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Assessment of Structural Integrity of Concrete Biological Shield Wall Considering Radiation-Induced Volumetric Swelling

Jinbok Choi[a*], Daegi Hahm[a]
[a]*Structural and Seismic Safety Research Division, Korea Atomic Energy Research Institute,*
111 Daedeok-Daero 989 beon-gil, Yuseong gu, Daejeon, Korea
**Corresponding author: jbchoi95@kaeri.re.kr*

1. Introduction

The renewal of operation license for nuclear power plants beyond the design life time is becoming an important issue for the countries that runs nuclear power plants around world because nuclear energy is recognized as one of the solutions that can contribute the carbon reduction policy and energy transfer paradigm. Especially for the U.S., 91% of the current operating nuclear power plants are in a state of continued operation (84 reactors out of 92 operating reactors). Besides, 16 reactors have applied the further license renewal for 80 year-operation and one of them already got the approval for 80 year-operation. However, it is well understood that the proper evaluation of the structural integrities of safety-related structures and equipment should be the critical prerequisite for the continuous operation of nu clear power reactor. Especially, the concrete biological shield (CBS) surrounding the reactor pressure vessel in common PWRs is the most vulnerable structure against the effect of neutron irradiation that can degrade the material properties of the concrete and steel members. Therefore, in this study, what kinds of aspects and procedures should be considered when it comes to the structural evaluation of CBS considering the neutron irradiation in practical point of view.

2. Effects on neutron irradiation on concrete material properties

Generally, the neutrons can be classified according to their energy levels: thermal neutron (E<1eV), epi-thermal neutron (1eV<E<0.1MeV), and fast neutron (E>0.1MeV). It is known that the concrete material properties can be changed due to the exposure of fast neutron with its level of energy over 0.1MeV [1]. This level of energy can cause the lattice defects in the crystalline structure of concrete ingredients. There have been some studies to figure out the effect of neutron irradiation on the concrete or steel. Hilsdorf et al. suggested the threshold value of the neutron fluence that can initiate the degradation of major mechanical properties such as compressive stress, tensile stress, and elastic modulus as $1 \times 10^{19}\ n/cm^2$[2]. Research team at ORNL also concluded that remarkable degradation of concrete material properties can be seen at fluence level above $1 \times 10^{19}\ n/cm^2$ with lower bound at 50% of the reference concrete strength [3].

However, there is no periodic inspection or monitoring activities to check neutron fluence level of the CBS at nuclear power plants. The valuable data can be obtainable from the reactor pressure vessel (RPV) surveillance programs and this information can be used to infer the neutron fluence level of the CBS wall.

3. Estimation of neutron fluence level for CBS

The reactor surveillance program or neutron transport calculation can provide the neutron fluence (E >1.0MeV) at a certain inside point of reactor pressure vessel(RPV_i in the Fig. 1) as shown in the Fig. 2 according to the effective full power years of the nuclear power plants.

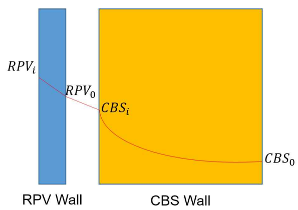


Fig. 1. Schematic of fluence profile from reactor pressure vessel (RPV)inside to concrete biological shield(CBS) outside

First we need to obtain the fluence level at outer surface of RPV(RPV_o in the Fig. 1). To this end, the attenuation equation provided by US NRC Regulatory Guide 1.00 can be used [4,5].

$$F_{out\,(1.0MeV)} = F_{surf}\ (e^{-0.33\,d}) \tag{1}$$

where, $F_{out\,(1.0MeV)}$ is neutron fluence (n/cm^2) at the outside surface of RPV, F_{surf} is neutron fluence at the inner surface of RPV, d is the thickness of RPV (inches)

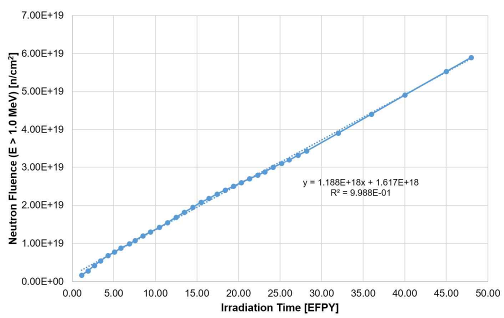


Fig. 2. Maximum neutron fluence according to EFPY (Effective Full Power Years) at RPV inner radius [6]

But the calculated fluence level is at an energy level lager than 1.0 MeV. The fluence at this energy level needs to be converted into the energy level of 0.1MeV because the material degradation can be occurred at this energy level.

