Lecture Note 6

Introduction to Nuclear Design

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Contents

Nuclear Design Goal and Objectives

☐ Goal

- **Determine fuel composition, configuration, and in-core arrangement for safe and economical operation of a nuclear reactor**

☐ Objectives

- **Meet Required Energy Production**
  - Rated Power x Duration (e.g. 2775 Mw x 15 months x 3 Cycles)
- **Meet Safety Requirements**
  - Peak Power Limit, Minimum DNBR Limit, Negative MTC, Discharge Burnup and etc.
- **Maximize Operational Flexibility**
  - Sufficient Operating Margins
- **Minimize Power Generation Cost**
  - Higher Capacity Factor and Lower Fuel Cost

Reactivity Requirements

☐ **Core should be kept critical for required period. (reactivity=0)**

Reactivity: Degree of Off-Criticality of a Core

$$\rho = 1 - \frac{1}{k_{eff}}$$

$$\rho \begin{cases} > 0, & \textit{SuperCritical} \quad \text{(Increasing Power)} \\ = 0, & \textit{Critical} \quad \text{(Constant Power)} \\ < 0, & \textit{Subcritical} \quad \text{(Decreasing Power), but constant with source} \end{cases}$$

- **Unit**
  - % or pcm (per cent milli = 10^{-5})
  - 1% Reactivity amounts to 1 month operation in a typical PWR

Factors Affecting Core Reactivity

- **Initial Fuel Enrichment and Burnable Absorber Loading**
- **Core Thermal Condition (MTC and FTC, Power Defect)**
- **Neutron Leakage**
- **Fission Product (e.g. Xe) Buildup**
- **Fuel Burnup**
- **Boron Concentration and Control Rod Position**

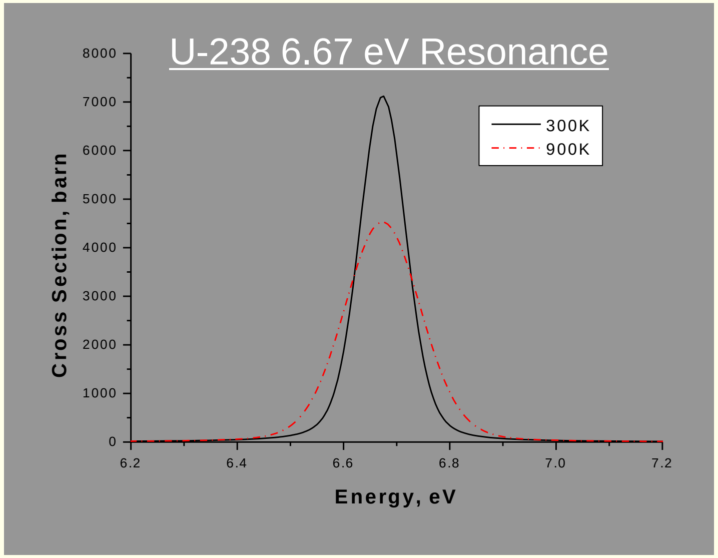
Fuel Temperature Effect

□ T_F↑ ⇒ 원자 열운동 활발 ⇒ **U-238, Pu-240** 등 중핵종의 공명 흡수폭 및 흡수량 증가 **(Doppler Broadening)** ⇒ 반응도 감소

$$\alpha_F = \frac{\partial \rho}{\partial T_F} < 0$$

□ 열궤환 효과 **(Thermal Feedback)**

- **T↑ ⇒ ρ↓ ⇒ p↓ ⇒ T↓**
- 내재적 안전성 보장



□ 계수 크기: 약 **-3 pcm/C**

□ 핵연료 온도 결손

- 온도 변화 범위: 약 **600C**
- 약 **1800 pcm = 1.8%**

Moderator Temperature Effect

□ $T_M\uparrow \Rightarrow D_M\downarrow$

- 감속 효과 감소 ⇒ $\rho\downarrow$
- 보론에 의한 흡수 감소 ⇒ $\rho\uparrow$

$$\alpha_M = \frac{\partial \rho}{\partial T_M} \begin{cases} < 0, & \text{usually} \\ > 0, & \text{in case of high boron concentration} \end{cases}$$

□ 붕산의 영향

- 붕산이 없으면 **MTC** 항상 음(-), 약 **-60 pcm/C**
  (내재적 안전성 보장 요건 충족)
- 붕산증가에 따라 점점 양의 방향으로 접근
- 주기초 고붕산 상황에서는 양(+)일 수도

□ 감속재 온도 결손

- **270 C * 30 pcm/C (평균) = 8100 pcm = 약 8%**

Required Reactivity by Component

Component	Approximate Value, %
CZP to HZP Temperature Defect	2 - 5
HZP to HFP Defect	1 - 2
Xenon Defect	2.5 - 3
Xenon Override	~ 1
Neutron Leakage	2.5 - 3.5
Fuel Depletion	5 - 8
Total	**14 - 22.5**

→ Must be compensated by initial fuel reactivity

Safety Requirements

☐ Peak Power Generation Rate Limit

- **No Fuel Centerline Melting to Maintain Coolant Geometry**
    - $T_{CenterLine} < 2800^{\circ}C$ (UO_2 Melting Point)
- **No Metal-Water Interaction (Hydrogen Explosion) During LOCA**
    - $T_{clad} < 1200^{\circ}C$ (~ $2200^{\circ}F$)
    - LOCA Limit on Linear Heat Generation Rate (LHGR)
        - 13.9 Kw/ft = 45.6 kw/m
        - Average LHGR 5.4 kw/ft (=2815x1000 kw/41772/12.5ft, 17.7 kw/m, 67 kw/rod)
        - Local Power Peaking Factor (**Fq**) Limit =13.9/5.4=2.58

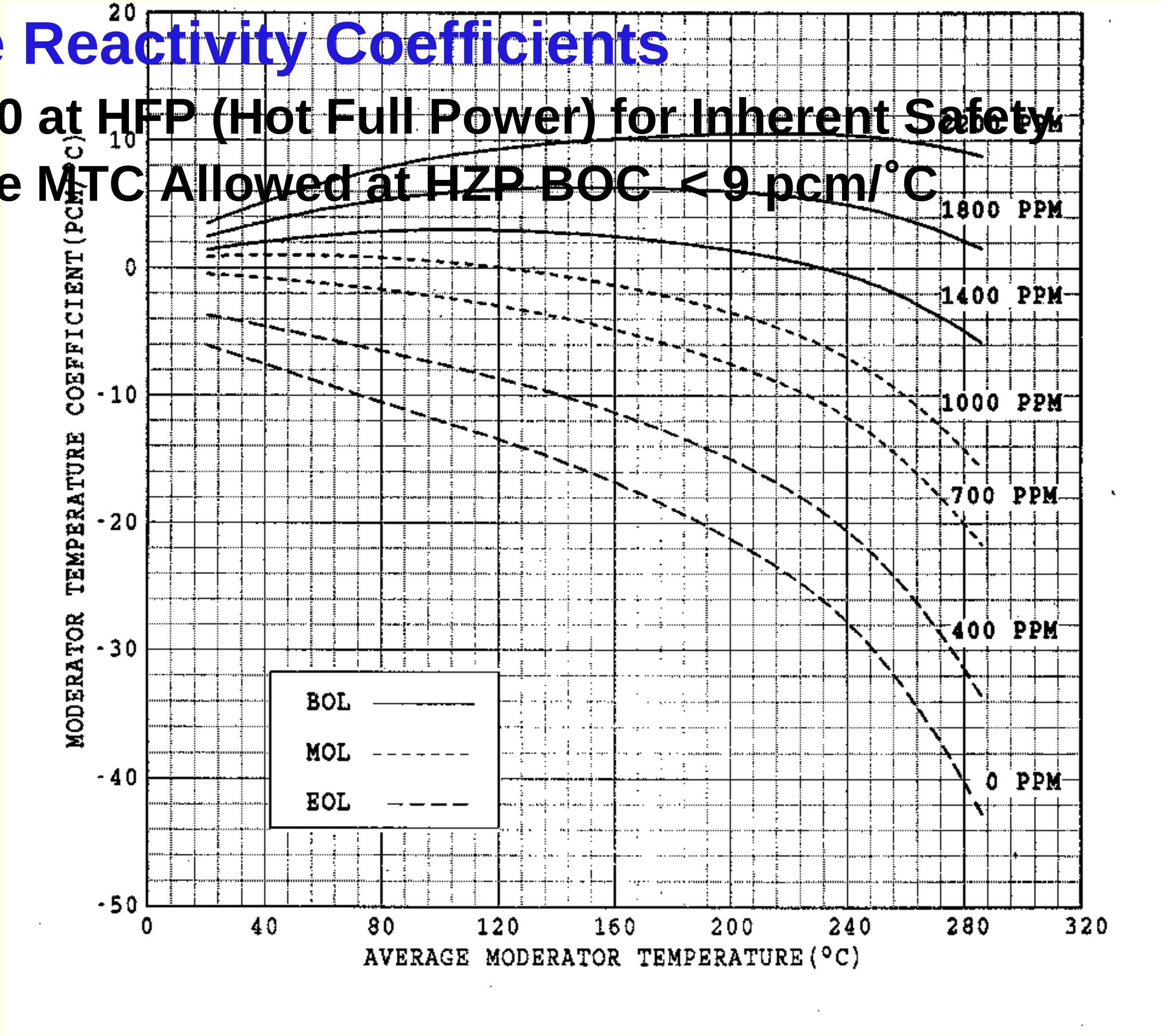
☐ DNB Limit

- **No Departure from Nucleate Boiling under Anticipated Operating Occurrences (AOOs)**
    - Axially Integrated Radial Power Peaking Factor (Fr) < 1.55

Safety Requirements - 2

Negative Reactivity Coefficients

- **MTC < 0 at HFP (Hot Full Power) for Inherent Safety**
- **Positive MTC Allowed at HZP BOC < 9 pcm/°C**



Safety Requirements - 3

☐ Fuel Discharge Burnup

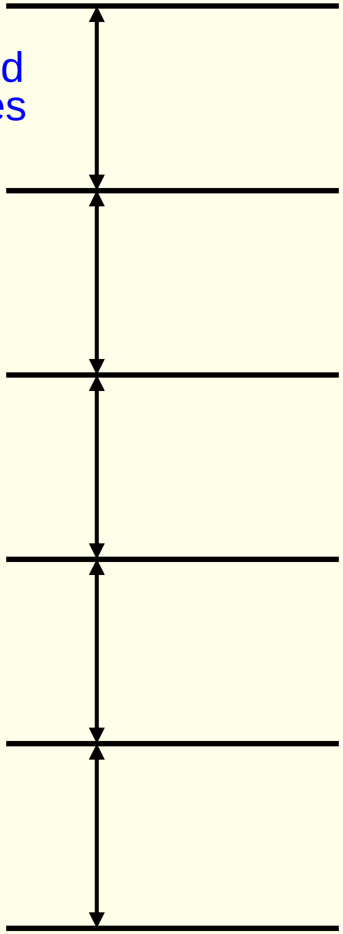
- **Fission Gas Production**
- **Pellet Swelling ← Lower Density of Fission Products**
  - Cladding Deformation
  - Degradation of Cooling Capability
- **Cladding Brittle and Vulnerable to Creep**
- **Discharge Burnup Limit of 50,000 MWD/T**

☐ Shutdown Margin

- **Reactor Must be able to be Shutdown at Any Condition**
- **Reactivity Increase Due to Temperature Decrease After Shutdown**
- **Total Control Rod Worth > Temperature Defect**
- **Stuck Control Rod Should be Assumed in Total Control Rod Worth**
  - Placing highly reactive fuel underneath control rod should be avoided
- **Shutdown Margin > 1%**
  - Total Available CR Worth – Temperature Defect> 1%
  - To Assure No Return to Power in Steamline Break Accident

☐ Ejected Rod Worth

Operating Margin



Failure Limit

Margin for Correlation and Monitoring Uncertainties

Limiting Condition for Operation

Overpower Factor (Operating Margin)

Maximum Peak Steady State Condition (i.e. Hot Spot with Eng. Uncertainties)

Engineering Uncertainty

Nominal Peak Steady State Conditions (i.e. Hot Spot)

Axial Power Peaking

Axial Average in Radial Pin Peak

Radial Power Peaking

Nominal Steady State Core Average Condition

Operating Margin

☐ Definition

- Margin to limiting condition for operating from current Condition

☐ Ways to Increase

- Can be increased by reducing power peaking and achieving flatter power-to-flow ratio

☐ Significance

- For normal operation, No economical benefit from higher operating margin
- In temporary upset conditions, Core can withstand perturbations without trip → Higher Capacity Factor

