A 48-MONTH EXTENDED FUEL CYCLE FOR THE B&W mPower™ SMALL MODULAR NUCLEAR REACTOR

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ABSTRACT

The B&W mPower™ reactor is a small, rail-shippable pressurized water reactor (PWR) with an integral once-through steam generator and an electric power output of 150 MW, which is intended to replace aging fossil power plants of similar output. The core is composed of 69 reduced-height, but otherwise standard, PWR assemblies with the familiar 17x17 fuel rod array on a 21.5 cm inter-assembly pitch. The B&W mPower core design and cycle management plan, which were performed using the Studsvik core design code suite, follow the pattern of a typical nuclear reactor fuel cycle design and analysis performed by most nuclear fuel management organizations, such as fuel vendors and utilities. However, B&W is offering a core loading and cycle management plan for four years of continuous power operations without refueling and without the hurdles of chemical shim.

Key Words: fuel management, extended fuel cycle, B&W mPower, advanced reactor designs, SMR

1. INTRODUCTION

The B&W mPower reactor is a simplified pressurized water reactor that uses an integral arrangement in which the reactor core, steam generator and pressurizer are combined into a common pressure vessel. The reactor core comprises 69 fuel assemblies, loaded in a 21.5 cm square pitch octant mirror-symmetric configuration and designed to meet the energy requirements of a 4-year "once-through" fuel cycle – i.e. there is no refueling and no shuffle of fuel assemblies during the cycle. The rated power output is 150 MWe, and the overall cycle capacity factor is 95%.

The B&W mPower reactor concept design does not use chemical shim (soluble boron) for reactivity control during normal operation. This results in a large negative moderator temperature coefficient of reactivity, which provides a strong inherent reactivity control mechanism, similar to a boiling water reactor (BWR).

Reactor coolant pressure is maintained by an electrically heated pressurizer, located above the steam generator, providing for stable operation and pressure response during all operating conditions. Reactor bulk coolant temperature is maintained below the saturation point, such that

there is no boiling in the core; this results in an approximately 32 °F subcooling at the core outlet.

The power density of the B&W mPower reactor core is approximately 65 kW/liter, significantly lower than the power density of a large domestic PWR. Core reactivity is controlled by 61 fine-motion control rod assemblies (CRAs).

Since the B&W mPower reactor uses control rods rather than soluble boron to suppress excess reactivity and has a rather low power density for a PWR, the nuclear fuel cycle design and management approaches, in some respects, that of a proven BWR fuel cycle.

The B&W mPower core loading was designed concomitant with the fuel assemblies to meet applicable design criteria, as well as reactivity and control requirements. The design parameters presented in Section 2.1 were all addressed to comply with the industry accepted and NRC approved safety and energy criteria.

2. FUEL CYCLE DESIGN AND REACTIVITY MANAGEMENT STRATEGIES

The B&W mPower 4-year once-through fuel cycle design was optimized for a number of competing parameters. The assembly enrichments and the loading pattern must provide sufficient reactivity for the cycle to achieve the desired energy, while also being constrained to meet technical specifications and other limits which include, but are not limited to, margin to thermal limits, cold shutdown margin (CSDM) capability, hot excess reactivity (HEX) (needed to overcome xenon transients during power ascension), shuffling limitations (if a shuffle core is designed) and linear heat generation rate LHGR ramp rate limitations designed to protect the fuel from PCI (pellet-clad interaction) during power maneuvering.

The fuel cycle design capitalizes on the value of some "hidden variables", of which probably the most obvious example is the optimum power shape spectral shift effect. This phenomenon, specific to boiling water reactors and characterized by undermoderation during the first half (or so) of the cycle, is also present in the unborated, rodded B&W mPower core – albeit the undermoderation is achieved in a different manner.

When a control rod assembly is withdrawn, the guide tubes are filled with water, thus neutron moderation is increased and fuel utilization improved. In the controlled fuel assemblies, the interior fuel pins are undermoderated, as guide tubes now host the control rod fingers. The resulting increased resonance region neutron flux results in the increased conversion of U-238 to fissile Plutonium. The undermoderation in controlled fuel bundles also acts in the direction of reducing reactivity in those areas, where neutrons are already lost by absorption in control poisons. As the fuel cycle advances and the initially loaded fuel (U-235) is consumed, the fissile atoms formed by the previous conversion process (Pu-239 and Pu-241) now contribute to energy production.

The target rod patterns need to provide a balance between maximizing the fuel utilization and the benefits of spectral shift operations without resulting in an end of cycle (EOC) axial power shape that is disadvantageous for operating limits and/or nodal peaking (axial power shape is preferred to be as center-peaked as possible, as opposed to top-peaked, a power profile that all rodded cores tend to exhibit towards the end of cycle, when all the control rods are fully withdrawn).

The core operations must, at all times, be bound by the licensing bases. The fuel assemblies in the core must not be allowed to exceed prescribed or licensed exposure limits. These include limits on the peak rod exposure, peak pellet exposure or maximum assembly average exposure.

The relatively low power density of the B&W mPower reactor allows peak LHGR (kW/ft) to remain well below (4 kW/ft on avearge) what is typical for a large PWR while suppressing as many as 9 bundles with deeply inserted control rods at peak hot excess. The control rods are divided into four mutually exclusive groups for power regulation. Individual members of a group may be ganged and moved in unison, or moved individually if necessary, in a manner very similar to the BWR reactivity management strategy. In operation, full power is maintained with movement of a rod pattern subset ("floater rods") and turbine load follow maintaining core inlet temperature within a tolerance band. Over much of the cycle the power-trimming rod insertion/withdrawal rate is on the order of centimeters per week for the two or four rods typically used in the "floater" subset.

2.1. Core Design Parameters

The B&W mPower fuel cycle design is performed based on industry verified and accepted safety criteria and also on other goals and assumptions, which can be classified under the following types of parameters:

(A) Design parameters (fuel bundle and core):

1. Core dimensions (total number of fuel assemblies);
2. Fuel assembly mechanical design and dimensions (height, assembly pitch, number of fuel rods in the square lattice, pin pitch);
3. Reactor core thermal output;
4. Reactor coolant flow;
5. Reactor operating/dome pressure.

(B) Energy parameters:

6. Cycle length – 48 months (including a 30 day outage);
7. End of cycle energy – 1400 Effective Full Power Days (EFPD);
8. Cycle capacity factor – 95%.

The bundle design and the core loading are performed in an iterative manner such that there is sufficient excess reactivity in the core to achieve the required cycle energy, while at the same time all the safety and fuel efficiency criteria are met. This usually translates into a minimum hot excess reactivity value at beginning of cycle (BOC). At the very least

1.0%Δk/k excess reactivity should be available at BOC and maintained throughout most of the cycle – a lesser value would not provide the cycle with the required energy.

