Fuel Batch Optimization for Extra Longer Initial Core Design of APR1400

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I

Introduction

Initial Core Design

- Loading pattern (LP) search and design is one of the most critical paths in Nuclear design.
- Most of the research on LP determination has focused on the minimization of maximum pin peaking factor (FXYP) and increasing burnup (BU).
- The most important factors are the number of feed FAs and their enrichment.
- The research on the evaluation of the number of feed FAs and fuel enrichment is hadn’t been found and a systematic method to determine the optimum value of these two parameters is proposed in this study.

Extra Long Fuel Cycle (24 month)

- Increase in discharge burnup (BU)
- Increase in energy production
- Reduce outage costs by reducing the number of refueling outages during the operating lifetime of a plant
- Decrease the fuel cycle cost
- Enhance energy planning (refueling will be held in one season)

- **This study aims :**

I. **Produce a cost-efficient, high burnup (24 GWD/MTU) initial core model for APR1400**

II. **Propose a three-step methodology for the Initial Core Design:**

- FMNG - to determine the core average enrichment satisfying utility requirement
- EA - to determine batch average enrichment satisfying FMNG
- SA - to determine an optimum LP

II

Initial core design methodology:

FMNG: Evaluation of core average enrichment and number of BA rods

Initial Core Design:

- What should be the core average enrichment?
- How many BA rods are required to reduce CBC?

FMNG

Step 1
- Core Average Enrichment
- Number of BA rods

Step 2
- Batch Average Enrichment
- Number of FA per batch

Step 3
- FA configuration
- Loading pattern

Fuel Management Net Graph is a **Simple** and **Intuitive** tool for the evaluation of:

- Cycle length VS core average enrichment
- Total number of BA rods for desired CBC at BOC

