OPG

Ontario Power Generation Update

Creative Intelligence and Innovation

April 30th, 2024 • Mo Movassat, Senior Manager, Data Analytics

2	2	2	1	66	85	4
Nuclear Stations	Leased **Nuclear** Stations	**Thermal** Stations	**Solar** Facility	**Canada Hydroelectric** Stations	**US Hydroelectric** Stations	**Atura Power Gas-Fired** Stations

from : **INL/EXT-21-64168**

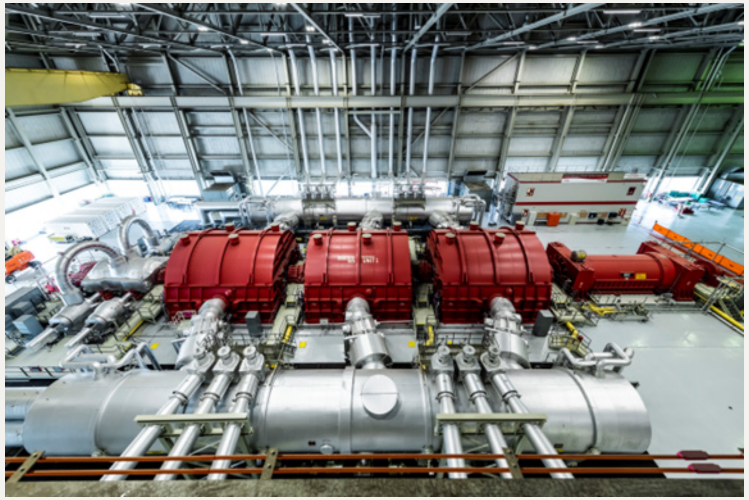
Technology,
PROCESSES &
People
Crucial for Digital Transformation

OPG

Digital Twin

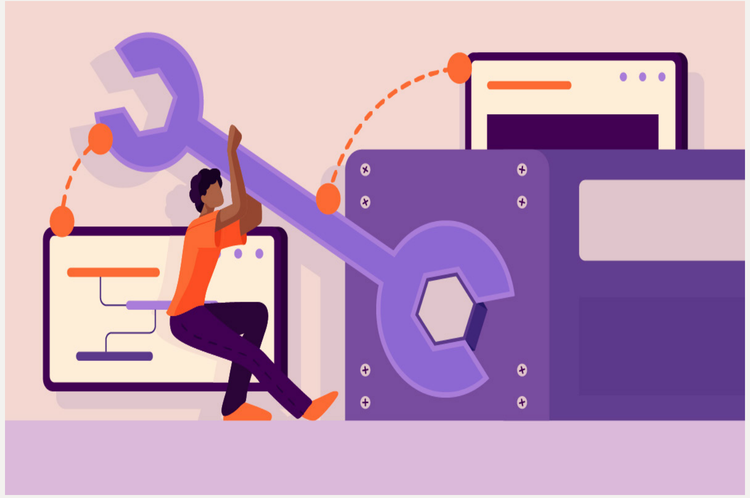
Benefits

Improve Plant Reliability



Providing Explainability and Diagnostics

PM Optimization



Integrating Work Management Data with Operational Data

Asset Management

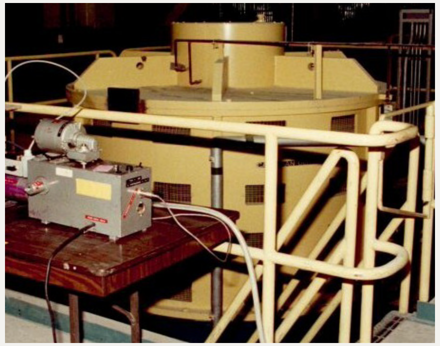
Holistic view on Asset Health

OPG

Digital Twin

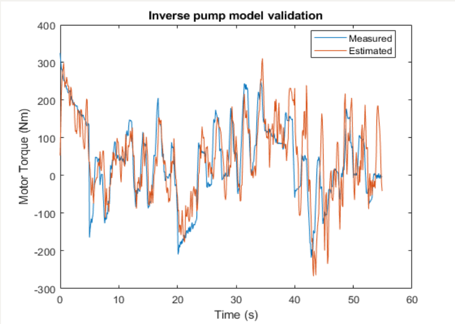
Where we are

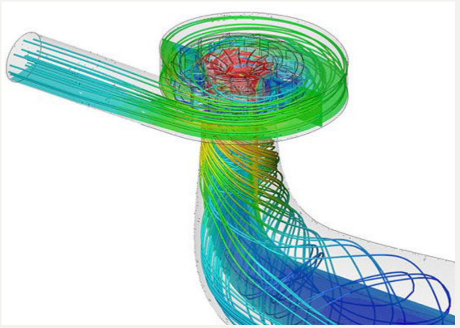
Idaho National Laboratory



- Collaborating with INL to adopt CWS (CCW) system model
- Existing INL model is being modified and tuned for OPG data
- Using WM data to provide explainability and diagnostics

Enhancements





- Advanced ML models for numerical analysis
- Physics-based models
- Application of Large Language Models

LLM Applications

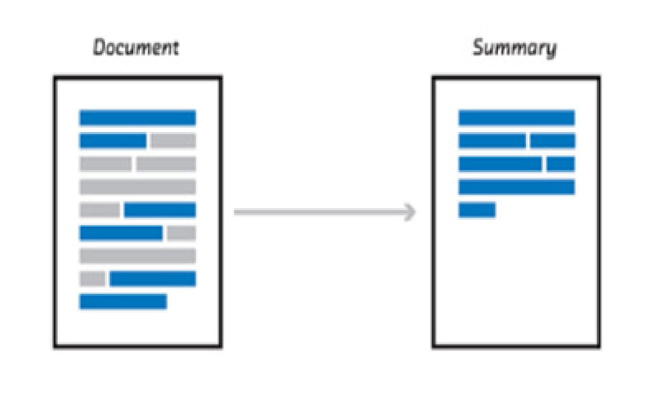
Semantic Search

To access and use text data in decision making

PM Optimization

To leverage available data about work management for PM optimization

Text Summarization



To facilitate reporting and insight extraction

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Robotics

Supporting Operations and Maintenance / RP	Supporting Engineering Inspection/drone
	

Drones For All (m-RPAS, <250g)

- Internal guide under development using the DJI Mini 3 Pro (RC) as a reference m-RPAS
- Transport Canada does not require a drone pilot license to operate an m-RPAS
- Goal is to enable use of micro-drones as a tool, while ensuring they are operated safely

m-RPAS field checklist

Reference:
OPG- Guid-76300-0000

- **Aircraft inspection**
- **Weather conditions**
- **RTH altitude set**
- **Battery checks**
- **SD Cards**
- **Take off area clear**
- **Away from people**
- **Clear of aircrafts**

Always remember that YOU are responsible for operating the m-RPAS safely and a responsible manner.

Condition Monitoring

Gateway Receiver

Battery Monitoring System (BMS)

4-20 mA Sensor

Ambient Temperature and Vibration Sensor

External Temperature and Vibration Sensor

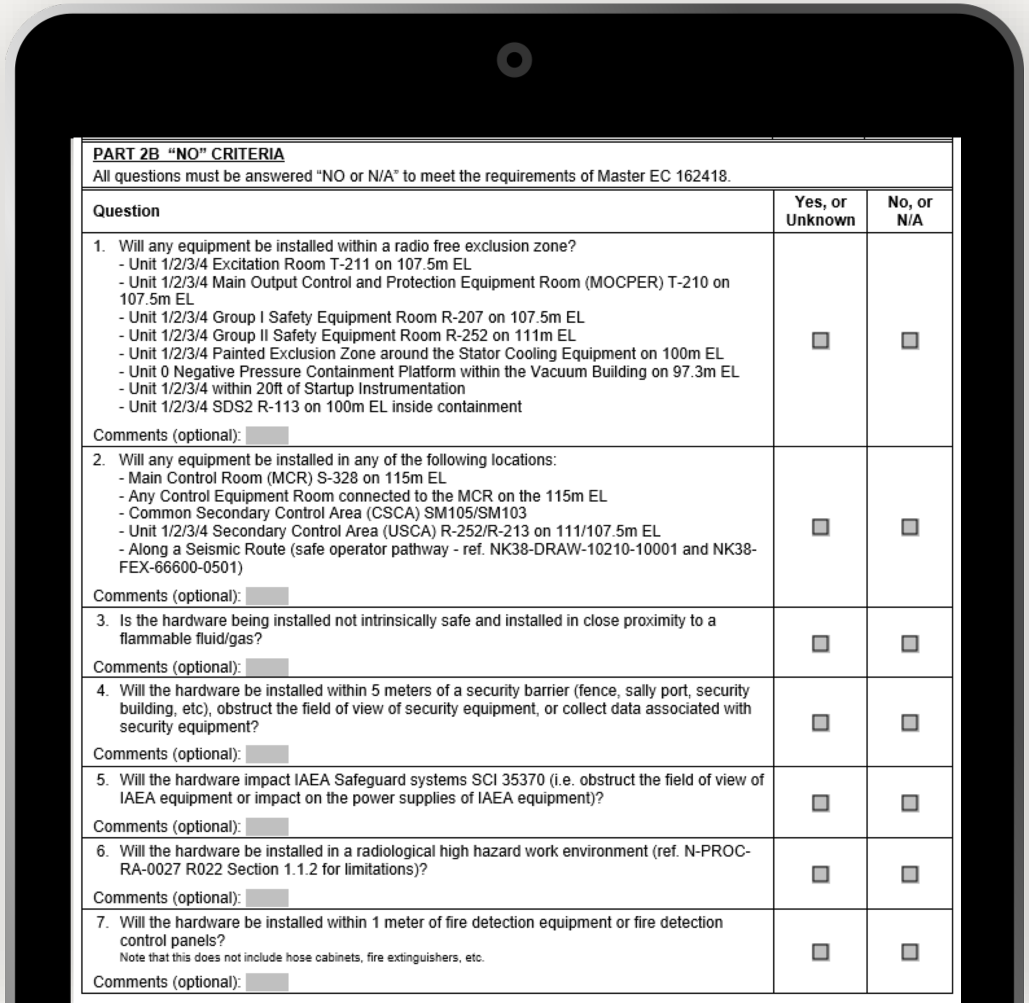
Non-Intrusive Sensor Process

Goal: Develop a process that reduces the amount of engineering rigor required to install condition monitoring sensors that do not pose any risk to station equipment or safe operation.

Boundary: Cannot replace PMs or be used for Operational decision making.

Examples: Temperature monitoring skin temperature of components, vibration monitoring, ambient temperature monitoring

Next Step: Replacing PMs, will be another process



PART 2B "NO" CRITERIA
All questions must be answered "NO or N/A" to meet the requirements of Master EC 162418.

Question	Yes, or Unknown	No, or N/A
1. Will any equipment be installed within a radio free exclusion zone? - Unit 1/2/3/4 Excitation Room T-211 on 107.5m EL - Unit 1/2/3/4 Main Output Control and Protection Equipment Room (MOCPER) T-210 on 107.5m EL - Unit 1/2/3/4 Group I Safety Equipment Room R-207 on 107.5m EL - Unit 1/2/3/4 Group II Safety Equipment Room R-252 on 111m EL - Unit 1/2/3/4 Painted Exclusion Zone around the Stator Cooling Equipment on 100m EL - Unit 0 Negative Pressure Containment Platform within the Vacuum Building on 97.3m EL - Unit 1/2/3/4 within 20ft of Startup Instrumentation - Unit 1/2/3/4 SDS2 R-113 on 100m EL inside containment Comments (optional):	☐	☐
2. Will any equipment be installed in any of the following locations: - Main Control Room (MCR) S-328 on 115m EL - Any Control Equipment Room connected to the MCR on the 115m EL - Common Secondary Control Area (CSCA) SM105/SM103 - Unit 1/2/3/4 Secondary Control Area (USCA) R-252/R-213 on 111/107.5m EL - Along a Seismic Route (safe operator pathway - ref. NK38-DRAW-10210-10001 and NK38-FEX-66600-0501) Comments (optional):	☐	☐
3. Is the hardware being installed not intrinsically safe and installed in close proximity to a flammable fluid/gas? Comments (optional):	☐	☐
4. Will the hardware be installed within 5 meters of a security barrier (fence, sally port, security building, etc), obstruct the field of view of security equipment, or collect data associated with security equipment? Comments (optional):	☐	☐
5. Will the hardware impact IAEA Safeguard systems SCI 35370 (i.e. obstruct the field of view of IAEA equipment or impact on the power supplies of IAEA equipment)? Comments (optional):	☐	☐
6. Will the hardware be installed in a radiological high hazard work environment (ref. N-PROC-RA-0027 R022 Section 1.1.2 for limitations)? Comments (optional):	☐	☐
7. Will the hardware be installed within 1 meter of fire detection equipment or fire detection control panels? Note that this does not include hose cabinets, fire extinguishers, etc. Comments (optional):	☐	☐

Thank you.