Means of Reactivity and Power Distribution Control

☐ Number of Feed Assemblies or Batch Size

- **Batch: Group of Assemblies to be Replaced at Each Cycle**
- **Batch Size for 177 FA Core**
  - 4 Batch: 44 FAs
  - 3 Batch: 59 FAs
  - 2.5 Batch: 71 FAs
  - Practically 64 or 68 Fas (2.7 batch)

☐ Enrichment of Fresh Fuel

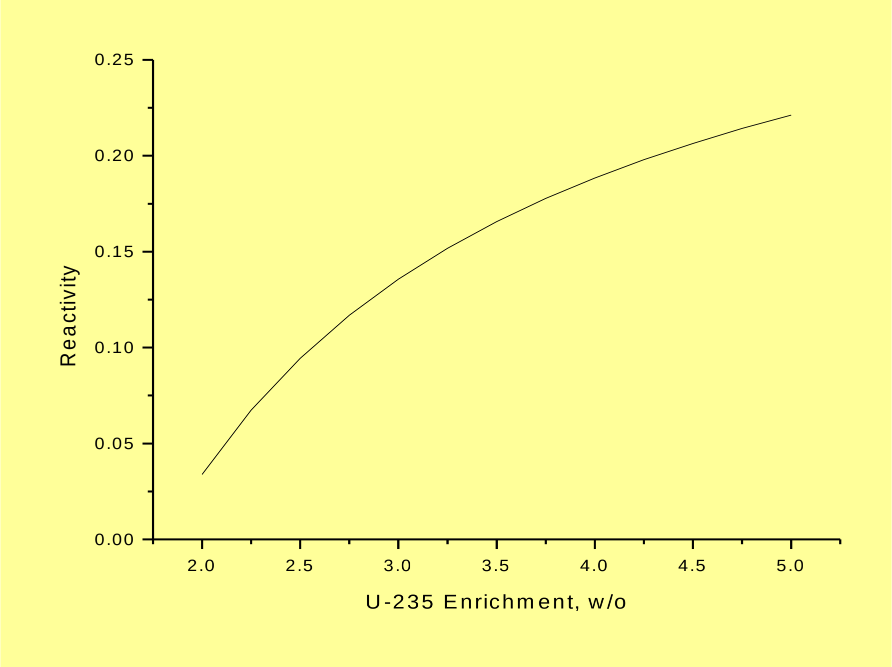
☐ Type and Content of Burnable Absorber

☐ Fuel Rod and Assembly Arrangement

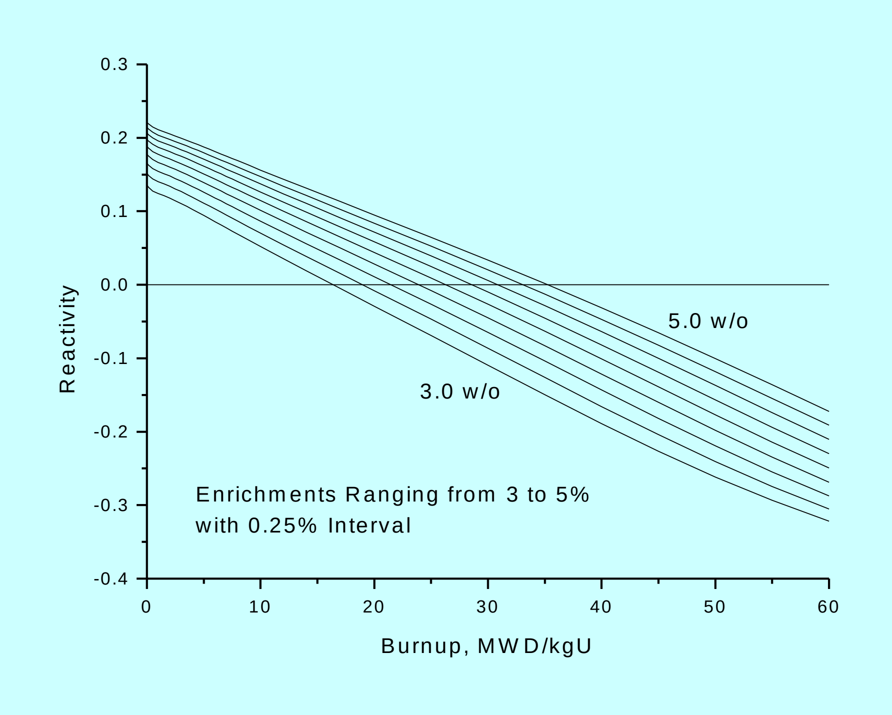
☐ Soluble Boron and Control Rods

Enrichment and Reactivity

Initial Reactivity vs. Enrichment



Reactivity Vs. BU for Different Enrichments



Linear Reactivity Model

$$\rho(B,\varepsilon) = \rho_o(\varepsilon) - a(\varepsilon)B$$

Batch Size Effect on Cycle Length and Discharge Burnup

Core Reactivity by Linear Reactivity Model

$$\rho(B) = \frac{1}{n}\sum_{i=1}^{n} \rho(B_i) - \rho_{HFP}$$

- **Assume One Enrichment Only**
- **ρ_{HFP} including all defects including neutron leakage**

Cycle Length for Single Batch

$$\rho(B_1) = 0 = \rho_o - aB_1 - \rho_{HFP} \rightarrow B_1 = \frac{\rho_o - \rho_{HFP}}{a}$$

Cycle Length for 2 Batch Core

$$B_k^d = kB_k = \frac{2k}{k+1}B_1$$

$$\rho(B_2) = \frac{1}{n}\left(\frac{n}{2}\rho_1(B_2) + \frac{n}{2}\rho_1(2B_2)\right) - \rho_{HFP} = \frac{1}{2}\left(\rho_o - aB_2 + \rho_o - 2aB_2\right) - \rho_{HFP}$$

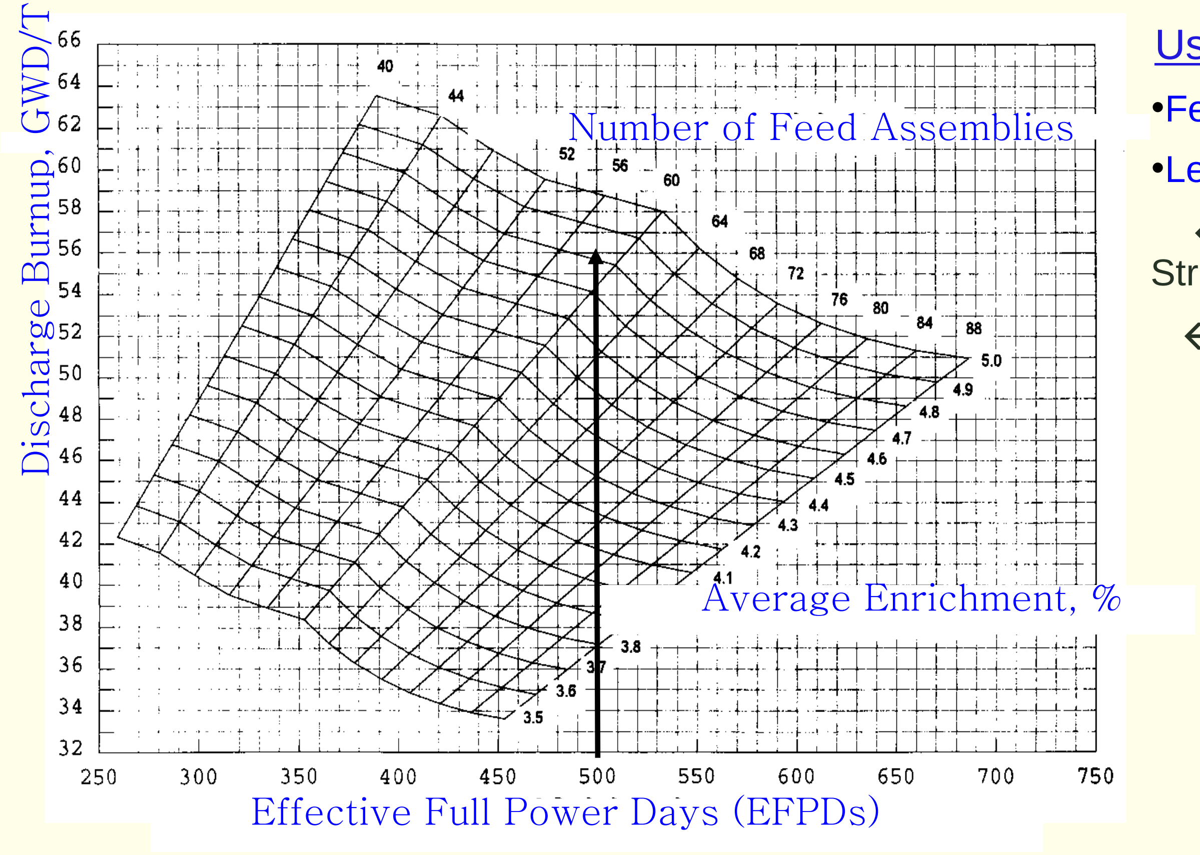
$$\rho(B_2) = 0 = \frac{1}{2}\left(2\rho_o - 3aB_2\right) - \rho_{HFP} \rightarrow B_2 = \frac{2\left(\rho_o - \rho_{HFP}\right)}{3a} = \frac{2}{3}B_1$$

In General, Discharge Burnup Increases with Batch Number

$$B_k = \frac{2}{k+1}B_1, \qquad B_k^d = kB_k = \frac{2k}{k+1}B_1$$

Batch Size and Fuel Enrichment

- **For given cycle length (e.g. 12-Month or 18-Month), Various combinations of feed assemblies and enrichment are possible**



Use of Higher Enrichment

- Fewer Assemblies
- Less Fuel Cost

←Lower Cost for Assembly Structure ~45만불

← Higher Discharge Burnup

Despite Higher Enrichment Cost

- Higher Power in Fresh Fuel → Hard to Meet Power Peaking Limit

Considerations on Batch Size and Cycle Length

More Batches (Small Batch Size)

- Higher Discharge Burnup → More economical in the aspect of fuel cost
- Short Cycle Length

Refueling Down Time Fraction Increasing with Short Cycle Length

Generation Cost Components

- 75, 10, 15% for Capital, Operation and Maintenance, Fuel Cost

Availability and Capacity Factor

$$D_{CL} = D_{OD} + D_{RD} + D_{TD}$$

$$\alpha = \frac{D_{OD}}{D_{CL}} \left(Availability\ Factor, \text{가동율} \right)$$

$$D_{EFPD} = \gamma D_{OD}$$

$$\xi = \frac{D_{EFPD}}{D_{CL}} = \gamma \alpha \ \left(Capacity\ \ Factor, \text{이용율} \right)$$

OD: Operating Days

RD: Refueling Down Days

TD: Temporary Down Days

EFPD: Effective Full Power Days

CL: Cycle Length in Days

γ: Average Load Factor during Operation Days

Economics of Longer Cycle

- **Better Spread of Capital Cost**
  - **Based 95% Load Factor and 65 Days of Refueling Down Time**
  - **Capacity Factor for 12 Month = 78%**
  - **Capacity Factor for 18 Month = 84%**
  - **Reduction in Generation Cost in Non-Fuel Cost**
    - 75% * (1-0.78/0.84) = 5.4%
- **Fuel Cost Increase**
  - **Less Discharge Burnup**
  - **Higher Enrichment Cost**
  - **7.5% Increasing as Seen in the Next Table**

Comparison of Generation Costs for 12 and 18 Month Cycles

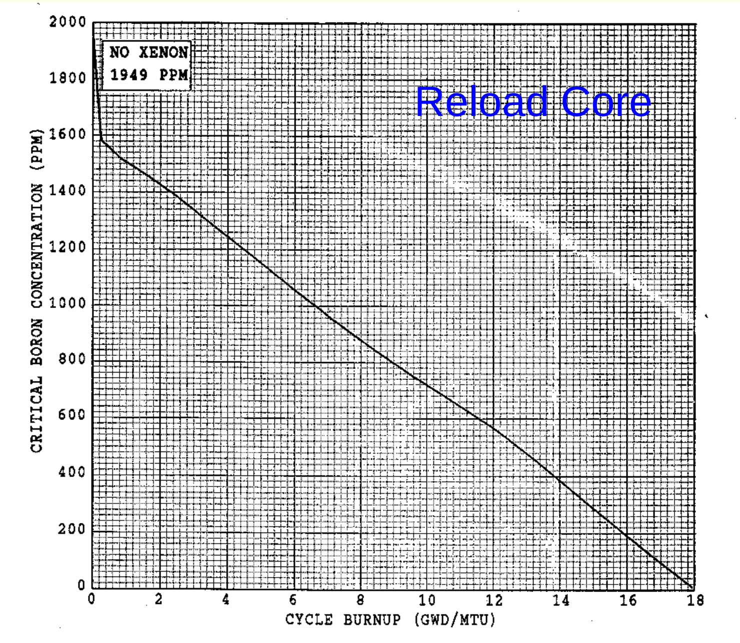
Item	12-month cycle	18-month cycle
Days of full power operation day	306	446
Feed enrichment, w/o	3.900	4.014
Number of feed fas(177 FAs in core)	44	68
Capacity factor, %	79.04	83.44
Cycle burnup, mwd/kgU	11.288	16.452
Discharge burnup, mwd/kgU	45.408	42.823
Electricity produced, kWh(e)	7.301×10^{9}	1.064×10^{10}
Fuel cost, milli-$/kWh(e)	4.83	5.19 (1.075)*
Fixed cost, milli-$/kWh(e)	34.45	32.63 (0.947)
Total cost, milli-$/kWh(e)	39.29	37.83 (0.963)