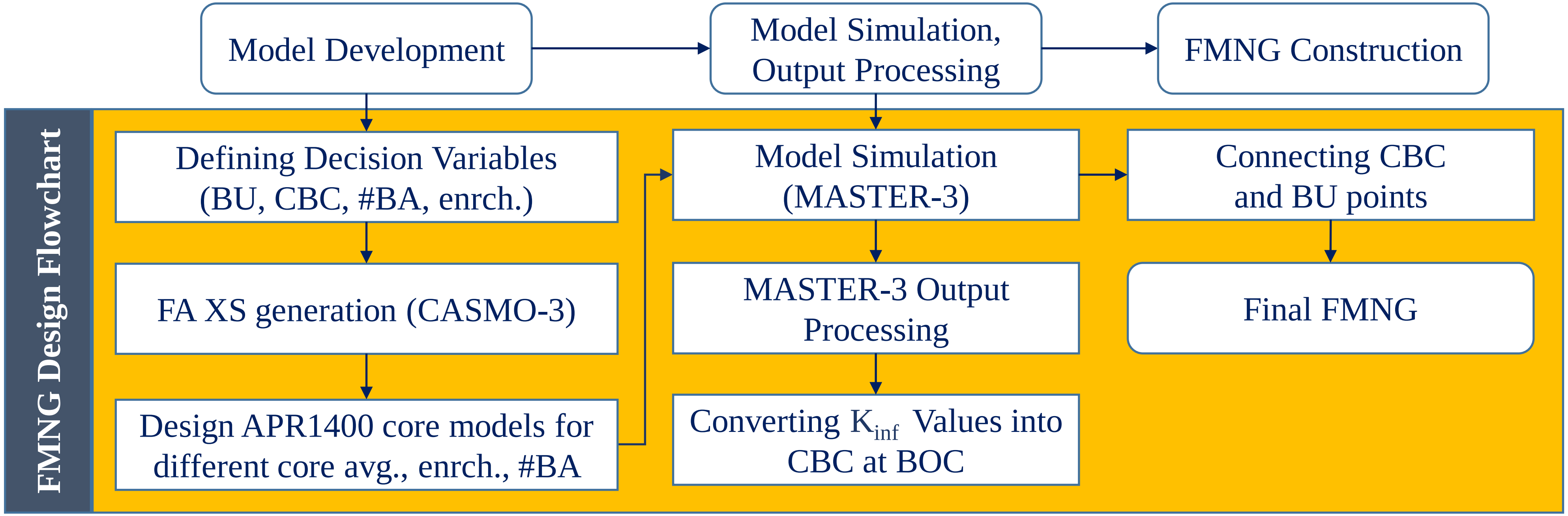


Figure: Schematic flowchart of FMNG design

II. FMNG: EVALUATION OF CORE AVERAGE ENRICHMENT AND NUMBER OF BA RODS

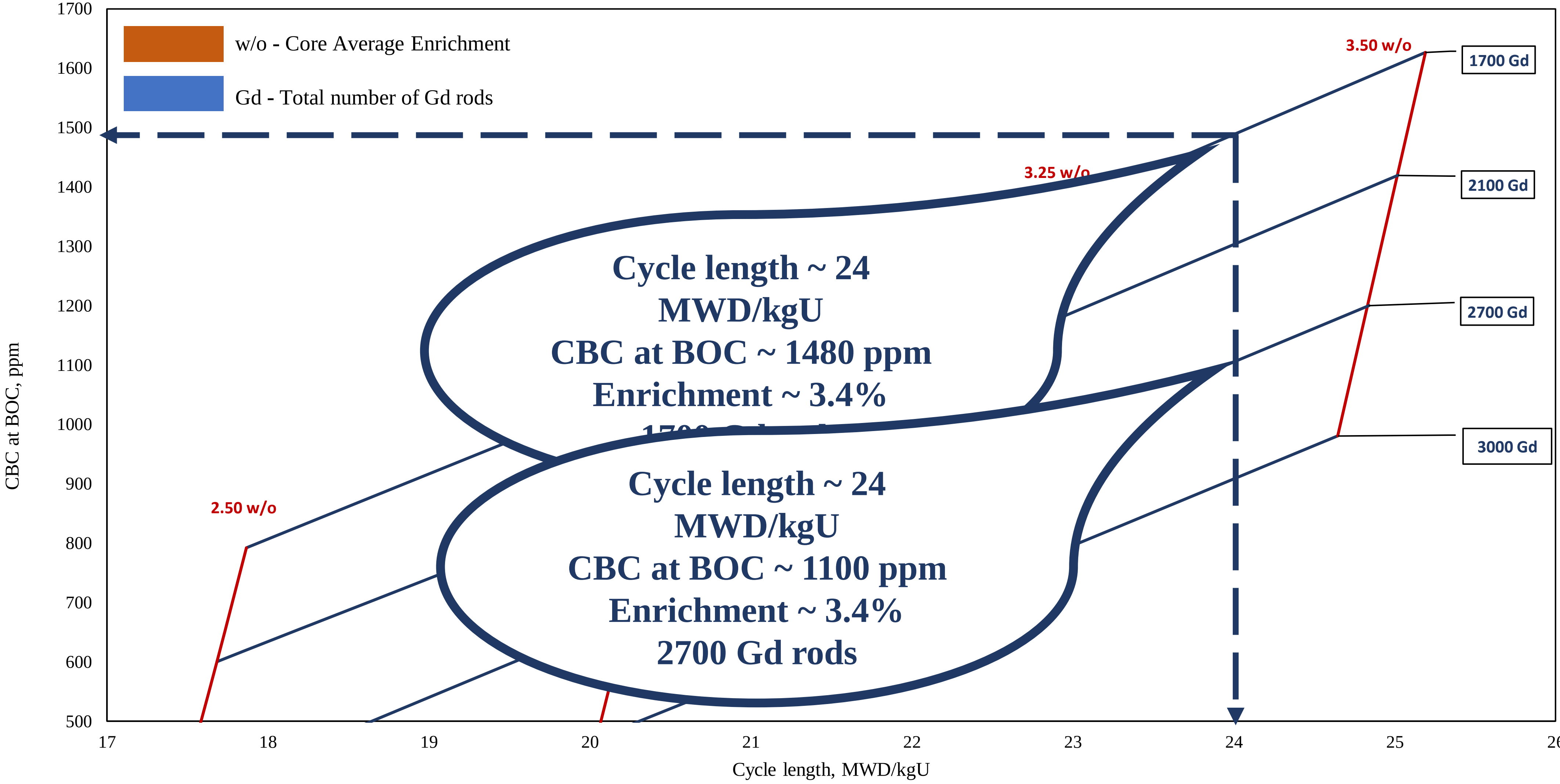


Figure: FMNG demonstration

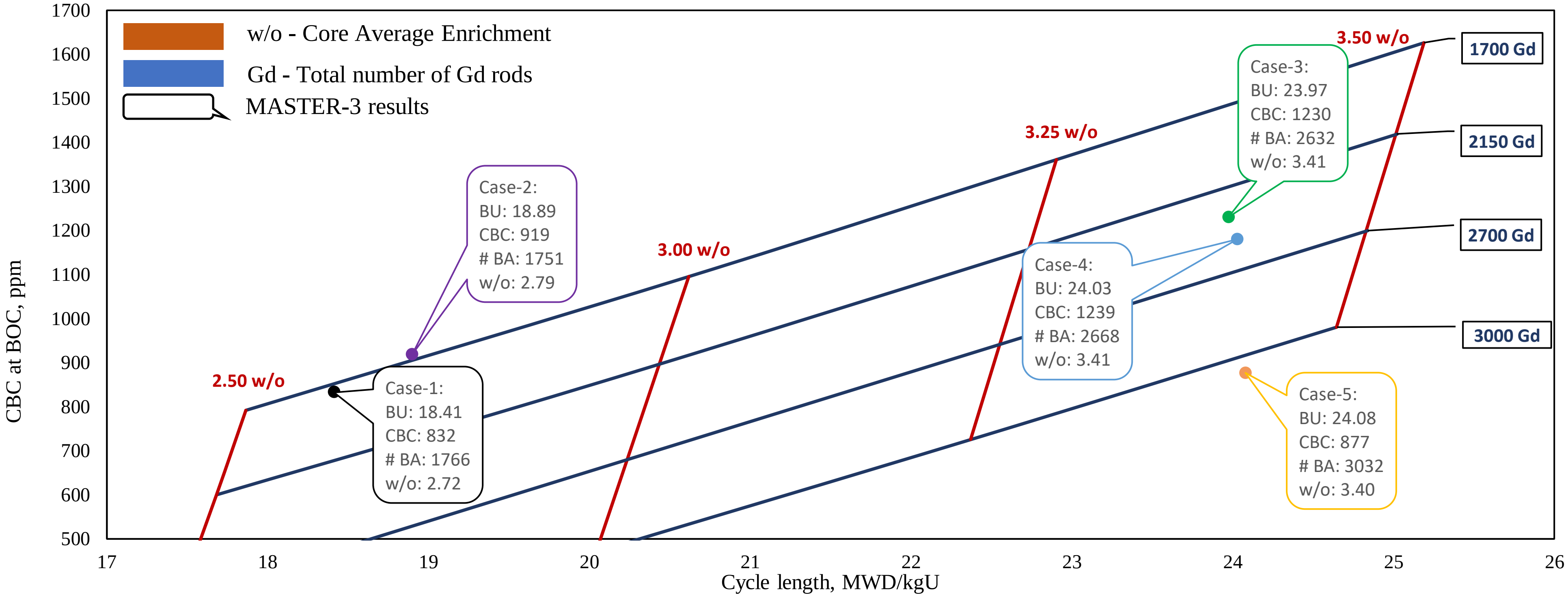


Table: FMNG verification

Case #	MASTER-3				FMNG		Δ (MASTER-FMNG)	
	# BA rods	BU	CBC	w/o %	CBC	BU	CBC, ppm	BU, MWD/kgU
1	1766	18.41	832.85	2.72	835.00	18.30	2.15	0.11
2	1751	18.90	919.00	2.79	915.00	18.90	4.00	0.00
3	2632	23.98	1230.47	3.41	1230.00	23.95	0.47	0.03
4	2668	24.03	1180.00	3.41	1185.00	24.00	5.00	0.03
5	3032	24.08	877.00	3.41	880.00	24.10	3.00	0.02

II

Initial core design methodology:

EA: Optimization of batch average enrichment and number of FA per batch

Where do these numbers come from ?

Based on **Engineering Judgment** which is based on **long experience** !

What if I am not experienced enough for this judgment?

Assembly Type	Number of Fuel Assemblies	Fuel Rod Enrichment (w/o)	No. of Rods Per Assembly	No. of Gd_2O_3 Rods per Assembly	Gd_2O_3 Contents (w/o)
A0	77	1.71	236	-	-
B0	12	3.14	236	-	-
