Burnup study of 18 months and 16/20 months cycle AP1000 cores using CASMO4E and SIMULATE-3 codes

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Abstract: AP1000 reactor is an advanced pressurized water reactor equipped with passive safety systems. AP1000 reactor core is designed for 18 month cycle length and can also be used for 16/20 month alternate cycle lengths to meet energy requirements during high demand periods. The purpose of this study is to analyze the feasibility of AP1000 core for both 18 and 16/20 alternate cycle lengths by using CASMO4E and SIMULATE-3 code package. For this purpose, burnup analysis of both the schemes is carried out from initial core loading through optimized transition cores to equilibrium core. The study is performed by modeling three dimensional full core in SIMULATE-3 with each fuel assembly divided into 40 axial and 4 radial quadrant nodes. Once and twice burned fuel reloading from one cycle to the next and removal of burnable poison rods from the core after first cycle options are used in these codes. The results of this study indicate that both the cycle schemes can be utilized by varying the core loading pattern. Moreover, reactivity coefficients, total power peaking factors and enthalpy rise factors are calculated which indicate that the AP1000 core provide adequate safety margins in both the cycle schemes.

Keyword: AP1000; burnup analysis; CASMO4E; SIMULATE-3

1 Introduction

AP1000 is an advanced passive pressurized water reactor designed to produce 1117 MWe (~3400 MWth). The reactor is designed for 18 month cycle length with provision to be used for 16 and 20 month alternate cycle length for optimized economy [1]. Both operating schemes have different reload core configuration, differing in fuel enrichment, number of burnable absorber rods and fuel loading pattern. In this study, core burnup analysis of both the cycle schemes is performed for typical AP1000 core from initial cycle to equilibrium cycle.

AP1000 core is composed of 157 fuel assemblies. Each assembly consists of 264 fuel rods, 24 control rod guide tubes and one central instrumentation guide tube, arranged in a 17 x 17 square array. Initial core design uses discrete burnable absorbers (PYREX) and integral fuel burnable absorbers (IFBA). PYREX is a borosilicate glass whereas IFBA rod is a fuel rod with thin boride coating on the fuel. These rods are arranged in different patterns within a fuel assembly and their function is to partly control the core excess reactivity, to limit power peaking factors and to keep the moderator temperature coefficient (MTC) negative at normal operating conditions.

In order to control relatively rapid reactivity changes and axial power distribution, control rod cluster assemblies are used. AP1000 core contain 69 such assemblies, each consist of 24 absorber rods. Two types of control rod cluster assemblies are used, *i.e.* black and gray. Absorber material of black rod is an alloy of Ag-In-Cd clad in stainless steel. The gray rod cluster assembly is similar to black rod cluster control assembly except that 20 out of 24 rodlets are made up of stainless steel; the remaining 4 are made up of reduced diameter Ag-In-Cd, clad in stainless steel. Gray rod cluster assemblies are used in load follow maneuvers and are named as 'Mechanical Shim (MSHIM)' as their operation minimizes the need for changes to concentration of soluble boron [2]. AP1000 design parameters given in table 1.

To meet the energy requirements during high demand periods, AP1000 core can be used for 16/20 months alternate operating cycles by changing the fuel reload pattern in the core [1] [3].

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Table 1 AP1000 design parameters [2]

Parameters	Value
Reactor core heat output	3400 MW_{th}
System pressure	15.5 MPa
Design flow rate	51.48×10^6 kg/hr
Effective flow rate	48.44×10^6 kg/hr
Coolant nominal inlet temperature	279.44 ℃
Average temperature rise	42.89 ℃
Average temperature	300.89 ℃
Average linear power	5.72kW/ft
Fuel Material	UO_2 sintered
Density	95.5% of theoretical
Core diameter, equivalent	304.04 cm
Core height, cold, active fuel	426.72 cm

2 Modeling methodology and assumptions

2.1 Computational codes

Calculations are performed using CASMO4E, CMSLINK and SIMULATE-3 code package. This code package is capable of modeling axially heterogeneous fuel assemblies. These codes have the capability to perform core calculations by reloading the once and twice burned fuel in the core from previous cycle to the next cycle. The burnable poisons can also be removed from the core after first cycle.

CASMO4E is an extended version of lattice physics code CASMO-4. CASMO4E is a 2D multigroup transport theory based nuclear code used for burnup calculations of PWR and BWR. CASMO4E uses ENDF/B-VI nuclear data library containing microscopic cross sections in 70 energy groups covering neutron energy range from 0 to 10 MeV [4][5][6]. The code generates homogenized two group cross section for SIMULATE-3. In this study full assembly model is used in CASMO4E. All types of AP1000 assemblies were modeled and cross sections were generated for SIMULATE-3.

CMSLINK is a linking code that processes CASMO4E card image files into a binary formatted nuclear data library to be used by SIMULATE-3 [7].

SIMULATE-3 is a three-dimensional two-group; diffusion theory based nodal code for PWR and BWR. SIMULATE-3 is used to perform in-core fuel management studies, core design and safety parameters calculation. SIMULATE-3 provide three dimensional depletion calculations using 1/8, 1/4, 1/2 symmetry or full core models [8] [9]. In this study full AP1000 core was modeled in SIMULATE-3, with each fuel assembly divided into 40 axial and 4 radial quadrant nodes.

AP1000 core burnup analysis is performed at steady state Hot Full Power (HFP) with all control rods out (ARO) and core reactivity being controlled by soluble boron (chemical shim) in the coolant. Some of the calculations are performed at Hot Zero Power (HZP), same are mentioned in following text.

2.2 Initial core loading

AP1000 initial core loading pattern is shown in Figure 1. The model is obtained from AP1000 European Designed Control Documents [2]. Initial core loading have three types of UO_2 fuel assemblies including $2.35^w/_o$, $3.40\ ^w/_o$ and $4.45\ ^w/_o$. Highest enriched fuel assemblies are loaded at the core periphery and other two lower enriched assemblies are arranged in a checkboard pattern in the central portion of core [2]. Arrangement of IFBA and PYREX rods in fuel assemblies are shown in Fig.2 and Fig.3. IFBA rods are distributed in a symmetrical pattern to reduce the pin to pin power peaking. PYREX rods are removable burnable absorbers and removed from the core after first cycle.

