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Multi-objective optimization of a compact pressurized water nuclear reactor computational model for biological shielding design using innovative materials

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HIGHLIGHTS

- Use of two n-γ transport codes leads to optimized model of compact nuclear reactor.
- It was possible to safely reduce both weight and volume of the biological shielding.
- Best configuration obtained by using new composites for both γ and n attenuation.

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ABSTRACT

The aim of the present work is to develop a computational model of a compact pressurized water nuclear reactor (PWR) to investigate the use of innovative materials to enhance the biological shielding effectiveness. Two radiation transport codes were used: the first one – MCNP – for the PWR design and the GEM/EVENT to simulate (in a 1D slab) the behavior of several materials and shielding thickness on gamma and neutron radiation. Additionally MATLAB Optimization Toolbox was used to provide new geometric configurations of the slab aiming at reducing the volume and weight of the walls by means of a cost/objective function. It is demonstrated in the reactor model that the dose rate outside biological shielding has been reduced by one order of magnitude for the optimized model compared with the initial configuration. Volume and weight of the shielding walls were also reduced. The results indicated that one-dimensional deterministic code to reach an optimized geometry and test materials, combined with a three-dimensional model of a compact nuclear reactor in a stochastic code, is a fast and efficient procedure to test shielding performance and optimization before the experimental assessment. A major outcome of this research is that composite materials (ECOMASS 2150TU96) may replace (with advantages) traditional shielding materials without jeopardizing the nuclear power plant safety assurance.

1. Introduction

The success of the biological shielding design in commercial nuclear power plants is largely due to mono-layers of concrete and lead bricks, since the volume, thickness and weight of the structures are not major concerns of the project. For a compact pressurized water nuclear reactor (PWR) – to be employed, for example, in hospitals for radioisotope production (Ruth, 2009) or even in compact energy sources for spaceships (El-Genk, 2009) – the biological shielding should be designed to meet several conflicting criteria.

Primary criteria include minimizing weight, volume and dose rate outside the shielding. This can be achieved with a new multi-layered approach: mixing materials in which thickness, density and geometric positioning are appropriate for the application. In addition, due to the severity of reactor environments, shielding materials must also be resistant to corrosion in high temperature and must sustain structural integrity in high levels of radiation damage (Fry et al., 1989). In the case of compact nuclear reactors (electrical output less than 300 MWe (Ingersoll, 2009)) cost and attenuation properties of the employed materials are additional criteria for the engineering project (Quapp et al., 2000). Finally,

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exposure of workers and employees to radiation must be minimum: the dose rate has to obey the ALARA principle (as-low-as-reasonably-achievable) (Valentin, 2007) and an optimization study must be carried out in order to satisfy such requirement. Since traditional shielding materials (concrete, polymers and steels) can lose their capabilities as thickness is decreased and as the former shielding methodology is not applicable regarding optimization procedures in compact reactors, nuclear engineering is facing new challenges to find innovative materials capable to replace traditional ones and to research alternative ways to increase biological shielding effectiveness.

Ordinary concrete (densities around 3–4 g cm^{-3}) is the most widely used shielding material in large commercials power plants, both for gamma and neutron attenuation since the beginning of nuclear age (Suzuki et al., 2013). Recent investigations in matrix compatibility of tricalcium silicate (C_3S) with high density elements has been conduced for multipurpose shielding improvement (Mortazavi et al., 2010). Some reports deal with the influence of boron additives, which may increase neutron absorption, since it has large absorption cross-section (Kimura and Kinno, 2009; Gencel et al., 2010). The utilization of borated concrete in shielding, however, must be better evaluated since it may jeopardize its resistance in nuclear reactor environment due to several mechanisms of degradation. Magnetite (Fe_3O_4) and barite (BaO) are alternative additives to enhance concrete specific applicability for gamma shielding (Li et al., 2003; Ouda, 2015). The research in concrete additives still remains a challenge in shielding technology due to matrix stability and solute solubility, in particular, the effect of these additions in mechanical properties is not sufficiently characterized.

Polymeric materials (densities of 0.880–0.97 g cm^{-3}) have been studied to complement concrete in shielding purposes. They exhibit low density and possess lighter elements in their composition, which makes them appropriate to dump neutron energy. Examples are epoxy resin and polyethylene with boron and gadolinium charges (Okuno, 2005). For compact power plants the use of such materials could be advantageous considering maneuverability (ease of substitution) and price, but they show insufficient mechanical and thermal strength, low durability and poor endurance to neutron and gamma irradiation: they cannot operate inside a nuclear reactor for long time without degradation. Furthermore, the low densities observed in such materials is a major problem regarding aspects of gamma shielding.