(C) Safety parameters:

9. Minimum Cold Shutdown Margin (CSDM) – 3% (Δk/k);
10. Maximum nodal peaking – 2.0;
11. Minimum Departure from Nucleate Boiling Ratio (DNBR) – 1.3 (under steady state operations, DNBR is consistently above 2.0);
12. Maximum average exposures for assembly, node and pellet equal (or lower) to industry established values.

(D) Control parameters for power operations:

13. Parked control rod position (insertion in core);
14. Maximum exposure between control rod pattern sequence exchanges;
15. Control rod utilization.

For fuel efficiency reasons, as well as for axial peaking management, it is preferable to avoid operating a rodded core with "shallow" parked control rods for an extended period of time. Rod insertion is defined as "shallow" for the first third of the rod length, "intermediate" for the 1/3 to 2/3 of rod length inserted, while "deep" is an insertion of 2/3 to 3/3 of the rod length. Keeping the rod insertion within the deep and intermediate range as much as possible (i.e., burning the entire core "more evenly" and the top of the core "better") provides better manageability and a better axial power profile. This preference pertains to parked rods only.

The last two control parameters above (14 and 15) are used to optimize both fuel burnup and control rod utilization. The control rods perform dual functions of power distribution and shaping – on one hand – and reactivity control – on the other hand. Power distribution in the core is controlled during cycle operation by manipulation of selected patterns of rods. Rotating the control rod groups (patterns) used during the cycle and using the rods in a scattered manner ensure a more evenly distributed control rod depletion as well as a flatter radial power distribution. Employment of a group of control rods for an extended period of time (i.e., controlling some fuel assemblies for too long) results not only in undesirable peaking in the controlled fuel assemblies after the control rods are withdrawn, but also in reduced lifetime of the control assemblies. The absorber in the control rod assemblies is "AgInCd" (AIC), the same type which is extensively used in the commercial PWRs. AIC, as fabricated, contains nominally 80 wt% Ag, 15 wt% In and 5 wt% Cd and it is a single-phase alloy.

While studies to specifically assess the mPower control rod assemblies lifetime are currently underway, the mechanism of AIC rod degradation is well understood and largely attributed to swelling due to metallurgical changes in the absorber under irradiation (depletion of Ag and In, but enrichment of Sn and Cd). This ultimately translates to a diametral swelling of the absorber rod. Over time, the gap between the absorber and the cladding closes, which may lead to cladding fracture and possibly control rod-to guide tube interference (i.e., slow drop time, incomplete rod insertions, etc.).

Generally, the CRAs in the main control bank of a typical PWR, which are inserted into the fuel region during operation, have a 2-3 cycle lifetime. The mPower CRAs expected lifetime is two 48-month cycles (based on accumulated exposure).

2.2. Fuel Assembly Design

The 17x17 lattices include several types of pins (Figure 1):

1. UO_2 fuel pins of different enrichments – variable number of pins per lattice;
2. Integral burnable poison fuel pins, $UO_2 – Gd_2O_3$, of different enrichments and Gd_2O_3 concentrations – variable number of pins per lattice;
3. Burnable poison pins (BPR), of different absorber concentrations– variable number of pins per lattice;
4. 24 guide tubes (non fuel) – fixed number per lattice;
5. 1 central instrument tube.
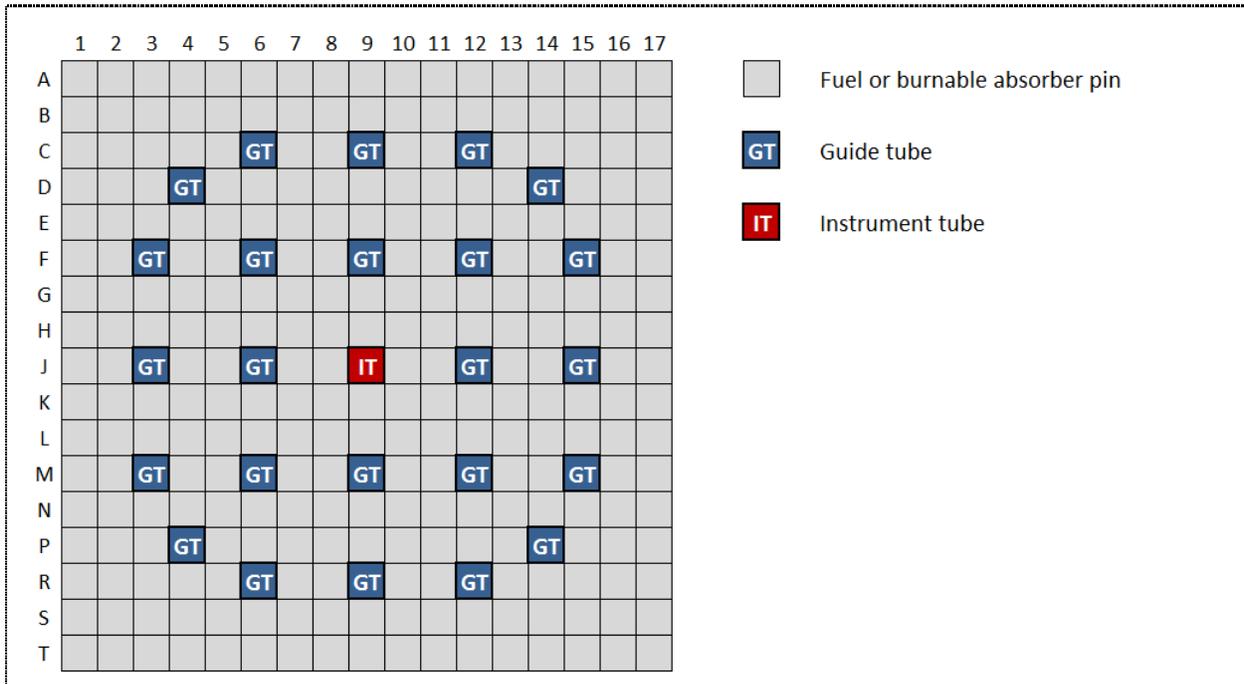
Figure 1. Fuel lattice layout

The fuel lattices were designed so that the radial pin-by-pin power distribution (peaking) within the lattice, as well as the reactivity changes with time (lattice k-inf) will be as flat as possible.

The pellet enrichments employed in the mPower fuel design are standard pellet enrichments used in the nuclear commercial world, with U-235 wt% up to 4.95. The gadolinia concentration in the UO_2-Gd_2O_3 fuel pellets is also the same as the rest of the nuclear power plants use, with Gd_2O_3 concentrations up to 6%. End lattices are lower enriched, but not natural blankets.

