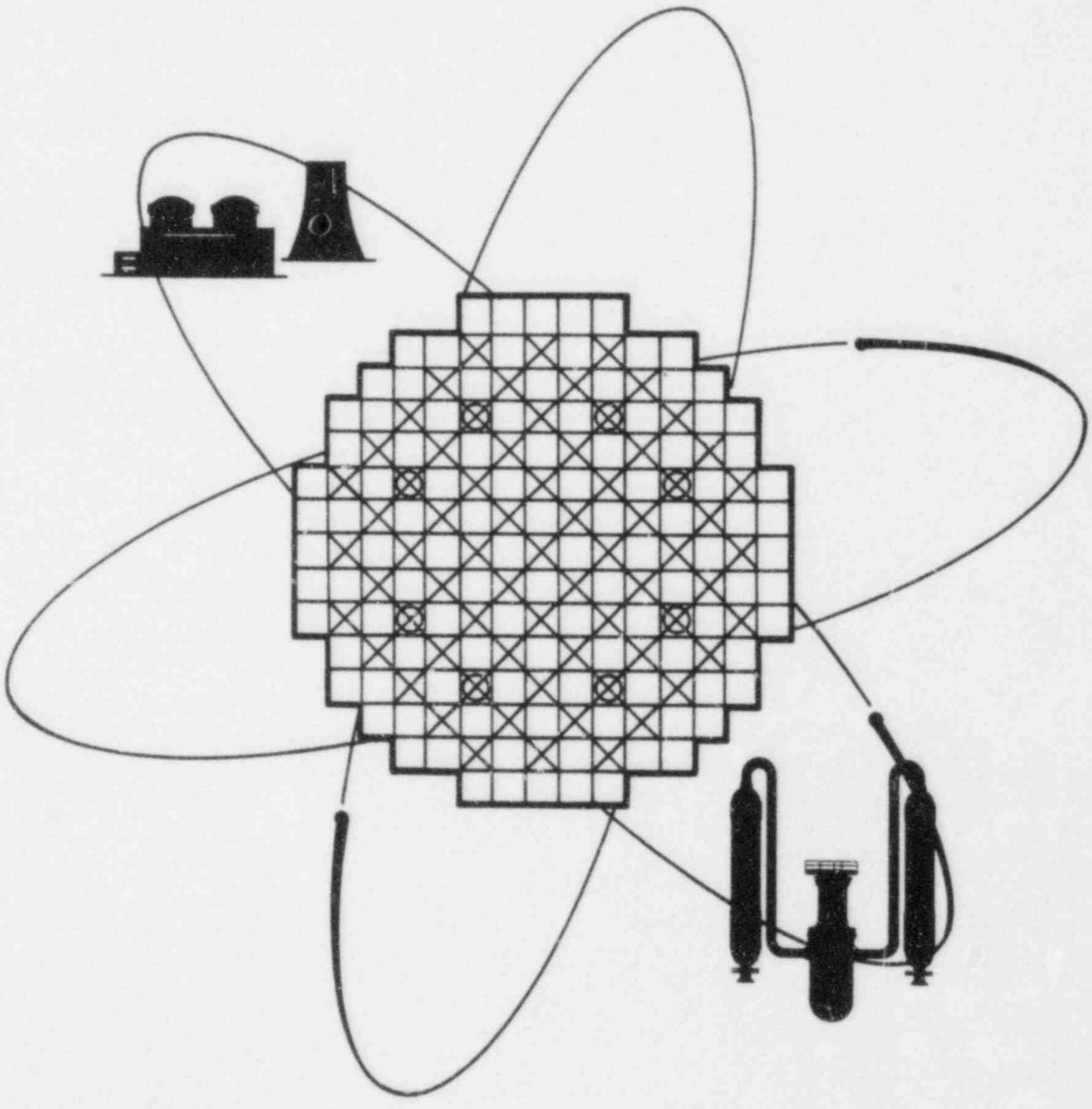
BAW-1884

December 1985

Vessel Fluence Reduction Fuel Cycle Study



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VESSEL FLUENCE REDUCTION
FUEL CYCLE STUDY

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Fuel Management Analysis and Services

Prepared for

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1. INTRODUCTION

This vessel fluence reduction fuel cycle study is Phase 2 of a three-phase project designed to reduce high-energy (>1.0 MeV) neutron fluence on reactor vessel weld material. Of concern is the ability of the vessel weld material to conservatively withstand pressurized thermal shock (PTS), while undergoing increasing embrittlement induced by high-energy neutrons, over the planned lifetime of the plant.

In Phase 1, a computer code, ADJ, was developed to economically correlate the power production in specific fuel assemblies to the fast flux at the reactor vessel inner wall.[1] ADJ uses specially prepared PDQ07 power distribution data, combined with a data file of adjoint fluxes from DOT computer runs generated for specific azimuthal angles relative to the core major axis, to calculate both the fast flux at a specific weld location and the fraction of flux contributed by each assembly. The weld locations considered were at 0, 11, 14, and 19 degrees relative to the core major axis. These angles represent weld locations of interest for the Rancho Seco, Three Mile Island Unit 1, and Oconee Unit 1 reactor vessels.

Phase 2, reported herein, consisted of developing several fuel cycle loading patterns to specifically reduce the fast neutron fluence at the aforementioned weld locations through reducing peripheral assembly power densities over that achieved with the very low leakage (VLL) fuel management scheme reported in reference 2. This was achieved by placing 1) highly burned fuel, 2) fresh lumped burnable poison (LBP) in burned fuel, or 3) fresh fuel containing natural uranium in peripheral assembly locations H15, K15, and L15 (and symmetric locations). Then, the ADJ code was used to assess the fluence reduction for each fuel cycle shuffle scheme. In addition, an analysis of the Technical Specification operating limits was addressed in section 5. The detailed calculations for the Phase 2 analysis are documented in reference 3.