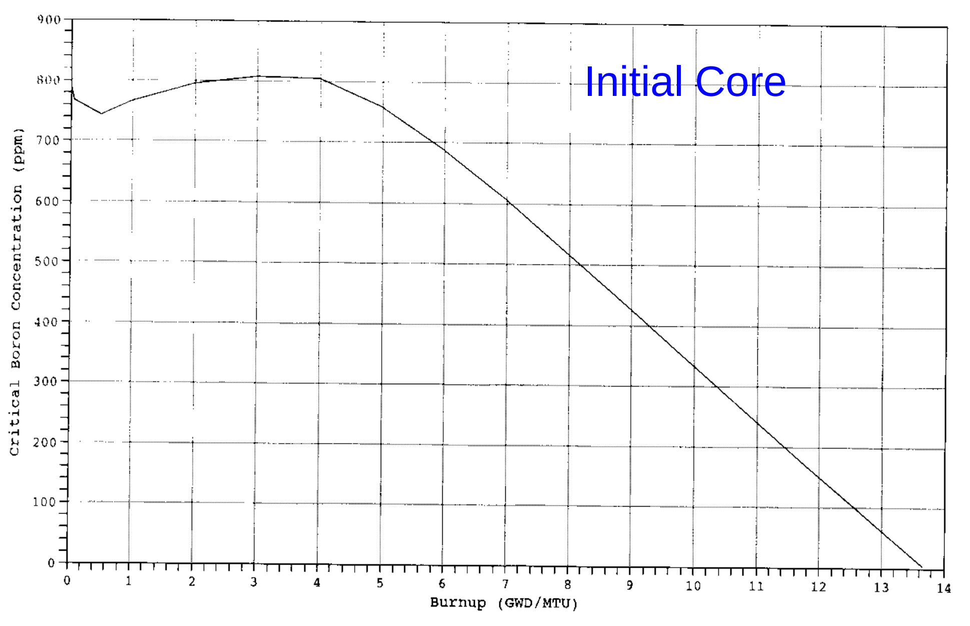
Excess Reactivity and Boron

Excess Reactivity

- **Surplus Reactivity Compensating for Fuel Depletion, Initially High but Decreasing with Burnup**
- **Need to Be Counterbalanced by Long Term Reactivity Control Means→ Boron or Burnable Absorber**

Boron Let-down Curves





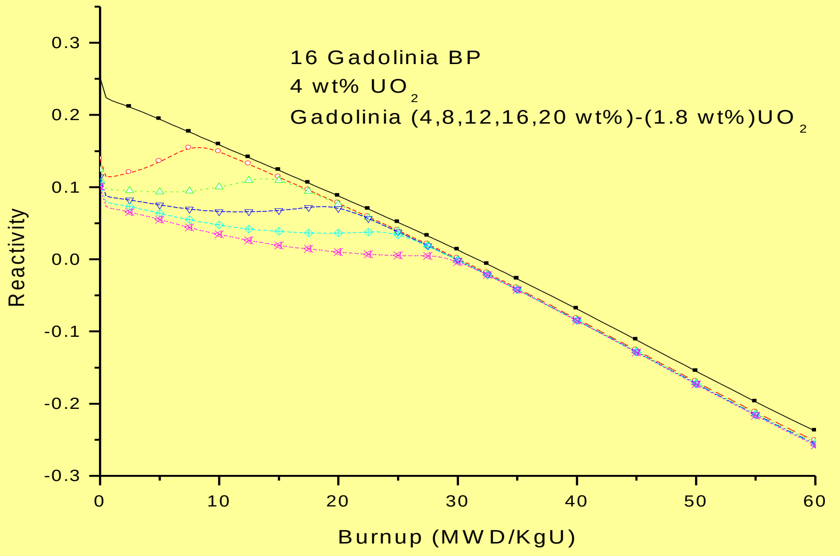
Burnable Absorbers

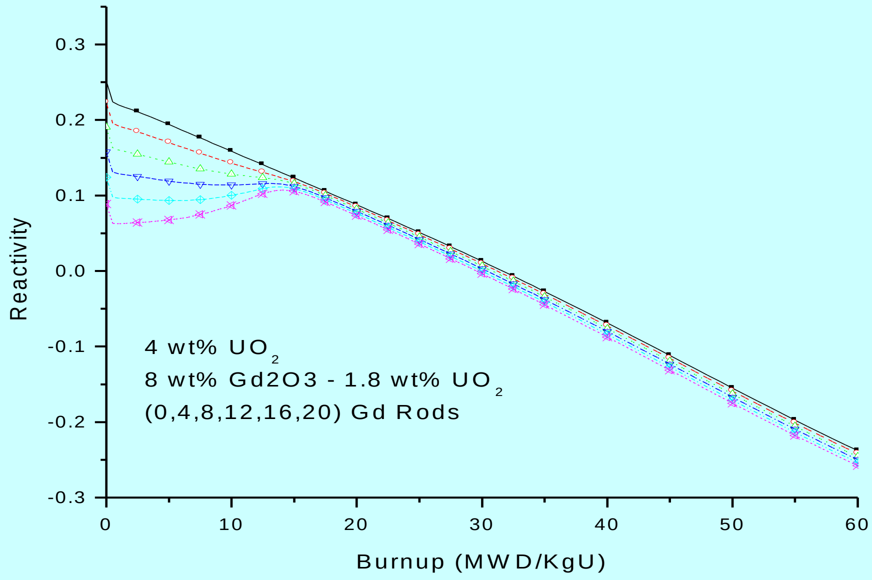
- **Functions**
  - **Absorb neutrons and burn out as cycle burnup increases**
  - **Suppress excess reactivity in initial phase of cycle**
  - **Reduce boron concentration to relieve the positive MTC problem at BOC**
  - **Control pin power distribution within assembly as well as inter-assembly**
- **Materials**
  - **Boron, Gadolinia (Gd_2O_3 +UO_2), Erbia**
- **Types**
  - **GT Mount Separated BA**
    - Inserted into Guide Tubes
    - WABA(Wetted Annular Burable Absorber), Pyrex (Borosillicate Glass)
    - Position Limited Due to Control Rod Positions
  - **Integral Burnable Absorber**
    - Placed on Any Fuel Rod Positions
    - Gadolinia, Erbia, Coated Boron (ZrB2+UO2) Mixed with Fuel
    - Reduction of Fuel Rods Causing Higher Power Density in Other Fuel Rods
    - Easier Intra-Assembly Power Distribution Control
  - **B4C**
    - Separated BA Placeable in Fuel Position

BA Assembly Characteristics

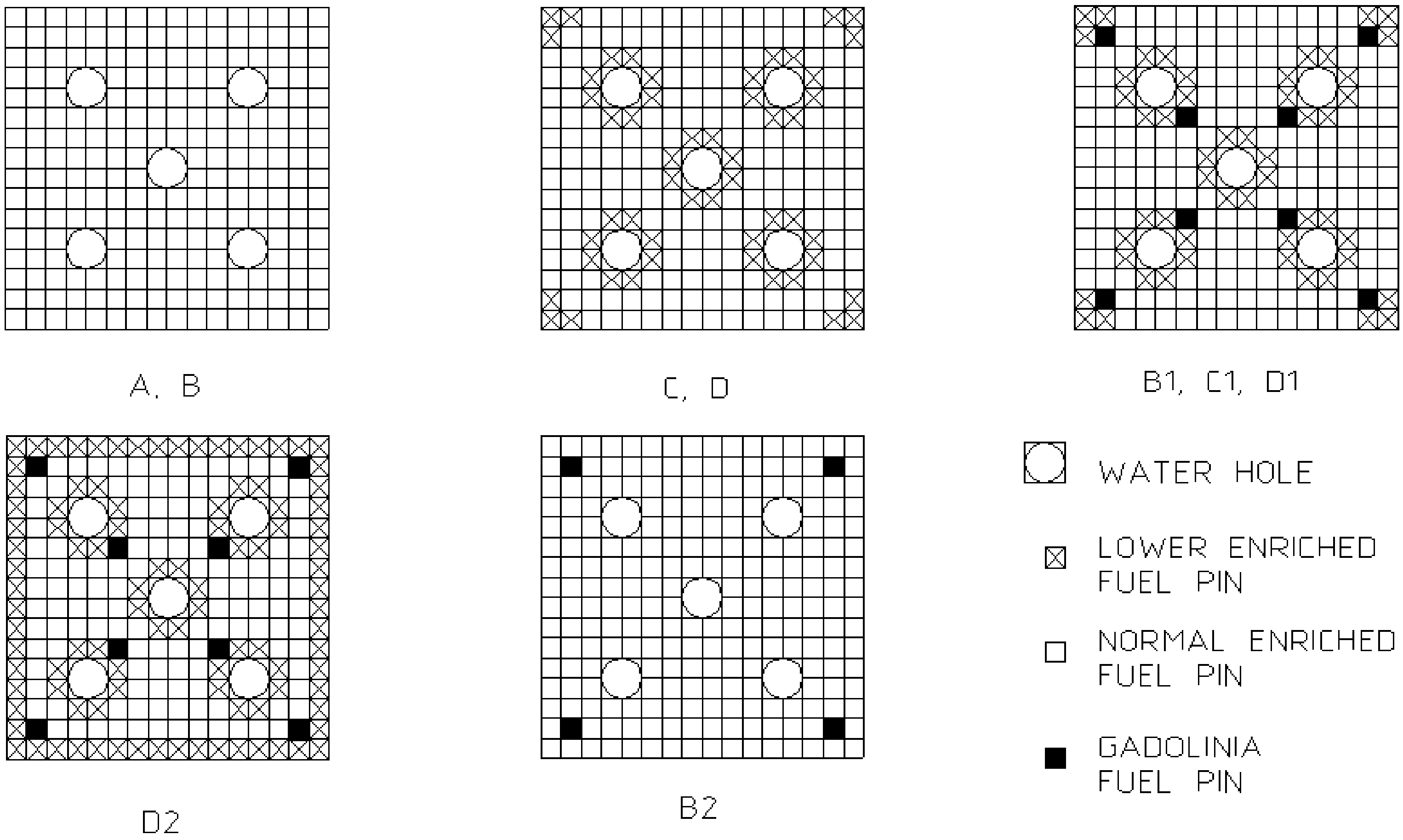
Control Parameters

- **Absorber Concentration – Controls Duration of Reactivity Hold-down**
- **Number of BA Rods – Controls Magnitude of Reactivity Hold-down (due to Strong Self-shielding)**





