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LATTICE CELL AND FULL CORE PHYSICS OF INTERNALLY COOLED ANNULAR FUEL IN HEAVY WATER MODERATED REACTORS

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LATTICE CELL AND FULL CORE PHYSICS OF INTERNALLY COOLED ANNULAR FUEL IN HEAVY WATER MODERATED REACTORS

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Increasing the burnup of reactor fuel can have advantages such as improved utilization of fissile resources, reduced spent fuel volume, and, in the case of reactors with on-power refuelling, decreased operational demand on the fuelling machines. Higher burnups are also desirable for many advanced fuel cycles, such as minor actinide-bearing fuels where high burnups are required to achieve better actinide destruction, and thorium based fuel cycles where increased irradiation time converts and burns more U-233 from Th-233. However, this will impose more challenging operating conditions on the fuel, particularly in the case of on-power refuelling. A program is underway at Atomic Energy of Canada Limited (AECL) to develop a new fuel bundle concept to enable greater burnups. One option that AECL is investigating is an internally cooled annular fuel (ICAF) element concept.

ICAF contains annular cylindrical pellets with cladding on the inner and outer diameters. Coolant flows along the outside of the element and through the centre. With such a concept, the maximum fuel temperature as a function of linear element rating is significantly reduced compared to conventional, solid-rod type fuel. The preliminary ICAF bundle concept considered in this study contains 24 half-metre long internally cooled annular fuel elements and one non-fuelled centre pin. The introduction of the non-fuelled centre pin reduces the coolant void reactivity (CVR), which is the increase in reactivity that occurs on voiding the coolant in accident scenarios.

Lattice cell and full core physics calculations of the preliminary ICAF fuel bundle concept have been performed for medium burnups of approximately 18 GWd/tU using WIMS-AECL and reactor fuel simulation program (RFSP). The results will be used to assist in concept configuration optimization. The effects of radial and axial core power distributions, linear element power ratings, refuelling rates and operational power ramps have been analyzed. The results suggest that burnups of greater than 18 GWd/tU can be achieved in current reactor designs. At approximately 18 GWd/tU, expected maximum linear element ratings in a pressure tube heavy water reactor (PT-HWR) with online-refuelling are approximately 90 kW/m. These conditions would be prohibitive for solid-rod fuel, but may be possible in ICAF fuel given the reduced maximum fuel temperature as a function of linear element rating.

I. INTRODUCTION

Extending the fuel burnup beyond current practice presents advantages in improved utilization of fissile resources, reduced spent fuel volume, and, in the case of reactors with on-power refuelling, decreased operational demand on the fuelling machines. The current average discharge burnup for natural uranium (NU) fuel bundles in a 700-MWe-class pressure tube heavy water type reactor (PT-HWR) is approximately 7.5 GWd/tU [1], [2].

As the burnup is extended in the PT-HWR reactor, the increases in power experienced by the fuel during refuelling (power ramps) are greater, and maximum bundle powers are higher. Existing fuel bundle designs based on solid-ceramic fuel pellets with Zr-4 cladding may exceed defect thresholds under these more demanding operating conditions. AECL is investigating an internally cooled annular fuel (ICAF) element concept as an alternative fuel carrier that is expected to have superior heat transfer and fuel performance characteristics relative to conventional solid-rod fuel elements.

The ICAF contains annular cylindrical pellets with cladding on the inner and outer diameters. Coolant flows along the outside and inside of the fuel element surfaces. With such a concept, the maximum fuel temperature as a function of linear element rating is significantly reduced compared to conventional, solid-rod type fuel. The preliminary ICAF bundle concept considered in this study contains two circular rings with a total of 24 half-meter long ICAF elements and one non-fuelled solid centre pin (see Fig. 1). The outer ring contains 16 ICAF elements and the inner ring contains 8 ICAF elements. The introduction of the non-fuelled centre pin reduces the coolant void reactivity (CVR), which is the change in reactivity that occurs on voiding the coolant.