Questions?

OPG

Assessing the Impact of the Inflation Reduction Act on Power Uprate and Hydrogen Cogeneration

Project Summary

May 1, 2024

Background

- The Department of Energy (DOE) tasked the Light Water Reactor Sustainability (LWRS) Program with an effort to demonstrate the value of increased power output for the current fleet with consideration of the Inflation Reduction Act (IRA) tax credits
  - Section 45Y – Clean Electricity PTC
  - Section 48E – Clean Electricity ITC
  - Section 45V – Clean Hydrogen PTC

- The report was developed in 2023 by the Nuclear Energy Institute (NEI), MPR Associates Inc. (MPR), and Idaho National Laboratory (INL) with assistance from an industry uprate working group
  - https://www.osti.gov/biblio/2007297
  - In late 2023, follow-on effort initiated to refine user interface and develop brief user guide

Overall Project Scope

- **Project Objectives**
  - Develop business cases that demonstrate the value of implementing the tax incentives of the IRA
  - Provide insights and information to the domestic nuclear fleet which can be used to support assessing the financial impact of power uprate with the IRA

- **Project Tasks**
  - Task 1: Market Overview
  - Task 2: System, Structures, Components (SSCs) Capability Assessment
  - Task 3: Business Case Development

Task 1: Market Overview

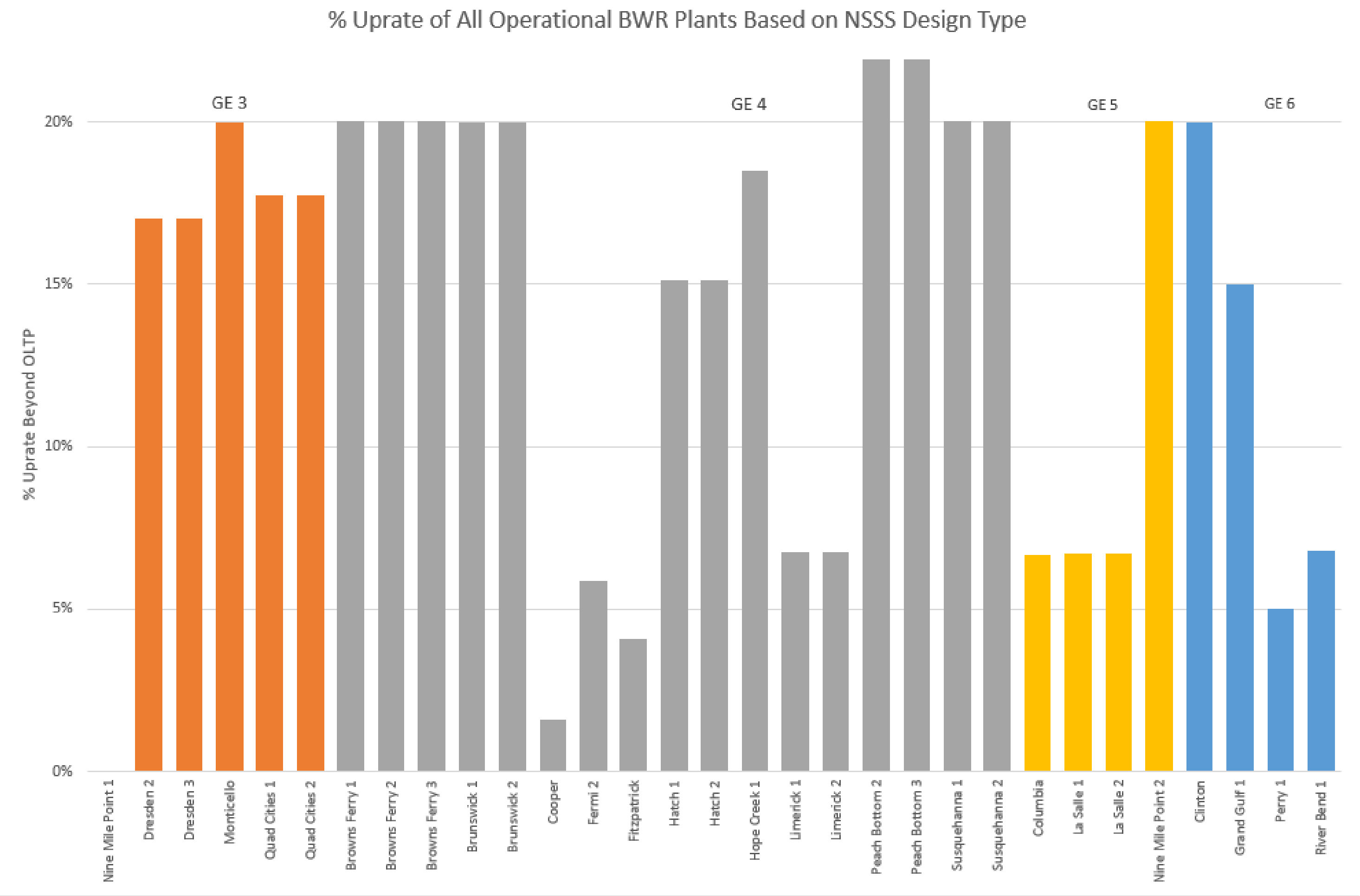
- **Objective:** Establish the potential for increasing output from existing fleet along with potential for hydrogen co-generation considering the IRA

- **Activities:**
  - **IRA Policy Overview –** Detailed description of the relevant IRA tax credits including applicability criteria, financial benefits, and other insights
  - **Power Uprate Market Overview –** Overview of power uprate process, current industry uprate status, assessment of potential opportunity for further power uprates
  - **Hydrogen Market Overview –** Overview of incentive to generate hydrogen from nuclear power plants, summary of current industry efforts, and assessment of potential opportunity of hydrogen co-generation going forward

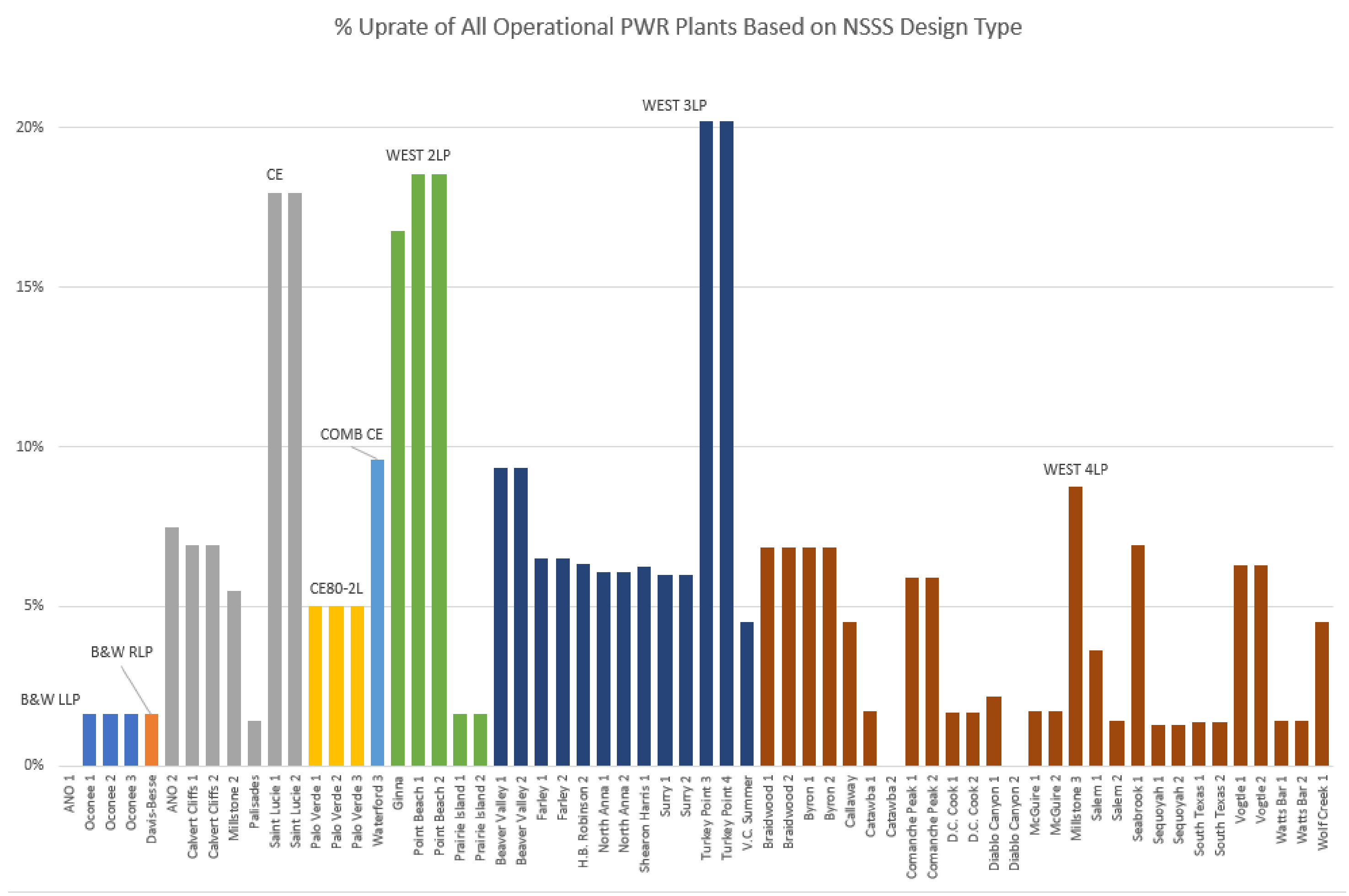
Task 1: Inflation Reduction Act Overview

- **Power Uprate**
  - Section 45Y – Clean Electricity PTC
    - Expected base of $30 MWh for 10 years indexed to inflation if wage requirements met
    - Opportunity to increase 10% for energy communities and 10% for domestic content requirements
    - Capacity added between 2025 and later of 2032/CO2 emissions 75% below 2022 levels
  - Section 48E – Clean Electricity ITC
    - Expected base of 30% of construction expenses if wage requirements met
    - Same adders and dates as PTC
- **Hydrogen Cogeneration**
  - Section 45V – Clean Hydrogen PTC
    - $3/kg base for 10 years of operation if wage requirements met
    - Size of credit based on emission intensity
- Other considerations such as direct payments, transfers for all credits
- Model utilizes latest available information at time of publication – NEI has requested guidance from Treasury to confirm assumptions