Figures 2 and 3 present some of the lattice k-infinities and lattice peaking factors for lattices employed in the B&W mPower core design.
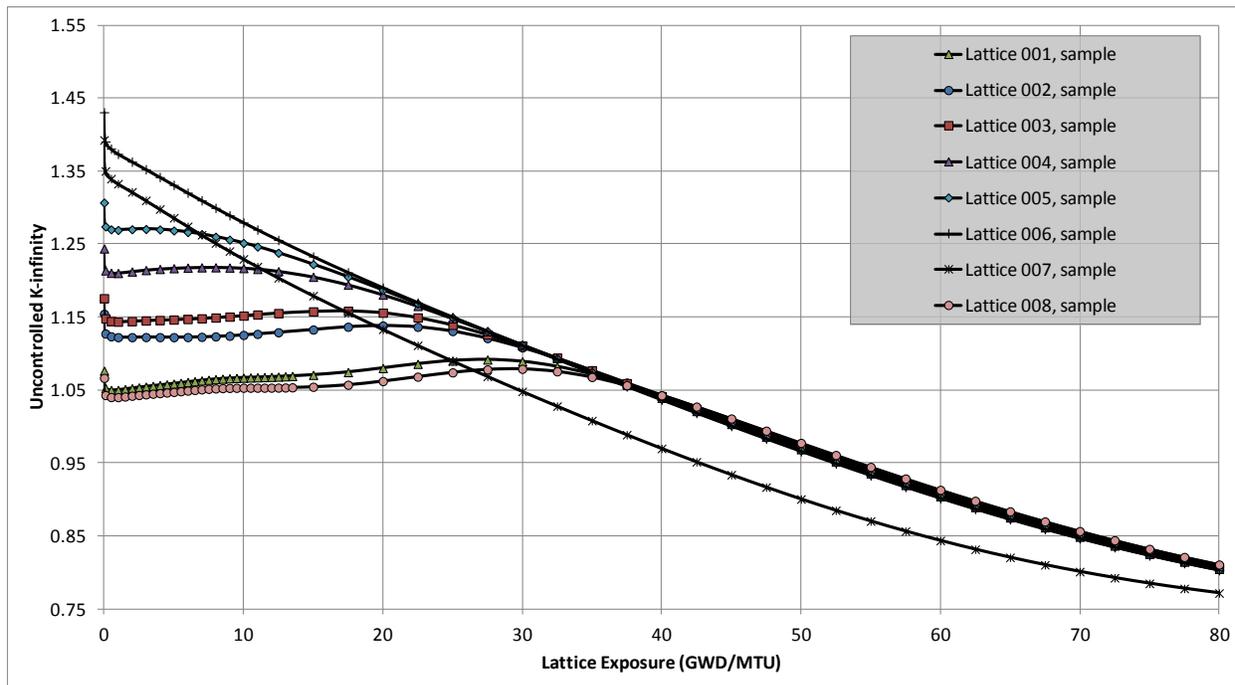

Figure 2. Sample lattice uncontrolled hot k-inf
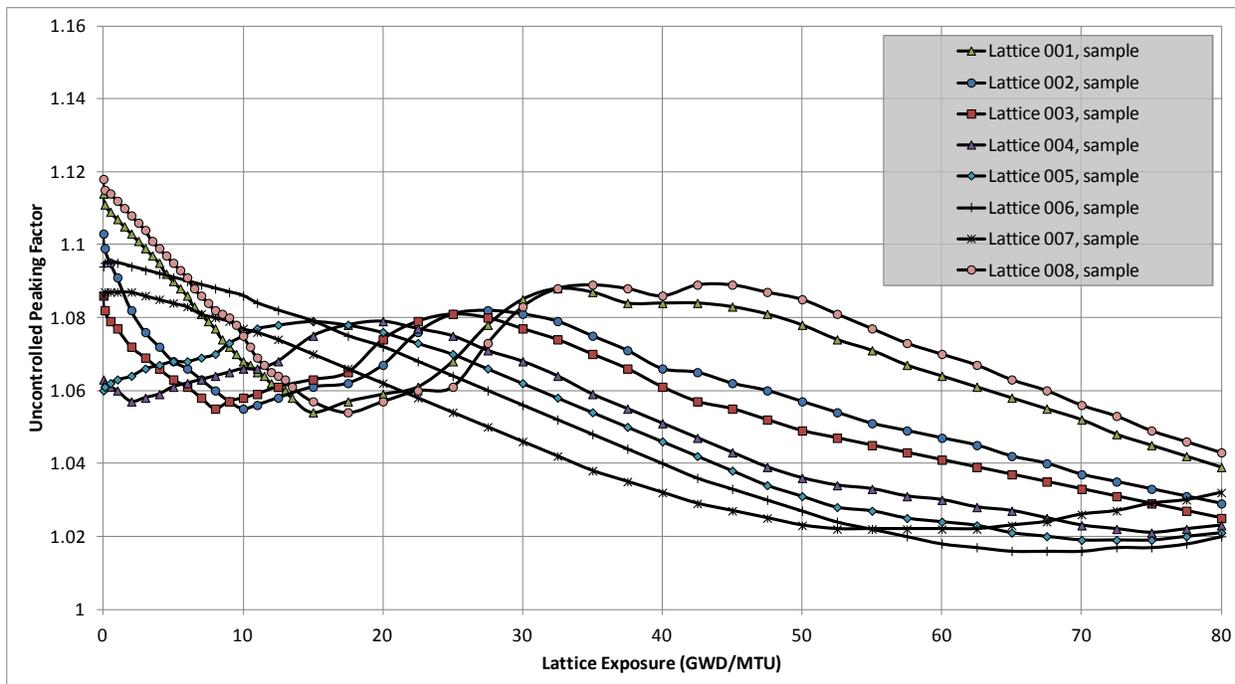

Figure 3. Sample lattice uncontrolled hot peaking factors

A flat pin-by-pin power distribution ensures a more evenly burnt fuel, whereas a flat lattice reactivity allows core operations with minimal control rod adjustments.

Fuel pins may have axially varying Gd_2O_3 content and BPR pins may have axially varying poison content, but UO_2 and BPR materials are never combined in a single pin. The number, layout and content/enrichment of the fuel rods and burnable poison rods are specific to each neutronic fuel type. Several combinations of different fuel pin enrichments and poison concentration and number of pins were used in the B&W mPower fuel assembly design to extend the overall cycle energy, to optimize safety parameters and to maximize fuel utilization.

