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ADVANCED CHECKMATE^{SM} CORE DESIGN FOR BWR FUEL MANAGEMENT

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Abstract – *A concept in core loading strategy termed the Advanced Checkmate Core Design (ACCD) is presented for the improvement of In Core Fuel Management (ICFM). ACCD differs from traditional "checkerboard" loaded cores by the arrangement of fresh fuel bundles in cruciform sub-patterns distributed within the core loading patterns. The key feature of ACCD is the design of the fresh bundles within the cruciform sub-patterns within the core loading patterns. Through proper fresh bundle design, as defined by the radial and axial distributions of uranium enrichment and gadolinium burnable poison, significant improvements in energy, thermal margins, and shutdown margin can be realized. For a currently operating BWR, these improvements over a traditional checkerboard translate into +10 EFPD in energy, +5% MFLCPR/MFLPD, and +0.1% SDM (reactivity margin).*

I. INTRODUCTION

The move towards long operating cycles on extended power up rated cores, especially on small cores, has exacerbated the problem of finding enough locations to load fresh fuel to meet such high energy demands. Although locations near the periphery could be used, this has raised the need for additional core design constraints in order to lower the neutron fluence primarily on the moderator barrel and/or reactor pressure vessel without limiting the capability for power operation. Such additional constraints severely restrict design freedom.

The traditional core design strategy employed has been "checkerboard" loadings, whereby fresh and exposed fuel assemblies are arranged according to a periodic placement within the core interior with high exposed fuel placed on the core periphery. Checkerboard loadings achieve a balance between maximum energy production, thermal margins, reactivity margins, and neutron fluence. This paper discusses the Advanced Checkmate^{SM} Core Design (ACCD)[1], a new concept in core loading strategies developed by Studsvik, based upon the principle of arranging fresh fuel bundles in cruciform sub-patterns within the core loading pattern. The special characteristics of ACCD are improvements in energy production or, equivalently, thermal and shutdown reactivity margin - all while minimizing neutron fluence.

The figure below contrasts the differences between traditional checkerboard and ACCD design.

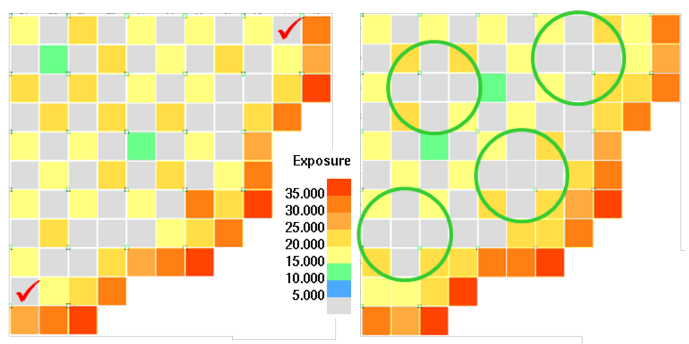


Fig. 1 Checkerboard vs ACCD Loading - 152 Fresh

A study was performed of the ACCD concept with the Studsvik Scandpower Core Management System (CMS) that includes:

- CASMO-4[2] and SIMULATE-3[3] model of Duane Arnold BWR constitute the base for the study.
- XIMAGE-BWR[4] has been used for the core designs and multi cycle studies cycle, and fuel cycle cost (FCC) calculations and comparisons.

For the core layout shown in Fig. 1 (left side), there was an expressed wish to limit the neutron fluence on the barrel/vessel and therefore fresh fuel (gray in the figure) should be avoided in the two check marked positions. So the following question was raised:

- Is it possible to load152 fresh bundles while lowering the neutron fluence compared to the undesired 152 loading in Fig. 1 (left side), and at the same time also fulfill or improve all other design constraints?

II. CONDITION AND DESIGN CONSTRAINTS

In this paper, ACCD has been examined both for single cycle studies as well as for equilibrium cycles. Both of those alternatives have been compared to standard checkerboard loaded cores. Constraints, listed in Table I and II, were applied to the core design for the single and equilibrium cycle studies respectively.