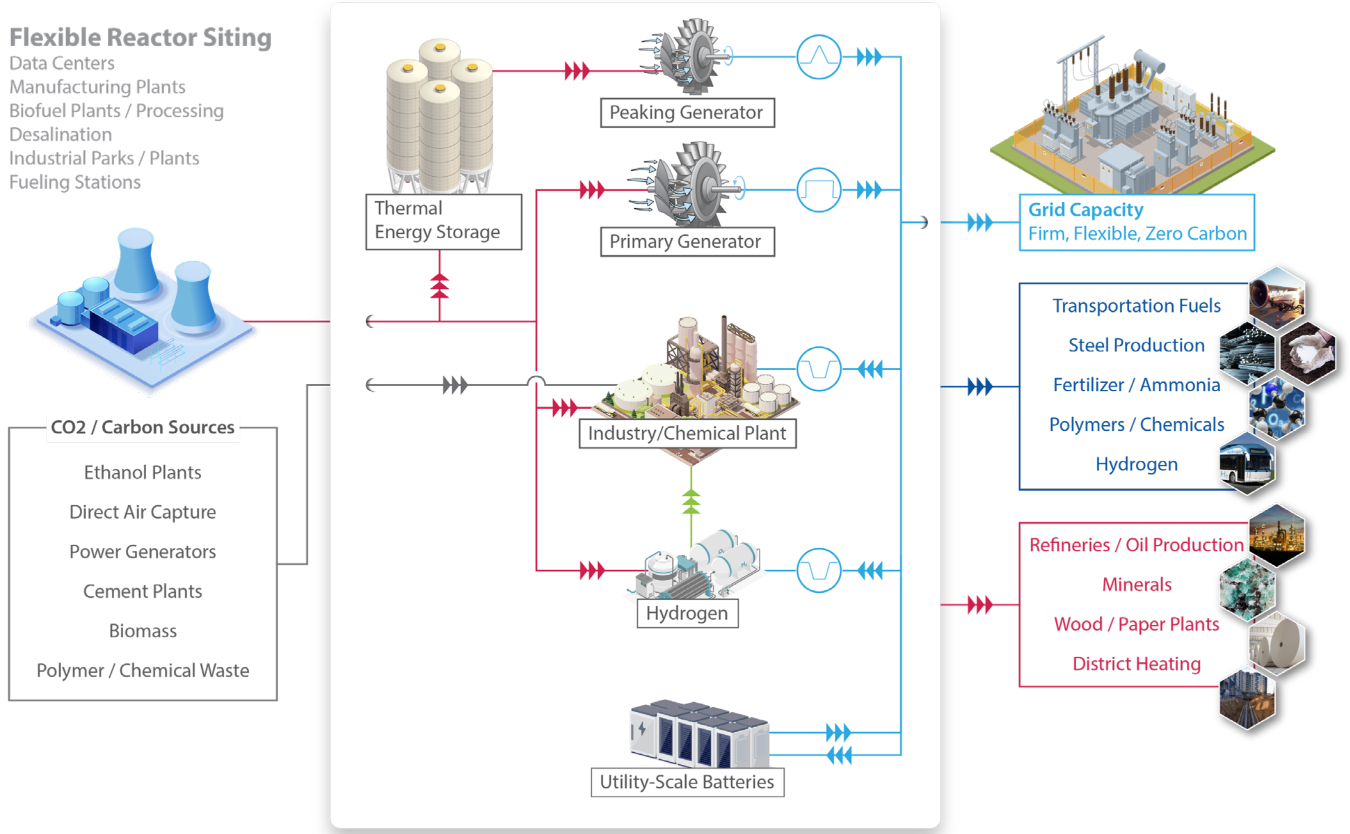
Task 1: Uprate Market Overview



Task 1: Uprate Market Overview



Task 1: Hydrogen Market Overview



- Current US hydrogen consumption is ~10 million metric tonnes per yr
- Hydrogen demand is projected to increase by 10+ million metric tonnes per year by 2030

Task 2: Conduct SSCs Capability Assessment

- **Objective:** High-level overview of historical impact of power uprate on existing plant SSCs to demonstrate viability of further power uprates

- **Activities:**
    - List historical SSCs impacted by power uprate and common modifications
    - Utilize and reference available information from previous industry efforts (e.g., NEI, IAEA, EPRI)
    - Develop summary table of most recent Extended Power Uprates (EPUs) and subsequent modifications

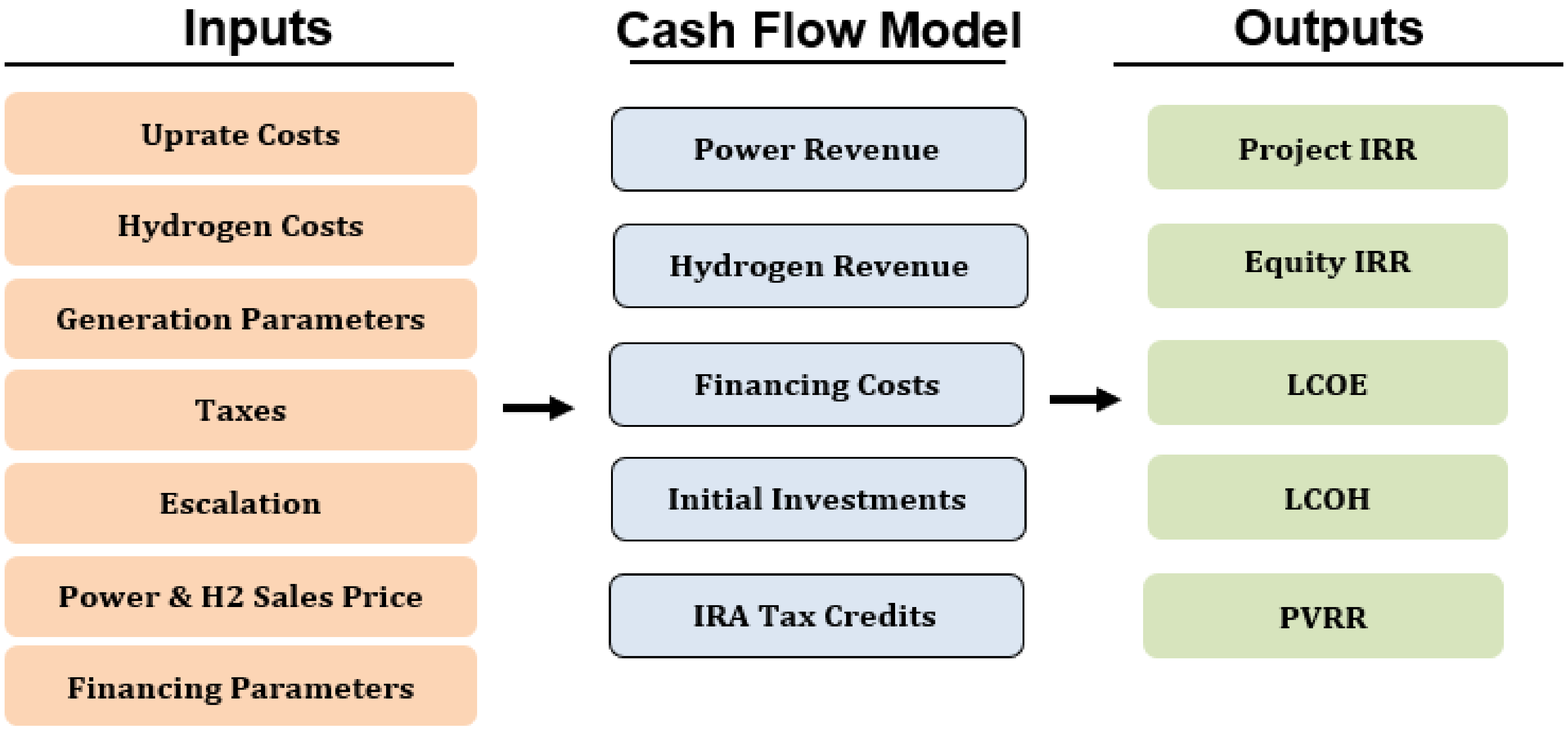
Task 2: Conduct SSCs Capability Assessment

Table 4-2. Survey of Recent EPU Experience for BWRs

Parameter or Modification	Plant			
	Browns Ferry	Peach Bottom	Monticello	Grand Gulf
Thermal Power Increase	494 MWt	437 MWt	229 MWt	510 MWt
NRC Approval Date	August 2017	August 2014	December 2013	July 2012
Steam Dryer Modifications	Replaced	Replaced	Replaced	Replaced
Pump and Prime Mover Modifications	All condensate and condensate booster pump impellers changed and larger motors installed Reactor feedwater pumps replaced with higher capacity pumps Reactor feedwater pump turbine enhancements Re-rate of reactor recirculation pumps and motors	All condensate pump impellers changed and larger motors installed (six total) Reactor feedwater pump turbines retrofitted	Condensate pump impellers enlarged and larger motors installed (replaced 4KV motors with new 13.8KV motors) Reactor feedwater pumps replaced with larger pumps and motors (replaced 4KV motors with new 13.8 KV motors)	Reactor feedwater pump turbines retrofitted

Task 3: Business Case Development

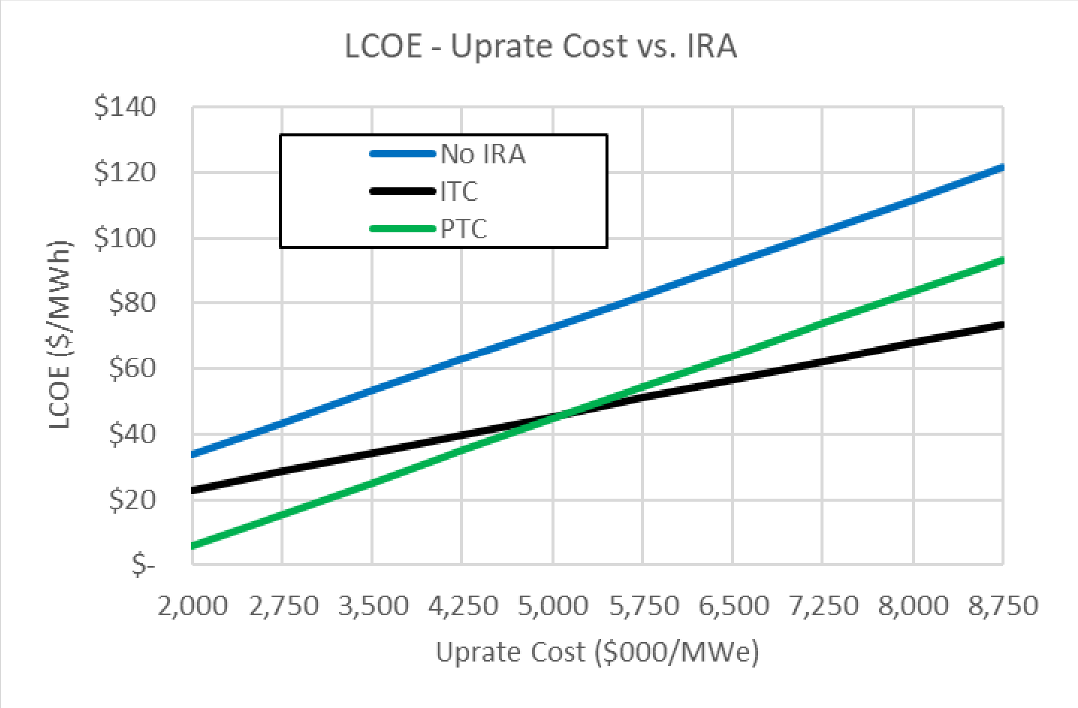
Objective: Develop high-level financial model to assess impact of IRA on power uprates with and without hydrogen cogeneration