The combination of annular cylindrical pellets and the non-fuelled centre pin reduces the fuel mass compared to conventional solid-rod designs ([3], [4]). This study uses lattice cell and full core physics calculations to assist in feasibility studies and concept optimization. The fuel used in this study was LEU (1.25 wt% $^{235}U/U$), in the form of UO_2, which allowed a core average discharge burnup of ~18 GWd/tU.

II. ANALYSIS METHOD

Models were created to assess the neutronic aspects of the 24-element ICAF bundle concept. Simulations of the neutron transport and burnup were completed using 2-D lattice and 3-D core physics codes to obtain preliminary results (e.g., maximum powers, power ramps, maximum linear element ratings, CVR and bundle power histories, etc.) to assess the performance of this ICAF bundle concept in a 700-MWe-class PT-HWR.

Simulations of an ICAF-fuelled core first involved performing 2-D lattice physics calculations of bundles using multi-group neutron transport calculations. The data from the lattice physics calculations were homogenized and collapsed to two-group diffusion data, which were then used in 3-D core physics calculations.

Lattice physics calculations were performed using WIMS-AECL Version 3.1 [5], in combination with an 89-group nuclear data library, based on ENDF/B-VII.0 [6]. The lattice cell calculations also provided the relative element power distributions necessary to convert bundle powers from the full core calculations into linear element ratings. The CVR was determined from the lattice cell calculations by averaging the reactivity change from the sudden removal of the coolant at predefined time steps up to the average core exit burnup.

WIMS Utilities Version 2.0 [7] was used to generate homogenized and collapsed 2-group diffusion data, using the multi-group neutron flux and reaction rate data obtained from the WIMS-AECL calculations. This homogenized data was used later in the 3-D core analysis. The properties of the heavy water reflector were also evaluated in the same manner using a super-cell model with an additional annulus of heavy water.

Core physics calculations were performed using RFSP v3.5.1 [8]. RFSP provided a steady state diffusion calculation to determine the “Time-Average” [9] power distributions and channel refuelling rates. Maximum powers were predicted by applying an instantaneous snapshot to the “Time-Average” calculation, where each channel was assigned a specific age (burnup) between refuelling cycles to represent an operational equilibrium core. RFSP then provided a steady state diffusion calculation to determine the “Instantaneous” [10] power distributions.

These core calculations provided bundle powers and linear element ratings as applied to a PT-HWR using online refuelling. Parameters specific to online refuelling included power increases from refuelling, and refuelling rates. This study was limited to a once-through bi-directional refuelling scheme.

Reactivity devices were modeled to approximate the steady state core reactivity. The reactivity devices were approximated as incremental cross-sections, which were taken from a previous physics model using a 37-element bundle geometry with natural uranium fuel [11]. The previous model generated a series of incremental cross-sections by using a supercell method in a 3-D neutron transport model containing a reactivity device and two lattice cells [12], using the DRAGON [13] neutron transport code.

II.A. Lattice Model

The ICAF bundle concept is illustrated in Fig. 1. A 24-element configuration was used with 15.2 mm outer diameter fuel elements in two rings. Details are given in Table I. A central Zr-4 tube was filled with ZrO_2. The composition of this central pin is still under development and was treated as solid ZrO_2 at 75% of the theoretical density for the purpose of this study. The annular fuel was 1.25 wt% $^{235}U/U$ LEU in the form of UO_2 encased in Zr-4 cladding. The lattice model included the pressure tube and calandria tube dimensions from previously described PT-HWR designs [11].