TABLE I

Condition and Design Constraints, Single Cycle

Condition	Constraint
Cycle length	EOC = 649.5 EFPD, EOFP ≥ 622 EFPD, Coast Down < 30 Calendar Days
Fresh sub-batches	Type 2541, Type 40001 and Type 40002 To be used in an unlimited mix
# of fresh loaded	2 Cases - 152 and 160

TABLE II

Condition and Design Constraints, Equilibrium Cycle

Condition	Constraint
Cycle length $C_n – C_\infty$	$EFPD_{EOFP}$ fixed and altered from $C_n – C_\infty$ to match EOFP condition at Eq. cycle $C_{n+m} – C_\infty$, Coast Down length fixed to 20 EFPD for all cycles.
Loading pattern	Fixed for $C_n – C_\infty$
Fresh sub-batches	Type 2541, Type 40001 and Type 40002. # per sub batch fixed
# of fresh loaded	2 Cases - 152 and 160

III. CHECKERBOARD vs. ACCD

In Fig. 2, the principal difference between a classic checkerboard design (in the following sections referred to as Reference or Ref.) and ACCD (in some figures marked as Checkmate^{SM}) is noted. ACCD differs from traditional checkerboard loaded cores by the arrangement of fresh fuel bundles in cruciform sub-patterns distributed within the core loading pattern.

The capability to arrange the fresh bundles in this cruciform manner creates the possibility to load the core with more than 152 fresh bundles, without challenging the design constraint limit regarding neutron fluence on the vessel. As noted from Fig. 2, ACCD does not contain fresh fuel bundles (fresh indicated as gray in figure below) loaded in any peripheral or semi-peripheral locations.

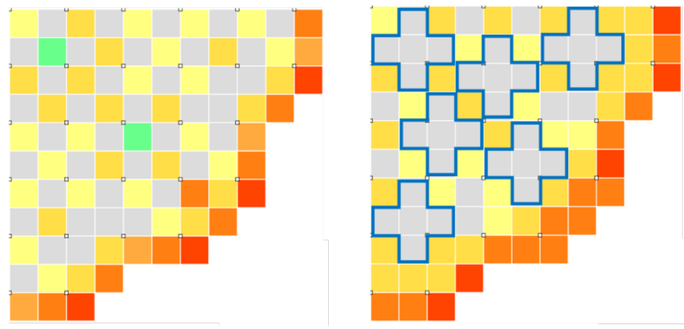


Fig. 2. Checkerboard vs. ACCD - 152 Fresh

IV. SIMULATION RESULTS

IV.A. Introduction

Figs. 3 and 4 illustrate the ACCD concept (Reference loading to the left and ACCD to the right) when employed for improvement of thermal and reactivity margins, respectively. In the examples, ACCD is applied to a single cycle and comparisons are made with the traditional checkerboard design at equivalent fresh loading and energy. The Ref. and ACCD loading serve as the basis for Figs. 3 and 4 are of a similar kind to the layout found in Fig. 5.

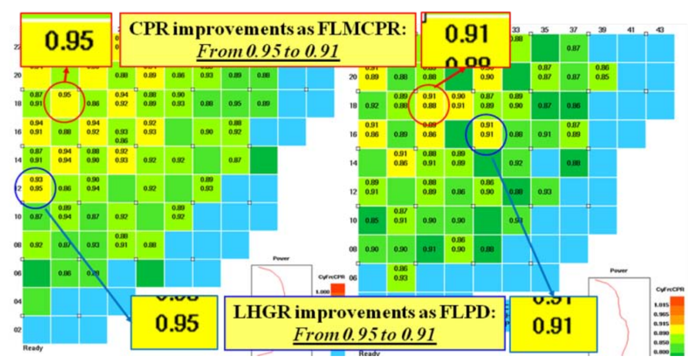


Fig. 3. Thermal Margins Comparison

Fig. 4. Shutdown Margin Comparison

As shown, Fig. 3 displays an improvement, in the most limited position, for ACCD in both linear heat generation rate (LHGR) and critical power ratio (CPR) of 4.2% versus a traditional checkerboard loading. Fig. 4 displays an improvement for ACCD, in the most limited position, in shutdown margin (SDM) of 0.1%. It is worth noting, from Figs. 3 and 4, that Checkmate^{SM} not only results in single position improvements, but general or more evenly distributed load reductions are also gained.

