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LIGHT WATER REACTOR SUSTAINABILITY

**Boyan Ivanov, Adam Donell, Seth Spooner**
Constellation

**Junyung Kim, Mohammad G. Abdo, Svetlana Lawrence**
Idaho National Laboratory

**Juan C. Luque-Gutierrez, Nicholas Rollins, Jason Hou**
North Carolina State University

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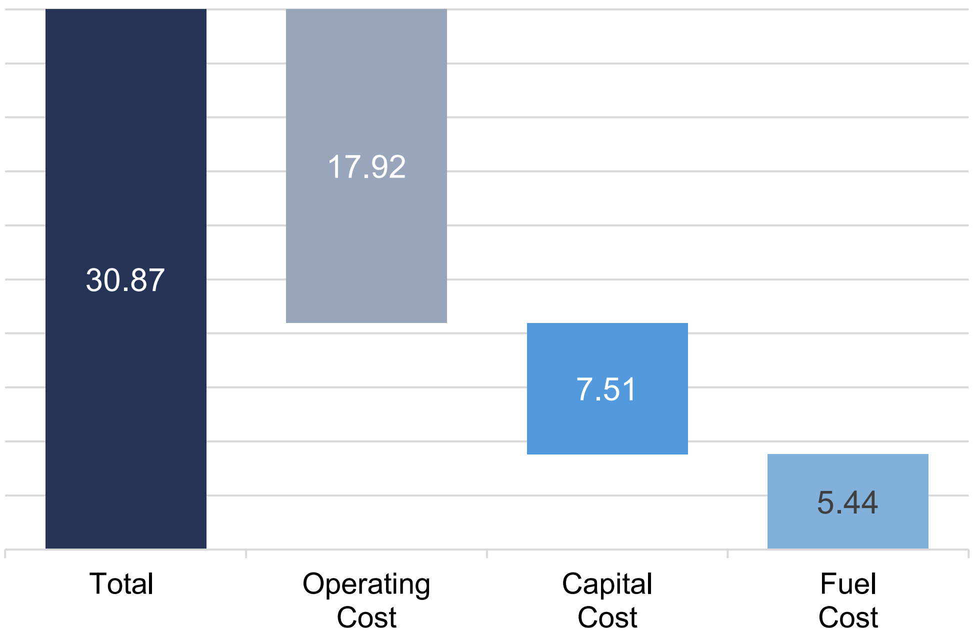
# Gains in operational flexibility, safety margins, and cost efficiencies via integrated Plant Reload Optimization platform

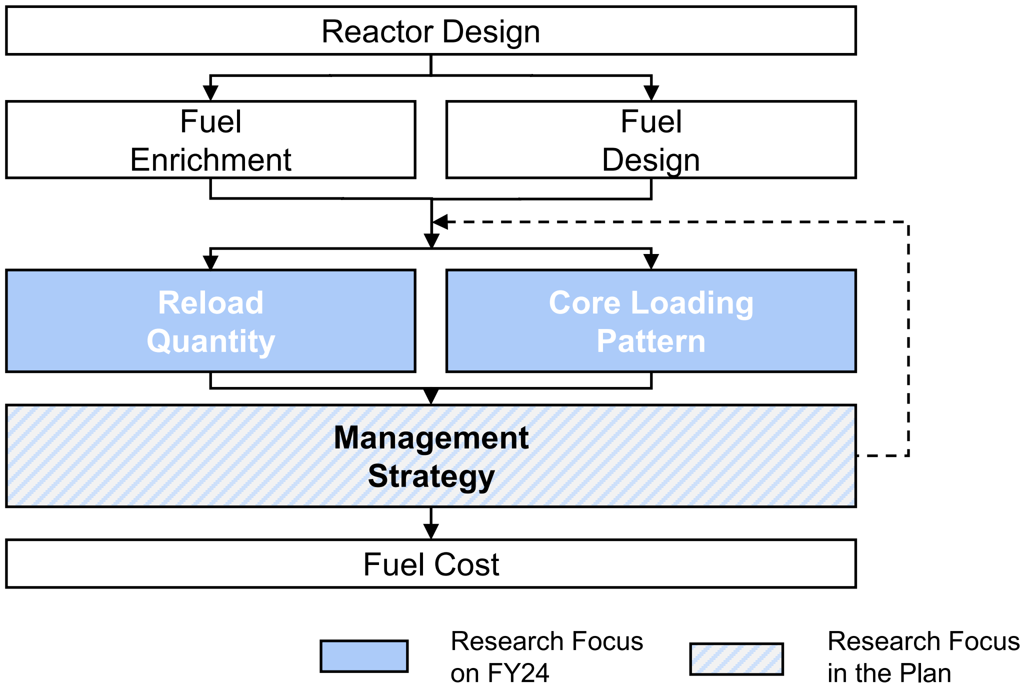
# Background:
# Why it is important?

## 2022 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**



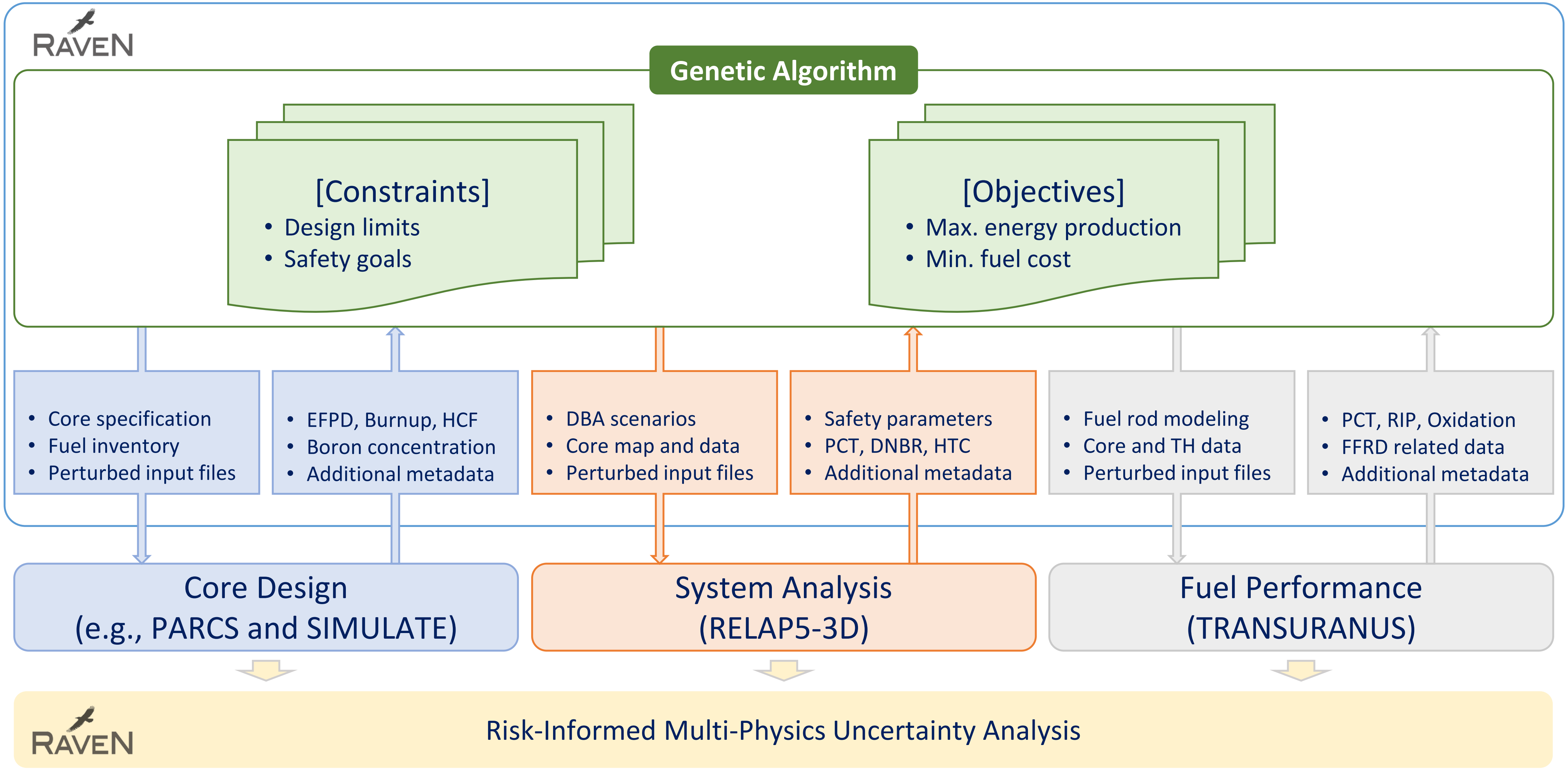
- **Traditional methods deciding core loading pattern and reload quantity are labor-intensive and time-consuming.**
  - More than 10E+30 combinations for 17x17 PWR core

***Automated simulation-based fuel reloading analysis Framework is needed.***

* 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.

