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Radiation Effects in Be and Al for a Magnetic Fusion Production Reactor[1]

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Estimates of the expected performance of beryllium and several aluminum alloy structural components of the breeding blanket of a magnetic fusion production reactor are made based on the known behavior and properties of these materials in fission reactor applications. Comparisons of the irradiation damage effects resulting from the fission reactor neutron spectra and the fusion reactor blanket spectra indicate that beryllium will perform well in the breeding blanket for at least one year and the aluminum alloy 5052 will retain structural integrity for about 5 years.

KEY WORDS: magnetic fusion production reactor; tritium production; fusion breeder; radiation effects; beryllium; aluminum.

INTRODUCTION

The components of the tritium breeding blanket, which surrounds the solenoid section of the tandem mirror fusion reactor, are presently envisioned as aluminum and beryllium. These components will be subjected to a fusion neutron flux and spectra similar to those shown in Figs. 1 and 2. The blanket will be water-cooled, and the component temperatures should not exceed 150°C. The objective of this paper is to assess the expected behavior and performance of components in this service environment.

Beryllium has been used extensively as a neutron moderator and reflector in water-cooled fission reactors such as the materials test reactor (MTR) at Idaho National Engineering Laboratory and in the high-flux isotope reactor (HFIR)[(1)] at Oak Ridge.

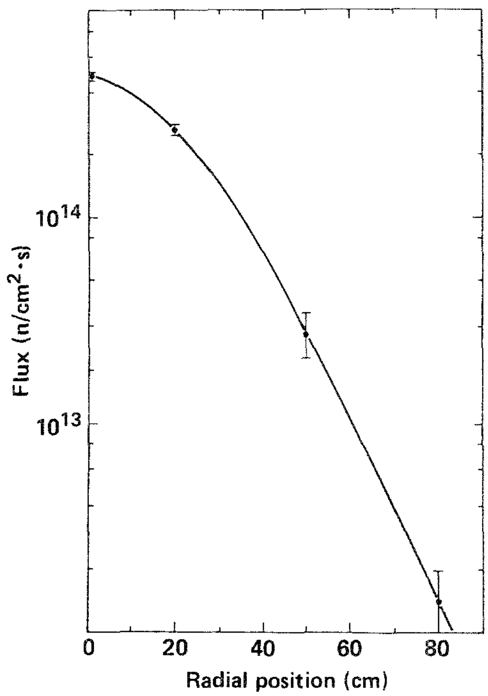

Fig. 1.

[1] This paper represents work carried out from 1980 to 1982 and was in draft form in 1982. It was received for publication with only minor editing of its 1982 version, explaining the fact that some of the material is dated.

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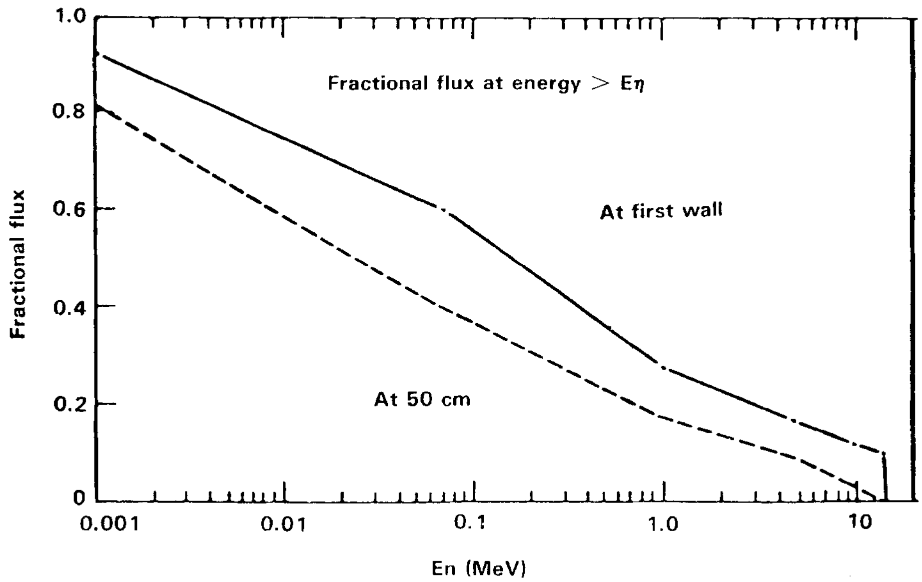

Fig. 2.