Fuel assemblies (several types) were developed and loaded in the reactor core in an eighth-symmetric manner and further optimized to work in concert with the control rod sequences and to fit the specific axial and radial conditions of their location in the core. Figure 4 presents schematically the philosophy behind the B&W mPower fuel assembly design.
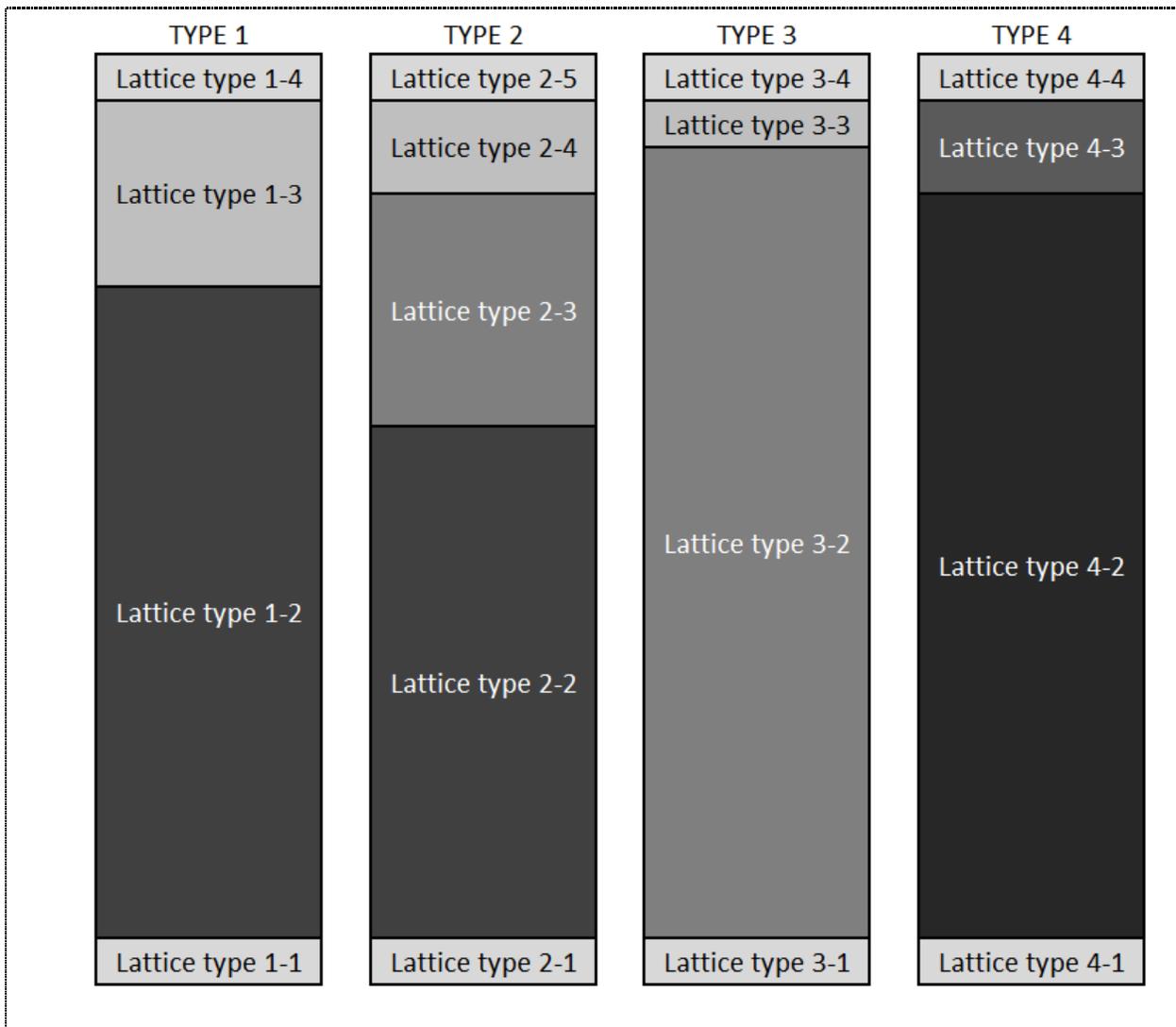

Figure 4. Sample fuel assembly axial layout

2.3. Core Loading Pattern

The fuel assemblies are loaded in the reactor in a manner consistent with the assemblies' axial design, so that they perfectly fit the specific radial conditions of their location in the core and they provide the maximum benefit from cycle energy and fuel utilization point of view, without any impact on safety parameters.

The loading of the B&W mPower fuel, as described in this report, results in a projected cycle full power energy capability of 590.75 GWd (35.25 GWd/MTU). Beyond the full power capability, the B&W mPower core can achieve additional energy via power coastdown operation.
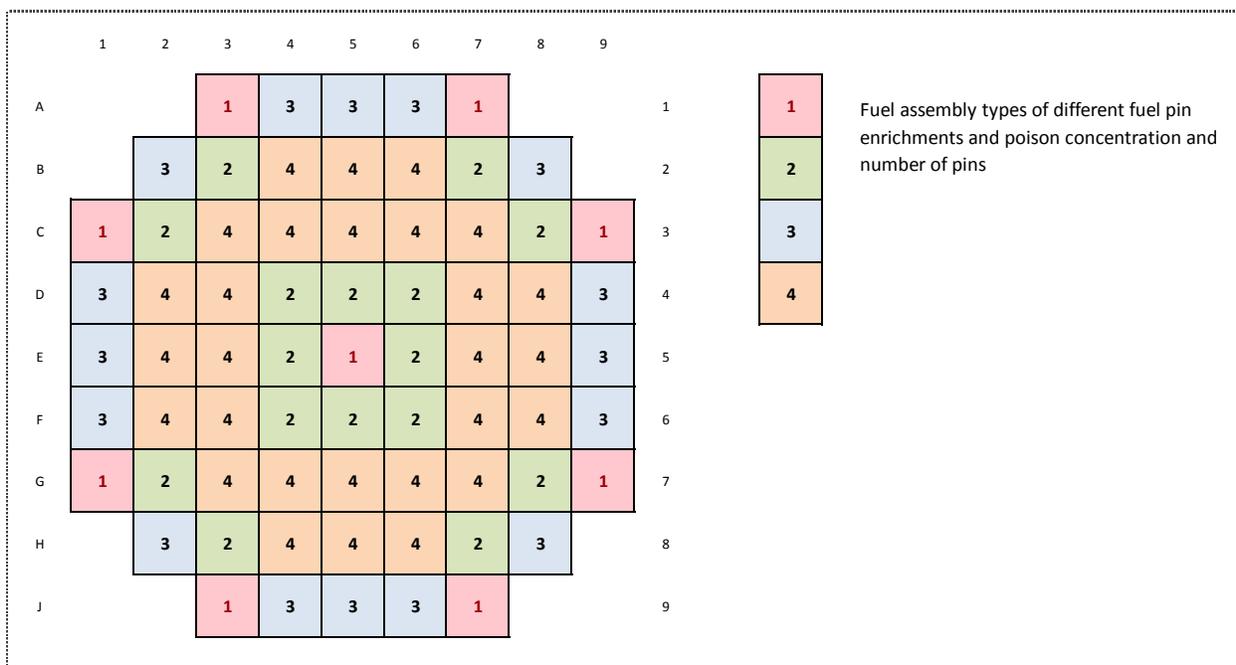
Figure 5. Sample core loading of the B&W mPower reactor core

