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Application of the N-Streaming^{SM} Concept to Peach Bottom 2 Cycle 17

Mehdi Asgari, David J. Kropaczek, and Christian C. Oyarzun

Global Nuclear Fuel – Americas
P.O.Box 780, M/C F12
Wilmington, N.C. 28402
Mehdi.Asgari@gnf.com
Dave.Kropaczek@gnf.com

James J. Tusar and Matthew M. Heverly
Exelon Corporation
200 Exelon Way, KSA 2-N
Kennett Square, PA 19348
james.tusar@exeloncorp.com
matthew.heverly@exeloncorp.com

Abstract

This paper discusses the application of the N-Streaming concept developed at Global Nuclear Fuel for the design of a Boiling Water Reactor (BWR) fuel cycle. The paper presents the N-Streaming concept and discusses the application of N-Streaming to the recent fuel cycle for Peach Bottom Unit 2 Cycle 17. It is demonstrated that the application of N-Streaming provides extra design freedom to optimize design margins allowing better operational flexibility while reducing the fuel cycle cost.

KEYWORDS: N-Streaming, Fuel Cycle, Core Design, and Optimization

1 INTRODUCTION

An N-Streaming^{SM} concept[1] developed at Global Nuclear Fuel is applied to the design of the Peach Bottom 2 Cycle 17 fuel cycle. N-Streaming [1] is a new approach to Boiling Water Reactor (BWR) design that is characterized by the use of standardized fuel rod types to design a multitude of complex bundle designs, which may then be used to improve fuel cycle efficiency. The process of improvement is achieved through a local / global approach, whereby, local constraint problems are fixed by localized bundle changes followed by local / global changes that target fuel cycle energy.

2 BACKGROUND AND N-STREAMING CONCEPT

The current design of BWR fuel bundles is performed in an iterative process with the core loading and rod pattern design utilizing customer criteria as input, which includes plant cycle energy requirements, thermal and operational limits, shutdown margin, etc. The bundle design can be broken down into two components: the design of the fuel rods (i.e., axial zoning of enrichment and gadolinium) and the radial placement of the rods within the bundle lattice. During the iterative process of designing the fuel bundle, either one or both of the two components may be targeted for modification in order to address specific customer criteria. The result is that each customer bundle design can be thought of as “customized” to provide maximum economic and operational performance for a given plant cycle.

The number of unique fresh fuel bundles within a design refers to the number of streams. Thus, a single-stream design utilizes one unique bundle; a two-stream design utilizes two unique bundles; and so on. Because of the amount of effort involved in developing a given customized bundle, current practice is typically limited to one or two streams for a given fuel cycle.

To understand why N-Streaming has such benefits to the fuel cycle, one must look at the characteristics of current fuel cycle designs. Each design is characterized by a set of independent variables including fresh fuel bundle design, fresh fuel and exposed fuel placements, control blade placements (as a function of time) – both blade location and axial position, core flow, and control blade sequence exchange times. The outputs for a given design are such parameters as eigenvalue, thermal limits, and shutdown margin, which are both time dependent and spatially dependent. Each of these output parameters, at every time and spatial point, must be below a constraint limit that is set by operational and safety concerns. When one examines a fuel cycle design solution, it is found that, in general, a given design is limited by only a few parameters out of thousands of parameters that have the potential to violate the design constraints. For example, a solution may have a Maximum Fraction on Limiting Critical Power Ratio (MFLCPR) location at end-of-cycle (EOC) at its design limit while all other values of MFLCPR have values that are substantially below their design limits. Similarly, shutdown margin may be limited by a single location at beginning-of-cycle (BOC).

N-Streaming is a new concept in the bundle design and manufacturing process that allows any number of bundle streams within a fuel cycle design, so long as the fuel rod types comprising each of the ‘N’ bundle designs are selected from a standard palette of pre-specified fuel rod types. At a minimum, N=1 refers to a single stream solution. At a maximum, N=number of fresh fuel assemblies to be loaded in the fuel cycle (i.e., every fresh bundle is unique).

