Physics Review on Inherently Safe Features of ESBWR

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Abstract

The scope of this physics review includes: 1) the major differences among ESBWR, ABWR and conventional BWR cores, 2) the reason why ESBWR operation is inherently safe based on stability analysis, 3) an innovative wide-blades control rod conceptual core design to reduce cost by reducing number of control rod drives by near 50% for a natural circulation BWR, and 4) an innovative top-entry control rod conceptual core design to take advantage of additional space in the chimney area in order to reduce the plant size and cost for a natural circulation BWR.

KEYWORDS: BWR, ESBWR, stability, natural circulation, passive

1. Introduction

The operating boiling water reactors (BWR) have evolved from natural circulation in the Dodewaard BWR/1 to external recirculation pump in BWR/2, to jet pump in BWR/3 to BWR/6, to internal recirculation pump in Advanced BWR (ABWR), and back to natural circulation in Economic Simplified BWR (ESBWR)[1]. However, the ESBWR (1132 assemblies with 4500 MWt rated power) is not just a "step design change" from the small Dodewaard BWR/1 (164 assemblies with 183 MWt rated power), but rather evolves from the design and operating experience of all BWRs in the past four decades. The major differences among GE BWR cores are summarized in Table 1.

Table 1 Major Differences among GE BWR Cores

	ESBWR	ABWR	BWR/3-BWR/6
Core Flow	Natural circulation	Forced	Forced
Circulation Pumps	No	Internal pumps	Jet pumps
Thermal Power (MW)	4500	3926	947-3833
Active Fuel Length (Ft)	10	12	12
Fuel Lattice Pitch (Inch)	6.1	6.1	6
Number of Assemblies	1132	872	240-800
Number of Control Rods	269	205	57-205
Control Rod Movement	Fine motion	Fine motion	Notch-wise
Av. Power Density (KW/L)	54	51	36-54

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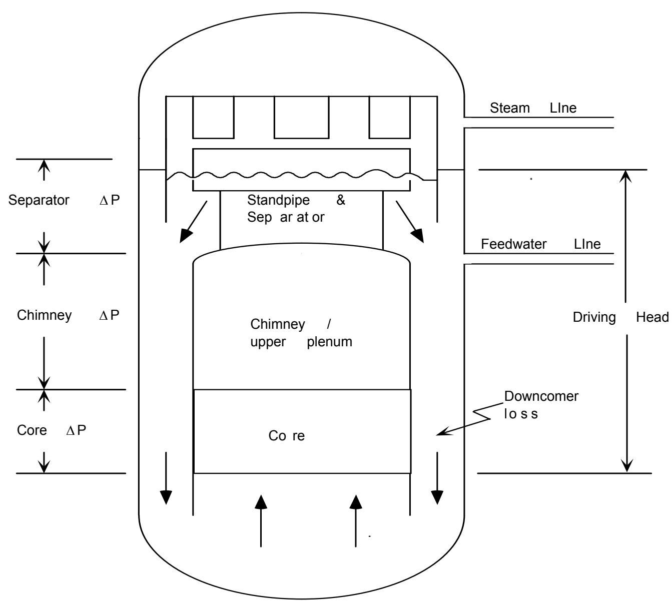
The utilization of natural circulation and passive safety systems in the ESBWR design simplifies reactor system designs, reduces cost, and provides a reliable stability solution for inherently safe operation. The conceptually reliable stability solution for inherently safe ESBWR operation is developed by establishing a sufficiently high natural circulation flow line, which has a core flow margin at least 5% higher than the stability boundary flow at 100% rated power of a conventional BWR, and then by designing a high flow natural circulation system to achieve this high natural circulation flow line[2]. The design of a high flow natural circulation system in an ESBWR can be achieved by eliminating the restricted downcomer in conventional BWRs with an unrestricted downcomer and by optimizing the chimney height, active fuel length, and separator configurations. A simplified diagram of an ESBWR is shown in Figure 1.

To reduce cost, two innovative conceptual core designs were studied for a natural circulation BWR: 1) wide-blades control rod core design[3] to reduce number of control rod drives by near 50% and 2) top-entry control rod core design[4] to take advantage of additional space in the chimney area in order to reduce the plant size.

