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Radiation flux and damage at accelerator-driven spallation neutron sources

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ABSTRACT

Radiation damage (displacement, helium, and hydrogen production) at proton-driven spallation neutron sources is analyzed and compared for SNS SB (316SS at the nose of the Hg-container vessel), SNS PEW (Al6061 at a hypothetical proton entrance window), and SINQ EW (Al–3 wt% Mg entrance window at Target 5). Spallation neutrons at the three components exhibit differential fluxes, ϕ', that increase monotonically with decreasing energy E. For SINQ EW, ϕ' is roughly proportional to 1/E, which is attributed to the moderating effect of the D_2O coolant and moderator tank. For 316SS at SNS SB, the calculated total displacement production rate due to protons and neutrons is 34 dpa/yr at full power, with about 37% due to protons. For the Al at SNS PEW and SINQ EW, however, the total rate is 4–5 dpa/yr, with about 90% due to protons. He and H production in all three components is dominated by the incident protons. For He, comparison of experimental and calculated production cross sections for protons on 316SS and Al indicates the need to employ the non-default Jülich ILVDEN option in running LAHET. The resulting total production rates for SNS SB, SNS PEW, and SINQ EW are about 3000, 2400, and 1900 appmHe/yr, respectively. These rates are 1.5–2 times the rates previously calculated using the default GCCI ILVDEN option. The high mobility of H atoms promotes H escape from thin targets of 316SS and Al. For 0.1 cm-thick samples, we tallied the H where it comes to rest using IOPT 14, and obtained production rates at SNS SB, SNS PEW, and SINQ EW of 11500, 4300, and 3500 appmH/yr, respectively.

1. Introduction

Our aim is to analyze and compare calculations of radiation damage (displacements, He, and H production) due to protons and spallation neutrons at two components at SNS and one component at SINQ. The three components are:

(1) SNS SB: This is the ‘Smallest Box’ at the innermost 316-stainless-steel shell of the nose of the SNS target container module. As described in [1,2], the SNS SB is a 0.1 cm^3 tally volume, 0.13 cm thick, that extends from the outer to the inner surface of the shell. It is in contact with the Hg spallation target material. The SNS SB receives a 2 mA current of 1000 MeV protons with a central incident current density of 1.4×10^{14} protons/cm^2 s.
(2) SNS PEW (Proton Entrance Window): This is a hypothetical Al6061 component (the actual material for the proton entrance window is now taken to be Inconel 718). The SNS PEW lies 2.38 m upstream of the SNS SB. The incident current density of the 1000 MeV protons on the SNS PEW is 1.75×10^{14} protons/cm^2 s [3].
(3) SINQ EW (Entrance Window): The calculations for this component are directed toward Target 5 at SINQ, which receives a beam of 570 MeV protons at a current of 1.1 mA [4–6]. The target vessel is a double-walled structure of an Al-3 wt% Mg alloy designated as AlMg3. The entrance window consists of outer and inner hemispheres, which are connected to mating outer and inner cylinders. The protons are incident on the entrance window from below, and we focus our attention on the inner shell at the centerline lowest point of the hemisphere (see Fig. 6 in [4] or Fig. 1 in [5]). The incident current density at this point is 1.75×10^{14} protons/cm^2 s (coincidentally the same as for SNS PEW). The spallation target material at SINQ Target 5 is Pb. SINQ EW is separated from the nearest Pb spallation target rod by about 15 cm of D_2O coolant.

The three materials (316SS at SNS SB, Al6061 at SNS PEW, and AlMg3 at SINQ EW) receive the maximum proton current density in the incident beams. The nominal composition for 316SS is Fe + 16–18 wt% Cr + 10–14 wt% Ni. A nominal composition for Al6061 is Al + 1.0 Mg + 0.6 Si + 0.3 Cu + 0.2 Cr (in wt%) [3], and for AlMg3 it is Al + 2.7 Mg + 0.35 Mn + 0.30 Si + 0.25 Fe (in wt%)

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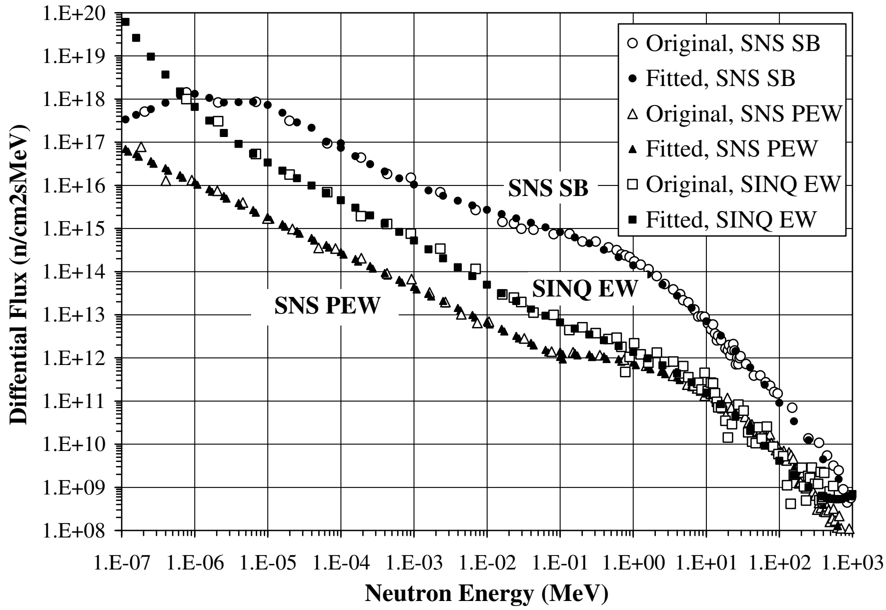

