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The Program for Alloy Development for Irradiation Performance in Fusion Reactors*

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The Division of Magnetic Fusion Energy of ERDA is about to embark on the most ambitious alloy development program in history — the identification and perfection of a material to withstand the hostile environment of the first wall of a fusion reactor. For a neutronic wall loading of ~3 MW/m^2, atoms will be displaced from their lattice positions at rates equivalent to those in current fast fission reactors, but because of the current of 14 MeV neutrons born in the d-t fusion process, damaging transmutation products, especially helium, will be produced at rates orders of magnitude higher. A comparison of critical damage parameters is given in Table 1.

Table 1

A Comparison of Displacement Damage and Helium Production in Fast Fission and Fusion Reactors for Stainless Steel

	Damage Accumulated in One Year of Operation	
	Displacements per Atom	Parts per Million Helium
Fusion Reactor (3 MW/m^2)	36	525
EBR-II	35	10

Core components in fast breeder reactors are designed for service life of about two years. Replacement or repair of a fusion reactor first wall is expected to be a significantly more difficult task, so a longer life, in the range of five to ten years, will be required for economical generation of electricity. This will result in a cumulative damage level well above that of fast reactors.

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In Table 1 displaced atoms and helium are identified as the principal components of damage. Experiments in which these have been studied independently have demonstrated their capability for degrading properties. Other transmutation products, hydrogen as well as solids, also may be harmful, but except in special cases the evidence is not conclusive.

The biggest obstacle in the path of development of an alloy for fusion reactor use is lack of a testing facility with a neutron flux and spectrum that matches fusion reactor conditions. Fusion neutron sources available or authorized for construction, RTNS I and II and INS, have fluxes and experimental volumes that are much too low for use in testing large numbers of specimens to end of life exposures necessary for design of structural components. It is important to recognize that it is a combination of flux and volume that must be available for alloy development. Fluxes must be high enough to allow testing at damage rates close to those expected in reactor operation. A capability for accelerated testing clearly would be desirable. Development and eventual qualification of an alloy for reactor service will require an experimental volume in the range of ten liters. Thus, a testing facility for alloy development and qualification testing must satisfy simultaneously both flux and volume requirements.

The requirements of a large number of test specimens seems surprising at first glance. The reason for this is that there are several potential failure mechanisms that must be investigated. Fatigue and crack growth studies involve large numbers of large specimens, for results are sensitive to specimen geometry, temperature, mean stress level, stress variations and hold times as well as irradiation and environmental parameters. Additionally, since the expected damage levels are well beyond our present experience, we are unable to identify with assurance even a class of materials that will provide the best solution to the problem. This means that multiple materials options must be incorporated into the test matrix.

The fusion reactor is not unique in that early machines will have to be constructed without complete irradiation testing in the proper environment. The first fission reactors, for example, were built under this condition, but they did not suffer from significant damage to structural components. In the case of fusion reactors we know from experience with the Breeder Reactor program that the first wall will suffer from void swelling and irradiation-induced embrittlement.

To repeat, the real problem is lack of a suitable fusion environment testing facility. This is not a simple consequence of a lack of funding, since serious technical difficulties stand in the way of developing such a facility. Furthermore, structural components of a test reactor will certainly suffer from radiation effects themselves. In any case such a device likely will not be available for at least ten to fifteen years, and it as well as early fusion reactors will have to be designed on the basis of data from non-fusion irradition experiments.

The flux-volume requirement discussed previously limits our current choice of existing irradiation facilities to fission reactors. As can be seen in Table 1, fast reactors provide only a partial solution to the testing dilemma; atoms are displaced at the proper rate, but helium is generated much too slowly. Nature, which usually conspires against us, has given us a partial solution to this problem. Nickel—58 undergoes a two step reaction with thermal neutrons to produce helium via the sequence

$$^{58}Ni + n \longrightarrow {}^{59}Ni$$

$$^{59}Ni + n \longrightarrow {}^{56}Fe + {}^{4}He \; .$$

In mixed (fast/thermal) spectrum research reactors currently available atoms can be displaced by fast neutrons and helium generated by thermal neutrons (for materials containing nickel). Cross sections for both processes are high enough that damage levels close to those given in Table 1 for fusion reactors can be produced in existing reactors. The situation is complicated by the two step reaction for the production of helium. As a consequence of this, helium is generated at an accelerating rate, but displacements are produced by the fast neutrons at a constant rate. This deficiency can be overcome in some reactors by varying the ratio of thermal to fast fluxes during the irradiation. For materials that contain nickel, therefore, an acceptable approach exists for approximating the damage expected in fusion reactors. For other materials the situation is far less satisfactory. There is a possibility that fast reactor irradiations may be useful if the irradiation temperature is maintained below the range where helium effects are important, but this remains to be demonstrated by experiments. For a material like vanadium that might correspond to temperatures below about 600°C and for austenitic stainless steel to temperatures of 450—500°C or less.

