Nuclear Engineering and Design 295 (2015) 534–548

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Structural effects of radiation-induced volumetric expansion on unreinforced concrete biological shields

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HIGHLIGHTS

- A 1D-cylindrical structural model for concrete bio-shield is developed.
- A probabilistic model for concrete irradiated properties is proposed.
- Commercial reactor bio-shield can experience long-term irradiation damage.
- A conservative evaluation of the irradiation-induced damage depth is derived.

ARTICLE INFO

Article history:
Received 14 April 2015
Received in revised form 10 August 2015
Accepted 15 September 2015
Available online 22 November 2015

ABSTRACT

Limited literature (Pomaro et al., 2011; Mirhosseini et al., 2014; Salomoni et al., 2014; Andreev and Kapliy, 2014) is available on the structural analysis of irradiated concrete biological shield (CBS), although extended operations of nuclear powers plants may lead to critical neutron exposure above $1.0 \times 10^{+19}$ n cm^{-2}. To the notable exception of Andreev and Kapliy, available structural models do not account for radiation-induced volumetric expansion, although it was found to develop important linear dimensional change of the order of 1%, and, can lead to significant concrete damage (Le Pape et al., 2015). A 1D-cylindrical model of an unreinforced CBS accounting for temperature and irradiation effects is developed. Irradiated concrete properties are characterized probabilistically using the updated database collected by Oak Ridge National Laboratory (Field et al., 2015). The overstressed concrete ratio (OCR) of the CBS, i.e., the proportion of the wall thickness being subject to stresses beyond the resistance of concrete, is derived by deterministic and probabilistic analysis assuming that irradiated concrete behaves as an elastic materials. In the bi-axial compressive zone near the reactor cavity, the OCR is limited to 5.7%, i.e., 8.6 cm ($3\frac{1}{2}$ in.), whereas, in the tension zone, the OCR extends to 72%, i.e., 1.08 m ($42\frac{1}{2}$ in.). These results, valid for a maximum neutron fluence on the concrete surface of $3.1 \times 10^{+19}$ n cm^{-2} ($E > 0.1$ MeV) and, obtained after 80 years of operation, give an indication of the potential detrimental effects of prolonged irradiation of concrete in nuclear power plants.

1. Introduction

1.1. Structures of interest

The perspective of extended operations of nuclear power plants NPPs beyond 60 years has lead the U.S. Department of Energy Office of Nuclear Energy's Light Water Reactor Sustainability program to consider the effects of radiation on concrete as an area of a high-priority research (Graves et al., 2014). The most exposed concrete structure to high radiation flux is the concrete biological shield CBS. The containment internal structures in pressurized water reactor PWR plants (see Fig. 1) tend to be more massive in nature than internal structures in boiling water reactor BWR plants because they typically support the reactor pressure vessel RPV, steam generators, and other large equipment. The structural function of the RPV supporting structure (RPVSS) is to transfer the static or seismic load of the reactor to the foundation system. Depending on the nuclear steam supply system NSSS (i.e., reactor, reactor coolant pump generator, steam generator in the PWR, and associated piping), a PWR RPV can weigh as much as 427,000 kg (941,600 lbs.) (Mager et al., 1999) without the core and the refueling cavity elements.

Also, the containment internal structures provide support for shielding of radiation emitted by the NSSS. The CBS structure

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http://dx.doi.org/10.1016/j.nucengdes.2015.09.018

Acronym

BWR	boiling water reactor
CBS	concrete biological shield
ID	inner diameter
LWR	light water reactor
NPP	nuclear power plant
NSSS	nuclear steam supply system
OD	outer diameter
PWR	pressurized water reactor
RC	reinforced concrete
RH	relative humidity
RIVE	radiation-induced volumetric expansion
RPV	reactor pressure vessel

encloses the RPV leaving an air gap of the order of about 10 cm (4 in.). The thickness of the biological shield wall varies with the NSSS design (Verrall and Fitzpatrick, 1985). It typically ranges between 1.5 and 2.2 m (4.9–7.2 ft.) for PWRs and 0.60 and 1.20 m (2–4 ft.) for BWRs.

Containment internal structures at currently operating US commercial nuclear reactors are generally constructed of conventional reinforced concrete RC (Hookham, 1991), i.e., ordinary Portland cement concrete of normal density. Unlike in a water–water power reactor VVER biological shield, the use of heavy aggregate, such as hematite, ilmenite, or magnetite, incorporated in the concrete mixture seems uncommon for PWRs. Esselman and Bruck (2013) noted that, "[Although] specifications for the concrete in all plants in the US fleet were not available, preliminary review of currently operating relatively "early" vintage plants for the design specification of concrete in their biological shield walls [confirmed the presence of ordinary concrete]." Reinforcement consists of carbon steel bars.