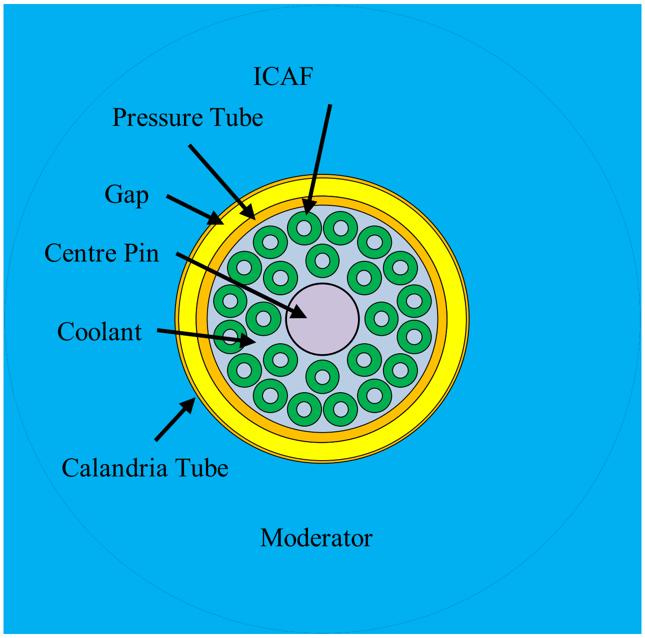

Fig. 1 ICAF Bundle Concept with UO_2 Fuel Rings and a ZrO_2 Central Pin

Changes were made to material densities in the 2-D lattice model to account for a 495 mm long bundle with a 480 mm fuel stack length.

II.B. Full Core Model

A 2,084 MW_{th} PT-HWR with 380 fuel channels was used as the reference model [11] for ICAF bundle full core calculations. General reactor core specifications are shown in Table II. To simulate nominal conditions, the liquid zone controllers used for fine reactivity control were modeled at a nominal 50% full, the adjuster rods were left 100% in-core and the shut-off/control rods were left 100% out-of-core. The bundle refuelling scheme used even numbered bundle shifts in recognition of existing fuelling machine limitations.

Table I ICAF Bundle Parameters

Bundle Parameter	Value
Centre Pin Material	75% theoretical density ZrO_2 sheathed in Zr-4
Centre Pin Outer Diameter	34.3 mm
Centre Pin Sheath	Zr-4 Thickness: ~0.4 mm
Fuel Composition	UO_2, 1.25 wt% $^{235}U/U$ Density: ~10.6 g/cm^3
Fuel Elements per Ring	Inner: 8 Outer: 16
Annular Fuel Pellet Dimensions	Inner Diameter: ~8.5 mm Outer Diameter: ~14.4 mm
Fuel Cladding	Zr-4 Thickness: ~0.4 mm
Fuel Stack Length	480 mm
Bundle Uranium Mass	11.4 kg
Coolant/Moderator	D_2O/ D_2O
Coolant Temperature	561 K
Moderator Temperature	336 K

Table II Core Specifications

Core Parameter	Value
Number of Fuel Channels	380
Number of Bundles per Channel	12
Number of Bundles in the Core	4,560
Total Fission Power	2,182 MW
Reactor Thermal Power	2,084 MW
Liquid Zone Controller Positions	14, Half Full
Adjuster Rods Positions	11, In-Core
Shut-Off/Control Rod Positions	46, Out-of-Core

The time-average exit irradiations were iteratively adjusted for each channel until the following parameters were achieved:

1. Core reactivity (k_{eff}) = 0.997±0.005.
2. The maximum instantaneous channel power was less than 7.3 MW.

Bundle power limits have not yet been determined for the ICAF bundle and no limits were applied in this study. Instead, the maximum bundle power was minimized, while meeting the other parameters.

Adjusting exit irradiations is complicated by the 380 channels (i.e., 380 average exit irradiations) in a conventional 700-MWe-class PT-HWR. To simplify this, the core was divided into 20 irradiation zones where the channel average exit irradiations were set the same.