# Plant ReLoad Optimization (PRLO) Platform: Data Flow



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**Genetic Algorithm**

[Constraints]
- Design limits
- Safety goals

[Objectives]
- Max. energy production
- Min. fuel cost

- Core specification
- Fuel inventory
- Perturbed input files

- EFPD, Burnup, HCF
- Boron concentration
- Additional metadata

- DBA scenarios
- Core map and data
- Perturbed input files

- Safety parameters
- PCT, DNBR, HTC
- Additional metadata

- Fuel rod modeling
- Core and TH data
- Perturbed input files

- PCT, RIP, Oxidation
- FFRD related data
- Additional metadata

Core Design
(e.g., PARCS and SIMULATE)

System Analysis
(RELAP5-3D)

Fuel Performance
(TRANSURANUS)

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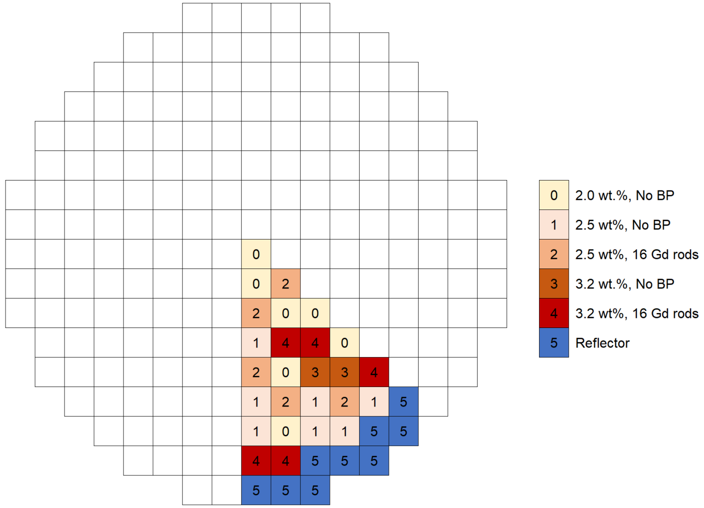
Risk-Informed Multi-Physics Uncertainty Analysis

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

# Case Study: Single-objective Optimization for Core Design Introduction

- Settings
  - PWR core with 157 fuel assemblies (FA)
  - Quarter-core symmetry
  - 6 FA designs → design space = $7.1 \times 10^{32}$
  - 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)

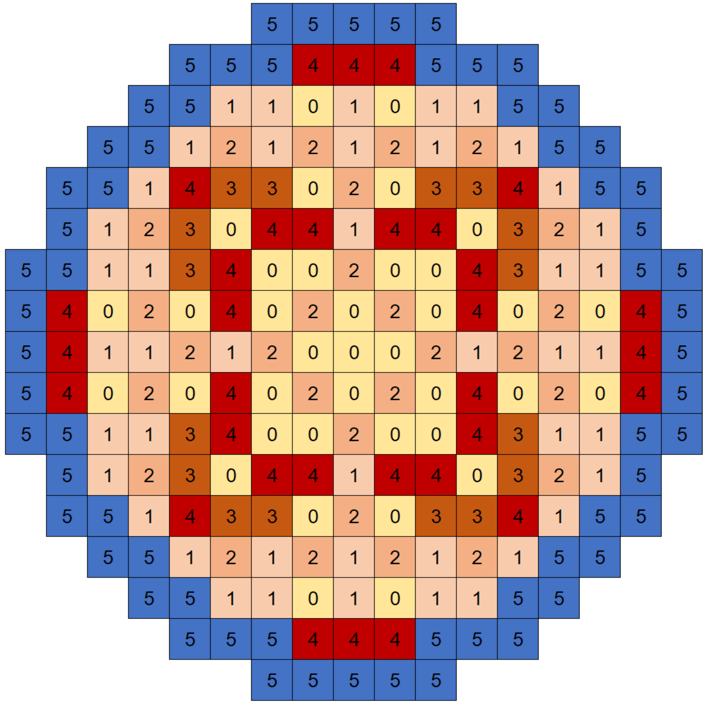
- Constraints
  - $F_Q$ (Heat flux hot channel factor) < 2.1
  - $F_{\Delta H}$ (Nuclear enthalpy rise hot channel factor) < 1.48
  - Peak critical boron concentration (CBC) <1300 pcm

*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.*

# Case Study: Single-objective Optimization for Core Design Demonstration

# Case Study: Single-objective Optimization for Core Design Demonstration

## Initial Fuel Loading Pattern

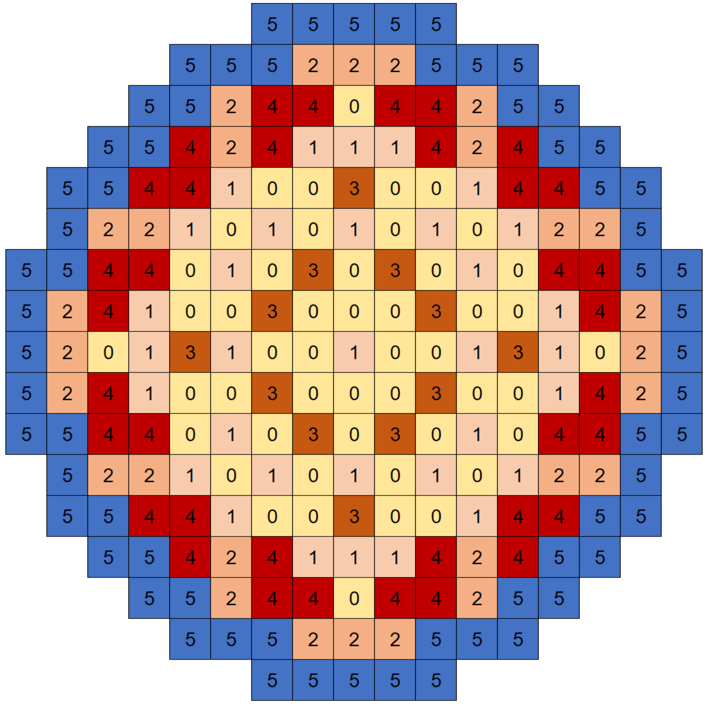


| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 5 | 5 | 5 | 5 | 5 | | | | | | |
| | | | | 5 | 5 | 5 | 4 | 4 | 4 | 5 | 5 | 5 | | | | |
| | | | 5 | 5 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 5 | 5 | | | |
| | | 5 | 5 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 5 | 5 | | |
| | 5 | 5 | 1 | 4 | 3 | 3 | 0 | 2 | 0 | 3 | 3 | 4 | 1 | 5 | 5 | |
| | 5 | 1 | 2 | 3 | 0 | 4 | 4 | 1 | 4 | 4 | 0 | 3 | 2 | 1 | 5 | |
| 5 | 5 | 1 | 1 | 3 | 4 | 0 | 0 | 2 | 0 | 0 | 4 | 3 | 1 | 1 | 5 | 5 |
| 5 | 4 | 0 | 2 | 0 | 4 | 0 | 2 | 0 | 2 | 0 | 4 | 0 | 2 | 0 | 4 | 5 |
| 5 | 4 | 1 | 1 | 2 | 1 | 2 | 0 | 0 | 0 | 2 | 1 | 2 | 1 | 1 | 4 | 5 |
| 5 | 4 | 0 | 2 | 0 | 4 | 0 | 2 | 0 | 2 | 0 | 4 | 0 | 2 | 0 | 4 | 5 |
| 5 | 5 | 1 | 1 | 3 | 4 | 0 | 0 | 2 | 0 | 0 | 4 | 3 | 1 | 1 | 5 | 5 |
| | 5 | 1 | 2 | 3 | 0 | 4 | 4 | 1 | 4 | 4 | 0 | 3 | 2 | 1 | 5 | |
| | 5 | 5 | 1 | 4 | 3 | 3 | 0 | 2 | 0 | 3 | 3 | 4 | 1 | 5 | 5 | |
| | | 5 | 5 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 5 | 5 | | |
| | | | 5 | 5 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 5 | 5 | | | |
| | | | | 5 | 5 | 5 | 4 | 4 | 4 | 5 | 5 | 5 | | | | |
| | | | | | | 5 | 5 | 5 | 5 | 5 | | | | | | |

| | | |
|---|---|---|
| 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



| | | | | | | | | | | | | | | | | |
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| | | | | 5 | 5 | 5 | 2 | 2 | 2 | 5 | 5 | 5 | | | | |
| | | | 5 | 5 | 2 | 4 | 4 | 0 | 4 | 4 | 2 | 5 | 5 | | | |
| | | 5 | 5 | 4 | 2 | 4 | 1 | 1 | 1 | 4 | 2 | 4 | 5 | 5 | | |
| | 5 | 5 | 4 | 4 | 1 | 0 | 0 | 3 | 0 | 0 | 1 | 4 | 4 | 5 | 5 | |
| | 5 | 2 | 2 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 2 | 2 | 5 | |
| 5 | 5 | 4 | 4 | 0 | 1 | 0 | 3 | 0 | 3 | 0 | 1 | 0 | 4 | 4 | 5 | 5 |
| 5 | 2 | 4 | 1 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 0 | 0 | 1 | 4 | 2 | 5 |
| 5 | 2 | 0 | 1 | 3 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 3 | 1 | 0 | 2 | 5 |
| 5 | 2 | 4 | 1 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 0 | 0 | 1 | 4 | 2 | 5 |
| 5 | 5 | 4 | 4 | 0 | 1 | 0 | 3 | 0 | 3 | 0 | 1 | 0 | 4 | 4 | 5 | 5 |
| | 5 | 2 | 2 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 2 | 2 | 5 | |
| | 5 | 5 | 4 | 4 | 1 | 0 | 0 | 3 | 0 | 0 | 1 | 4 | 4 | 5 | 5 | |
| | | 5 | 5 | 4 | 2 | 4 | 1 | 1 | 1 | 4 | 2 | 4 | 5 | 5 | | |
| | | | 5 | 5 | 2 | 4 | 4 | 0 | 4 | 4 | 2 | 5 | 5 | | | |
| | | | | 5 | 5 | 5 | 2 | 2 | 2 | 5 | 5 | 5 | | | | |
| | | | | | | 5 | 5 | 5 | 5 | 5 | | | | | | |

