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Burnable absorber-integrated Guide Thimble (BigT) – I: design concepts and neutronic characterization on the fuel assembly benchmarks

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This paper presents the conceptual designs of a new burnable absorber (BA) for the pressurized water reactor (PWR), which is named “Burnable absorber-integrated Guide Thimble” (BigT). The BigT integrates BA materials into standard guide thimble in a PWR fuel assembly. Neutronics sensitivities and practical design considerations of the BigT concept are points of highlight in the first half of the paper. Specifically, the BigT concepts are characterized in view of its BA material and spatial self-shielding variations. In addition, the BigT replaceability requirement, bottom-end design specifications and thermal-hydraulic considerations are also deliberated. Meanwhile, much of the second half of the paper is devoted to demonstrate practical viability of the BigT absorbers via comparative evaluations against the conventional BA technologies in representative 17 × 17 and 16 × 16 fuel assembly lattices. For the 17 × 17 lattice evaluations, all three BigT variants are benchmarked against Westinghouse’s existing BA technologies, while in the 16 × 16 assembly analyses, the BigT designs are compared against traditional integral gadolinia-urania rod design. All analyses clearly show that the BigT absorbers perform as well as the commercial BA technologies in terms of reactivity and power peaking management. In addition, it has been shown that sufficiently high control rod worth can be obtained with the BigT absorbers in place. All neutronic simulations were completed using the Monte Carlo Serpent code with ENDF/B-VII.0 library.

Keywords: PWR type reactor; fuel assembly; burnable absorber; BigT; boron; gadolinium; guide thimble; excess reactivity; Serpent

1. Introduction

Modern pressurized water reactor (PWR) core designs generally aim for improved reactor performance via optimal uranium utilization or long cycle length [1]. This consequently drives fuel enrichment of a modern PWR to almost 5 w/o, which then necessitates substantial loading of neutron absorbers to compensate the excess fissile content in the core. The development of ultra-low leakage in-in-out fuel management scheme in commercial PWRs further demands advancement in how the absorbers are loaded in the core, which are typically supplied in the forms of control rods, chemical shims in coolant and physically fixed burnable absorbers (BAs). In PWRs, the BA has been intensively utilized and its demand is still growing since it can effectively be used for both the reactivity hold-down and the power distribution control in the reactor core with minimal adverse effects.

BAs typically used in PWRs include gadolinium, erbium, and boron. Gadolinium (Gd) is a well-known thermally black absorber that produces a shift in the local thermal neutron spectrum, which effectively prevents thermal neutrons from penetrating into a lumped block of Gd [2]. As such, Gd is very sensitive to spatial self-shielding, making it difficult to be used as a homogenous rod or ring in a PWR core. In light of its large capture cross sections, Gd can lead to noticeable reactivity residual due to the conversion of $^{154}$Gd to $^{155}$Gd and $^{156}$Gd to $^{157}$Gd during irradiation. On the other hand, erbium (Er) depletes rather slowly due to its much smaller capture cross section than Gd. Similarly to Gd, Er also exhibits a continual chain of residual reactivity suppression, chiefly due to the naturally occurring $^{166}$Er and its immediate isotopic successor $^{167}$Er, which is also naturally occurring but quite highly absorbing [3]. Er is therefore usually considered as a BA material for a

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long-cycle PWR [4]. In addition, Er also has a unique thermal absorption resonance that may help improving the coolant temperature coefficient [3]. Meanwhile, boron has a moderately high absorption cross-section with negligible reactivity residual since it is converted into helium and Li-7 through an \((n,\alpha)\) reaction after depletion [2]. However, it is noted that the \((n,\alpha)\) reaction is exothermic and generates gaseous helium. Therefore, careful consideration must be taken when using boron as a BA in the core. Regarding material compatibility of the rare-earth Gd and Er elements, it is known that they react quite quickly with hot water [5,6]. Therefore, any Gd- or Er-based BA design should be securely separated from the water coolant. Due to this potentially undesirable reaction with water, Gd and Er are usually utilized in the forms of \(\text{Gd}_2\text{O}_3\) (gadolinia) and \(\text{Er}_2\text{O}_3\) (erbia). \(\text{B}_4\text{C}\) (boron carbide) is also known to react with hot water but rather slowly [7]. It is thus necessary to prevent \(\text{B}_4\text{C}\) from being in contact with the hot coolant as well.

The three aforementioned materials have successfully been deployed as either integral or discrete BA designs in modern PWRs. In the integral design, BA such as gadolinia and erbica is directly admixed with the \(\text{UO}_2\) fuel. In spite of its relatively simple fabrication, admixing absorber to ceramic fuel clearly reduces the fuel inventory and adversely affects the fuel thermal–mechanical properties [8,9]; e.g., degraded thermal conductivity and reduced melting point. In addition, Gd-based integral-type fuel rod may also produce a distorted, rapidly changing radial power profile [1] since the BA is loaded into only a few fuel rods per fuel assembly. Another variant of the integral absorber is a thin coating layer of BA on the outer surface of the fuel pellet, as in the integral fuel burnable absorber (IFBA) rod. The IFBA concept has a clear advantage in that the local pin power peaking can be very small since many IFBAs are rather uniformly loaded into a fuel assembly. In the IFBA design, initial backfilled gas pressure is reduced so as to accommodate the gaseous helium production from \(^{10}\text{B}\) neutron absorption [10,11]. It is worthwhile to note that all integral absorbers can only be loaded into fresh fuels and they are non-removable; i.e., they remain in the lattice throughout the fuel lifetime with some reactivity penalties.

The discrete BA design, on the other hand, loads BA materials into non-fuel element of the fuel assembly. One example is the wet annular burnable absorber (WABA) rod, which is loaded into the water hole of a standard guide thimble. Fully occupying the space, WABA rod denies insertion of control rod. Another example is the solid BA rod, which is installed in place of a fuel rod. This design effectively displaces some fissile content originally available in the fuel assembly. Furthermore, the discrete BA designs require separate radioactive waste items which need to be separately disposed of. In addition, they also displace a portion of water moderator from the guide thimbles, thereby possibly hardening the spectrum [1].