In a fuel rod, axial blanket is used to enhance fuel utilization, to improve axial power profile and to reduce axial leakage of neutrons. Axial blanket is a reduced enrichment fuel pellets at the end of fuel rod. In this study, annular axial blanket of 20.32cm in length with $3.2^w/_o$ enrichment is used. The diameter of central hollow annular is assumed as 3.5mm to achieve total fuel inventory of 84.5T of uranium. Configuration of fuel, PYREX and IFBA rods is shown in Fig.4.

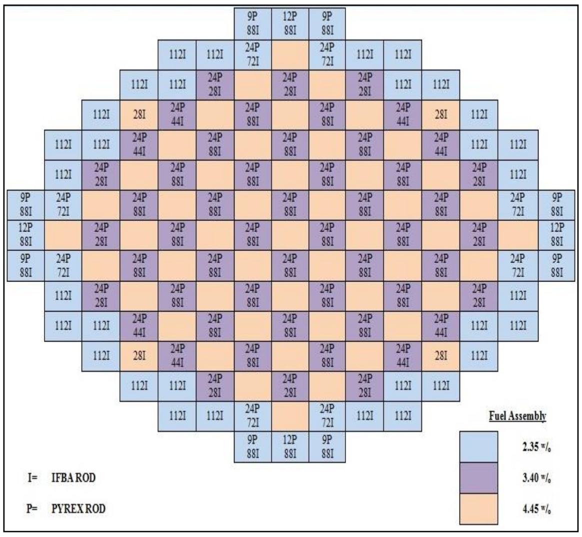

Fig.1 AP1000 initial core loading.

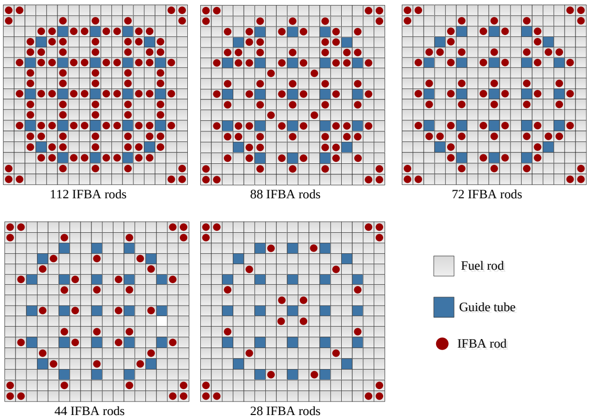

Fig.2 Arrangements of IFBA rods in fuel assembly.

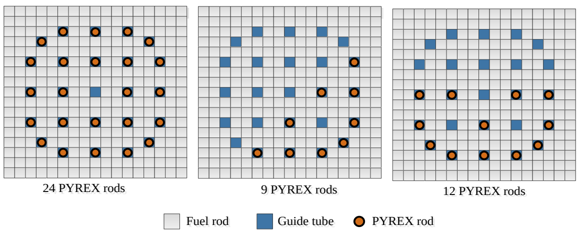

Fig.3 Arrangements of PYREX rods in fuel assembly.

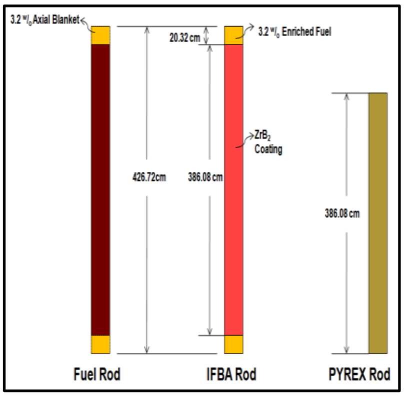

Fig.4 Configuration of fuel, IFBA and PYREX rods.

AP1000 core contain 69 control rod cluster assemblies which are divided in 11 control banks including gray rod banks, black rod banks, Axial Offset (AO) control bank and shutdown banks. The arrangement of control rod banks within core is shown in Fig.5. Initial core description is given in table 2.

Table 2 AP1000 first core parameters [2]

Fuel assemblies	
Number	157
Rod array	17 x 17
Rods per assembly	264
Rod pitch	1.260 cm
Fuel rods	
Number	41,448
Outside diameter	0.950 cm
Diameter gap	0.0165 cm
Clad thickness	0.0572 cm
Fuel pellets diameter	0.81915 cm
Fuel enrichments	
Region 1	2.35 $^{w}/_{o}$
Region 2	3.40 $^{w}/_{o}$
Region 3	4.45 $^{w}/_{o}$
Rod cluster control assemblies	
Absorber material	Ag-In-Cd
Diameter	0.866 cm
Cladding material	304SS
Clad thickness	0.047 cm
Number of clusters	53
Absorber rods per cluster	24
Gray rod cluster assemblies	
Absorber material	Ag-In-Cd/ 304SS
Diameter	4.06 mm
Cladding material	304SS
Clad thickness	0.47 mm
Number of clusters	16
Absorber rods per cluster	12 - Ag-In-Cd 12 - 304SS
Discrete burnable absorber rods (PYREX)	
Material	Borosilicate Glass
Outer diameter	9.68 mm
Inner tube, Outer diameter	4.61 mm
Clad and inner tube material	Stainless steel
B_{10} content	6.24 mg/cm
Absorber length	368.3 cm
Integral fuel burnable absorbers (IFBA)	
Material	Boride Coating
B_{10} content	0.772 mg/cm
Absorber length	386.1 cm

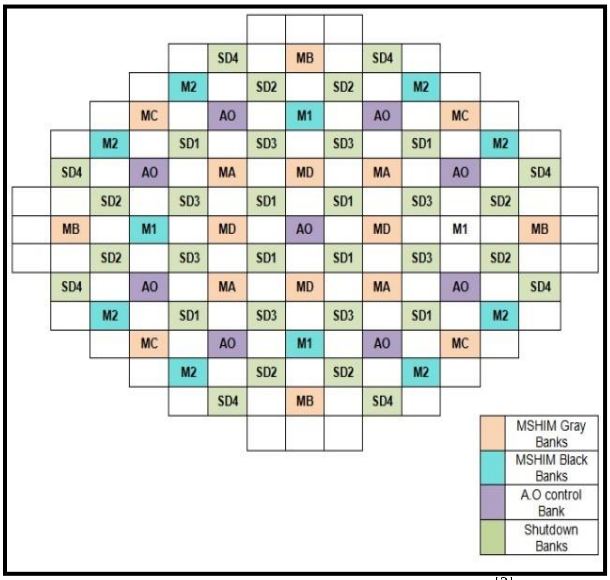

Fig.5 Location of control rods in the core [2].