| | | |
|---|---|---|
| Pin_Peaking Factor | 2.075 | o |
| Boron Concentration | 1297.6 | o |
| FΔH | 1.454 | o |

| | |
|---|---|
| Effective Full Power Day (EFPD) | 392.7 |

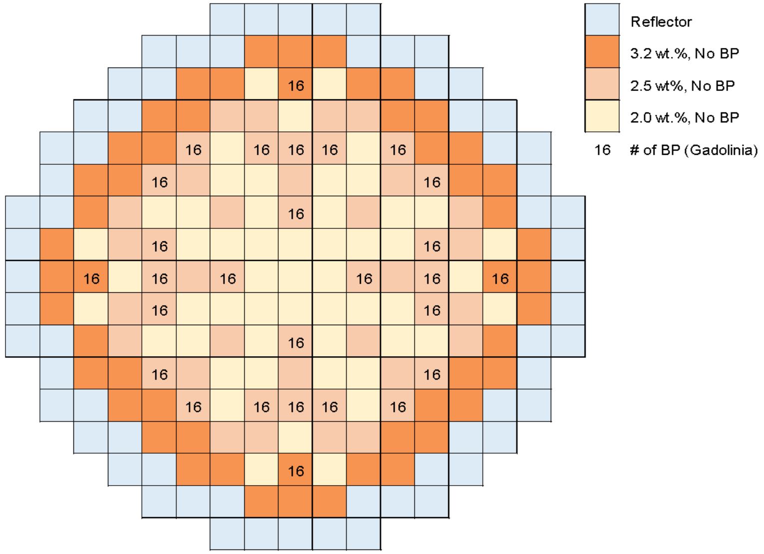
| | |
|---|---|
| 0 | 2.0 wt.%, No BP |
| 1 | 2.5 wt%, No BP |
| 2 | 2.5 wt%, 16 Gd rods |
| 3 | 3.2 wt.%, No BP |
| 4 | 3.2 wt%, 16 Gd rods |
| 5 | Reflector |

A generic PWR reactor core is used for the demonstration

# Case Study: Multi-objective Optimization for Core Design Introduction

- Settings
  - PWR core with 157 fuel assemblies (FA)
  - Quarter-core symmetry
  - 6 FA designs → design space = $7.1 \times 10^{32}$
  - 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 |

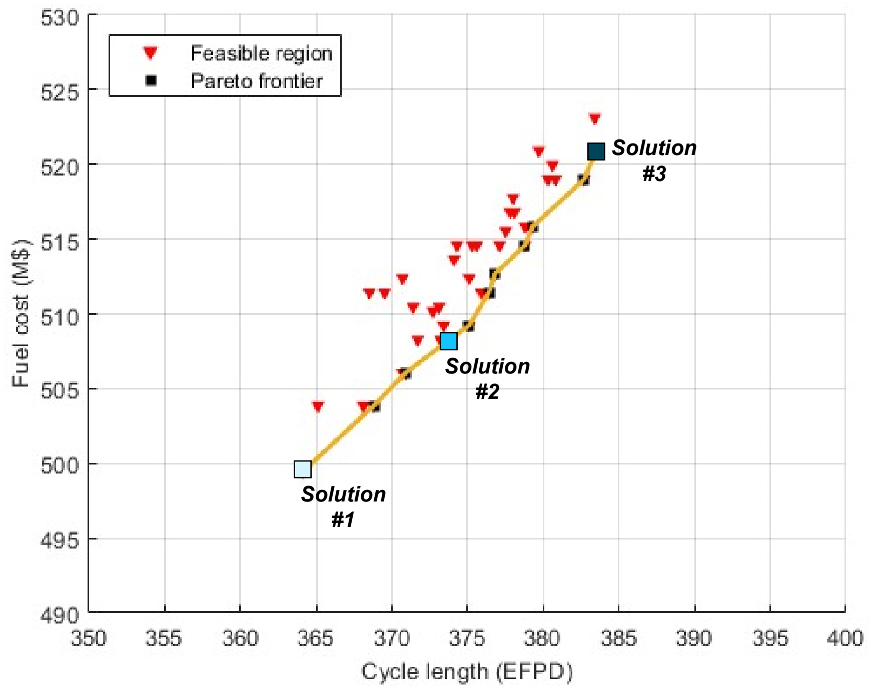
- Objectives
  - Maximize cycle length (cycle energy production)
  - Minimize fuel cost

- 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.*

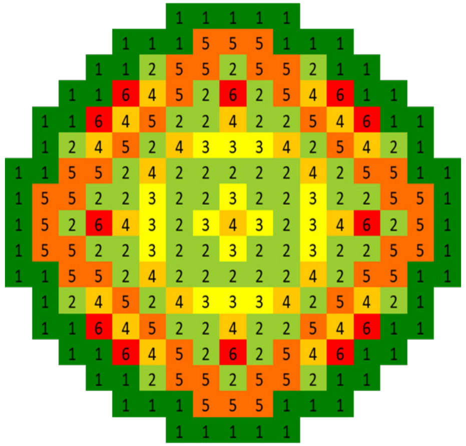
A generic PWR reactor core is used for the demonstration

# Demonstration with Multi Objective Optimal Core Patterns



A generic PWR reactor core is used for the demonstration

**Solution #3**



| | | | | | | | | | | | | | | | | |
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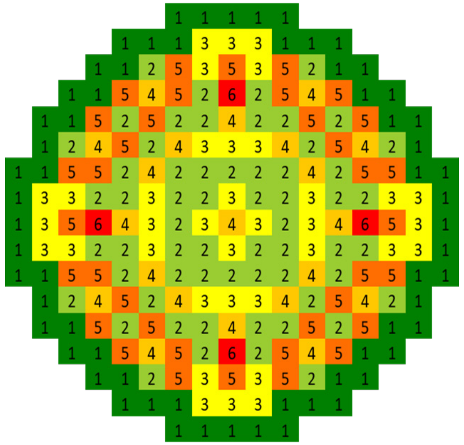
| | | | | 1 | 1 | 1 | 5 | 5 | 5 | 1 | 1 | 1 | | | | |
| | | | 1 | 1 | 2 | 5 | 5 | 2 | 5 | 5 | 2 | 1 | 1 | | | |
| | | 1 | 1 | 6 | 4 | 5 | 2 | 6 | 2 | 5 | 4 | 6 | 1 | 1 | | |
| | 1 | 1 | 6 | 4 | 5 | 2 | 2 | 4 | 2 | 2 | 5 | 4 | 6 | 1 | 1 | |
| | 1 | 2 | 4 | 5 | 2 | 4 | 3 | 3 | 3 | 4 | 2 | 5 | 4 | 2 | 1 | |
| 1 | 1 | 5 | 5 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | 4 | 2 | 5 | 5 | 1 | 1 |
| 1 | 5 | 5 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 5 | 5 | 1 |
| 1 | 5 | 2 | 6 | 4 | 3 | 2 | 3 | 4 | 3 | 2 | 3 | 4 | 6 | 2 | 5 | 1 |
| 1 | 5 | 5 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 5 | 5 | 1 |
| 1 | 1 | 5 | 5 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | 4 | 2 | 5 | 5 | 1 | 1 |
| | 1 | 2 | 4 | 5 | 2 | 4 | 3 | 3 | 3 | 4 | 2 | 5 | 4 | 2 | 1 | |
| | 1 | 1 | 6 | 4 | 5 | 2 | 2 | 4 | 2 | 2 | 5 | 4 | 6 | 1 | 1 | |
| | | 1 | 1 | 6 | 4 | 5 | 2 | 6 | 2 | 5 | 4 | 6 | 1 | 1 | | |
| | | | 1 | 1 | 2 | 5 | 5 | 2 | 5 | 5 | 2 | 1 | 1 | | | |
| | | | | 1 | 1 | 1 | 5 | 5 | 5 | 1 | 1 | 1 | | | | |
| | | | | | | 1 | 1 | 1 | 1 | 1 | | | | | | |

| | |
|---|---|
| *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**



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| | | | | 1 | 1 | 1 | 3 | 3 | 3 | 1 | 1 | 1 | | | | |
| | | | 1 | 1 | 2 | 5 | 3 | 5 | 3 | 5 | 2 | 1 | 1 | | | |
| | | 1 | 1 | 5 | 4 | 5 | 2 | 6 | 2 | 5 | 4 | 5 | 1 | 1 | | |
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| 1 | 1 | 5 | 5 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | 4 | 2 | 5 | 5 | 1 | 1 |
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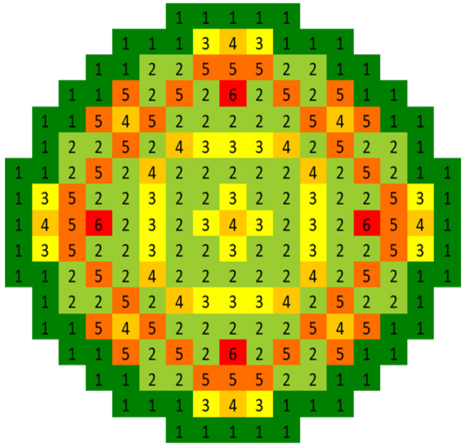
| | 1 | 2 | 4 | 5 | 2 | 4 | 3 | 3 | 3 | 4 | 2 | 5 | 4 | 2 | 1 | |
| | 1 | 1 | 5 | 2 | 5 | 2 | 2 | 4 | 2 | 2 | 5 | 2 | 5 | 1 | 1 | |
| | | 1 | 1 | 5 | 4 | 5 | 2 | 6 | 2 | 5 | 4 | 5 | 1 | 1 | | |
| | | | 1 | 1 | 2 | 5 | 3 | 5 | 3 | 5 | 2 | 1 | 1 | | | |
| | | | | 1 | 1 | 1 | 3 | 3 | 3 | 1 | 1 | 1 | | | | |
| | | | | | | 1 | 1 | 1 | 1 | 1 | | | | | | |

