Progress in Nuclear Energy 99 (2017) 96–102

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Evaluation of radiation damage in belt-line region of VVER-1000 nuclear reactor pressure vessel

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ARTICLE INFO

Article history:
Received 6 February 2017
Received in revised form
3 May 2017
Accepted 4 May 2017

Keywords:
RPV
DPA
Radiation damage
VVER-1000
Monte Carlo
SRIM

ABSTRACT

Regarding irradiation damage, the most sensitive region in the reactor pressure vessel (RPV) is the area adjacent to the reactor core; the so called belt-line region. Belt-lines and their related heat affected zones (HAZs) in the belt-line region are constantly under neutron and gamma irradiation and have a higher potential to various flaws. The microscopic defects produced in materials due to irradiation are referred to as radiation damage; the units of displacements per atom (DPA) are used routinely to characterize the extent of such damage. In this research, for a typical VVER-1000 (V446) RPV, the areas of the highest neutron radiation flux (belt-line) is first identified by using a Monte Carlo neutron transport code. This is used to calculate and validate the neutron flux and fluence at the belt-line. Employing the PTRAC output from MCNP and the SRIM Monte Carlo code, radiation damage in the RPV is simulated and assessed in terms of DPA. The integrated damage for a full effective year is evaluated to be order of 5E-04 displacements per cm thickness of RPV belt-line metal.

1. Introduction

Radiation damage results from nuclear collisions and reactions which produce energetic recoil atoms of the host material or reaction products. An important limiting factor of a nuclear power plant (NPP) lifetime is the status of its reactor pressure vessel (RPV). Structural materials, such as the RPV, in a nuclear reactor are continuously irradiated and damaged by energetic neutrons, gammas and other particles resulting from the fission reactions. Accordingly, neutron irradiation affects the RPV's mechanical properties by increasing the strength (neutron hardening) and decreasing the fracture toughness (neutron embrittlement).

The degradation of RPV metal is a complicated process depending on many factors such as thermal treatments and radiation exposure, chemical composition, fabrication and post-production processing conditions. One of the fundamental causes of RPV steel degradation is radiation damage. Structural materials in a nuclear reactor are damaged by radiation resulted from fission reactions. Radiation damage occurs when energetic particles (neutrons, ions, protons, electrons, etc.) collide with a crystalline solid. The incident particle transfers part of its kinetic energy initiating a recoil energy to a lattice atom, forming a primary knock-on atom (PKA). A PKA displaces neighboring atoms as well and jolts an atomic displacement cascade. The overall result is a formation of point defects called Frenkel Pair (FP) and defect clusters of vacancies and interstitial atoms. The consequences of FP and other irradiation damages on the RPV are hardening, embrittlement, segregation, swelling, radiation creep and in brief, changes in physical and mechanical properties (Was, 2016).

Previous studies of the neutron flux effects on radiation embrittlement of RPV alloys have reported inconsistent results (Margolin et al., 2003, 2013; Stoller, 2004; Chernobaeva et al., 2004; Erak et al., 2010; Kirk, 2010; Williams, 2011). In one report, it is claimed that the sign of this effect depends on the flux value (Margolin et al., 2013) while in another paper, a positive flux effect is discussed (Chernobaeva et al., 2004), i.e. with increasing neutron flux a ductile to brittle transition temperature shift (ΔT_F) was obtained. Russian scientist have undertaken comprehensive experimental studies to derive correlations between embrittlement of VVER-1000 RPV materials and irradiation conditions (Was, 2016; Margolin et al., 2003).

In this paper, full core of a VVER-1000 NPP is simulated with MCNP Monte Carlo code (Briesmeister, 2000) to identify the location of maximum neutron flux in the RPV and evaluate neutron flux spectra with E > 0.5 MeV. The results are compared with the reference data presented in the Final Safety Analysis Report (FSAR)

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http://dx.doi.org/10.1016/j.pnucene.2017.05.003
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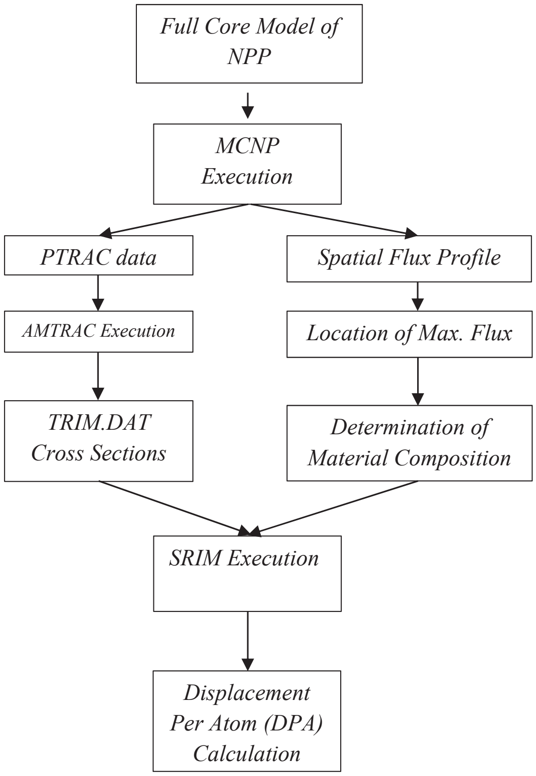