For the gamma shielding, high density materials are preferred. Stainless Steels are metallic alloys with good mechanical, thermal and metallurgical properties (as corrosion resistance and weldability) which make them good candidates for neutron shielding (El-Guebaly, 1997; Santoro et al., 1980). Such alloys are also capable to satisfy gamma shielding purposes thanks to their high density (7–8 g cm^{-3}). Some typical alloying elements of stainless steels, like boron, carbon and chromium may enhance neutron capture (El-Guebaly, 1997). In addition, steels can be easily machined, formed and shaped in many geometric configurations and they are not toxic (contrary to lead, for example). The main drawbacks of steels in nuclear engineering are the alloy embitterment due irradiation and irradiation assisted stress corrosion cracking (IASCC) which are subjects of many recent studies (Andresen and Was, 2012).

To overcome the main drawbacks of the traditional shielding materials, new investigations focus in the development of some composite materials, which have demonstrated compelling properties for radiation shielding purposes (Hu et al., 2008; Gwaily et al., 2002). Composite materials are produced when two or more materials are combined, resulting in a (new) material with designed properties (Jones, 1998). The main advantage is that the new material may exhibit improved properties (mechanical, thermal, optical etc) compared with the corresponding monolithic ones. In the present work, a composite material which has been developed to replace Lead in radiation shielding technology is investigated: the ECOMASS 2150TU96 (DurkeeIII, 2006). This composite is made of 97 vol% tungsten powder filled with 3 vol% polyamide (PA6/6) and present high density (11 g cm^{-3}).

Regarding optimization techniques, a couple of studies with MCNP were performed using genetic algorithms, linear programming, transmission matrix methods and brute-force optimization (Kimura et al., 2012; Calzada et al., 2011; Piotrowski et al., 2012; Kebwaro et al., 2015; Leech and Rohach, 1972) in slab and complex geometries and using experimental data: the main objective of these studies was to reduce the dose rate outside the shielding. Composite materials were studied for gamma shielding optimization with Genetic Algorithms (Hu et al., 2008) to demonstrate MNCP5 usefulness to support new materials design.

The aim of the present work is to perform multiobjective (Jaeggi et al., 2005; Ben-Dor et al., 2011) optimization in biological shielding for a compact modular reactor using MCNP (X-5 Monte Carlo Team, 2008), GEM/EVENT (deOliveira and Goddard, 1997) and MATLAB Optimization Toolbox. Contrary to the previously quoted investigations, the present work will aim at reducing volume, mass and external dose rate simultaneously.

2. Materials and methods

The optimization procedure is organized in three stages. First, a compact computational model of a PWR is developed in the MCNP with a specific biological shielding start configuration, and the non-optimized dose rate after shielding is computed. Then, test calculations using GEM/EVENT and MATLAB are performed in a 1D slab geometry, alternating materials and thickness, for screening the best combinations, in order to reduce both neutron and gamma fluxes (to reduce the dose rate)- These new configurations are inserted in the computational model (optimized) for MNCP and the external dose rate is computed. Finally, a multiobjective algorithm (Brayton et al., 1979) is applied to optimize the new geometry and the results for thickness (hence, volume and mass). With the optimized model the new dose rate is computed in the complex 3D model and the results are compared with the equivalent dose limit (Valentin, 2002) for workers in the nuclear industry.

Detailed information about the PWR computational model in MCNP and the one-dimensional slab model in GEM/EVENT for materials testing are presented in this section. It may be reminded that MCNP5 (Monte Carlo N-Particle version 5.0) is based on a statistical approach to the Neutron Transport Equation (NTE) while the second code, GEM/EVENT, solves the multi-energy group transport equation using a finite element-spherical harmonics expansion. The PWR model is verisimilar to the Brazil's ANGRA-1 nuclear power plant.

2.1. PWR computational model in the MCNP

The core consists of 21 fuel assemblies of UO_2 (Uranium Dioxide Fuel) 5 wt% enriched in U-235 with 50 MW power. Each assembly has 17×17 rods: 28 are guide-tubes for control/security rods instrumentation, 20 burnable poison rods and 241 fuel rods. Fig. 1 shows the core and assembly configurations and Table 1 summarizes the main geometric characteristics of the model with the corresponding materials.

Regarding the ex-core components, first the SA-240-347 austenitic stainless steel was chosen to form the core's baffle due the good corrosion resistance (ASTM, 2007b). The heat resisting steel SA-336-F347 (ASTM, 2007a) was used for the thermoshield due to its excellent properties for pressurized and high-temperature