The conventional refuelling scheme for a PT-HWR with NU fuel replaces 8 bundles in a channel for each refuelling operation (8-bundle shift), with bi-directional fuelling in alternating channels. This scheme was used as the starting point for the refuelling scenario examined here. If the acceptance criteria could not be achieved, the number of bundles per channel refuelling operation was reduced (i.e., from 8 bundles to 4 bundles) and the process was repeated.

The “instantaneous” power distribution was checked against the acceptance criteria and the time-average irradiations were iteratively adjusted until both the time-average and “instantaneous” results were acceptable.

III. RESULTS

III.A. Lattice Physics Results

Lattice cell calculations with WIMS-AECL predicted that the ICAF bundle should be able to achieve a discharge burnup of ~20 GWd/tU. Fig. 2 shows the linear element ratings for the bundle operating at a constant total bundle power of 840 kW.

The two circular fuelled rings in the ICAF bundle achieved a relatively even radial power distribution, which helped to reduce the maximum linear element ratings and improve fissile resource utilization (see Fig. 2). The eight fuel elements on the inner ring experienced 8% to 17% lower linear element ratings than the 16 elements on the outer ring.

Reducing CVR allows for an improved safety margin in a PT-HWR. The burnup-averaged CVR is an approximation of the overall reactivity in a core with an equilibrium fuel burnup distribution. The burnup-averaged CVR was +12.3 mk, which is ~14% lower than what would be found using a 37-element solid rod fuel bundle enriched to achieve a burnup of ~20 GWd/tU [3]. The ICAF CVR was ~+13 mk at burnups less than 10 GWd/tU and declined to +9.5 mk at ~20 GWd/tU, as shown in Fig. 3.

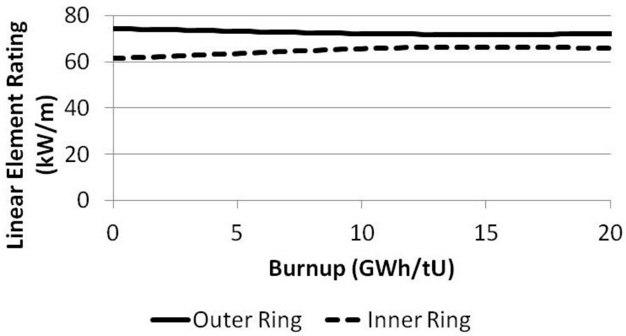

Fig. 2 Linear Element Ratings for Outer and Inner Fuel Elements in a 24 Element ICAF Bundle operating at a Constant Power of 840 kW

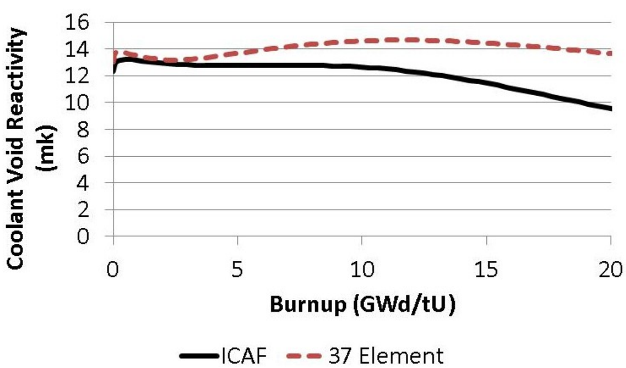

Fig. 3 CVR for ICAF and 37-Element LEU Bundles targeting 20 GWd/tU

III.B. Full Core Physics Results

The results of the full core analyses are summarized in Table III. The ICAF bundles achieved a full core average exit burnup of ~18 GWd/tU. This is approximately 90% of the 20 GWd/tU burnup estimated based solely on lattice physics calculations with WIMS-AECL results.