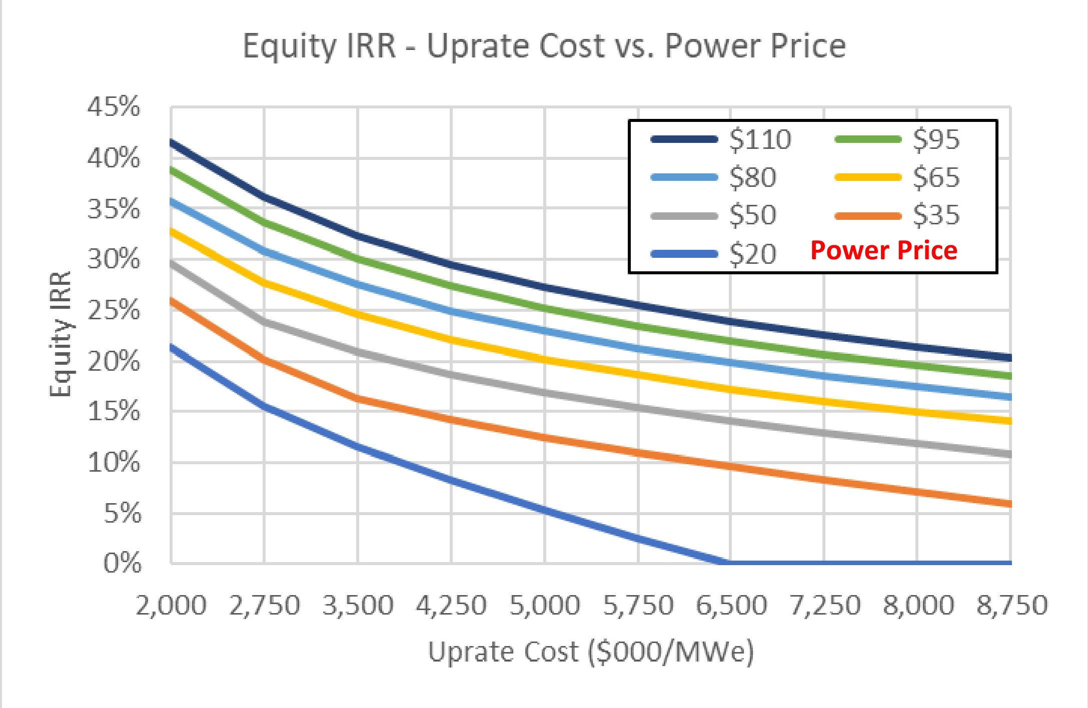


Task 3: Results Summary Example

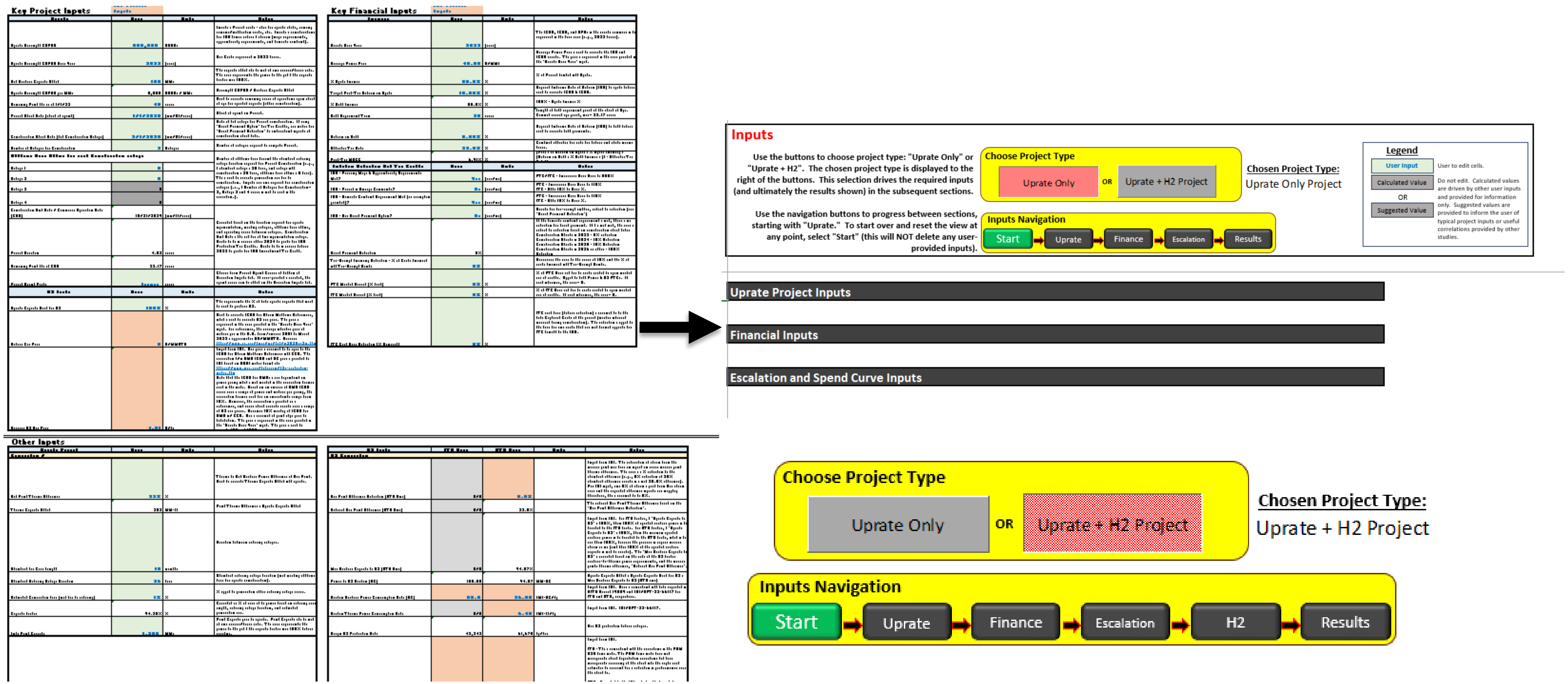
	Total Capital Costs		Project IRR	LCOE ($/MWh)	LCOH ($/kg)
Uprate Only	$631,568	No IRA	5.1%	$72.69	No H2 Gen
		ITC	8.3%	$45.40	No H2 Gen
		Power PTCs	8.2%	$44.66	No H2 Gen
Uprate + LTE	$775,466	No IRA	1.1%	NA	$5.31
		ITC + H2	9.8%	NA	$1.34
		Power PTCs + H2	9.5%	NA	$1.30
Uprate + HTE	$847,483	No IRA	2.0%	NA	$4.46
		ITC + H2	11.8%	NA	$0.88
		Power PTCs + H2	11.2%	NA	$0.85

Task 3: Output Sensitivity Examples





Task "4": Refined User Interface and User Guide

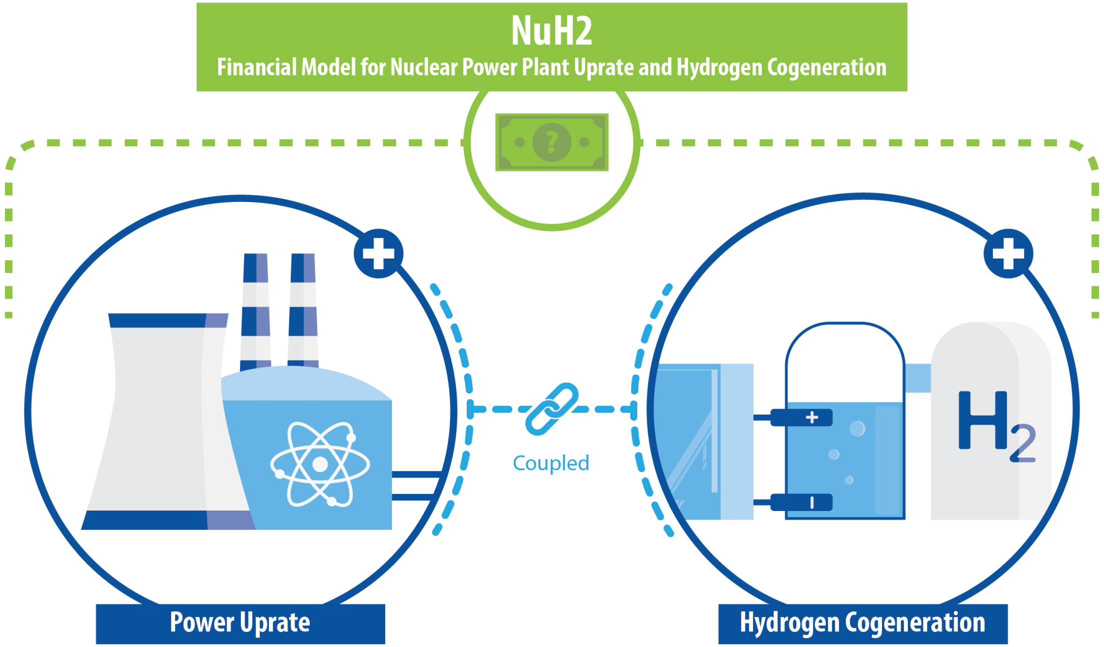


Process to Acquire the Uprate Model

- Email a request for the "NuH2" model to the INL Tech Development group -> agradmin@inl.gov
- Follow tech developments guidance to officially request a license agreement
- Sign the license agreement and return it to INL

Note: The model is free. No fees or costs will be incurred with the license agreement or model acquisition.

- **Upon License Execution, User Will Receive:**
  - Excel based uprate model for economic analysis of nuclear reactor capacity uprate and hydrogen production integrated with a nuclear reactor
  - A "How to" manual for the model operation



QUESTIONS?

INL/MIS-24-77706

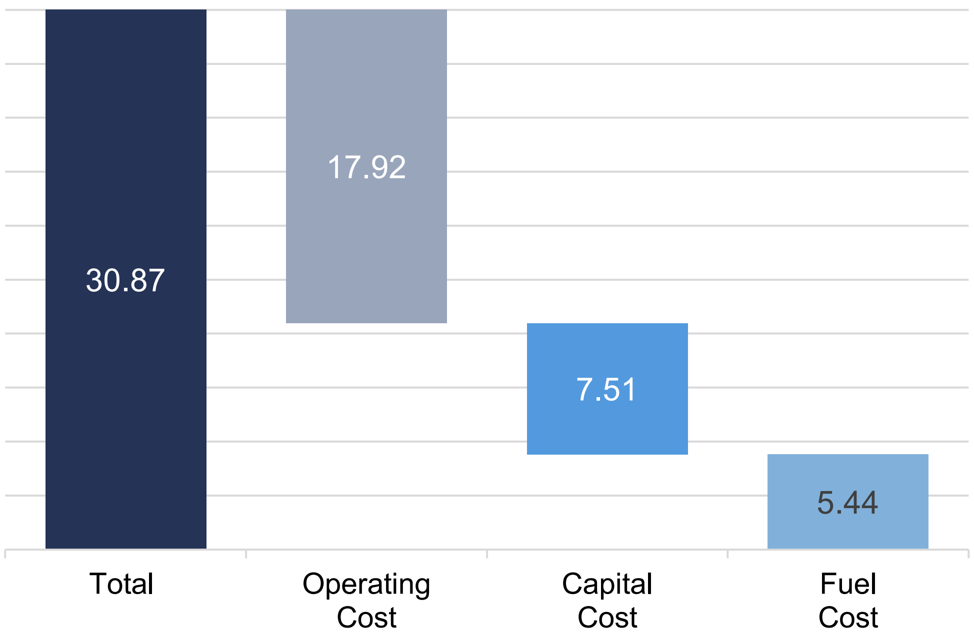
Boyan Ivanov, Adam Donell, Seth Spooner
Constellation
Junyung Kim, Mohammad G. Abdo, Svetlana Lawrence
Idaho National Laboratory
Juan C. Luque-Gutierrez, Nicholas Rollins, Jason Hou
North Carolina State University

May 2024

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

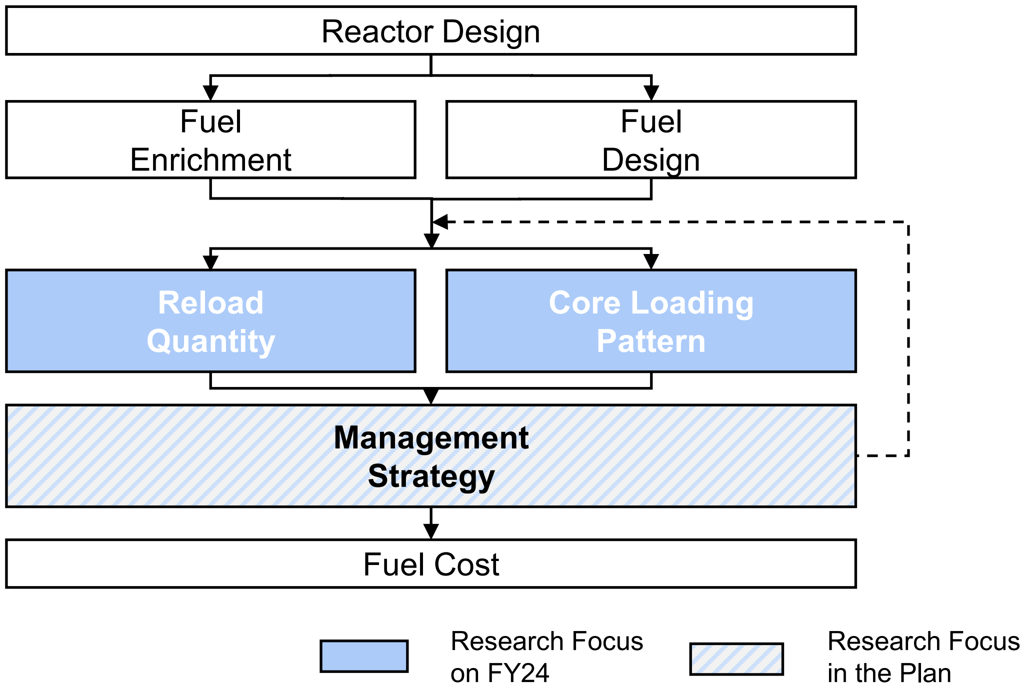
Background:
Why it is important?

