Materials for Fusion Energy

Theodore C. Reuther, Guest Editor

Materials research and development specifically for potential application in fusion energy development had its origin in the early 1970s, following the impetus of the 1973 report to the President on "The Nation's Energy Future" by Dixie Lee Ray, then chairman of the U.S. Atomic Energy Commission.¹ The first scientific conferences on fusion materials took place in the summer and the fall of 1975 at Argonne National Laboratory² and at Gatlinburg, Tennessee.³ Argonne's international conference set a direction for the use and development of irradiation testing facilities for fusion materials which continues today.⁴

In his keynote to the Gatlinburg meeting on "Radiation Damage and Tritium in Fusion Materials," E.E. Kintner, then deputy director of the U.S. magnetic fusion program, spoke directly to the hearts of the materials community:

"Materials is the Queen Technology of any advanced technical system. The economics eventually depend upon the materials, the reliability depends upon the materials, and the safety depends upon the materials. I assure you that before we are through with fusion, the physicists will give way to the materials engineers as being the leading lights of fusion."

Kintner spoke from his experience in naval and civilian nuclear power systems, with reference to the special threats of the fusion reactor environment to the integrity of materials, and from practical engineering issues in a broad sense. Today, there is an even more specific materials argument—the attractiveness of fusion as an energy source may well depend on the development and application of "low activation" structural and functional materials, particularly to reduce the long-term burden of radioactive waste management.^{5,6}

The special threat of the fusion reactor environment to the integrity of engineering materials has long been recognized to

be due to the intense bombardment of materials by the energetic neutron and particle radiation from the reacting plasma. In 1975, some design studies suggested reactor first-wall lifetimes as short as two years based on then-known data.⁷

That technical situation and the strong endorsement and associated challenge of the U.S. Atomic Energy Commission (AEC), Energy Research and Development Administration (ERDA), and the Department of Energy (DOE) led to a strong and well-structured materials research and development program in support of fusion energy development.⁸

This issue of the MRS BULLETIN will examine these materials issues by: focusing on the consequences of the primary threat of intense, extensive, high-energy neutron irradiation on materials for fusion reactor systems; illustrating some of the accomplishments of the continuing fusion materials research program initiated in the 1970s; and looking at new directions. The articles in this issue will:

- Examine the fundamental scientific phenomena that occur in fusion neutron irradiation damage;
- Explain the innovative experimental methods developed to deal with the sharp constraints of available test environments in order to approximate the effects of the fusion reactor environment;
- Describe the application of the full range of modern metallurgical investigation in conjunction with these special test methods in the evolution of a high-performance, radiation-resistant alloy steel;
- Outline the opportunity and the challenge to the materials research community to advance the attractiveness of fusion with the development of new materials that can substantially reduce the burden of long-term radioactive waste management; and
- Illustrate the breadth of the materials issues by looking at the materials requirements of a current major international experimental fusion reactor design project.

Despite their scope, these articles do not present a comprehensive review of fusion materials R&D. For a comprehensive treatment of the field, the reader can go to the most recent proceedings of the Third International Conference on Fusion Reactor Materials⁹ (and its predecessor, the American Nuclear Society's domestic conference series) and the Seventh International Conference of Plasma Surface Interaction in Controlled Fusion Devices.¹⁰ The American Nuclear Society conference series on Fusion Reactor Technology¹¹ should also be considered.

The Radiation Damage Threat and Materials Research for Fusion

The central axiom of materials science and engineering is that virtually all fundamental and engineering properties of solid crystalline materials depend on details of the microstructure and microchemistry of those materials—metallic, ceramic, organic, and graphitic. Energetic neutron irradiation profoundly changes microstructure and microchemistry relative to normal thermal processes, sharply affecting important properties of solids. In fusion reactor systems, a wide array of materials will be subject to high energy, high flux and high exposure neutron irradiation—and the effects of that irradiation must be known.

The primary damage of neutron irradiation occurs in lattice displacement reactions and in nuclear transmutation reactions. The products of these reactions (cascades of interstitial and vacancy point defects, electronic excitation, and composition changes) produce dynamic (instantaneous) and cumulative phenomena including evolving changes in microstructure and microchemistry. The consequent property changes vary as a function of starting composition, starting structure, temperature, neutron energy spectra, neutron flux intensity, neutron fluence, mechanical and chemical environment, and other factors. The response will vary with property and with the above factors.