2.3 Transition to equilibrium cores

In 18 month cycle core, three batch reloading scheme is used in which 64 fresh fuel assemblies are loaded at each refueling. The fresh fuel is loaded at central portion of the core and twice burned fuel assemblies are placed at the periphery to reduce radial leakage and to enhance fuel utilization at central portion of the core by improving neutron economy. IFBA is used as burnable poison for partial control of excess reactivity in varying arrangements in different assemblies. PYREX rods are removed from the core after first cycle. 18 month cycle equilibrium core loading pattern is shown in the following text.

In 16/20 month cycle cores, three batch reloading scheme is used and at each refueling 57 fresh fuel assemblies are required to be loaded for 16 month cycle core and 72 fresh fuel assemblies are required for 20 month cycle core [1]. Similar to 18 month cycle, IFBA is used as burnable absorber in varying arrangements in different fuel assemblies. Similar to 18 month cycle, the fresh fuel is loaded at central portion of the core and twice burned fuel assemblies are placed at the periphery of the core at each refueling. Similar to 18 month cycle, twice burned fuel assemblies are loaded to the core periphery and fresh fuel is placed at the central portion of the core.

The selection of transition core loading pattern is very important in the sense that it affects the core power distribution, power peaking factors, cycle length, assembly burnup and cycle burnup. In order to determine the transition core loading patterns, the EOC burnup of each assembly is analyzed after each cycle and assemblies are grouped according to their burnup, enrichment scheme and location in the core. The highly burned assemblies are removed from the core and fresh fuel assemblies are loaded. The number of removed assemblies depends on the next cycle scheme *i.e.* 64 assemblies for 18 month cycle, 57 assemblies for 16 month cycle and 72 assemblies for 20 month cycle. The remaining burned assemblies are rearranged in the core as per their burnup and the enrichment scheme. The arrangement of assemblies is

Table 3 AP1000 first cycle core parameters

Parameter	Design limits [2]	This study
Total heat flux hot channel factor (F_q)	2.60	1.861 (Max)
Nuclear enthalpy rise hot channel factor ($F_{\Delta H}^N$)	1.65	1.414 (Max)
Doppler temperature coefficient (pcm/ ℉)	-3.5 to -1.0 (Design Limit)	-1.43 to -1.6
	-2.1 to -1.3 (Best Estimate)	
Moderator temperature coefficient (pcm/ ℉)	0 to -40 (Design Limit)	-11 to -30
	0 to -35 (Best Estimate)	
Boron coefficient (pcm/ppm)	-13.5 to -5 (Design Limit)	-7.84 to -6.98
	-10.5 to -6.9 (Best Estimate)	
Delayed neutron fraction (β_{eff})	0.0075	0.00713
Prompt Neutron Lifetime (μs)	19.8	20.1
Boron concentration (ppm)		
Hot Zero Power RCCAs out K_{eff} =1.0	1382	1378
Hot Full Power RCCAs out K_{eff} =1.0, No Xe	1184	1158
Hot Full Power RCCAs out K_{eff} =1.0, Eq. Xe	827	830

carefully chosen such that the radial core power distribution remains symmetrical at each quadrant of the core.

The criteria for transition cores is selected as the power peaking factor and enthalpy rise factors should not exceed the design limits of 2.60 and 1.65 respectively during complete cycle length.

Following criteria and assumptions are made for equilibrium core burnup analysis:

- The enthalpy rise factor should not exceed 1.60.
- The Peak pin exposure should not exceed 60 GWD/MTU
- Convergence criteria for cycle length exposure = 0.01 GWD/MTU.
- Convergence criteria for batch exposure = 0.02 GWD/MTU
- EOC boron concentration ≤ 10 ppm

3 Results and discussion

3.1 Initial core

The AP1000 initial core parameters are mentioned in table 2. A full 3D core is modeled in SIMULATE-3 and burnup study is carried out. End of cycle (EOC) criteria is considered the same as mentioned in AP1000 design control documents *i.e.* when concentration of soluble boron reaches to approximately 10 ppm with all control and gray rods withdrawn from the core [1].

In order to benchmark the model used in this study, the core neutronic parameters at different operating conditions were calculated and compared with nuclear design parameters available in AP1000 DCD [2]. The obtained results are found within designed limits. The results are shown in table 3.

In burnup study of initial core, the amount of critical boron concentration is calculated at each burnup step. Critical boron concentration calculations are carried out at hot full power (HFP), all control and gray rods withdrawn condition with iodine and xenon update with depletion option *i.e.* no xenon at BOC. The burnup curve is shown in Fig.6.

At BOC, the small burnup step is selected 0.1 GWD/MTU (from 0 to 1 GWD/MTU) to observe the effect of burnable absorber depletion and buildup of xenon, afterwards burnup step increased to 1GWD/MTU to reduce computation time. Fig.6 shows that requirement of initial boron concentration is 1158 ppm, initial dip in the curve shows buildup of xenon at its equilibrium concentration. The xenon poisoning in core decreases the requirement of critical boron concentration to 830 ppm. As burnup increases the reactivity is added in the core due to depletion of burnable absorbers at relatively higher rate than the fuel. As a result, requirement of boron in the core increases, the effect is shown in Fig.6 till 5 GWD/MTU. Further then, the effect of burnable poison is not significant and requirement of boron in the core decrease with burnup due to fuel depletion till EOC. The burnup analysis results in 21.4 GWD/MTU of cycle exposure equivalent to 530 Effective Full Power Days (EFPD).

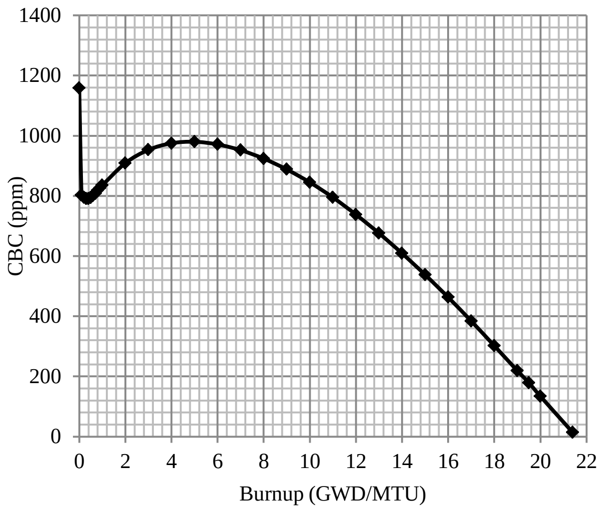

Fig.6 CBC with cycle exposure.