Figure 1: Simplified Diagram of an ESBWR



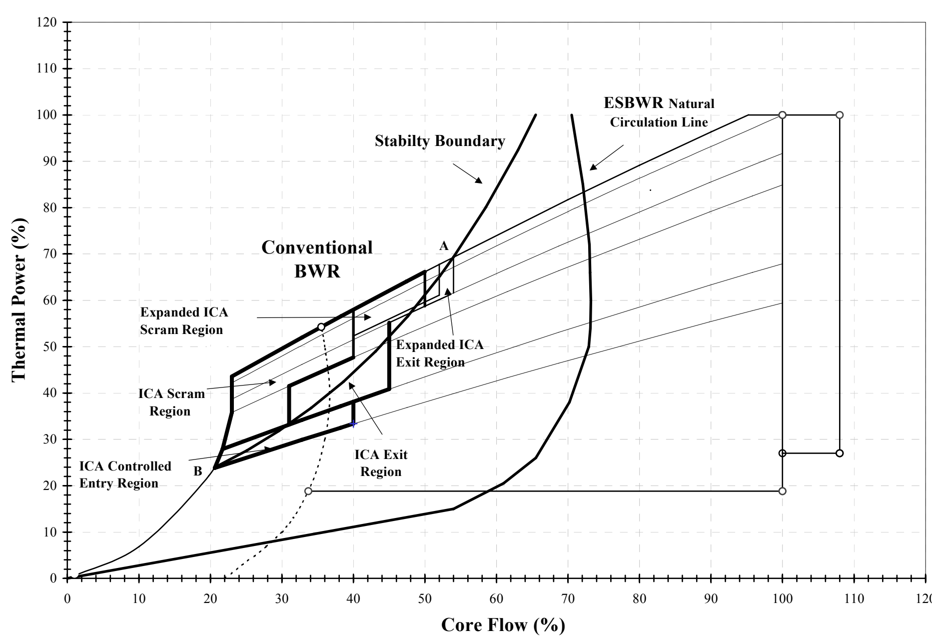
2. ESBWR Core Stability Analysis Review[2]

The BWR Owners Group issued recommended guidelines in 1994[5] and an update in 2002[6] for BWR operation, which emphasize instability prevention. The guidelines define three stability Interim Corrective Actions (ICA) operating regions: Scram, Exit, and Controlled Entry Regions in a power/flow map (as shown in Figure 2) that are excluded from planned entry and prescribe specific actions upon unplanned entry. Since the ICA Regions are based on empirical evaluations and experience, the standard ICA Region boundaries may be validated or expanded based on decay ratio analyses at various region boundary state points that are compared against the decay ratio (DR) acceptance criterion for nominal feedwater temperature (FWT) operation and minimum FWT operation on a cycle-specific basis.

An example of expanded ICA Regions of a conventional BWR for minimum FWT operation is shown in Figure 2. Since the expanded ICA Regions for minimum FWT operation bound those for nominal FWT operation, any operation outside the expanded ICA Exit/Controlled Entry Region boundary for minimum FWT operation is adequate for nominal FWT operation. The core DRs at the two bounding state points A (on the high flow control line) and B (on the natural circulation line) of the expanded ICA Exit/Controlled Entry Region boundary for minimum FWT operation are 0.787 and 0.300, respectively, and the corresponding highest channel DRs are 0.251 and 0.233, respectively. A stability boundary is established by connecting the two bounding state points A and B of the expanded ICA Exit/Controlled Entry Region boundary with a fitting function and by extending the boundary to 100% rated power as shown in Figure 2. Consequently, the stability boundary plus a conservative (at least 5%) core flow margin at 100% rated power can be used to design an inherently safe ESBWR with a sufficiently high natural circulation flow line as shown in Figure 2.

The design of a high flow natural circulation system in an ESBWR can be achieved by: 1) replacing a restricted downcomer with an unrestricted downcomer, i.e., opening up the restricted flow area in a conventional BWR (the jet pump suction in a jet pump BWR or the pump impeller passage in an internal pump BWR), and 2) optimizing the chimney height, active core length, and separator configurations. The natural circulation core flow can be increased significantly, as much as 100%, by replacing a restricted downcomer with an unrestricted downcomer, i.e., from roughly 23% rated with a restricted downcomer to roughly 46% rated with an unrestricted downcomer. Moreover, the natural circulation core flow can be further increased from 46% rated to over 70% rated with a flow margin at least 5% higher than the stability boundary flow at 100% rated power by optimizing the chimney height, active core length, and separator configurations.

Figure 2: Comparison between ESBWR and conventional BWR power/flow maps



3. Wide-blades Control Rod Conceptual Core Design Review[3]

An innovative wide-blades natural circulation BWR and a conventional natural circulation BWR equilibrium cores are designed using GE11 fuel to operate on a 12-month fuel cycle. The near-50% reduction in the number of control rod drives (CRD) makes the wide-blades natural circulation BWR economically very attractive, and there is no problem to provide an adequate cold shutdown margin even if a wide-blades control rod has higher reactivity worth. However, there is a small trade off between the cold shutdown margin and the cycle energy in the wide-blades natural circulation BWR core design.

For feasibility studies, the conventional natural circulation BWR and the wide-blades natural circulation BWR equilibrium core designs were developed to operate on a 12-month fuel cycle using the PANACEA 3D core design simulator[7]. The natural circulation BWR N-lattices core, which employs conventional control rods, is used here as the reference case for the natural circulation BWR F-lattices core that employs wide-blades control rods. A N-lattice fuel control cell is composed of four GE11 fuel assemblies subdivided by four control blades with one assembly in each quadrant, whereas a F-lattice fuel control cell is composed of 16 GE11 fuel assemblies subdivided by four two-times-wide control blades with four assemblies in each quadrant. The fuel designs were done using the fuel lattice design computer program TGBLA[8]. For comparison purpose, the rated core power used in this study is 3613 MW_{th} and the reload batch fraction is 0.194.