YGN-3/4 Initial Core Fuel Types



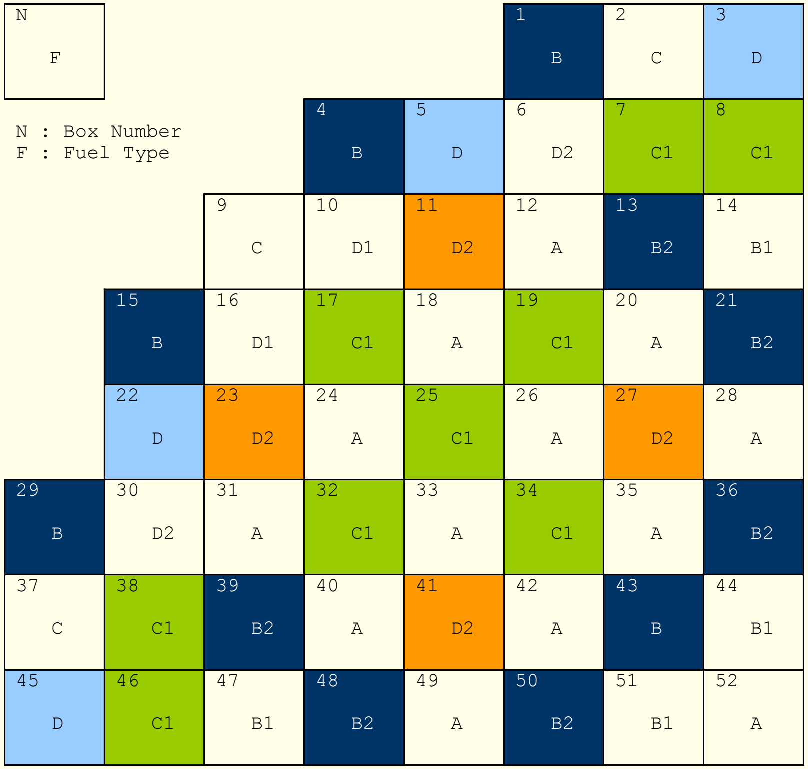
Fuel Loading Design

Problems of Single Batch

- **Higher Peaking**
- **Low Discharge Burnup**

Loading Pattern Search Goals

- **Minimize Localized Power Peaking**
- **Maximize Cycle Length by Reducing Neutron Leakage**
- **Meet All the Safety Requirements**
  - Fq
  - Fr
  - Negative MTC
  - Sufficient Shutdown Margin



N F					1 B	2 C	3 D
			4 B	5 D	6 D2	7 C1	8 C1
		9 C	10 D1	11 D2	12 A	13 B2	14 B1
	15 B	16 D1	17 C1	18 A	19 C1	20 A	21 B2
	22 D	23 D2	24 A	25 C1	26 A	27 D2	28 A
29 B	30 D2	31 A	32 C1	33 A	34 C1	35 A	36 B2
37 C	38 C1	39 B2	40 A	41 D2	42 A	43 B	44 B1
45 D	46 C1	47 B1	48 B2	49 A	50 B2	51 B1	52 A

N : Box Number
F : Fuel Type

Fuel Loading Schemes

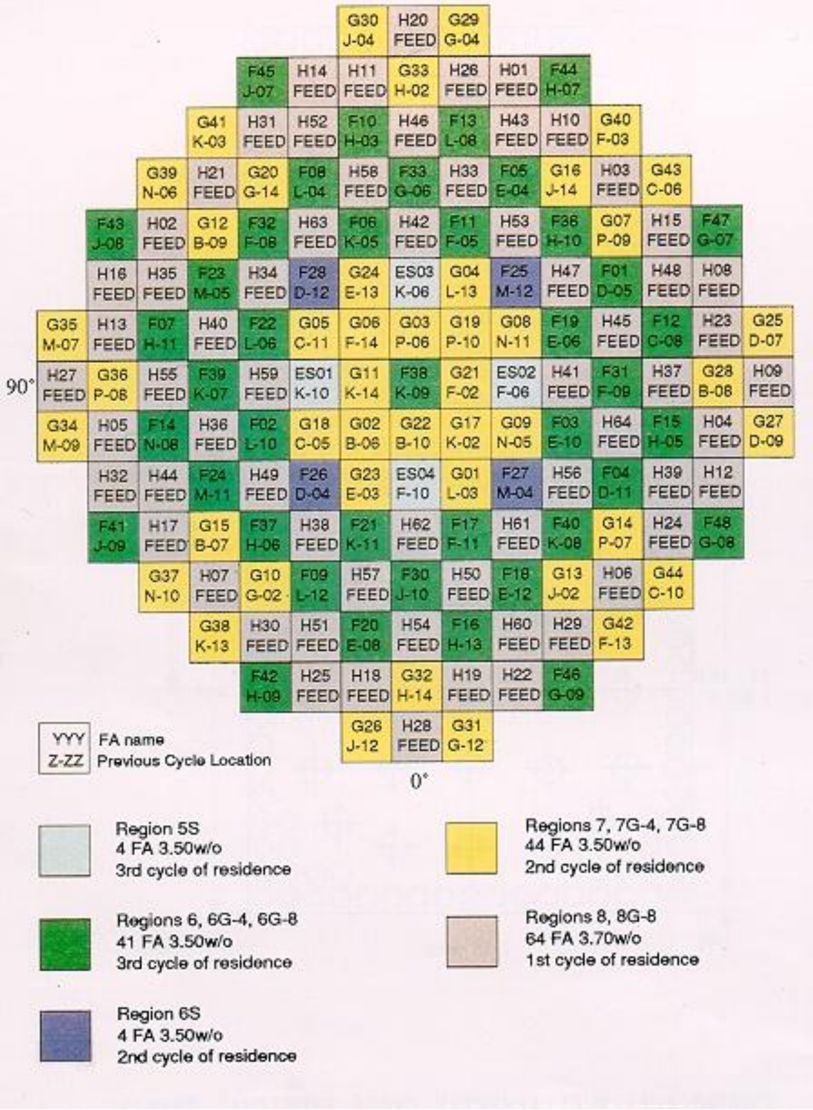
☐ Out-In Loading Scheme

- **Fresh fuel placed mostly at core periphery**
- **Easier control of interior power peak**
- **Involve large neutron leakage**
  - Vessel fluence problem as well as poor neutron economy

☐ Low-Leakage Loading Scheme

- **Once or twice burned fuel placed in core periphery**
- **Fresh fuel placed in core interior with high BA loading to suppress reactivity of fresh fuels**
- **Difficult peaking control → require significant optimization effort in loading pattern design**

Typical Low Leakage Loading Pattern



						G30 J-04	H20 FEED	G29 G-04						
				F45 J-07	H14 FEED	H11 FEED	G33 H-02	H26 FEED	H01 FEED	F44 H-07				
			G41 K-03	H31 FEED	H52 FEED	F10 H-03	H46 FEED	F13 L-08	H43 FEED	H10 FEED	G40 F-03			
		G39 N-06	H21 FEED	G20 G-14	F08 L-04	H58 FEED	F33 G-06	H33 FEED	F05 E-04	G16 J-14	H03 FEED	G43 C-06		
	F43 J-08	H02 FEED	G12 B-09	F32 F-08	H63 FEED	F06 K-05	H42 FEED	F11 F-05	H53 FEED	F36 H-10	G07 P-09	H15 FEED	F47 G-07	
	H16 FEED	H35 FEED	F23 M-05	H34 FEED	F28 D-12	G24 E-13	ES03 K-06	G04 L-13	F25 M-12	H47 FEED	F01 D-05	H48 FEED	H08 FEED	
G35 M-07	H13 FEED	F07 H-11	H40 FEED	F22 L-06	G05 C-11	G06 F-14	G03 P-06	G19 P-10	G08 N-11	F19 E-06	H45 FEED	F12 C-08	H23 FEED	G25 D-07
H27 FEED	G36 P-08	H55 FEED	F39 K-07	H59 FEED	ES01 K-10	G11 K-14	F38 K-09	G21 F-02	ES02 F-06	H41 FEED	F31 F-09	H37 FEED	G28 B-08	H09 FEED
G34 M-09	H05 FEED	F14 N-08	H36 FEED	F02 L-10	G18 C-05	G02 B-06	G22 B-10	G17 K-02	G09 N-05	F03 E-10	H64 FEED	F15 H-05	H04 FEED	G27 D-09
	H32 FEED	H44 FEED	F24 M-11	H49 FEED	F26 D-04	G23 E-03	ES04 F-10	G01 L-03	F27 M-04	H56 FEED	F04 D-11	H39 FEED	H12 FEED	
	F41 J-09	H17 FEED	G15 B-07	F37 H-06	H38 FEED	F21 K-11	H62 FEED	F17 F-11	H61 FEED	F40 K-08	G14 P-07	H24 FEED	F48 G-08	
		G37 N-10	H07 FEED	G10 G-02	F09 L-12	H57 FEED	F30 J-10	H50 FEED	F18 E-12	G13 J-02	H06 FEED	G44 C-10		
			G38 K-13	H30 FEED	H51 FEED	F20 E-08	H54 FEED	F16 H-13	H60 FEED	H29 FEED	G42 F-13			
				F42 H-09	H25 FEED	H18 FEED	G32 H-14	H19 FEED	H22 FEED	F46 G-09				
						G26 J-12	H28 FEED	G31 G-12						

YYY Z-ZZ	FA name Previous Cycle Location

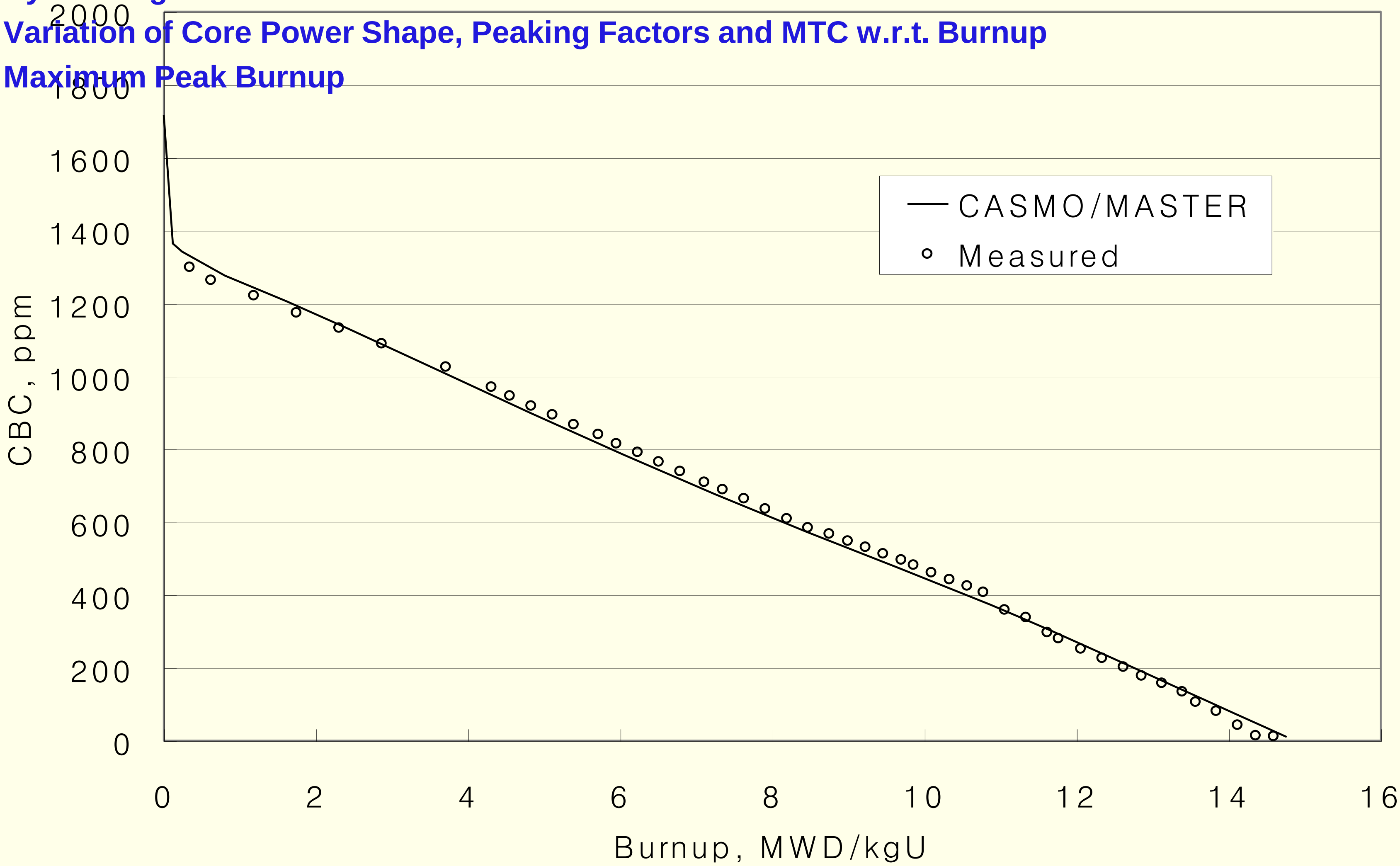
⬜	Region 5S 4 FA 3.50w/o 3rd cycle of residence	🟨	Regions 7, 7G-4, 7G-8 44 FA 3.50w/o 2nd cycle of residence
🟩	Regions 6, 6G-4, 6G-8 41 FA 3.50w/o 3rd cycle of residence	▨	Regions 8, 8G-8 64 FA 3.70w/o 1st cycle of residence
🟦	Region 6S 4 FA 3.50w/o 2nd cycle of residence		