While ACCD provides significant gains in thermal and reactivity margins, translation of those gains into improvements in fuel cycle cost (FCC), without degradation of operating flexibility, is the ultimate goal of the core design process. To this end, detailed single and equilibrium studies of 152 and 160 fresh fuel batch sizes are performed. Analyses of results are focused on gains in FCC rather than thermal margin improvements, so that the results and figures are independent of operating strategy.

IV.B. Single and Equilibrium Cycle – 152 Fresh

Figs. 5 and 6 display the results for the single and equilibrium cycle Ref. and ACCD loading patterns for the 152 fresh loading scenarios. Within the ACCD patterns, the cruciform sub-patterns have been marked with "crosses". It should be noted that in the ACCD layout for the equilibrium study a more aggressive loading has been used, with six cruciform sub-patterns compared to four cruciform sub-patterns in the single cycle in each quarter.

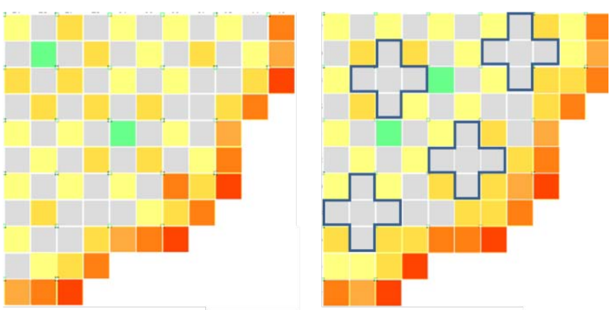


Fig.5. Single Cycle, 152 Fresh Loading
Reference vs. ACCD

Figs. 7 and 8 display the operational results for the single and equilibrium cycle Ref. and ACCD loading patterns. Fig. 7 shows the thermal margin comparisons for CPR (as Maximum Fraction of Limiting CPR or MFLCPR) and LHGR (as Maximum Fraction of Limiting Power Density of MFLPD). Fig. 8 displays the shutdown margin results for all cases. As shown, ACCD manages well to fulfill both the thermal and reactivity margins.

