a broad range of experimental and theoretical activities. A number of papers on the in-reactor tritium release indicated that several solids exhibited excellent tritium release characteristics, that is, a high tritium diffusion coefficient, for high-density Li_2O (86%) and Li_4SiO_4 (95%). Diffusion coefficients from the Li_4SiO_4 irradiation experiment confirmed earlier reported laboratory studies on the same material. Relevant to tritium release mechanisms were a number of experimental and theoretical studies that focused on desorption of tritium from ceramic breeders. Theoretical studies suggested that desorption could be the rate-limiting step at higher temperature, i.e., 650°C and above. Capsule-type irradiation experiments indicated that Li_2O exhibited swelling and grain growth while several other materials have a more favorable response to the neutron environment. An experimental paper focused on creep of Li_2O in an effort to answer the concern that exists for in-reactor swelling of Li_2O. Several papers focused on the transport and mechanical properties of breeders. These data are needed for performance evaluation and blanket design. Preparation and fabrication studies tended to concentrate on the relationships between breeder structural characteristics, fabrication parameters, and sintering. Corrosion studies revealed that Li_2O exhibited the greatest reactivity with the structural materials. These studies also identified that moisture-forming LiOH (LiOT) is the reactant and that the extent of reaction is directly dependent on the local oxygen potential. One paper focused on the preparation of Zr_5Pb_3, not a breeder material but a material that could be used for neutron multiplication instead of beryllium. While a few data are currently available, the real need is for neutronic data to assess its multiplication characteristics.

HIGH-HEAT FLUX MATERIALS

Twenty-seven papers were presented on high-heat flux materials. A number of these papers addressed important questions on the effects of the particle and heat flux environment on the performance of high-heat flux materials. For example, the behavior of titanium carbide coatings was experimentally studied. The TiC coatings were deposited on steel, molybdenum, and copper alloys as well as on graphite by the electron-beam evaporation technique, and subsequently evaluated using a variety of surface heating techniques. The TiC coating was found to withstand thermal pulses of up to 2 kW/cm^2 for $\sim$20 ms without visible change. However, exfoliation and change of coating composition were observed to result from deuterium ion bombardment.

Complicated surface topography was reported by several authors for graphite bombarded with deuterium. Also, several experiments showed the formation of hydrocarbons, and even sublimation of the graphite resulting from intense energy deposition. Most of the experiments in this area indicated that surface erosion mechanisms are controlled by a complex interdependence of collisional, nonequilibrium thermodynamic, and chemical activities near the surface layers.

Some aspects of mechanical failure were also analyzed by the Sandia group. The notch sensitivity of POCO AXF5Q and ATJ graphite was examined using a rastered electron beam that rapidly heated the surface of specimens containing premachined flaws. Failure of POCO graphite was observed at 2 kW/cm^2 after a 1.5-s pulse for the notched specimens, as compared with no failure at 10 kW/cm^2 for the unnotched specimens.

The Grumman group presented work on the development of duplex and triplex structures composed of plasma side, heat sink, and tritium barrier materials. Successfully bonded combinations of duplex laminates included: beryllium/tungsten, beryllium/molybdenum, boron nitride/molybdenum, silicon carbide/tungsten, boron nitride/vanadium, carbon/molybdenum, carbon/tantalum, carbon/vanadium, and carbon/copper. Successfully bonded triplex laminates included boron nitride/molybdenum/vanadium, carbon/molybdenum/vanadium, and silicon carbide/tungsten/vanadium.

In addition to developing laminates, a number of experimenters reported results of studies into the effects of irradiation on the properties of copper alloys. Results reported included swelling measurements, changes in electrical resistivity, and tensile strength for a number of commercial copper alloys. An interesting piece of research was in the development of a lithium-copper alloy that combined dispersion strengthening with greater sputtering resistance than pure copper.