B1	28	3.14/2.64	172/52	12	8
B2	8	3.14/2.64	124/100	12	8
B3	40	3.14/2.64	168/52	16	8
C0	36	3.64/3.14	184/52	-	-
C1	8	3.64/3.14	172/52	12	8
C2	12	3.64/3.14	168/52	16	8
C3	20	3.64/3.14	120/100	16	8

Evolutionary algorithm

Step 1
- Core Average Enrichment ?
- Number of BA rods ?

Step 2
- Batch Average Enrichment
- Number of FA per batch

Step 3
- FA configuration
- Loading pattern

Fuel Cost for extra long cycle:

- **High BU**: Higher enrichment fuel – Higher enrichment costs
- **Non-Linearity**: Cost of enrichment is non-linear
- **Minimal Cost**: Find minimal Batch enrichment and number of FAs cost Satisfying FMNG

Evolutionary **A**lgorithm

Evolutionary Algorithm sets:

- **Objective Function**: The sum of every batch fuel cost
- **Decision Variables**: Batch enrichments and number of FA per each batch
- **Constraint**: Range of core and batch enrichment, and the number of FA per batch

Objective Function (fitness):

$$\sum_{i=1}^{batch} N_i \times f_i(F_1, F_2, F_3, F_4),$$

F_1: ore purchase cost
F_2: enrichment cost
F_3:conversion cost
F_4: fabrication cost

N_i: Number of FA in a batch i.