Phase 3 will consist of plant- and cycle-specific work to be determined after the completion of Phases 1 and 2. This would relate the fuel cycle design to reach a given fluence reduction to the specific characteristics of each plant.

2. FUEL SHUFFLE SCHEMES

The basis for all core shuffle patterns was the equilibrium VLL Cycle D developed in reference 2. This scheme employs an in-in-out fuel shuffle arrangement. Fresh fuel, typically containing LBP to control power peaking, is placed in the core interior, intermixed with once-burned fuel assemblies. Twice-burned fuel is placed on the core periphery. This arrangement achieves a significant reduction in core radial neutron leakage relative to the in-out-in (LBP or low leakage) shuffle scheme predominantly used in all B&W operating plants. Typical examples of LBP and VLL fuel shuffle schemes are illustrated in Figures 2-1 and 2-2, respectively.

Before investigating specific vessel fluence reduction shuffle schemes, the results produced in Phase 1 were evaluated to determine the relative contribution of each fuel assembly to the total fluence at a given weld location[1]. The weld locations analyzed in Phase 1 were limited to angles of 0 to 19 degrees relative to the major axis (specifically 0, 11, 14, and 19 degrees). Using the average power distribution of Oconee 1, cycles 3 through 7 as a reference case[1], assemblies H15, K15, and L15 (and symmetrics) were found to contribute most of the fast fluence. The combined total contribution of these assemblies ranged from 86% at 0 degrees to 63% at 19 degrees off the major axis. Therefore, emphasis was placed on reducing the power only in H15, K15, and L15, rather than at other locations on the periphery.

Starting with the base VLL shuffle scheme, several methods were employed to reduce the power in locations H15, K15, and L15: 1) highly burned fuel, 2) burned fuel containing fresh burnable poison rod assemblies (BPRAs), and 3) natural uranium in place of enriched uranium.

Figure 2-1. In-Out-In (LBP) Fuel Loading Diagram

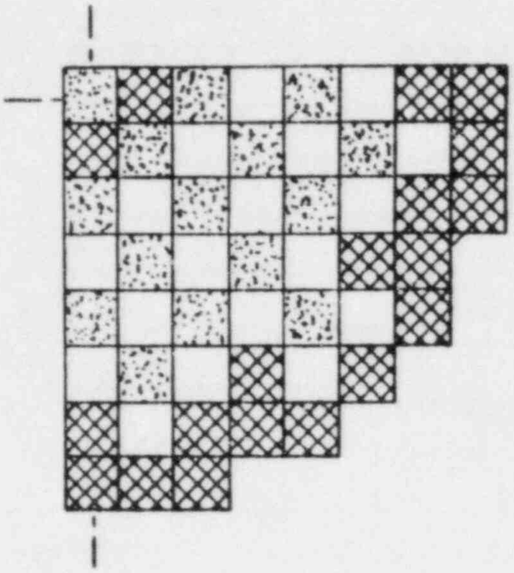
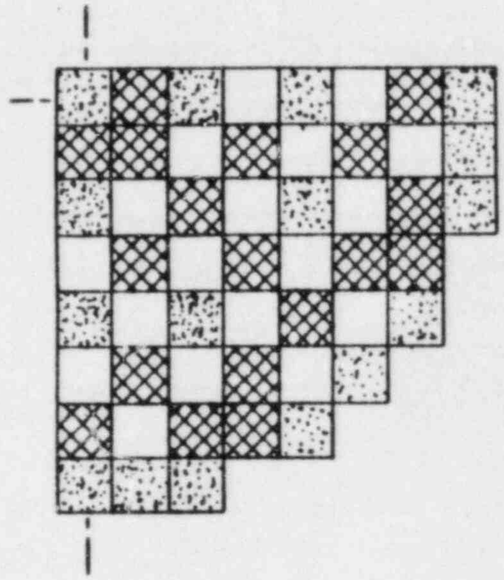
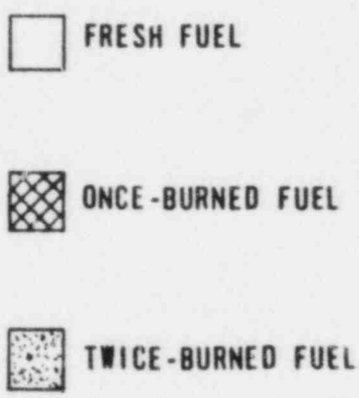


Figure 2-2. In-In-Out (VLL) Fuel Loading Diagram





3. CALCULATIONAL PROCEDURE

The calculations performed for each fuel shuffle scheme proceeded as shown in Figure 3-1. The FCYCLS code was used to develop most of the shuffle schemes for subsequent analysis with PDQ07. FCYCLS is a fast-running, one neutron energy group, nuclear analysis tool for calculating two-dimensional radial assembly average power and burnup distributions. Various trial shuffle schemes were depleted for one cycle. Those schemes showing promise for low peripheral assembly power densities and acceptably low maximum peaking were subsequently evaluated with PDQ07.

The PDQ07 model employed for this study uses two neutron energy groups to calculate two-dimensional pin-by-pin power distributions in quarter-core geometry. Each shuffle scheme was depleted to 415 effective full power days (EFPD) for comparison to the base VLL scheme. The design criteria listed in Table 3-1 were used as a guideline for this study and are consistent with that used in reference 2 (VLL scheme), with the exception of assuming a higher allowable maximum fuel assembly burnup. The key parameters compared in the base VLL scheme and the various vessel fluence reduction schemes included peripheral assembly peaking, maximum peak pin, maximum assembly burnup, and cycle length. In addition, an assessment of the impact on Technical Specification operating limits is addressed in section 5. Each shuffle scheme was depleted for one cycle. One cycle was deemed sufficient to establish the relative merits of each shuffle scheme relative to the VLL. The determination of equilibrium cycle lengths and power peaking is highly dependent on specific plant and cycle conditions and would be performed in Phase 3.