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**

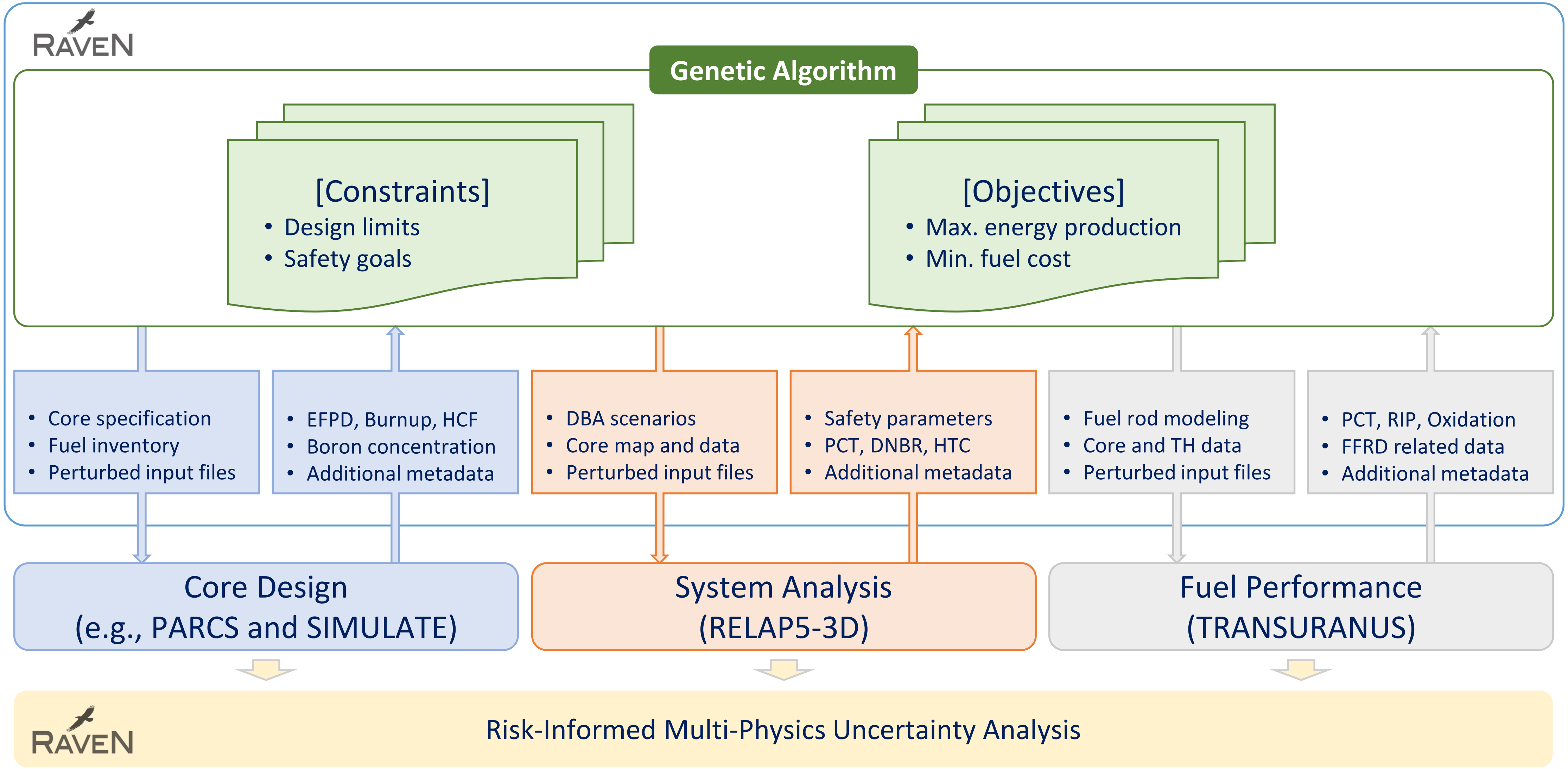


- **Traditional methods deciding core loading pattern and reload quantity are labor-intensive and time-consuming.**
  - More than 10E+30 combinations for 17x17 PWR core

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

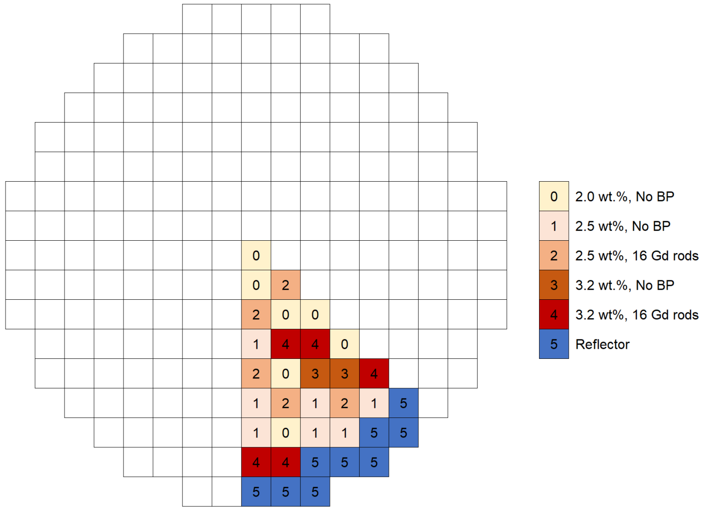


EFPD: Effective full power day
HCF: Hot channel factor
DBA: Design basis accident
PCT: Peak cladding temperature
DNBR: Departure of nucleate boiling rate
HTC: Heat transfer coefficient
TH: Thermal-hydraulics
RIP: Rod internal pressure
FFRD: Fuel failure, relocation and dispersal

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 = 7.1×10^{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)

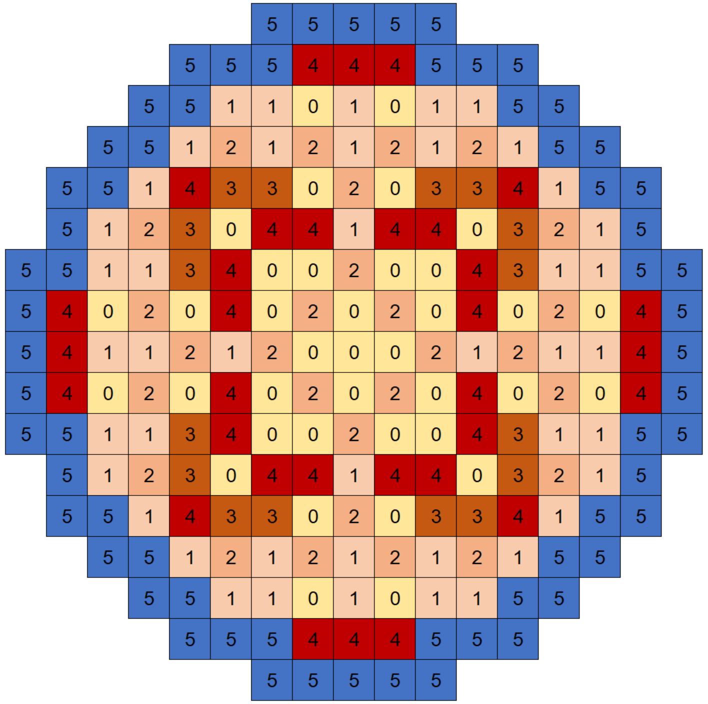
- Constraints
  - F_Q (Heat flux hot channel factor) < 2.1
  - $F_{\Delta H}$ (Nuclear enthalpy rise hot channel factor) < 1.48
  - Peak critical boron concentration (CBC) <1300 pcm

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

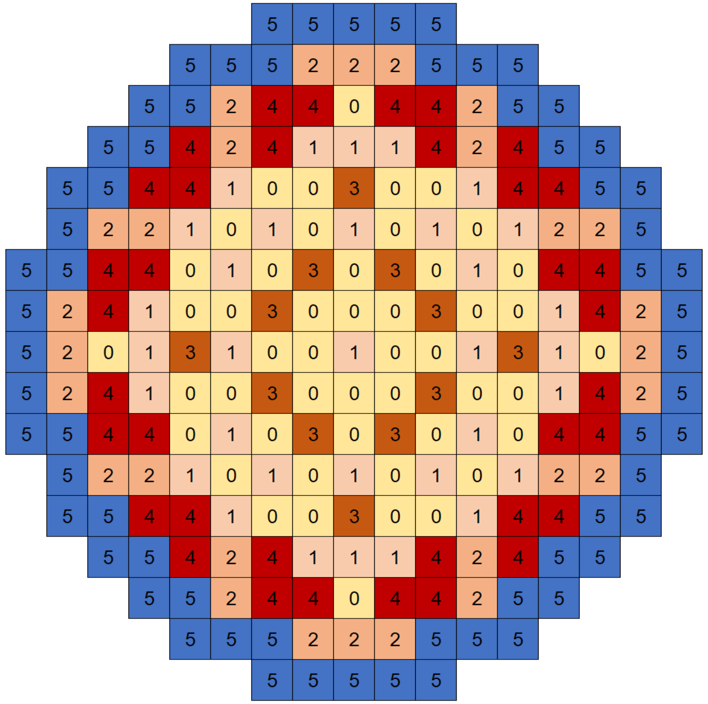
Initial Fuel Loading Pattern



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



Pin_Peaking Factor	2.075	o
Boron Concentration	1297.6	o
FΔH	1.454	o

Effective Full Power Day (EFPD)	392.7

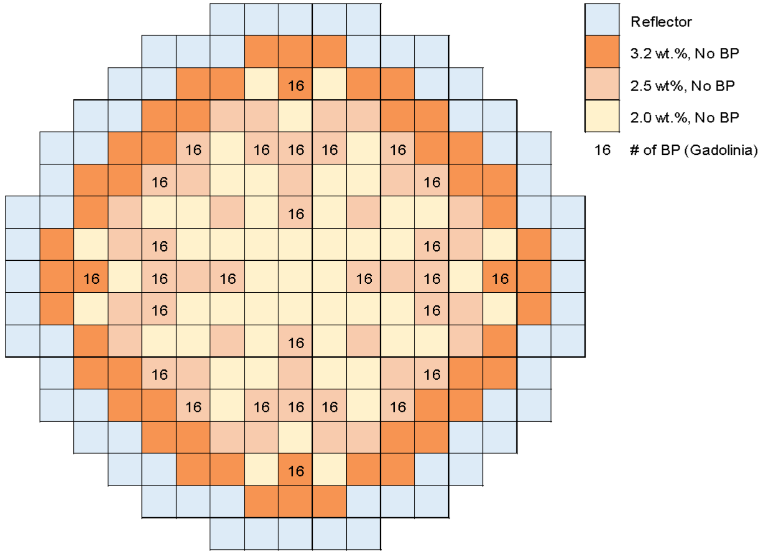
0	2.0 wt.%, No BP
1	2.5 wt%, No BP
2	2.5 wt%, 16 Gd rods
3	3.2 wt.%, No BP
4	3.2 wt%, 16 Gd rods
5	Reflector

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 = 7.1×10^{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

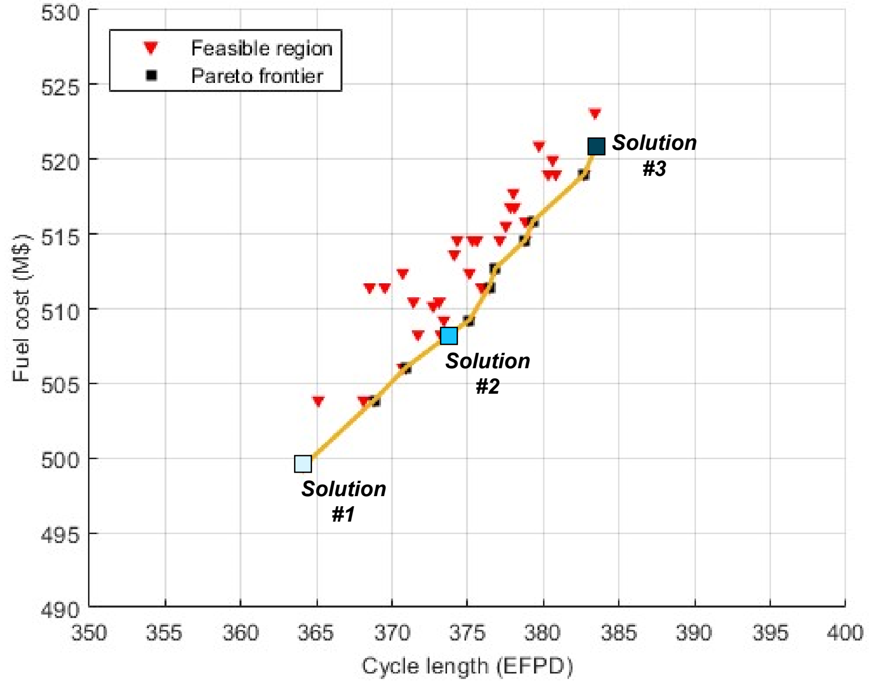
- Objectives
  - Maximize cycle length (cycle energy production)
  - Minimize fuel cost

- 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.