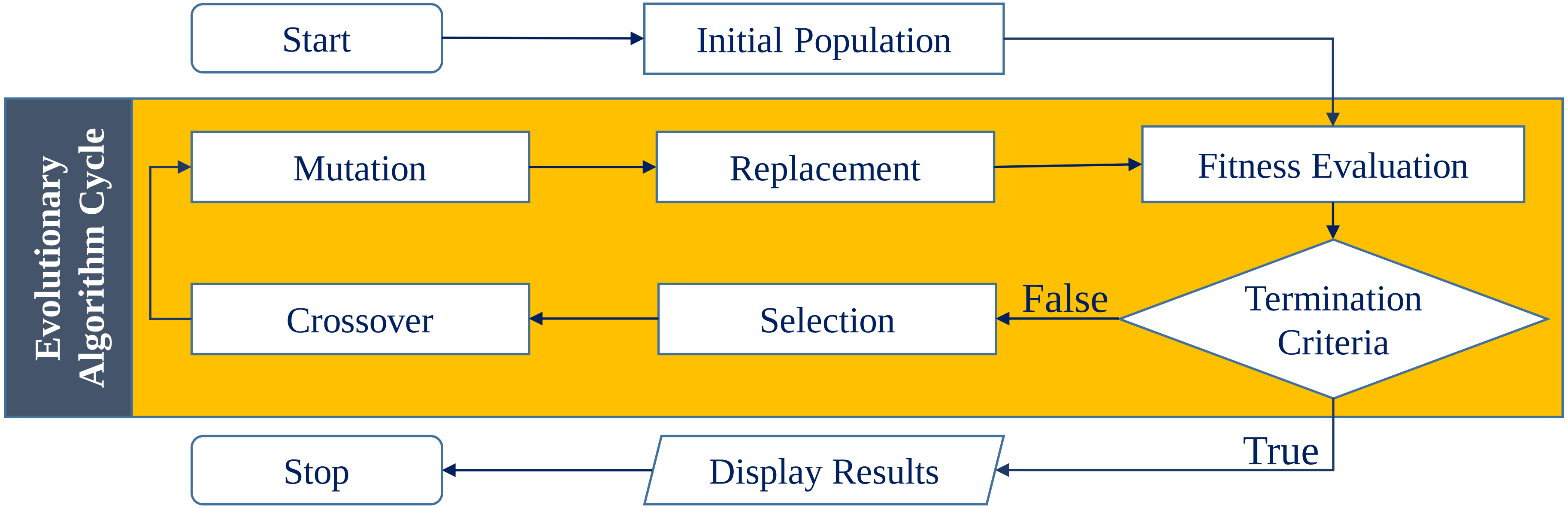


Figure: Schematic flowchart for Evolutionary algorithm

II

Initial core design methodology:

SA: FA configuration and Core Loading Pattern Determination

Simulated annealing

- Easy implementation for nonlinear, combinatorial problems
- Proven effectiveness for LP determination
- LP search criteria - minimum FXYP