The intent of this discussion is to show that in the near future only fission reactors can provide the basis for irradiation testing of structural materials to generate engineering data and that there is reason to believe that under certain conditions fission reactors may provide a reasonable approximation of the effects of the fusion environment. The program plan prepared by the Division of Magnetic Fusion Energy to address the alloy development task rests on this premise. It recognizes as well that this by itself is insufficient to guarantee a reliable structural material. Important considerations such as differences in the primary recoil spectra and differences in rates of production of other transmutation products such as hydrogen between the fission and fusion reactor neutron spectra also must be considered. In the DMFE program a separate task group on Damage Analysis and Fundamental Studies has been established to examine quantitatively the relationships between damage produced in different neutron sources. The damage analysis technique, which develops energy dependent damage cross sections, has been used successfully in fission reactor programs by interpolating between known spectra. Although combined displacement and helium effects present a more complicated situation, there is reason to believe that such techniques founded on a fundamental understanding of the relevant physical processes can be applied to fusion reactor problems. An essential requirement is that data be available from spectra that overlap the spectrum for which property estimates are required. For the fusion reactor application fission reactor data alone are not sufficient. Additional data covering the energy range between fission reactor energies and 14 MeV are required. Such a source must have a flux high enough to reach the damage levels of interest on a limited number of specimens.* A Li (d,n) source having a useful volume of several hundred cubic centimenters meets this need. Such a source also will provide information on the effects of large amounts of hydrogen on properties and will allow a test of the idea that helium effects can be neglected in low temperature irradiations. It also will permit flux cycling experiments that can not be performed easily in fission reactors. It is not intended that this type of source will be used to generate statistical engineering data but rather that it be used for specialized experiments that allow interpretation and projection of data generated in fission reactors for fusion environments. Its purpose is to tell us how to use those data. Of course, high energy cross section data are needed to tell us how to use the Li (d,n) source.

The DMFE Materials Radiation Effects Program is organized around four Task Groups as shown in Table 2. The Alloy Development for Irradiation Performance Task Group is charged with conducting engineering tests on engineering materials using the full range of metallurgical options to develop an acceptable material. The Damage Analysis and Fundamental Studies Task Group is concerned with developing correlations among the several irradiation test environments as well as with conducting fundamental experiments (usually on model materials) directed at uncovering mechanisms of material behavior under high energy neutron irradiation. The Plasma-Materials Interaction Task Group investigates interactions between the first wall surface and the plasma, including both material wastage and plasma contamination processes. The Special Purpose Materials Task Group pursues materials problems in other parts of the reactor system, such as insulators, magnets, coolant and breeding materials and ceramics. Although the task groups are organized around distinct and well identified areas, there is appreciable overlap and interaction, especially between the first two.

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*The approach is that the very large engineering test matrix is conducted in fission reactors with a limited number of tests in the high energy source to provide the parameters for interpolating to the fusion reactor spectrum. Lower flux and exposure experimentation in the 14 MeV d-t sources such as RTNS will provide complementary data on model materials to help establish the necessary correlations among the various test environments.

Table 2

Task Group Organization of the DMFE Materials and Radiation Effects Program

Alloy Development for Irradiation Performance
Damage Analysis and Fundamental Studies
Plasma-Material Interaction
Special Purpose Materials

Since the fusion reactor environment is outside the range of our experience and since the properties required by reactor design are not yet identified, the Alloy Development for Irradiation Performance Task Group is taking a broad approach in which four distinct classes of materials are investigated in parallel as illustrated below:

PATH A — AUSTENITIC ALLOYS
PATH B — HIGHER STRENGTH Fe-Ni-Cr ALLOYS
PATH C — REACTIVE/REFRACTORY METAL ALLOYS
PATH D — INNOVATIVE CONCEPTS

The Austenitic Alloys are modifications of 300 series stainless steels with composition and microstructure optimized for fusion applications. The principal components are given in Table 3. The

Table 3

Components of Austenitic Alloys

65% Iron
15% Nickel
15% Chromium
Small Additions of
Molybdenum
Silicon
Manganese
Titanium
Carbon

Path B alloys contain significantly larger amounts of nickel as shown in Table 4. Commercial materials in this composition range include the class of so-called Super Alloys. Many of these alloys offer potential for significantly higher strengths via precipitation reactions. These alloys have been developed for service in oxidizing atmospheres, which is not a requirement for first wall applications. By relaxing this requirement many exciting possibilities f .. alloy development occur. Path C Alloys include both the refractory and reactive metals as indicated in Table 5.

Table 4

Components of Higher Strength Fe-Ni-Cr Alloys

20–75% Nickel
Major Additions of Iron and Chromium
Small Additions of
Aluminum Titanium Niobium Molybdenum Carbon

Table 5

Composition Bases for Reactive/Refractory Metal Alloys

Titanium Zirconium
Vanadium Niobium

Possibilities are even broader in this class since so few commercial alloys based on these materials are available, but the details of the approach are less well defined at this time.

In summary, the Division of Magnetic Fusion Energy has established the planning and organizational basis for the development and testing of alloys for the intense high energy neutron flux that will be encountered in the first wall of a fusion reactor. Because of the lack of fusion testing environment, most irradiations for obtaining engineering data will have to be carried out in fission reactors. A Key element of the program is the Li (d,n) neutron source which will allow relationships to be established between the fission and fusion environments. Since such a source supplies a broad spectrum of neutrons extending up to about 40 MeV, extensive cross section measurements are required in order for it to be used effectively to develop alloys for fusion reactors. Specific section needs are discussed by D. G. Doran in a separate paper at this conference.