N-Streaming allows the user to target specific ‘problem’ locations in a fuel cycle design in a systematic manner by perturbing one or several fresh fuel bundles within the solution. For example, to ‘fix’ a shutdown margin problem, one might simply exchange a fresh fuel bundle in the problem location for a fresh bundle containing more gadolinium content (by 'fix', it is implied that a limiting location is made non-limiting with some level of margin to the constraint limit). To fix an LHGR problem, one might target the problem location with a fresh fuel bundle containing axial gadolinia zoning changes to shift the axial power profile locally. By targeting and fixing specific problem locations, it is then possible to capitalize on the excess margins on other locations or to make global changes to the design (such as a global fresh enrichment change) that target cycle energy. As a result, well-optimized enrichment and gadolinium distributions will be inherent in the N-Streaming core design. Such designs maximize the cycle energy by minimizing the gadolinium residual without violating reactivity and thermal design constraints.

The deployment of the N-Streaming concept is facilitated by the use of the ePrometheus™ system[2] [2], which performs optimization of the fresh fuel bundle designs, exposed fuel loading, control rod patterns, sequence exchanges and core flow throughout a BWR fuel cycle. Within the ePrometheus system, tens of thousands of design solutions are examined as part of an optimization search algorithm [3] that readily incorporates fresh bundle design as an independent variable.

3 PEACH BOTTOM 2 CYCLE 17 DESIGN

The N-Streaming concept is being applied for the first time to the Peach Bottom Unit 2 Cycle 17 core design. Peach Bottom Unit 2 is a 764 bundle size core with full GE14 fuel and has been operating with a pseudo-equilibrium energy utilization plan with a typical fresh fuel batch size of 276 or 280 loaded during the last few cycles. These batch sizes were achieved through well-optimized two stream bundle and core designs during multi cycle analyses.

The current cycle under design as well as the two successive follow-on cycles are targeted for further cycle efficiency improvement and fuel cycle cost reduction utilizing the N-Streaming concept. To implement N-streaming, several fresh fuel bundle designs were created for each cycle through a series of fuel rod type perturbations to maximize cycle efficiency while meeting all reactivity and thermal design limits, such as hot excess reactivity and critical power ratio.

The final Cycle 17 design consists of six different streams. The bundle designs are different in enrichment distribution, number of gadolinium rods, gadolinium concentration, and axial shaping. Each stream was designed to specific characteristics to target certain problems while minimizing gadolinium residual and maximizing cycle efficiency. The final batch size for Peach Bottom Unit 2 Cycle 17 with six streams is 272 bundles compared to the previous estimate of 280 bundles for this cycle or the 276 bundles during previous cycles. A saving of eight bundles relative to the previous estimates for Cycle 17.

Figures 1 and 2 present the core loadings in terms of the fresh and exposed fuel types for the Cycle 16 two-stream design and Cycle 17 N-Streaming design, respectively. Shown are the BOC bundle average exposure values (giga-Watt Days per short-Ton) and the bundle design identifier (IAT). As shown, the N-Streaming design is a six-stream design.

Tables 1 and 2 present the characteristics of the bundles loaded in Cycles 16 and 17, respectively. The tables show for each cycle the inventory of fresh bundle designs and their characteristics as defined by: 1) IAT identifier, 2) the number of unique fuel rod designs, 3) the number of unique gadolinium containing fuel rod designs, 4) the number of gadolinium containing fuel rods, 5) the average concentration of gadolinium by weight across the gadolinium containing fuel rods, 6) the average uranium enrichment, and 7) the number of bundles loaded. As shown in these two tables, one can design multiple numbers of different bundle types from a set of unique rod designs to maximize fuel utilization and cycle efficiency. The six stream reload for Cycle 17 has almost the same number of total rod designs as the two stream reload in Cycle 16. The fresh fuel average enrichment for both cycles are identical whereas the average number of unique fuel rod designs and gadolinium concentration in Cycle 17 are lower than Cycle 16. The elimination of the excess gadolinium and the flexibility of loading certain unique bundle designs in different regions of the core resulted in improved fuel utilization and cycle efficiency thus reducing fuel cycle cost. An eight fresh bundle improvement was also realized in the follow-on two cycles, demonstrating a sustained decrease in fuel cycle costs.