Vessel fluences were calculated from PDQ07 power distributions through a three-step process. The PINPOW code was used to convert PDQ07 partition powers to pin powers. Then, the pin powers for each depletion time step were input to the SORREL code. SORREL calculates the cycle-average pin powers and converts these pin powers from x-y geometry to r-theta geometry. ADJ then combines the r-theta pin power distributions from SORREL with the adjoint flux from a DOT-prepared data file and calculates the fast flux at a given weld location and the fraction of flux contributed by each fuel assembly. Further details concerning ADJ can be found in reference 1.

Table 3-1. Design Criteria and Guidelines

1. Peak pin power calculational limits

   Inner flow zone - 1.587
   Outer flow zone - 1.507

2. Maximum FA burnup calculational limit ~50,000 MWd/mtU

3. Depletion of reactivity conditions

   17 ppm boron
   APSRs inserted (L12 and symmetric locations)
   Hot full power, equilibrium xenon

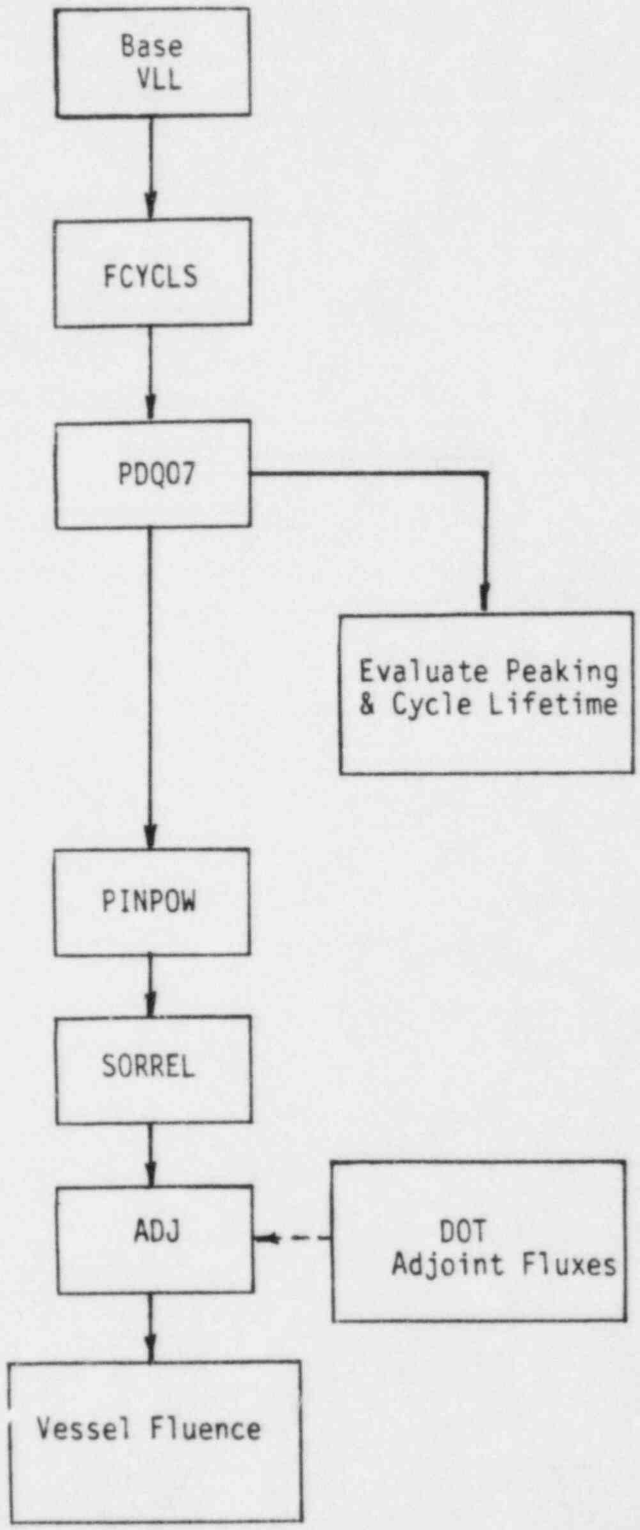
4. No thermal-hydraulic feedback

5. Constant feed batch configuration of 64-FAs at 3.36 wt % U-235.

6. All full-length control rods fully withdrawn.

7. Power level - 2568 MWt.

Figure 3-1. Vessel Fluence Calculations



4. RESULTS

This section describes the PDQ07 and ADJ results for the various vessel fluence reduction schemes relative to the base VLL design described in reference 2. In addition, similar results from the LBP shuffle scheme[2] are included since this type of scheme is typical of that currently used in B&W operating plants. The core loading diagrams for each of these schemes are shown in Figures 4-1 and 4-2.

4.1. PDQ07 and FCYCLS Results

Four vessel fluence reduction schemes were investigated in detail. Each scheme was a basic modification to the VLL scheme, with the specific intent to reduce the power and flux in locations H15, K15, and L15 (and symmetrics). In two schemes, designated as ULLNAT1 and ULLNAT2, assemblies containing natural uranium, rather than conventional enriched uranium, were used to reduce peripheral powers. Another scheme used fresh LBP inserted in the burned fuel in these locations (ULLBP1), and the fourth scheme used very high burnup fuel (45,000 MWd/mtU) to lower peaking (ULLHBU). The core loading diagrams for each of these schemes are shown in Figures 4-3 through 4-6 and the LBP loadings are shown in Figure 4-7.