Fig. 1. Differential flux vs neutron energy for SNS SB, SNS PEW, and SINQ EW. Open symbols, original calculated points; filled symbols, fitted points.

[7]. Damage cross sections for the two Al alloys will differ only slightly from those for pure Al, and we refer to the two materials simply as 'aluminum'.

2. Proton and neutron fluxes

As mentioned above, the proton current densities for SNS SB, SNS PEW, and SINQ EW are 1.4, 1.75, and 1.75, respectively, in units of 10^{14} protons/cm^2 s at energies of 1000, 1000, and 570 MeV, respectively. Since the protons are directly incident on the target metal, there is only a slight admixture of lower energy protons in the proton flux. For the 316SS at SNS SB, about 92% of the displacement-producing protons have energies above 900 MeV, and the proton flux of all energies is about 8.5% greater than the incident current density, which is attributed to the secondary protons [1]. Similarly, for the aluminum at SINQ EW more than 98% of the protons in the flux at the center of the entrance window have energies between 569 and 570 MeV [5], and the proton flux of all energies is about 4.6% greater than the incident current density, due to the secondary protons [4]. Thus, we may neglect the relatively small damage contribution due to secondary protons, as was done for SNS PEW in [3].

In contrast to the proton flux, the neutron flux spectra are distributed over a wide range of energies. Fig. 1 shows the differential neutron flux for SNS SB, SNS PEW, and SINQ EW over the full neutron energy range above 10^{-7} MeV. Except for the SNS SB region below 10^{-6} MeV, the differential neutron flux increases with decreasing neutron energy. These neutron spectra are quite different from the accustomed prompt fission spectra in nuclear reactors, as can be seen in Fig. 2 by comparing the SNS SB and prompt fission curves, corresponding to the same total neutron flux of all energies of 8×10^{14} n/cm^2 s. For the fission flux, we used the expression determined by Cranberg et al. [8] for the differential U-235 fission neutron number density.

$$N'(E) = N(0)\frac{2a}{\sqrt{\pi}}(aE)^{1/2}\exp(-aE) \tag{1}$$

where $a = 0.775$ MeV^{-1}. $N(0)$ is the number of neutrons per unit volume of all energies. The differential fission flux is then given by

$$\phi'(E) = vN'(E) = \left(\frac{2E}{m}\right)^{1/2} N'(E) = BE\exp(-aE) \tag{2}$$

where v is the neutron velocity, m is the neutron mass, and B is a constant. Integrating (2) over all energies, we find that the flux of neutrons of all energies = $\phi(0) = B/a^2$, whereby

$$\phi'(E) = \phi(0)a^2E\exp(-aE) \tag{3}$$

The most probable neutron energy in this flux spectrum is $1/a = 1.3$ MeV and the average energy is $2/a = 2.6$ MeV. We see in Fig. 2 that the differential neutron fluxes for SNS SB and prompt fission are in rough agreement only for neutrons with energies between about 1 and 10 MeV. As the neutron energy decreases below 1 MeV and increases above 10 MeV, the SNS SB differential flux becomes increasingly much higher than for prompt fission.

The moderated flux curve in Fig. 2 is based on the analysis of the slowing down of neutrons for fission reactors (see, for example, [9], Chapter 3), which indicates that, depending upon considerations such as source parameters and the degree of neutron absorption or escape, the differential neutron flux for the slowing-down energy range may be approximated by

$$\phi'(E) = \frac{\phi_0}{E} \tag{4}$$

where ϕ_0 is a constant flux value. The total moderated flux of neutrons from $E_1 = 10^{-7}$ MeV to $E_2 = 1000$ MeV is therefore

$$\phi(E_1, E_2) = \phi_0 \ln\left(\frac{E_2}{E_1}\right) = 23.0\phi_0 \tag{5}$$

and ϕ_0 for the moderated flux curve in Fig. 2 is equal to 3.58×10^{13} n/cm^2 s, consistent with the same total flux of 8.2×10^{14} n/cm^2 s as for SNS SB. It is clear in Fig. 2 that the differential flux for SNS SB is much better approximated by the moderated flux curve than the prompt fission flux curve. It follows from Eq. (4), that the average energy, <E>, in the moderated flux over energy range (E_1,E_2) is given by

$$\langle E\rangle = \frac{E_2 - E_1}{\ln(\frac{E_2}{E_1})}. \tag{6}$$