Depletion Analysis

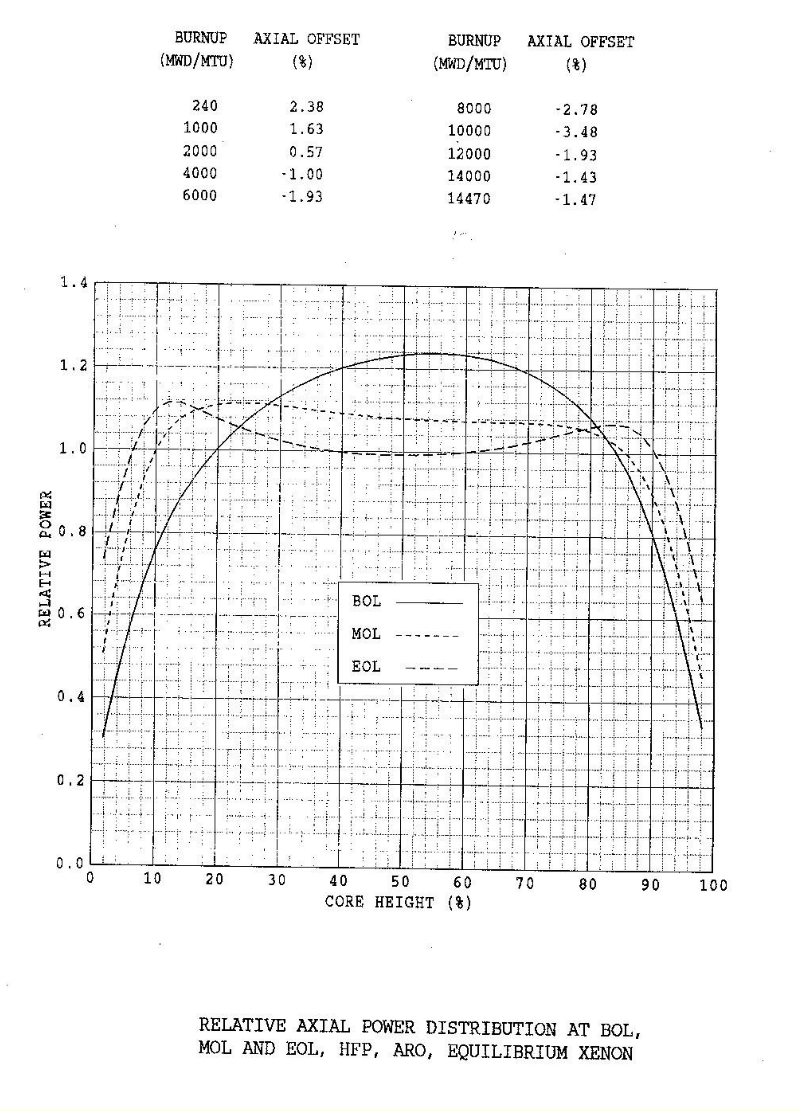
Cycle Length Determination

Variation of Core Power Shape, Peaking Factors and MTC w.r.t. Burnup

Maximum Peak Burnup



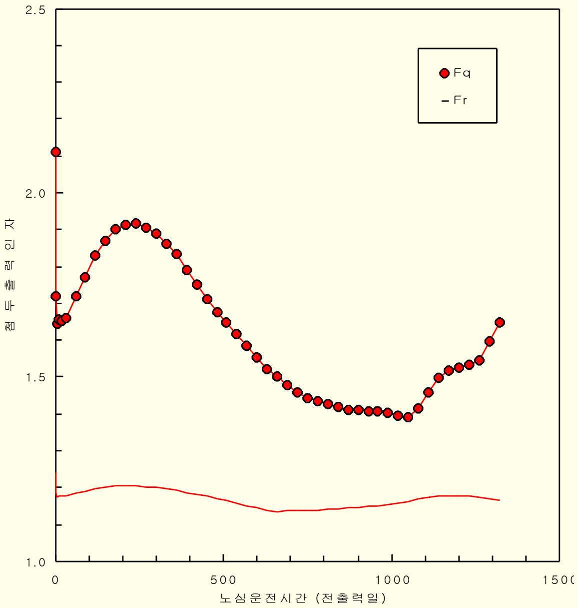
Axial Power Shape Change During Burnup



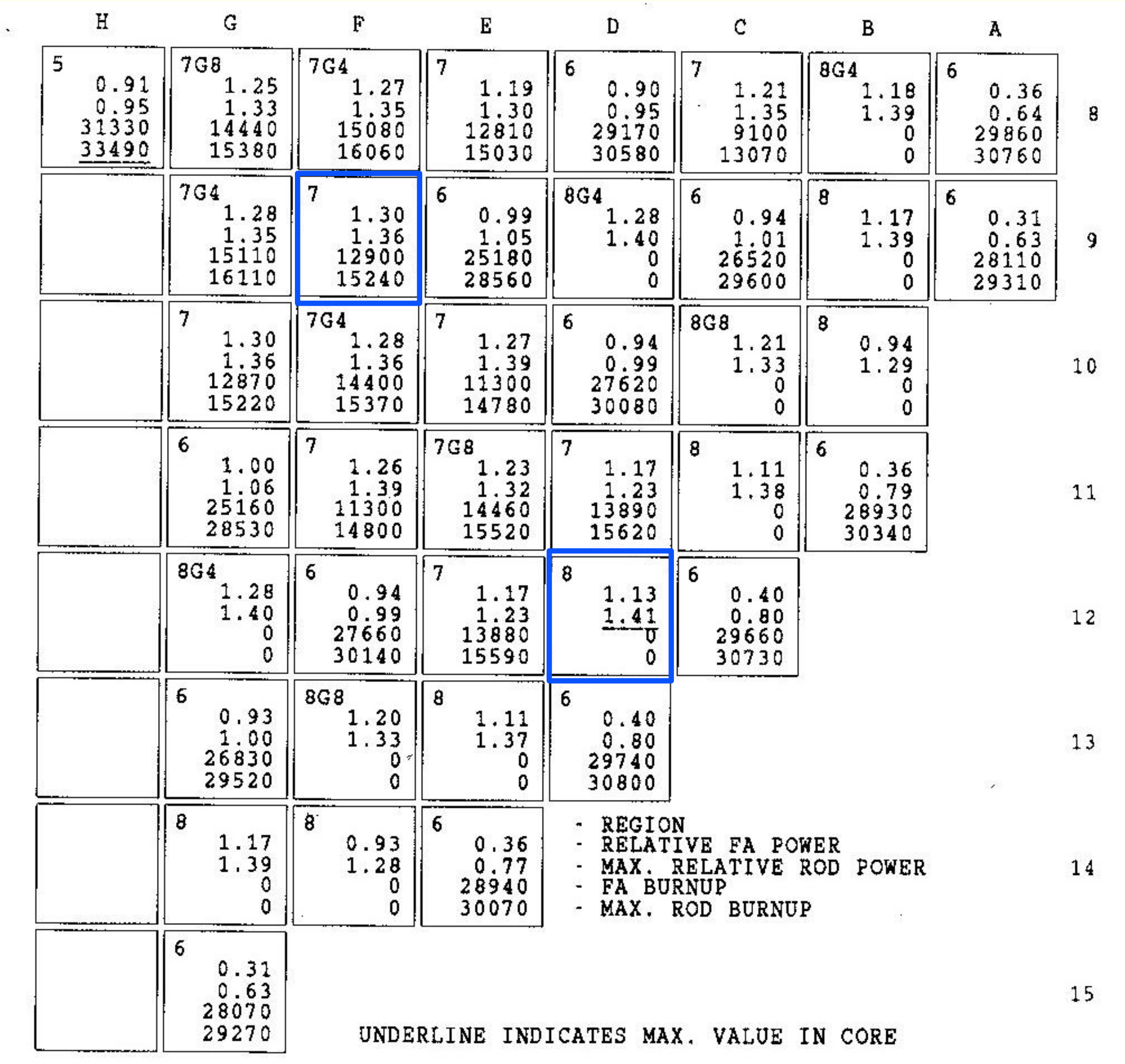
BURNUP (MWD/MTU)	AXIAL OFFSET (%)	BURNUP (MWD/MTU)	AXIAL OFFSET (%)
240	2.38	8000	-2.78
1000	1.63	10000	-3.48
2000	0.57	12000	-1.93
4000	-1.00	14000	-1.43
6000	-1.93	14470	-1.47

RELATIVE AXIAL POWER DISTRIBUTION AT BOL, MOL AND EOL, HFP, ARO, EQUILIBRIUM XENON

Fq and Fr Variation vs. Burnup



Power and Burnup Distribution at BOC

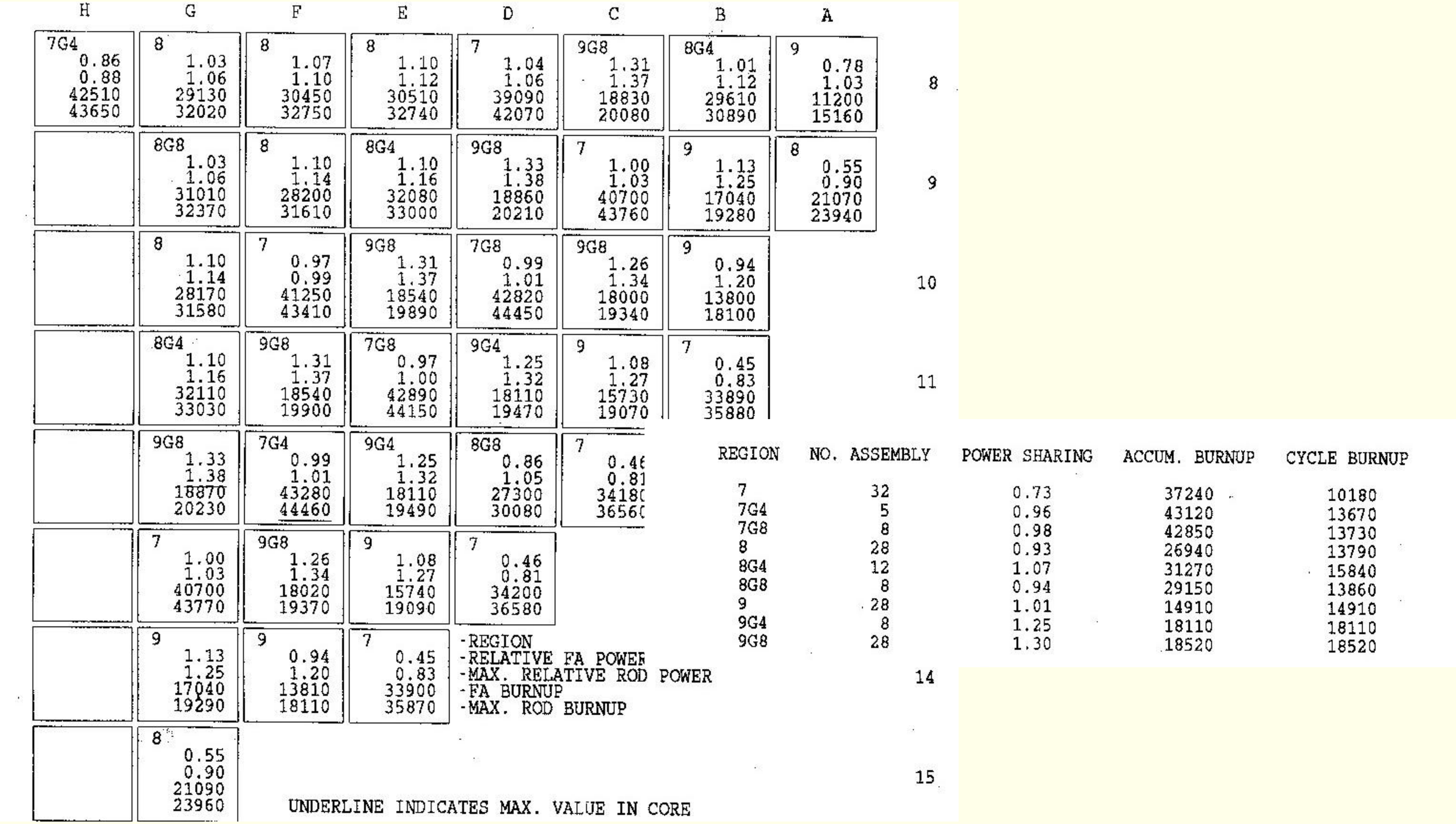


H	G	F	E	D	C	B	A	
5 0.91 0.95 31330 33490	7G8 1.25 1.33 14440 15380	7G4 1.27 1.35 15080 16060	7 1.19 1.30 12810 15030	6 0.90 0.95 29170 30580	7 1.21 1.35 9100 13070	8G4 1.18 1.39 0 0	6 0.36 0.64 29860 30760	8
	7G4 1.28 1.35 15110 16110	7 1.30 1.36 12900 15240	6 0.99 1.05 25180 28560	8G4 1.28 1.40 0 0	6 0.94 1.01 26520 29600	8 1.17 1.39 0 0	6 0.31 0.63 28110 29310	9
	7 1.30 1.36 12870 15220	7G4 1.28 1.36 14400 15370	7 1.27 1.39 11300 14780	6 0.94 0.99 27620 30080	8G8 1.21 1.33 0 0	8 0.94 1.29 0 0		10
	6 1.00 1.06 25160 28530	7 1.26 1.39 11300 14800	7G8 1.23 1.32 14460 15520	7 1.17 1.23 13890 15620	8 1.11 1.38 0 0	6 0.36 0.79 28930 30340		11
	8G4 1.28 1.40 0 0	6 0.94 0.99 27660 30140	7 1.17 1.23 13880 15590	8 1.13 1.41 0 0	6 0.40 0.80 29660 30730			12
	6 0.93 1.00 26830 29520	8G8 1.20 1.33 0 0	8 1.11 1.37 0 0	6 0.40 0.80 29740 30800				13
	8 1.17 1.39 0 0	8 0.93 1.28 0 0	6 0.36 0.77 28940 30070					14
	6 0.31 0.63 28070 29270							15