By design, the temperature in the CBS is limited to 65 °C (150 °F) with a permitted increase of up to 93 °C (200 °F) locally. Note that because of irradiation heating by energy deposition, the maximum temperature in concrete is located inside the CBS wall, and not, at the inner diameter ID. The irradiation exposure varies from one specific plant to another; as a general rule, BWR receive less dose than PWR. Esselman and Bruck (2013) suggest a bounding fluence for the US fleet of $6.1 \times 10^{+19}$ n cm^{-2} ($E > 0.1$ MeV) for 80 years of operation at an average of 92% generation capacity. Open access literature (Hilsdorf et al., 1978; Seeberger and Hilsdorf, 1982; Field et al., 2015) suggests that irradiated concrete properties are affected for fluences higher than $\approx 1.0 \times 10^{+19}$ n cm^{-2}. 4-loop reactors are less susceptible to develop high neutron exposure (<$4.0 \times 10^{+19}$ n cm^{-2}). BWRs maximum fluence should barely exceed $1.0 \times 10^{+19}$ n cm^{-2} at 80 years of operation. Hence, BWRs CBS are likely to be relatively immune to irradiation effects since the effects of radiation on concrete mechanical and physical properties are observed for fluence above $1.0 \times 10^{+19}$ n cm^{-2}. The flux attenuation (Remec et al., 2014) in ordinary concrete is about one order of magnitude per ≈12–15 cm (5–6 in.). Hence, radiation-induced effects are expected to be predominant primarily in the same region depending on the actual fluence at the CBS inner diameter although constrained radiation-induced volumetric expansion RIVE could potentially develop detrimental stresses deeper in the CBS wall. Silicate-bearing aggregates seem more prone to RIVE than calcareous aggregate (Field et al., 2015; Le Pape et al., 2015). Thus, the development of detrimental effects (direct radiation damage and restrained-expansion-induced stress) should also vary with the concrete composition.

1.2. Structural models of irradiated concrete

Limited literature is available on the structural significance of irradiation for concrete primarily because irradiated concrete has been mostly studied with the perspective of material design and qualification. Nevertheless, a few structural models for concrete containment and internal structures (Mirhosseini, 2010; Mirhosseini et al., 2014) and for shield structures (Pomaro et al., 2011; Salomoni et al., 2014; Andreev and Kapliy, 2014) were recently published.

Mirhosseini et al. have developed a RC membrane model accounting for the concrete strength reduction resulting from the irradiation. The finite element model uses the modified compression-field theory developed by Vecchio and Collins (1982, 1986) from an extensive set of structural experiments on RC panels subjected to varied combined compression and shear in-plane loadings. The behavior of RC membrane elements, viewed as scale models for RC walls and shells in NPPs, under shear, and combination of shear and tension and compression is analyzed in terms of strength (in-plane loading), ductility and failure mode. The concrete compressive and tensile strength reduction is based on a direct interpretation of Hilsdorf et al.'s curves including, in particular, Dubrovskii et al.'s debatable data (Dubrovskii et al., 1966; Fujiwara et al., 2009) at very high fluences (>10^{+21} n cm^{-2}). Possible irradiation effect on carbon steel reinforcement is not accounted for. This assumption can be justified only for fluence below $1.0 \times 10^{+20}$ n cm^{-2} based on Janowiak et al. (2010) report: "Neutron irradiation produces changes in the mechanical properties of carbon steel (increase in yield stress and rise in the ductile-brittle transition temperature). As a consequence, steel reinforcement exposed to high cumulative neutron fluence (above $1.0 \times 10^{+20}$ n cm^{-2}) can experience reduced ductility." The interest of Mirhosseini et al.' approach is to conduct structural failure analysis of NPP RC components using a nonlinear finite element tool. However, the use of membrane elements for modeling irradiated-CBSs (or RPVSSs) is particularly debatable because of the actual thickness to height ratio of such component and because of the presence of radiation fields profile (Remec et al., 2014) through the member thickness. Modeling nonuniform thermo-hygro-radiological effects in the CBS requires either the use of multilayers shell elements or 3D-volume elements, or 2D-surface element r-z in a cylindrical model, or 1D-r segment element in a radial-cylindrical model. Finally, although Mirhosseini et al. acknowledge that "Deterioration of shielding concrete is mostly due to volume changes of concrete. Aggregate expansion is the main factor of radiation deterioration in concrete in NPPs", the possibility RIVE-induced stresses is surprisingly not accounted for, in their modeling work.

The approach followed by Pomaro et al. (2011) and Salomoni et al. (2014) is developed on the basis of an existing coupled nonlinear thermo-hygro mechanical (TH → M) model initially developed by Schrefler et al. (1989), Baggio et al. (1995) and Majorana et al. (1998). Heat transfer and moisture transport are coupled following a scheme developed by Schrefler et al. (1989), derived from the pioneer work of Luikov (1975). Radiation effects are assumed uncoupled from thermal and moisture transport. The concrete mechanical model is fairly extensive: It includes thermal expansion, autogenous shrinkage, creep, load-induced thermal strain rate, damage and plasticity effects. The incremental isotropic damage formulation follows Mazars and Pijaudier-Cabot (1989)'s theory combining tensile and compression strain effects on damage. Equivalent damage index is assumed to result from a cumulative (multiplicative effect in the sense of Gérard et al. (1998) and Nechnech et al. (2002)) effect of mechanical, thermo-chemical and radiation damage: $\tilde{D} = 1 - (1 - D_m)(1 - D_T)(1 - D_r)$, where $\tilde{D}$, D_m, D_T and D_r are respectively the overall, mechanical, thermal and