2.4. Reactivity Management Strategy of the B&W mPower Reactor

During normal reactor operation, control rods are inserted to balance the excess reactivity in the core. When inserted, a control rod assembly perturbs the local power shape; subsequently, the exposure accumulation will differ between neighboring fuel assemblies as well as between different axial nodes of the same fuel bundle. When previously controlled nodes are again "uncovered", the fuel pins will run at higher peaking factors than in an uncontrolled scenario, and at an increased local heat generation rate. The magnitude of the peaking depends on the length of the control interval, the frequency of the control intervals and the lattice design.

To minimize these negative aspects, the control rod history effects can be minimized by simply reducing the control frequency and the exposure interval over which a fuel node/assembly is controlled. For this purpose, the CRAs were grouped in a manner similar to that in a BWR core

into two main control rod patterns, A and B, distributed in a checkerboard pattern, as shown in Figure 6. Several control rod sequences are used throughout the cycle, so that each bundle is controlled (totally or partially) for a total of approximately six months out of the cycle.
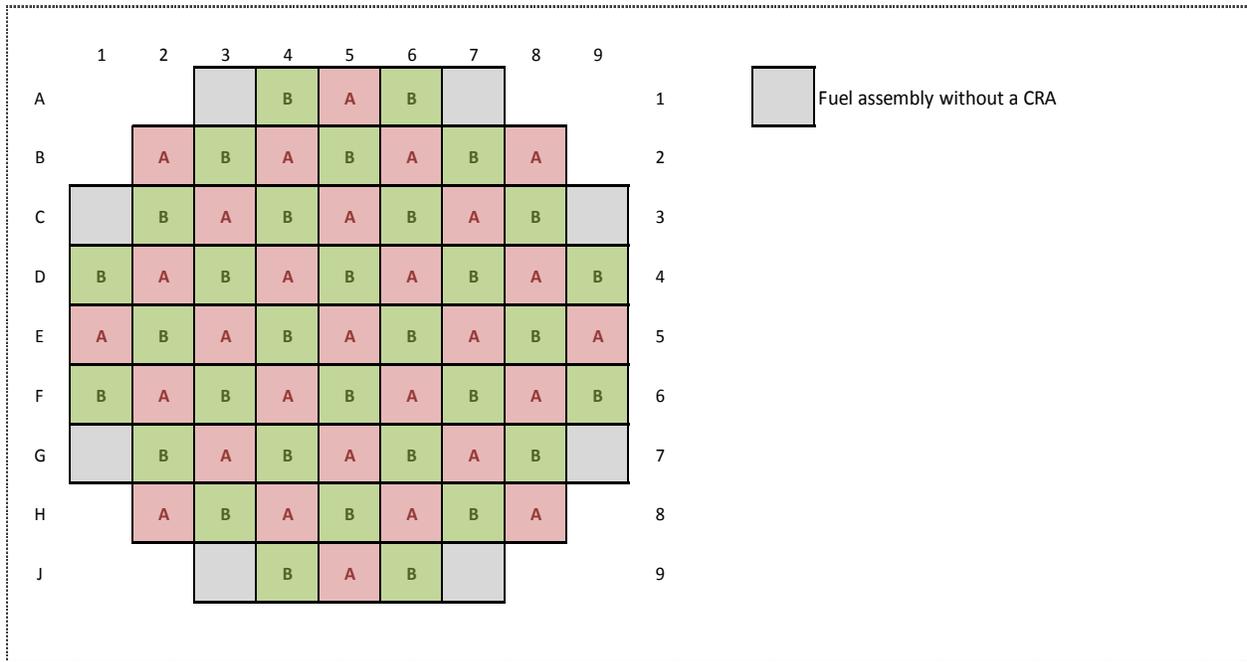

Figure 6. The two main control rod sequences used with the B&W mPower core

2.5. B&W mPower Reactor Core Performance Indicators

2.5.1. Core average peaking factors, axial offset and axial power and exposure distributions

The axial and radial power and exposure distributions, along with the core axial offset and the nodal and radial peaking factors are means to assess the core performance and margin to safety limits. It is always desired that the axial and radial distributions of parameters that show the performance of the core, quantitatively and qualitatively, be as flat as reasonably achievable.

Axial offset (core average) is defined as the percent difference between the power generated in the upper and the lower halves of the core:

$$\text{Axial Offset} = (P_t - P_b) / (P_t + P_b) \times 100$$

where P_t and P_b are the integrated powers (sum of calculated nodal powers) in the top and bottom halves of the core, respectively.

Nodal peaking values represent the highest bundle planar power, at a given exposure, normalized to the core average power. Since a fuel lattice is defined with four nodes, the planar bundle power represents the "collapsed" power in the four nodes.