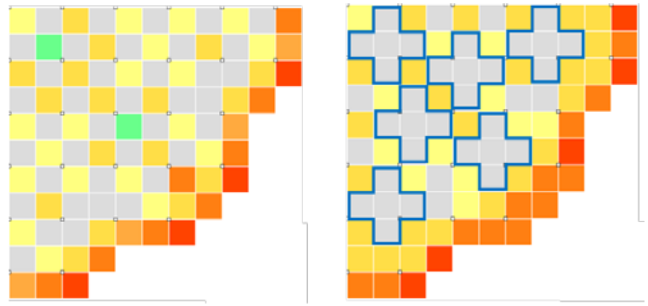


Fig. 6. Equilibrium Cycle, 152 Fresh Loading
Reference vs. ACCD

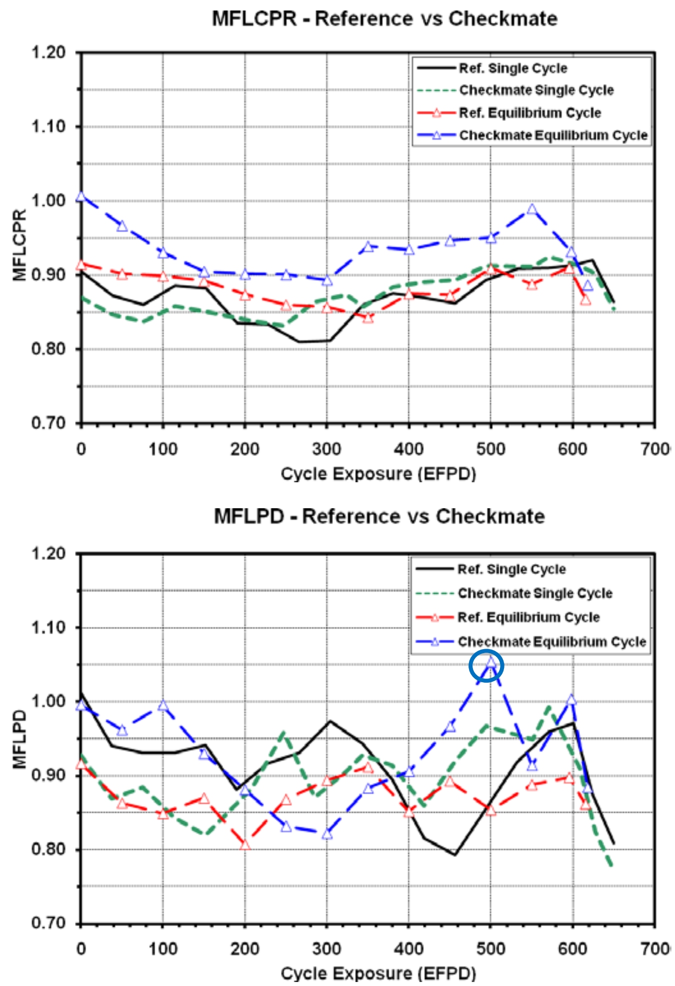


Fig. 7. Thermal Margin Comparisons

In Fig. 7 MFLPD for ACCD equilibrium cycle exceeds the design limit at 500 EFPD, see the marked "blue circle". This is easily corrected by either a better and more proper CR sequence or a single bundle shuffle/swap. The LHGR design limit excess at 500 EFPD does not have any significance on the conclusions drawn.

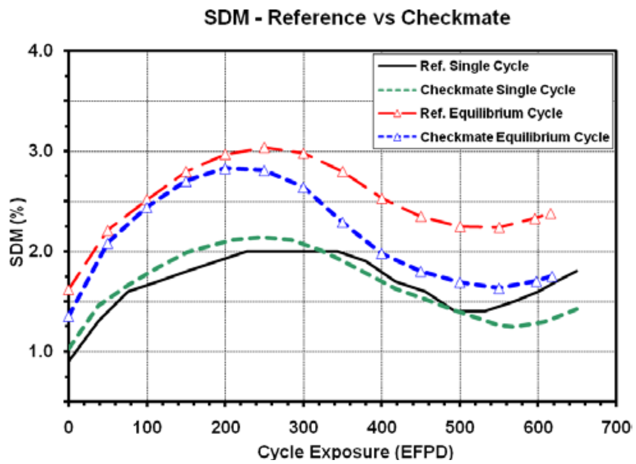


Fig. 8. Shut Down Margin Comparisons

The total neutron leakage from the core was used as a measure of neutron fluence on the vessel and is shown in Fig. 9 for the different studies. It is clear from Fig. 9 that the ACCD layout reduces the neutron leakage from the core. With this large reduction in neutron leakage, a major part is assumed to be a reduction of the radial leakage component (ACCD layout less fresh close the radial boundary), it could be concluded that the ACCD layout also will have a positive contribution to lowering the fluence on the vessel.

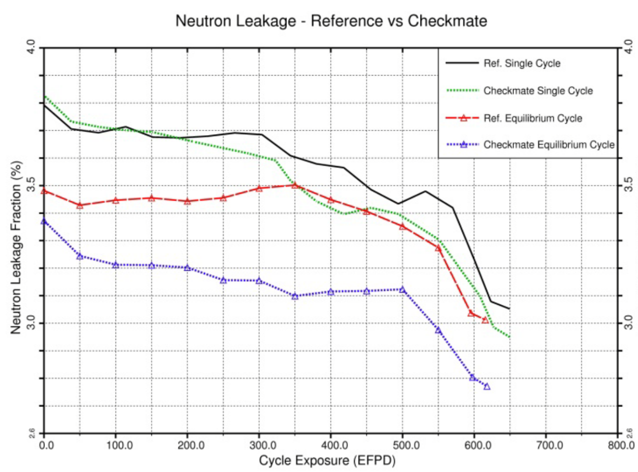


Fig. 9. Neutron leakage Comparisons

IV.C. Single and Equilibrium Cycle – 160 Fresh

The 160 loaded equilibrium designs confirm results shown in Figs. 7 and 8, with the notable difference that the fuel design, enrichment and Gd layout, were not as well optimized for the 160 fresh bundle core design study in comparison to the 152 fresh bundle core design. This was evidenced by the following observations:

- Too high SDM in equilibrium which in return causes too low hot excess reactivity at BOC.
- Too high LHGR values near EOC.
- The ACCD equilibrium cycle has a higher neutron leakage during the first part of the cycle than the corresponding reference design.