Hot channel factors have significant impact on nuclear reactor safety margins and they affect the core thermal hydraulic design. These factors must remain below the design safety limits of the core during normal operation. In this study, total power peaking factor (Fq) and enthalpy-rise hot channel factor ($F_{\Delta H}$) are calculated at each burnup step. Fig.7 shows the behavior of hot channel factors with core burnup. The results indicate that maximum value of $F_{\Delta H}$ and F_q remain well below the design limits, thus provide adequate safety margin.

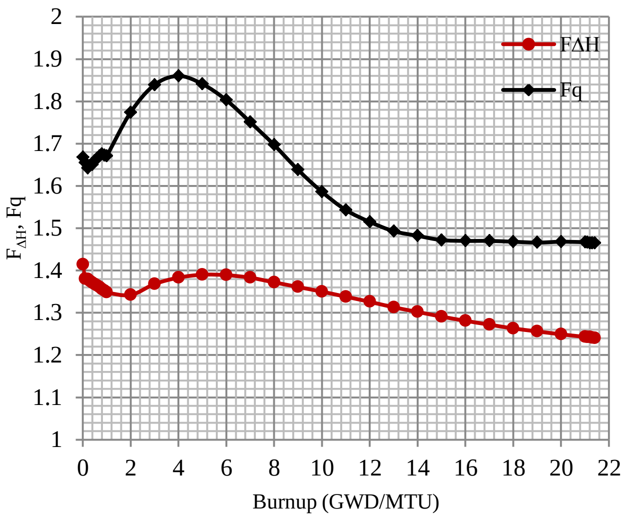

Fig.7 Hot channel factors with cycle burnup.

Reactivity coefficients have a significant role in safety of a reactor under transient conditions. These coefficients determine the inherently safe capability of a reactor. In this study, reactivity coefficients including, Moderator Temperature Coefficient (MTC), doppler coefficient, isothermal reactivity coefficient and boron worth coefficient are calculated at each burnup step in SIMULATE-3. The calculations were performed at Hot Full Power (HFP), all rods out (ARO) and equilibrium xenon (Eq. Xe) conditions with 5 ^{o}F perturbation for reactivity coefficients and 10 ppm perturbation for boron worth coefficient.

Figure 8 shows the behavior of reactivity coefficients vs. core burnup. The results illustrate that all coefficients remain negative throughout the cycle length. Isothermal and moderator temperature coefficients curve shows an initial increasing trend and later a large decreasing trend with increasing burnup (due to depletion of burnable absorbers in the core) and become relatively more negative at EOC whereas the doppler coefficient and boron worth coefficient curve shows slight decreasing trend with increase in cycle exposure. Moderator temperature coefficient (MTC) becomes more negative with burnup due to dilution of boric acid and buildup of plutonium and fission products.

Moderator temperature coefficient (MTC) is defined as change in reactivity with change in moderator temperature. Fig.9 shows MTC as a function of average moderator temperature. The results are obtained at different burnup steps at HFP, ARO and equilibrium xenon concentration by varying moderator temperature from 498 ^{o}F to 594 ^{o}F. The moderator temperature coefficient curves are shown in Fig.9 at various critical boron concentrations for the corresponding burnup step. The results show that MTC remain negative within operating temperature ranges and become more negative with increase in core burnup. However, effect of soluble boron is significant if the concentration is large enough at BOC. The increase in moderator temperature decreases the moderator density and hence boron density. Both the phenomena has opposite effect on reactivity *i.e.* decrease in moderator density also decrease the reactivity due reduced moderation whereas decrease in boron density increases core reactivity due decrease in poison contents in the core. If concentration of soluble boron is large enough, the effect of positive reactivity addition with increase in moderator temperature may be dominant.

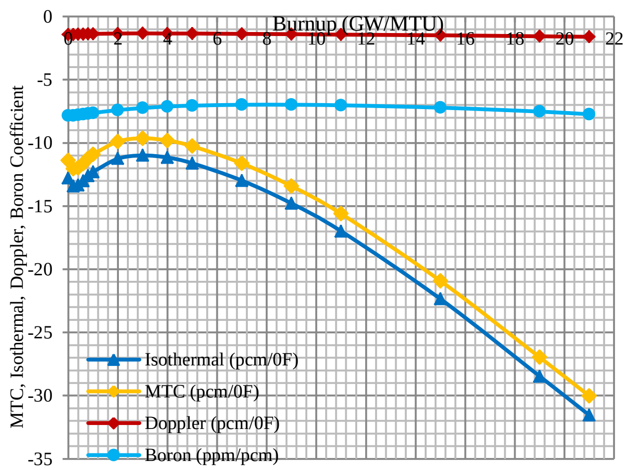

Fig.8 Cycle 1 reactivity coefficients.

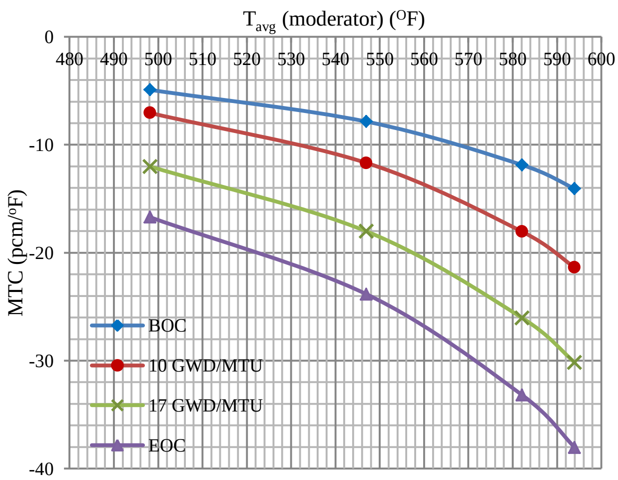

Fig.9 MTC variation with moderator temperature.