- REGION
- RELATIVE FA POWER
- MAX. RELATIVE ROD POWER
- FA BURNUP
- MAX. ROD BURNUP

UNDERLINE INDICATES MAX. VALUE IN CORE

Power and Burnup Distribution at EOC



H	G	F	E	D	C	B	A	
7G4 0.86 0.88 42510 43650	8 1.03 1.06 29130 32020	8 1.07 1.10 30450 32750	8 1.10 1.12 30510 32740	7 1.04 1.06 39090 42070	9G8 1.31 1.37 18830 20080	8G4 1.01 1.12 29610 30890	9 0.78 1.03 11200 15160	8
	8G8 1.03 1.06 31010 32370	8 1.10 1.14 28200 31610	8G4 1.10 1.16 32080 33000	9G8 1.33 1.38 18860 20210	7 1.00 1.03 40700 43760	9 1.13 1.25 17040 19280	8 0.55 0.90 21070 23940	9
	8 1.10 1.14 28170 31580	7 0.97 0.99 41250 43410	9G8 1.31 1.37 18540 19890	7G8 0.99 1.01 42820 44450	9G8 1.26 1.34 18000 19340	9 0.94 1.20 13800 18100		10
	8G4 1.10 1.16 32110 33030	9G8 1.31 1.37 18540 19900	7G8 0.97 1.00 42890 44150	9G4 1.25 1.32 18110 19470	9 1.08 1.27 15730 19070	7 0.45 0.83 33890 35880		11
	9G8 1.33 1.38 18870 20230	7G4 0.99 1.01 43280 44460	9G4 1.25 1.32 18110 19490	8G8 0.86 1.05 27300 30080	7 0.4 0.81 3418 3656			
	7 1.00 1.03 40700 43770	9G8 1.26 1.34 18020 19370	9 1.08 1.27 15740 19090	7 0.46 0.81 34200 36580				
	9 1.13 1.25 17040 19290	9 0.94 1.20 13810 18110	7 0.45 0.83 33900 35870					14
	8 0.55 0.90 21090 23960							15

-REGION
-RELATIVE FA POWEF
-MAX. RELATIVE ROD POWER
-FA BURNUP
-MAX. ROD BURNUP

UNDERLINE INDICATES MAX. VALUE IN CORE

REGION	NO. ASSEMBLY	POWER SHARING	ACCUM. BURNUP	CYCLE BURNUP
7	32	0.73	37240	10180
7G4	5	0.96	43120	13670
7G8	8	0.98	42850	13730
8	28	0.93	26940	13790
8G4	12	1.07	31270	15840
8G8	8	0.94	29150	13860
9	28	1.01	14910	14910
9G4	8	1.25	18110	18110
9G8	28	1.30	18520	18520

Design Bases Reactivity Insertion Accidents

☐ Control Rod Ejection

- **Sudden Rupture of CEDM Housing on Vessel Head**
- **Control Ejected Due to Pressure Difference Introducing Positive Reactivity into Core**
- **Ejected Rod Worth Depending on Inserted Position**
  - Power Dependent Insertion Limit
- **Rapid Burst of Power Mitigated Soon by Doppler Feedback**
- **Enthalpy Accumulation in Pellet < 280 cal/g**

☐ Steam Line Break

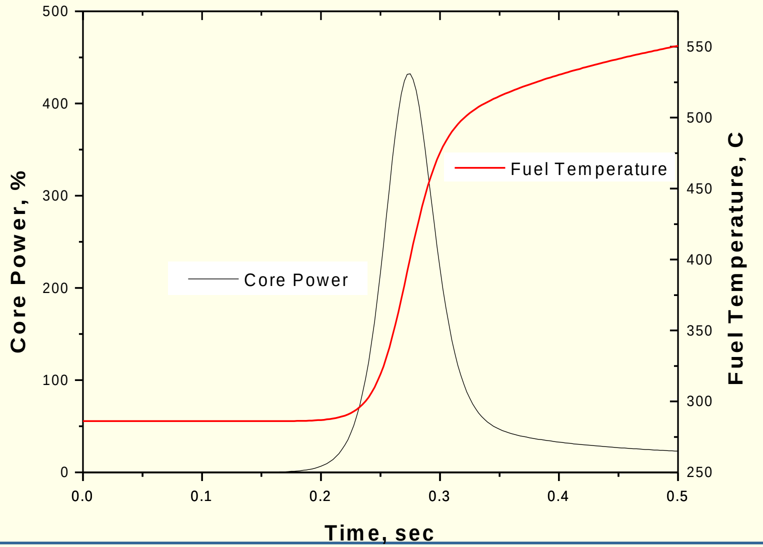
- **Break in a Steam Line**
- **Rapid Evaporation Leading to Overcooling of Primary Coolant**
- **Positive Reactivity Insertion Due to Inlet Cooling**
- **Power Increase Followed by Shutdown with a Stuck Rod Assumed**
- **Subcritical Multiplication Potentially Causing Return-to-Power**
- **Shutdown Margin Important**

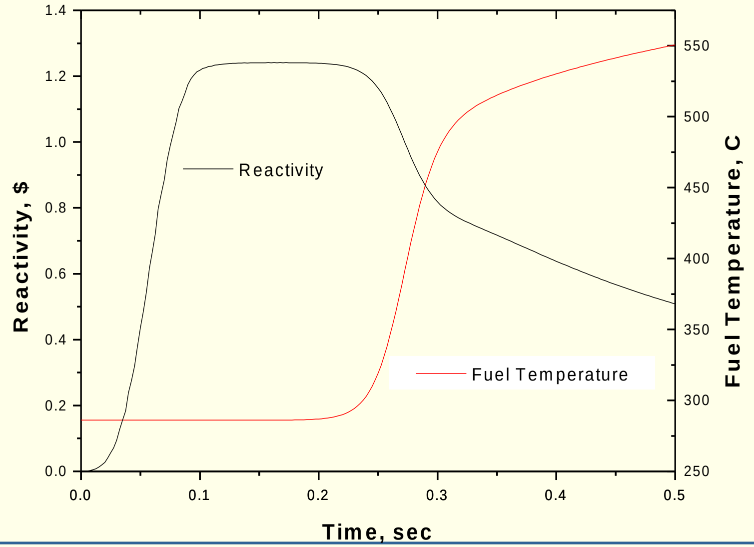
HZP Rod Ejection and Doppler Effect

☐ **Inherent Safety by Doppler Effect**

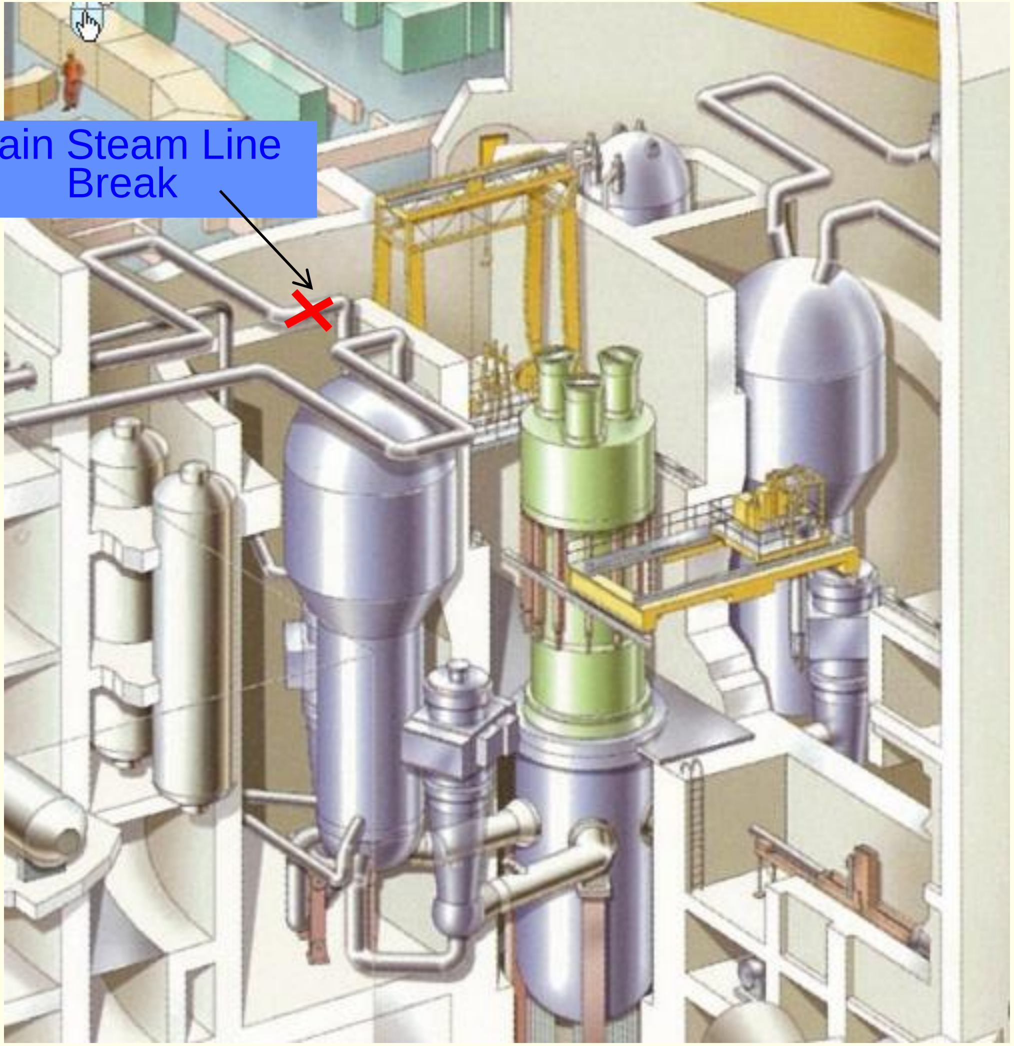
☐ **Control Rod Ejection Ejection Accident**

- **Initially Critical at ~0 Power (10^{-4}% Nominal)**
- **Control Rod Ejection in 0.1 sec → Positive Reactivity (1.2$) Insertion**
- **Power Increase Exponentially → Fuel Temperature Increase**
- **Negative Temperature Feedback**
- **Autonomous Power Reduction**





Nuclear Steam Supply System (OPR100)