In a nutshell, while state-of-the-art PWR BAs reliably help to control the core reactivity, each comes with characteristic drawbacks; e.g., integral absorber is not removable, thimble-occupying discrete absorber denies insertion of control rod, and rod-displacing discrete absorber lowers fissile inventory in the assembly. In addition, all concepts are generally designed to be used in the first irradiation cycle of the fresh fuel assembly only, hence rather limiting their applications in the core. It is upon these observations that a new BA design that potentially offers solutions not currently viable with the existing technologies is being pursued.

This paper presents a novel BA concept for the PWR named ‘Burnable absorber-integrated Guide Thimble’ (BigT) [12–16]. Aptly named, the BigT absorber integrates BA materials into the standard guide thimble in a PWR fuel assembly. It is designed such that spatial self-shielding of the BA materials can easily be adjusted so as to attain the desired reactivity depletion pattern. In contrast to other thimble-occupying discrete absorbers, the BigT still allows insertion of control rods, thereby enabling the absorber to be installed in any fuel assembly in the PWR core. In addition, the BigT absorber is also removable and replaceable during refueling per operational specifications. These conceptual improvements of the BigT offer design flexibilities that may feasibly enable different loading patterns and core management objectives, such as those of first core, low boron and soluble boron-free cores [17–22].

In this work, the fundamental design features of the BigT concepts are described and they are evaluated and characterized in view of the fuel assembly design. Theoretical investigation on the neutronic properties of the BigT absorber is not deliberated in this work since physics of typical BA materials are well known and documented in many literatures [23–25]. All neutronics analyses including assembly depletions are performed using the Monte Carlo Serpent [26] code with ENDF/B-VII.0 library.

2. BigT: a new burnable absorber concept for the PWR

2.1. The BigT design concepts

The BigT comes in three different design variants, namely BigT-AHR (‘Azimuthally Heterogeneous Ring’), BigT-fAHR (‘fixed AHR’), and BigT-Pad, as illustrated in Figure 1. BigT-AHR is a ring containing azimuthally-heterogeneous BA layers which is loaded into the PWR guide thimble. One notes that geometrical aspect ratio (i.e., thickness and azimuthal span) of the BA layers dictates its spatial self-shielding and the subsequent depletion pattern [23]. Different geometries of the BA layers can be incorporated into a single BigT-AHR ring so as to achieve desirable depletion characteristics. On the other hand, BigT-fAHR is a BigT-AHR permanently fixed onto the guide thimble. The BigT-fAHR can
also be designed as an admixed BA-cladding thimble or by coating azimuthally heterogeneous BA layers onto the internal surface of the guide thimble. Meanwhile, BigT-Pad calls for a slight expansion of the thimble so as to accommodate four corner pockets for the integration of BA materials. The BigT-Pad must properly be oriented to ensure that it does not physically interfere with the adjacent grid spacers. Both BigT-fAHR and BigT-Pad are not conceptually replaceable. One notes that the BigT can be manufactured separately and independently from the fuel rods. Since the use of the BigT only requires minor modifications on the existing PWR fuel assembly, it is expected that the BigT can therefore be easily and readily retrofitted into PWRs in commercial operation.

Two representative PWR fuel assemblies are considered for the BigT applications in this work; one is the popular Westinghouse-type $17 \times 17$ design with 25 small guide thimbles as used in the AP1000 core [27] and the other is the Combustion Engineering-type $16 \times 16$ fuel assembly with 5 big guide thimbles as used in the APR1400 core [28]. In the usual applications of the BigT, 24 guide thimbles in the $17 \times 17$ fuel assembly and all 5 thimbles in the $16 \times 16$ fuel assembly are modified into the BigT absorbers, as illustrated in Figure 2. Although the BigT can be applied to all 25 thimbles in the $17 \times 17$ fuel assembly, only 24 non-central guide thimbles are used since the small central thimble is reserved for in-core instrumentation. However, in the $16 \times 16$ design, it is recommended to load the BigT into all thimbles since there are only 5 available; i.e., the BA loading is rather limited and lumped. Figure 2 also shows a typical U enrichment zoning in the $16 \times 16$ fuel assembly design to reduce local power peaking resulting from the large water holes and possible BA loadings. The depicted BigT loading in Figure 2 allows for an assembly-wide dispersion of the BA materials, which should result in a fairly uniform suppression of thermal flux across the fuel assembly. Nevertheless, number of the BigT absorbers installed in a single fuel assembly can still be varied per operational specifications.

The BigT can possibly use Gd, Er, cadmium, samarium, europium, and boron as its BA materials. Selective enrichment of the efficient neutron-absorbent isotopes and homogeneous mixing of the different BA compounds are technically feasible with the BigT. Furthermore, different BA materials and geometries can also be stacked vertically in a BigT design so as to adjust the axial offset of the reactor core.

Figure 1. Design concepts of the BigT-AHR (top), BigT-fAHR (middle), and BigT-Pad (bottom).

Figure 2. Representative BigT-loaded $17 \times 17$ (top) and $16 \times 16$ (bottom) fuel assembly designs.
Regardless of the BA materials for the BigT-AHR and BigT-fAHR concepts, dimensional stability in the BigT geometry should always be guaranteed for a reliable control of rod movement inside the thimble. In addition, the absorber should also be securely protected from the hot coolant. As shown in Figure 1, the conventional clad material (Zircaloy) is used as the protective layers of the BigT designs. Based on the current PWR designs and engineering judgement, the following dimensions are used in this neutronic study: water gap between the guide thimble and the BigT-AHR absorber = 0.4 mm, outer protective layer in BigT-AHR = 0.1 mm, inner protective layer of BigT-AHR = 0.2 mm, protective layer in BigT-fAHR = 0.2 mm. BA thickness in the BigT design is optimally <0.4 mm. Unfortunately, helium (He) gas produced by boron cannot be retained in the thin BA region of the BigT design in order to secure dimensional integrity of the protective layers. For the purpose of the discussion in this work, it is assumed that the He gas produced can be vented through specially-designed water-protective micro-holes provided at the top and bottom plenum of the guide thimble, similar to the patented fission gas venting with porous plug closure at both ends of the PWR axial blankets [29]. Detailed designs of the micro-holes are however beyond the scope of this discussion.