3.2 18 months transition to equilibrium cycles

AP1000 core uses three batch reload scheme for 18 month operating cycle. At each refueling, 64 fresh fuel assemblies are loaded in the core. 18 months equilibrium core enrichment scheme in shown in table 4, and core loading pattern is shown in Fig.10 [1].

Table 4 18 month equilibrium cycle enrichment scheme [1]

Assembly type	U235 ($^{w}/_{o}$)	No. of	Assemblies
X1-128	4.342	4	Twice burned fuel
X1-156	4.345	8	
X2-64	4.791	12	
X2-128	4.799	4	
Y1-128	4.342	20	Once burned fuel
Y1-156	4.345	16	
Y2-64	4.791	16	
Y2-128	4.799	12	
Z1-128	4.342	20	Fresh fuel
Z1-156	4.345	16	
Z2-64	4.791	16	
Z2-128	4.799	12	

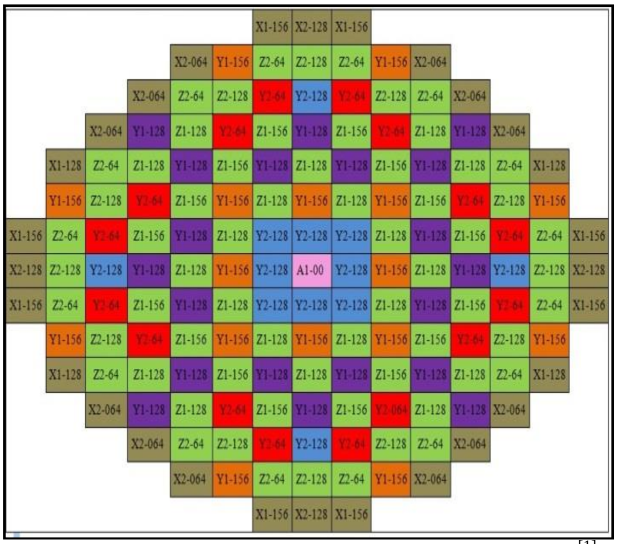

Fig.10 Equilibrium cycle core loading pattern for 18 month [1].

Criteria for transition cores may be established by keeping the core performance parameters within design limits. These parameters include hot channel factors, burnup limits, reactivity coefficients and the desired cycle length *etc.* The transition cores model were selected such that these parameters should remain below the maximum allowable limits. The criteria for transition and equilibrium cores is mentioned in preceding text.

Burnup calculations from transition to equilibrium cycles were carried out at HFP with all control rods out (ARO) and equilibrium iodine and xenon conditions (Cycle1 curve is with no xenon condition at BOC). The behavior of critical boron concentration with burnup is similar to the first cycle. The initial increase in reactivity is due to depletion of burnable poisons. Later, the critical boron concentration decreases with burnup. Requirement of critical boron concentration with burnup for transition cycles (*i.e.* Cycle2 and Cycle3) and first equilibrium cycle (Cycle 4) is shown in Fig.11. All the subsequent cycles are equilibrium cycle and have same cycle length and neutronic parameters as that of Cycle 4. Average cycle exposure of equilibrium cycle is 19.5GWD/MTU and the cycle length is 483EFPD. Table 5 shows the beginning of cycle critical boron concentration, K_{eff} and the cycle length of cycle-1 through equilibrium cycle. Table 6 shows batch exposure summary of equilibrium cycle. Discharge burnup is well below the maximum allowable limit of 60 GWD/MTU [2].

Table 5 Core parameters from cycle 1 to equilibrium cycle

Cycle	BOC CBC (ppm)	BOC K_{eff}	Cycle Burnup (GWD/MTU)	Cycle length (EFPD)
1	1158	1.0718	21.4	530
2	1441	1.1139	20	495
3	1347	1.0887	19.1	470
4	1409	1.0924	19.5	483

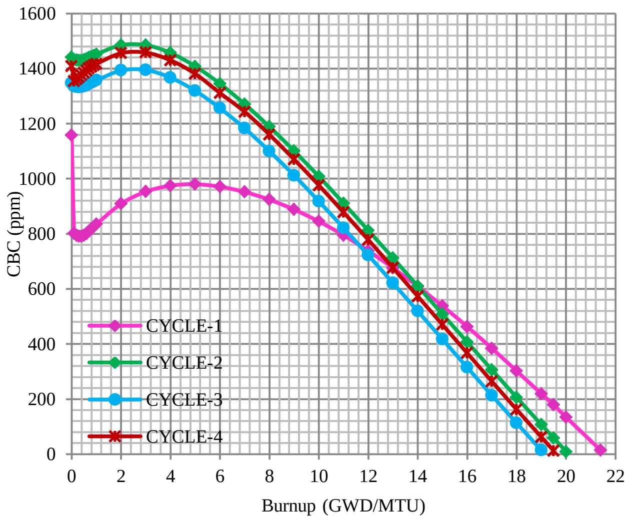

Fig.11 CBC with burnup for cycle 1 to equilibrium cycle.

Table 6 18 month equilibrium cycle batch exposure summary (GWD/MTU)

Batch	Maximum Assembly	Batch Average	Minimum Assembly
Fresh	25.78	23.64	20.46
Once burned	47.139	43.57	38.02
Twice burned	52.91	50.0	45.90

The results illustrate that the critical boron concentration of first cycle is much less than the transition and equilibrium cycles. The initial core has more burnable absorbers as compare to transition and equilibrium cycle. The PYREX rods are used in the fresh core to counter the excess reactivity and removed from the core after first cycle.

Figure 12 illustrates the behavior of equilibrium core hot channel factors *i.e.* F_q and $F_{\Delta H}$, as a function of core average cycle exposure. Maximum values of these factors are within design limits of 1.65 and 2.60 for $F_{\Delta H}$ and Fq respectively. Factors (other than thermal hydraulic parameters) that affect the core hot channel factors are, initial core loading pattern, fuel enrichment and amount of burnable poison in the core.