In a wide range of practical materials, observed property changes due to irradiation include:

- Density changes that may exceed 100%,
- Loss of strength,
- Increase in hardness and yield strength of several times,
- Conductivity change that may exceed 100%,
- Embrittlement at both high and low temperatures,
- Loss of fracture toughness,
- Increased sensitivity to stress corrosion cracking, and

■ Irradiation-induced creep.

We know that the elementary phenomena, as well as the resultant property changes, may depend on neutron spectra. Thus, the response of materials to the fusion neutron environment will be different from that of the fission reactor. A critically important issue in materials research for fusion is that the fission reactor exists but the fusion one does not.

In the neutron environment of D-T fusion, the high levels of transmutant He and H, in combination with displacement damage, are fully expected to cause property changes at a rate and degree substantially different from those in a fission neutron environment. These expectations have been confirmed in spectral tailoring experiments which approximate the helium and displacement rates of a fusion environment.¹²

Given this background, research on neutron interactive materials in the DOE fusion program has been structured in two major elements: (1) to sort the environmental factors to allow projecting to the conditions of the absent fusion reactor environment, and (2) to sort materials variables, i.e., to develop the higher performance materials required by fusion, including low-activation properties. In each, the approach is based on building a fundamental understanding of the phenomena and mechanisms that control or result from irradiation effects. The primary approach to that understanding is to relate observed property changes to the underlying changes in microchemistry and microstructure. This is first done in reference and model materials, and the control principles are then applied to new alloys. The development and application of theory (both damage and alloy theories) is a major part of the ongoing program.

Alloy development proceeds through several stages: (1) fundamental studies, (2) scoping of engineering properties, and (3) development of an engineering data base. The first stage indicates the direction is acceptable, the second may be sufficient for design studies, and the third is required for meaningful conceptual design and for engineering design, construction, and operation. Present funding levels place the current fusion materials program at stage 1 or 2, depending on the material.

The approach to radiation damage analysis has been through mechanistic studies in existing low-flux, high-energy irradiation facilities and in existing fission reactors, using special irradiation techniques (including neutron spectral tailoring and isotopic tailoring) and theory to develop physically realistic models for projecting the conditions expected in the fusion reac-

tor environment. This element has also guided the arguments for facility requirements and development for fusion materials research.

International Activities

Fusion research is very much an international undertaking, both scientifically and programmatically. Currently about 60% of the U.S. fusion materials program is specifically linked to formal international agreements. This is implicit in the references that follow this introduction as well as in the previously mentioned international conference series. A brief outline of these international arrangements is included here.

Multinational fusion research has been conducted since 1980 under the auspices of an implementing agreement of the International Energy Agency. Partners in this agreement are agencies of Japan, the European Community (EURATOM), Canada, Switzerland, and the United States. Cooperative research has included radiation effects in austenitic stainless steel, insulating ceramics, and tritium breeding solids. The latter includes a jointly funded experiment of *in situ* tritium gas release and recovery in DOE's Fast Flux Test Facility reactor at Richland, Washington. The agreement has served as the framework for major assessments of materials research requirements for fusion.⁴ In addition to recommendations for materials R&D, the agreement calls for developing, constructing, and operating an irradiation facility specifically for fusion materials development on an international basis.¹³

Fusion research is very much an international undertaking.

DOE's bilateral agreements with the Japan Atomic Energy Research Institute and with Monbusho (Japan's university support agency) for collaborative programs in the use of DOE fission research reactors and, formerly, the Rotating Target Neutron Source (RTNS-II), have become central to fusion materials R&D in the United States and Japan. Research activities encompass a mix of fundamental studies of radiation effects, alloy development, and radiation effects on engineering properties.

Bilateral exchange activities with the Soviet Union have been firmly reestablished in the last three years. The principal area of cooperation is the development of low activation Mn-stabilized austenitic steels,

development that is near to Soviet industrial-grade steels.