Table III Summary Full Core Results

Parameter	Value
Core Burnup (GWd/tU)	15.3 to 20.7 Average: 18.0
Time-Average Max. Channel Power	6,149 kW
Time-Average Max. Bundle Power	782 kW
Time-Average Max. Linear Element Rating	72 kW/m
Time-Average Max. ΔP from refuelling	51 kW/m
Instantaneous Max. Channel Power	7,278 kW
Instantaneous Max. Bundle Power	993 kW
Instantaneous Max. Linear Element Rating	92 kW/m
Time-Average Core k-effective	0.9969
Bundles Refuelled per Channel Visit	4
Channel Visits per Full Power Day	2.66

The ICAF bundles met all of the proof-of-concept requirements. However, the number of bundles shifted during refuelling had to be reduced from the 8 bundles used in previous natural uranium fuel studies [11] to 4 bundles to maintain a maximum channel power of less than 7.3 MW. The maximum bundle powers were also somewhat higher and several other core characteristics were different than previous natural uranium based studies [11].

The discharge burnup of the ICAF bundles ranged from 15.3 to 20.7 GWd/tU. The burnup distribution is illustrated in Fig. 4. The bundles were well distributed across the burnup range with the exception of the 17 to 18 GWd/tU burnup range, which only had 4% of the bundles. The core burnup distribution was similar to that of natural uranium studies [11]. Lower burnup bundles were located in the peripheral channels, while higher burnup bundles were in the channels adjacent to the central core. The central core channels had medium-burnup bundles.

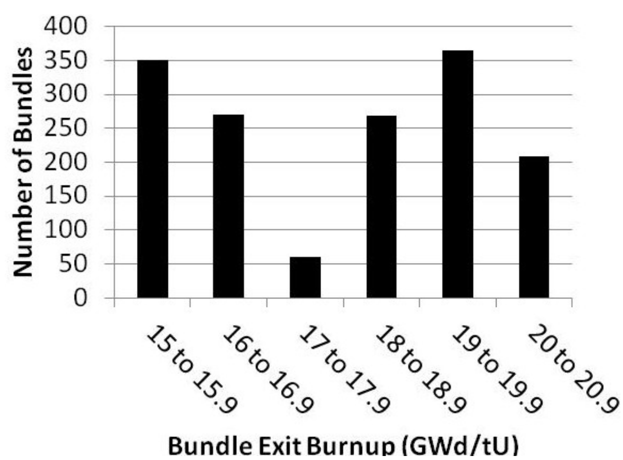

Fig. 4 Bundle Discharge Burnup Distribution

Fig. 5 shows the time-average channel power distributions. The maximum time-average channel power was 6.15 MW. The time-average channel power distribution was similar to that of natural uranium studies with higher power channels near the centre and lower power channels near the periphery.

The instantaneous maximum channel power was 7.28 MW, below the 7.3 MW limit. The higher enrichment of the ICAF bundles caused the maximum instantaneous channel powers to increase. To compensate, power production was moved from the inner channels to the outer channels by reducing the exit burnup in the outer channels (refuelling them more frequently). This partially flattened the time-average channel radial power distribution, which in turn helped reduce the instantaneous maximum channel power.

The maximum time-average bundle power was 782 kW, which is comparable to previous studies using natural uranium fuel [11]. However, the maximum instantaneous bundle power was significantly higher than previous studies using natural uranium fuel; 993 kW compared to 840 kW [14]. The higher ICAF instantaneous bundle powers compared to the natural uranium models are partly attributed to the greater instantaneous axial peaking factor (discussed later) from the enriched ICAF bundles. The time-average and instantaneous maximum linear element ratings were 72 kW/m and 92 kW/m respectively.