2.2. The BigT neutronic characterizations

Thoughtful deliberations must be taken in the selection of the BigT-BA material, shape and loading inventory since these design variables heavily influence the initial reactivity suppression and the ensuing reactivity depletion pattern. These are clearly demonstrated in the following study on the spatial self-shielding sensitivities of Gd, B, and Er in the different BigT designs. A quick recap on the self-shielding of lumped-poison mixtures, which is very relevant to the understanding of the BigT spatial self-shielding, is available in Appendix A (see supplementary materials to this article). All simulations were performed in the reference 17 (see supplementary materials to this article). All simulations were performed with 120,000 particles per cycle for 500 active and 100 inactive cycles. The resulting standard deviations of \( k_{\infty} \) values are less than 9 pcm. To demonstrate convergence of these Monte Carlo simulations, a sensitivity study on the simulated histories per cycle and the depletion time-step interval is presented in Supplemental data. It is clear that the analyses reach sufficient calculational convergence as the simulations are able to track depletion of BA materials in the BigT absorbers very well.

Figure 3 shows assembly depletion results of the different Gd-based BigT-AHR designs with either metallic Gd or ceramic Gd\(_2\)O\(_3\). Gd loading per BigT ring of 1 cm height is \( \sim 0.252 \) g for Gd and \( \sim 0.226 \) g for Gd\(_2\)O\(_3\) (i.e., about 31.92 mm\(^3\) BA per ring), which are pre-determined so as to yield \( k_{\infty} \) of the BigT-AHR 3° variant about 1.20. One can note that both Gd and Gd\(_2\)O\(_3\) show quite similar depletion behavior amongst the plotted BigT depletions. This ensures only the change in BA shapes (i.e., thickness and azimuthal span) would dictate the assembly reactivity depletion patterns. For the depletion of fuel assemblies, a specific power of \( \sim 37.4 \) W/g is assumed for an operational period of 510 effective full power days (EFPDs), which corresponds to 21.62 MWd/kgU burnup. All Serpent depletion simulations were performed with 120,000 particles per cycle for 500 active and 100 inactive cycles. The resulting standard deviations of \( k_{\infty} \) values are less than 9 pcm. To demonstrate convergence of these Monte Carlo simulations, a sensitivity study on the simulated histories per cycle and the depletion time-step interval is presented in Supplemental data. It is clear that the analyses reach sufficient calculational convergence as the simulations are able to track depletion of BA materials in the BigT absorbers very well.

| Parameter | Value |
|-----------|-------|
| Pressure (bar) | 155 |
| Specific power (W/g) | 37.4 |
| Fuel assembly lattice | 17 \times 17 |
| Number of fuel rod | 264 |
| Number of guide thimble | 24 |
| Number of instrumentation tube | 1 |
| Assembly pitch (cm) | 21.6038 |
| Pin pitch (cm) | 1.2623 |
| Fuel rod | |
| \( \text{U}_2\)O\(_3\) pellet radius (cm) | 0.4096 |
| Zircaloy clad inner radius (cm) | 0.4187 |
| Zircaloy clad outer radius (cm) | 0.4760 |
| Guide thimble and instrumentation tube | |
| Zircaloy inner radius (cm) | 0.5531 |
| Zircaloy outer radius (cm) | 0.6133 |
| Control rod | |
| Ag-In-Cd absorber radius (cm) | 0.4331 |
| SS-304 Clad inner radius (cm) | 0.4369 |
| SS-304 Clad outer radius (cm) | 0.4839 |
| Control rod (alternative for BigT-AHR and BigT-Pad) | |
| B\(_2\)C absorber radius (cm) | 0.3711 |
| SS-304 clad inner radius (cm) | 0.3749 |
| SS-304 clad outer radius (cm) | 0.4219 |
| Control rod (alternative for BigT-AHR) | |
| Absorber radius (cm) | 0.3230 |
| Clad inner radius (cm) | 0.3268 |
| Clad outer radius (cm) | 0.3738 |

Table 1. ACE7 fuel assembly lattice design parameters [28].
Table 2. Geometrical parameters of the simulated BigT designs of Section 2.2.

| BigT type       | BA material  | Azimuthal span (°) | Thickness (mm) | Average azimuthal width (mm) |
|-----------------|--------------|--------------------|----------------|-------------------------------|
| BigT-AHR Gd 10°| Natural Gd   | 10                 | 0.952          | 0.839                         |
| BigT-AHR Gd 20°| Natural Gd   | 20                 | 0.452          | 1.765                         |
| BigT-AHR Gd 40°| Natural Gd   | 40                 | 0.221          | 3.610                         |
| BigT-AHR Gd 90°| Natural Gd   | 90                 | 0.097          | 8.219                         |
| BigT-AHR Gd₂O₃ 10° | Gd₂O₃  | 10                  | 0.952          | 0.839                         |
| BigT-AHR Gd₂O₃ 40° | Gd₂O₃  | 40                  | 0.221          | 3.610                         |
| BigT-AHR Gd₂O₃ 90° | Gd₂O₃  | 90                  | 0.097          | 8.219                         |
| BigT-Pad Gd 10° | Natural Gd   | 10                 | 0.690          | 1.157                         |
| BigT-Pad Gd 20° | Natural Gd   | 20                 | 0.354          | 2.255                         |
| BigT-Pad Gd 40° | Natural Gd   | 40                 | 0.179          | 4.449                         |
| BigT-AHR B₄C 10° | Natural B₄C | 10                 | 0.559          | 0.873                         |
| BigT-AHR B₄C 20° | Natural B₄C | 20                 | 0.272          | 1.796                         |
| BigT-AHR B₄C 40° | Natural B₄C | 40                 | 0.134          | 3.640                         |
| BigT-AHR B₄C 90° | Natural B₄C | 90                 | 0.059          | 8.245                         |
| BigT-AHR Er 20° | Natural Er   | 20                 | 1.785          | 1.532                         |
| BigT-AHR Er 40° | Natural Er   | 40                 | 0.803          | 3.407                         |
| BigT-AHR Er 70° | Natural Er   | 70                 | 0.442          | 6.182                         |
| BigT-AHR Er 90° | Natural Er   | 90                 | 0.341          | 8.028                         |

The self-shielding is minimized; i.e., its initial reactivity suppression is maximized, and the lattice reactivity tends to increase quickly from the beginning due to the fast depletion of Gd. Such a fast depletion behavior is a well-known non-favorable feature of the Gd as a BA, leading to restrictive loading of Gd in modern PWRs. It is important to note that when Gd azimuthal span in the BigT application is reduced, the Gd becomes more self-shielded, resulting in smaller initial reactivity suppression and slower assembly reactivity depletion. This is especially evidenced with the most spatially self-shielded Gd (i.e., BigT-AHR 10°), which yields quite flat reactivity depletion and relatively negligible mid-cycle upswing. The Gd-based BigT design can therefore be easily tailored in term of the spatial self-shielding so as to provide the most favorable reactivity behavior during the fuel irradiation.