A more recent element of international cooperation in fusion is conceptual design of the International Thermonuclear Engineering Reactor (ITER), a cooperative project involving the European Community, Japan, the Soviet Union, and the United States. The ITER partners contribute staff to a common design team and also contribute through design activities and supporting materials research conducted within their home laboratories.

About the Articles in This Issue

In addition to this introductory perspective, five articles focus on materials for fusion energy: Two address fundamental radiation damage and experimental methodology that may help approximate the absence of a fusion reactor irradiation test environment; two illustrate alloy research and development with specific performance objectives; and one spans the broad range of materials issues in the design of an experimental fusion reactor.

■ **M.W. Guinan** introduces the fundamentals of radiation damage, treats the specifics of the fusion environment, and describes the prolific work resulting from U.S. and Japanese collaboration in using the RTNS-II facility at Lawrence Livermore National Laboratory. Today, that cooperation continues in fundamental research in high fluence radiation effects in irradiation testing at the FFTF reactor in Richland, Washington. Guinan also explains the use of the very small RTNS-II test environment to determine the engineering properties of materials for superconducting magnets.

■ **G.E. Lucas, G.R. Odette, and A.F. Rowcliffe** illustrate the innovative testing techniques that experimentalists in fusion materials research have had to develop. The sharp volume constraints of available test facilities have forced the development and use of specimen miniaturization. Some of these methods have substantial potential to increase efficiency in general materials research for quantitative characterization of materials properties and the behavior. The authors examine another major category of test development—the adjustment of isotopic concentration and/or adjustment of the neutron spectrum to generate the quantity of transmutant He or H which would correspond to that produced in the fusion reactor neutron environment. The techniques of isotopic tailoring and spectral tailoring are limited to only a few materials. These techniques and materials are, however, critically important to our ability to simultaneously approximate the ratio of He production to displacement damage using existing irra-

diation test facilities, and then to generalize from our understanding of those materials.

■ **P.J. Maziasz, R.L. Klueh, and A.F. Rowcliffe** trace the development of a high-performance, radiation-resistant steel for fusion (and fission) reactor applications. This development is the outgrowth of 20 years of research in the mechanisms of high fluence irradiation effects at Oak Ridge National Laboratory. Furthermore, their research in alloy design through microstructure control (developed for radiation damage resistance in the fusion environment) also yields an austenitic steel with rupture properties that correspond to some superalloys at 700°C.

■ Referring again to the perspective offered by Kintner in 1975, there is today an even more specific argument that the attractiveness of fusion energy source may well depend on the development and application of *low activation* structural and functional materials, particularly to reduce the long-term burden of radioactive waste management. Analysis of this issue⁵ led to adopting it as a fusion energy program goal in 1983...it was a central fact in defining materials as one of four *key issues* in the formal DOE plan for fusion energy development⁶...it was a critical assumption in a analysis of the economic, safety and environmental potential of magnetic fusion¹⁴...and that policy continues to be endorsed in administration testimony to the U.S. Congress.¹⁵ Furthermore, the post-Chernobyl focus on radioactivity has stimulated the fusion programs in Japan, the European Community, and the Soviet Union to launch research activities on low activation materials.

D.G. Doran and R.L. Klueh cover the background, technical rationale, and ongoing materials research in the U.S. fusion program on low activation materials. In the five years spent working toward developing alloys with reduced long-term radioactivity, as well as other required engineering properties, substantial progress has been made, particularly in elemental tailoring of ferritic/martensitic steels and in austenitic steels. Of clear concern is the issue of criteria to judge radioactivity in terms of waste management and thus set specific compositional goals in alloy development.

■ The final article by **D.L. Smith** will give the reader a fair measure of the broad scope of materials applications that must be considered in fusion reactor development. While the balance of these articles has focused on the consequences of the

high flux, high energy, neutron environment of fusion reactors, the scope of the materials issues before fusion is much broader. The problems associated with plasma particle damage and heat loads are clearly more limiting for the relatively low neutron fluence expected for more near-term experimental devices. Other important materials applications for fusion include materials for tritium breeding (specifically, Li-bearing solids and liquids), neutron multipliers (e.g., Be), nuclear shielding, energy conversion, insulators (ceramic and organic), and magnet systems (normal and superconducting).