Figure 7 summarizes the axial offset and the radial and nodal peaking factors of the B&W mPower reactor core throughout the cycle. Figure 8 illustrates the axial power and exposure distributions at three points in core life: beginning (BOC), middle (MOC) and end of cycle (EOC).
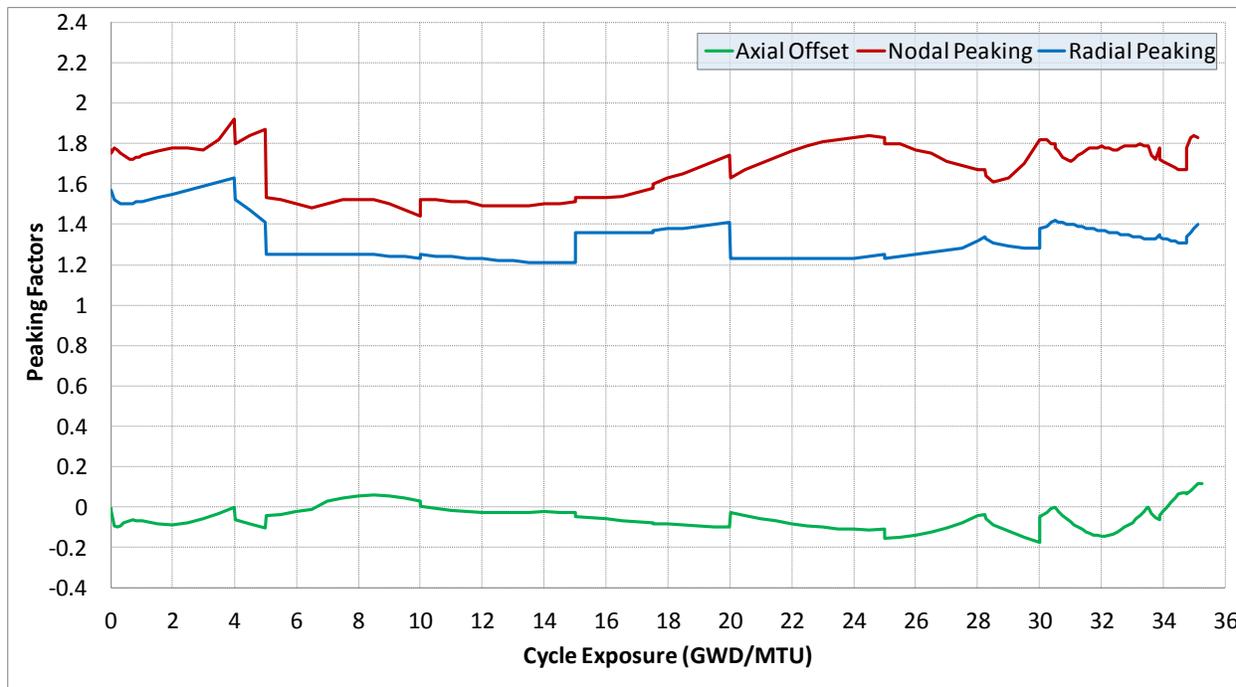

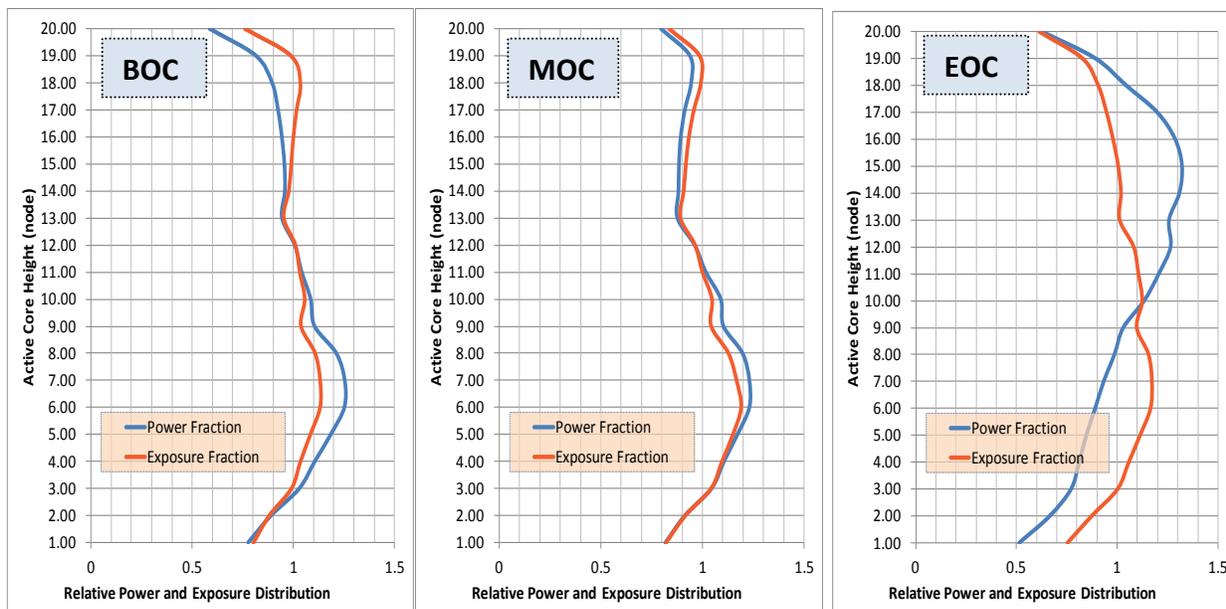**Figure 7. Axial offset, nodal and radial peaking factors of the B&W mPower core**

Figure 8. Axial power and exposure distributions of the B&W mPower core

2.5.2. Cold shutdown margin (CSDM)

The shutdown margin (SDM) is defined as the amount of reactivity, expressed in % Δ k/k, by which the reactor is subcritical with the analytically determined maximum worth control rod assembly assumed stuck in the fully withdrawn position and all other assemblies fully inserted. The cold shutdown margin (CSDM) is the level of core subcriticality at 68 F°, atmospheric pressure and xenon-free conditions (the three parameters that define the "cold" state) with the strongest CRA out. CSDM is calculated with SIMULATE-3 by running 1-rod-out cases, at cold conditions, restarting from the desired statepoints (exposures) in the nominal cycle run.

CSDM is highly dependent on the local conditions surrounding the CRA which is assumed to be fully withdrawn. Therefore, CSDM is usually loading pattern dependent. The B&W mPower reactor presents the unique characteristic of having 8 peripheral fuel assemblies without control rods, so the CRAs located in the adjacent fuel assemblies have the highest worth under cold conditions, making the core periphery CSDM limiting.

For an established operating plant with benchmarked physics, the standard industry minimum accepted value for CSDM is 1 % Δ k/k; however, the B&W mPower core was designed so that a minimum of 3 % Δ k/k is maintained at all times.

