Journal of Nuclear Materials 488 (2017) 46–62

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Accelerated materials evaluation for nuclear applications

M. Griffiths [a, *], L. Walters [b], L.R. Greenwood [c], F.A. Garner [d]

[a] Department of Mechanical and Materials Engineering, Queen's University, Kingston, Ontario, K7L 3N6, Canada
[b] Canadian Nuclear Laboratories, Chalk River, ON, K0J 1J0, Canada
[c] Pacific Northwest National Laboratory, Richland, WA, 99352, USA
[d] Radiation Effects Consulting, Richland, WA, 99352, USA

ARTICLE INFO

Article history:
Received 1 December 2016
Received in revised form
2 February 2017
Accepted 25 February 2017
Available online 28 February 2017

ABSTRACT

This paper addresses the opportunities and complexities of using materials test reactors with high neutron fluxes to perform accelerated studies of material aging in power reactors operating at lower neutron fluxes and with different neutron flux spectra. Radiation damage and gas production in different reactors have been compared using the code, SPECTER. This code provides a common standard from which to compare neutron damage data generated by different research groups using a variety of reactors.

1. Introduction

The operating life of nuclear reactors is often dictated by the performance of the materials in the reactor core. Reactor components subjected to a neutron flux will undergo radiation-induced changes that impact their ability to function as designed. Typically, the materials comprising these components undergo changes in dimensions (swelling and creep) and changes in mechanical properties (yield strength, ultimate tensile strength, ductility and fracture toughness) that are irradiation effects and cannot be simulated in the laboratory.

To predict future performance of components in operating reactors, or for the design of new reactors, materials test reactors (MTRs) have been utilized over many years to perform accelerated materials evaluations. The main value from testing in MTRs comes from the higher neutron fluxes and radiation damage production rates. Not only does the MTR provide the researcher with the ability to obtain information on materials degradation in advance of operating reactors, but also one can test material properties using standardized test specimens in controlled (known) conditions of temperature and neutron flux. Testing in MTRs is not just about having a higher atomic displacement damage rate compared with power reactors (not always the case). Often, testing under controlled conditions is the primary value of the MTR. Comparisons of neutron fluxes for different MTRs have been conducted previously by Karasiov and Greenwood [1]. Building on this work Table 1 shows an expanded list of MTRs that have been utilised, or are currently being utilised, for materials testing. In this table and throughout this paper neutron fluxes are given in units of $n.cm^{-2}.s^{-1}$ to be consistent with common usage in the USA and appearing in many of the references. Some reactors (FFTF and EBR-II) are no longer operating but are included in the table because of the large amount of experimental data that is still being processed and assessed today. The approximate maximum fluxes available for materials test sites are listed for different neutron energy ranges. As power reactors are also sources for material that can be used for research, they are also included in the table for completeness. In the case of power reactors, the fluxes are nominal values at specific locations. Of course, when considering the neutron flux for a given power reactor component, or testing a given material in an MTR, the neutron flux and energy spectrum will vary as a function of: the coolant medium, location within the reactor, the material, component or holder geometry, and all other reactor operating variables. The neutron energy spectrum is largely dictated by the coolant, the biggest effect being observed for liquid metal reactors where low energy (thermal) neutrons are essentially absent. Test temperatures vary and are subject to the ambient conditions at the location of interest in the reactor (when the material is immersed in a coolant medium, for example) and insert designs, which provide a means of temperature control where heat is generated from gamma and nuclear interactions in the material or from a separate heat source. Gamma radiation can also induce atomic displacements, primarily through an intermediary process in which the

* Corresponding author.
E-mail address: malcolm.griffiths@queensu.ca (M. Griffiths).

http://dx.doi.org/10.1016/j.jnucmat.2017.02.039

Table 1
List of different reactors that are sources of irradiated materials for research and maximum neutron fluxes achievable in various materials test sites or core components in these reactors.