| | |
|---|---|
| *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**



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| | | | | | | 1 | 1 | 1 | 1 | 1 | | | | | | |
| | | | | 1 | 1 | 1 | 3 | 4 | 3 | 1 | 1 | 1 | | | | |
| | | | 1 | 1 | 2 | 2 | 5 | 5 | 5 | 2 | 2 | 1 | 1 | | | |
| | | 1 | 1 | 5 | 2 | 5 | 2 | 6 | 2 | 5 | 2 | 5 | 1 | 1 | | |
| | 1 | 1 | 5 | 4 | 5 | 2 | 2 | 2 | 2 | 2 | 5 | 4 | 5 | 1 | 1 | |
| | 1 | 2 | 2 | 5 | 2 | 4 | 3 | 3 | 3 | 4 | 2 | 5 | 2 | 2 | 1 | |
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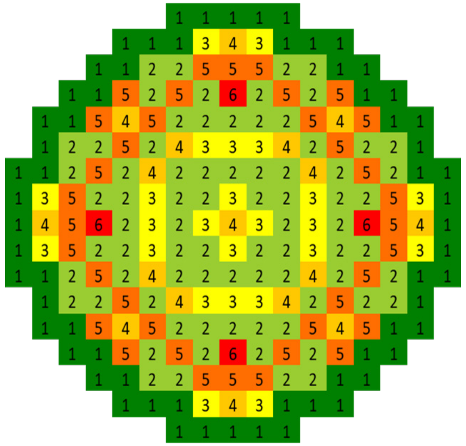
| 1 | 3 | 5 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 5 | 3 | 1 |
| 1 | 1 | 2 | 5 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | 4 | 2 | 5 | 2 | 1 | 1 |
| | 1 | 2 | 2 | 5 | 2 | 4 | 3 | 3 | 3 | 4 | 2 | 5 | 2 | 2 | 1 | |
| | 1 | 1 | 5 | 4 | 5 | 2 | 2 | 2 | 2 | 2 | 5 | 4 | 5 | 1 | 1 | |
| | | 1 | 1 | 5 | 2 | 5 | 2 | 6 | 2 | 5 | 2 | 5 | 1 | 1 | | |
| | | | 1 | 1 | 2 | 2 | 5 | 5 | 5 | 2 | 2 | 1 | 1 | | | |
| | | | | 1 | 1 | 1 | 3 | 4 | 3 | 1 | 1 | 1 | | | | |
| | | | | | | 1 | 1 | 1 | 1 | 1 | | | | | | |

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

# Demonstration with Multi Objective
# Common Features of Optimal Core Designs

- **All three core designs present the Low Leakage Loading pattern (L3P)**
  - Low/medium reactivity fuel at inner region to reduce the power peaking at core center
  - High reactivity fuel at outer region to balance the power
  - Use of BP to suppress the excess reactivity
  - Low reactivity fuel at core boundary to reduce the leakage / increase the neutron economy

***Solution #1***



| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 1 | 1 | 1 | 1 | 1 | | | | | | |
| | | | | 1 | 1 | 1 | 3 | 4 | 3 | 1 | 1 | 1 | | | | |
| | | | 1 | 1 | 2 | 2 | 5 | 5 | 5 | 2 | 2 | 1 | 1 | | | |
| | | 1 | 1 | 5 | 2 | 5 | 2 | 6 | 2 | 5 | 2 | 5 | 1 | 1 | | |
| | 1 | 1 | 5 | 4 | 5 | 2 | 2 | 2 | 2 | 2 | 5 | 4 | 5 | 1 | 1 | |
| | 1 | 2 | 2 | 5 | 2 | 4 | 3 | 3 | 3 | 4 | 2 | 5 | 2 | 2 | 1 | |
| 1 | 1 | 2 | 5 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | 4 | 2 | 5 | 2 | 1 | 1 |
| 1 | 3 | 5 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 5 | 3 | 1 |
| 1 | 4 | 5 | 6 | 2 | 3 | 2 | 3 | 4 | 3 | 2 | 3 | 2 | 6 | 5 | 4 | 1 |
| 1 | 3 | 5 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 5 | 3 | 1 |
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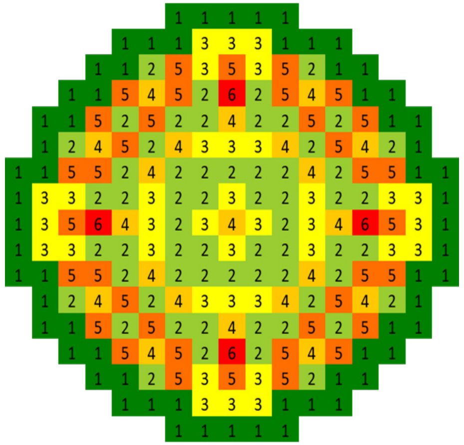
| | | 1 | 1 | 5 | 2 | 5 | 2 | 6 | 2 | 5 | 2 | 5 | 1 | 1 | | |
| | | | 1 | 1 | 2 | 2 | 5 | 5 | 5 | 2 | 2 | 1 | 1 | | | |
| | | | | 1 | 1 | 1 | 3 | 4 | 3 | 1 | 1 | 1 | | | | |
| | | | | | | 1 | 1 | 1 | 1 | 1 | | | | | | |

***Solution #2***



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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 1 | 1 | 1 | 1 | 1 | | | | | | |
| | | | | 1 | 1 | 1 | 3 | 3 | 3 | 1 | 1 | 1 | | | | |
| | | | 1 | 1 | 2 | 5 | 3 | 5 | 3 | 5 | 2 | 1 | 1 | | | |
| | | 1 | 1 | 5 | 4 | 5 | 2 | 6 | 2 | 5 | 4 | 5 | 1 | 1 | | |
| | 1 | 1 | 5 | 2 | 5 | 2 | 2 | 4 | 2 | 2 | 5 | 2 | 5 | 1 | 1 | |
| | 1 | 2 | 4 | 5 | 2 | 4 | 3 | 3 | 3 | 4 | 2 | 5 | 4 | 2 | 1 | |
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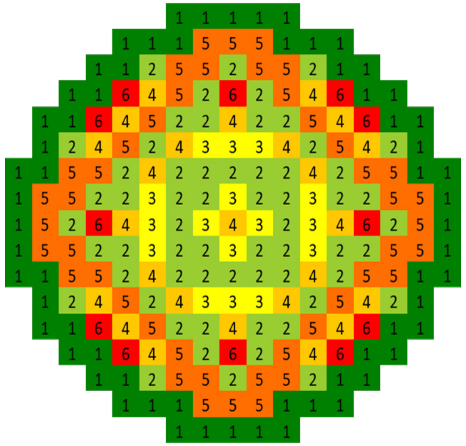
| | 1 | 2 | 4 | 5 | 2 | 4 | 3 | 3 | 3 | 4 | 2 | 5 | 4 | 2 | 1 | |
| | 1 | 1 | 5 | 2 | 5 | 2 | 2 | 4 | 2 | 2 | 5 | 2 | 5 | 1 | 1 | |
| | | 1 | 1 | 5 | 4 | 5 | 2 | 6 | 2 | 5 | 4 | 5 | 1 | 1 | | |
| | | | 1 | 1 | 2 | 5 | 3 | 5 | 3 | 5 | 2 | 1 | 1 | | | |
| | | | | 1 | 1 | 1 | 3 | 3 | 3 | 1 | 1 | 1 | | | | |
| | | | | | | 1 | 1 | 1 | 1 | 1 | | | | | | |

***Solution #3***



| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 1 | 1 | 1 | 1 | 1 | | | | | | |
| | | | | 1 | 1 | 1 | 5 | 5 | 5 | 1 | 1 | 1 | | | | |
| | | | 1 | 1 | 2 | 5 | 5 | 2 | 5 | 5 | 2 | 1 | 1 | | | |
| | | 1 | 1 | 6 | 4 | 5 | 2 | 6 | 2 | 5 | 4 | 6 | 1 | 1 | | |
| | 1 | 1 | 6 | 4 | 5 | 2 | 2 | 4 | 2 | 2 | 5 | 4 | 6 | 1 | 1 | |
| | 1 | 2 | 4 | 5 | 2 | 4 | 3 | 3 | 3 | 4 | 2 | 5 | 4 | 2 | 1 | |
| 1 | 1 | 5 | 5 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | 4 | 2 | 5 | 5 | 1 | 1 |
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| 1 | 5 | 2 | 6 | 4 | 3 | 2 | 3 | 4 | 3 | 2 | 3 | 4 | 6 | 2 | 5 | 1 |
| 1 | 5 | 5 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 5 | 5 | 1 |
| 1 | 1 | 5 | 5 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | 4 | 2 | 5 | 5 | 1 | 1 |
| | 1 | 2 | 4 | 5 | 2 | 4 | 3 | 3 | 3 | 4 | 2 | 5 | 4 | 2 | 1 | |
| | 1 | 1 | 6 | 4 | 5 | 2 | 2 | 4 | 2 | 2 | 5 | 4 | 6 | 1 | 1 | |
| | | 1 | 1 | 6 | 4 | 5 | 2 | 6 | 2 | 5 | 4 | 6 | 1 | 1 | | |
| | | | 1 | 1 | 2 | 5 | 5 | 2 | 5 | 5 | 2 | 1 | 1 | | | |
| | | | | 1 | 1 | 1 | 5 | 5 | 5 | 1 | 1 | 1 | | | | |
| | | | | | | 1 | 1 | 1 | 1 | 1 | | | | | | |