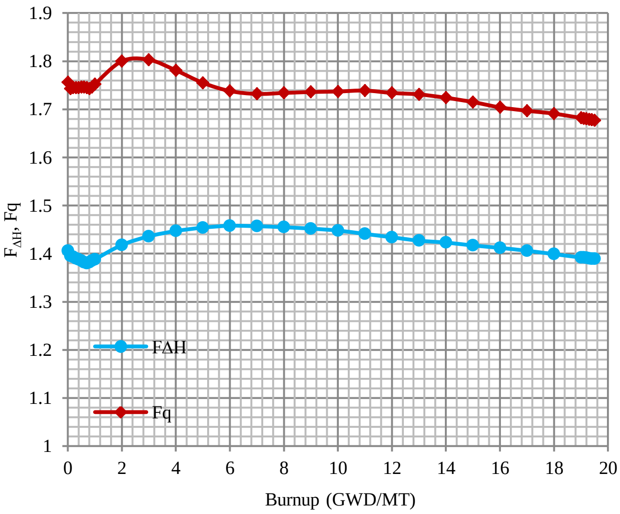

Fig.12 Equilibrium cycle hot channel factors.

Reactivity coefficients determine the tendency of the core to protect itself against temperature and power excursions. Reactivity coefficients of equilibrium core are calculated in SIMULATE-3 at HFP, ARO, equilibrium xenon conditions. Variation of equilibrium core MTC with average moderator temperature at different burnups is shown in Fig.13.

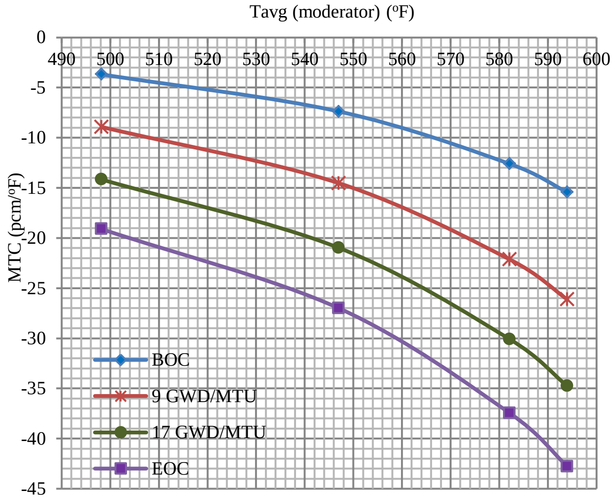

Fig.13 Equilibrium cycle MTC variation with moderator temperature.

Reactivity coefficients behavior with core burnup is given in Fig.14. All the coefficients remain negative during the operating cycle and show similar trend as that of initial core. The moderator temperature coefficient (MTC) becomes more negative with burnup due to dilution of boric acid and buildup of plutonium and fission products.

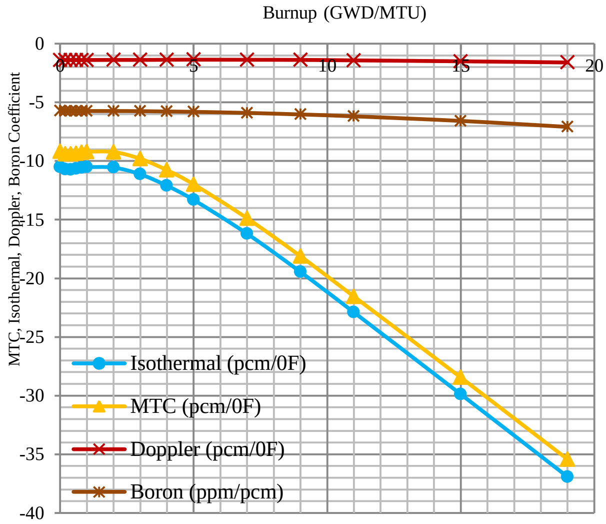

Fig.14 Equilibrium cycle reactivity coefficients.

3.3 16/20 months transition to equilibrium cycles

In this loading scheme 57 and 72 fresh fuel assemblies are loaded in the core at each refueling for 16 and 20 month cycle cores respectively. The equilibrium core fuel loading pattern of 16 and 20 month cycle cores is shown in Fig. 15 and Fig. 16. The equilibrium cycle enrichment scheme is given in table 7 and table 8.

The burnup analysis results show that the cycle length of transition cycles varies as per fuel loading scheme.

The requirement of critical boron concentration at BOC varies according to the fuel loading and amount of burnable poisons within the core. Cycle 2 to cycle 5 are transition cycles. Cycle 6 is the first equilibrium cycle for 16 month cycle core and cycle 7 is the first equilibrium cycle for 20 month cycle core. All the subsequent cycles are equilibrium cycles and the burnup is same as that of first equilibrium cycle.

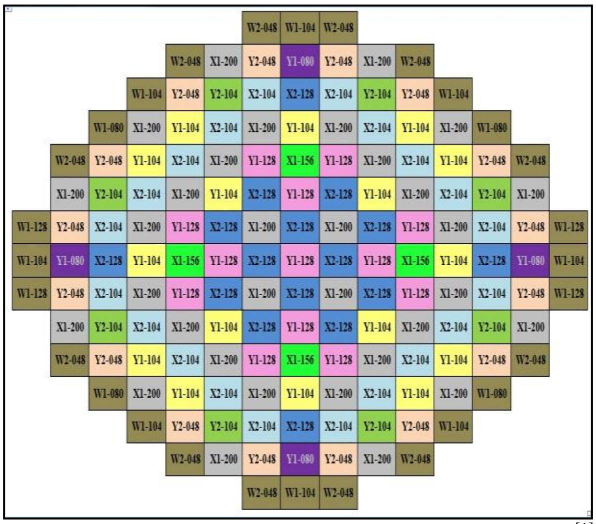

Fig.15 Equilibrium cycle core loading pattern for 16 month [1].

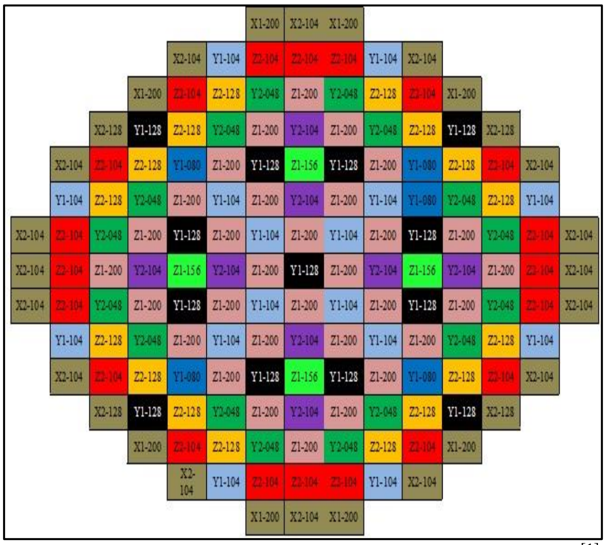

Fig.16 Equilibrium cycle core loading pattern for 20 month [1].