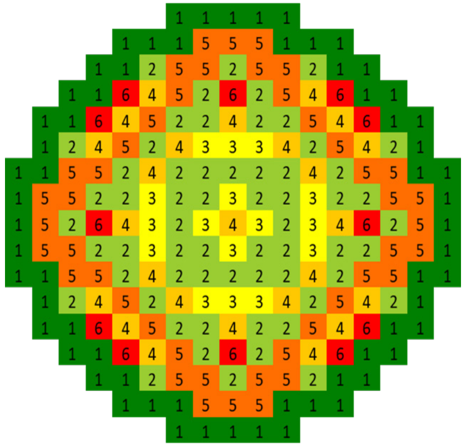
A generic PWR reactor core is used for the demonstration

Demonstration with Multi Objective Optimal Core Patterns



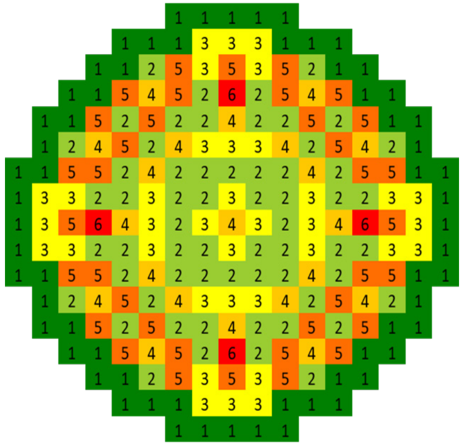
A generic PWR reactor core is used for the demonstration

Solution #3



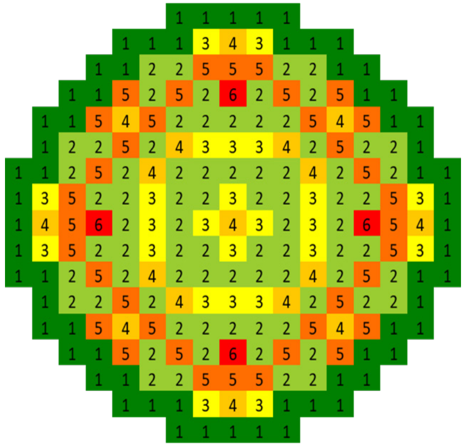
Cycle length (EFPD)	383.50
Fuel cost (M$)	520.92
F_Q	2.098
CBC (ppm)	1296.8
$F_{\Delta H}$	1.476

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

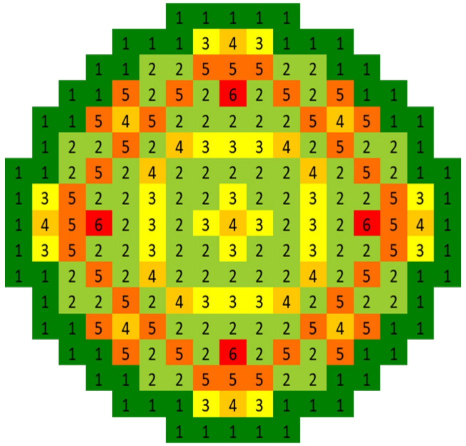


Cycle length (EFPD)	364.10
Fuel cost (M$)	499.45
F_Q	2.092
CBC (ppm)	1295.6
$F_{\Delta H}$	1.479

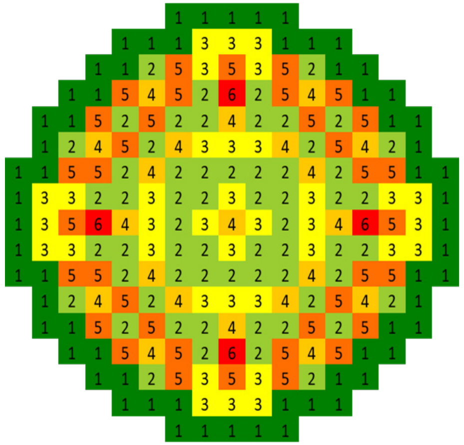
Demonstration with Multi Objective
Common Features of Optimal Core Designs

- **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

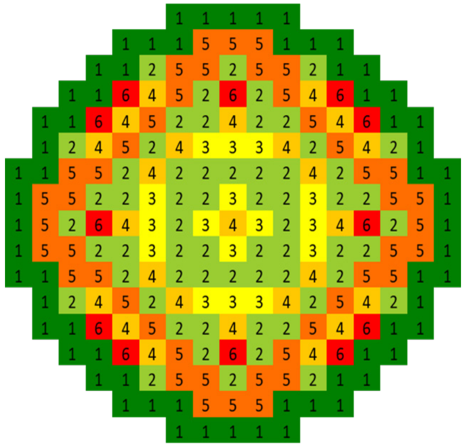
Solution #1



Solution #2



Solution #3

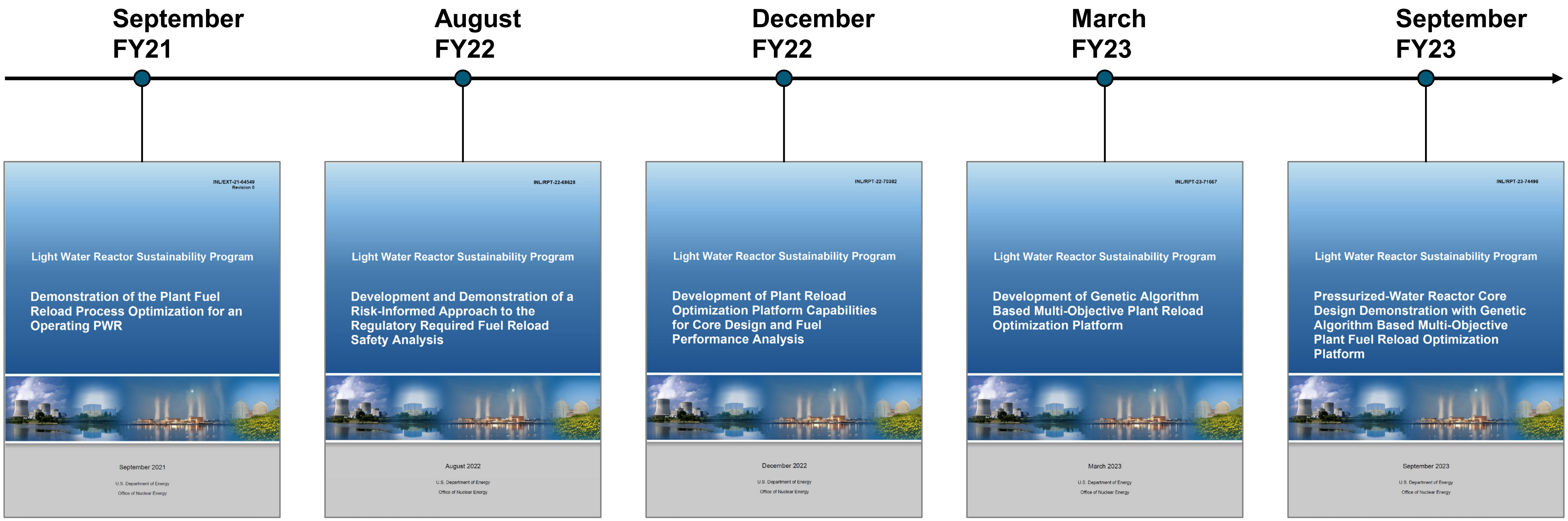


A generic PWR reactor core is used for the demonstration

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)