Figure 4 plots assembly reactivity depletion of BigT-AHR B₄C absorbers against burnup. The predetermined B₄C loading amount is 0.049 g per BigT ring of 1 cm height (i.e., 19.51 mm³ B₄C per ring), so as to yield $k_{\infty}$ of the BigT-AHR 30° variant about 1.20. As discussed previously, boron (B) is a moderate absorber without resonances and its depletion behavior is usually rather linear as shown in Figure 4. Nevertheless, it is noteworthy that the self-shielding of B can still be effectively adjusted in the BigT design. In the case of small spanning angle such as 10°, the reactivity shows a monotonic decrease. Meanwhile, the reactivity shows a gradual increase with burnup when the B₄C self-shielding is minimized as in the 90° azimuthal angle variation. Consequently, a quite flat reactivity change can possibly be obtained with a moderately self-shielded design, e.g., the BigT-AHR 40° variation. The B₄C is thereby an

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Figure 3. Neutronic characteristics of Gd-based BigT-AHR designs.

Figure 4. Neutronic characteristics of BigT-AHR B₄C of different BA shapes.
excellent BA candidate in the BigT design, should a flat reactivity depletion is desired.

Figure 5 meanwhile shows assembly reactivity depletions of the BigT-AHR Er absorbers against burnup. The pre-determined loading amount of natural Er is 0.992 g per BigT ring of 1 cm height (i.e., 109.39 mm³ Er per ring), so as to yield $k_{\infty}$ of the BigT-AHR 30° variant about 1.20. It is clear that fairly gentle depletion patterns with very large EOC poisonous residuals are observed for all cases, chiefly due to erbium’s weakly-high capture cross-section and the continual creation of $^{167}$Er isotopes. Although the natural Er is not a strong absorber, the BigT design can still noticeably affect its spatial self-shielding through a simple shape change. It is expected that 100% $^{167}$Er can be used as an efficient BA material in the BigT design.

Figure 6 compares neutronic characteristics of the Gd-based BigT-AHR and BigT-Pad designs with burnup. One notes that the BigT-Pad places Gd on the outside of the guide thimble in contrast to the BigT-AHR which houses the Gd inside. As such, with the same loading content and azimuthal span, Gd in the BigT-Pad should relatively be thinner (i.e., of smaller thickness) than that in the BigT-AHR, resulting in a smaller spatial self-shielding and, consequently, higher initial reactivity suppression and upswing. The trend is more obvious with bigger spanning angles (i.e., BigT 40°). One must however note that the range of BA azimuthal span in the BigT-Pad design is unfortunately quite restrictive (<45°) due to the limited allowable pad areas imposed by the spacer grids.

Figures 3–6 clearly illustrate impacts of the BigT-BA geometrical aspect ratios (i.e., shape and thickness) on the initial assembly lattice reactivity hold-downs and the subsequent depletion patterns. BA with a high ratio of surface area to volume has a minimum spatial self-shielding, in agreement with the expected physics of the BA self-shielding presented in Supplemental data. As such, with the same loading content, a wider and thinner fresh BA may suppress more reactivity and is depleted quicker (i.e., earlier reactivity upswing) as the BA is burnt more efficiently and ‘completely’. This is especially evidenced with the Gd-based and B₄C-based configurations. While depletion pattern of the BigT absorber is highly-dependent on the BA geometrical shape, it is also rather insensitive to BA orientation in the fuel assembly lattice. This is clearly demonstrated in Supplemental data. In brief, it can be assured that the BigT neutronic performance and effectiveness are not compromised even if the BigT is to be displaced from its initial aligned orientation during irradiation.

The above study also clearly demonstrates neutronic flexibilities of the BigT concepts. Depending on the design requests, the BigT absorbers can easily provide both increasing and decreasing reactivity evolutions, in addition to a relatively flat reactivity change with the BigT design optimization.

2.3. The BigT practical design considerations

2.3.1. The replaceable BigT design

The BigT-AHR is envisioned to be operated similarly like other thimble-occupying discrete absorber (e.g., WABA rod). The BigT-AHR would nevertheless require an innovative handling mechanism so as to assure its replaceability during refueling. One solution is by modifying the releasable latch in the current WABA handling tool [30], such that the modified tool can then be used to detach the BigT-AHR from the fuel assembly. One must however note that the Big-AHR can only be removed after the rod cluster control assembly is completely disengaged from top-head of the fuel assembly, thereby necessitating a minor change in the standard refueling procedure. Another solution is by altering the existing hold-down assembly design so as to temporarily fasten the BigT-AHR inside the guide thimble during
normal operation. This temporary lock can manually be undone during refueling to release the spent BigT-AHR from the fuel assembly.

In addition, the BigT replaceable concept can also possibly be accomplished by combining the use of the different BigT design variants. For example, in a two-batch fuel management, fresh fuel assemblies can be loaded first with the BigT-Pad absorbers. During refueling, BigT-AHR absorbers can later be inserted into the annulus hole of the spent BigT-Pad so as to assure the availability of fresh BA materials in the fuel assembly. This BigT loading strategy is also possibly practical for a 3-batch PWR fuel management. Detailed engineering discussion of the BigT replaceability is beyond the scope of this work.

2.3.2. The BigT bottom-end design

The BigT-AHR bottom must be designed, either open-ended or plugged, with adequate length to enable full insertion of control rod in its thimble. Furthermore, its bottom end must also be equipped with an alignment guide to properly and securely attach the BigT-AHR onto the standard guide thimble. A ‘valve’ to minimize the possible vortex-induced vibration in the thimble may also be necessary. In addition, an appropriate length of BigT-BA cutbacks should also be considered to better manage the reactor axial power distribution.

On top of the abovementioned specifications, all BigT bottom-end designs must be dashpot-compliant. This is because modern PWR guide thimble normally comes with a dashpot, which is to dampen the sudden drop of the control rod during shutdown. This can possibly be accomplished by designing the BigT bottom-end with either a traditional dashpot design (i.e., smaller thimble diameter at bottom-end) or with an ‘appendix’ that would induce similar dashpot effect (i.e., dampening of the rod drop). In either case, the BigT dashpot-compliant design must correctly be aligned with the existing dashpot so as to assure the desired dampening effect can efficiently be produced. Related detailed study is beyond the scope of this neutronic evaluation of the BigT absorbers.