The 16 month equilibrium cycle (cycle 6) results illustrate that EOC average exposure is 17.1GWD/MTU and the cycle length is 427 EFPD. The BOC critical boron concentration is 1391 ppm. Similarly, cycle exposure of 20 month equilibrium cycle (cycle 7) is 21.7 GWD/MTU and the cycle length is 541 EFPD and the BOC critical boron concentration is 1278 ppm at HFP, ARO, EQ Xe conditions. Table 9 shows the BOC CBC, K_{eff}, cycle length and average cycle exposure of first, transition and equilibrium cycles. Fig.17 demonstrates the critical boron concentration behavior with cycle burnup from cycle 1 to equilibrium cycle. Table 10 and table 11 shows the batch exposure summary of equilibrium cycles.

Table 7 16 month equilibrium cycle enrichment scheme [1]

Assembly type	U-235 ($^w/_o$)	No. of Assemblies	
W1-080	4.1743	4	Twice burned fuel
W1-104	4.1762	8	
W1-128	4.1782	4	
W2-048	4.5622	12	
X1-156	4.5470	4	Once burned fuel
X1-200	4.5519	32	
X2-104	4.7966	20	
X2-128	4.7998	16	
Y1-080	4.1743	4	Fresh fuel
Y1-104	4.1762	16	
Y1-128	4.1782	13	
Y2-048	4.5622	16	
Y2-104	4.5685	8	

Table 8 20 month equilibrium cycle enrichment scheme [1]

Assembly type	U-235 ($^w/_o$)	No. of Assemblies	
X1-200	4.5519	8	Twice burned fuel
X2-104	4.7966	16	
X2-128	4.7998	4	
Y1-080	4.1743	4	Once burned fuel
Y1-104	4.1762	16	
Y1-128	4.1782	13	
Y2-048	4.5622	16	
Y2-104	4.7966	8	
Z1-156	4.5470	4	Fresh fuel
Z1-200	4.5519	32	
Z2-104	4.7966	20	
Z2-128	4.7998	16	

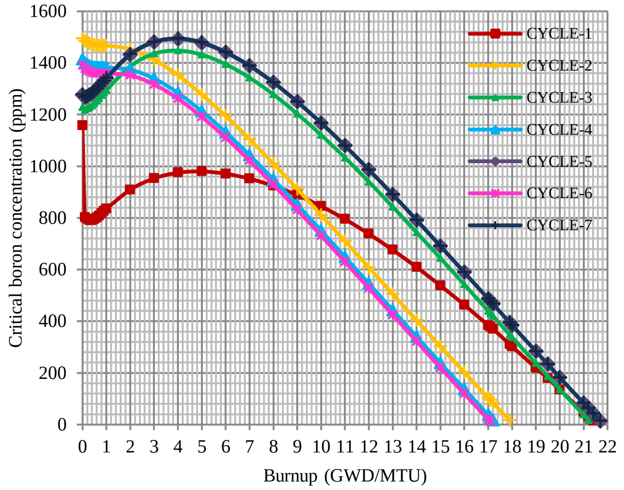

Fig.17 CBC with burnup for cycle 1 to equilibrium cycle.

The behavior of critical boron concentration vs. burnup curve in Figure 17 shows that in the initial increase in CBC is due to depletion of burnable poisons in reactor core which cause an increase in reactivity. The effect is more pronounced in cycle 3, 5 and 7 as these cycles are of 20 month loading scheme which has relatively more IFBA rods and high enriched fuel than those used in 16 month cycle. Depletion of burnable absorber increases the reactivity and results in higher peak that appear late in the 20 month cycle burbup curve as compare to 16 month cycle curve due to high excess reactivity at BOC.

Table 9 Core parameters from cycle 1 to equilibrium cycle

Cycle	BOC CBC (ppm)	BOC Keff	Cycle Burnup (GWD/MTU)	Cycle length (EFPD)
1	1158	1.0718	21.4	530
2	1495	1.1068	17.9	446
3	1229	1.0786	21.2	525
4	1414	1.096	17.3	429
5	1276	1.082	21.7	541
6	1391	1.094	17.1	427
7	1278	1.0822	21.7	541

Table 10 16 month equilibrium cycle batch exposure summary (GWD/MTU)

Batch	Maximum Assembly	Batch Average	Minimum Assembly
Fresh	22.87	20.74	18.05
Once	48.40	44.29	39.68
Twice	50.76	47.62	43.52

Table 11 20 month equilibrium cycle batch exposure summary (GWD/MTU)

Batch	Maximum Assembly	Batch Average	Minimum Assembly
Fresh	28.66	26.15	21.41
Once	46.72	43.27	35.60
Twice	53.70	50.19	47.55

Hot channel factors of 16 and 20 month equilibrium cycles are shown in Figure 18 and Figure 19 respectively. The values of hot channel factors remain below the maximum design limits of 1.65 and 2.50 for $F_{\Delta H}$ and F_q respectively throughout the cycle length.

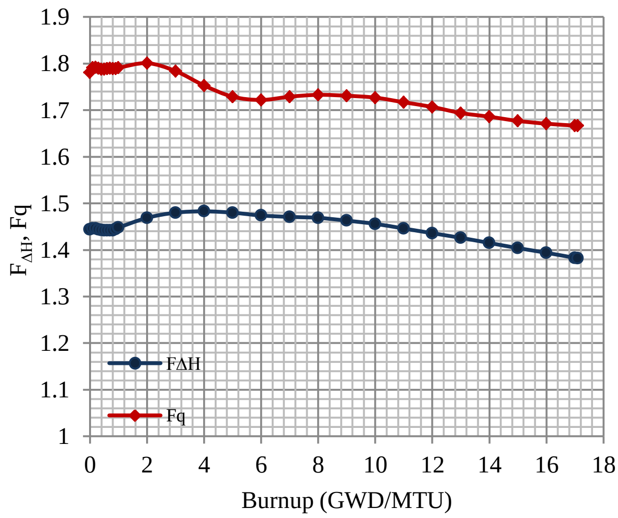

Fig.18 16 month equilibrium cycle hot channel factors.