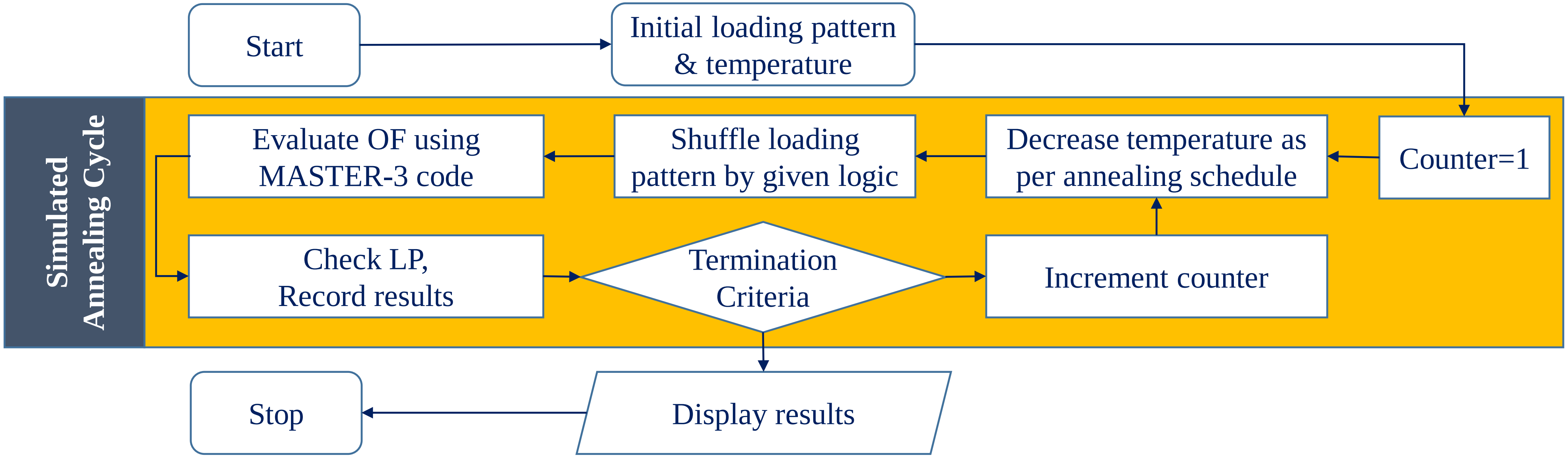


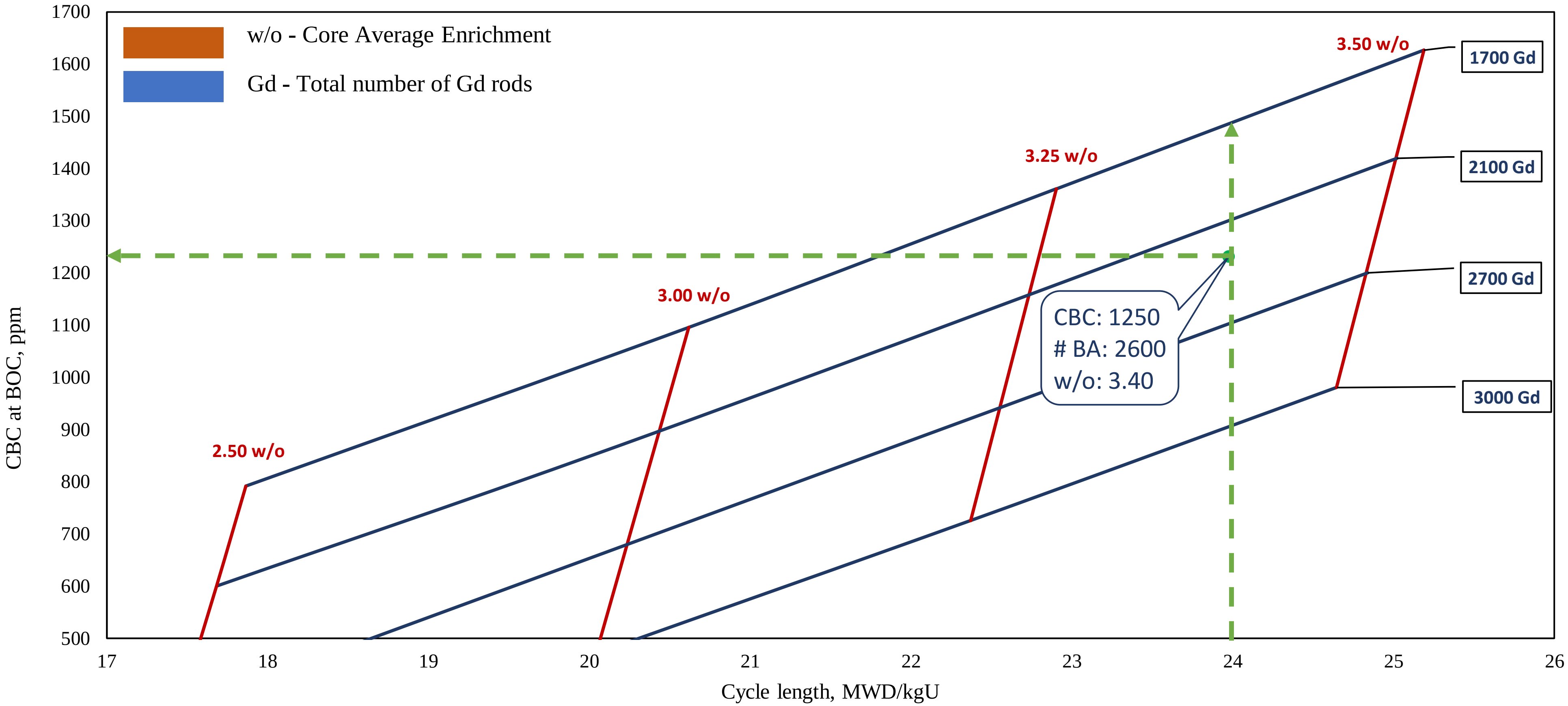
Figure: Schematic flowchart for Simulated Annealing

III

Result:Extra long initial core model for APR1400

- Design requirements and criteria

  - ✓ Target cycle burnup : 24 MWD/kgU
  - ✓ CBC at BOC : < 1300 ppm
  - ✓ Design criteria : radial peaking factor < 1.55
  - ✓ Reference core/fuel : APR1400/PLUS7



FMNG illustrates that for a given cycle length of 24 MWD/kgU the core average enrichment is determined at about 3.4 w-t % of 235U while CBC is 1250 ppm for the total number of poison rods of about 2600.

