Plant Reload Optimization

Framework Overview & Demonstration

Junyung Kim
Mohammad G. Abdo
Congjian Wang
Idaho National Laboratory

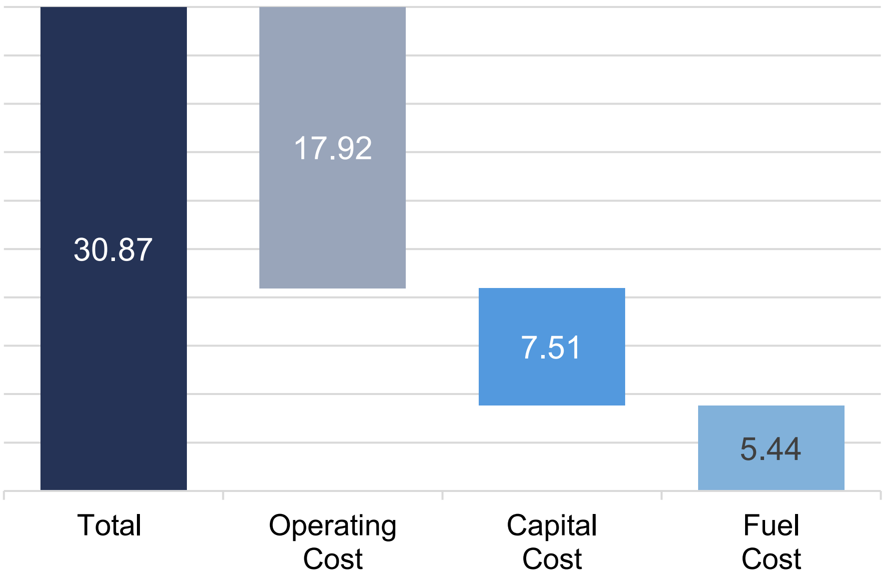
Jason Hou
North Carolina State University

November 2024

Framework Overview

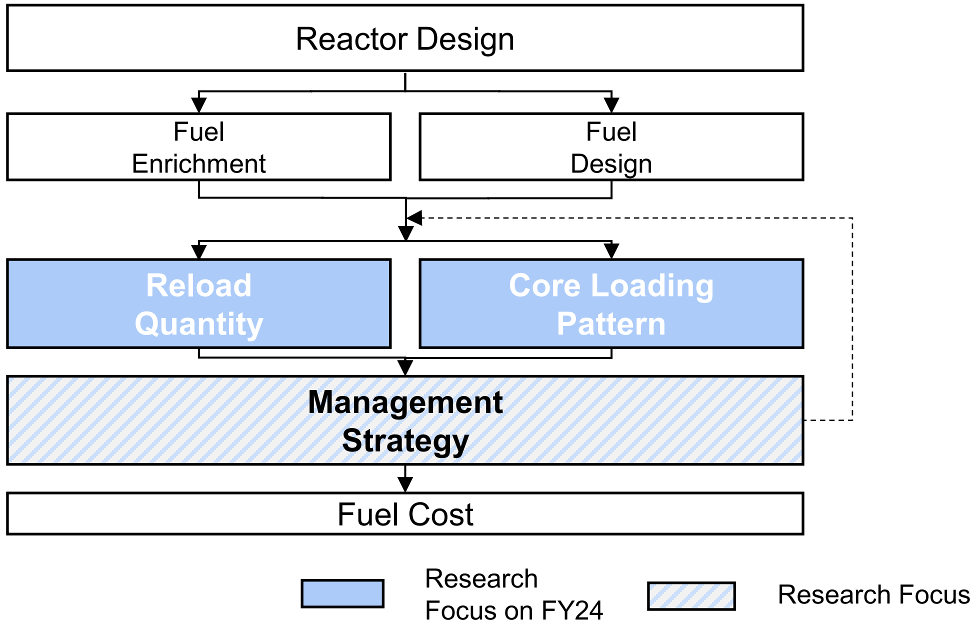
Background: Why it is important?

2022 Nuclear Cost Summary ($/MWh)*



- **Fuel takes ~17% of the total generating cost**
  - Costs ~$43M for a typical LWR fuel reload in a year

Factors affecting Fuel Cost**



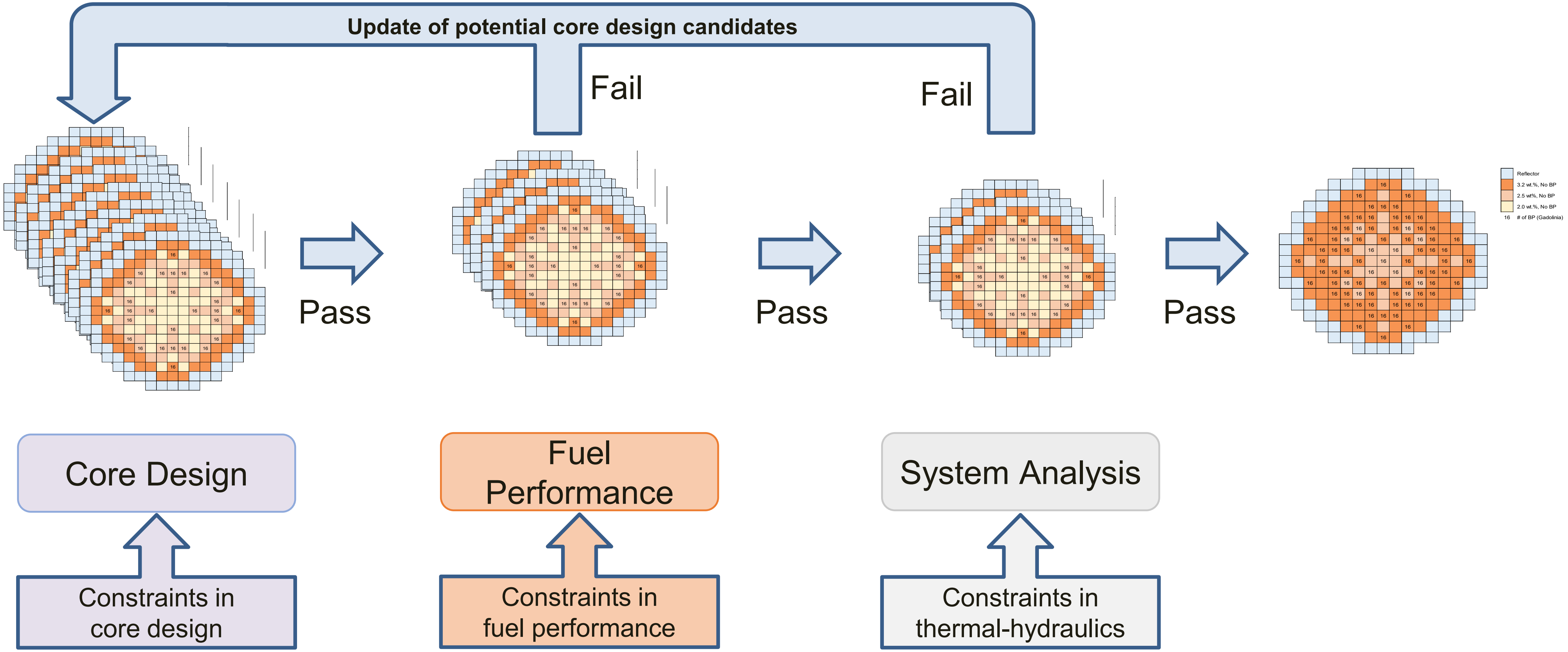
- **Traditional methods deciding core loading pattern and reload quantity are labor-intensive and time-consuming.**
  - More than 10E+30 combinations for 17x17 PWR core

Automated simulation-based fuel reloading optimization framework is needed.

Applicable to flexible operations, ATF, high burn-up and extended cycle reactor core design

* Nuclear Energy Institute (2023). “Nuclear Costs In Context.” NEI
** International Atomic Energy Agency (2020). “Reload Design and Core Management in Operating Nuclear Power Plants.” IAES-TECDOC-1898, IAEA.

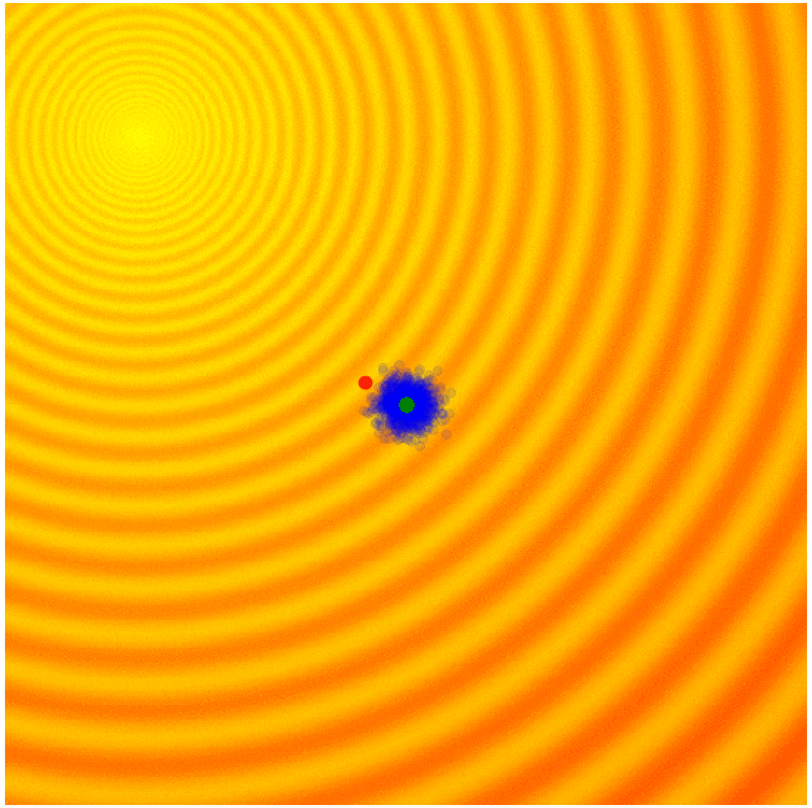
Core Design Development Process



Optimization of Reactor Core Design

- **Balance between economics and safety**
  - Optimize fuel batch for economic benefits
  - Multiple “safety” parameters to be considered
  - Flexible for computational tools
- **AI-based optimization methodology**
  - Genetic Algorithm (GA)
    - Based on Darwin’s theory of evolution
    - Select best results from potential solutions
    - Multi-objective optimization with Non-Dominated Sorting Genetic Algorithm II (NSGA II)
- **Looking for wide applications**
  - LEU+, ATF, HBU, power-uprate, flexible operation
  - Non-LWRs or advanced nuclear systems
  - Multi-physics/Uncertainty analysis