The beryllium in these reactors is subjected to temperatures between 50 and 150°C and to neutron fluences greater than 10^{22} n/cm^2 ($E > 0.1$ MeV). In addition, it receives a significant dose of thermal neutrons.

Examinations of the beryllium after service in MTR and HFIR reveal that, at these low temperatures (50 to 150°C), beryllium exhibits no significant swelling although it undergoes substantial hardening and embrittlement. Extensive cracking occurs predominantly along grain boundaries, causing the spalling of small pieces up to about 1 in. long. The holes and channels observed at grain boundaries are characteristic of gas-bubble formation.

A major contributor to radiation damage in Be, in addition to displacement damage (DPA), is the creation of He and H from (n, 2n) and (n, α) reactions according to the equations

$$^9\text{Be} + \text{n} \rightarrow {}^8\text{Be} + 2\text{n} \qquad E_1 = 1.7\text{–}27 \text{ MeV}$$

$$^8\text{Be} \rightarrow 2^4\text{He} \qquad (1)$$

$$^9\text{Be} + \text{n} \rightarrow {}^6\text{He} + {}^4\text{He} \qquad E_1 = 0.71 \text{ MeV}$$

$$\text{He} \rightarrow {}^6\text{Li} \qquad (2)$$

$$^6\text{Li} + \text{n} \rightarrow {}^4\text{He} + {}^3\text{H}$$

$$^3\text{H} \rightarrow {}^3\text{He} \qquad \text{Primarily thermal neutrons}$$

$$^3\text{He} + \text{n} \rightarrow {}^1\text{H} + {}^3\text{H} \qquad (3)$$

Helium is the major gas produced, and the ratio of helium to DPA in beryllium is 100 to 1000 times greater than any other metal for which data are available. When there is a significant flux of thermal neutrons, such as in HFIR where the thermal flux can be twice the fast flux, substantial quantities of hydrogen isotopes can be generated.

At the elevated temperatures (> 500°C) where He and vacancies are mobile, internal helium-filled bubbles and voids form and the beryllium swells considerably.[2] At lower temperatures, however, the He atoms are probably trapped at vacant Be lattice sites and held in enforced solid solution, causing high internal stresses and hardening.

The gas bubbles observed at the grain boundaries of fission-reactor-irradiated Be are clearly related to grain boundary cracking and spalling. These bubbles are created by internal gas migration to voids and the interfaces of such particles as BeO that are present at the grain boundaries of powder-metallurgy-processed Be, where it precipitates as bubbles with high internal gas pressures. As mentioned, He atoms at irradiation temperatures near 100°C are probably trapped by immobile vacancies in the Be lattice and, consequently, could not contribute significantly to gas-bubble formation at grain boundaries. Hydrogen, on the other hand, should be quite mobile and may be the major gas involved in the grain-boundary bubbles in the fission-reactor-irradiated Be. If this is the case, the formation of grain-boundary bubbles and the associated cracking and spalling may be much less serious in Be irradiated with the fusion neutron spectrum shown in Fig. 2 because the absence of a thermal neutron component in this spectrum will result in a much lower production of hydrogen.

The ratio of He to DPA produced in Be is approximately the same for a moderated fission spectrum and the neutron spectrum in Fig. 2. Therefore, the damage effects produced in Be by a given fluence of the fusion neutron spectrum, by these two major damage components, should be similar to the damage effects produced in the fission reactors when scaled by damage energy. The damage-energy scaling factor is approximately 5, which means that the fusion neutron spectrum produces, for the same neutron fluence, about five times the displacement damage and five times more He as does the fission reactor spectrum.

The most significant consequence is that, with the possible exception of grain-boundary effects earlier conjectured to be associated with hydrogen, we can expect the trends of the damage effects in Be irradiated with the fusion spectrum to be quite similar to those observed in Be irradiated in fission reactors.

The past performance of Be in fission reactors suggests that it should perform well in the tritium breeding blanket for at least one year ($\sim 2\times10^{22}$ n/cm^2 fluence) at temperatures near 100°C; however, more data should be collected. If grain-boundary cracking and spalling are not caused by hydrogen-filled gas bubbles alone, but also by helium gas, the Be components should be contained in a cladding.