III. RESULTS: EVALUATION OF BATCH AVERAGE ENRICHMENT AND NUMBER OF BA RODS

Constraints for Evolutionary Algorithm:

I. Core average enrichment : $3.4\ \% \leq w/o \leq 3.5\%$

II. Total number of FA: 241

III. Number of FA per batch: $40 \leq N \leq 70$

IV. Batch average enrichments:

$2.5\ \% \leq A0 \leq 3.0\%$

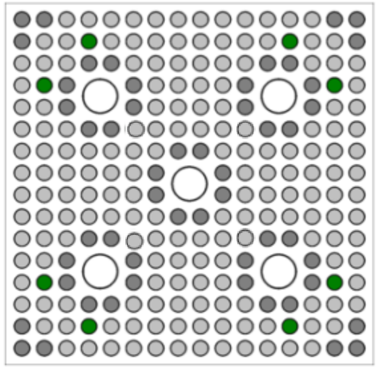
$3.0\ \% \leq B1 \leq 3.5\%$

$3.5\ \% \leq C1 \leq 4.0\%$

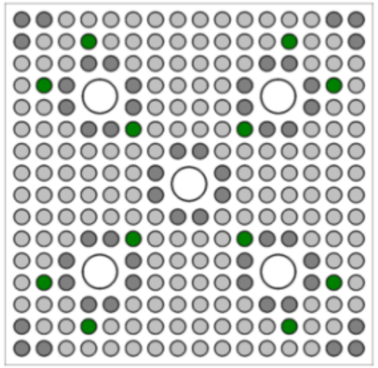
$D1 \leq 4.55\%$

Table: EA results satisfying FMNG and given constraints

Batch	A0	B1	C1	D1
Enrichment, w/o	2.72	3.00	3.53	4.55
Number of FAs	65	64	56	56



A0



B1, C1, D1

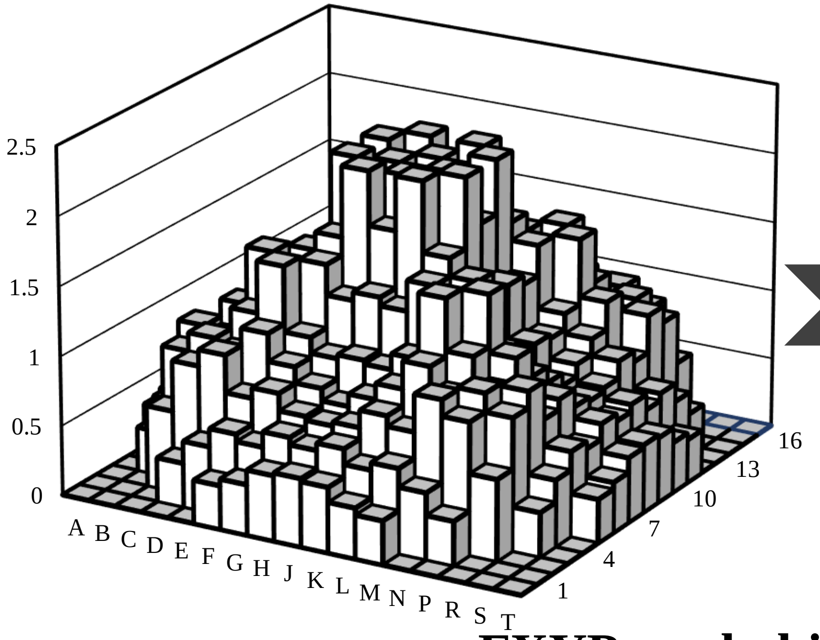
Enrichment zoning and absorber rod positions for assemblies A0, B1, C1, and D1