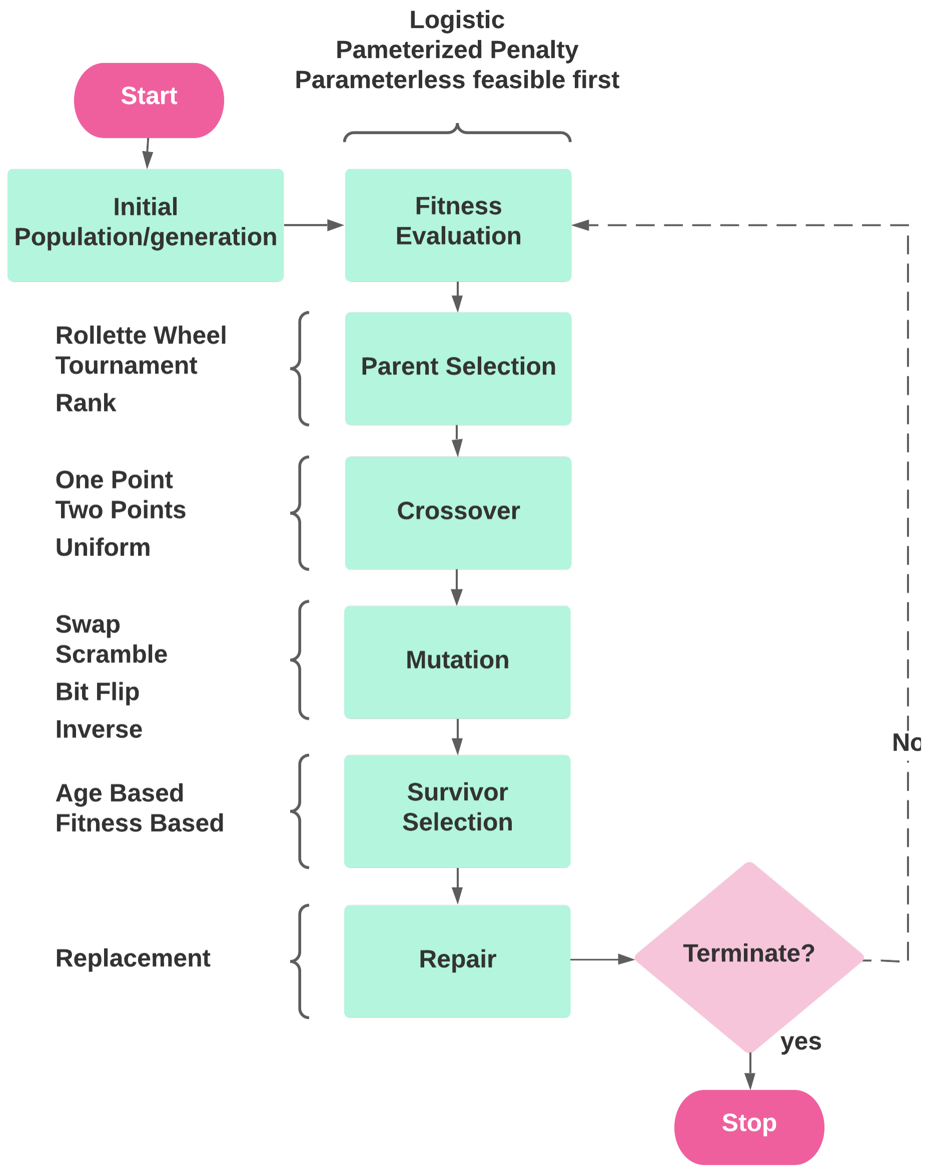
Converging



Source: A Visual Guide to Evolutionary Strategies. https://blog.otoro.net/2017/10/29/visual-evolution-strategies.

Optimization of Reactor Core Design
Genetic Algorithm (GA) Overview

- **GA mimics natural selection and evolution**
  - No need of derivatives calculation
  - Solves non-linear and non-convex problems by random evolution
  - Removes biased results
  - Constrained and unconstrained
  - Continuous and discrete variables
- **GA iterates groups of solutions**
  - Set initial list of solutions (neutronics, thermal-hydraulics, etc)
  - Evaluate and determine potential solutions
  - Random select best solution by
    - Clone, cross-over, and mutation operations.



Optimization of Reactor Core Design
Non-Dominated Sorting Genetic Algorithm II (NSGA II) Overview

- **NSGA-II is…**
  - Multi-objective, fast non-dominated sorting elite GA
- **Why NSGA-II?**
  - Lower computational complexity than NSGA-I
  - Population diversity is guaranteed.
  - One of the multi-objective evolutionary computation benchmark

A multi-objective optimization problem can be written as

Minimize (or maximize) $(f_1(\mathrm{x}), f_2(\mathrm{x}), \ldots, f_M(\mathrm{x}))^T$

Subject to

$$\mathrm{g_j(x)} \geq (\mathrm{or}\ \leq)\ 0$$
$$\mathrm{h_k(x)} = 0$$
$$x_i^{(L)} \leq x_i \leq x_i^{(U)}$$

- $f_m(x)$ is m-th objective, where m = 1, 2, …, M.
- $\mathrm{g_j(x)}$ is j-th inequality constraint, where j = 1, 2, …, J
- $\mathrm{h_k(x)}$ is k-th equality constraint, where k = 1, 2, …, K
- $\mathrm{x} = (x_1, x_2, \ldots, x_n)^T$ is a n-dimensional vector
- $x_i^{(L)}$ and $x_i^{(U)}$ are the lower and upper bounds on i-th variable

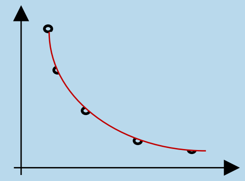
Multi-objective optimization problem subject to constraints

↓

Multi-objective optimization technique

↓

Multiple optimal solutions

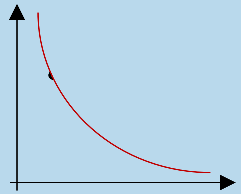


↓

Higher-level information (or operator's decision)

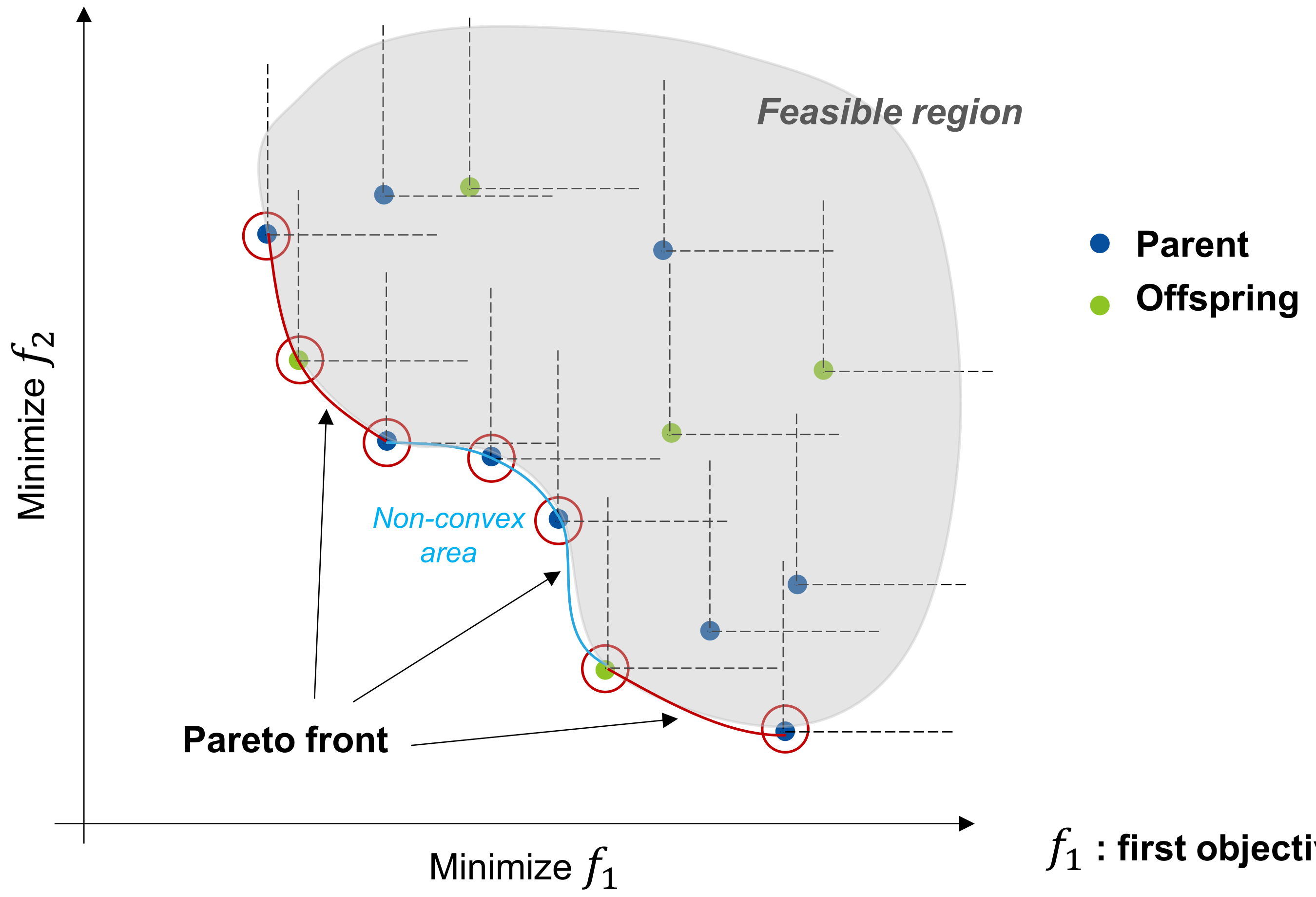
↓

One optimal solution



Optimization of Reactor Core Design
Non-Dominated Sorting Genetic Algorithm II (NSGA II) Overview

Elitism



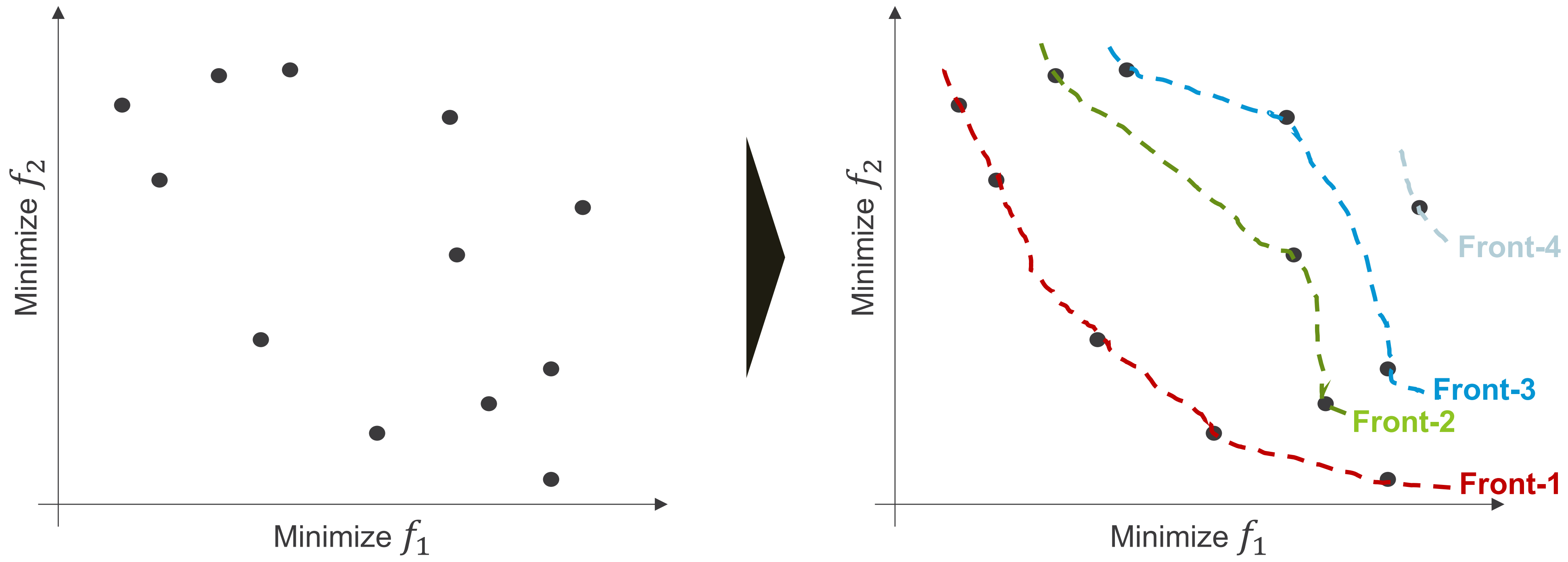
- **Keep the best chromosomes from parent and offspring population**
- **Elitism does not allow an already found optimal solutions to be deleted.**

f_1 **: first objective function**

f_2 **: second objective function**

Optimization of Reactor Core Design
Non-Dominated Sorting Genetic Algorithm II (NSGA II) Overview