Figures 3 through 5 present the comparison of the minimum Shutdown Margin (SDM), Critical Power Ratio (CPR) and Maximum Fraction of Limiting Power Density (MFLPD) as a function of cycle exposure, respectively, for Peach Bottom Unit 2 Cycles 16 and 17. As shown, all thermal and reactivity margins were maintained for each design, although it is evident that the excess SDM was used to compensate for the reactivity loss due to the elimination of the 8 fresh bundles. The application of N-Streaming for this cycle allowed the designers to gain extra margins where necessary while reducing the excess margins to maintain or to improve operational flexibility and reduce overall fuel cycle cost.

4 SUMMARY

The N-Streaming concept is shown to significantly improve fuel cycle costs and core loading efficiencies. For the Peach Bottom 2 Cycle 17 fuel cycle, a benefit of 8 reload bundle savings at an equivalent enrichment is realized when compared with previous estimates. The N-Streaming concept provides opportunities to pursue expansive alternate design strategies by capitalizing on the efficiency gains through N-Streaming to offset any increased fuel cycle cost.

ENDNOTES

[1] N-Streaming^{SM} is a servicemark of Global Nuclear Fuel – Americas LLC

[2] ePrometheus^{TM} is a trademark of Global Nuclear Fuel – Americas LLC

REFERENCES

[1] Asgari, M., Kropaczek, D.J. and Tusar, J.J., "N-Streaming Concept for Boiling Water Reactor Fuel Cycle Design," *Trans. Am. Nucl. Soc*, San Diego (2005).

[2] Oyarzun, C.C, et. al.," The GNF Optimization System for BWR Fuel Cycle Management," *Proc. Topical Meeting on Advances In Fuel Management II-118*, Hilton Head, (2003).

[3] Kropaczek, D.J. and Russell, William E., "Method for Optimization of BWR Fuel Management and Plant Operations" *Proc. Topical Meeting on Advances In Fuel Management II-117*, Hilton Head, (2003).

Table 1. Characteristics of Cycle 16 Reload

IAT	Total Number of Rod Designs	Number of Gad Rod Designs	Number of Gad Rods In Bundle	Avg. Gad Concentration	Avg. Uranium Enrichment	Number of Bundles Loaded in Core
12	17	4	15	7.23	4.15	188
13	17	5	16	7.87	4.16	88
Total for Reload	19	7	15.32 (Avg.)	7.43	4.15	276

Table 2. Characteristics of Cycle 17 Reload

IAT	Total Number of Rod Designs	Number of Gad Rod Designs	Number of Gad Rods In Bundle	Avg. Gad Concentration	Avg. Uranium Enrichment	Number of Bundles Loaded in Core
2	18	5	15	7.26	4.16	56
3	14	2	13	6.00	4.17	32
4	16	4	15	7.67	4.15	48
5	18	5	15	6.93	4.16	64
6	17	4	15	7.27	4.16	40
7	17	4	15	7.67	4.09	32
Total for Reload	21	7	14.76 (Avg.)	7.16	4.15	272

Figure 1. Peach Bottom 2 Cycle 16 Core Design (2 Stream, 276 Fresh Batch Size)

Exposure (GWD/sT)

Bundle Type (IAT)