Each scheme was depleted to 415 EFPD, then compared to the VLL scheme. Table 4-1 shows the key parameters of maximum pin peak, K15 and L15 average RPD (indicative of the peripheral peaking most affecting vessel welds of interest), maximum assembly burnup, cycle length impact relative to the VLL scheme, and relative negative imbalance limit impact. For additional comparison, data from the LBP shuffle scheme are also included. Detailed power peaking data for each vessel fluence reduction scheme can be found in reference 3. Figures 4-8 and 4-9 give the cycle-average assembly radial RPDs (eighth-core) for the LBP and VLL schemes, and the vessel fluence reduction schemes, respectively.

As shown in Table 4-1 and Figure 4-9, each fluence reduction scheme, particularly the natural uranium scheme designated ULLNAT1, produced substantially lower peripheral peaking than the VLL. The peripheral peaking, K15 and L15 average of 0.178, is the lowest of all patterns investigated. While the peak pin (1.551) meets the peaking guidelines given in Table 3-1, subsequent evaluation (see section 5) suggests that this scheme would require more restrictive operational limits. Another natural uranium pattern, ULLNAT2, was developed that would achieve a peak pin comparable to the VLL scheme, but at the expense of slightly higher peripheral power and shorter cycle length.

The LBP scheme, ULLBP1, with 1.8 wt % B_4C BPRAs produced a peak pin of 1.534. This peak is higher than desirable but through pattern optimization the peak pin could be reduced to that comparable to the VLL, yet maintain approximately the same peripheral power. The high-burnup scheme, ULLHBU, was depleted with H15, K15, and L15 starting with assembly burnups of 45,000 MWd/mtU (3.36 wt % U-235 initial enrichment). The FCYCLS code was used to calculate this cycle because of the ease with which high-burnup fuel could be modelled. Since FCYCLS is a nodal code, it only calculates assembly average RPDs. However, by careful comparison to the PDQ07 calculations in the other shuffle schemes, an accurate estimate of 1.505 for the pin peak was made. The peripheral RPD of 0.246 for ULLHBU is comparable to the 0.228 value of the ULLBP1 scheme. Starting with an assembly burnup of 45,000 MWd/mtU, this scheme naturally produced the highest end-of-cycle (EOC) assembly burnup of all schemes with 48,753 MWd/mtU. Burnup limits for fuel assembly designs currently undergoing irradiation do not allow burnups this high, but burnup limits for future assembly designs can allow limits in excess of 50,000 MWd/mtU. Alternatively, fuel of lower initial enrichment and burnup could provide the equivalent reactivity for lowering peripheral RPDs.

All four schemes exhibited cycle lengths of 10 to 15 EFPD shorter than the VLL because of the reduced reactivity contribution from H15, K15, and L15. The 10 to 15 EFPD should be viewed with caution since the vessel fluence reduction schemes are not "equilibrium" cycles and are therefore not directly comparable to the VLL. However, it gives an indication of the relative cycle lengths achievable between the various designs.

4.2. ADJ Results

Following the PDQ calculations, ADJ was run for each scheme to calculate the fast flux (>1.0 MeV) at angles of 0, 11, 14, and 19 degrees relative to the major axis. The fluxes for the LBP and VLL designs were also computed for comparison, as were the results obtained from reference 1 for the average power distribution of Oconee Unit 1 cycles 3 through 7. These cycles of Oconee represent a composite of out-in and LBP type shuffle schemes and are typical of the average peripheral peaking experienced by many operating reactors to date. The resulting fast flux data for the schemes above are compared in Table 4-2. Also shown is the ratio of calculated flux to the corresponding value of both the VLL scheme and the average of Oconee 1 cycles 3 through 7. These ratios illustrate the substantial reductions achieved both with the VLL relative to earlier fuel management schemes, and the various vessel fluence reduction schemes relative to the VLL. For example, the ULLNAT2 pattern was 20 to 30% lower than the VLL scheme and 60 to 66% lower than the average of Oconee 1 cycles 3 through 7 between the angles of 0 to 19 degrees. The preceding fluxes calculated with ADJ assume 2568 MWt operation and a flat axial core power shape. In addition to overall flux reduction, these results indicate that the angular position of peak vessel flux changes from approximately 11 to 19 degrees (and possibly higher angles). Extending the ADJ results to actual, yet conservative, operating conditions is addressed in the next section.

4.3. Vessel Fluence Results

This section presents specific examples of the vessel fluences calculated for the various fuel shuffle schemes and the impact of these schemes on vessel lifetime, relative to Nuclear Regulatory Commission (NRC) calculations presented in their "NRC Staff Evaluation of Pressurized Thermal Shock."[4] Rancho Seco and Oconee 1 were selected for specific analysis; however, the ADJ results can easily be applied to other B&W plants as well.

In the previous section, the fluxes calculated with ADJ were based on 2568 MWt operation and two-dimensional RPDs. Extending ADJ to actual operating conditions requires the addition of an axial shape factor, normalization to actual rated power, and corrections to account for measured versus calculated fluences obtained from specimen capsule analyses. For illustrative purposes only, a conservative average axial shape factor of 1.17 and a 1.26 correction factor based on specimen capsule analyses[5] were applied. The ADJ calculated fluxes were converted to maximum fluences per effective full power year (EFPY) at the limiting weld locations for Oconee Unit 1 (19 degrees) and Rancho Seco (14 degrees). Using the calculated additional fluence required to reach the screening criteria for Oconee Unit 1 and Rancho Seco (updated from reference 4 from December 31, 1981 to January 1, 1986, assuming operation with an LBP low-leakage shuffle scheme), the EFPY needed to reach these criteria were calculated and compared to the remaining EFPY for each plant. For Oconee 1, the remaining EFPY was calculated assuming a 32-EFPY lifetime, and for Rancho Seco, an 80% capacity factor was assumed for operation over the remainder of the licensed operating period (October 11, 2008). The results for each scheme are shown in Table 4-3 for Oconee Unit 1 and Rancho Seco. For both Oconee Unit 1 and Rancho Seco, the results show that converting to the base VLL scheme is sufficient to increase the EFPY to reach the screening criteria well above the remaining plant lifetime. Consequently, further vessel fluence reduction may not be necessary.