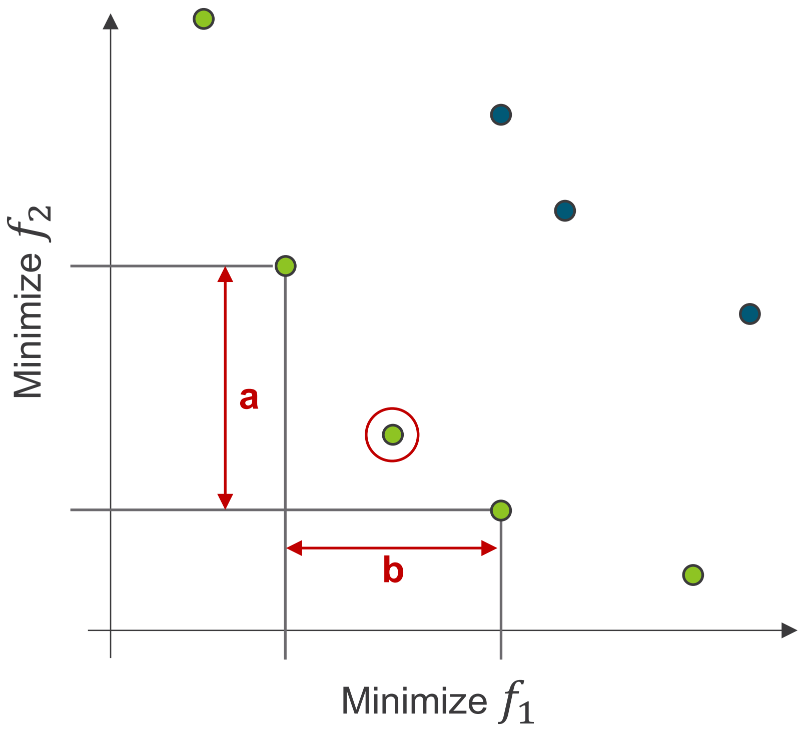
Dominance Depth Method



- **Assign rank to each chromosome using the dominance depth**
- **Non-dominated points belong to first rank.**
- **The non-dominated solutions from remainder are in second rank, and so on.**

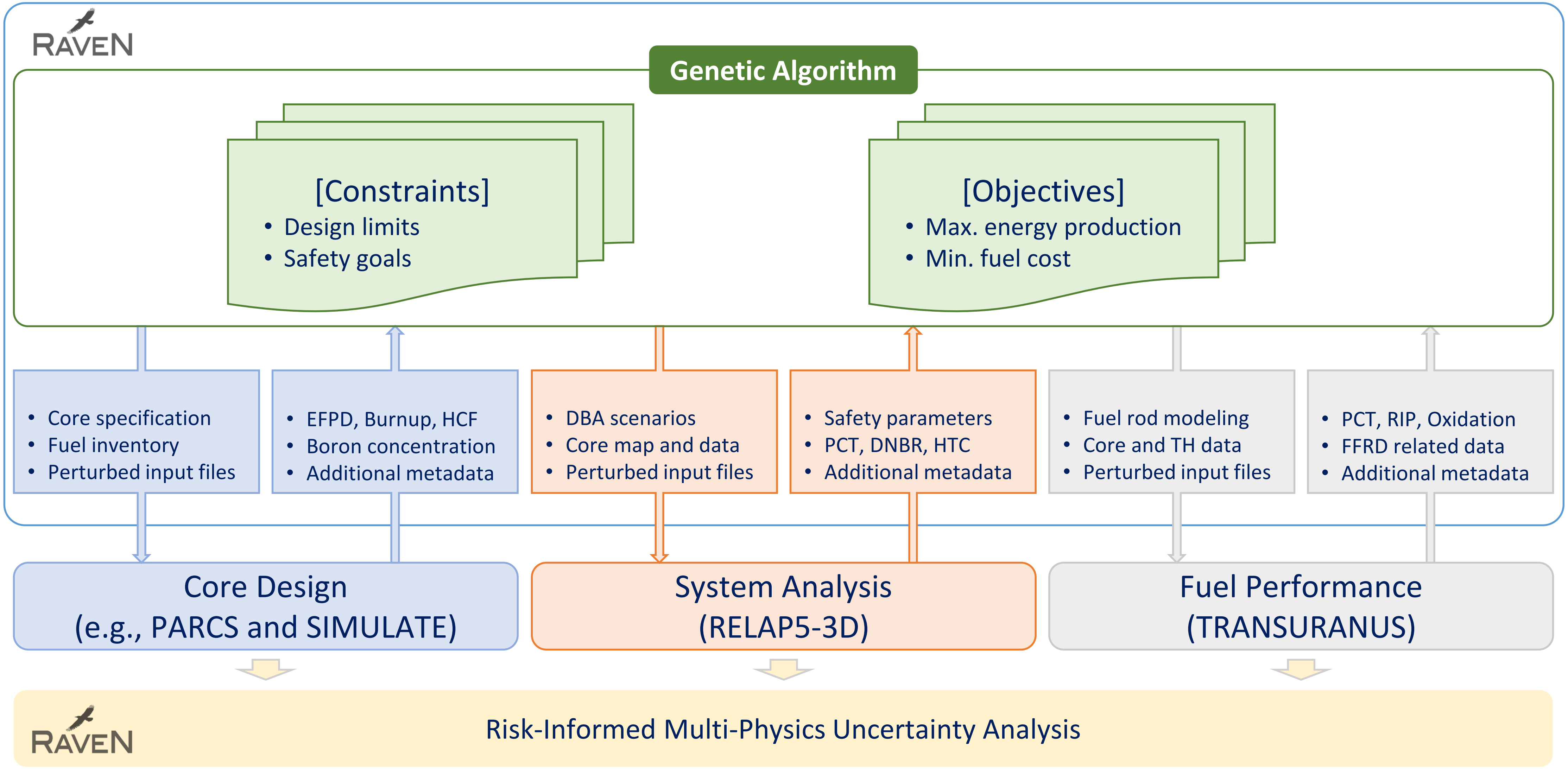
Optimization of Reactor Core Design
Non-Dominated Sorting Genetic Algorithm II (NSGA II) Overview

Niching for the First Rank



- **Niching gives preference to chromosomes that are not crowded.**
- **Crowding distance measures crowdedness of a chromosome w.r.t. its neighbors lying on the same front.**
  - Crowding distance = a + b
  - a and b are normalized distances.
- **Chromosomes from the first rank are selected based on niching.**

Plant ReLoad Optimization (PRLO) Project Overview



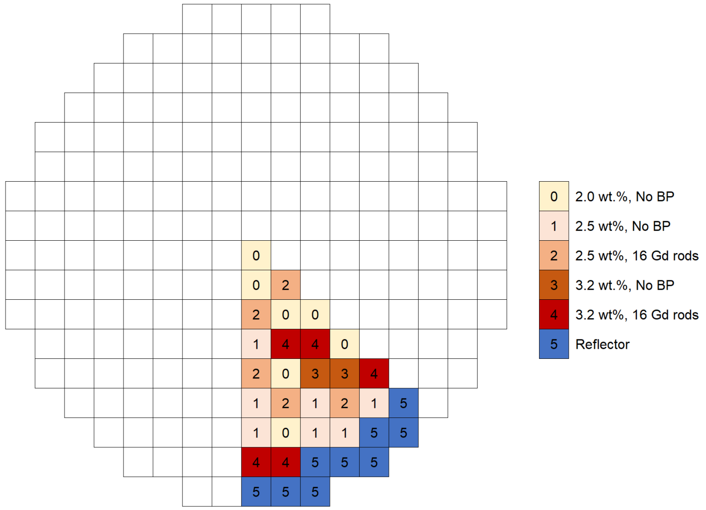
EFPD: Effective full power day
HCF: Hot channel factor
DBA: Design basis accident
PCT: Peak cladding temperature
DNBR: Departure of nucleate boiling rate
HTC: Heat transfer coefficient
TH: Thermal-hydraulics
RIP: Rod internal pressure
FFRD: Fuel failure, relocation and dispersal

Single Cycle
Core Design Optimization

Single Cycle / Single Objective Optimization for Core Design
Case Study Introduction

- **Settings**
  - PWR core with 157 fuel assemblies (FA)
  - Quarter-core symmetry
  - 6 FA designs → design space = 7.1×10^{32}
  - 200 Population w/ 90 Iteration for GA

Fuel type ID	0	1	2	3	4	5
Enrichment (wt%)	2	2.5	2.5	3.2	3.2	Reflector
Burnable poison	None	None	16 Gd rods	None	16 Gd rods	-



Randomly generated 1/8 PWR Core

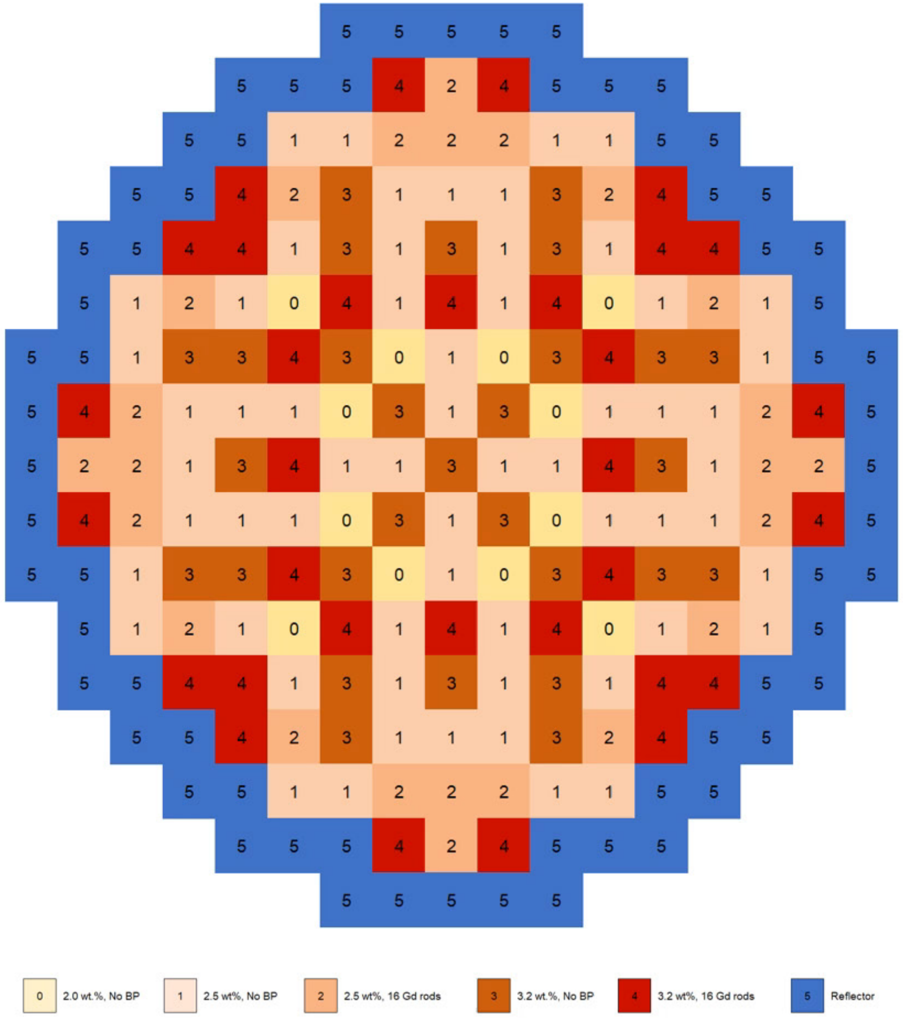
- **Objective**
  - Maximize cycle length (cycle energy production)