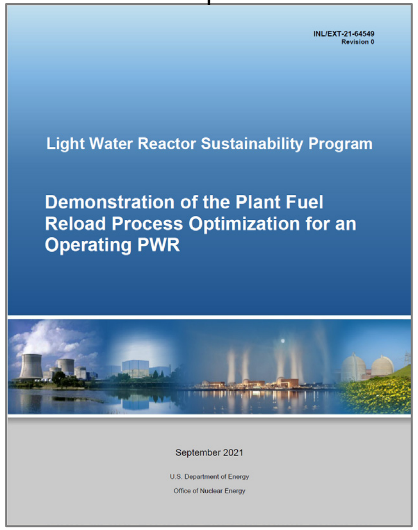
A generic PWR reactor core is used for the demonstration

# Conclusion & Future Work

- **Presented the PRLO framework, aimed at AI-driven reactor core design for addressing real-world challenges.**
- **Demonstrated constrained multi-objective core design optimization problem for a 17 × 17 PWR core to minimize fuel cost and maximize fuel cycle length.**
- **Future works include…**
    - Conducting a full-scale demonstration of a PWR core design with multi-cycle problem incorporating safety analysis.
    - Enhancing multi-objective optimization capabilities (e.g., adaptive mutation and crossover)

# Completed Works (~FY24)

**September FY21**


INL/EXT-21-64549
Revision 0

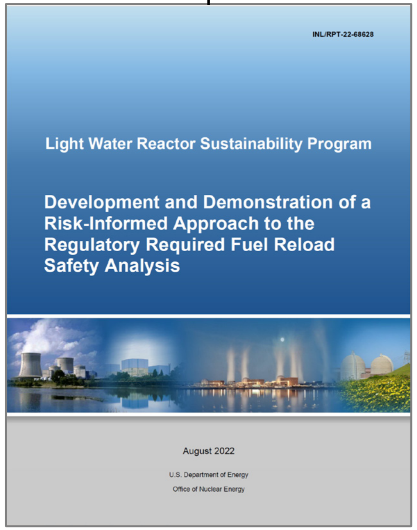
Light Water Reactor Sustainability Program

Demonstration of the Plant Fuel Reload Process Optimization for an Operating PWR

September 2021

U.S. Department of Energy
Office of Nuclear Energy

**August FY22**


INL/RPT-22-68628

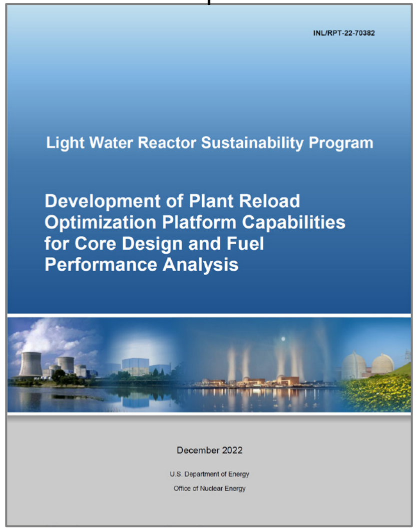
Light Water Reactor Sustainability Program

Development and Demonstration of a Risk-Informed Approach to the Regulatory Required Fuel Reload Safety Analysis

August 2022

U.S. Department of Energy
Office of Nuclear Energy

**December FY22**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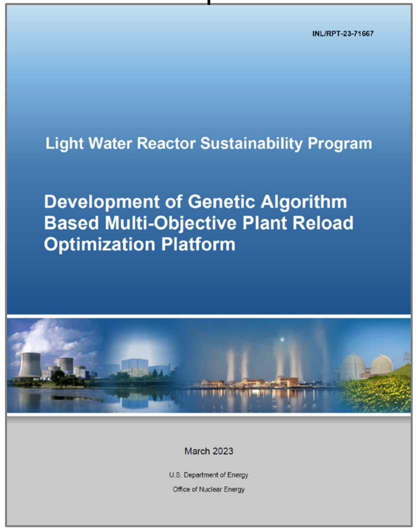
Light Water Reactor Sustainability Program

Development of Plant Reload Optimization Platform Capabilities for Core Design and Fuel Performance Analysis

December 2022

U.S. Department of Energy
Office of Nuclear Energy

**March FY23**


INL/RPT-23-71667

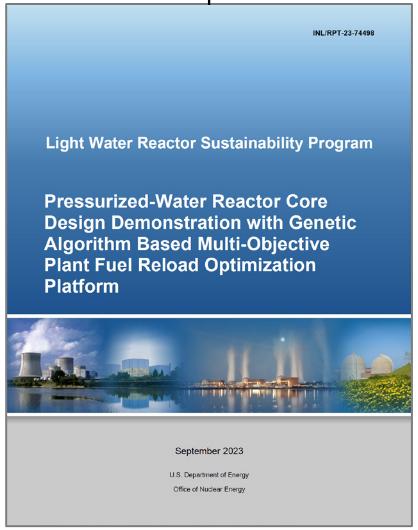
Light Water Reactor Sustainability Program

Development of Genetic Algorithm Based Multi-Objective Plant Reload Optimization Platform

March 2023

U.S. Department of Energy
Office of Nuclear Energy

**September FY23**


INL/RPT-23-74498

Light Water Reactor Sustainability Program

Pressurized-Water Reactor Core Design Demonstration with Genetic Algorithm Based Multi-Objective Plant Fuel Reload Optimization Platform

September 2023

U.S. Department of Energy
Office of Nuclear Energy

- Demonstration of Genetic Algorithm-based optimization framework with single/multi-objective(s).
- Design of optimized reactor core which considers system safety analysis and fuel performance, thus multi-physics methodology.
- Reports are available at: https://www.osti.gov/

LWRS

LIGHT WATER
REACTOR
SUSTAINABILITY

INL
Idaho National Laboratory

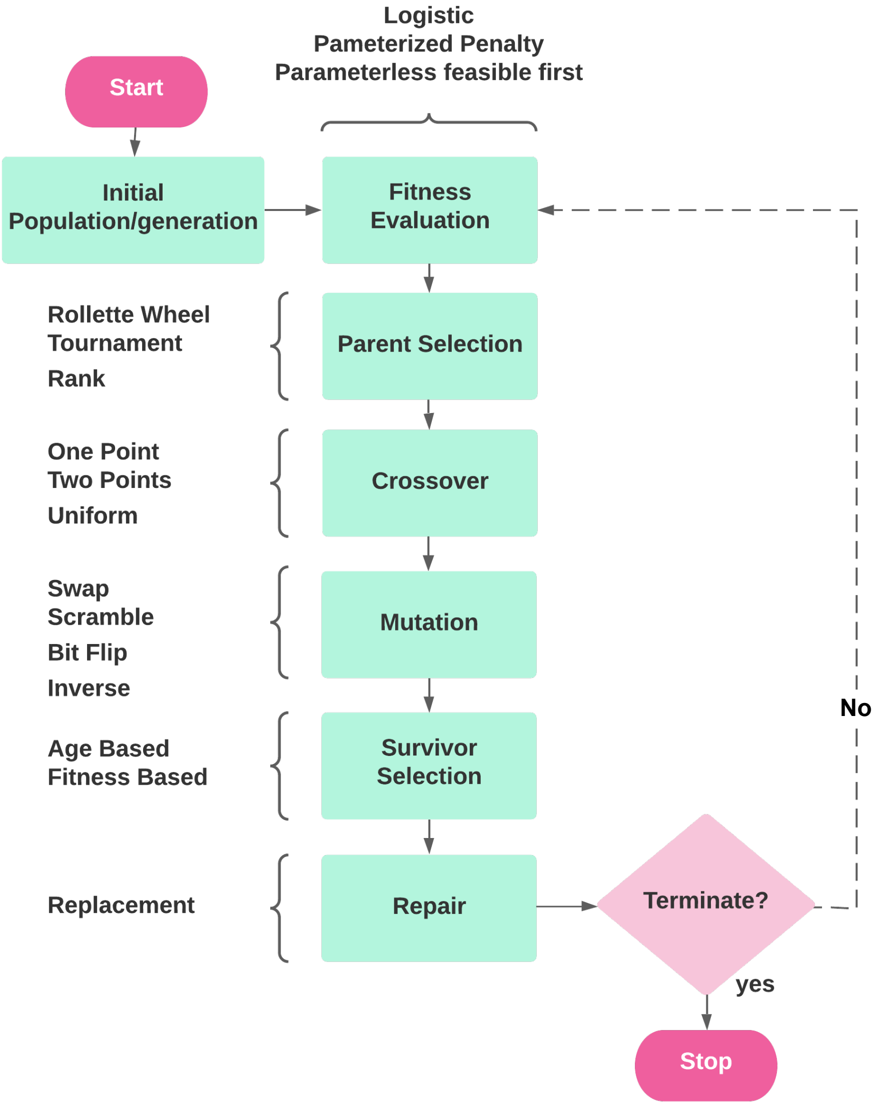
NC STATE
UNIVERSITY

Constellation

# Genetic Algorithm

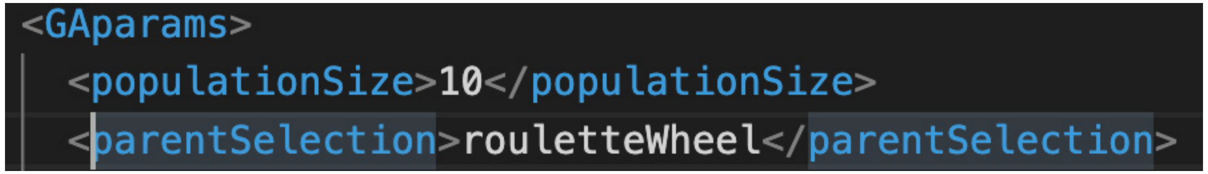
- GA mimics natural selection and evolution
  - No need of gradient calculation
  - Suits non-linear and non-convex problems
  - Constrained and unconstrained
  - Continuous, discrete, or mixed variables

