The effect of neutron and gamma radiation on magnet components

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Results of irradiation experiments in a TRIGA Mark II reactor are reported. The radiation in a fission reactor consists of neutrons and γ rays with a broad energy distribution. The fission of ^{235}U following neutron capture releases an energy of about 200 MeV, the largest portion (about 165 MeV) in form of the kinetic energy of the fission products (which are absorbed in the fuel rods). Around 6 MeV are transferred to the emitted neutrons, about 7 MeV to prompt γ radiation, and approximately 6 MeV are released by γ radiation during the radioactive decay of the fission products. The energy spectrum of the neutrons has two peaks, one at high energy (~ 1MeV) – corresponding to the energy distribution just after fission (fast neutrons, 0.1 MeV < E_n < 15 MeV) – and one at low energy (~30 meV, 340 K) corresponding to the highly thermalized neutrons. Neutrons during thermalization have intermediate energies (epithermal neutrons, 0.55eV < E_n < 0.1 MeV). The energy distribution of the prompt γ emission (100 keV < E_γ < 8 MeV) peaks at around 300 keV. The dose rates as well as the energy distributions of the γ radiation arising from the radioactive decay of the fission products and from the prompt γ emission are similar.

Neutrons damage the irradiated material either by direct collisions with the lattice atoms, or by nuclear reactions. In the first case, the transferred energy increases with decreasing mass of the lattice atom. If the energy of the primary knock-on atom exceeds ~1 keV, a whole cascade of further collisions with neighboring atoms is initiated leading to local melting and the creation of a nanometer sized defect. While these defects are stable in the cuprates, they disintegrate in metals with increasing temperature and finally form small clouds of point defects at room temperature. The cascade formation is induced most efficiently by fast neutrons, lower energy neutrons produce (clusters of) point defects.

The cross sections for nuclear reactions (capture of a neutron followed by fission or the emission of α, β, or γ radiation) are usually highest at low neutron energies and strongly depend on the nucleus. The recoil can displace the decaying nucleus, emitted α particles further damage the material (e.g. magnesium diboride). γ rays interact with matter via the electronic system and lead to ionization, which has little effect in crystalline materials (superconductors), but can break chemical bonds of organic molecules (insulators).

Numerical damage calculations (with the computer code SPECTER) were made in order to compare and predict property changes in different radiation environments (e.g. fusion power plants) on the basis of irradiation experiments in a fission reactor. The damage energy per atom was found to be the appropriate scaling quantity for superconductors, as demonstrated experimentally on NbTi (irradiation in different neutron sources). The damage energy depends on the elements of the irradiated material and on the energy spectrum of the high energy neutrons. The whole neutron energy spectrum and the γ dose have to be taken into account in case of the insulators. Successful scaling by the total absorbed energy (dose) was obtained for the irradiation with neutrons, electrons and γ rays.

The irradiation reduces the superconducting transition temperature (T_c) of Nb_3Sn, MgB_2 and the cuprates. The critical current, I_c, initially increases but decreases at high fast neutron fluences (>1-2×10^{22} m^{-2}). The degradation of T_c and I_c at high fluences is smaller in NbTi (without an initial increase of I_c).

The mechanical properties of epoxy based insulators severely degrade at a fast neutron fluence of 10^{22} m^{-2}. Cyanate ester based resins are much less sensitive to irradiation enabling their use up to ~5×10^{22} m^{-2}.

The temperature during irradiation does not have a big influence on the property changes of the superconductors or insulators.