Table 4-1. Comparison of Vessel Fluence Reduction Schemes[a]

Pattern	Code used	Maximum pin peak	K15 and L15 RPD avg. for cycle	Maximum Assembly Burnup, MWd/mtU	Relative cycle length impact, EFPD	Relative Tech. Spec. negative imbalance limit reduction, %
Reference Patterns						
LBP	PDQ07	1.483	0.484	41112	-5	-1.2
VLL	PDQ07	1.501	0.300	42095	--	0.0
Natural Uranium in H15, K15, L15						
ULLNAT1	PDQ07	1.551	0.178	42384	-10	3.3
ULLNAT2	PDQ07	1.511	0.186	44129	-15	0.7
Fresh LBP in H15, K15, L15						
ULLBP1	PDQ07	1.534	0.228	42344	-10	2.2
High-Burnup Fuel in H15, K15, L15						
ULLHBU	FCYCLS	1.505	0.246	48753	-10	0.3

[a] 64 feed, 3.36 wt % U-235.

Table 4-2. Fast Flux (>1.0 MeV) at the Vessel Wall

Shuffle Scheme	Angle, degrees	Fast Flux, $n/cm2\text{-}sec \times 10^{-9}$	Fast Flux Ratios: Relative to VLL	Fast Flux Ratios: Relative to Oconee 1 Cy 3-7
Oconee 1 Cy 3-7 Average	0	9.417	1.97	- -
	11	9.979	2.05	- -
	14	9.920	2.06	- -
	19	9.321	1.98	- -
LBP	0	7.168	1.50	0.76
	11	7.421	1.52	0.74
	14	7.291	1.51	0.73
	19	6.748	1.43	0.72
VLL	0	4.770	- -	0.51
	11	4.869	- -	0.49
	14	4.822	- -	0.49
	19	4.713	- -	0.51
ULLNAT1	0	3.171	0.66	0.34
	11	3.343	0.69	0.34
	14	3.413	0.71	0.34
	19	3.669	0.78	0.39
ULLNAT2	0	3.239	0.68	0.34
	11	3.371	0.69	0.34
	14	3.446	0.72	0.35
	19	3.752	0.80	0.40
ULLBP1	0	3.736	0.78	0.40
	11	3.891	0.80	0.39
	14	3.918	0.81	0.40
	19	4.043	0.86	0.43
ULLHBU[a]	0	4.031	0.85	0.43
	11	4.198	0.86	0.42
	14	4.227	0.88	0.43
	19	4.362	0.93	0.47

[a] Estimated using ULLBP1 x 0.246/0.228

Table 4-3. Estimate of Additional Years to Reach Screening Criteria[a] for Oconee 1 (19 degrees) and Rancho Seco (14 degrees)

Shuffle Scheme	Add'l fluence to reach screen. criteria, $n/cm^2 x10^{19}$	Fluence/EFPY, $n/cm^2 x10^{19}$	EFPY to reach screen. crit.	EFPY Left in plant life	Fluence reduction factor
Oconee 1 (8.30 EFPY)					
NRC estimate[b]	0.955	0.054	17.69	23.70	1.34
LBP low leak	0.955	0.03137	30.44	23.70	0.78
VLL	0.955	0.02191	43.59	23.70	0.54
ULLNAT1	0.955	0.01706	55.98	23.70	0.42
ULLNAT2	0.955	0.01744	54.76	23.70	0.43
ULLBP1	0.955	0.01880	50.80	23.70	0.47
ULLHBU	0.955	0.02028[c]	47.09	23.70	0.50
Rancho Seco (5.32 EFPY)					
NRC estimate[b]	0.500	0.058	8.62	18.22[d]	2.11
LBP low leak	0.500	0.03659	13.66	18.22	1.33
VLL	0.500	0.02420	20.66	18.22	0.88
ULLNAT1	0.500	0.01713	29.19	18.22	0.62
ULLNAT2	0.500	0.01729	28.92	18.22	0.63
ULLBP1	0.500	0.01966	25.43	18.22	0.72
ULLHBU	0.500	0.02121[c]	23.57	18.22	0.77

(a) Screening criteria are as of January 1, 1986.

(b) NRC value from the PTS report updated to January 1, 1986.

(c) Estimated.

(d) Based on the October 11, 2008 license expiration and an 80% capacity factor.

Figure 4-1. LBP Cycle D, Assembly Burnup Distribution

	8	9	10	11	12	13	14	15
H	11B 30341 41112	12 17353 30660	11B 24596 38511	13 0 17774	11B 24002 38886	13 0 17356	12 17366 30307	12 17770 24798
K	12 17351 30668	11B 23786 36959	13 0 17261	11B 23791 38563	13 0 17371	11B 21304 35794	13 0 14324	12 14280 21419
L	11B 24584 38516	13 0 17267	11B 23995 38770	13 0 17355	11B 21762 34954	13 0 15965	12 11941 23577	12 16207 21481
M	13 0 17782	11B 23809 38584	13 0 17363	11B 22455 37000	13 0 16189	12 17289 30093	12 15950 24079	
N	11B 24002 38890	13 0 17376	11B 21760 34959	13 0 16190	11B 22436 35099	13 0 11937	12 17374 22666	
O	13 0 17359	11B 21299 35793	13 0 15967	12 17291 30090	13 0 11921	12 17367 23769		
P	12 17366 30309	13 0 14327	12 11925 23565	12 15945 24072	12 17373 22659			
R	12 17775 24802	12 14276 21415	12 16207 21481	LBPCYD Batch ID LBPCYD T0 Burnup (MWd/mtU) LBPCYD T410 Burnup (MWd/mtU)				