The correlation between fluence at an energy of 1.0MeV and 0.1MeV is given by [7]:

$$F_{out\,(0.1MeV)} = F_{out\,(1.0MeV)}\,(2.123e^{0.191\,d}) \qquad (2)$$

where, $F_{out\,(0.1MeV)}$ is neutron fluence at the outside surface (E>0.1MeV).
The fluence at outside of the RPV is usually smaller than the fluence at inner surface of CBS wall due to the gap between them. The previous calculation [8] shows that the fluence at inner surface of the CBS wall is reduced by 10% in a conservative manner compared to the outside of the RPV.

The fluence profile through the CBS wall is important because the structural capacity depends on it. The fluence attenuation for typical two-loop and three-loop reactors can be shown as a reference [4]. The more exact profile should be evaluated considering the plant specific conditions.

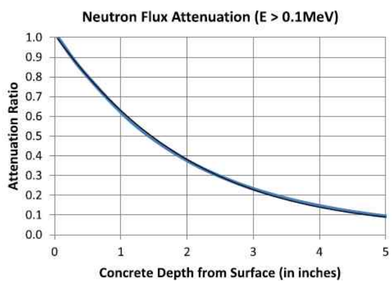
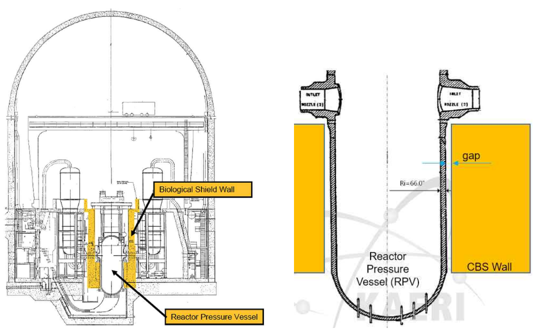


Fig. 3. Fluence attenuation in Portland cement concrete (E>0.1 MeV) [4]



(a) (b)

Fig. 4. (a) Section view of typical PWRs [9], (b) Schematic drawing of CBS wall around the RPV

3. Swelling of CBS wall due to neutron irradiation and FEA considering swelling effect

It is reported that the radiation-induced volumetric expansion (RIVE) is the main cause of concrete mechanical property degradation [9]. Swelling strain ($\varepsilon_{swelling}$) along the distance from the inside of the CBS wall was calculated by Eqn. (3) [9,10].

$$\varepsilon_{swelling}(\Phi) = \kappa\varepsilon_{max}\frac{e^{\delta\Phi}-1}{\varepsilon_{max}+\kappa e^{\delta\Phi}} \qquad (3)$$

where ε_{max} is the maximum volumetric expansion. The non-dimensional parameter(κ) and inverse of fluence(δ) determines the shape of the curve. In this study, the best fit parameters for the curve was used having the values: $\kappa = 0.968\%$, $\varepsilon_{max} = 0.936\%$, and $\delta = 3.092 \times 10^{-20} n^{-1}cm^{2}$ [9].
Therefore, we can get the RIVE according to the change in the fluence level as shown in Fig. 5.

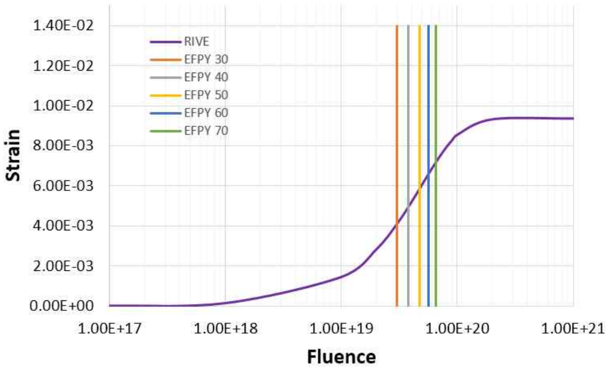


Fig. 5. RIVE curve

The finite element model was constructed to see the effect of RIVE in the CBS wall. In this study the CBS section experiencing the maximum radiation along the axial direction which usually corresponds to the reactor core center elevation was selected so that the radial distribution of fluence was only considered at current stage (Fig. 6).