FAs specifications

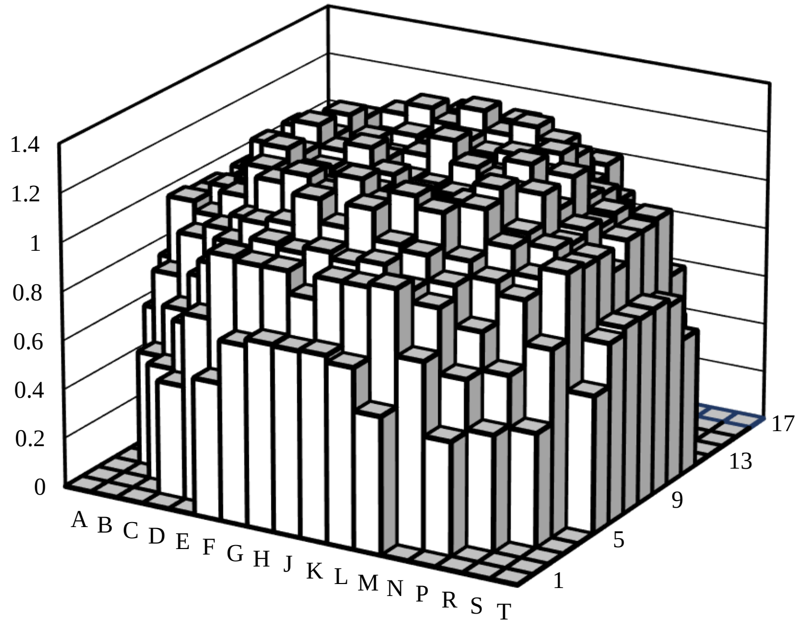
Type	# of Fas	235U w/o		# of rods		# of BA rods	batch avg. w/o
		High	Zoning	High	Zoning	8 w/o Gd	
A0	65	2.87	2.37	176	52	8	2.72
B1	64	3.18	2.68	172	52	12	3.00
C1	56	3.74	3.24	172	52	12	3.53
D1	56	4.81	4.31	172	52	12	4.55
Sum	241					2632	3.41