The Al–2% Mg solid solution alloy 5052 has been used extensively in water-cooled research reactors and in the construction of the calandria in the British steam-generating heavy water reactor.[3] Its application in fission reactors was dictated primarily by its good unirradiated strength and ductility, good corrosion resistance in contact with cooling water, and good weldability. More recently, studies of neutron radiation damage effects in 5052, conducted in the HFIR reactor at temperatures between 50 and 150 °C and at fluences up to 2×10^{23} n/cm^2 ($E > 0.1$ MeV) and 4×10^{23} thermal neutrons/cm^2, have shown it to have very good resistance to internal void formation and swelling.[4,5] Figure 3 shows the percent decrease in density (swelling) of several Al alloys vs neutron fluence at an irradiation temperature of about 50 °C. As can be seen in the plot, the 5052

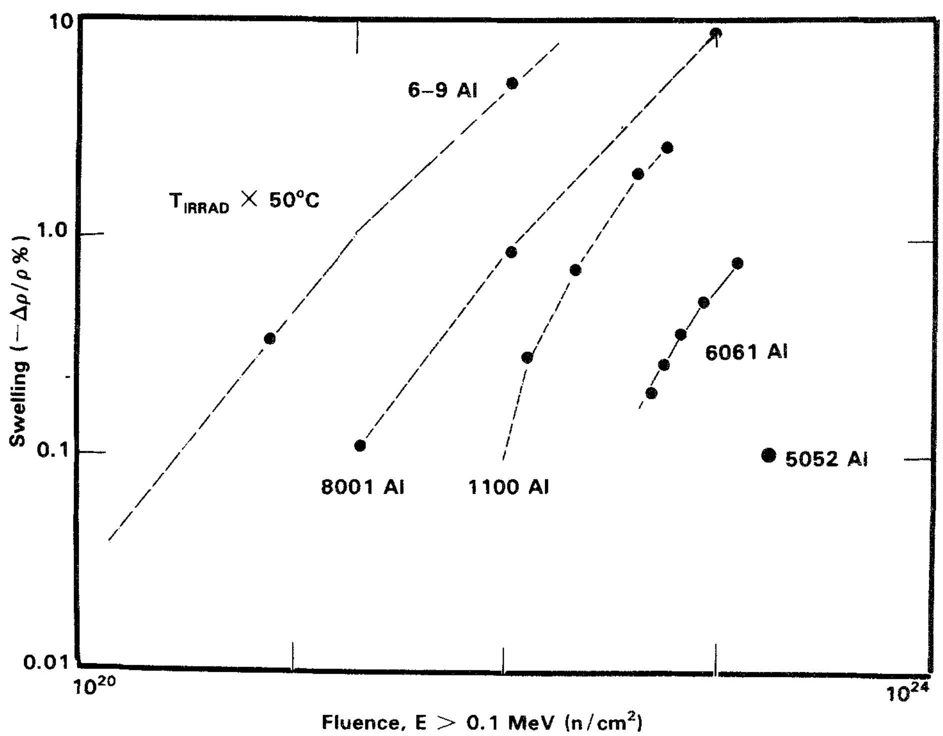

Fig. 3.

alloy swells only 0.1% at a fluence of 2×10^{23} n/cm^2 while the other alloys exhibit from 1% to more than 10% swelling at this fluence.

The large thermal neutron flux produces a substantial amount of silicon (~ 2 at %/year) from the transmutation reaction $^{27}Al(n, T) \rightarrow {}^{28}Si + \beta^-$. The Si combines with the Mg in the 5052 alloy to form Mg_2Si precipitates that have a dominant effect on the mechanical properties of the irradiated alloy.[4,6,7]

Figure 4 shows the fluence dependence of the tensile properties of 1100 Al (Ref. 8), 5052–O Al (Ref. 4), and 6061-T6 (Ref. 9) irradiated in the HFIR reactor at about 55 °C and tested at 150 °C. The 6061-T6 alloy contains about 0.87 wt% Mg and 0.58 wt% Si, and it is age-hardened to produce Mg_2Si precipitates that give it a high unirradiated yield strength. Both alloys exhibit radiation strengthening, but that of the 5052 alloy is significantly greater because of the in situ precipitation of Mg_2Si. The two alloys also exhibit a substantial decrease in ductility at fluences above about 10^{22} n/cm^2, where the uniform elongation drops to less than 1% at 150 °C.