2.3.3. The BigT thermal–mechanical–hydraulic concerns

The BigT must be able to withstand standard shipping and handling loads required for a typical thimble-occupying discrete absorber. In addition, the BigT creep and corrosion behaviors must also properly be understood. Specifically, thermal expansion of the BigT must be accounted for so as to assure adequate gap would always be available for the full insertion of control rod inside the thimble throughout normal operation. Furthermore, adequate amount of bypass flow allowed in the BigT thimble must be determined and controlled to accommodate the expected pressure differentials and cooling requirement. One may note of the possible pressure drop imbalance in the core with the BigT absorbers in place. However, it is expected that the possible pressure drop imbalance will be marginal since only a small bypass flow is allowed through the BigT thimble.

There is also a typical concern with the critical heat flux (CHF) in a standard thimble sub-channel. It is because CHF in a sub-channel with an unheated wall is relatively lower than that in a typical four-rod sub-channel. This is chiefly due to the cold-wall effect which causes the thimble sub-channel to be more limiting with respect to the departure from nucleate boiling ratio (DNBR) [31–34]. In the BigT-AHR and BigT-fAHR designs, this concern can possibly be discounted in light of the non-DNBR issue with the WABA operation (note that the two BigT design variants are to be operated similarly like the WABA rod).

The DNBR-limiting issue with BigT-Pad, on the other hand, requires some investigations since the design introduces fin-like appendages to the standard guide thimble. Nonetheless, since the BigT-Pad requires only minor modifications on the thimble, this concern may somewhat be assuaged. This is because thermal fluxes are more suppressed in the BigT sub-channel due to the presence of neutron-absorbent materials, which in turn subdues pin power in the neighboring fuel rods. Hot-wall temperature in the sub-channel consequently drops, so as its exit enthalpy, effectively mitigating the cold-wall effect in the BigT sub-channel. This possibly results in the BigT sub-channel to be ‘less’ limiting with respect to the DNBR.

Meanwhile, a noticeable reduction in the coolant flow area is also expected with the BigT-Pad sub-channel (Figure 7), whose approximated equivalent hydraulic and heated diameters are listed in Table 3. Conceptually, a smaller hydraulic diameter yields a higher flow friction, resulting in a bigger pressure drop and better thermal mixing in the sub-channel. On the other hand, a smaller equivalent heated diameter represents less ‘coolability’ of the sub-channel, leading to a higher fluid bulk temperature and a correspondingly bigger average exit enthalpy. All these may additionally weaken the cold-wall effect in the BigT-Pad sub-channel.

In summary, the BigT design may not negatively affect thermal–hydraulic performance of the existing PWR assembly. Nonetheless, empirical evaluations are
still required to form a conclusive verdict on the thermal–mechanical–hydraulic impacts of the BigT absorbers.

3. Neutronic characteristics of the BigT against commercial BA technologies

This section presents neutronic evaluations of the BigT absorbers against commercial technologies in $17 \times 17$ and $16 \times 16$ fuel assembly configurations. Basic calculational conditions for the Monte Carlo Serpent simulations are identical to those in Section 2.2.

3.1. The BigT absorbers in $17 \times 17$ fuel assembly designs

In this sub-section, 264 4.5 w/o UO$_2$ fuel rods and 24 absorbers of the three different BigT variants were modeled in the representative $17 \times 17$ fuel assemblies and the depletion analyses were done with Serpent. All geometrical parameters are based on the ACE7 lattice design [28] as tabulated in Table 1. The commercial BA technologies chosen as benchmarks are ‘112-IFBA’ and ‘16-WABA’ designs, which were used in the AP1000 initial core [27] and Yonggwang Unit 1 Cycle 15 core [28], respectively. In the ‘112-IFBA’ case, 112 IFBA rods are used and 16 WABA rods are loaded in the ‘16-WABA’ case. For a consistent comparison with the IFBA and WABA, only B$_4$C-based BigT designs are considered. Also, no enrichment zoning is adopted. Loading amounts of 65% TD B$_4$C in the BigT designs are pre-determined such that their initial reactivity hold-downs are similar to those of the benchmarks.

Figure 8 depicts burnup-dependent assembly reactivity of all BA schemes, while Table 4 summarizes important results of the analyses. It is clear that the BigT absorbers perform as well as the IFBA and WABA as their reactivity depletions are quite comparable. In fact, residual reactivity penalties of the BigT-AHR and BigT-fAHR are quite small ($<500$ pcm) over the 510-EFPD depletion. BigT-Pad meanwhile shows a bigger residual reactivity due to its enhanced BA self-shielding (i.e., the smallest BA geometrical aspect ratio of the three BigT designs). However, it is noted that the residual reactivity of the BigT-Pad is loosely similar to that of the

Table 4. Summary of neutronic performances of the BigT-loaded $17 \times 17$ assembly lattices with 12-pin corner enrichment zoning.

|                         | Reactivity penalty at 510 EFPDs (pcm) | Peak power peaking | R0.433 cm Ag-In-Cd worth (pcm) | R0.371 cm natural B$_4$C worth (pcm) |
|-------------------------|--------------------------------------|-------------------|--------------------------------|--------------------------------------|
| No absorber             | 0                                    | 1.058             | 32,375                         | Not applicable                       |
| 112 IFBA rods           | 224                                   | 1.052             | 31,610                         | Not applicable                       |
| 16 WABA rods            | 1,066 (1,131)$^a$                     | 1.085 (1.086)$^a$| Not applicable                 | Not applicable                       |
| BigT-AHR B$_4$C         | Thickness 0.074 mm, azimuthal span 50$^b$ | 1.063             | 17,892$^b$                     | 25,879$^d$                           |
|                         | Thickness 0.033 mm, azimuthal span 90$^c$ | 1.063             | 21,787$^c$                     | 31,438                               |
| BigT-Pad B$_4$C         | Thickness 0.178 mm, azimuthal span 25$^e$ | 1,510             | 27,308                         | 32,324                               |

$^a$16 WABA rods configuration with 12-pin corner enrichment zoning.
$^b$Ag-In-Cd rod with radius of 0.323 cm for BigT-AHR.
$^c$Ag-In-Cd rod with radius of 0.371 cm for BigT-fAHR.
$^d$B$_4$C rod with radius of 0.323 cm for BigT-AHR.
$^e$50%-enriched B$_4$C rod with radius of 0.323 cm for BigT-AHR.
WABA case. It is also noted that the IFBA design displays a noticeable upswing during the burnup, while the BigT-AHR and BigT-fAHR show less upswing but still reach similar residual reactivity penalties at EOC (end-of-cycle). The BA design in BigT-AHR (50° azimuthal span) is chosen intentionally to be very different from that of the BigT-fAHR (90° azimuthal span, i.e., a homogenous ring) in order to demonstrate the neutronic flexibility of the BigT concepts. In spite of having very different BA designs, the two plots interestingly display similar reactivity suppression characteristics.