Batch	Edit Set	Fuel Assembly	Initial wt% U-235	T0 Burnup MWd/mtU	T410 Burnup MWd/mtU	Delta Burnup MWd/mtU
11B	89	49	3.36	23067	37074	14007
12	90	64	3.36	15995	24759	8764
13	91	64	3.36	0	15997	15997
CORE	53	177	3.36	12169	25000	12831

Figure 4-2. VLL Cycle D, Assembly Burnup Distribution

	8	9	10	11	12	13	14	15
H	11B 29919 42095	12 14375 29446	11B 26534 40866	13 0 18120	11B 26482 41125	13 0 17066	12 16967 29271	11B 29542 34407
K	12 14375 29447	12 17897 33551	13 0 18151	12 17950 34674	13 0 17646	12 15851 31483	13 0 14437	11B 31649 36203
L	11B 26534 40870	13 0 18163	12 17954 35105	13 0 18048	11B 25152 38241	13 0 15919	12 17308 27331	11B 34874 38091
M	13 0 18125	12 17962 34691	13 0 18041	12 17945 34480	13 0 17427	12 12167 26106	12 17537 25027	
N	11B 26482 41127	13 0 17645	11B 25140 38216	13 0 17367	12 14373 29347	13 0 12266	11B 27528 31912	
O	13 0 17070	12 15833 31469	13 0 15909	12 12123 26032	13 0 12226	11B 29918 35070		
P	12 16965 29273	13 0 14440	12 17249 27279	12 17531 25015	11B 27500 31882			
R	11B 29538 34405	11B 31635 36192	11B 34891 38109	VLLCYD Batch ID VLLCYD T0 Burnup (MWd/mtU) VLLCYD T415 Burnup (MWd/mtU)				

Batch	Edit Set	Fuel Assembly	Initial wt% U-235	T0 Burnup MWd/mtU	T415 Burnup MWd/mtU	Delta Burnup MWd/mtU
11B	89	49	3.36	29251	36803	7552
12	90	64	3.36	16314	30019	13705
13	91	64	3.36	0	16430	16430
CORE	53	177	3.36	13996	26984	12987

Figure 4-3. ULLNAT1 Core Loading and Assembly Burnup Distribution

	8	9	10	11	12	13	14	15
H	11B 29919 42384	12 14375 29797	11B 26534 41211	13 0 18564	11B 26482 41505	13 0 17683	12 16967 28954	13A 0 2735
K	12 14375 29798	12 17897 33918	13 0 18590	12 17950 35061	13 0 18038	12 15851 31661	13 0 14095	13A 0 2685
L	11B 26534 41215	13 0 18602	12 17954 35500	13 0 18464	11B 25152 38500	13 0 16060	12 17308 27184	13A 0 1930
M	13 0 18569	12 17962 35078	13 0 18458	12 17945 34834	13 0 17771	12 12167 26302	12 17537 25005	
N	11B 26482 41507	13 0 18037	11B 25140 38474	13 0 17710	12 14373 29637	13 0 12487	11B 27528 31972	
O	13 0 17686	12 15833 31647	13 0 16051	12 12123 26226	13 0 12447	11B 29918 35174		
P	12 16965 28955	13 0 14099	12 17249 27133	12 17531 24993	11B 27500 31942			
R	13A 0 2736	13A 0 2686	13A 0 1931	ULLNAT1 Batch ID ULLNAT1 T0 Burnup (MWd/mtU) ULLNAT1 T415 Burnup (MWd/mtU)				

Batch	Edit Set	Fuel Assembly	Initial wt% U-235	T0 Burnup MWd/mtU	T415 Burnup MWd/mtU	Delta Burnup MWd/mtU
11B	89	29	3.36	26998	37155	10158
12	90	64	3.36	16314	30183	13869
13	91	64	3.36	0	16698	16698
13A	8	20	0.711	0	2394	2394
CORE	53	177	3.36	10322	23309	12987

Figure 4-4. ULLNAT2 Core Loading and Assembly Burnup Distribution

	8	9	10	11	12	13	14	15
H	11B 29919 41838	12 16967 31699	11B 26534 40927	13 0 18264	11B 29918 44119	13 0 17503	12 14375 26953	13A 0 2861
K	12 16965 31702	12 17897 33399	13 0 17940	12 17950 34754	13 0 17984	12 15851 31878	13 0 14537	13A 0 2799
L	11B 26534 40945	13 0 17980	11B 26482 41484	13 0 17965	11B 25152 38568	13 0 16419	12 17308 27499	13A 0 2008
M	13 0 18287	12 17962 34797	13 0 17989	12 17945 34684	13 0 17805	12 12167 26645	12 17537 25272	
N	11B 29918 44129	13 0 17995	11B 25140 38550	13 0 17745	12 14373 30005	13 0 12932	11B 27528 32211	
O	13 0 17511	11B 15833 31868	13 0 16413	12 12123 26570	13 0 12888	12 17954 24796		
P	12 14373 26958	13 0 14542	12 17249 27448	12 17531 25260	11B 27500 32179			
R	13A 0 2862	13A 0 2800	13A 0 2009	ULLNAT2 Batch ID ULLNAT2 T0 Burnup (MWd/mtU) ULLNAT2 T415 Burnup (MWd/mtU)				