- **Constraints**
  - F_Q (Heat flux hot channel factor) < 2.1
  - $F_{\Delta H}$ (Nuclear enthalpy rise hot channel factor) < 1.48
  - Peak critical boron concentration (CBC) <1300 pcm

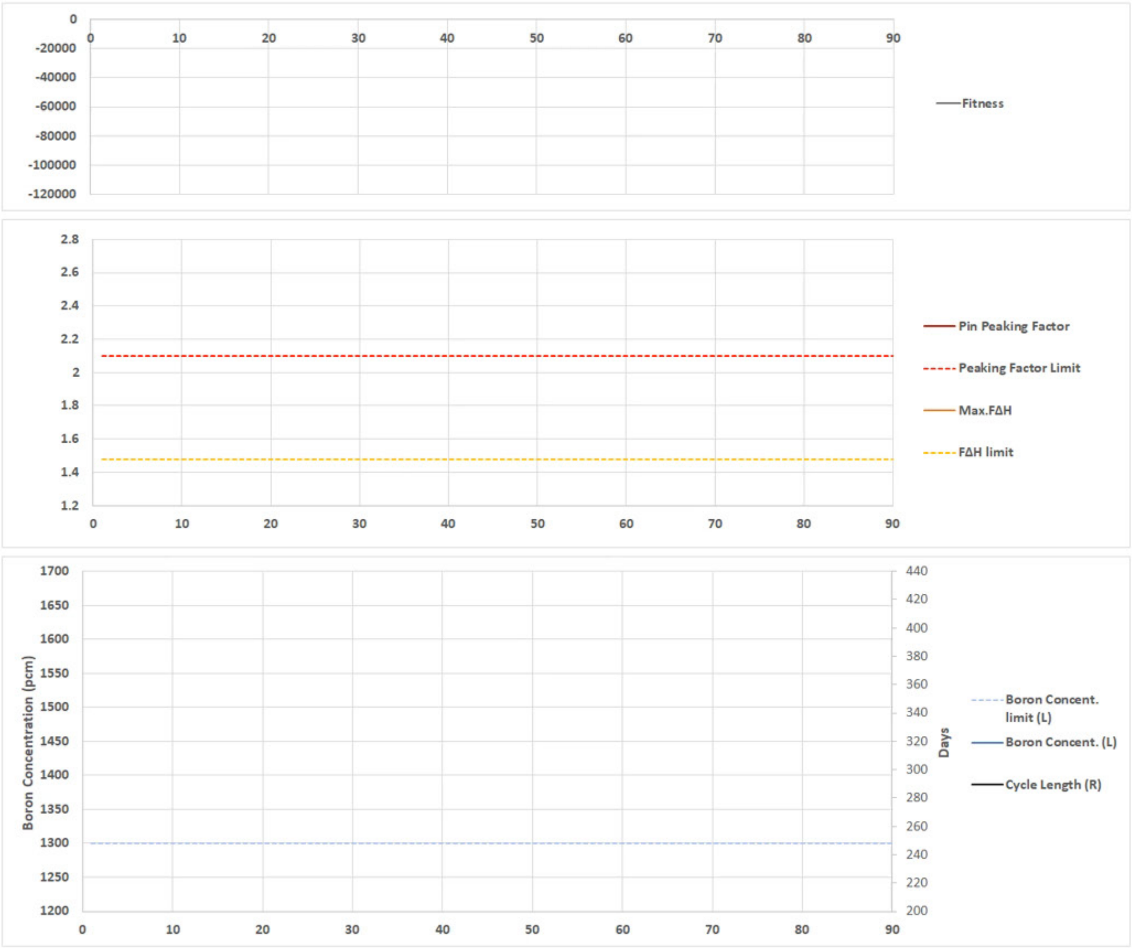
NOTE: F_Q and $F_{\Delta H}$ are peaking factors used to characterize core power distribution in terms of ratios of local maximum power output to average core output.

Single Cycle / Single Objective Optimization for Core Design Demonstration

Reactor Core Fuel Pattern



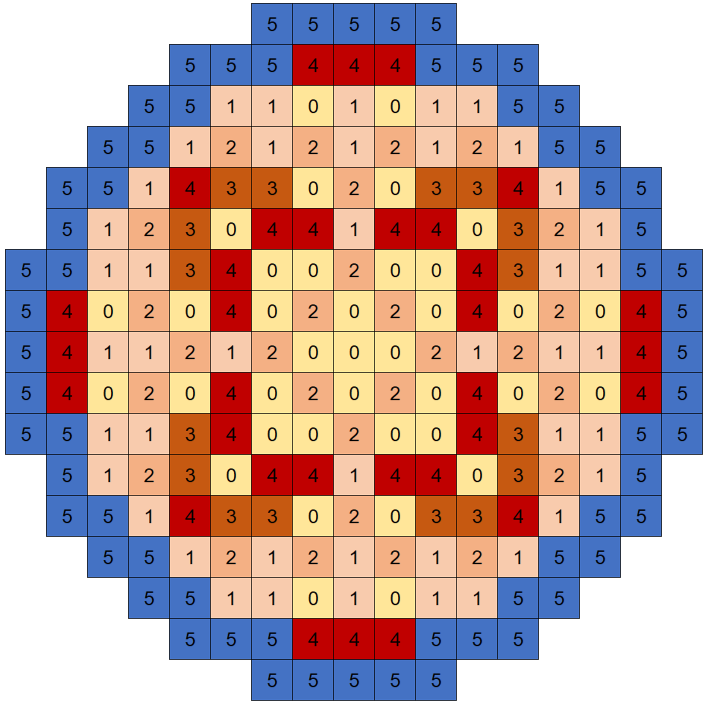
Fitness of Pattern, Constraints, Objective



A generic PWR reactor core is used for the demonstration

Single Cycle / Single Objective Optimization for Core Design Demonstration

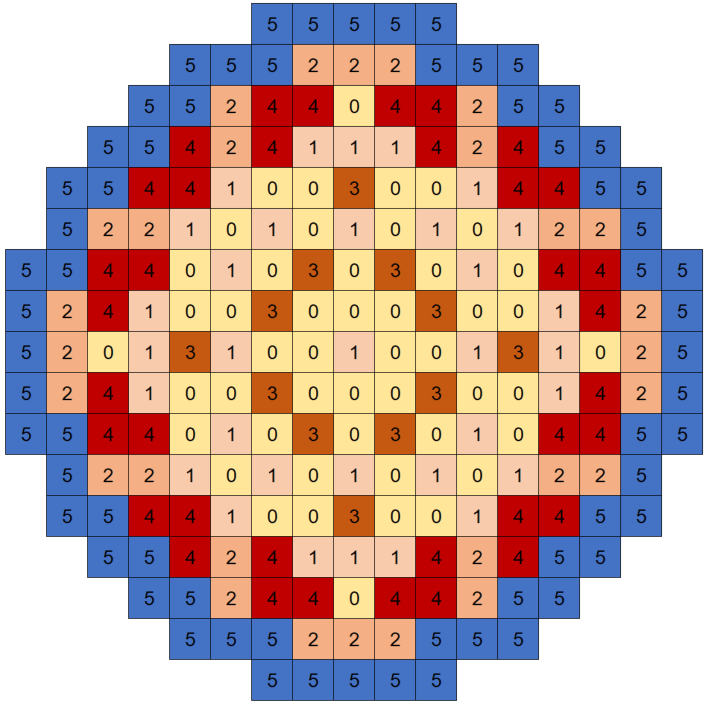
Initial Fuel Loading Pattern



Pin_Peaking Factor	3.121	x
Boron Concentration	1492	x
FΔH	2.317	x

Effective Full Power Day (EFPD)	412.6

Optimized Fuel Loading Pattern



- 0 — 2.0 wt.%, No BP
- 1 — 2.5 wt%, No BP
- 2 — 2.5 wt%, 16 Gd rods
- 3 — 3.2 wt.%, No BP
- 4 — 3.2 wt%, 16 Gd rods
- 5 — Reflector

Pin_Peaking Factor	2.075	o
Boron Concentration	1297.6	o
FΔH	1.454	o

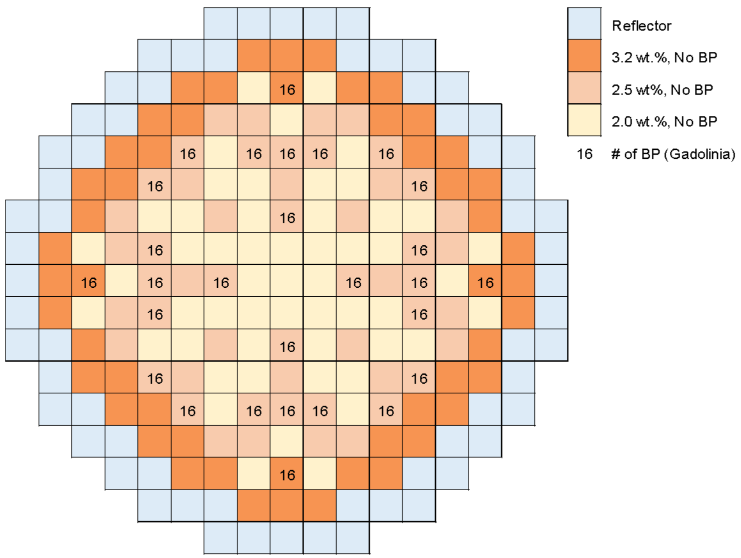
Effective Full Power Day (EFPD)	392.7

A generic PWR reactor core is used for the demonstration

Single Cycle / Multi Objective Optimization for Core Design
Case Study Introduction

- **Settings**
  - PWR core with 157 fuel assemblies (FA)
  - Quarter-core symmetry
  - 6 FA designs → design space = 7.1×10^{32}
  - 100 Population w/ 50 Iteration for GA

Randomly generated PWR Core



Fuel type ID	1	2	3	4	5	6
Enrichment (wt%)	Reflector	2	2.5	2.5	3.2	3.2
Burnable poison	-	None	None	16 Gd rods	None	16 Gd rods