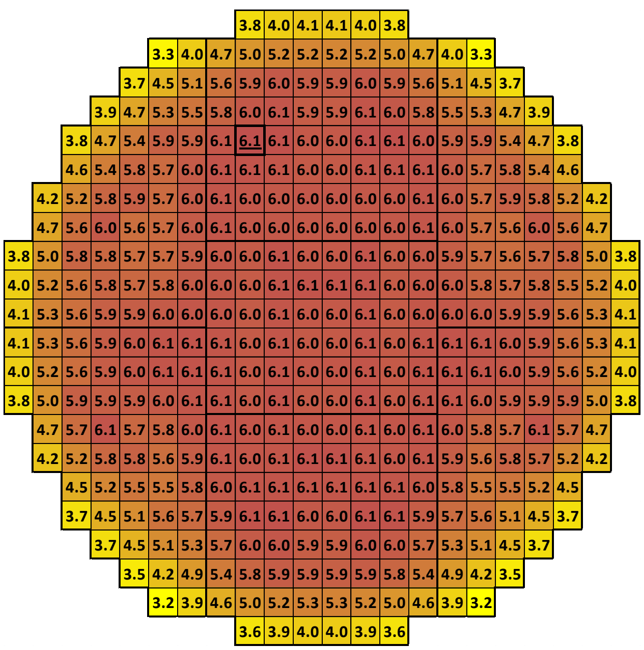

Fig. 5 Time-Average Channel Power Distribution (MW)

Fig. 6 shows examples of the more demanding time-average power histories. A sample bundle power history with high mid-life power was converted into linear element ratings (see Fig. 7). The bundle experienced a maximum linear element rating of just over 71 kW/m up to approximately 11 GWd/tU. Standard solid-rod fuel performance models do not apply to ICAF elements because of their geometry. The power history in Fig. 7 will need to be assessed against future ICAF performance models, currently under development.

A detailed determination of power ramps was not performed for this analysis. However, an approximation was made based on the fuelling power increase/decrease using the time-average calculation. Fig. 8 shows the time-average linear element rating increases during refuelling. The maximum change in the linear element rating (ΔP) was 51 kW/m at a burnup of <2 GWd/tU and declined steadily to <20 kW/m at approximately 5.3 GWd/tU. Thermal-mechanical finite element analysis of this ICAF element concept indicated that the sheath stress induced by power increases was approximately 6 times lower than for an equivalent 37-element solid-rod bundle [15]. The 51 kW/m power increase in an ICAF element was estimated to be comparable with a 9 kW/m increase in solid-rod fuel. At low burnups (<2 GWd/tU), Zr-4 cladding has a large power ramp failure threshold.