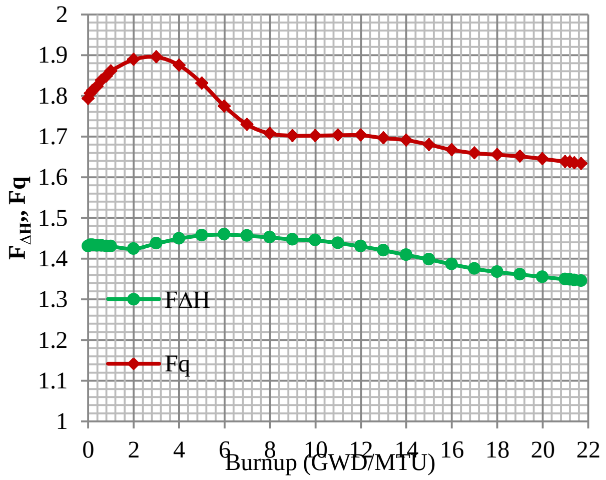

Fig. 19 20 month equilibrium cycle hot channel factors.

Reactivity coefficient of 16 and 20 month equilibrium cores are calculated at each burnup step at Hot Full Power (HFP), all rods out (ARO) and equilibrium xenon (Eq. Xe) conditions. The calculations are performed at 5^oF perturbation for reactivity coefficients and 10 ppm perturbation for boron worth coefficient. The behavior of reactivity coefficients for 16 month and 20 month equilibrium cycles are shown in Fig. 20 and Fig. 21 respectively. The results demonstrate that values of these coefficients remain negative throughout the cycle length.

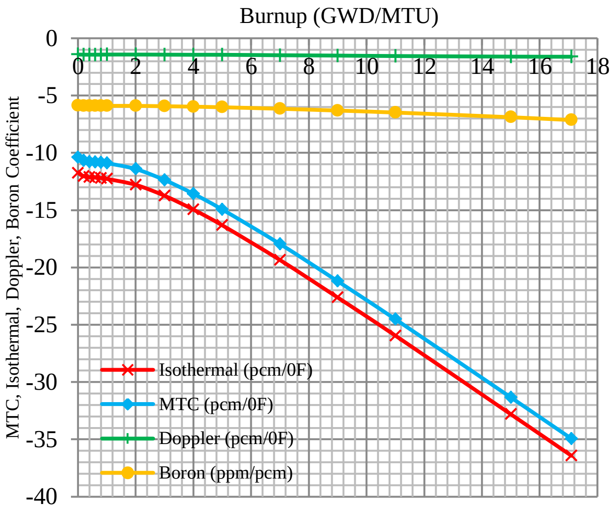

Fig.20 16 month equilibrium cycle reactivity coefficients.

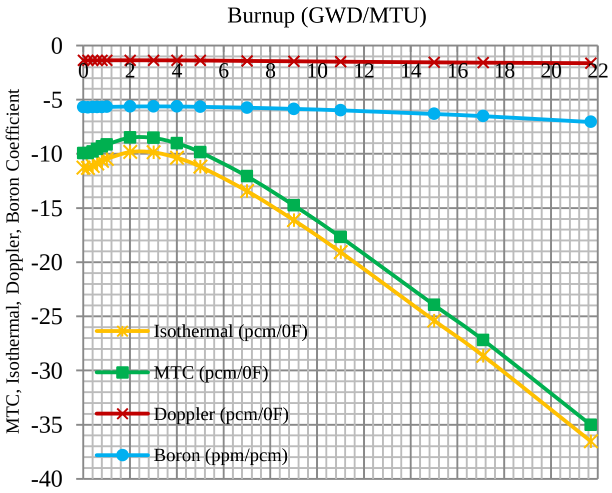

Fig.21 20month equilibrium cycle reactivity coefficients.

4 Conclusions

AP1000 reactor core is designed for 18 month cycle length and can also be used for 16/20 month alternate cycle lengths to meet energy requirements during high demand periods. The aim of this study is to analyze the feasibility of AP1000 cores for both the cycle schemes by performing burnup analysis of the cores. The study is performed for initial, transition and equilibrium cores using CASMO4E/ CMSLINK/ SIMULATE-3 code package.

The results illustrate that the EOC average burnup of initial cycle is 21.4 GWD/MTU and the cycle length is 530 EFPD. Cycle 4 is the first equilibrium cycle and all subsequent cycles are equilibrium cycles and have the same burnup as of cycle 4. The equilibrium cycle provides the cycle burnup of 19.5 GWD/MTU and cycle length of 483 EFPD. Cycle 6 is the first equilibrium cycle of 16 month cycle core which provide the cycle length of 427 EFPD and EOC average burnup of 17.1 GWD/MTU. The cycle 7 is the first equilibrium cycle of 20 month cycle core with the cycle length of 541 EFPD and cycle burnup of 21.7 GWD/MTU. All the subsequent cycles are equilibrium cycles and provide same cycle length and cycle burnup. The analysis shows that both schemes provide same average cycle burnup and cycle lengths if compared after every two cycles (*i.e.* 36 month cycle).

The reactivity coefficient of equilibrium cores remains negative throughout the core life which indicates the inherently safe capability of the reactor. The hot channel factors of equilibrium cores remain well below the upper design limit of the core.

The analysis results indicate that both the loading schemes can be utilized in AP1000 core by varying the core loading pattern. This work provides the basis for further study on fuel behavior analysis and thermal hydraulic analysis of AP1000 to evaluate the safety aspect of various core irradiation/ burnup conditions.

Nomenclature

AO	Axial Offset
ARO	All Rods Out
ARI	All Rods In
BOC	Beginning of Cycle
CBC	Critical Boron Concentration
DCD	Design Control Documents
EOC	End of Cycle
F_q	Total Power Peaking Factor
$F_{\Delta H}$	Enthalpy Rise Hot Channel Factor
HFP	Hot Full Power
HZP	Hot Zero Power
IFBA	Integrated Fuel Burnable Absorber
MTC	Moderator Temperature Coefficient
MSHIM	Mechanical Shim
MOC	Middle of Cycle
PYREX	Discrete Burnable Absorber

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