The conventional natural circulation BWR and the wide-blades natural circulation BWR cores have the same number of reload batch but different loading patterns and control rod patterns. The important design parameters for annual equilibrium cycles of the conventional natural circulation BWR and the wide-blades natural circulation BWR cores are summarized in Table 2. The design parameters of the wide-blades core are very close to those of the conventional core except that the number of control rod drives in the wide-blades core is only about one half of that in the conventional core. However, the cycle length of the wide-blades core design is slightly shorter than that of the conventional core design due to the lower hot excess reactivity. This represents a small trade off between the cold shutdown margin and the cycle energy.

All safety-related reactivity and thermal limits such as CSDM (cold shutdown margin), MLHGR (maximum linear heat generation rate), and MCPR (minimum critical power ratio) of both natural circulation BWR core designs satisfy the design criteria.

Table 2: Design parameters summary for annual equilibrium cycle of conventional and wide-Control-blades natural circulation BWR conceptual cores

Core Type	Conventional	Wide-Blades
Plant Thermal Power Rating, MWth	3613	3613
Effective Full-Power Days, EFPD	352	351
Overall Capacity Factor	96%	96%
Number of CRDs	269	137
Reload Batch, assemblies	220	220
Reload Batch Fraction	0.194	0.194
Initial Uranium mass (MT)	144.7	144.7
Cycle Exposure, GWd/MT	8.80	8.77
EOC Av. Exposure, GWd/MT	30.7	29.3
Max. Discharge Exposure, GWd/MT	47.1	46.8
Av. Discharge Exposure, GWd/MT	45.3	45.1

4. Top-entry Control Rod Conceptual Core Design Review[4]

The innovative top-entry control-rod core design takes advantage of additional space in the chimney area and reduces the plant size and cost for a natural circulation BWR. A BWR conceptual core design with top-entry control rods is shown feasible to meet the cycle energy, hot and cold reactivity margin, and other thermal limits by optimizing axial fuel Gd loading.

The core excess reactivity is mainly stored by insertion of control rods and use of burnable poison, gadolinia (Gd), throughout a cycle. The Gd is distributed with fresh fuel and provides globally and slowly varying, mild reactivity control, whereas the control rods provide local strong reactivity control. It has more advantage to maximize and optimize the use of Gd and to confine and simplify the use of control rods for BWR normal operations during a cycle. For example, the utilization of a control-cell core design is a very good case to illustrate this principle. For designing a BWR conceptual core with top-entry control rods, this principle can also be employed to optimize axial Gd loading and Gd utilization in order to overcome the difficulties associated with the severe bottom peak due to partially inserted deep control rods and un- or low-voided bottom in-channel water.

The axial Gd loading is mostly needed at the beginning and during the middle of cycle to balance out the local reactivity effect of partially top-inserted control rods. At the end of cycle, the control rods are withdrawn for providing additional reactivity to compensate fuel depletion and there is no need to use Gd to balance out partially top-inserted control rods. Consequently, the residual Gd should be minimized in the core design at the end of cycle.

A 15-month-cycle, equilibrium BWR conceptual core with top-entry control-rods and GE11 fuel is designed satisfactorily and the results are summarized in Table 3. All safety-related design parameters such as CSDM, MLHGR, and MCPR satisfy the design criteria.

Table 3: Design Summary for 15-Month Equilibrium-Cycle BWR Conceptual Core with Top-Entry Control Rods

Plant Thermal Power Rating, MWth	3926
Effective Full-Power Days, EFPD	416
Overall Capacity Factor	91%
Number of CRDs	205
Reload Batch, assemblies	200
Reload Batch Fraction	0.229
Initial Uranium mass (MT)	148.8
Cycle Exposure, GWd/MT	10.17
EOC Av. Exposure, GWd/MT	29.7
Max. Discharge Exposure, GWd/MT	46.9
Av. Discharge Exposure, GWd/MT	44.5

5. Conclusion

The conceptually reliable stability solution for inherently safe ESBWR operation has been developed by establishing a sufficiently high natural circulation flow line, which has a core flow margin at least 5% higher than the stability boundary flow at 100% rated power of a conventional BWR, and then by designing a high flow natural circulation system to achieve this high natural circulation flow line. The design of a high flow natural circulation system in an ESBWR can be achieved by replacing a restricted downcomer with an unrestricted downcomer and by optimizing the chimney height, active core length, and separator configurations. The ESBWR stability solution eliminates instability risk in reactor operation.

An innovative wide-blades natural circulation BWR core and a conventional natural circulation BWR equilibrium conceptual core have been designed to operate on a 12-month fuel cycle. The design parameters of the wide-blades core are very close to those of the conventional core except that the number of control rod drives in the wide-blades core is only about one half of that in the conventional core. The reduced number of control rod drives makes the wide-blades natural circulation BWR economically very attractive, but there is a small trade off between the cold shutdown margin and the cycle energy in the wide-blades natural circulation BWR core design.

An innovative BWR conceptual core design with top-entry control rods has been shown feasible to meet the cycle energy, hot and cold reactivity margin, and other thermal limits by optimizing axial fuel Gd loading. The top-entry control-rod core design takes advantage of additional space in the chimney area and, therefore, reduces the plant size and cost for a natural circulation BWR.

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