- GA explores group of solutions at each iteration
  - Starts with initial list of solutions (neutronics, thermal-hydraulics, etc.)
  - Evaluates and determines potential solutions
  - Randomly proposes new solutions, then selects best solution (cross-over, mutation, and survivor selection operations).



# Evolutionary Operators of GAs

- Parent selectors:
  - Roulette Wheel
  - Tournament Selection
  - Rank Selection



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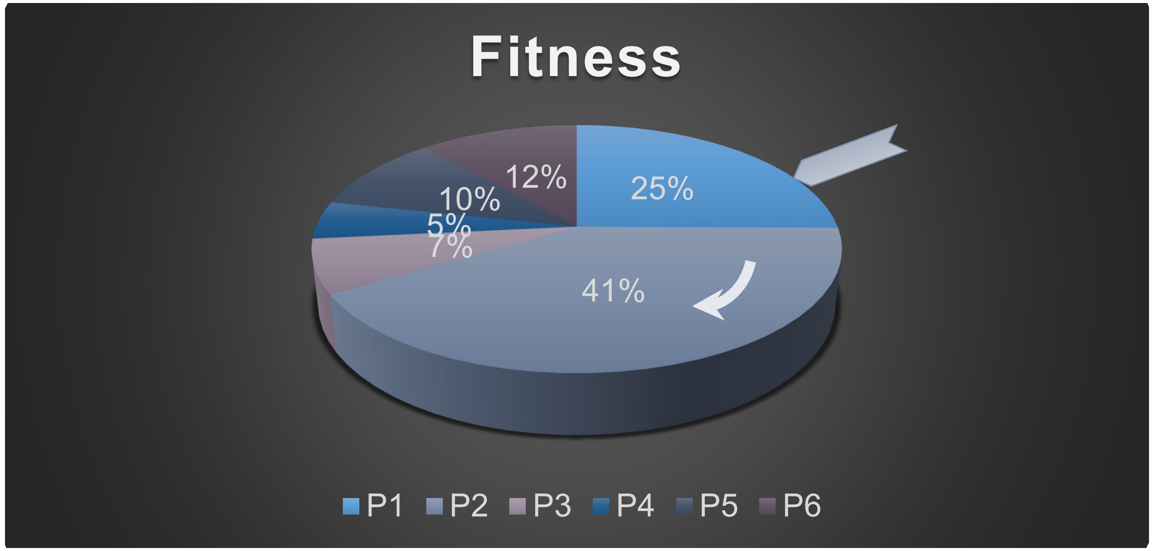
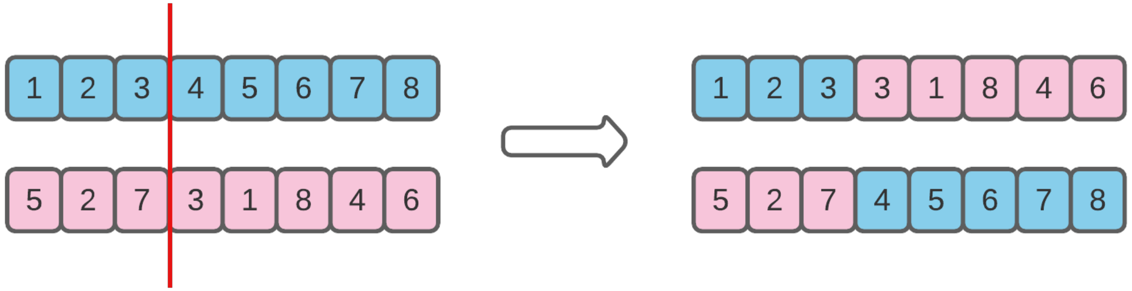
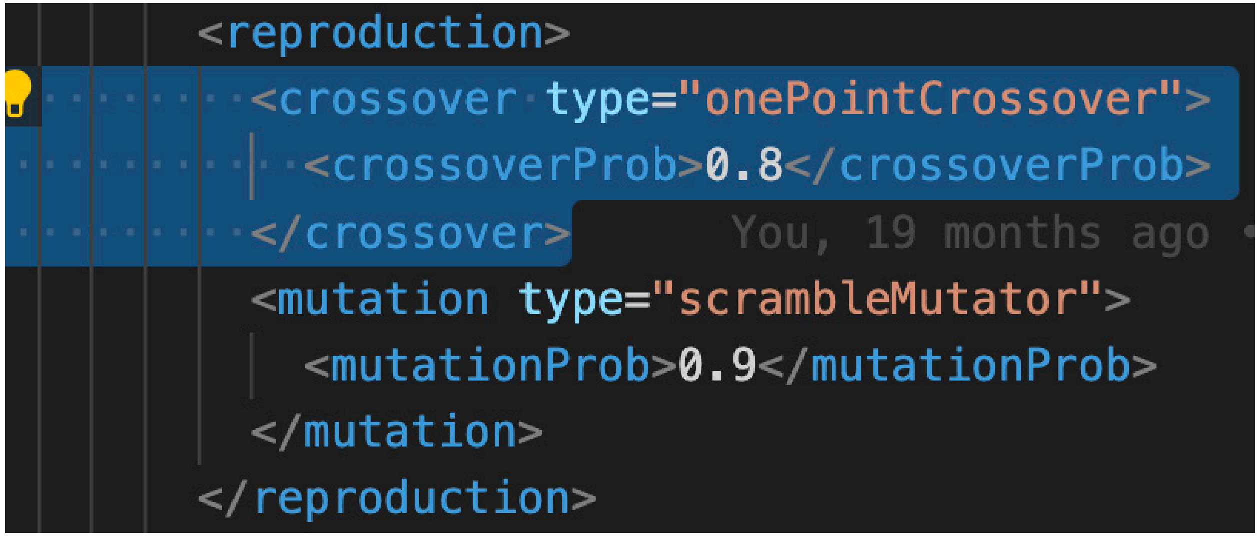


| Individual | Fitness |
|---|---|
| P1 | 5 |
| P2 | 8.2 |
| P3 | 1.4 |
| P4 | 0.98 |
| P5 | 2 |
| P6 | 2.3 |

# Evolutionary Operators of GAs

- Crossovers:
  - One Point
  - Two points
  - Uniform





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    <mutation type="scrambleMutator">
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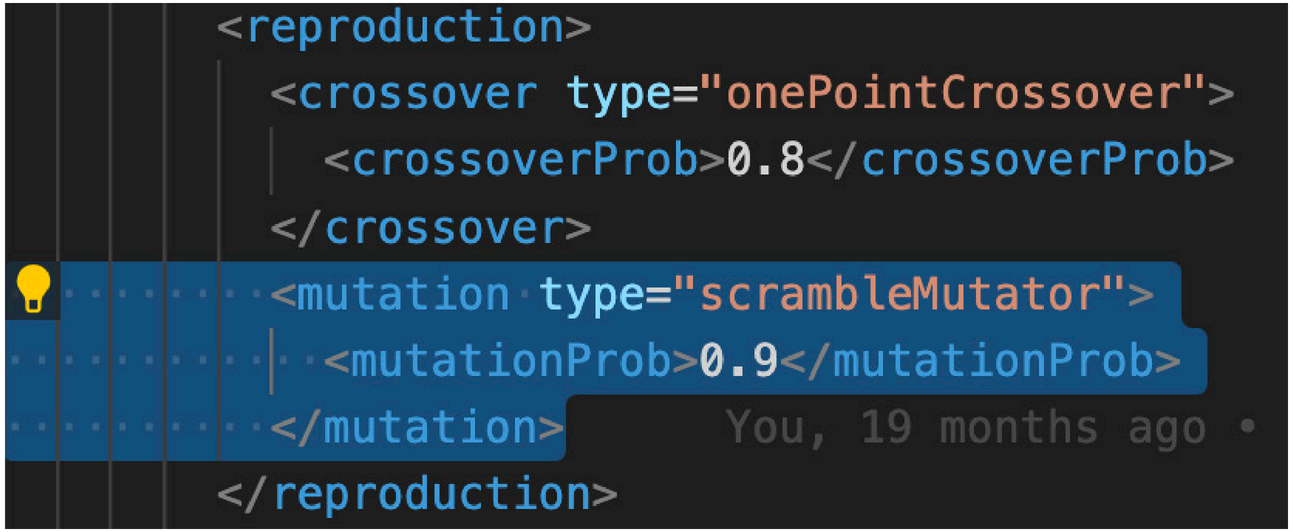
</reproduction>
```

# Evolutionary Operators of GAs

- Mutators:
  - Swap Mutation
  - Scramble Mutation
  - Bit Flip Mutation
  - Inversion Mutation



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  <mutation type="scrambleMutator">
    <mutationProb>0.9</mutationProb>
  </mutation>      You, 19 months ago •
</reproduction>
```