Figure 9 plots evolution of the burnup-dependent assembly peaking factors of all BA schemes. It is apparent that the BigT power peaking factors are quite similar to WABA throughout the depletion, $<1.09$. From Figure 10, one notes that the BigT-AHR pin power peaks initially occur at assembly corners, but slowly migrate inwards with burnup. BigT-Pad and Big-fAHR also display the same pin power profiles at similar burnup. The assembly power peaking in a BigT-loaded fuel assembly can therefore be lowered via optimization of corner fuel enrichments. It should again be noted that Figures 8 to 10 were simulated with uniform fuel enrichment throughout the assembly lattice (i.e., no corner enrichment zone).

Figure 11 depicts burnup-dependent assembly peaking factors of the BigT-loaded assemblies with 12-pin corner enrichment zones against the benchmarks. In this simulation, 3 UO$_2$ fuel rods of 4.1 w/o enrichment are loaded at each corner of the BigT-loaded assemblies. It is apparent that the assembly power peaking factors are well controlled in these BigT-loaded assemblies as they were smaller than 1.07, much smaller than that of the WABA at low burnup. This is because BOC (beginning-of-cycle) power of the corner fuel pins have effectively been subdued as clearly shown in Figure 12. Interestingly, when the same 12-pin corner enrichment zones are applied to the ‘16 WABA’ lattice, no such reduction of assembly power peaking factors are observed. It should also be mentioned that this improved pin power control in the BigT-loaded assembly lattices is obtained at a small cost of assembly reactivity reduction of about 75 pcm only. As such, the impact of decreasing U enrichment in the corners pins on the overall fuel cycle is expected to be quite small.

It is also clear from Table 4 that, in the BigT-loaded fuel assemblies with corner enrichment zones, worth of the conventional Ag-In-Cd absorbers at BOC is substantially reduced by about 5,000–15,000 pcm. In this
evaluation, a smaller control rod radius was considered by taking into account typical BigT designs, 0.373 cm absorber rod for BigT-fAHR and 0.323 cm for BigT-AHR. In the BigT-fAHR design, maximum BA thickness is considered to be 0.4 mm and the protective layer is 0.2 mm. For BigT-AHR, water gap of 0.4 mm is additionally considered and the inner and outer protective layers are considered to be 0.2 mm and 0.1 mm thick, respectively, with the BA thickness set at 0.4 mm (even though the actual BA thickness is quite smaller than 0.1 mm in the BigT-AHR and BigT-fAHR designs). It should also be noted that the original rod size (0.433 cm) can still be used in the BigT-Pad design. Nevertheless, Table 4 shows that sufficiently high control rod worth can be obtained in the BigT-loaded cases by replacing the metallic absorber with B4C rod. The said worth can further be increased with selective 10B enrichment in the rod, if necessary. Nonetheless, actual control rod worth should be evaluated in a 3-D core model since the number of rodded assemblies is much smaller than the total number of fuel assemblies. In addition, it should be mentioned that control rod worth in the BigT-loaded case should increase a lot when the BA is largely depleted. The 3-D control rod worth evaluation for BigT-loaded PWR cores are discussed in a companion paper to this work. The economics of replacing and enriching absorber materials in the control rod is also not quantified and covered in this manuscript as it is beyond the scope of this neutronic evaluation.

3.2. The BigT absorbers in 16 × 16 fuel assembly designs

In this sub-section, Gd- and B4C-based BigT-fAHR absorbers are loaded into the 5 guide thimbles of the representative 16 × 16 fuel assembly designs shown in Figure 2. BigT-fAHR variant is arbitrarily chosen since this analysis only aims to demonstrate neutronic characteristics of the different BA materials in a BigT design against a commercial technology. Performance of other BigT variants (BigT-AHR and BigT-Pad) can easily be inferred from the analyses in this sub-section and from the previous discussions in this work. The simulated assembly design, which are based on the PLUS7 design parameters tabulated in Table 5 [28], contains 184 5.0 w/o UO2 fuel rods and 52 fuel rods of 4.5 w/o enrichment. The Serpent depletion analysis was performed at a specific power of 32.2 W/g, with basic calculational conditions similar to those in Section 2.2. The commercial BA technology selected as benchmark is the ‘12-GBF’ design used in Hanbit Unit 3 Cycle 6 [28]. In the ‘12-GBF’ configuration, 12 gadolinia-bearing fuel (GBF) rods are symmetrically loaded throughout the fuel assembly. The GBF rod is consisted of 8.0% Gd2O3 admixed with natural UO2 fuel. BA loading amounts of the BigT absorbers are again pre-determined such that their initial reactivity suppressions are similar to that of the benchmark.