								38.88 20	38.11 1	37.87 1	37.84 1	37.41 1	37.39 1	37.17 20
							38.47 20	37.98 20	34.71 20	33.98 1	33.42 20	32.18 1	32.70 1	31.73 1
					38.16 1	38.31 20	37.16 20	33.90 1	31.70 20	31.10 1	20.78 11	19.55 11	19.69 11	21.88 11
					37.99 1	37.15 20	20.16 11	18.93 10	19.04 11	17.48 10	18.83 10	0.00 12	0.00 12	0.00 12
				36.99 20	35.05 1	30.95 1	20.24 11	18.31 10	0.00 12	19.75 10	0.00 12	20.08 10	0.00 12	18.56 10
		38.18 1	38.87 20	35.03 1	20.04 11	21.31 11	20.95 10	0.00 13	0.00 12	0.00 12	0.00 12	0.00 12	0.00 12	0.00 12
		38.28 20	37.14 20	30.96 1	21.85 11	21.33 11	0.00 13	0.00 12	0.00 12	20.69 10	0.00 12	18.87 10	0.00 13	21.72 10
	38.40 20	37.18 1	21.19 11	19.99 11	20.90 10	0.00 13	0.00 12	0.00 12	21.70 10	0.00 12	19.97 11	0.00 12	20.66 11	0.00 13
38.87 20	37.26 20	33.90 1	18.93 10	21.31 10	0.00 13	0.00 12	0.00 12	21.09 10	0.00 12	21.05 11	0.00 12	19.94 11	0.00 13	21.79 11
38.04 1	34.70 20	31.71 20	19.02 11	0.00 12	0.00 12	0.00 12	21.71 10	0.00 12	21.42 10	0.00 12	19.38 10	0.00 12	18.19 10	0.00 12
37.90 1	33.98 1	31.10 1	17.47 10	19.71 10	0.00 12	20.67 10	0.00 12	21.02 11	0.00 12	21.24 10	0.00 13	21.50 10	0.00 13	21.45 11
37.83 1	33.37 20	20.71 11	18.82 10	0.00 12	0.00 12	0.00 12	19.96 11	0.00 12	19.37 10	0.00 13	21.64 11	0.00 12	21.22 11	0.00 12
37.37 1	32.17 1	19.47 11	0.00 12	20.06 10	0.00 12	18.86 10	0.00 12	19.67 11	0.00 12	21.46 10	0.00 12	20.05 11	0.00 13	21.23 11
37.42 1	32.70 1	18.53 11	0.00 12	0.00 12	0.00 12	0.00 13	20.81 11	0.00 13	18.17 10	0.00 13	21.16 11	0.00 13	20.24 11	0.00 13
37.12 20	31.72 1	21.92 11	0.00 12	18.53 10	0.00 12	21.73 10	0.00 13	21.79 11	0.00 12	21.30 11	0.00 12	21.23 11	0.00 13	21.13 10

Figure 2. Peach Bottom 2 Cycle 17 Core Design (6 Stream, 272 Fresh Batch Size)