It's interesting to note that Smith's principal example for materials requirements is the International Thermonuclear Experimental Reactor (ITER), now midway through conceptual design and a cooperative undertaking of the European Community, Japan, the Soviet Union, and the United States.

Conclusion and Acknowledgments

The topics and the authors in this issue of the *MRS BULLETIN* were selected to represent and to illustrate a field of materials science and technology that is composed of several hundred practitioners worldwide. The examples are from only a portion of the materials research that is part of the U.S. Department of Energy's magnetic fusion energy program. We acknowledge our fellow researchers in the U.S. program and many colleagues in the international community. U.S. program activity owes a special acknowledgment to the DOE Basic Energy Sciences (BES) program for its support over the past 25 years for the foundation of understanding of basic radiation effects, and to both BES and the DOE Office of Nuclear Energy for the use of DOE fission research and test reactors.

On a personal note, I would like to acknowledge Dr. K.M. Zwilsky for inviting me to join him in the start of the fusion materials R&D program in the United States. I am also deeply grateful to the authors of the articles for willingly adding this task to their already overcrowded lives.

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Theodore C. Reuther, Guest Editor for this issue of the *MRS BULLETIN*, is manager of neutron interactive materials programs for the magnetic fusion energy program of the U.S. Department of Energy. He has been involved in nuclear systems materials R&D management for the fission and fusion energy programs of DOE and its predecessor agencies for 20 years. The primary focus of his program interest has been the effect of the neutron irradiation environment on the properties and the performance of materials. He has been a principal author of DOE and International Energy Agency programs in research and development on fusion materials, and he has represented DOE in formulating cooperative materials research programs with Japan and the Soviet Union.

Donald G. Doran recently retired as manager of fusion materials programs at the Pacific Northwest Laboratory, Richland, Washington. He has been involved with fusion materials research for 15 years, including leadership of the Damage Analysis and Fundamental Studies Task Group. His current primary interests are defining criteria for low activation materials development and achieving a high flux, fusion energy neutron source for materials testing.

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Glenn E. Lucas is professor and associate chair of the Department of Materials, University of California at Santa Barbara (UCSB). He received his ScD in nuclear engineering from the Massachusetts Institute of Technology in 1978, and subsequently joined the faculty at UCSB. His research interests are in structural materials for advanced systems and the effects of service environment on changes in material properties. Systems of interest include both fusion and fission reactors, advanced coal utilization systems, and space and aircraft.

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ing and his MS in nuclear engineering are both from the University of Michigan in Ann Arbor. He received his PhD in metallurgical engineering in 1984 from the University of Tennessee in Knoxville. Since coming to ORNL in 1974, Maziasz has worked on microstructural characterization of neutron-irradiated steels for fusion application. Much effort was focused on characterizing the effects of helium on overall microstructural evolution and on understanding precipitate phase formation and stability in reactor-irradiated steels. In recent years, this microstructural information has been used to design radiation-resistant and high-temperature creep-resistant steels and alloys.

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Dale L. Smith is acting director of the Fusion Power Program at Argonne National Laboratory. He received his PhD from Iowa State University and was a member of Argonne's Materials Science and Technology Division from 1966 to 1983. He has been a member of the Fusion Power Program since 1974 and was appointed associate director in 1983. Smith served as a U.S. participant to the International Tokamak Reactor Study and is currently involved with the International Thermonuclear Experimental Reactor project. He also served on the technical program committees of several topical meetings on fusion technology and fusion reactor materials, and he was general chairman of the Second International Conference on Fusion Reactor Materials.

Participants Debate Cold Fusion
During MRS Spring Meeting
Panel Session...see p. 66

- Spectroscopic Ellipsometer
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A cross comparison between Spectroscopic Ellipsometry and X-TEM gives very good agreement and show a better resolution of the multilayer structure.

Materials	S.E. Thickness in nm	X-TEM
SiO ₂	2.5	2.5
Si	96.6	95.1
SiO ₂	388.5	419
SiO ₂ + Si _{3N₄}	19.5	
SiO ₂ + Si _{3N₄}	9.0	
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