Reactor	Acronym	Reactortype coolant	Fast flux (E > 1 MeV) $n \cdot cm^{-2} \cdot s^{-1}$	Thermal flux (E < 0.5 eV) $n \cdot cm^{-2} \cdot s^{-1}$	Total flux (E > 0 eV) $n \cdot cm^{-2} \cdot s^{-1}$
Materials Test Reactors					
Advanced Test Reactor	ATR	High Flux Light water	0.2×10^{15}	0.1×10^{15}	0.6×10^{15}
High Flux Isotope Reactor	HFIR	High Flux Light water	0.6×10^{15}	1.6×10^{15}	4×10^{15}
High Flux Research Reactor	OSIRIS	High Flux Light water	0.2×10^{15}	0.2×10^{15}	1×10^{15}
High Flux Research Reactor SM	SM-2/3	High Flux Light water	0.6×10^{15}	1.5×10^{15}	3.5×10^{15}
Fast Flux Test Facility	FFTF	Fast Flux Na liquid metal	0.6×10^{15}	5.6×10^{15}	5.6×10^{15}
Experimental Breeder Reactor II	EBR-II	Fast Flux Na liquid metal	0.6×10^{15}	0.00001×10^{15}	2.6×10^{15}
Fast Reactor	BOR-60	Fast Flux Na liquid metal	0.5×10^{15}	0.00001×10^{15}	2.0×10^{15}
National Research Universal	NRU	Low Flux Heavy water	0.1×10^{15}	0.2×10^{15}	0.5×10^{15}
Halden Boiling Water Reactor	HBWR	Low Flux Heavy water	0.1×10^{15}	0.2×10^{15}	0.5×10^{15}
Power Reactors					
Boiling Water Reactor	BWR	Pressure vessel Light water	0.06×10^{15}[a]	0.04×10^{15}[a]	0.3×10^{15}[a]
Pressurised Water Reactor	PWR	Pressure vessel Light water	0.07×10^{15}[a]	0.06×10^{15}[a]	0.4×10^{15}[a]
Channel Reactor of High Power	RBMK	Pressure tube Light water	0.05×10^{15}[b]	0.03×10^{15}[b]	0.2×10^{15}[b]
Canada Deuterium Uranium	CANDU	Pressure tube Heavy water	0.02×10^{15}[b]	0.1×10^{15}[b]	0.3×10^{15}[b]

[a] Mid-core flux.
[b] Mean pressure tube flux.

gamma photons create energetic electrons through Compton scattering. Although gamma-induced displacements damage are not significant in reactor cores, the contribution of gamma rays to atomic displacement damage increases for a larger water gap between the core and the pressure vessel [2].

Often the most critical reactor components are complex and, until the advent of nano-scale testing capabilities allowing test specimens to be extracted directly from the irradiated component, information on property changes had to be gleaned from irradiating standardized test specimens. Such specimens would be made from the same material and subject to the same thermo-mechanical processing as applied in fabricating the reactor component of interest.

The primary effect of neutron irradiation on material properties is through the displacement of atoms [1,3,4]. Transmutation is another effect, but the changes in elemental composition resulting from transmutation do not often have a significant effect on material properties. Production of gaseous atoms (He and H) from (n,α) and (n,p) reactions, however, can have deleterious consequences for component properties [5].

Atomic displacement by neutrons can occur through two main mechanisms: (i) direct displacement of an atom by an energetic neutron, creating a displacement cascade; and (ii) absorption of a neutron by an atom and emission of a photon (γ-ray), or particle (β, p and α), that can induce further displacements and, more importantly, create a displacement cascade through the recoiling atom. The effects of β-particle emission are minor and not discussed in this paper, although their effects are included in the SPECTER code [6] that is used to determine atomic displacement rates for comparison between the different reactors. The mechanism of displacement damage through neutron absorption applies to neutrons of all energies. The creation of a collision cascade by direct displacement of a primary knock-on atom (PKA) only occurs for neutrons with sufficient energy that the PKA itself has a high enough energy (dictated by momentum transfer) to create multiple atomic displacements as it dissipates energy within the crystal. For example, a 1 MeV neutron can produce PKAs with energies up to about 70 keV in elastic collisions with Fe atoms. Each PKA can then create 100's of atomic displacements in the subsequent cascade.

2. Methodology

2.1. Atomic displacement by collision with neutrons

Neutrons with energies >0.1 MeV are called fast neutrons, as opposed to the slower thermal neutrons, e.g., those with energies <0.5 eV, that may be absorbed by material within the reactor core. Some elements (Zr for example) have very low thermal neutron capture cross sections and thus the most important damage mechanism for Zr is by direct atomic displacement. Assuming an atomic threshold displacement energy of 40 eV, the Zr atom (mass = 91.22 amu) can be displaced by neutrons (amu = 1) with energies >930 eV[1] [1]. For elements such as Cr, Fe and Ni, a neutron with energy >600 eV is sufficient to cause atomic displacement. For neutrons with energies >100 keV (0.1 MeV), the energy transferred to the PKA is sufficiently high that it creates many additional displacements as the PKA energy is dissipated within the crystal lattice in the form of a collision cascade.

Typically, neutrons with energies >0.1 MeV create most of the damage and, for Zr in particular, an approximate measure of the relative displacement damage dose can be obtained by measuring and comparing neutron fluxes in these high energy ranges.

[1] The maximum momentum transferred by a head-on hard-sphere collision is $A = \frac{4M_1M_2}{(M_1+M_2)^2}$ where M_1 is the mass of the bombarding particle (neutron) and M_2 is the mass of the target atom.