The fusion neutron spectrum will produce about 1000 times less Si in Al than the thermal neutrons in HFIR, and the Mg_2Si precipitation and associated hardening and loss of ductility in the 5052 alloy should be reduced substantially. However, the fusion neutron spectrum will produce about 300 times more He and H and 5 times more displacement damage in aluminum than is produced by a fission reactor spectrum. The combined effects of increased He and H generation and displacement damage on the behavior of aluminum alloys is not known quantitatively, and no high-flux fusion neutron source is available to determine these effects. Simulation experiments on dilute Al–^{6}Li alloys have given us some insight into the effects produced in aluminum with a high gas content combined with displacement damage.[10,11]

These experiments have shown that a high gas content (~ 4000 ppm), corresponding to those expected at the first wall of the blanket after 10 years, produces a very high density of small gas-filled cavities along grain boundaries. While these higher cavity densities do not appear to increase the swelling of Al significantly, they will, when combined with a relatively small amount of displacement damage (2 to 3 DPA), cause a considerable increase in hardness and severe embrittlement and fracturing along grain boundaries. The results of these experiments strongly suggest that the high He and H content acts synergistically with displacement damage to cause severe hardening and grain-boundary embrittlement. Thus it appears that the fusion neutron spectrum will

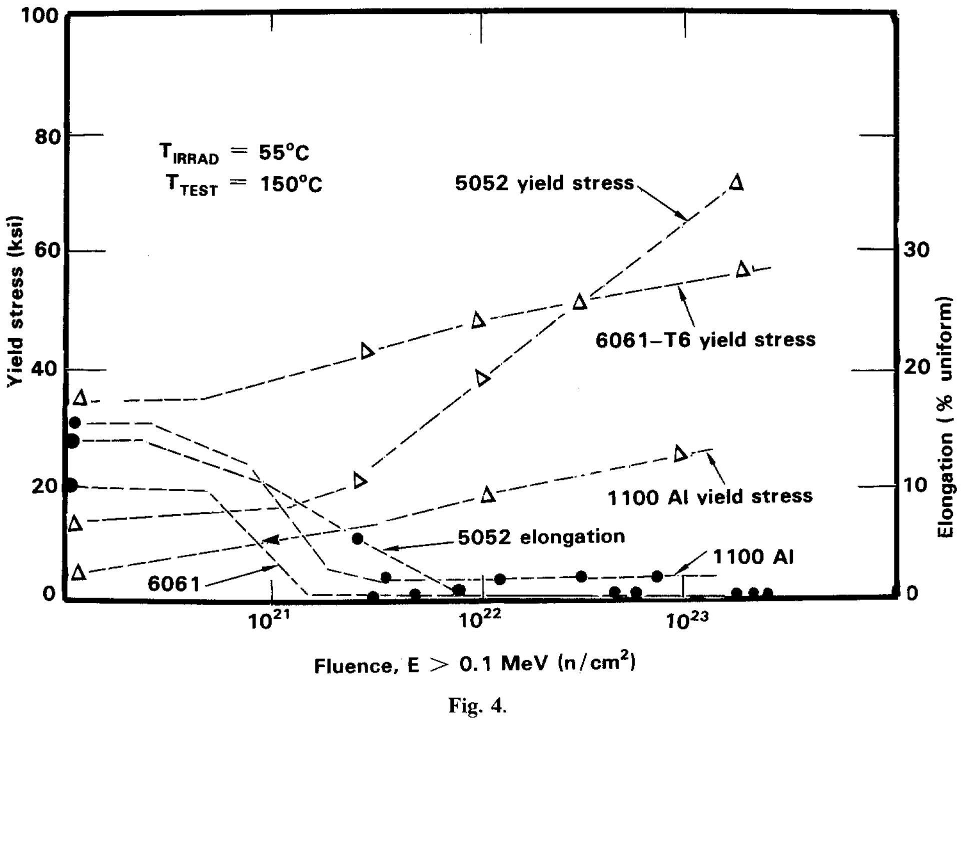

Fig. 4.

cause severe radiation hardening and embrittlement of Al alloys in less than 5 years in the tritium breeding blanket.

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