Given the layout of fresh fuel and the aforementioned observations, opportunities exist for improved optimization of both the core periphery and the interior of the core (especially for the marked bundles in Fig. 11). In light of this fact, it is clear that with a better adapted bundle design (i.e. mix of sub-batches, enrichment splits and Gd layout) up to 160 fresh bundles could be loaded with the ACCD concept with improved overall results compared to reference loaded cores.

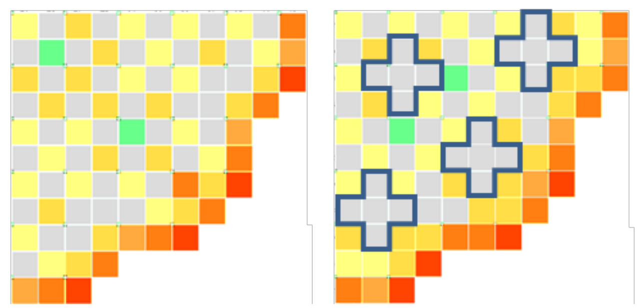


Fig. 10. Single Cycle, 160 Fresh Loading
Reference vs. ACCD

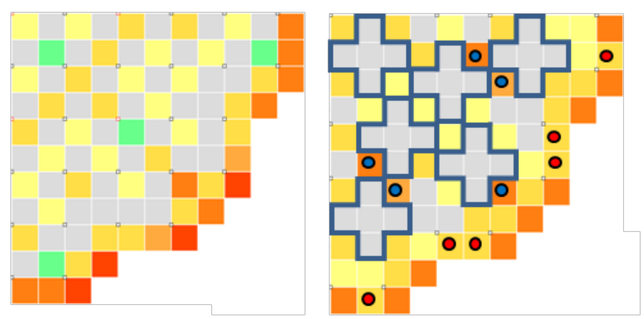


Fig. 11. Equilibrium Cycle, 160 Fresh Loading
Reference vs. ACCD

IV.D. Single and Equilibrium Cycle - Radial Power

In addition to the neutron leakage the relative power at the core periphery (the outermost radial ring when the core is divided in 6 radial equally thick rings) has also been compared for the different core loading alternatives.

TABLE III

Relative Power Reduction at Core Periphery

# Bundle Loaded	***Cycle type, Ave. % diff*** [a]. Single	Equilibrium
152 fresh	-0.9%	-6.7%
160 fresh	-3.1%	-3.7% [b]

[a] *Diff = (ACCD - Reference)/Reference*
[b] *The result used is based on the peripheral optimized core, corresponding to the marked bundles in Fig. 11.*

The values in TABLE III above are averaged over the cycle. The reduced relative power in the peripheral zone of the core confirms that the ACCD concept will reduce neutron fluence on the core's internal and external components, such as moderator barrel and reactor pressure vessel.

V. FUEL CYCLE ECONOMY

Fuel cycle cost (FCC) has been estimated for the same cycles reported above. Beyond those eight cycles also one extra ACCD -160 equilibrium cycle has been studied where the enrichment has been adjusted to give the same discharged burnup as in the Ref. 160 equilibrium cycle. All FCC results are expressed as relative measures, since the results would be valid despite variations in Uranium cost components. U-235 tails that factor in the enrichment process have been set to 0.271%. For comparison purposes, no carrying charges, interest or escalation rates, taxes, revenue delays or lead times are accounted for in the results.

V.A. Single Cycle Results

Referring to TABLE IV for a 152 loaded design the ACCD concept gives a total FCC saving of 0.4% even though the average burnup of the 152 highest exposed bundles at EOC is less (-270 MWd/tU) than in the reference case. ACCD also uses a lower average enriched mix of fresh bundles of 0.016 wt%, which could be translated to a savings of 4.353 kg less of U-235. This also reduces the needed SWU by 0.086 SWU/GWh(e). The ACCD end of cycle conditions shows a longer cycle length up to EOFP by +3.8 EFPD and a power level at EOC that is 0.9% higher than in the reference loaded core. For the 160 loaded designs, the corresponding values of the FCC cost saving are in the magnitude of two to three times higher in favor of the ACCD concept.