Batch	Edit Set	Fuel Assembly	Initial wt% U-235	T0 Burnup MWd/mtU	T415 Burnup MWd/mtU	Delta Burnup MWd/mtU
11B	89	29	3.36	26998	38415	11418
12	90	64	3.36	16314	29596	13282
13	91	64	3.36	0	16682	16682
13A	8	20	0.711	0	2496	2496
CORE	53	177	3.36	10322	23309	12987

Figure 4-5. ULLBP1 Core Loading and Assembly Burnup Distribution

	8	9	10	11	12	13	14	15
H	11B 29919 42344	12 14375 29746	11B 26534 41150	13 0 18450	11B 26482 41310	13 0 17058	12 16967 28804	11B 29542 33183
K	12 14375 29747	12 17897 33862	13 0 18515	12 17950 34970	13 0 17880	12 15851 31498	13 0 13946	11B 31649 35087
L	11B 26534 41154	13 0 18527	12 17954 35432	13 0 18383	11B 25152 38434	13 0 16009	12 17308 27102	11B 34874 37353
M	13 0 18455	12 17962 34987	13 0 18377	12 17945 34770	13 0 17709	12 12167 26269	12 17537 25025	
N	11B 26482 41312	13 0 17880	11B 25140 38409	13 0 17647	12 14373 29589	13 0 12454	11B 27528 31967	
O	13 0 17061	12 15833 31484	13 0 15999	12 12123 26194	13 0 12414	11B 29918 35158		
P	12 16965 28805	13 0 13950	12 17249 27050	12 17531 25013	11B 27500 31937			
R	11B 29538 33181	11B 31635 35075	11B 34891 37371	ULLBP1 Batch ID ULLBP1 T0 Burnup (MWd/mtU) ULLBP1 T415 Burnup (MWd/mtU)				

Batch	Edit Set	Fuel Assembly	Initial wt% U-235	T0 Burnup MWd/mtU	T415 Burnup MWd/mtU	Delta Burnup MWd/mtU
11B	89	49	3.36	29251	36492	7241
12	90	64	3.36	16314	30112	13798
13	91	64	3.36	0	16575	16575
CORE	53	177	3.36	13996	26984	12987

Figure 4-6. ULLHBU Core Loading and Assembly Burnup Distribution

	8	9	10	11	12	13	14	15
H	11B 29919 41800	12 16967 31586	11B 26534 40825	13 0 18351	11B 29918 44015	13 0 17547	12 14375 26843	11B 45000 48753
K	12 16967 31586	12 17897 33281	13 0 18038	12 17950 34509	13 0 17862	12 15851 31662	13 0 13718	11B 45000 48650
L	11B 26534 40825	13 0 18038	11B 26534 41351	13 0 17838	11B 25152 38667	13 0 16327	12 17308 27435	11B 45000 47732
M	13 0 18351	12 17950 34509	13 0 17838	12 17954 34274	13 0 17591	12 12167 26470	12 17537 25473	
N	11B 29918 44015	13 0 17862	11B 25152 38667	13 0 17591	12 14375 29999	13 0 12926	11B 27528 32303	
O	13 0 17547	12 15851 31662	13 0 16327	12 12167 26470	13 0 12926	12 17954 24997		
P	12 14375 26843	13 0 13718	12 17308 27435	12 17537 25473	11B 27528 32303			
R	11B 45000 48753	11B 45000 48650	11B 45000 47732	ULLHBU Batch ID ULLHBU T0 Burnup (MWd/mtU) ULLHBU T415 Burnup (MWd/mtU)				

Batch	Fuel Assembly	Initial wt% U-235	T0 Burnup MWd/mtU	T415 Burnup MWd/mtU	Delta Burnup MWd/mtU
11B	49	3.36	34353	42457	8104
12	64	3.36	16322	29505	13183
13	64	3.36	0	16531	16531
CORE	177	3.36	15412	28399	12988

Figure 4-7. LBP Loadings

	8	9	10	11	12	13	14	15
H				1.1 1.8 1.8 1.8		0.8 1.4 0.8 1.4		
K			1.1 1.8 1.8 1.8		1.1 1.4 1.4 1.4		0.5 0 0 0	
L				1.1 1.8 1.8 1.8		0.8 0.8 0.8 0.8		
M					1.1 1.1 1.1 1.4			
N						0.2 0.2 0.2 0.5		
O								

LBP
VLL and ULLBPI
ULLNAT1
ULLNAT2 and ULLHBU

Figure 4-8. Cycle Average RPDs for LBP and VLL Reference Cycles

	8	9	10	11	12	13	14	15
H	0.839 0.938	1.037 1.160	1.084 1.104	1.385 1.395	1.160 1.128	1.353 1.314	1.009 0.947	0.548 0.375
K		1.027 1.205	1.345 1.398	1.151 1.288	1.354 1.359	1.129 1.204	1.116 1.112	0.556 0.351
L			1.152 1.321	1.353 1.390	1.028 1.008	1.244 1.226	0.907 0.772	0.411 0.248
M				1.134 1.273	1.262 1.342	0.998 1.073	0.634 0.577	
N					0.987 1.153	0.930 0.944	0.412 0.338	
O						0.499 0.397		