Figure 13 depicts burnup-dependent assembly reactivity depletions of the BigT absorbers against the benchmark and Table 6 summarizes important results of the analyses. It is clear that the BigT perform reasonably well against the conventional GBF technology. This is because depletion pattern of the Gd-based BigT-fAHR, by virtue of BA design optimization, closely matches with that of the ‘12-GBF’ technology. Meanwhile, reactivity depletion of the BigT-fAHR B4C is rather flat without any mid-cycle upswing due to the linear and quick depletion of boron in the homogeneous ring design (i.e., 90° azimuthal span). Second, the residual

| Parameter                          | Value |
|------------------------------------|-------|
| Pressure (bar)                     | 155   |
| Specific power (W/g)               | 32.2  |
| Fuel assembly lattice              | 16 × 16 |
| Number of fuel rod                 | 236   |
| Number of guide thimble            | 4     |
| Number of instrumentation tube     | 1     |
| Assembly pitch (cm)                | 20.8756 |
| Pin pitch (cm)                     | 1.2878 |
| Fuel rod                           |       |
| Pellet radius (cm)                 | 0.4096 |
| Clad inner radius (cm)             | 0.4187 |
| Clad outer radius (cm)             | 0.4760 |
| Guide thimble                      |       |
| Inner radius (cm)                  | 1.1376 |
| Outer radius (cm)                  | 1.2395 |
| Instrumentation tube (central thimble) | 1.1452 |
| Outer radius (cm)                  | 1.2470 |
| Control rod                        |       |
| B4C absorber radius (cm)           | 0.9360 |
| Clad inner radius (cm)             | 0.9474 |
| Clad outer radius (cm)             | 1.0363 |
| Control rod (alternative for BigT-fAHR) |       |
| B4C absorber radius (cm)           | 0.8900 |
| Clad inner radius (cm)             | 0.9014 |
| Clad outer radius (cm)             | 0.9903 |

Table 5. PLUS7 fuel assembly lattice design parameters [28].

![Figure 13. Assembly reactivity depletions of the BigT-fAHR-loaded 16 × 16 fuel lattices against commercial 12-GBF technology.](image-url)
Table 6. Control rod worth and power peaking of BigT-loaded 16 × 16 assembly lattices.

| No absorber          | EOC penalty (pcm) | Peak power peaking | R0.936 cm natural B4C worth (pcm) | R0.890 cm 95% B4C worth (pcm) |
|----------------------|-------------------|--------------------|----------------------------------|-------------------------------|
| 12 GBF rods          | 1,161             | 1.148              | 18,641                           | Not applicable                |
| BigT-fAHR B4C        | 738               | 1.100              | 11,251*                          | 17,678                        |
| Thickness 0.092 mm, azimuthal span 90° |                  |                    |                                  |                               |
| BigT-fAHR Gd         | 615               | 1.102              | 10,980*                          | 17,361                        |
| Thickness 0.411 mm, azimuthal span 41° |                  |                    |                                  |                               |

*Natural B4C rod with radius of 0.890 cm for BigT-fAHR.

For the evaluation of control rod worth in the 16 × 16 fuel assemblies, 5 B4C absorber rods were loaded into the large water holes of the guide thimbles. In the case of the BigT-fAHR design, an absorber radius of 0.890 cm was used, which is much smaller than the conventional radius of 0.936 cm. This new control rod dimension is suggested based on current PWR designs and engineering judgment, taking into account the necessary gap between BigT-fAHR and control rod: maximum BA thickness of 1.0 mm and a protective layer of 0.2 mm. The use of BigT-AHR necessitates an even smaller control rod, which is however not deliberated in this discussion. Table 6 shows worth of the B4C absorber rods in the conventional and BigT-loaded fuel assemblies at BOC. One can note that the control rod worth is reduced by ~6,000 pcm in the BigT-loaded cases. The control rod worth is also shown to be easily enhanced by enriching 10B in the B4C absorber rods, although a high 10B enrichment is required for a full recovery of the control absorber worth. Again it is important to note that the high 10B enrichment is not a necessary condition in the actual BigT applications in 3-D core designs, which is discussed in a companion paper to this work.

4. Conclusions

Innovation in BA technologies for the PWR must continuously be pursued to expedite the advancement of a PWR core design. While state-of-the-art PWR BA technologies function reasonably well as a supplementary reactivity management scheme, they unfortunately...
come with noteworthy design setbacks; e.g., a thimble-occupying discrete absorber fills-up spaces reserved for a control rod, and a non-removable integral absorber degrades thermal–mechanical properties of the fuel element. It is upon these observations that the ‘BigT’ design is proposed in this work.

The BigT, which can easily and readily be retrofitted into commercial PWR, is neutronically very flexible in which its BA spatial self-shielding can easily be adjusted to attain the desired reactivity depletion pattern. The BigT also allows full insertion of control rods in its thimble and is conceptually replaceable during refueling. These advantages can enable the loading of fresh BA materials into any fuel assembly in the core, consequently help to realize any loading pattern and core management objective of the PWR, including those of initial core configuration, low boron and soluble boron-free core designs.

This paper demonstrates the promising potentials of the BigT concepts in representative 17 × 17 and 16 × 16 fuel assembly applications. The BigT absorbers are shown, in this work, to perform reasonably well in comparison with the commercial BA technologies, especially in terms of reactivity depletion and power distribution managements. Furthermore, sufficiently high control rod worth can also be obtained with the BigT in place.

Further studies to fully investigate the practical applications of the BigT concepts must be pursued. This includes detailed designs of the BigT replaceable and dashpot-compliant concepts, thermal–hydraulic analyses of the BigT-Pad sub-channel, and a design that accommodates helium gas venting in the B4C-based BigT absorber. Furthermore, combination of the BigT with the existing BA configurations should also be investigated in the future.

Nomenclature

- AHR Azimuthally heterogeneous ring
- B4C Boron carbide
- BA Burnable absorber
- BigT Burnable absorber–integrated Guide Thimble
- BOC Beginning of cycle
- CHF Critical heat flux
- DNBR Departure from nucleate boiling ratio
- EFPD Effective full power day
- EOC End of cycle
- fAHR fixed-AHR
- GBF Gadolinia-urania bearing fuel
- IFBA Integrated fuel burnable absorber
- PWR Pressurized water reactor
- TD Theoretical density
- WABA Wet annular burnable absorber

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Disclosure statement

No potential conflict of interest was reported by the authors.

Supplemental data

Supplemental data for this article can be accessed here.