TABLE IV

Single Cycle - Non-recurrent Profit:
ACCD vs. Reference

# of Fresh	***Spectrum of fresh*** ACCD	Ref	***Savings in*** Fuel Cycle Cost
152	32/92/28	40/88/24	0.40%
160	32/108/20	48/88/24	1.06%
	Saving in Fuel Cycle Cost as …		
	U-235		SWUs/energy
# of Fresh	Enr. w/o	kg	SWU/GWh(e)
152	0.016	4.353	0.086
160	0.028	8.019	0.219
	Cycle length and Burnup		
	EOFP	@ EOC	Ave. Burnup [a]
# of Fresh	Δ EFPD	Δ Power	Δ MWd/tU
152	+ 3.8	+ 0.9%	- 270
160	+ 7.6	+ 1.8%	- 190

[a] Based on the 152 or 160 highest burnt bundle @ EOC

V.B. Equilibrium Cycle Results

The FCC, in TABLE V shows high savings in favor of the ACCD concept also in equilibrium conditions. The result therefore confirms that introducing the ACCD concept will not only result in a transition cycle profit, it will also give a consistently reduced FCC.

TABLE V

Equilibrium Cycle Profit:
ACCD vs. Reference

# of Fresh	***Spectrum of fresh*** ACCD	Ref	***Energy contr.*** Δ GWh(e)/batch [a]
152	40/88/24	40/88/24	-43/+54/+18
160	48/88/24	48/88/24	+99/-13/+60
	Savings in Fuel Cycle Cost as …		
	FCC	Feed/energy	SWUs/energy
# of Fresh	w/o interest	kgU/GWh(e)	SWU/GWh(e)
152	0.37%	0.096	0.062
160	1.72%	0.460	0.300
	Cycle length and Burnup		
	Cycle Energy		Ave. Dis. Burn.
# of Fresh	Δ EFPD	Δ GWh(e)	Δ MWd/tU
152	+ 2.3	+ 29	+ 160
160	+ 11.0	+ 136	+ 730

From TABLE VI below, it is hard to see any clear trend between the different loading concepts. However, if we also take into account the fact that the ACCD concept gives higher average discharged burnup (TABLE V), the standard deviation and skewness indicate that ACCD will give some higher min-max spread. This spread could be utilized so that some of the lowest exposed bundles could potentially be used for an additional cycle of operation. The skewness and spread is illustrated in Figs. 13 and 14.

TABLE VI

Equilibrium Cycle - Batch Burnup:
On discharged bundle

	Sub-batch		
Ref-152	*2541*	*40001*	*40002*
Ave Dis. Burnup GWd/tU	46.7	41.1	42.2
St-dev in Burnup	4.6%	5.1%	1.9%
Skewness	2.343	-0.419	-0.568
ACCD -152			
Ave Dis. Burnup GWd/tU	45.9	41.6	42.8
St-dev in Burnup	4.8%	10.4%	5.9%
Skewness	-0.390	-2.924	-1.378
Ref-160			
Ave Dis. Burnup GWd/tU	43.3	42.4	34.2
St-dev in Burnup	6.7%	4.9%	25.4%
Skewness	0.684	0.629	-0.530
ACCD -160			
Ave Dis. Burnup GWd/tU	44.9	42.3	35.9
St-dev in Burnup	10.3%	11.7%	17.1%
Skewness	0.813	-2.035	-1.219

Skewness [1] defined as in Eq. (1) below.

$$Skewness = \frac{n}{(n-1)(n-2)}\sum\left(\frac{x_i - x}{\sigma}\right)^3 \qquad (1)$$

From Figs. 13 and 14 it could be noted that for the ACCD concept:

- A major number of bundles within a batch will have a higher and narrower spread in burnup (see batch 40001 as an example).
- The lowest exposed bundles will have a significant lower burnup in the Checkmate[SM] concept. See the marked bundle "red circle" in Fig. 14.

The differences noted for the 152 fresh loaded cores could also be seen in 160 fresh loaded cores. From the results it is evident the lowest exposed discharge bundles will have exposures sufficiently low to allow for subsequent reinsertion after a "cooling" cycle to the fuel pool. Such a reinsertion strategy would drive these bundles towards maximum discharge exposure allowing for maximum uranium utilization. This possible profit is not accounted for in any conclusions.