Main Steam Line Break

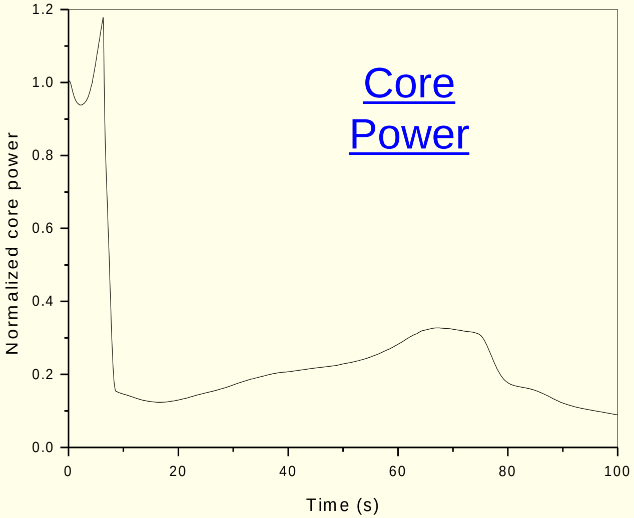
MSLB Progress Scenario – 1/2

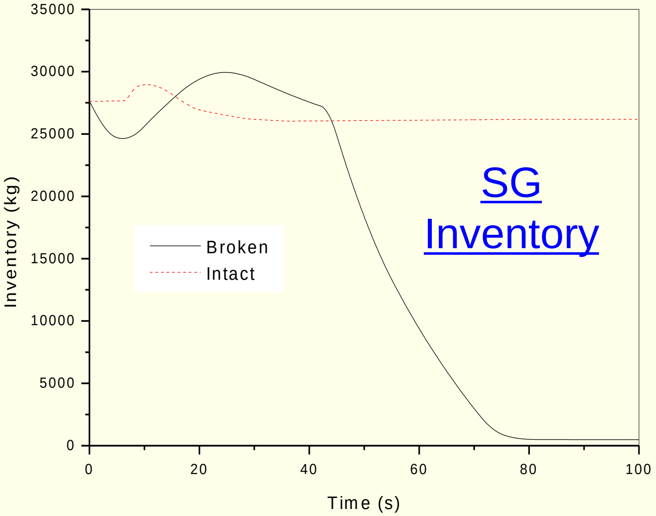
- ☐ Break in One of the Main Steam Lines (Four or More)
  - Leak of High Pressure Steam Through the Break (Critical Flow)
  - Depressurization of SG and Rapid Evaporation
- ☐ Cool-down of Primary Coolant Causing Depressurization of Primary Loop
  - Initially Coolant Density Decrease in the Core
  - Core Power Decrease due to Less Moderation
- ☐ Transport of Chilled Coolant to Core
  - Core Reactivity Increase Due to Negative MTC
  - Core Power Increase
- ☐ Overpower or Low Pressure Trip
  - Control Rod Inserted, but with One Control Rod Stuck Out
  - Core Power Decrease to Shutdown Level
  - Turbine Stop Valve Close
  - Feedwater Block Valve Close

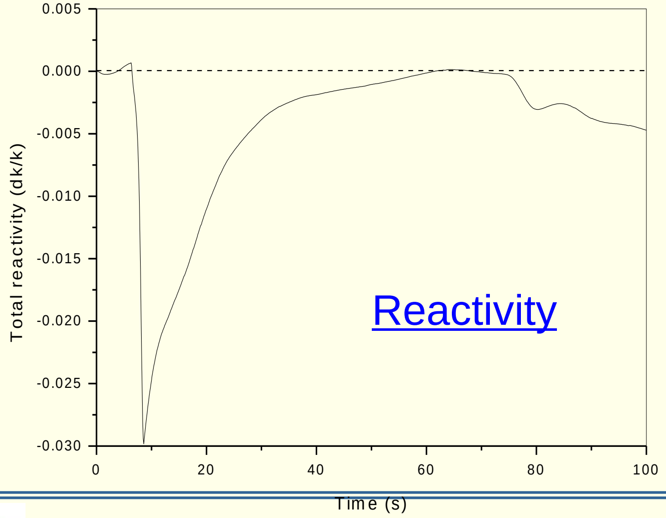
MSLB Progress Scenario – 2/2

- Continued Evaporation of Secondary Coolant and Overcooling of Primary Coolant in one Loop
  - Asymmetric Flow Inlet Flow
- Continued Core Reactivity Increase
  - Subcritical Neutron Multiplication
  - Core Power Increase
  - Possibility of Return-to-Critical or Return-to-Power
- Dry-out of Feedwater in Broken Side SG
  - No Further Decrease in Coolant Temperature
  - Core Power Decreases due to Negative Temperature Coefficients

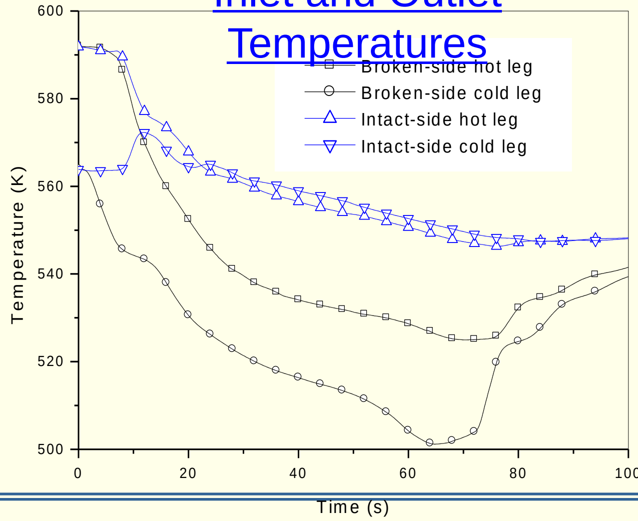
Steam Line Break Accident Progress


Core Power


SG Inventory

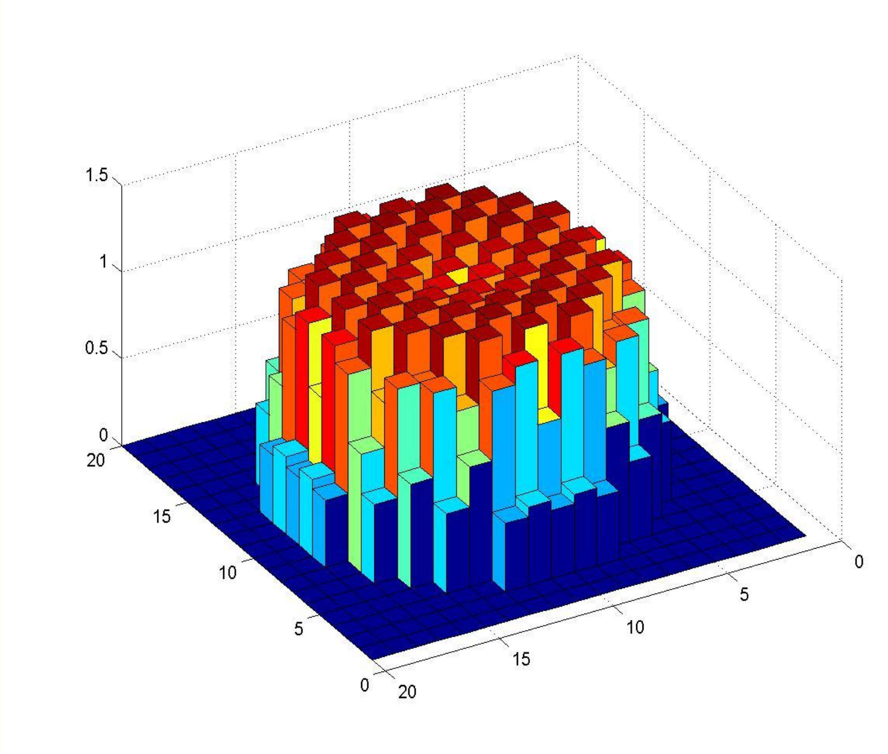

Reactivity

Inlet and Outlet Temperatures

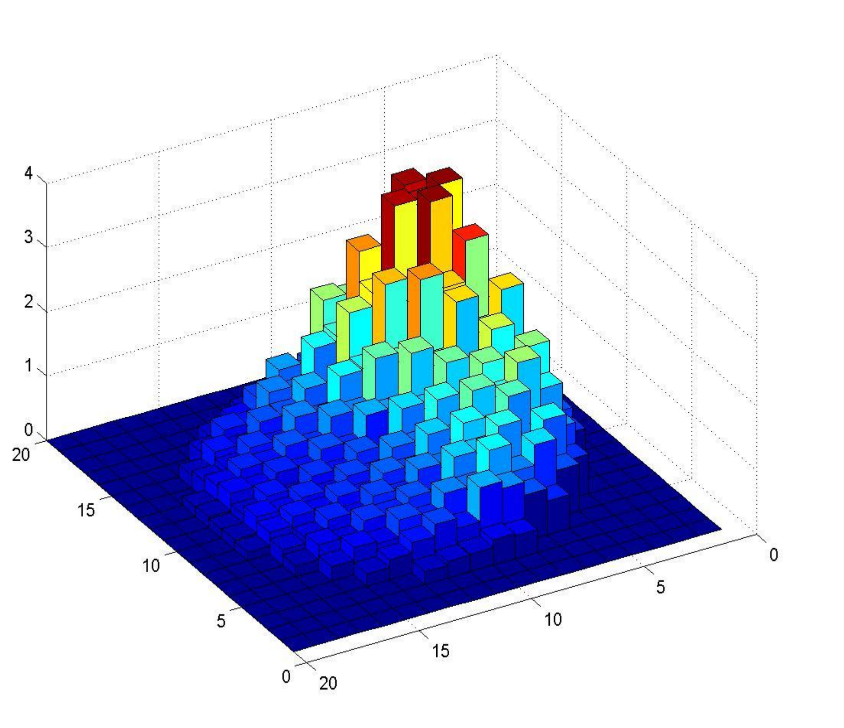


Core Power Shape

at Initial Steady-State

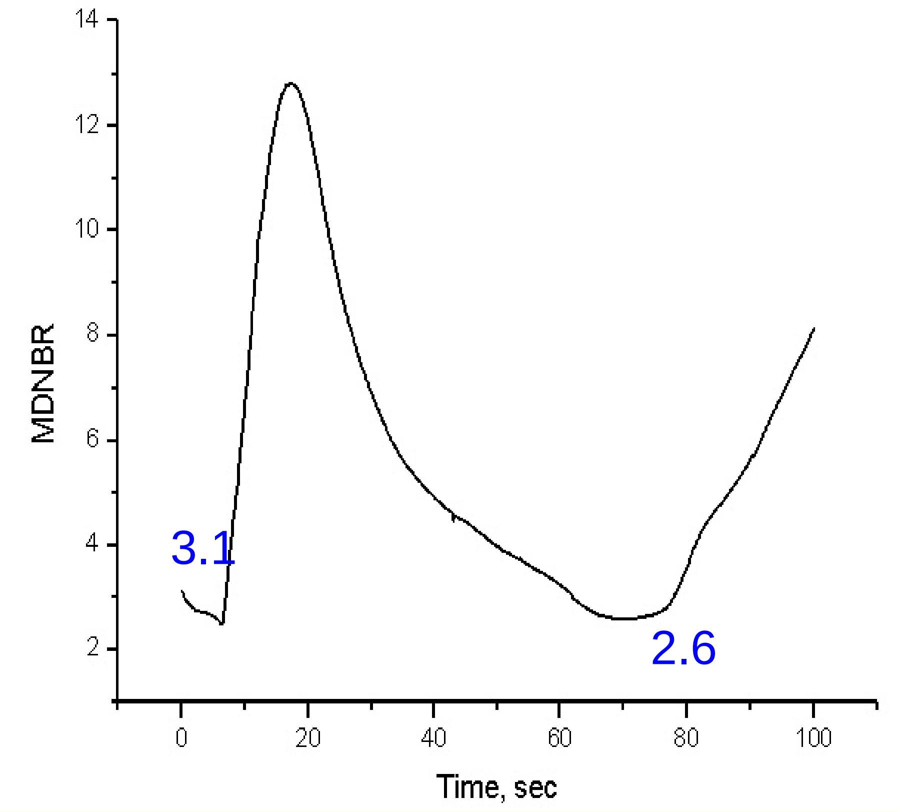


at Maximum Return-to-Power



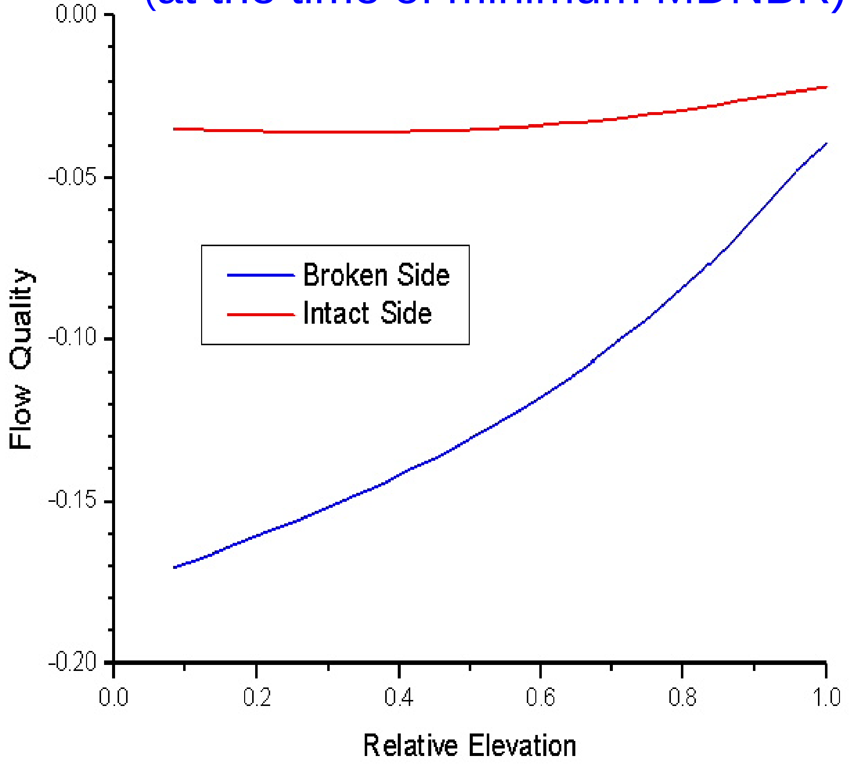
Minimum DNBR Behavior during MSLB

MDNBR



Axial Quality Profile

(at the time of minimum MDNBR)