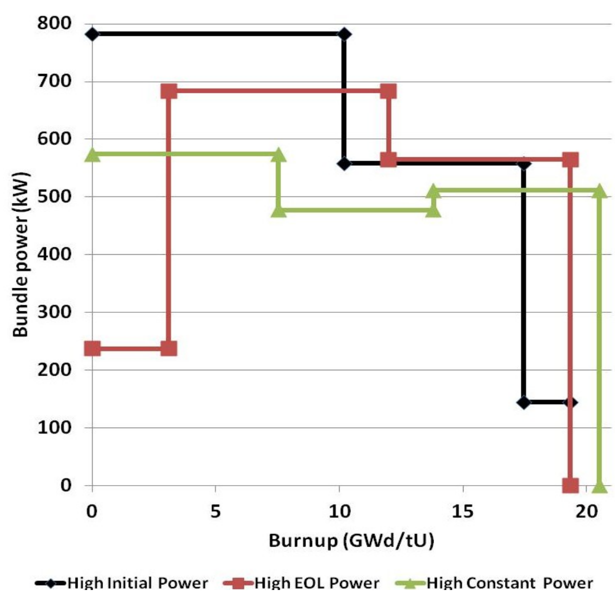

Fig. 6 Example Time-Average Bundle Power Histories

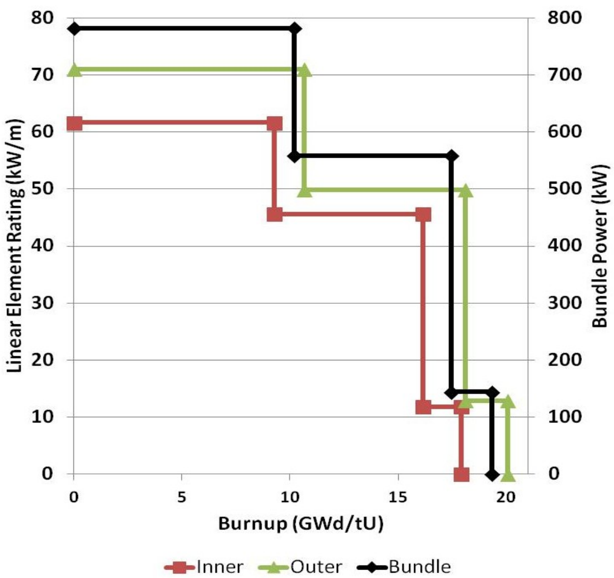

Fig. 7 Example Time-Average Linear Element Ratings for a High Power Bundle

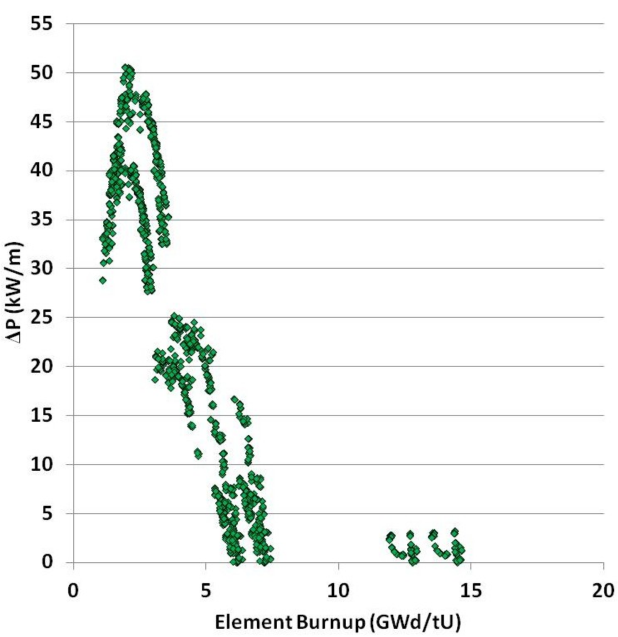

Fig. 8 Time-Average Linear Element Rating Increases from Refuelling

Other parameters of note are the channel axial power profile and the axial peaking factor. The axial peaking factor is a measure of the axial power gradient in a channel based on the maximum bundle power relative to the average of the bundle powers. Fig. 9 shows the typical time-average axial profiles observed in the high peaking channels. The outer channel (i.e., near the edge of the core) axial profiles were a typical cosine shape with the peak slightly offset towards the lower burnup end of the channel. However, the higher powered inner channels exhibited a bimodal power distribution with a primary peak in the innermost fresh bundle (i.e., bundle position 4 relative to the low burnup end of the channel). A small secondary peak occurred around position 8 and 9 relative to the low burnup end of the channel; these positions are adjacent to the highest power bundles in the neighboring channels, which are fuelled in the opposite direction. The inner core region (i.e., axial positions 6 and 7) had depressed powers. The magnitude of the bimodal axial profile is not expected to be significant enough to cause a fundamental barrier. The axial peaking factor for the maximum instantaneous channel power was 1.64 and approximately 17% larger than the ~1.4 in previous natural uranium studies.

The ICAF fuelling schemes were kept the same as the existing natural uranium fuelling schemes (i.e., once-through bi-directional fuelling), with changes to the refuelling rates and the number of fresh fuel bundles inserted per refuelling operation (bundle shift). The ICAF bundle shift was reduced from the standard 8 bundle shift to a 4 bundle shift to stay within the channel power limit. This was partially offset by the higher bundle residency time. The result was a ~30% increase in the number of channel visits per full power day compared to similar natural uranium based models [11].