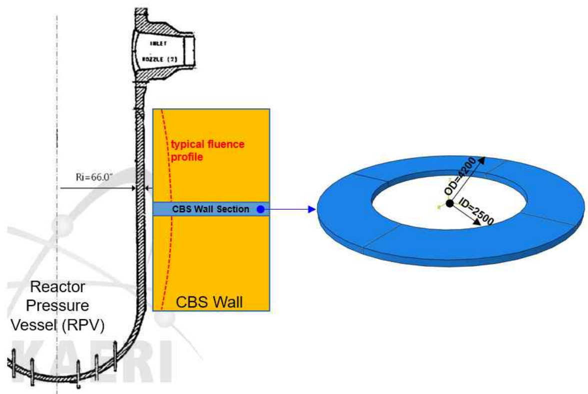


Fig. 6. CBS wall section considered in the numerical analysis

The RIVE along the distance between the inside and outside surface of CBS wall can be calculated like Figure 7 considering the attenuation ratio given in Fig. 3. The RIVE values are gradually decreasing along the distance from the inner surface of the CBS wall and the radiation-induced swelling effect is almost diminished beyond the distance of 300 mm because of the radiation shielding effect of concrete material.
The material properties of concrete considered in this study is summarized in Table 1 and the CBS wall section with 200 mm thickness and, inner and outer radius of 2500 mm and 4200 mm respectively was considered (Fig. 6).

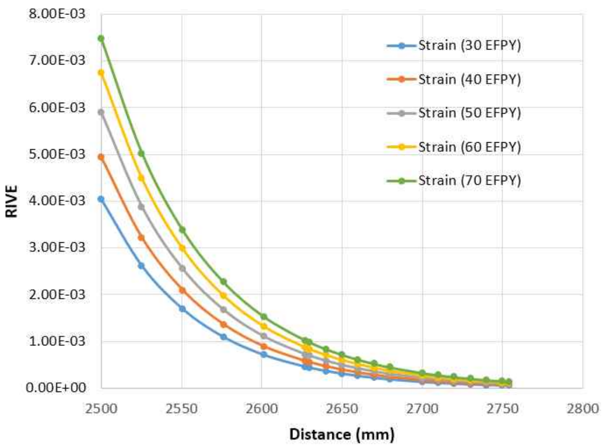


Fig. 7. RIVE along the distance for each EFPY

Table 1. Concrete material properties

Elastic modulus (MPa)	Poisson's ratio	Density (ton/mm^3)	Compressive strength (MPa)	Tensile strength (MPa)
2.01E4	0.2	2.5E-9	29.1	3.6
Concrete Damage Plasticity Parameters				
Dilation angle	Eccentricity	fb0/fc0	k	Viscosity parameter
40	0.1	1.16	0.6667	0

As you can see from the Fig. 7, the RIVE is gradually decreasing along the distance due to the fluence attenuation. So the functionally graded material approach was adopted to implement this trend of RIVE variation through the radial direction of the CBS wall. In this way, we don't need to divide the CBS wall section physically to apply different RIVE values for each segment. Fig. 8 represents the RIVE distribution that decreases along radial direction of CBS wall.

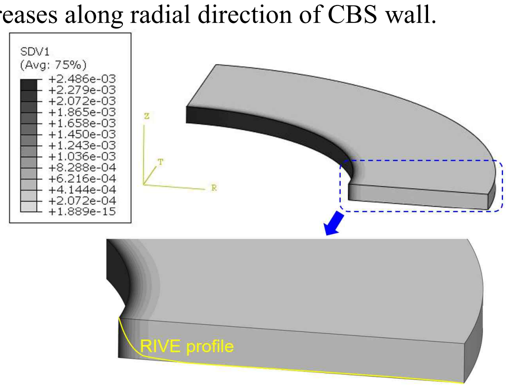


Fig. 8. RIVE distribution in radial direction

The Fig. 9 shows the analysis results of CBS wall under EFPY 40 condition as an example. We can observe the compressive stresses in hoop and axial directions exceeds the compressive strength limit of considered concrete in the inner region of CBS wall and the tensile stress in the outside region (Fig. 10). This means that the concrete would lose its structural capacity locally in the region of inner surface area of CBS experiencing significant fluence level and there might be a possibility of cracks due to excessive tensile stress on outside of CBS wall. Of course the deteriorated depth should be different depending on the position and accumulated fluence level. The similar trend of stress distribution can be seen in other studies [9,11] to evaluate the structural effects of RIVE on CBS even though the fluence level, material properties and used constitutive equation of the model are different.