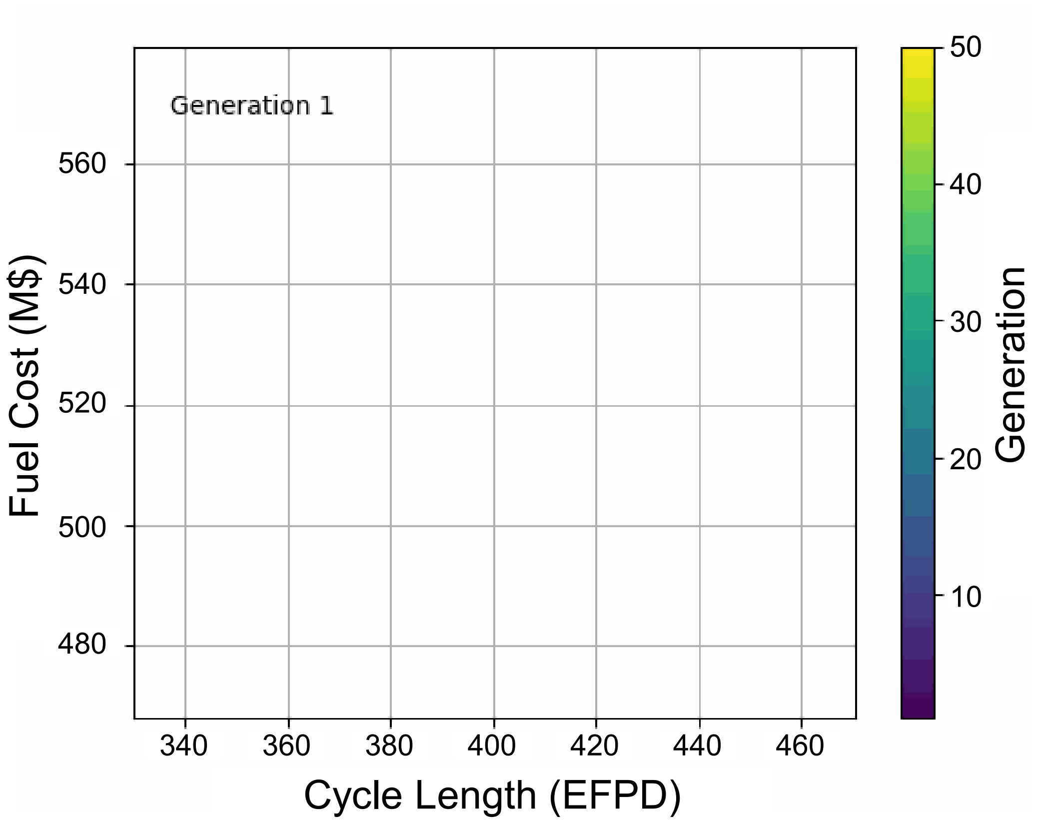
- **Objectives**
  - Maximize cycle length (cycle energy production)
  - Minimize fuel cost

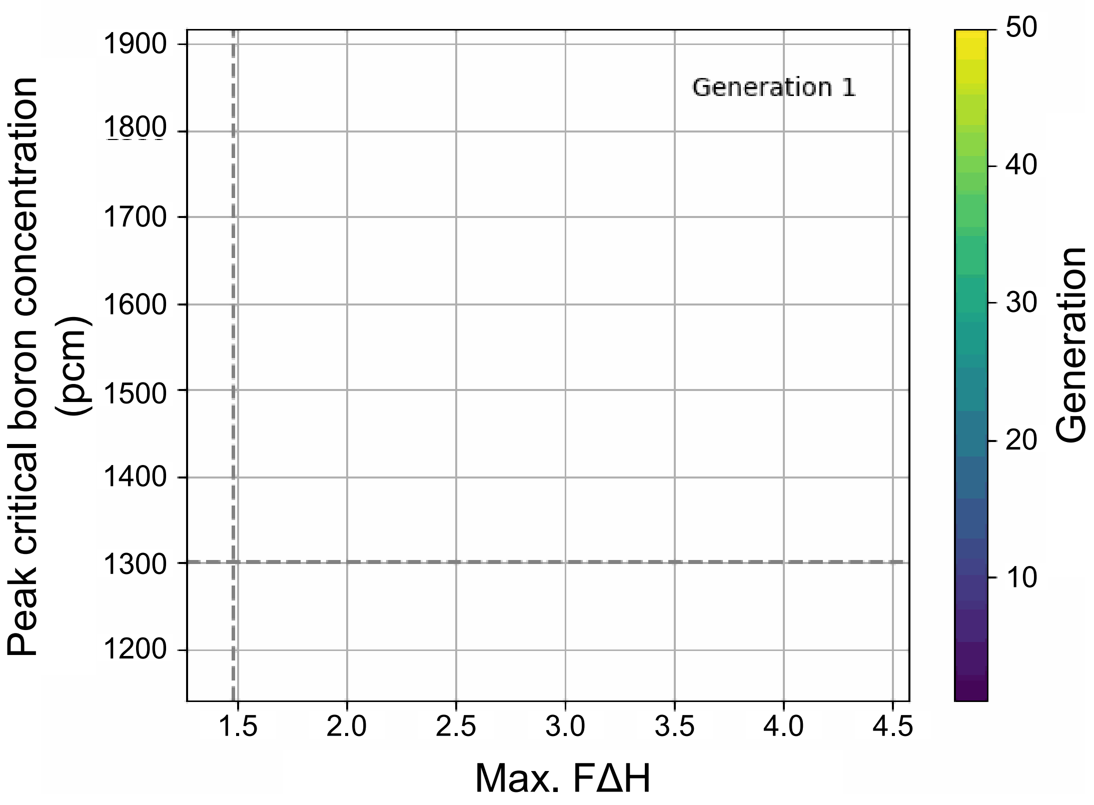
- **Constraints**
  - F_Q (Heat flux hot channel factor) < 2.1
  - $F_{\Delta H}$ (Nuclear enthalpy rise hot channel factor) < 1.48
  - Peak critical boron concentration (CBC) <1300 pcm

NOTE: F_Q and $F_{\Delta H}$ are peaking factors used to characterize core power distribution in terms of ratios of local maximum power output to average core output.

A generic PWR reactor core is used for the demonstration

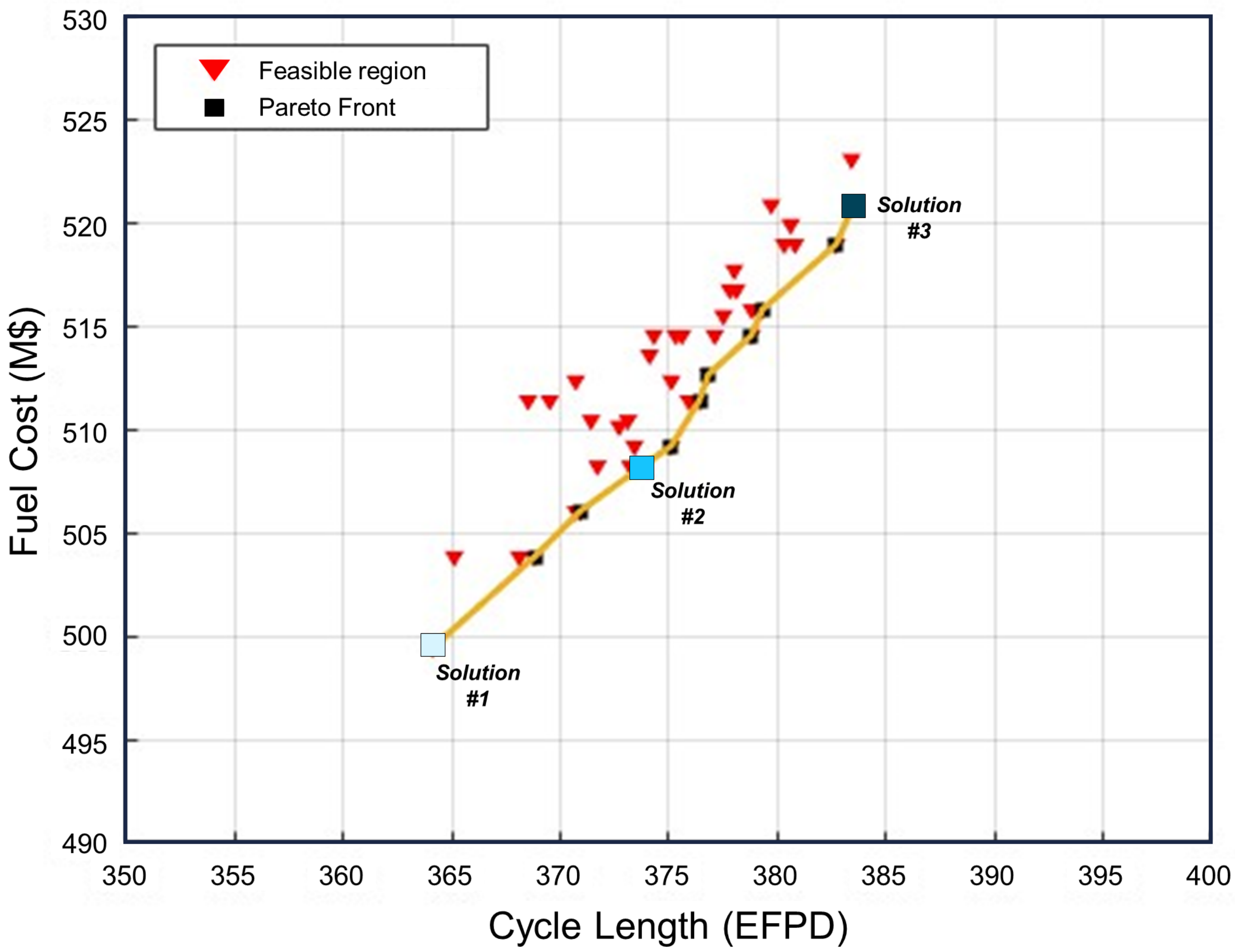
Single Cycle / Multi Objective Optimization for Core Design Demonstration





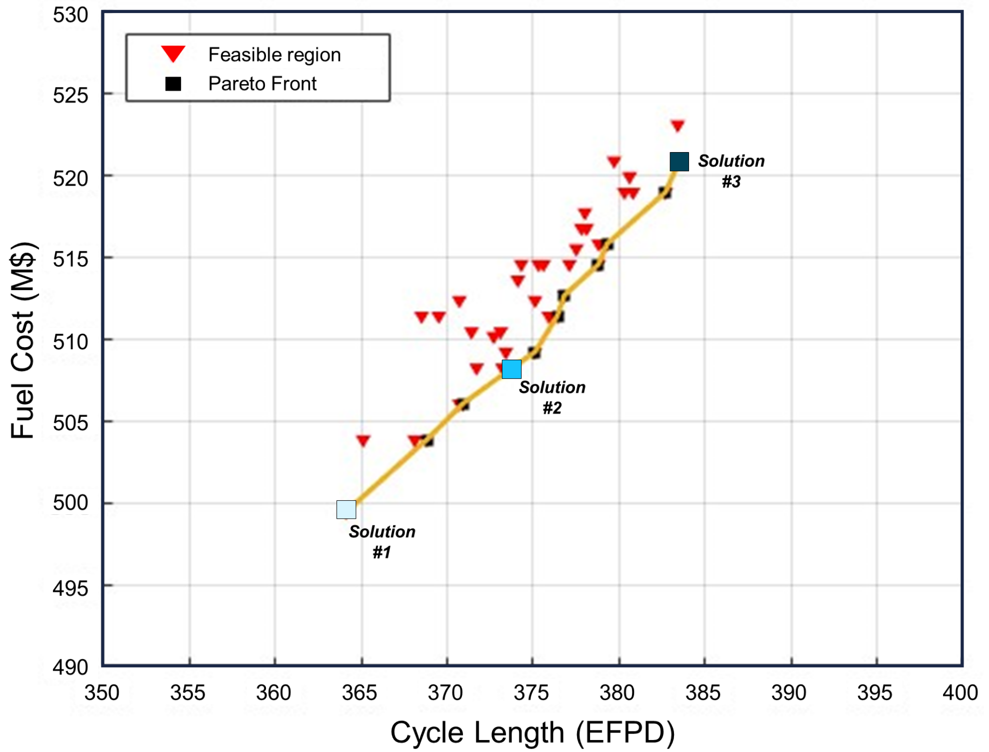
A generic PWR reactor core is used for the demonstration