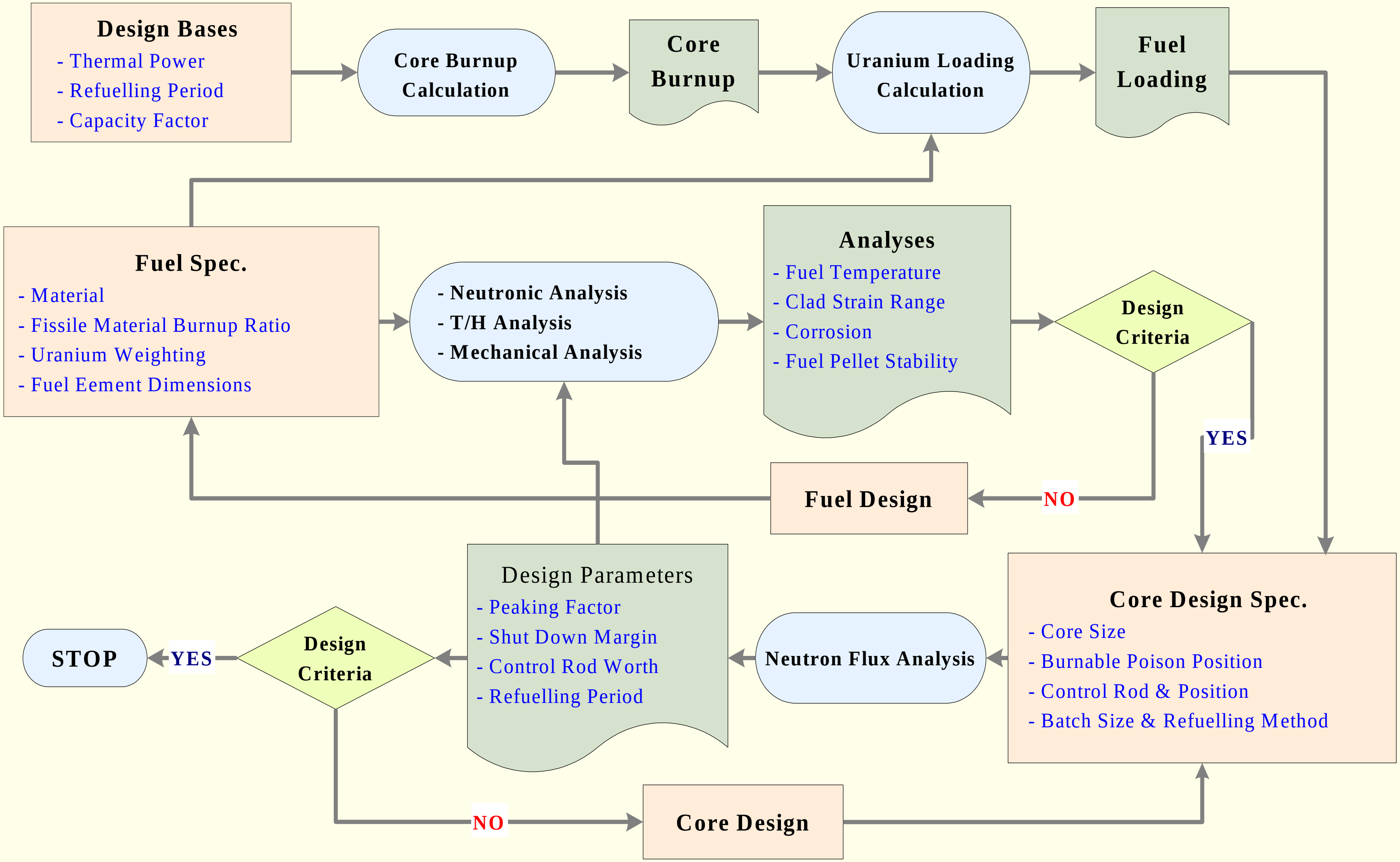
- DNB is not limiting because of large inlet subcooling.

Summary

☐ Nuclear Design Considerations

- **Economical Required Energy Production with Proper Fuel Loading**
  - Enrichment and Amount of Fresh Fuels
  - Suitable Use of Burnable Absorbers
  - Elaborated Arrangement of Fresh and Burned Fuels in Core (Low Leakage Loading Pattern)
- **Satisfying Safety Requirements**
  - Fq and Fr Limits for Peak Cladding Temperature and Minimum DNB
  - Peak Discharge Burnup
  - Shutdown Margin (SLB)
  - Ejected Rod Worth (Rod Ejection)
- **Operating Margin**
  - Peaking as low as Possible
- **Longer Cycle for Better Economics in Generation Cost**

Overall Design Flow



Design Bases
- Thermal Power
- Refuelling Period
- Capacity Factor

Core Burnup Calculation

Core Burnup

Uranium Loading Calculation

Fuel Loading

Fuel Spec.
- Material
- Fissile Material Burnup Ratio
- Uranium Weighting
- Fuel Eement Dimensions

- **Neutronic Analysis**
- **T/H Analysis**
- **Mechanical Analysis**

Analyses
- Fuel Temperature
- Clad Strain Range
- Corrosion
- Fuel Pellet Stability

Design Criteria

YES

NO

Fuel Design

Design Parameters
- Peaking Factor
- Shut Down Margin
- Control Rod Worth
- Refuelling Period

Core Design Spec.
- Core Size
- Burnable Poison Position
- Control Rod & Position
- Batch Size & Refuelling Method

Neutron Flux Analysis

STOP

YES

Design Criteria

NO

Core Design

General Design Criteria
(10CFR50 Appendix A)

☐ Reactor Design (Criterion 10)

- Fuel design limits not exceeded during normal operation including anticipated operational occurrences (AOOs)

☐ Fuel Design Limits (FDL)

- Fuel Melting Temperature (~5000°F or ~2700°C)
- Peak Cladding Temperature (2200°F or ~1200°C)
- Minimum DNBR (~1.3)
- Maximum Discharge Burnup (~50000 MWD/T)
- Maximum Deposited Energy (~280 cal/g)
- Cladding Oxidation (< 17% of the Cladding Thickness)

General Design Criteria (10CFR50 Appendix A)

☐ **Reactor Inherent Protection (Criterion 11)**

- **Inherent nuclear feedback to compensate for a rapid increase in reactivity**
  - Negative Fuel Temperature Coefficient (FTC)
  - Negative Moderator Temperature Coefficient (MTC)

☐ **Suppression of Reactor Power Oscillation (Criterion 12)**

- **Power oscillation detected and suppressed by proper means**

☐ **Instrumentation and Control (Criterion 13)**

- **Monitor variables and systems over their anticipated ranges for normal operation, for AOOs, and for accident conditions.**
- **Appropriate controls provided to maintain these variables and systems within prescribed operating ranges**

☐ **Protection System Functions (Criterion 20)**

- **Automatically initiated reactivity control system**
- **Sense accident condition and initiate safety systems**

General Design Criteria
(10CFR50 Appendix A)

- **Protection System Reliability and Testability (Criterion 21)**
  - **Redundancy and independence of the protection system**
  - **No single failure resulting in loss of protection function**
- **Protection System Requirement for Reactivity Control Malfunction (Criterion 25)**
  - **FDL not exceeded for any single malfunction of the reactivity control system**
  - **Control rod withdrawal**

General Design Criteria
(10CFR50 Appendix A)

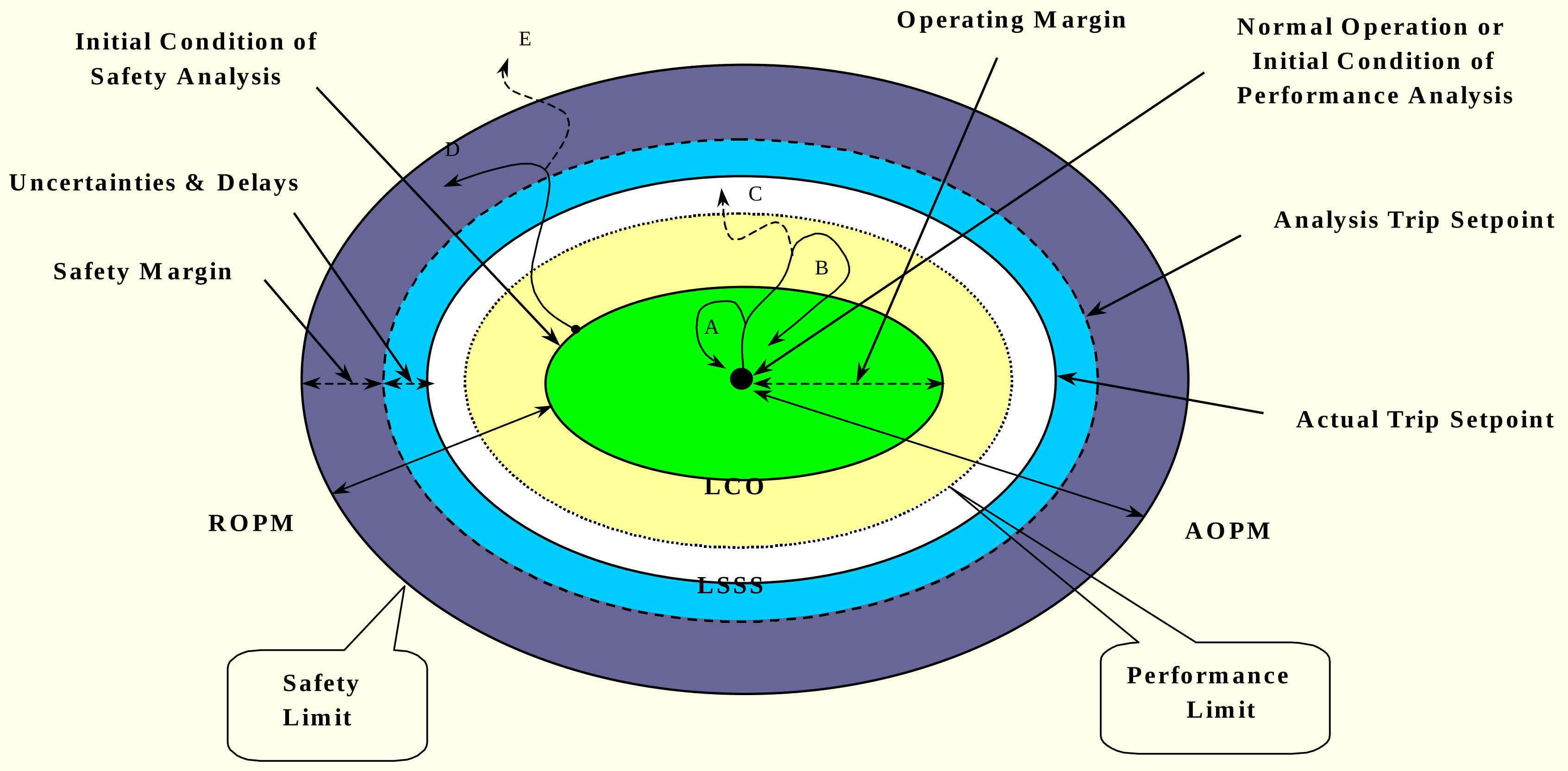
☐ Reactivity Control System Redundancy and Capability (Criterion 26)

- **Two independence reactivity control system**
- **Use of control rods essential**
- **Appropriate margin for malfunctions such as stuck rods**
- **The second system controlling slow reactivity changes occurring normal operation**
- **Hold the reactor subcritical under cold condition**
  - Subcriticality during Refueling (k<0.95)

☐ Reactivity Limits (Criterion 28)

- **Reactivity control system having appropriate limits on the potential amount and rate of reactivity increase**
- **Rod ejection, drop, steam line rupture, and cold water addition**
- **Maximum CEA Speed**
- **Not too much Negative MTC (SLB Consideration)**

Operating Space



LCO (Limiting Conditions for Operation)

LSSS (Limiting Safety System Settings)