Maximum linear element rating limits applied to standard solid-rod elements are not expected to be applicable to ICAF elements. An increase in the maximum linear element rating limits will translate into higher bundle power limits. This will allow higher burnups and a reduction in channel visits per full power day. For example, increasing the maximum bundle power by ~4% (1030 kW) would result in a 10% increase in burnup and a 9% reduction in channel visits per full power day.

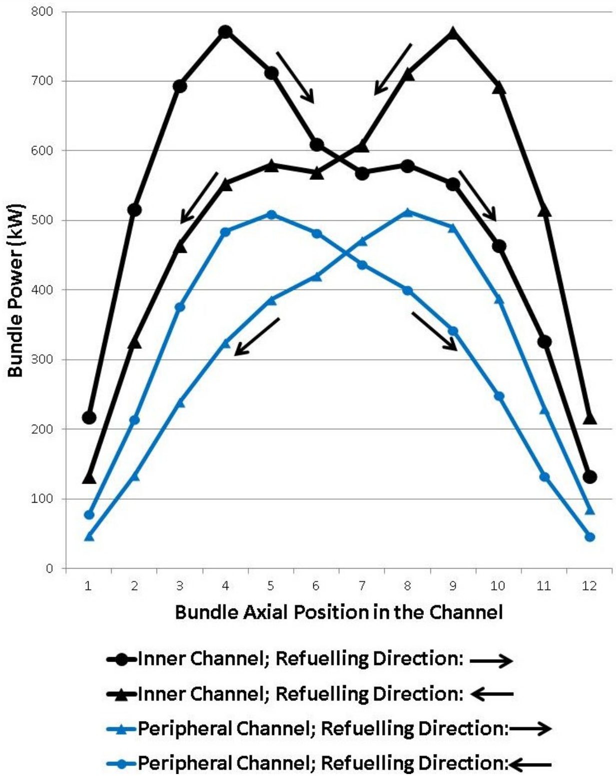

Fig. 9 Axial Power Profiles for Channels with High Axial Peaking Factors

IV. CONCLUSIONS

The full core proof-of-concept calculations of the ICAF bundle carrier concept revealed no fundamental barriers to using enriched uranium fuel to achieve average burnups of 18 MWd/kgU (ICAF 1.25 wt% ^{235}U/U bundles) in a conventional 700-MWe-class PT-HWR.

The ICAF bundle has a flatter power distribution across its fuel elements compared to conventional pressure tube heavy water reactor fuel bundles. An even power distribution reduces the linear element ratings and maximizes the fissile content utilization by spreading the burnup more evenly across a bundle.

The burnup-averaged CVR was +12.3 mk, which is 14% lower than previous PT-HWR fuel concepts. The centre pin concept is still under development and further reduction in the coolant void reactivity may be possible by investigating materials other than ZrO_2.

The predicted maximum linear element rating was 92 kW/m. The maximum power increases from refuelling was estimated at 51 kW/m. A complete thermalhydraulic assessment of the ICAF bundle has not been completed to date and conclusions about maximum linear element ratings cannot be drawn. Thermal-mechanical analysis suggests the ICAF element sheath stress induced by power increases would be ~15% of that for an equivalent 37-element solid-rod fuel bundle [15].

The 700-MWe-class PT-HWR core with ICAF bundles had ~30% increase in the refuelling channel visits compared to similar natural uranium based models. An increase in refuelling channel visits is not desirable because of the impact on fuelling machine duty. However, further optimization is possible through modifications to the target burnup and refuelling schemes.

The axial power distributions had a bimodal ("double-hump") distribution in the high powered channels, in contrast to the cosine-type power distribution typically observed in PT-HWR core with lower-burnup natural uranium fuel. This change in shape is a result of reducing the number of fresh fuel bundles inserted per refuelling operation from 8 to 4, and also due to the larger change in reactivity of the LEU fuel between the channel inlet and exit. The channel axial peaking factors were higher than found in cores with natural uranium fuel.

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