Single Cycle / Multi Objective Optimization for Core Design Demonstration



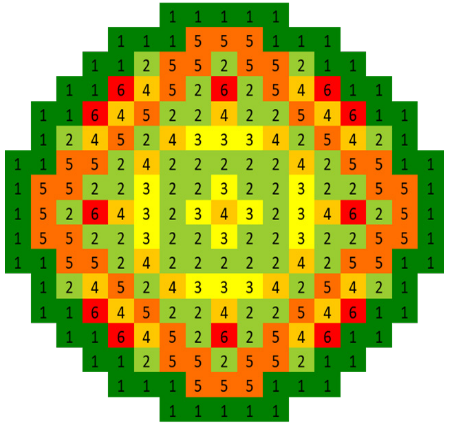
A generic PWR reactor core is used for the demonstration

Single Cycle / Multi Objective Opti… Demonstration



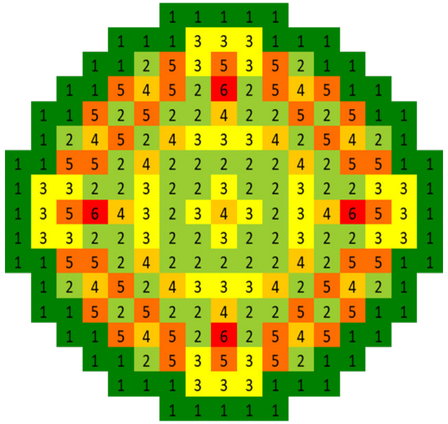
A generic PWR reactor core

Solution #3



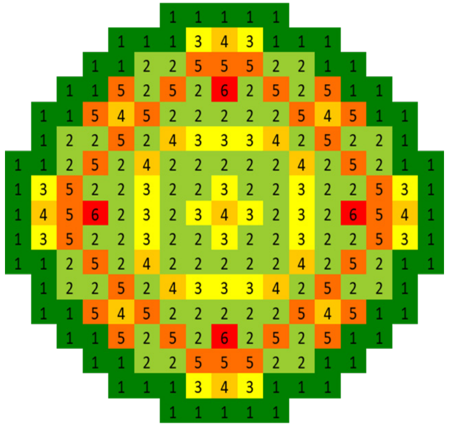
Cycle length (EFPD)	383.50
Fuel cost (M$)	520.92
F_Q	2.098
CBC (ppm)	1296.8
$F_{\Delta H}$	1.476

Solution #2



Cycle length (EFPD)	373.80
Fuel cost (M$)	508.28
F_Q	2.090
CBC (ppm)	1293.9
$F_{\Delta H}$	1.466

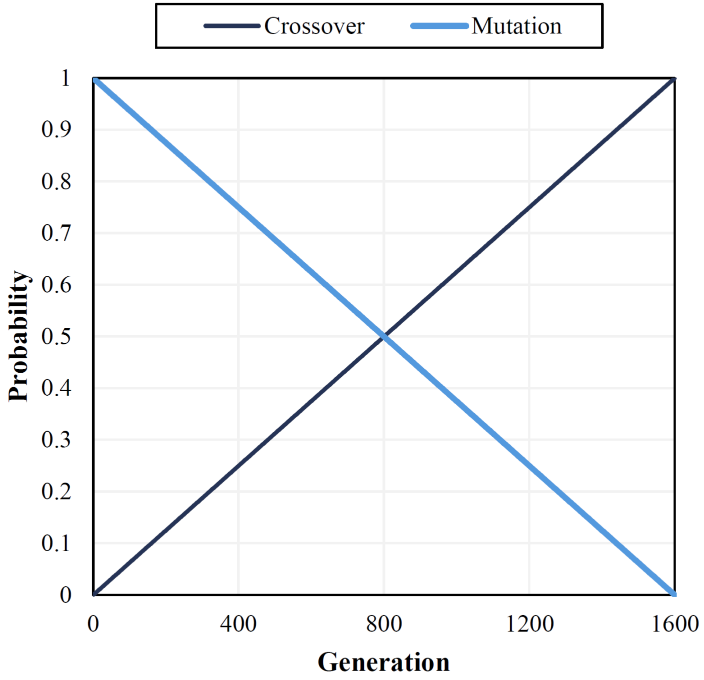
Solution #1



Cycle length (EFPD)	364.10
Fuel cost (M$)	499.45
F_Q	2.092
CBC (ppm)	1295.6
$F_{\Delta H}$	1.479

Optimization Acceleration Technique

Adaptive Mutation / Crossover Probabilities

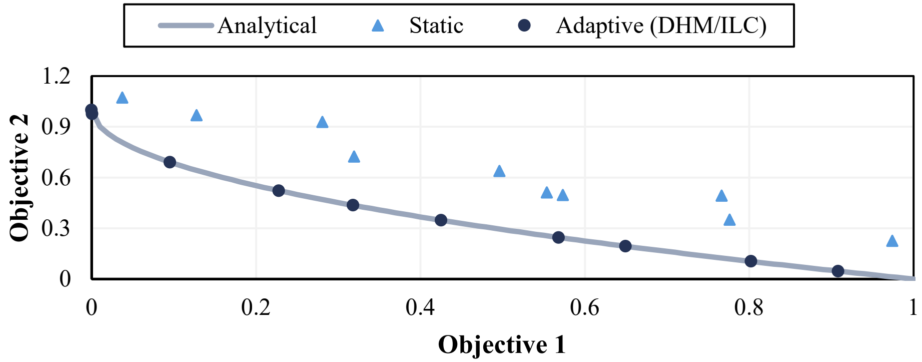


$$\text{Mutation Prob.} = 1 - \frac{\text{Current \# of Generation}}{\text{Total \# of Generation}}$$

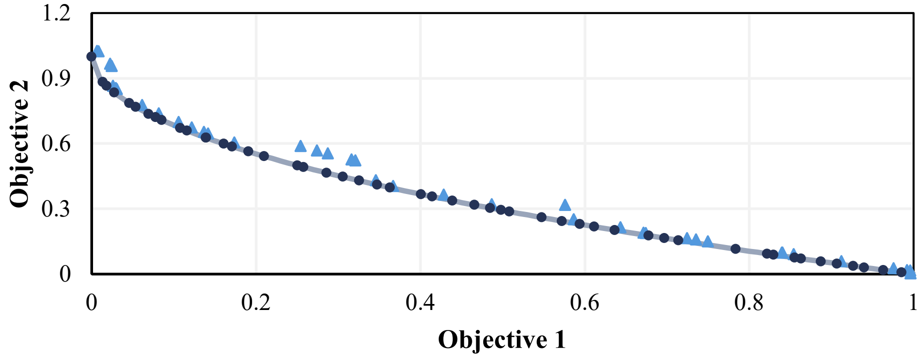
$$\text{Crossover Prob.} = \frac{\text{Current \# of Generation}}{\text{Total \# of Generation}}$$

Demonstration with ZDT1 Test

Population size of 10 and 30 iterations



Population size of 50 and 30 iterations

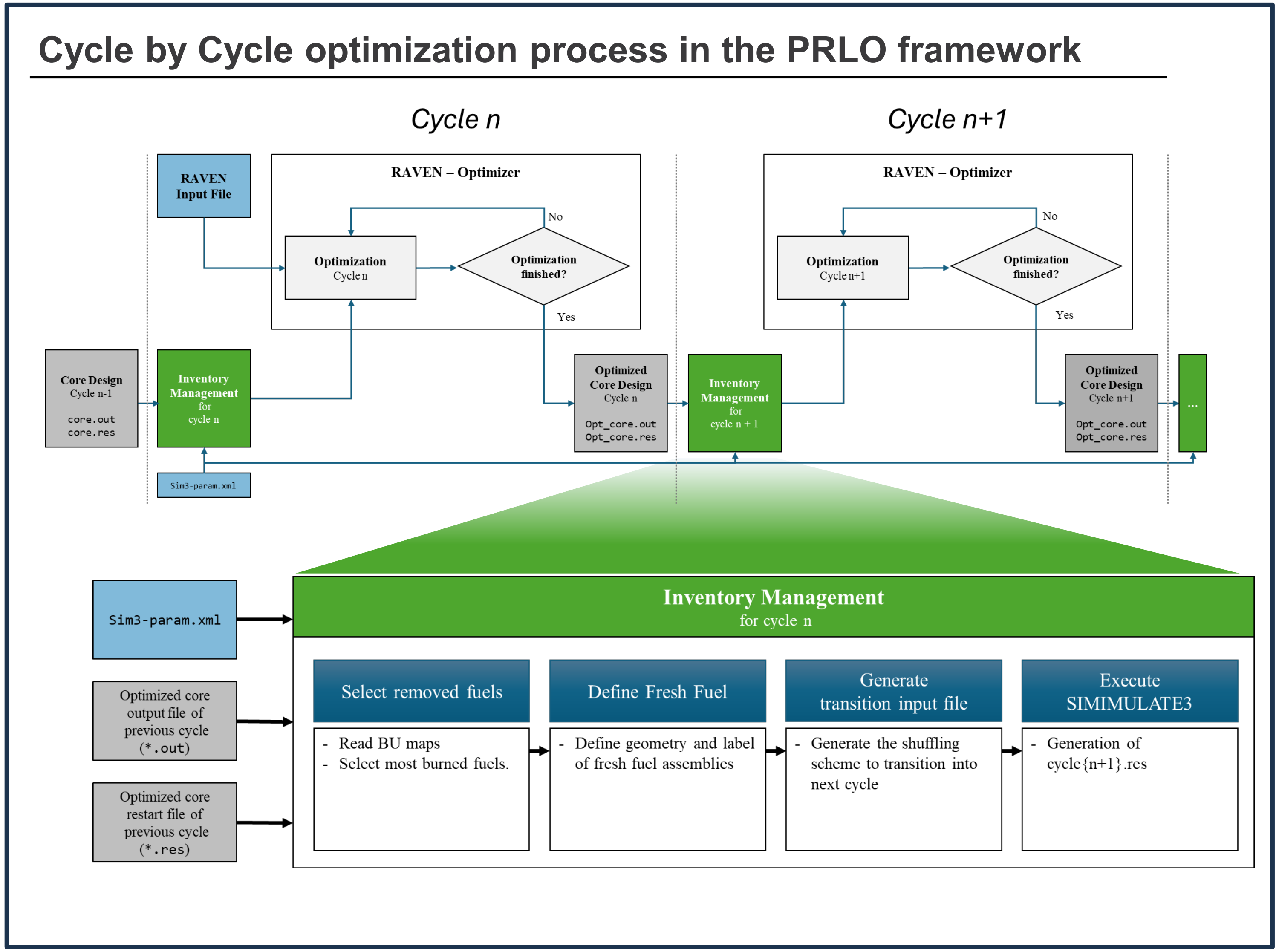


Method	Number of Iteration	Elapsed time (sec)	Mean Squared Error (%)
Static	300	846 sec	0.001%
Adaptive (DHM/ILC)	15	13.89 sec	0.0001%