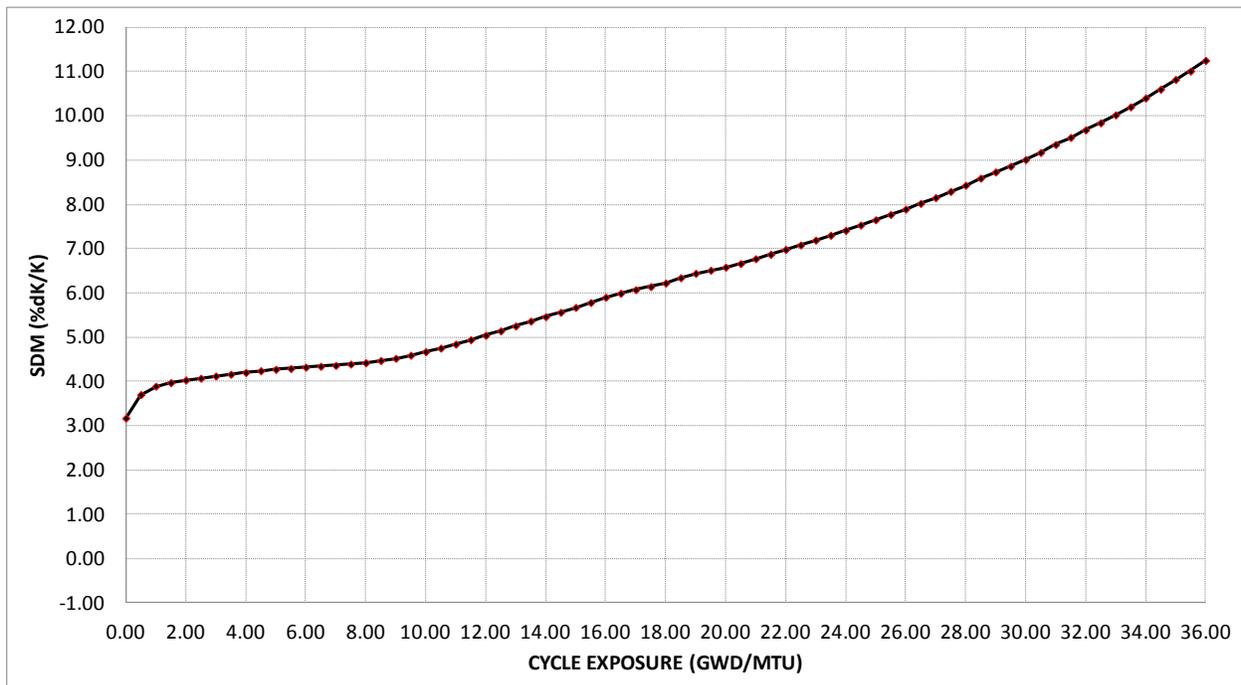Figure 9 summarizes the cold shutdown margin of the B&W mPower reactor core throughout the cycle.

Figure 9. B&W mPower core cold shutdown margin versus cycle exposure

2.5.3. Hot excess reactivity (HEX)

The hot excess reactivity (HEX) is the amount of reactivity that must be controlled at normal full power operating conditions using control rods. The higher the hot excess reactivity, the greater the control rod density needed to maintain the reactor at the full power critical state.

Too much HEX is disadvantageous, since it would require high control rod densities to control the reactivity. Too little HEX is also undesirable, because it may leave the core with limited capability to overcome xenon transients during power maneuvers. In any case, HEX needs to be greater than 1 in order to maintain a 100% power level (HEX < 1 during coastdown).

HEX is defined as the amount of reactivity, expressed in % $\Delta k/k$, by which the reactor would exceed criticality if all CRAs were withdrawn at rated conditions. HEX is calculated with SIMULATE-3 by running "all rods out" (ARO) cases, at rated conditions, restarting from the desired statepoints (exposures) in the nominal cycle run. Unlike the cold shutdown margin, hot excess reactivity is a core-wide phenomenon.

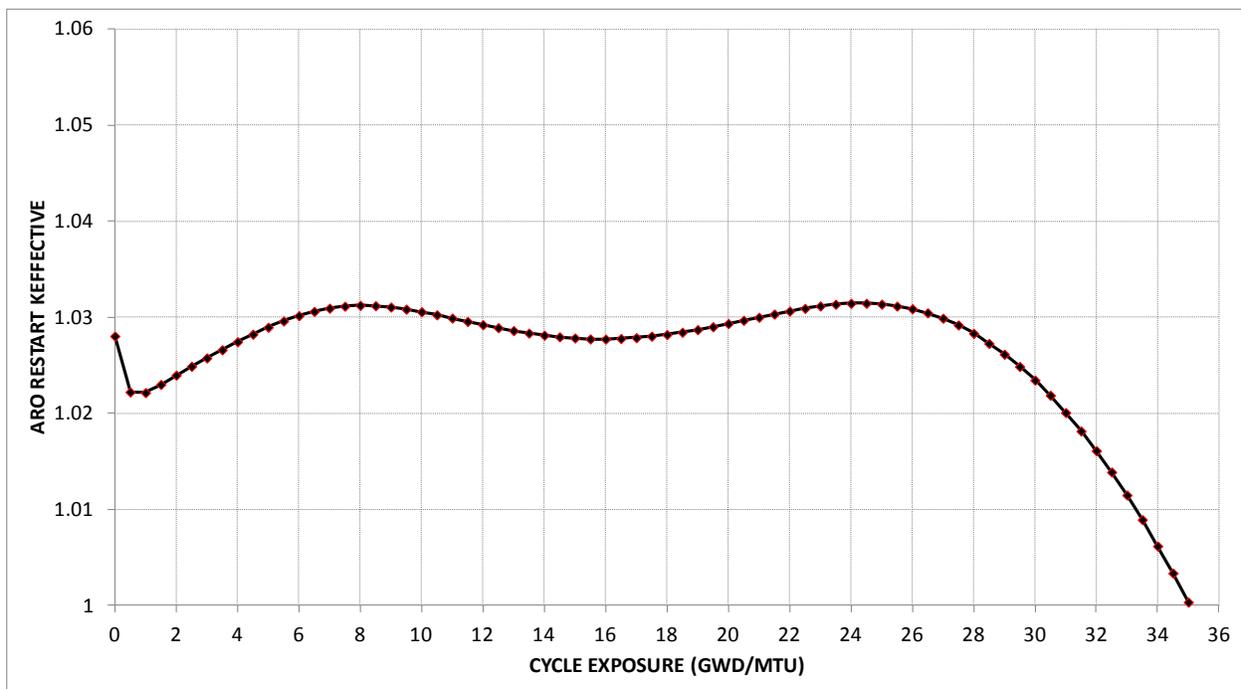Figure 10 summarizes the hot excess reactivity of the B&W mPower reactor core throughout the cycle.

Figure 10. B&W mPower hot excess reactivity versus cycle exposure

2.5.4. Control rod movement throughout the cycle

Control rod movement is calculated as centimeters of control rod length inserted (+) or withdrawn (−) in a day and is determined based on initial and final control rod position during a control sequence (or sub-sequence) and assuming continuous adjustment of the "floaters." The B&W mPower core design, with its "flat" hot excess reactivity, allows power operations with very little reactivity control adjustments.