[1] A distribution is totally symmetric around the mean value if the skewness factor is equal to 0. A negative value indicate in this case a "tail" that hold low burnup fuels, and a positive value indicate a "tail" that hold high burnup fuels, causing a skewed/tilted non symmetric distribution.

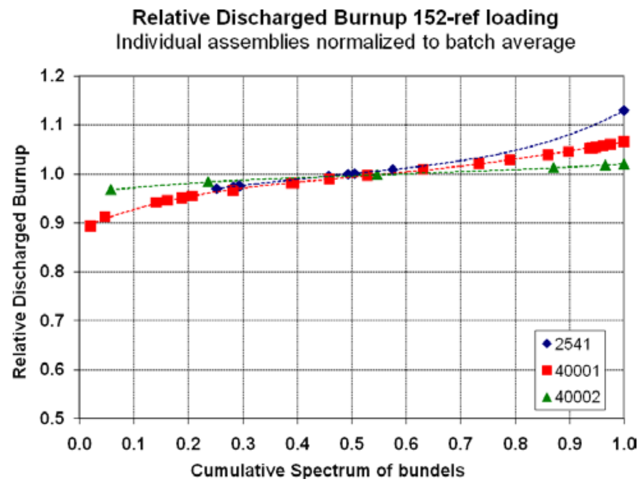


Fig. 13. Skewness and Spread in Discharged Burnup
152 Reference Equilibrium Core

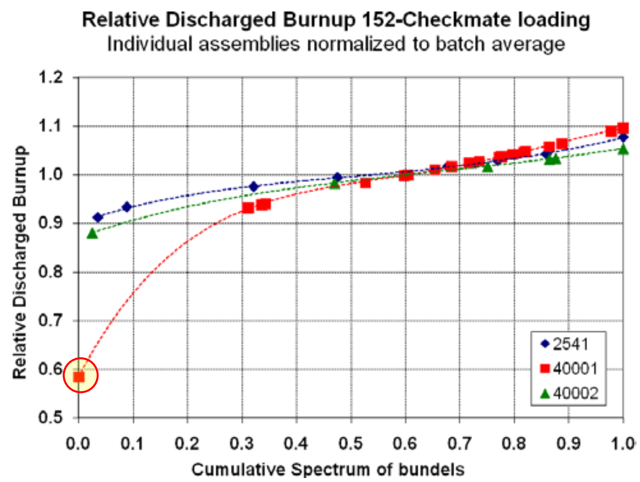


Fig. 14. Skewness and Spread in Discharged Burnup
152 ACCD Equilibrium Core

V.C. Equilibrium Cycle – Adjusted Enrichment

A special study has been done on a 160 fresh loaded ACCD concept trace, where the freshly loaded average U-235 enrichment was adjusted to make the discharged burnup at equilibrium cycle equal to the discharged burnup from the reference loaded equilibrium trace. The result from this type of study reflects the impact (i.e., profit) of using ACCD and is indicative of any limitations that may exist on discharged burnup.

From the result in TABLE VII it could be noted that the gain is reduced by around 2/3 of the one using ACCD with maximum discharged burnup (TABLE V, second line). Even with this big reduction in gain, it is still significant.