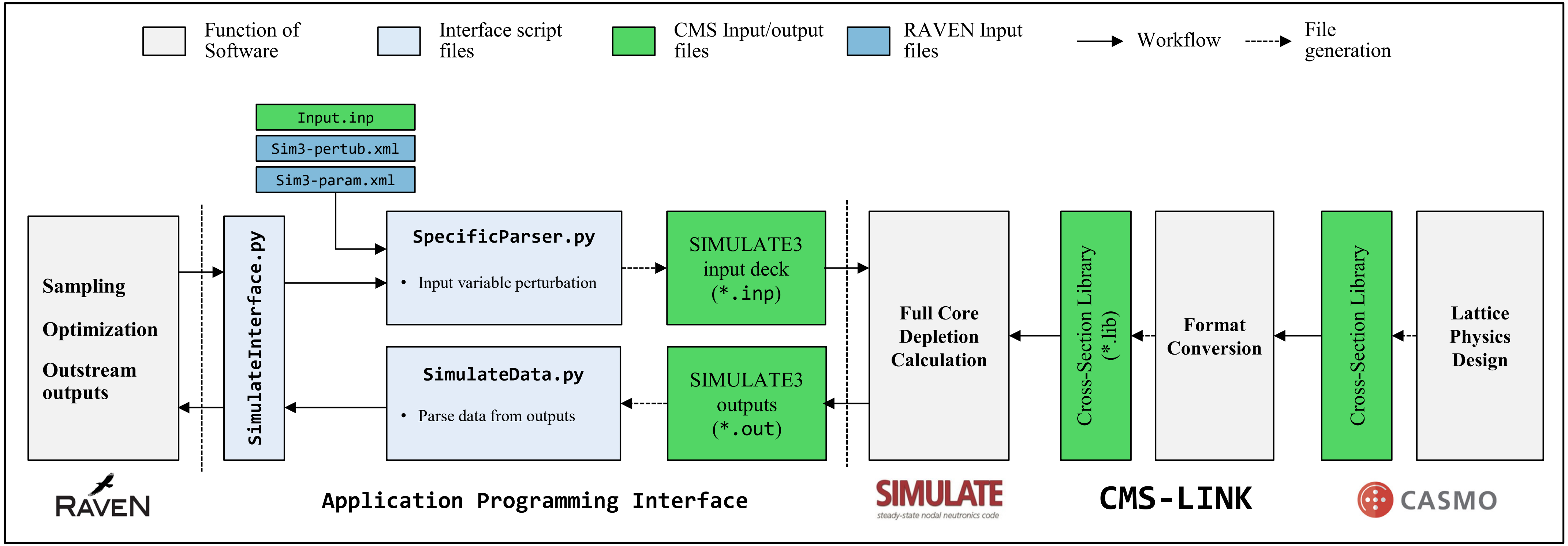
Cycle by Cycle
Core Design Optimization

Introduction of Cycle–by–Cycle Optimization Process
Process Overview

- **Cycle *n* optimization is linked to Cycle *n+1* optimization through the Inventory Management step.**



Introduction of Cycle–by–Cycle Optimization Process
System Code Interface with RAVEN



Introduction of Cycle–by–Cycle Optimization Process
AP1000 Reference Model

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1							J-01	H-01	G-01						
2					L-02	K-02	J-02	H-02	G-02	F-02	E-02				
3				M-03	L-03	K-03	J-03	H-03	G-03	F-03	E-03	D-03			
4			N-04	M-04	L-04	K-04	J-04	H-04	G-04	F-04	E-04	D-04	C-04		
5		P-05	N-05	M-05	L-05	K-05	J-05	H-05	G-05	F-05	E-05	D-05	C-05	B-05	
6		P-06	N-06	M-06	L-06	K-06	J-06	H-06	G-06	F-06	E-06	D-06	C-06	B-06	
7	R-07	P-07	N-07	M-07	L-07	K-07	J-07	H-07	G-07	F-07	E-07	D-07	C-07	B-07	A-07
8	R-08	P-08	N-08	M-08	L-08	K-08	J-08	H-08 ID = 1	G-08	F-08	E-08	D-08	C-08	B-08	A-08
9	R-09	P-09	N-09	M-09	L-09	K-09	J-09	H-09 ID = 2	G-09 ID = 3	F-09 ID = 4	E-09 ID = 5	D-09 ID = 6	C-09 ID = 7	B-09 ID = 8	A-09 ID = 9
10		P-10	N-10	M-10	L-10	K-10	J-10	H-10 ID = 10	G-10 ID = 11	F-10 ID = 12	E-10 ID = 13	D-10 ID = 14	C-10 ID = 15	B-10 ID = 16	
11		P-11	N-11	M-11	L-11	K-11	J-11	H-11 ID = 17	G-11 ID = 18	F-11 ID = 19	E-11 ID = 20	D-11 ID = 21	C-11 ID = 22	B-11 ID = 23	
12			N-12	M-12	L-12	K-12	J-12	H-12 ID = 24	G-12 ID = 25	F-12 ID = 26	E-12 ID = 27	D-12 ID = 28	C-12 ID = 29		
13				M-13	L-13	K-13	J-13	H-13 ID = 30	G-13 ID = 31	F-13 ID = 32	E-13 ID = 33	D-13 ID = 34			
14					L-14	K-14	J-14	H-14 ID = 35	G-14 ID = 36	F-14 ID = 37	E-14 ID = 38				
15							J-15	H-15 ID = 39	G-15 ID = 40						

Label map for a generic AP1000 reactor using quarter symmetrical perturbations

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1							J-01	H-01	G-01						
2					L-02	K-02	J-02	H-02	G-02	F-02	E-02				
3				M-03	L-03	K-03	J-03	H-03	G-03	F-03	E-03	D-03			
4			N-04	M-04	L-04	K-04	J-04	H-04	G-04	F-04	E-04	D-04	C-04		
5		P-05	N-05	M-05	L-05	K-05	J-05	H-05	G-05	F-05	E-05	D-05	C-05	B-05	
6		P-06	N-06	M-06	L-06	K-06	J-06	H-06	G-06	F-06	E-06	D-06	C-06	B-06	
7	R-07	P-07	N-07	M-07	L-07	K-07	J-07	H-07	G-07	F-07	E-07	D-07	C-07	B-07	A-07
8	R-08	P-08	N-08	M-08	L-08	K-08	J-08	H-08 ID=0	G-08	F-08	E-08	D-08	C-08	B-08	A-08
9	R-09	P-09	N-09	M-09	L-09	K-09	J-09	H-09 ID=1	G-09 ID=2	F-09 ID=3	E-09 ID=4	D-09 ID=5	C-09 ID=6	B-09 ID=7	A-09 ID=8
10		P-10	N-10	M-10	L-10	K-10	J-10	C-12 ID=9	G-10 ID=10	F-10 ID=11	E-10 ID=12	D-10 ID=13	C-10 ID=14	B-10 ID=15	
11		P-11	N-11	M-11	L-11	K-11	J-11	H-11 ID=16	G-11 ID=17	F-11 ID=18	E-11 ID=19	D-11 ID=20	C-11 ID=21	B-11 ID=22	
12			N-12	M-12	L-12	K-12	J-12	H-12 ID=23	G-12 ID=24	F-12 ID=25	E-12 ID=26	D-12 ID=27	H-10 ID=28		
13				M-13	L-13	K-13	J-13	H-13 ID=29	G-13 ID=30	F-13 ID=31	E-13 ID=32	D-13 ID=33			
14					L-14	K-14	J-14	H-14 ID=34	G-14 ID=35	F-14 ID=36	E-14 ID=37				
15							J-15	H-15 ID=38	G-15 ID=39						

Example of a location perturbation using quarter-core symmetry, resulting in simultaneous permutation of the symmetrical counterparts in the other quadrants.

Introduction of Cycle–by–Cycle Optimization Process
Reference Solution

						0	0	0						
				0	0	0	25.752	0	0	0				
			0	0	16.402	30.071	14.471	30.071	16.402	0	0			
		0	31.79	16.234	30.86	10.446	25.989	10.446	30.86	16.234	31.79	0		
	0	0	14.714	27.053	10.565	25.95	10.683	25.95	10.565	27.053	14.714	0	0	
	0	16.672	28.951	12.352	29.388	10.795	31.212	10.795	29.388	12.352	28.951	16.672	0	
0	0	25.677	10.43	25.478	17.034	24.974	10.359	24.974	17.034	25.478	10.43	25.677	0	0
0	25.752	14.471	25.989	10.683	31.212	10.359	37.996	10.359	31.212	10.683	25.989	14.471	25.752	0
0	0	25.677	10.43	25.478	17.034	24.974	10.359	24.974	17.034	25.478	10.43	25.677	0	0
	0	16.672	28.951	12.352	29.388	10.795	31.212	10.795	29.388	12.352	28.951	16.672	0	
	0	0	14.714	27.053	10.565	25.95	10.683	25.95	10.565	27.053	14.714	0	0	
		0	31.79	16.234	30.86	10.446	25.989	10.446	30.86	16.234	31.79	0		
			0	0	16.402	30.071	14.471	30.071	16.402	0	0			
				0	0	0	25.752	0	0	0				
						0	0	0						

BOC exposure map in GWd/MT for the reference case of the generic AP1000 equilibrium cycle model.

Key performance parameters

Variable	Value
Cycle Length (EFPD)	353.2
Critical Boron Concentration (ppm)	1457.2
F_Q	1.901
$F_{\Delta H}$	1.552

Comparison of Objective Target: Genetic Algorithm Optimization

Case A: Maximize Cycle Length

37.996 3B	31.212 2B	16.402 1B	16.234 1B	24.974 2B	14.471 1B	25.989 2B	0 FF
31.212 2B	0 FF	30.86 2B	25.95 2B	12.352 1B	29.388 2B	0 FF	0 FF
16.402 1B	30.071 2B	10.446 1B	14.714 1B	25.677 2B	10.565 1B	0 FF	
16.234 1B	10.43 1B	17.034 1B	28.95 2B	10.683 1B	16.672 1B	0 FF	
24.974 2B	10.795 1B	25.752 2B	25.478 2B	10.359 1B	0 FF		
14.471 1B	31.79 2B	27.053 2B	0 FF	0 FF			
25.989 2B	0 FF	0 FF	0 FF				
0 FF	0 FF						