Fig. 1. Sequence of flux and radiation damage calculation.

of VVER-1000 NPP. VVER-1000 reactor core has been extensively studied for neutronic safety using MCNP and deterministic codes (Porhemmat et al., 2015; Hadad and Ayobian, 2006; Hadad and Kowsar, 2016; Erfan Nia et al., 2012).

Subsequent to the flux evaluation by MCNP, SRIM computer program is used to simulate the radiation damage in the RPV. For this purpose, the file TRIM.DAT is used as the input which contains the kinetic information about atoms which start recoil cascades. This file could be produces by either MCNP or AMTRACK codes; which contains the energy transferred to target atoms by neutrons, electrons. Sequence of flux and radiation damage calculation on the inner surface of RPV is shown in Fig. 1.

1.1. Reactor core simulation by MCNP

MCNP is a general purpose Monte Carlo radiation transport code designed to track many particle types over broad ranges of energies. Using MCNP and based on plant's FSAR documents, belt-line region and internal equipment are modeled and simulated. Reactor is critical in normal operating condition with coolant temperature of 291 °C, thermal power of 3000 MW and critical boric acid concentration of 6.56 g/kg. In this model, RPV height in core region is divided into 200 segments to determine the segment of peak flux and highest irradiation region. Using F2 tally in MCNP, surface fluxes on the RPV at ¼,½ and ¾ thickness are calculated for the entire height (Fig. 2).

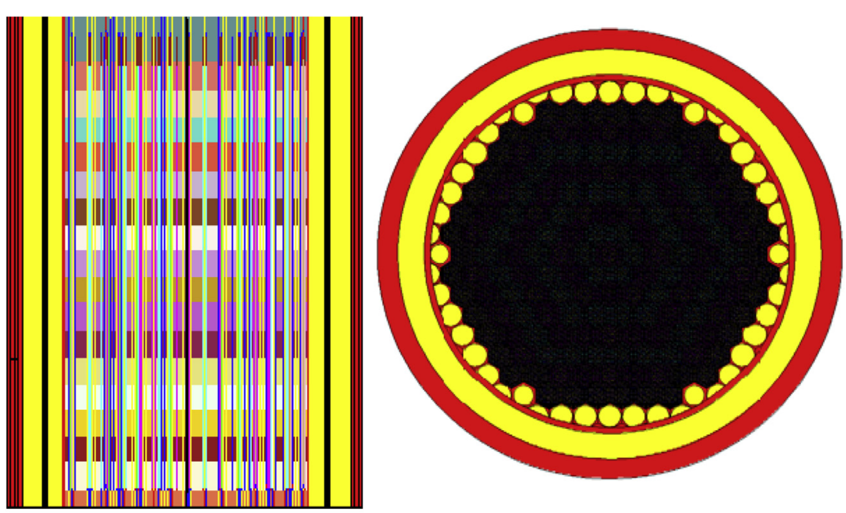
Fig. 3(a) shows the variation of flux with core height calculated by MCNP, and Fig. 3(b) presents the physical location of peak flux on the interior of reactor vessel surface. This location is the belt-line region in which the maximum neutron flux occurs. RPV weld number 2 and its heat affected zone (HAZ) is located in this area.

Validation of MCNP reactor core model is achieved in two ways: a) obtaining the critical boron concentration in Hot Full Power (HFP) as mentioned in plant's reference data, and b) comparing the axial and radial neutron flux with the plant's FSAR data.

Fig. 4 presents the evaluated surface flux spectrums on the vessel inner surface, and at ¼, ½ and ¾ cm depth thicknesses compared with the FSAR reference data.

1.1.1. Displacement per atom (DPA)

Bombarding particles that transfer their recoil energies T by elastic collision to a lattice atom start the radiation damage. The atom moves from its original location to an interstitial position provided the recoil energy exceeds a material-dependent threshold energy for displacement, E_{th}, generating a “Frenkel Pair”. If the recoil energy is expressively higher than E_{th} (e.g. fast neutrons) the atom firstly struck by the neutron, the “primary knock-on atom” (PKA) or “primary recoil atom” (PRA) is able to transfer energy by moving further into the crystal creating further Frenkel Pairs, so called, a displacement cascade (Fig. 5).



(a) (b)

Fig. 2. (a): Axial and (b): Radial cross section of the VVER-1000 reactor as modeled in MCNP.