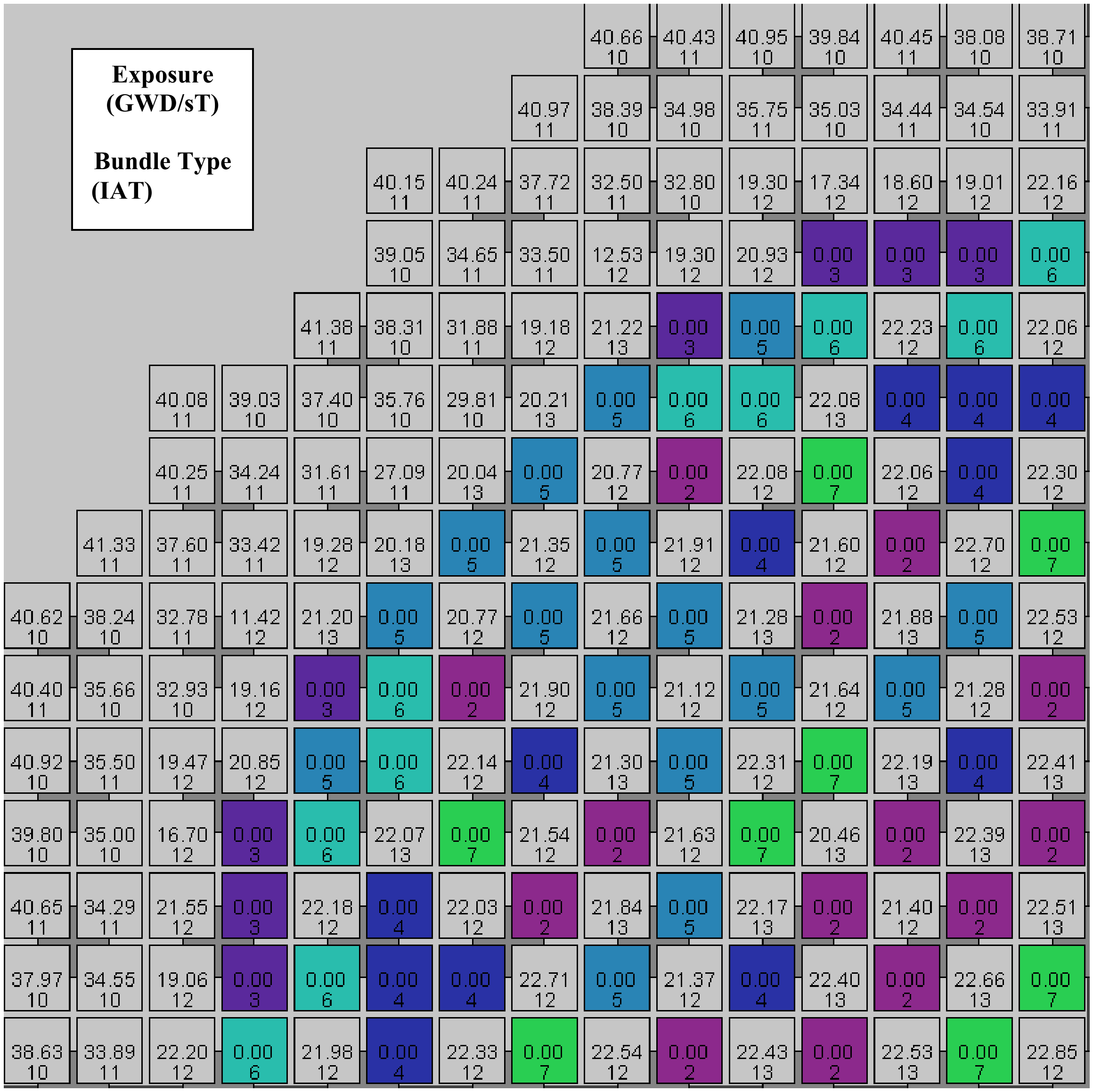

Figure 3. Comparison of the Minimum Shutdown Margin (SDM)