Figure 11 summarizes the B&W mPower reactor fine-motion control rods movement throughout the cycle.
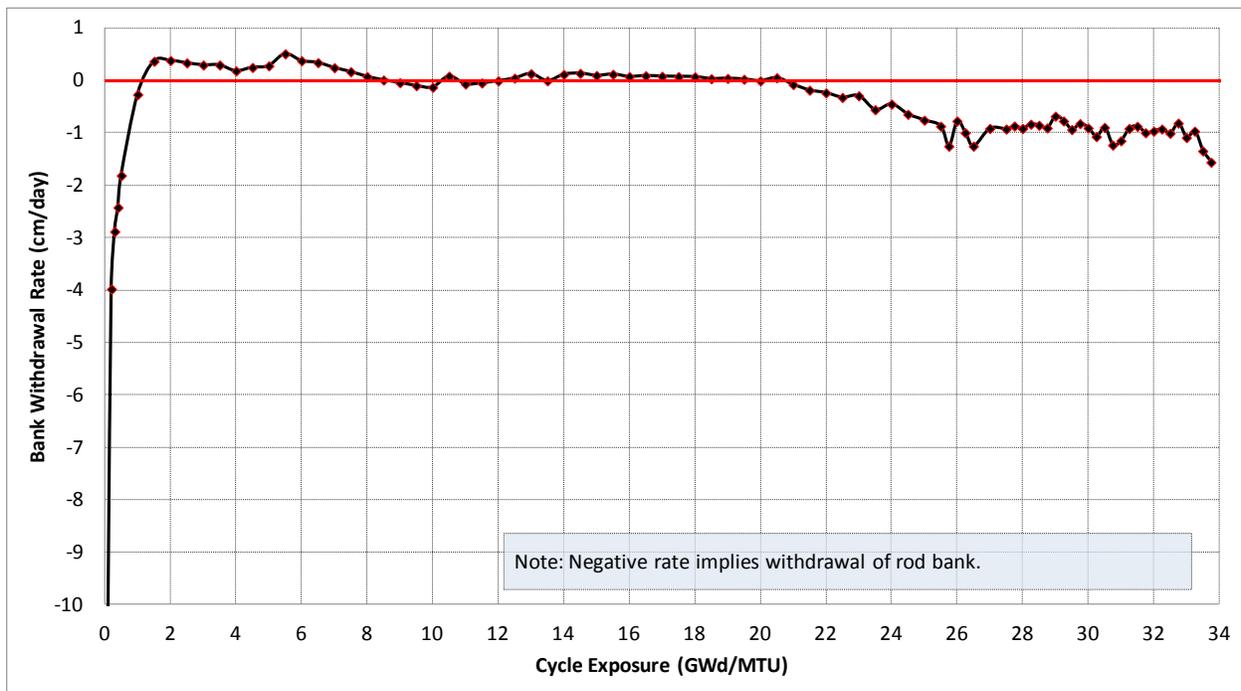

Figure 11. Control rod movement versus cycle exposure in the B&W mPower core

2.5.5. Sensitivity studies

The cycle management plan is flexible in that it can accommodate target eigenvalue biases of several milli-ρ in both the positive and negative directions. In other words, the same rod pattern concept (i.e., sequence) provides for acceptable power tilts and peaking over a range of target eigenvalues.

However, there is a limit to the amount of reactivity bias that can be accommodated by a cycle management plan before the rod patterns degenerate. Analyses performed showed that the cycle management plan cannot accommodate, "as is", a reactivity bias of 10 milli-ρ in the more reactive direction. An alternate cycle management plan was developed to accommodate this hopefully unrealistically large bias, with no negative impact on safety limits. Since cycle management plans are integral with a licensed core design, the customer would not be allowed to

2012 Advances in Reactor Physics – Linking Research, Industry, and Education (PHYSOR 2012), Knoxville, Tennessee, USA April 15-20, 2012

13/16

proceed with alternate rod patterns unless supporting licensing analyses were performed. The analysis was intended to show that the core design is robust, in that it is not precariously dependent on exact rod patterns.

In this scenario, the cycle would gain 2.5 GWd/MT in energy; this translates into approximately 98 EFPD (three more months of full power operation).

Conversely, analyses performed for the other direction of a hypothetical bias in core reactivity showed that, with minimal alterations, a reactivity bias of 10 milli-ρ in the less reactive direction can be easily accommodated. Supporting licensing analyses should also be performed, although this scenario would raise less safety concerns.

In this scenario, the cycle would lose 2.5 GWd/MT in energy; this translates into approximately three months less of full power operation.

3. CONCLUSIONS

The design of a fuel cycle is an iterative process between the lattice/assembly design and the core loading/cycle management design. Failure to meet certain safety criteria (CSDM, nodal peaking, etc.) or design goals (cycle energy) leads to the redesign of certain lattices and fuel assemblies.

The fuel assembly design was performed by iterating on nuclear parameters, both at lattice level and at assembly level. Lattice data libraries were created, specific lattices were assigned to specific elevations in fuel assemblies and specific assemblies to certain locations in the core; then, the in-core performance of the fuel assemblies was analyzed.

Since the B&W mPower reactor, although pressurized, is unborated, and core reactivity and margins to safety limits are controlled with rods, some core parameters tend to become more localized then they are in a typical, currently operating PWR. One significant example to illustrate this point is the cold shutdown margin, a strongly localized phenomenon. One other example is the evolution throughout the cycle of the core axial offset.

The way to balance or counteract some of these localized effects is to design optimized sets of lattices (i.e., optimized fuel assemblies) which will best fit certain locations in the core. For instance, core locations that are known to be limiting for CSDM will require fuel assemblies that are (or can be made) less reactive. This could be achieved by either decreasing the enrichment or increasing the neutron poison composition in those (or adjacent) locations. Since decreasing the enrichment would impact (lower) the EOC energy, the obviously better choice is to increase the neutron absorbing capability of certain lattices in limiting locations.

The B&W mPower core axial offset (A-O) presents a natural tendency to be positive towards EOC. It is determined throughout the cycle by the management of the control rod sequences (axial insertion and CRA radial position in the core). But, although the B&W mPower reactor will always be top-peaked at EOC, since all the rods are fully withdrawn at that point, optimizing

the design of the lattices located at the top of the fuel assemblies greatly reduced the EOC top peaking.

The lattices and bundles designed for the B&W mPower core meet the energy requirements and safety limitations imposed. CASMO-5 output files were used to analyze fuel nuclear characteristics on an infinite lattice basis. Further, with SIMULATE-3, all fuel assemblies were analyzed on an in-core location basis (nodal parameters, pin-by-pin values, etc.). The reactor core and cycle management simulation confirmed that the fuel satisfies the constrains and requirements of the cycle for which it was designed.

Not the least, Studsvik methods accuracy was benchmarked for different loading configurations – involving, among others, fixed burnable poison rods, heterogeneous clean loadings as well as UO_2-PuO_2 configurations. Eigenvalues and localized pin power distributions within a fuel assembly, calculated using CASMO-5/SIMULATE-3, were compared to the measured results from the respective experiments, with very good agreement of data.

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