References

[1] Cacuci DG (editor). Handbook of nuclear engineering. New York, NY: Springer; 2010. p. 1556.
[2] Goldstein L, Strasser AA. A comparison of gadolinia and boron for burnable poison applications in pressurized water reactor. Nucl. Tech. 1983 Mar;60:352–361.
[3] Secker JR, Brown JA. Westinghouse PWR burnable absorber evolution and usage. Trans. Am. Nucl. Soc. 2010 Nov;103:733–734.
[4] Barchevtsev V, Artisyuk V, Ninokata H. Concept of erbium doped uranium dioxide fuel cycle in light water reactors. J. Nucl. Sci. Technol. 2002 May;39(5):506–513.
[5] WebElements periodic table [Internet]. Sheffield, UK: The University of Sheffield and WebElements Ltd; 2015 Apr 12. p. c1993–2015. Gadolinium: reactions of elements. [cited 2015 Apr 12]; Available from: http://www.webelements.com/gadolinium/chemistry.html
[6] WebElements periodic table [Internet]. Sheffield, UK: The University of Sheffield and WebElements Ltd; 2015 Apr 12. p. c1993–2015. Erbium: reactions of elements; [cited 2015 Apr 12]; Available from: http://www.webelements.com/erbium/chemistry.html
[7] Litz LM, Mercuri RA. Oxidation of boron carbide by air, water, and air-water mixtures at elevated temperatures. J. Electrochem. Soc. 1963 Aug;110(8):921–925.
[8] Characteristics and use of uranium-gadolinia fuels. Vienna, Austria: International Atomic Energy Agency; 1995, Report no. IAEA-TECDOC-844.
[9] Yamanaka S, Kurosaki K, Katayama M, Adachi J, Uno M, Kuroishi T, Yamasaki M. Thermal and mechanical properties of (U,Er)O2. J. Nucl. Materials. 2009 May;389(1):115–118.
[10] Simmons RL, Jones ND, Mueller DE, Prichett JE. Integral fuel burnable absorbers with ZrB2 in pressurized water reactors. Nucl. Tech. 1988 Mar;80:343–344.
[11] Westinghouse burnable absorbers – advanced core management products. Pittsburgh, PA: Westinghouse Electronic Corporation; 2006.
[12] Kim Y, Yu HY, Yahya MS, Lee KW, Sohn JJ, Kim HH, Song IH, Bae IH. Burnable absorber integrated control rod guide thimble. Korea Advanced Institute of Science and Technology, Daejeon & KEPCO Engineering and Construction Company, Inc, Daejeon. Korea patent 10-1497893. 2015 Mar 5.
[13] Yahya MS, Kim Y, Chung CK. A novel burnable absorber concept for PWR. BigT (Burnable absorber-Integrated Guide Thimble), Trans. Korean Nucl. Soc. Spring Meeting; 2014 May 29–30; Jeju (Republic of Korea).
[14] Yahya MS, Yu HY, Kim Y. A burnable absorber-integrated control rod guide thimble for PWR. Trans. Am. Nucl. Soc. 2014 Jun;110:593–594.
[15] Yahya MS, Yu HY, Kim Y. BigT – a new burnable absorber concept for PWR. Proc. PHYSOR-2014; 2014 Sep 28–Oct 3; Kyoto (Japan).

[16] Yahya MS, Kim Y, Kim HH. Neutronics design flexibilities of the BigT gadolinium absorbers. Trans. Korean Nucl. Soc. Spring Meeting; 2015 May 7–8; Jeju (Republic of Korea).

[17] Yahya MS, Kim Y. Application of the BigT burnable absorber to AP1000 first core. Trans. Am. Nucl. Soc. 2015 Jun;112:811–813.

[18] Yu HY, Yahya MS, Kim Y. Burnable absorber-integrated guide thimble (BigT) – II: application to 3D commercial PWR cores. J. Nucl. Sci. Tech. [under review].

[19] Yu HY, Kim Y. Application of the BigT burnable absorber to an OPR1000 core for a low critical boron concentration. Trans. Korean Nucl. Soc. Autumn Meeting; 2014 Oct 29–31; Pyeongchang (Republic of Korea).

[20] Yu HY, Yahya MS, Kim Y. Application of the BigT burnable absorber to a soluble boron-free PWR core. Proc. PHYSOR-2014; 2014 Sep 28–Oct 3; Kyoto (Japan).

[21] Yahya MS, Kim Y, Kim HH. Preliminary investigation of the soluble boron free AP1000 core with the BigT burnable absorber. Trans. Korean Nucl. Soc. Autumn Meeting; 2014 Oct 29-31; Pyeongchang (Republic of Korea).

[22] Yahya MS, Kim Y. Application of the BigT burnable absorber to AP1000 core for a soluble boron free operation. Trans. Am. Nucl. Soc. 2014 Nov;111:1208–1210.

[23] Hurwitz H Jr, Zweifel PF. Self-shielding of lumped poison mixtures. Nucl. Sci. Eng. 1956;1:438–440.

[24] Bengston J. Neutron self-shielding in a simple plane lattice. Nucl. Sci. Eng. 1958;3:71–76.

[25] Radkowsky A. Reactor reactors physics handbook: selected basic techniques. Washington, DC: Atomic Energy Commission; 1964.

[26] Leppänen J. Serpent – A continuous energy Monte Carlo reactor physics burnup calculation code. Espoo, Finland: VTT Technical Research Centre of Finland; 2013.

[27] Public version of AP1000 design control document revision 19. Pittsburgh, PA: Westinghouse Electric Corp; 2011, Report No. APP-GW-GL-702.

[28] Benchmark matrix for verification and validation of the KARMA code. Daejeon, Republic of Korea: Korea Atomic Energy Research Institute; 2010, Report no. S06NX08-A-2-TR-04 Rev. 2.

[29] Stratton RW, Nicolet M, Andrews A. Nuclear fuel rod with porous plug closure. Gesellschaft zur Forderung der Industrieorientierten Forschung an den Schweizerischen Hochschulen und Weiteren Institutionen, Berne, Switzerland. United States patent US 4,627,957. 1986 Dec 9.

[30] Meuschke RE; Westinghouse Electric Corp. Gripper assembly for inserting and removing burnable absorber rods and thimble plugs in a nuclear reactor fuel assembly. United States patent US 4,772,446. 1988 Sep 20.

[31] Tong LS. Boiling crisis and critical heat flux. Washington, DC: US Atomic Energy Commission; 1972.

[32] Kim HK, Han KI. DNBR sensitivities to variations in PWR operating parameters. J. Korean Nucl. Soc. 1983 Dec; 15:234–247.

[33] Hwang DH, Chun SY, Kim KK, Lee CC. Mass velocity and cold-wall effects on critical heat flux in an advanced light water reactor. Nucl. Eng. Design. 2007 Feb; 237:369–376.

[34] Kim KH, Kim HJ, Lim JS, Yang SG, Park EJ. New unheated cold wall correction factor. Trans. Korean Nucl. Soc. Spring Meeting; 2007 May 10-11; Jeju (Republic of Korea).