Figure 4-9. Cycle Average Assembly RPDs for Vessel Fluence Reduction Schemes

	8	9	10	11	12	13	14	15
H	0.960 0.918 0.957 0.915	1.187 1.134 1.184 1.126	1.130 1.108 1.125 1.100	1.429 1.406 1.421 1.413	1.157 1.093 1.142 1.085	1.362 1.348 1.313 1.351	0.923 0.969 0.911 0.960	0.211 0.220 0.280 0.289
K		1.234 1.194 1.229 1.185	1.431 1.381 1.426 1.392	1.318 1.294 1.311 1.275	1.389 1.385 1.377 1.375	1.217 1.234 1.205 1.217	1.085 1.119 1.074 1.056	0.207 0.216 0.265 0.281
L			1.351 1.155 1.346 1.141	1.422 1.383 1.415 1.374	1.028 1.033 1.023 1.041	1.237 1.264 1.233 1.257	0.760 0.785 0.754 0.780	0.149 0.155 0.191 0.210
M				1.300 1.289 1.296 1.257	1.368 1.371 1.365 1.355	1.098 1.115 1.086 1.101	0.575 0.596 0.577 0.611	
N					1.175 1.204 1.172 1.203	0.961 0.996 0.959 0.995	0.342 0.361 0.342 0.368	
O						0.405 0.527 0.403 0.542		

ULLNAT1
ULLNAT2
ULLBP1
ULLHBU

5. OPERATING LIMIT ASSESSMENT

5.1. Base Limits

The most restrictive power peaking-related Technical Specification limits are normally the negative imbalance limits at full power. The two criteria that determine these are the loss-of-coolant accident (LOCA) kW/ft and the initial condition (IC) departure from nucleate boiling (DNB) maximum allowable peaking (MAP) limits. Each of these criteria will be discussed separately.

5.1.1. LOCA Based Limits

The LOCA kW/ft criteria normally determine the negative imbalance limit. A 1% increase in the radial power peak will reduce the imbalance limit by approximately 1%. Therefore, the impact on a specific fuel cycle can be estimated by reducing the current offset limit by the amount of margin between 1.501 and the pin peaks given in Table 4-1. For example, if the current limit is -12% imbalance and the ULLNAT1 option (1.551 pin peak) is used, then the margin difference between 1.551 and 1.501 is 3.3% and the new imbalance limit will be approximately -12 + 3.3 = -8.7% imbalance. A pin peak of 1.501 is used as the base since it, like the values in Table 4-1, reflects no thermal feedback. In this example, if a limit of -10% imbalance is required for operation, then a margin improver that affects LOCA margin by at least 1.3% is needed.

5.1.2. IC-DNB Based Limits

The IC-DNB peaking margin is not a strong function of imbalance. Therefore, a lack of positive IC-DNB margin will tend to limit the maximum achievable power rather than restrict the imbalance limits. In this evaluation, negative margin can be understood as a reduction in the rated power level. The maximum acceptable pin peaking for fuel cycle designs is 1.50 ± 0.02. This value reflects the closed-channel DNB analysis and no thermal feedback in the peaking evaluation. The ± 0.02 variation accounts for the variation of the actual margin due to loading differences from one fuel cycle to the next. Elimination of this unknown requires a three-dimensional evaluation of a specific fuel cycle.

If the ULLNAT1 option is considered with respect to IC-DNB margin, the margin difference is 3.3%. Since a variation of 2% in the fuel cycle design limit is possible, a 5% IC-DNB should be considered unless each specific fuel cycle design is evaluated for margin during the fuel cycle design process.

5.2. Margin Improvers

Margin improvers are available for most of the vessel fluence reduction schemes. The following list of improvers is provided to allow the choice to be tailored to the specific needs of the utility. Each type of limiting criteria needs to be addressed, but the same amount of margin improvement is not necessarily needed for each type, as shown in the examples above.

Table 5-1. Margin Improvers

	Improvement	
Option	LOCA	IC-DNB
Crossflow with Design Peak Modification	0%	4%
Statistical Core Design	0%	5%
Fixed Margin Technical Specification	10%	5%
Imbalance Error Reanalysis	2%	0%

6. SUMMARY AND CONCLUSIONS

This report examined several fuel management schemes for reducing the fast flux to the reactor vessel wall for a specified range of weld locations. These schemes built upon the results attained from the VLL design by further reducing peripheral assembly powers in locations symmetric to H15, K15, and L15. From an analysis of these schemes, the following conclusions are drawn:

1. The base VLL design offers a substantial vessel fluence reduction relative to typical previous fuel cycles, and may be sufficient for some utilities seeking to substantially reduce vessel fluence.
2. Shuffle schemes providing additional fluence reductions up to 30% lower than the VLL, and over 60% lower relative to typical previous cycles, can be implemented without unusual design modifications.
3. These fluence reductions can be realized without significantly affecting Technical Specification operating limits, relative to the VLL design. However, as addressed in reference 2, implementing the VLL design may entail additional core-specific physics, thermal-hydraulic, and safety analysis work relative to current fuel management schemes. The same is true for the schemes examined in this report.
4. Further reducing vessel fluence while maintaining maximum pin peaking comparable to the VLL design inherently requires fuel loadings that shorten cycle length, for a given feed batch size and enrichment. Cycle lengths may be reduced up to a maximum of 10 to 15 EFPD relative to that attainable with the VLL design.
5. Selectively reducing peripheral assembly RPDs can shift the angular location of the peak vessel flux, possibly causing another weld location to be limiting. In addition, decisions regarding placement of vessel

cavity dosimetry at the peak flux location may be influenced by the type of vessel fluence reduction scheme to be implemented.

Implementing one of the vessel fluence reduction schemes addressed in this report will necessitate the careful plant-specific evaluation of the desired level of fluence reduction relative to the economic considerations associated with

- Potentially shorter cycle lengths than attainable with the VLL.
- Irradiating fuel assemblies to very high burnup.
- Fabricating fuel assemblies containing natural uranium (or tails). Due to the very low incremental burnup that these assemblies would experience each cycle, the maximum residency time would be much longer than for typical fuel assemblies. The evaluation of maximum achievable residency time would need to be addressed in future mechanical design analyses.
- Alternative schemes, such as combination of very highly burned fuel and fresh LBP, may result in fluence reductions approaching that attained with natural uranium.

7. REFERENCES

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