Core Power Distribution

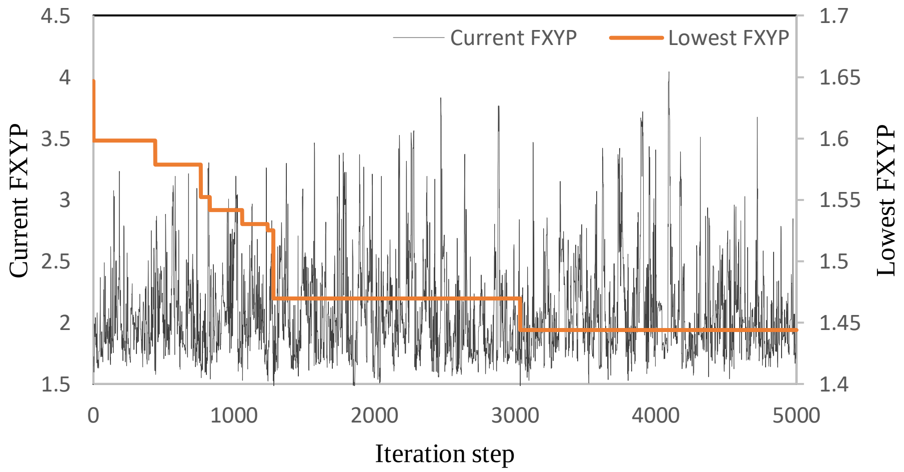
Before SA

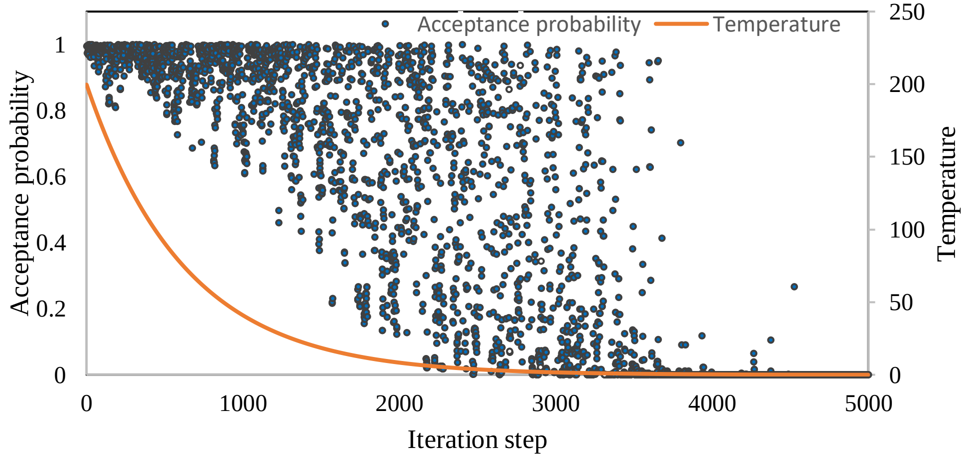


After SA



FXYP, probability & temperature during SA





III. RESULTS: LP DETERMINATION

	A	B	C	D	E	F	G	H	J	K	L	M	N	P	R	S	T
1						D1	D1	D1	D1	D1	D1	D1					
2				D1	D1	D1	C1	C1	B1	C1	C1	D1	D1	D1			
3			D1	A0	C1	B1	A0	B1	A0	B1	A0	B1	C1	A0	D1		
4		D1	A0	B1	A0	A0	B1	C1	B1	C1	B1	A0	A0	B1	A0	D1	
5		D1	C1	A0	B1	C1	C1	A0	C1	A0	C1	C1	B1	A0	C1	D1	
6	D1	D1	B1	A0	C1	B1	A0	B1	A0	B1	A0	B1	C1	A0	B1	D1	D1
7	D1	C1	A0	B1	C1	A0	B1	A0	C1	A0	B1	A0	C1	B1	A0	C1	D1
8	D1	C1	B1	C1	A0	B1	A0	B1	B1	B1	A0	B1	A0	C1	B1	C1	D1
9	D1	B1	A0	B1	C1	A0	C1	B1	A0	B1	C1	A0	C1	B1	A0	B1	D1
10	D1	C1	B1	C1	A0	B1	A0	B1	B1	B1	A0	B1	A0	C1	B1	C1	D1
11	D1	C1	A0	B1	C1	A0	B1	A0	C1	A0	B1	A0	C1	B1	A0	C1	D1
12	D1	D1	B1	A0	C1	B1	A0	B1	A0	B1	A0	B1	C1	A0	B1	D1	D1
13		D1	C1	A0	B1	C1	C1	A0	C1	A0	C1	C1	B1	A0	C1	D1	
14		D1	A0	B1	A0	A0	B1	C1	B1	C1	B1	A0	A0	B1	A0	D1	
15			D1	A0	C1	B1	A0	B1	A0	B1	A0	B1	C1	A0	D1		
16				D1	D1	D1	C1	C1	B1	C1	C1	D1	D1	D1			
17						D1	D1	D1	D1	D1	D1	D1					

High leak core

	A	B	C	D	E	F	G	H	J	K	L	M	N	P	R	S	T
1						C1	D1	D1	A0	D1	D1	C1					
2				A0	D1	D1	A0	C1	D1	C1	A0	D1	D1	A0			
3			D1	D1	B1	A0	D1	B1	A0	B1	D1	A0	B1	D1	D1		
4		A0	D1	B1	C1	A0	B1	A0	B1	A0	B1	A0	C1	B1	D1	A0	
5		D1	B1	C1	B1	C1	A0	C1	B1	C1	A0	C1	B1	C1	B1	D1	
6	C1	D1	A0	A0	C1	B1	C1	B1	C1	B1	C1	B1	C1	A0	A0	D1	C1
7	D1	A0	D1	B1	A0	C1	B1	A0	B1	A0	B1	C1	A0	B1	D1	A0	D1
8	D1	C1	B1	A0	C1	B1	A0	C1	B1	C1	A0	B1	C1	A0	B1	C1	D1
9	A0	D1	A0	B1	B1	C1	B1	B1	A0	B1	B1	C1	B1	B1	A0	D1	A0
10	D1	C1	B1	A0	C1	B1	A0	C1	B1	C1	A0	B1	C1	A0	B1	C1	D1
11	D1	A0	D1	B1	A0	C1	B1	A0	B1	A0	B1	C1	A0	B1	D1	A0	D1
12	C1	D1	A0	A0	C1	B1	C1	B1	C1	B1	C1	B1	C1	A0	A0	D1	C1
13		D1	B1	C1	B1	C1	A0	C1	B1	C1	A0	C1	B1	C1	B1	D1	
14		A0	D1	B1	C1	A0	B1	A0	B1	A0	B1	A0	C1	B1	D1	A0	
15			D1	D1	B1	A0	D1	B1	A0	B1	D1	A0	B1	D1	D1		
16				A0	D1	D1	A0	C1	D1	C1	A0	D1	D1	A0			
17						C1	D1	D1	A0	D1	D1	C1					

Lower leak core

Table: Summary for candidate LPs

Candidate	High leak	Lower leak	DCD
Core average enrichment, 235U w/o	3.41		2.72
Batch size	4		3
Cycle BU, MWD/kgU	23.97	24.53	17.51
Total number of BA rods	2632	2632	1680
Maximum FXYP	1.52	1.52	1.59
CBC at BOC, ppm	1230	1290	817
Fuel cost, Cents/kWhe	0.94	0.92	1.02

- Proposed core design process consists of three steps: core average enrichment determination and number of BA rods, batch size and enrichment determination, loading pattern search;
- In this process, FMNG is generated using a full core calculation to determine various core average enrichments depending on cycle length. The FMNG suggests possible candidates for a target core average enrichment and a number of BA rods satisfying a given cycle length;
- The batch size and enrichment is calculated using the evolutionary algorithm to minimize the fuel cost;
- The optimum LP search performed using SA;
- The initial core design generated by the proposed methodology satisfied design requirements;
- Finally, the fuel cost comparison of candidate cores to reference core showed a decrease of about 10 %.

THE END