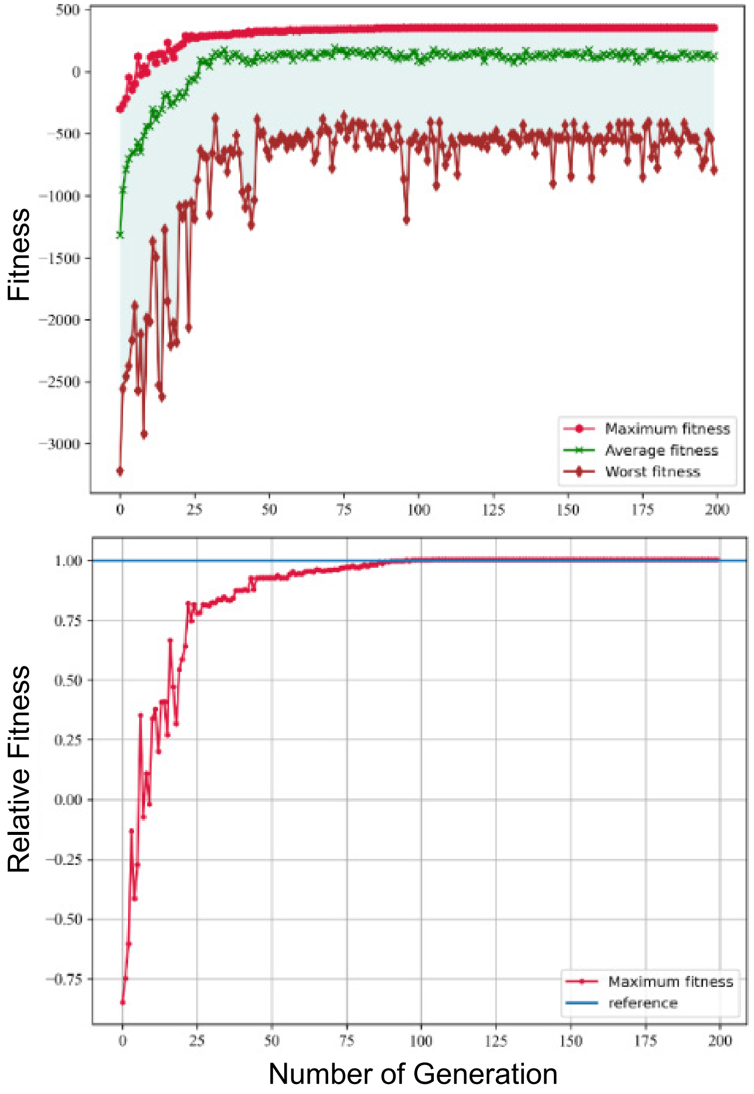
Case B: Maximize Core-averaged Burnup

37.996 3B	10.359 1B	10.43 1B	30.86 2B	17.034 1B	16.234 1B	25.989 2B	0 FF
10.359 1B	24.974 2B	25.478 2B	10.565 1B	16.672 1B	14.471 1B	12.352 1B	0 FF
10.43 1B	25.677 2B	16.402 1B	25.752 2B	14.714 1B	25.95 2B	0 FF	
30.86 2B	29.388 2B	0 FF	31.212 2B	30.071 2B	0 FF	0 FF	
17.034 1B	10.446 1B	31.79 2B	27.053 2B	0 FF	0 FF		
16.234 1B	28.95 2B	10.795 1B	10.683 1B	0 FF			
25.989 2B	0 FF	0 FF	0 FF				
0 FF	0 FF						

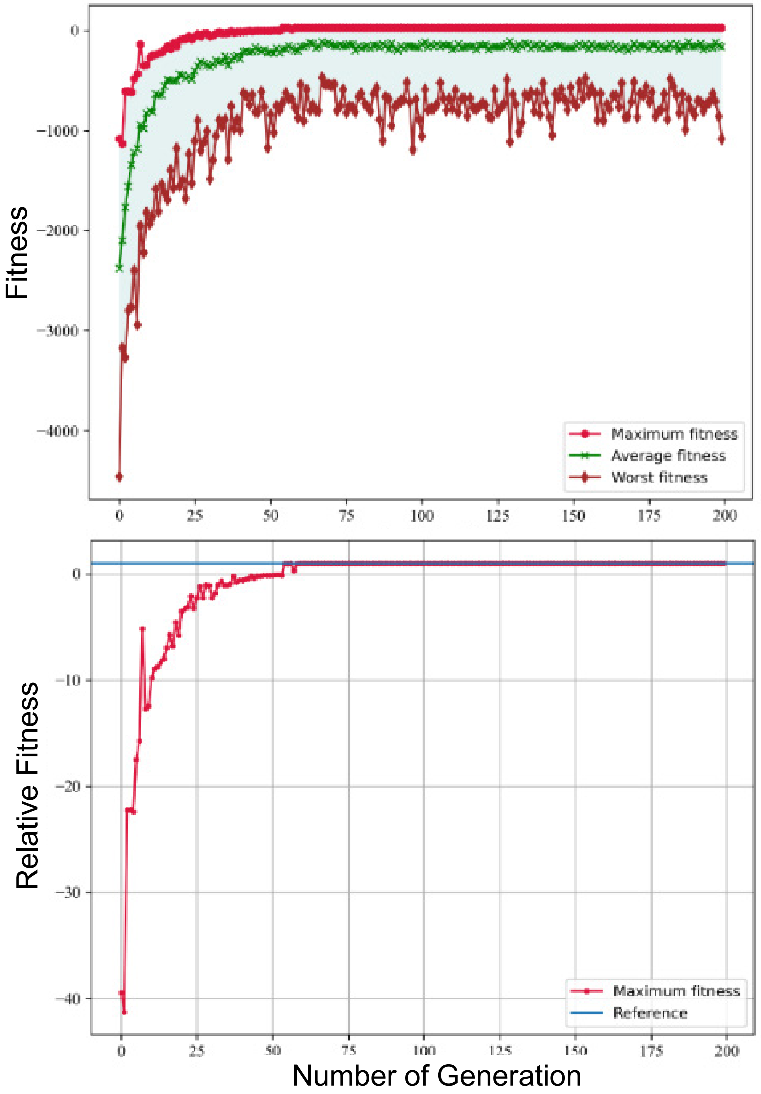
Variable	Reference	Case A	Case B
Cycle Length (EFPD)	353.2	353.5	353.5
Boron Concentration (ppm)	1457.20	1456.94	1456.90
F_Q	1.901	1.781	1.775
$F_{\Delta H}$	1.552	1.463	1.458

Comparison of Objective Target: Genetic Algorithm Convergence

Case A: Maximize Cycle Length

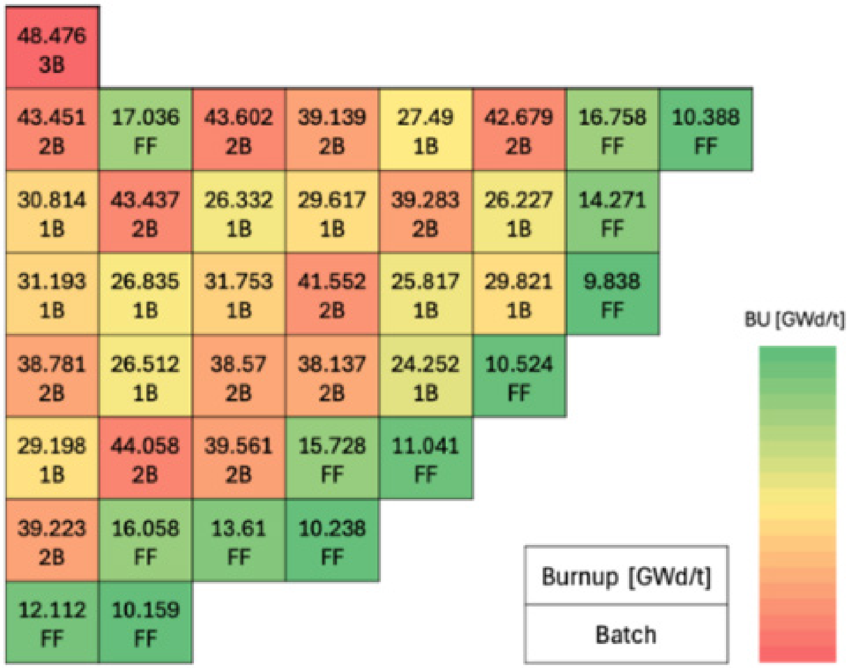


Case B: Maximize Core-averaged Burnup



Example of Fuel Inventory Management: Case A – Cycle n & Cycle n+1

Cycle n



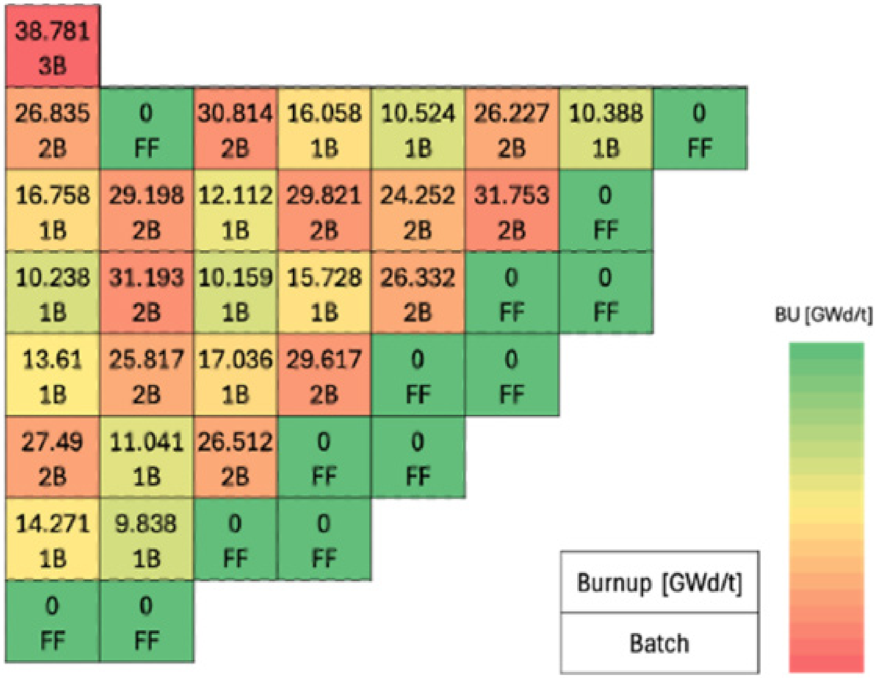
Cycle n+1

The most burned fuel assemblies are removed, and fresh fuel assemblies are temporarily placed in the positions of the discarded spent fuel.

Cycle-by-Cycle Optimization Results

Cycle n

Cycle n+1



Variable	Reference	*n* ycle 10	*n+1* le 11
Cycle Length (EFPD)	353.2	353.5	353.3
Boron Concentration (ppm)	1457.2	1456.9	1456.8
	1.90	1.78	1.83
	1.55	1.46	1.49

Accomplishment & Future Plan

Plant ReLoad Optimization (PRLO) Project Major Accomplishments

- **Development of GA-based optimization platform**
  - Single and multi-objective optimizer
  - Fuel Inventory Management Interface
  - Multi-cycle (Cycle-by-Cycle) optimization
- **Computational tools coupling and testing**
  - RAVEN is a base platform
  - PARCS, SIMULATE, RELAP5-3D, TRANSURANUS
- **Demonstration in Multiphysics optimization problem**
  - Core design / safety analysis / fuel performance
- **Development and demonstration of multi-physics uncertainty analysis capability with RELAP5-3D**
  - Focus on reflood phenomena in LBLOCA
- **Stakeholder engagement – Industrial Partner**
  - Benchmark test ongoing with historical data from NPP of Constellation Energy.

Plant ReLoad Optimization (PRLO) Project Technology Roadmap

	Phase 1 (FY 19 – 20) Development of Methodology	**Phase 2 (FY 21 – 22)** Improvement of Planform for PWR	**Phase 3 (FY 22 – 23)** Completion of Planform for PWR	**Phase 4 (FY 24 – 25)** Demonstration and Expansion for PWR
Multi–Physics Analysis	Set plant-based scenarios	Apply risk-informed approach	Analyze uncertainties from multi – physics	
	Simulate DBA with deterministic method			
	Use fixed core loading pattern			
	Evaluate recoverable margin			
Platform Development	Setup tools & methods	Assess constraints & issues of code interface	Investigate optimization acceleration methods	Apply optimization acceleration methods
		Investigate optimization algorithms for fuel reloading	Integrate of multi–objective optimization algorithm	Enhance platform capability for multi–cycle optimization
Demonstration			Demonstrate single-cycle optimization of a genetic PWR	Demonstrate multi–cycle optimization of a genetic PWR
				Demonstrate PWR core optimization performance in comparison to industry
Stakeholder Engagement			Initiate industrial partnership	Extend industrial partnership for PWR core optimization

Any Questions?

LWRS

LIGHT WATER REACTOR SUSTAINABILITY

LWRS
LIGHT WATER REACTOR SUSTAINABILITY

APPENDIX

“Cycle-by-Cycle” Optimization Process in the PRLO Framework