- **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

Idaho National Laboratory

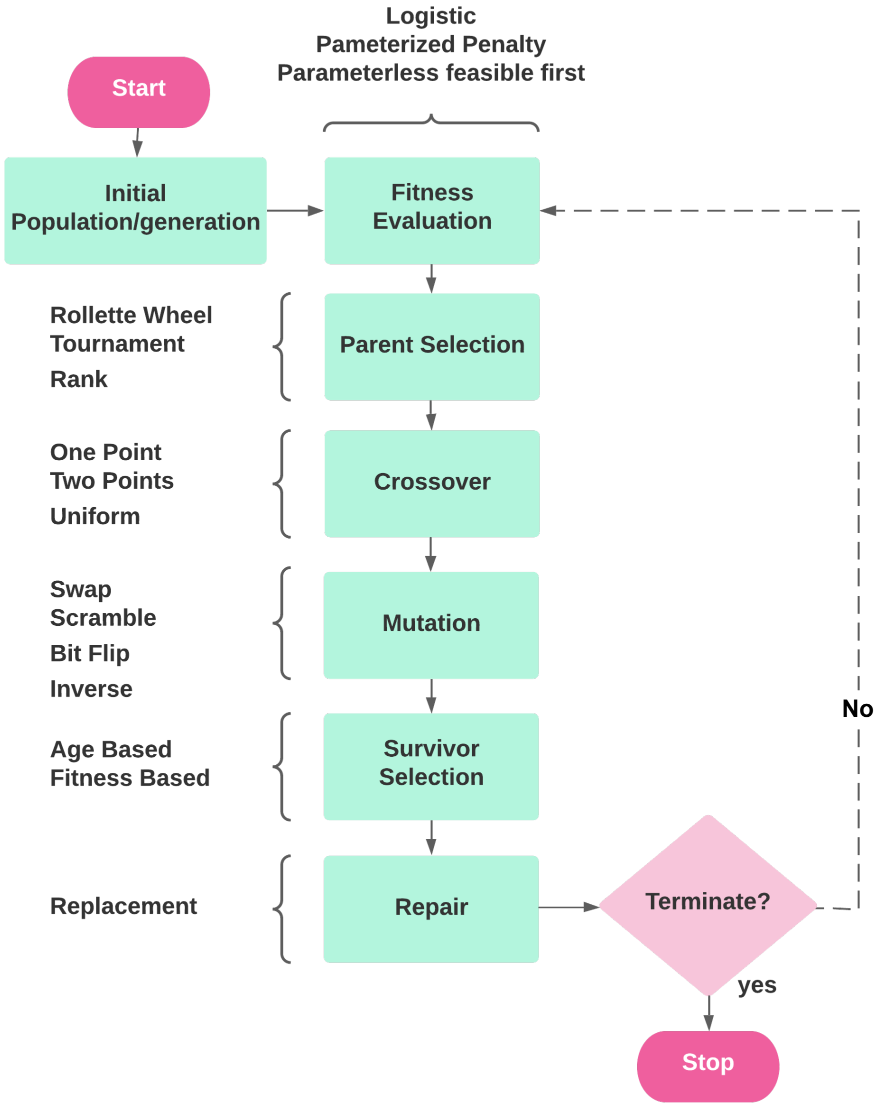
NC STATE
UNIVERSITY

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

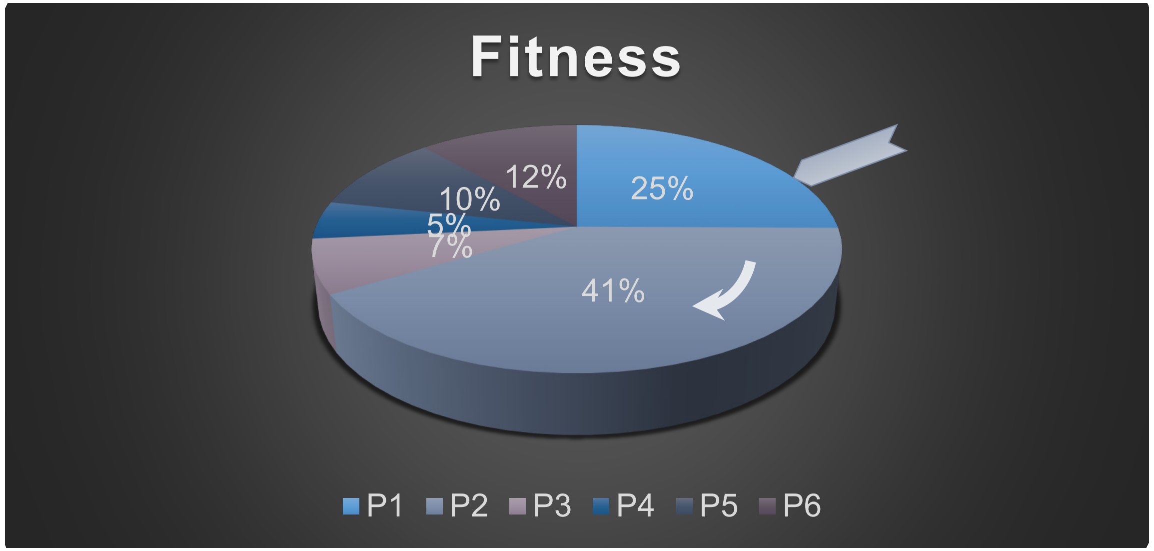
- GA explores group of solutions at each iteration
  - Starts with initial list of solutions (neutronics, thermal-hydraulics, etc.)
  - Evaluates and determines potential solutions
  - Randomly proposes new solutions, then selects best solution (cross-over, mutation, and survivor selection operations).



Evolutionary Operators of GAs

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

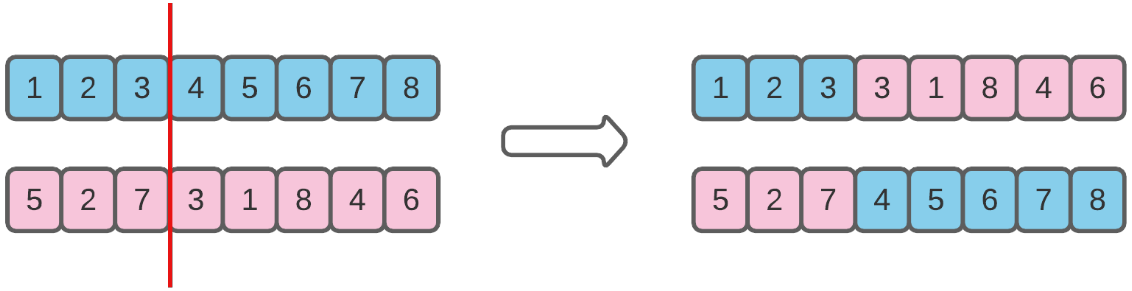
```xml
<GAparams>
  <populationSize>10</populationSize>
  <parentSelection>rouletteWheel</parentSelection>
```



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




```xml
<reproduction>
    <crossover type="onePointCrossover">
        <crossoverProb>0.8</crossoverProb>
    </crossover>        You, 19 months ago
    <mutation type="scrambleMutator">
        <mutationProb>0.9</mutationProb>
    </mutation>
</reproduction>
```