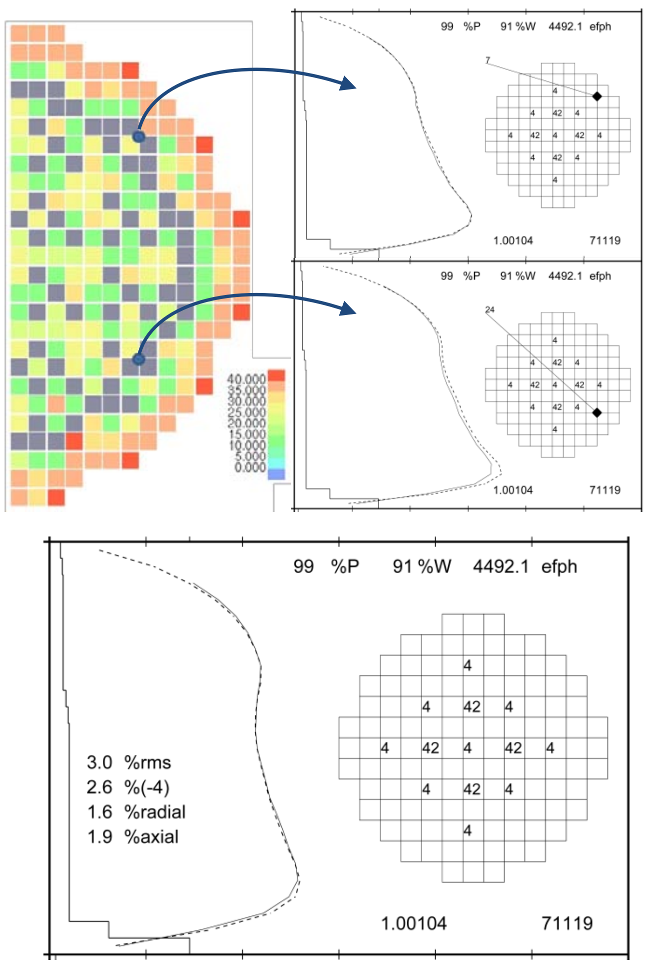
TABLE VII

Equilibrium Cycle - Fixed Dis. Burnup - 42 GWd/tU
160 fresh - ACCD vs. Reference

Savings in …			
Total FCC (Fuel Cycle Cost)	U-235		SWUs/energy SWU/GWh(e)
	Enr. w/o	kg	
0.55%	0.021	6.301	0.129

VI. FACE ADJACENT LOADED CORES

Experience using the Studsvik CMS code package on BWR cores with significant loadings of face adjacent, fresh assemblies show no extra uncertainty or restrictions compared to more evenly distributed core loadings. This is illustrated by Fig. 15, which displays representative TIP comparisons for Olkiluoto-1. Shown are the individual TIP string statistics from two face adjacent regions as well as the core average TIP statistics (nodal, axial and radial RMS values). These results show no bias or increased uncertainty between the individual traces and core average values, for example, a radial or axial power tilt.



The control rod number correspond to individual % withdraw.

Fig. 15. TIP RMS face adjacent core loading

VII. CONCLUSIONS

From the results presented in this paper the following conclusions could be drawn, comparing ACCD with a more traditional checkerboard loading concept.

1. Advanced Checkmate[SM] Core Design results in decreased FCC (from 0.3% - 2%) in transition cycles as well as for the equilibrium cycle.

2. Advanced Checkmate[SM] Core Design results in increased fuel utilization resulting in higher discharged burnup and longer cycle lengths.

3. Advanced Checkmate[SM] Core Design results in a significantly lower neutron leakage, core peripheral power and neutron fluence on the moderator barrel and the reactor pressure vessel.

4. Alternatively, Advanced Checkmate[SM] Core Design may be utilized to provide improved operational flexibility through increased margins:
   +4.2% improvements in thermal margins.
   +0.1% improvement in SDM.

ACKNOWLEDGMENTS

The engineers and specialist at FPL Energy and Duane Arnold Energy Center are acknowledged for their encouragement and illumination of new concepts beyond conventional core design methods.

NOMENCLATURE

Acronym	***Description***
APLHGR	Average Planar LHGR
Coast Down	(CD) Period between EOFP and EOC if power is coasting down due to reactivity deficit.
CPR	Critical Power Ratio
CR	Control Rod
EFPD	Effective Full Power Day
EOC	End Of Cycle = EOFP + CD
EOFP	End Of Full Power
FCC	Fuel Cycle Cost
LHGR	Linear Heat Generation Rate
MFLCPR	Maximum Fraction Limiting CPR
MFLPD	Maximum Fraction Limiting Power Density
SDM	Shutdown Margin
SWU	Separate Work Units – Number of times a unit of natural Uranium needs to be re circu-lated to give desired enrichment and resulting tail.
TIP	Traversing In-Core Probe
TIP RMS	Root Mean Square values comparing Calc. and Measured reaction rate

REFERENCES

1. Checkmate[SM] is a servicemark of Studsvik Scandpower, Inc., USA

   Checkmate, as a brand name for this loading concept, was first used by Studsvik Scandpower AB in a project sponsored by FPL Energy, April (2006).

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