# NSGA-II for Multi-Objective Problem 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) $(f_1(\boldsymbol{x}), f_2(\boldsymbol{x}), \dots, f_M(\boldsymbol{x}))^T$

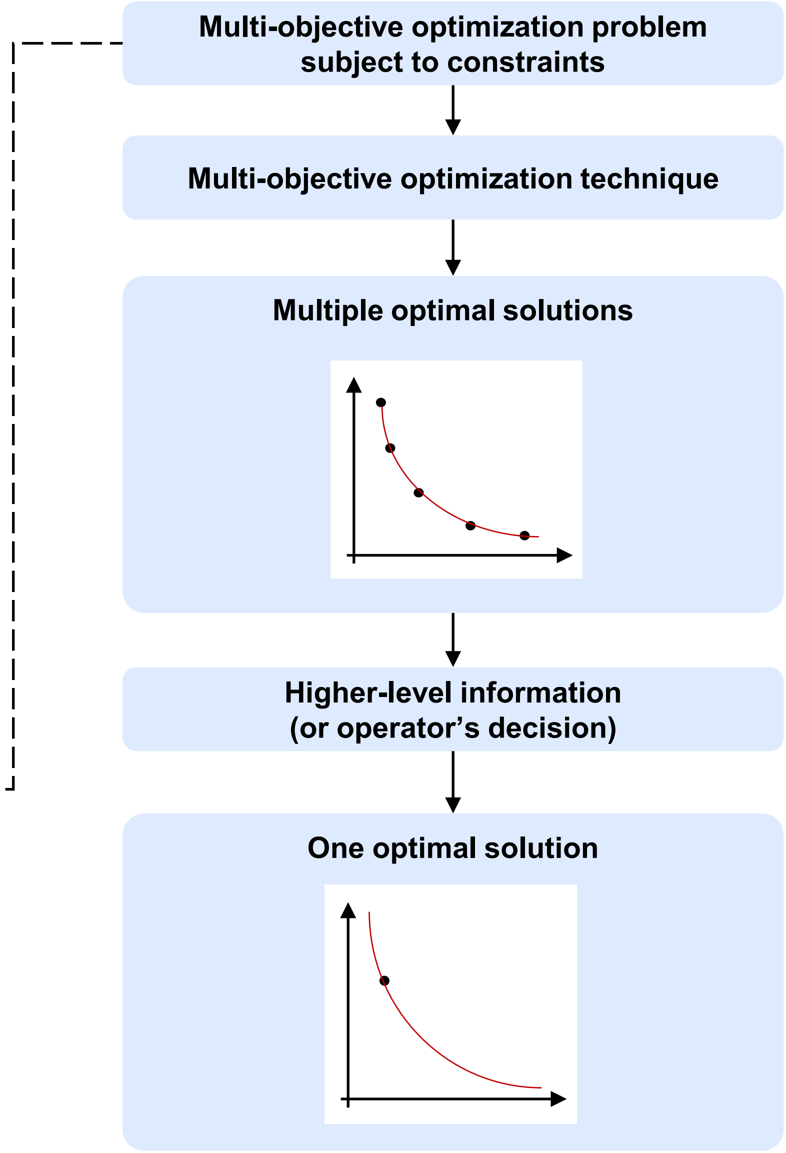
*Subject to*

$$g_j(\boldsymbol{x}) \geq (\text{or } \leq)\ 0$$

$$h_k(\boldsymbol{x}) = 0$$

$$x_i^{(L)} \leq x_i \leq x_i^{(U)}$$

- $f_m(\boldsymbol{x})$ is *m*-th objective, where *m* = 1, 2, …, M.
- $g_j(\boldsymbol{x})$ is *j*-th inequality constraint, where *j* = 1, 2, …, J
- $h_k(\boldsymbol{x})$ is *k*-th equality constraint, where *k* = 1, 2, …, K
- $\boldsymbol{x} = (x_1, x_2, \dots, x_n)^T$ 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**