Evolutionary Operators of GAs

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


```xml
<reproduction>
  <crossover type="onePointCrossover">
    <crossoverProb>0.8</crossoverProb>
  </crossover>
  <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) $(f_1(\boldsymbol{x}), f_2(\boldsymbol{x}), \ldots, f_M(\boldsymbol{x}))^T$

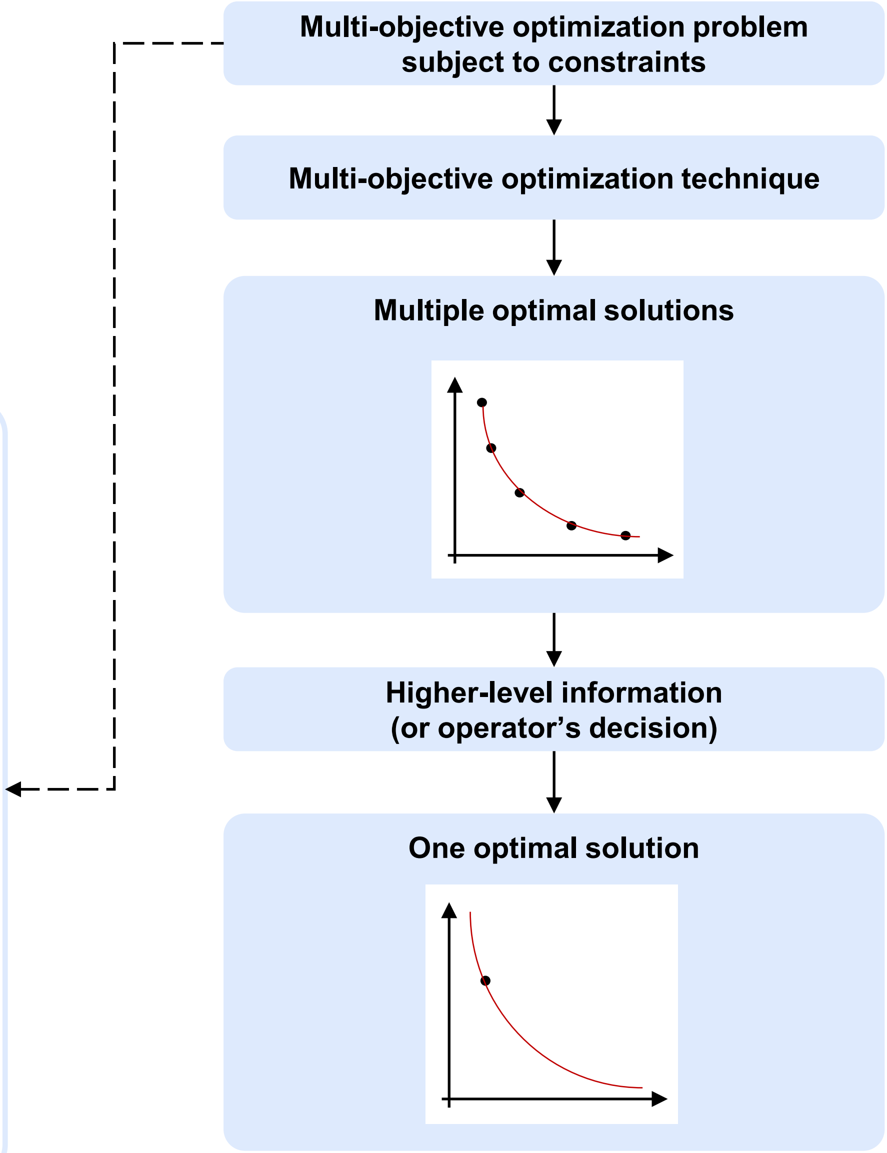
Subject to

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

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

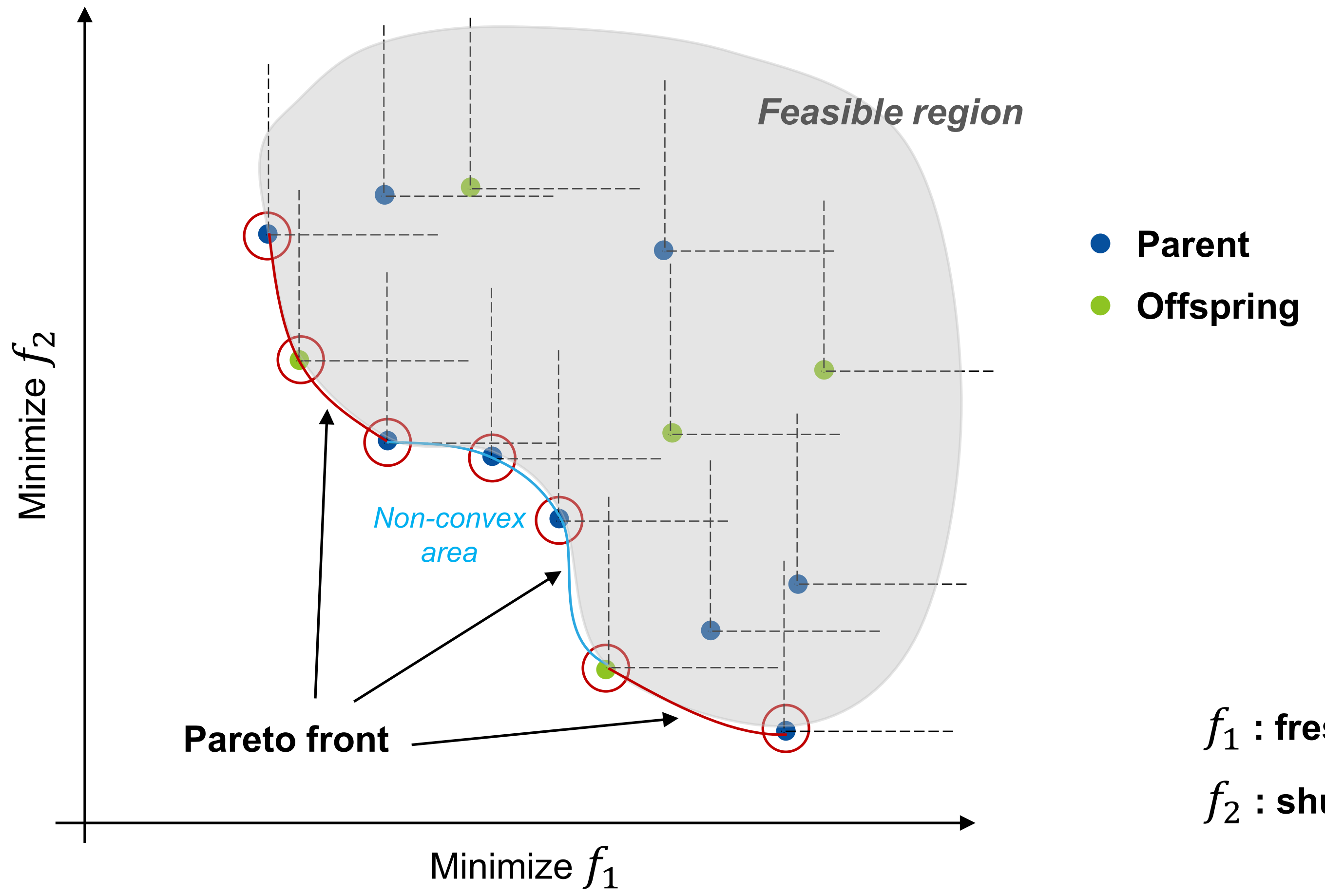
$$x_i^{(L)} \leq x_i \leq x_i^{(U)}$$

- $f_m(\boldsymbol{x})$ 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
- $\boldsymbol{x} = (x_1, x_2, \ldots, x_n)^T$ is a n-dimensional vector
- $x_i^{(L)}$ and $x_i^{(U)}$ are the lower and upper bounds on *i*-th variable



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.**

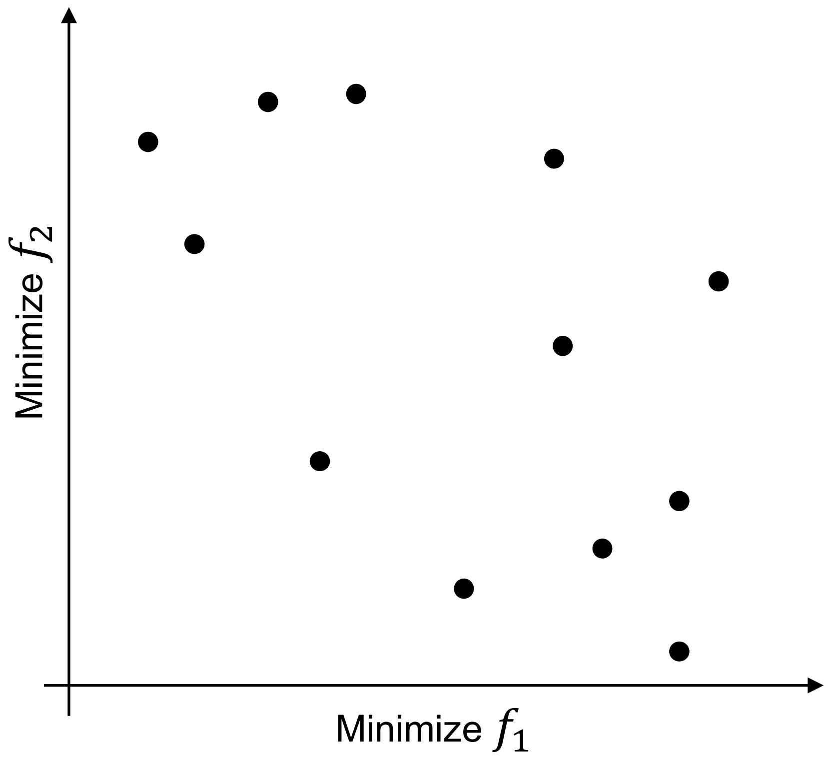


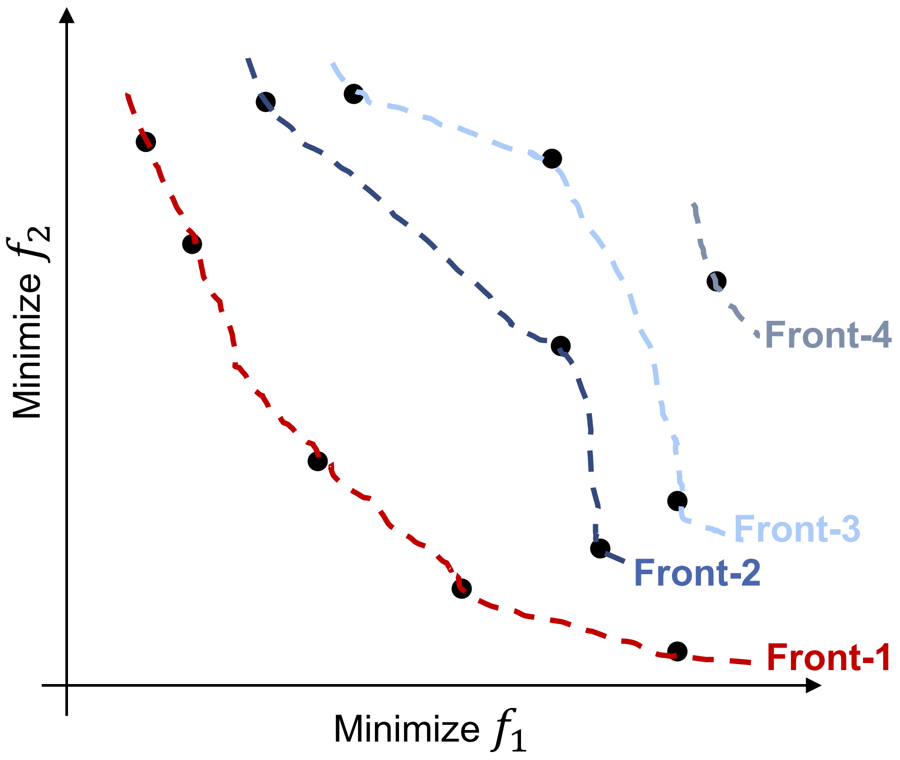
f_1 : **fresh fuel**

f_2 : **shutdown margin**

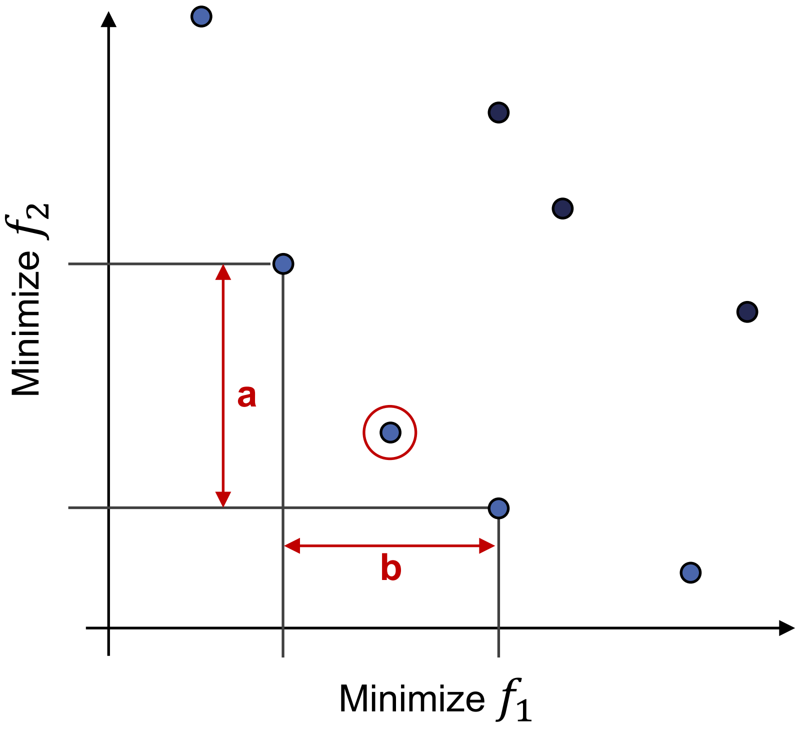
NSGA-II for Multi-Objective Problem
Dominance Depth Method

- **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.**



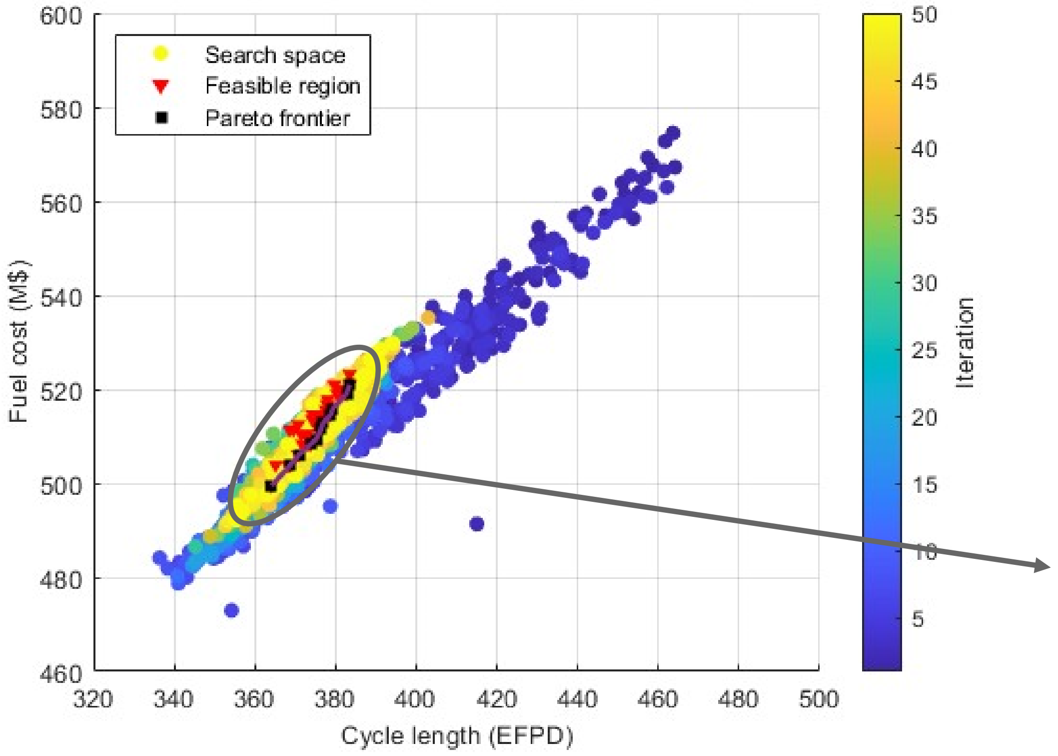


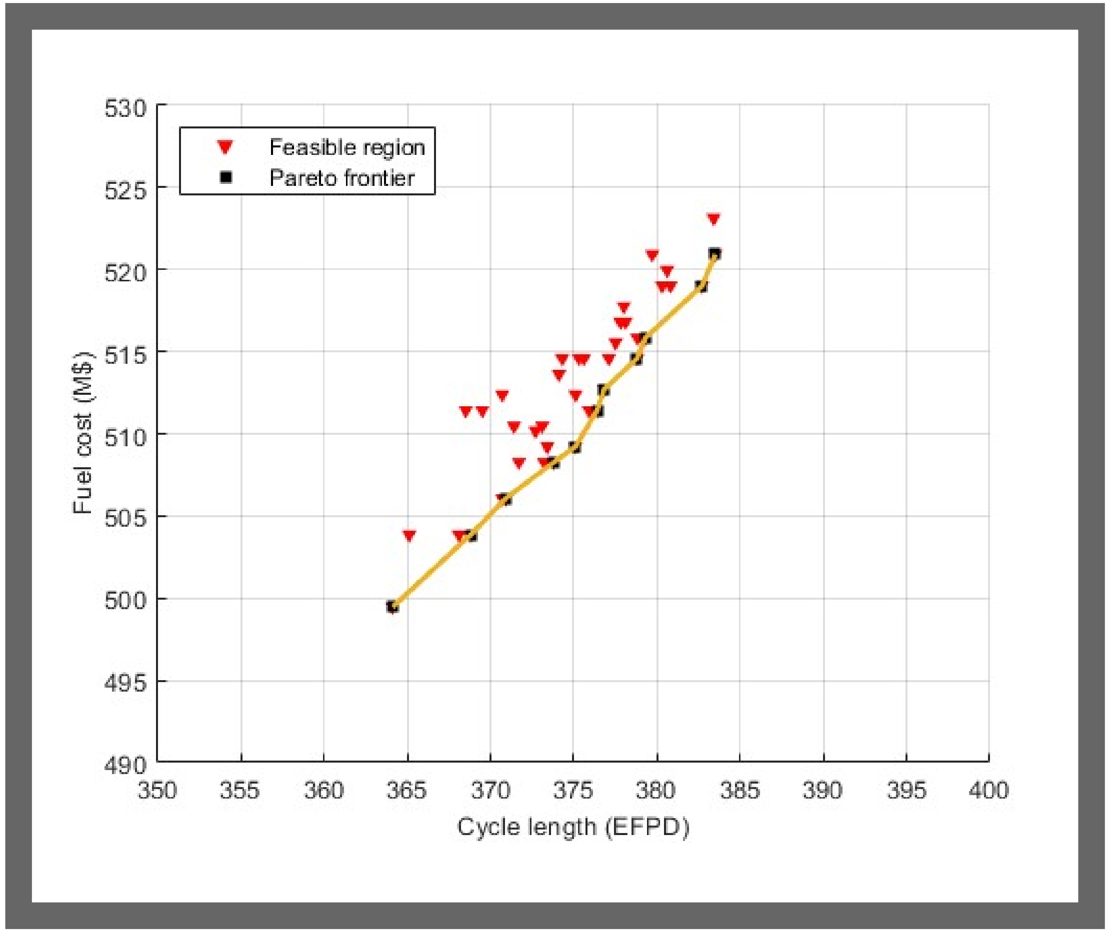
NSGA-II for Multi-Objective Problem
Niching for the first rank



- **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