MATERIAL ENGINEERING AND DESIGN

Thirteen papers were presented on the material requirements for elements ranging from testing of blanket components to material property needs for commercial reactors. These papers tended to concentrate on the engineering aspects of solving design problems associated with fusion reactors. The NET team described an approach to protecting the stainless steel first wall of their reactor with graphite tiles bonded to a molybdenum structure. Complementing this presentation was a paper describing the material development needs required to design plasma interactive components and the use of existing facilities to conduct the testing. The need for data was underscored in a presentation on the design issues encountered in designing the compact ignition tokamak. This study found that the dominant uncertainties in the strength properties of copper alloys and insulating composites were controlling the size of the toroidal field coils, which in turn was impacting the size of the experiment. In a change of pace, the implications of safety and environmental challenges on materials selection was also presented. This study identified the safety criteria that fusion needs to address in the design of reactors, along with possible solutions. The results of this study indicate that the single most significant factor in determining the safety and environmental characteristics of a deuterium-tritium reactor is the choice of materials near the plasma and first wall. Rounding out this session was a study that examined the criteria that commercial fusion reactors would probably be judged against before being introduced into the power grid and how materials development can be used to help improve this selection.

FUTURE SYMPOSIA

The next conference in this series will be held on October 4-8, 1987, in Karlsruhe, Federal Republic of Germany.

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SUMMARY OF THE FUSION REACTOR TECHNOLOGY CONTRIBUTIONS TO THE FOURTH EUROPEAN NUCLEAR CONFERENCE—ENC-86, GENEVA, SWITZERLAND, JUNE 1-6, 1986

INTRODUCTION

For the first time, Fusion Reactor Technology was presented under a separate heading in the European Nuclear Conference Series, reflecting the importance this technology has gained in the nuclear world. This was reflected as well in the Foratom exhibition where many participants exhibited their achievements in the field of fusion technology.

Approximately 2050 participants from 30 countries attended ENC-86. Contributions to the fusion reactor technology sessions consisted of 11 oral papers and 20 posters, which represent roughly 7% of the total contributions to the conference.

The present report reviews the most significant aspects of the fusion-related papers. Since all but one of the papers are European, this report reflects the European fusion technology approach. The papers were mainly of a general, informative character; hence, the present review is directed more toward the nonfusion specialist.

EXPERIMENTAL SYSTEMS

The oral session opened with a paper on the construction experience with the Joint European Torus (JET) in operation in the Culham Laboratory, United Kingdom, since 1983. Although this story has already been told, it is still fascinating. It reflects the strong management role taken by the JET team, the enthusiasm of all those involved, and the intimate team spirit apparent throughout JET and the contractors, which led to the assembly of the machine in a remarkably short time. The collaboration of 17 research organizations from 12 different countries and from contractors and suppliers from all over Europe resulted in completion of the machine close to budget and to a program established 5 years earlier.

In the invited contribution, P. H. Rebut highlighted the achievements of JET. At present, with moderate radiofrequency (rf) and neutral beam injection heating, JET is still a factor of 30 to 50 away from the Lawson criterion conditions. By the end of the operation, it is expected to reduce this factor to 3 to 5.

With the French Tore Supra, presented by the project leader Aymar, Europe intends to explore the field of the superconducting tokamak, with parameters close to those of the Tokamak Fusion Test Reactor and T15. Tore Supra is a medium high field machine (4.5 T) presently under construction in Cadarache. It is planned to be in operation by the end of 1987. The aim of Tore Supra is not to achieve ignition but to test a superconducting tokamak in conditions close to the operating conditions of a thermonuclear reactor and to contribute to the studies of initial heating of a plasma by transferring high power. The cooling of the superconductor is done by superfluid helium at 1.75 K.

SYSTEM STUDIES

Four system studies were presented at the conference:

1. near-future Next European Torus (NET) by R. Toschi (NET project leader)
2. reduced scale fusion reactor approach by Bathke [Los Alamos National Laboratory (LANL)]
3. stellarator reactor approach by Wobig (Max Planck Institute, Garching)
4. DEMO approach (Culham Laboratory team).

The NET is presently in the predesign phase. According to planning, the start of construction is foreseen in 1994, with