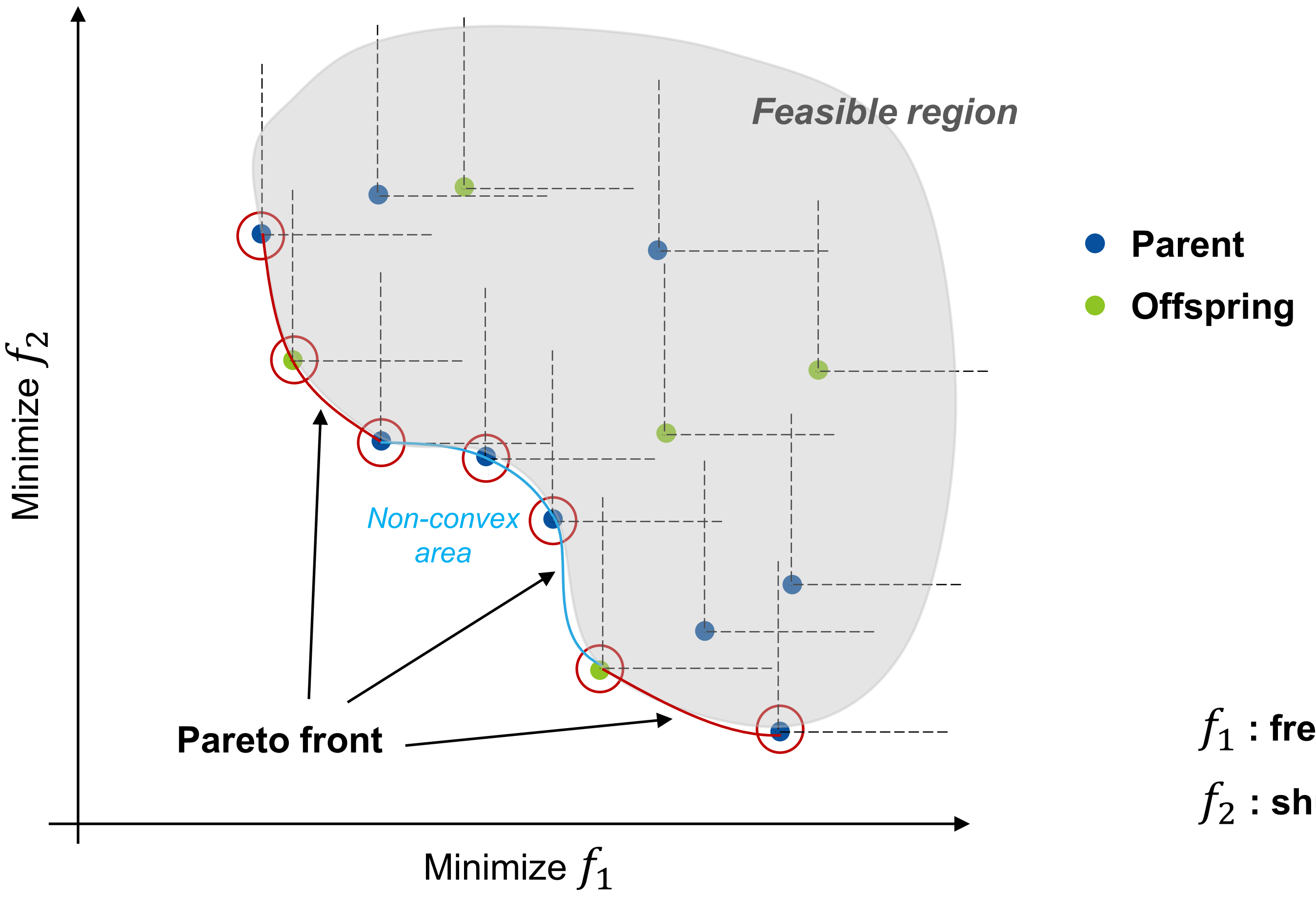
**Multiple optimal solutions**

**Higher-level information (or operator's decision)**

**One optimal solution**

# NSGA-II for Multi-Objective Problem
## Elitism

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

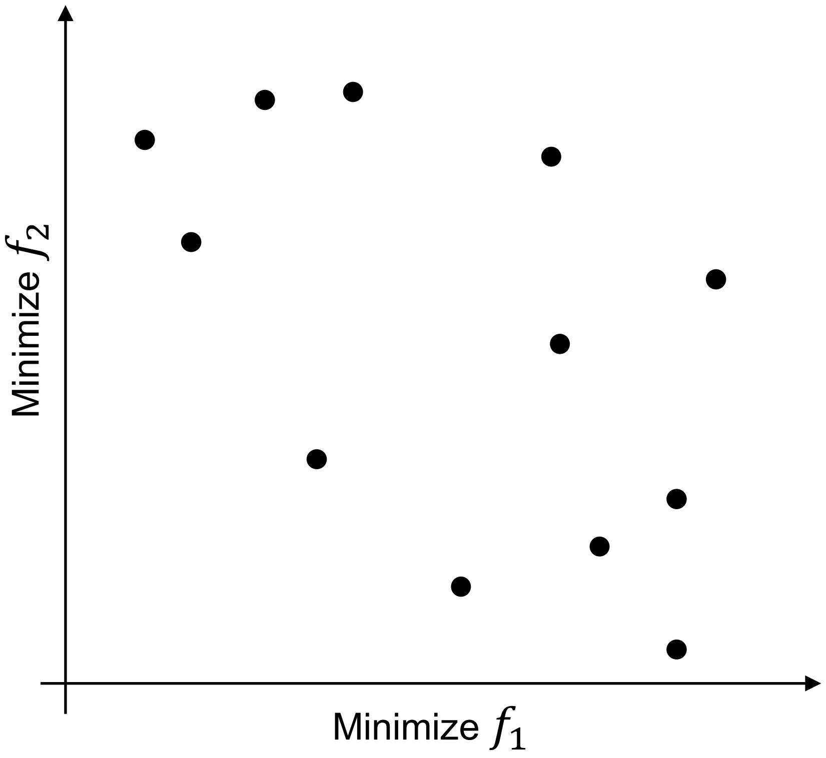


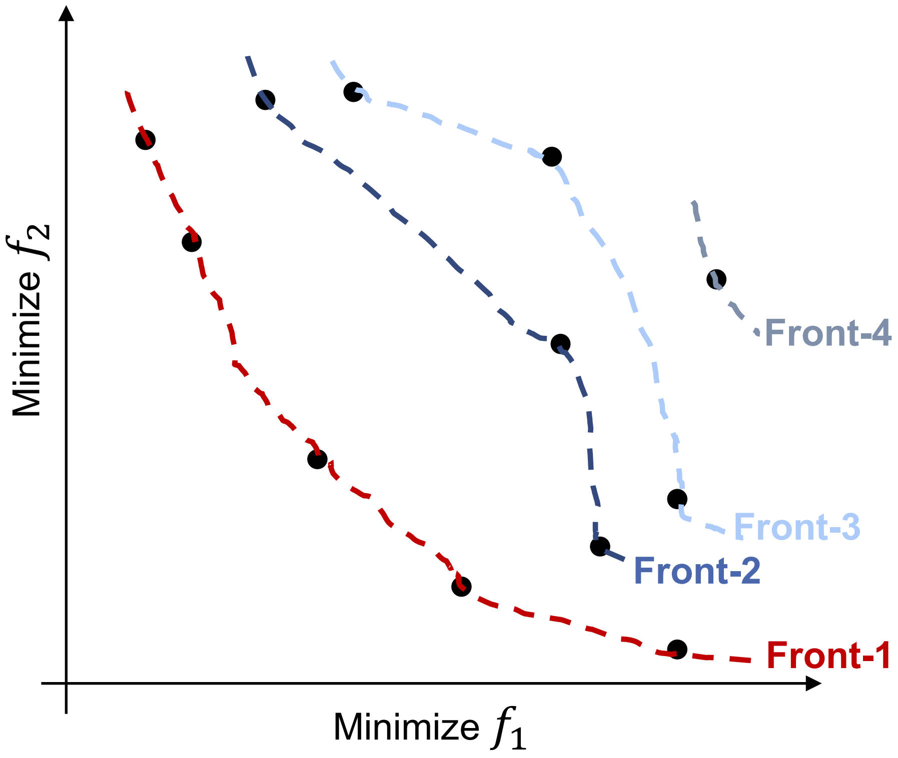
$f_1$ **: fresh fuel**

$f_2$ **: shutdown margin**

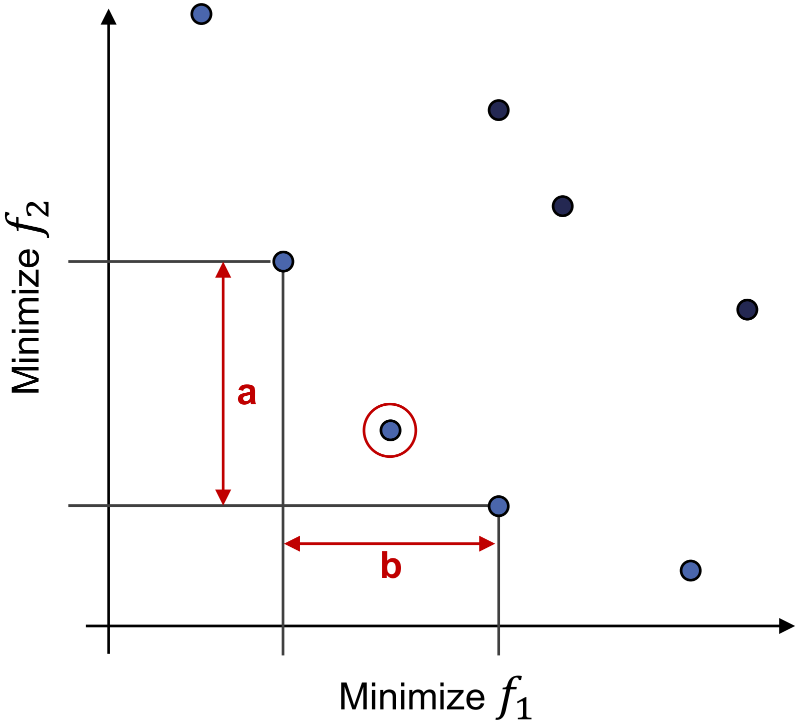
# NSGA-II for Multi-Objective Problem
# Dominance Depth Method

- **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.**



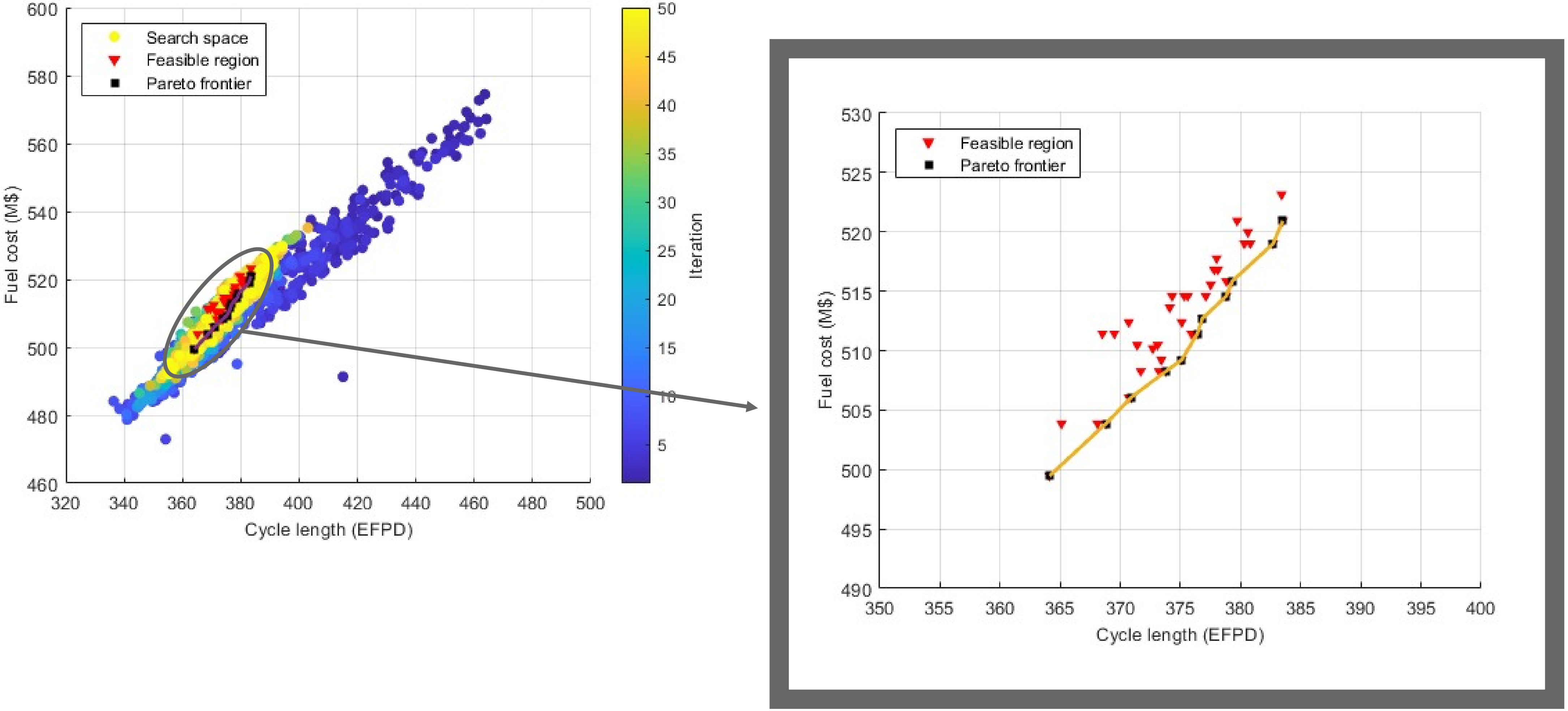


# NSGA-II for Multi-Objective Problem
## Niching for the first rank



- **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.**

# Case Study: Multi-objective Optimization for Core Design
## Feasible Region and Pareto Frontier



*NOTE: Feasible region: Search space region where all constraints are complied; Pareto frontier: Set of optimal solutions*