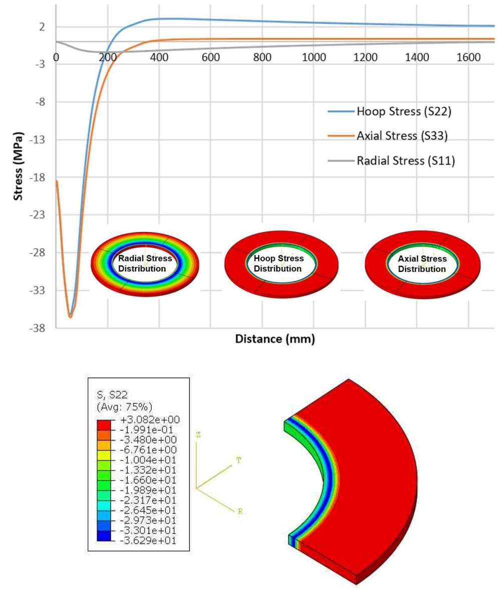


Fig. 9. Stress distribution due to RIVE of CBS wall

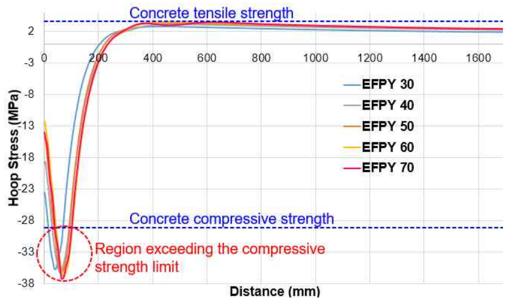


Fig. 10. Stress profile along the distance: the shaded area represents the allowable stress state

The level of compressive and tensile stress showed growing trend according to the amount of neutron fluence increase as shown in Fig. 11.

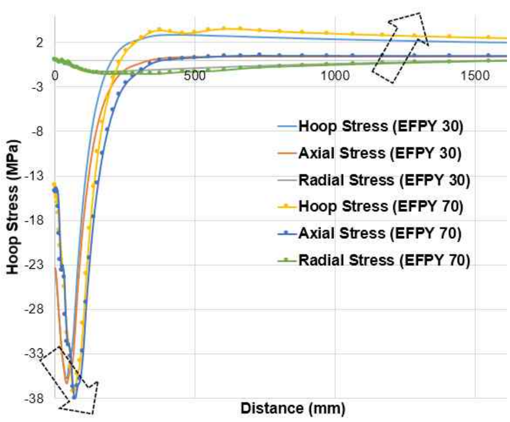


Fig. 11. Stress profile at EFPY 30 and 70

4. Conclusions

The basic process to estimate the fluence level in the CBS wall from the fluence data at the inside of reactor pressure vessel was introduced and the effect of radiation-induced volumetric expansion on the concrete material properties due to neutron irradiation were investigated in this study.

More practical geometry and fluence level of CBS wall including the fluence distribution in vertical direction should be considered as well as the consideration of reinforcing rebar elements of the CBS wall in the further study.

And the radiation effects on the RPV support structure and anchor system against severe loading case such as a seismic load also need to be considered in the future because the material properties of concrete and steel members can be degraded locally in case of the extended operation of the nuclear power plants beyond its original design lifetime.

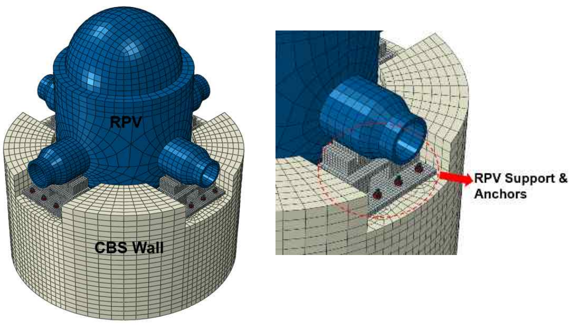


Fig. 12. Schematic drawing of RPV support & anchoring system

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