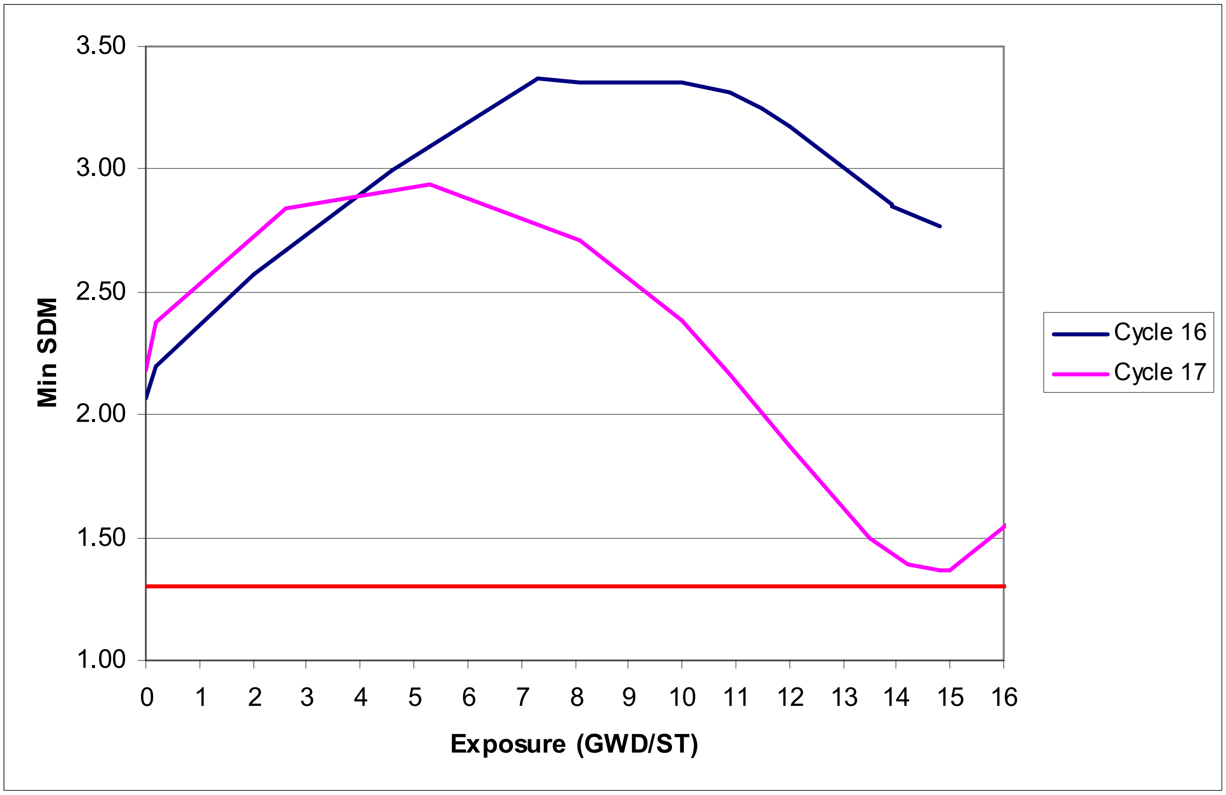

Figure 4. Comparison of the Critical Power Ratio (CPR)

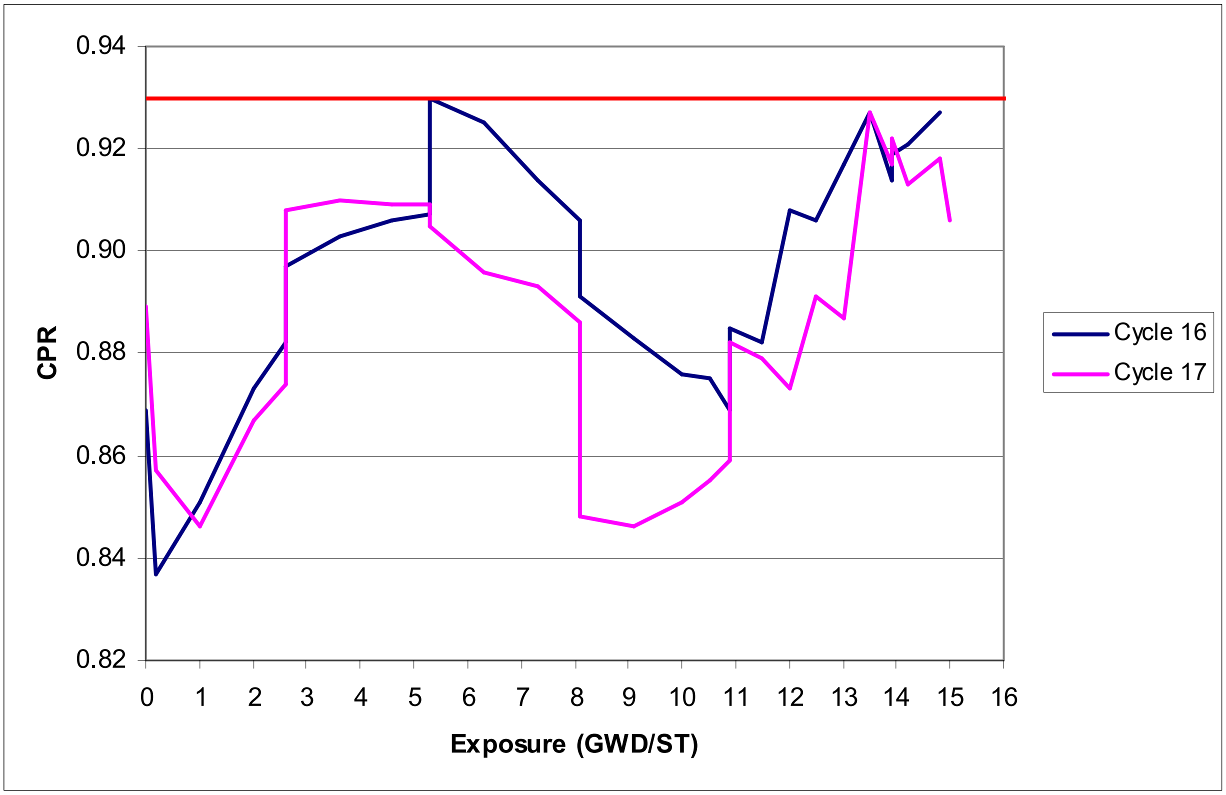

Figure 5. Comparison of the Maximum Fraction of Limiting Power Density (MFLPD)