INL/CON-26-92620

May 18-21, 2026

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RELAP5-3D with RAVEN/PRLO: Automated Multiphysics Analysis for PWR Capacity Expansion

International RELAP5 User Group Meeting 2026

Idaho Falls, ID, USA

Outline

- Light Water Reactors Sustainability (LWRS) - Power uprate project
- Plant ReLoad Optimization (PRLO) in RAVEN
- Data-driven reactor design with multiphysics coupling: PARCS-RELAP coupling scheme
- Reference plant: Vogtle 1
- Preliminary results for PARCS-RELAP coupling in RAVEN
- Conclusions and future works

LWRS Power Uprate Project Overview 1/2

- US LWR fleet looking for significant power uprates for improving plant economics and sustain the massive electricity increase requested by the artificial intelligence (AI) revolution
- Recent studies identify **at least** ~6 GW of potential power uprates for the PWR fleet
- More energy can be generated by performing plant power uprate **and** extending the fuel cycle length (transition from 18 to 24 months cycle)


NATIONAL

Three Mile Island nuclear plant will reopen to power Microsoft data centers

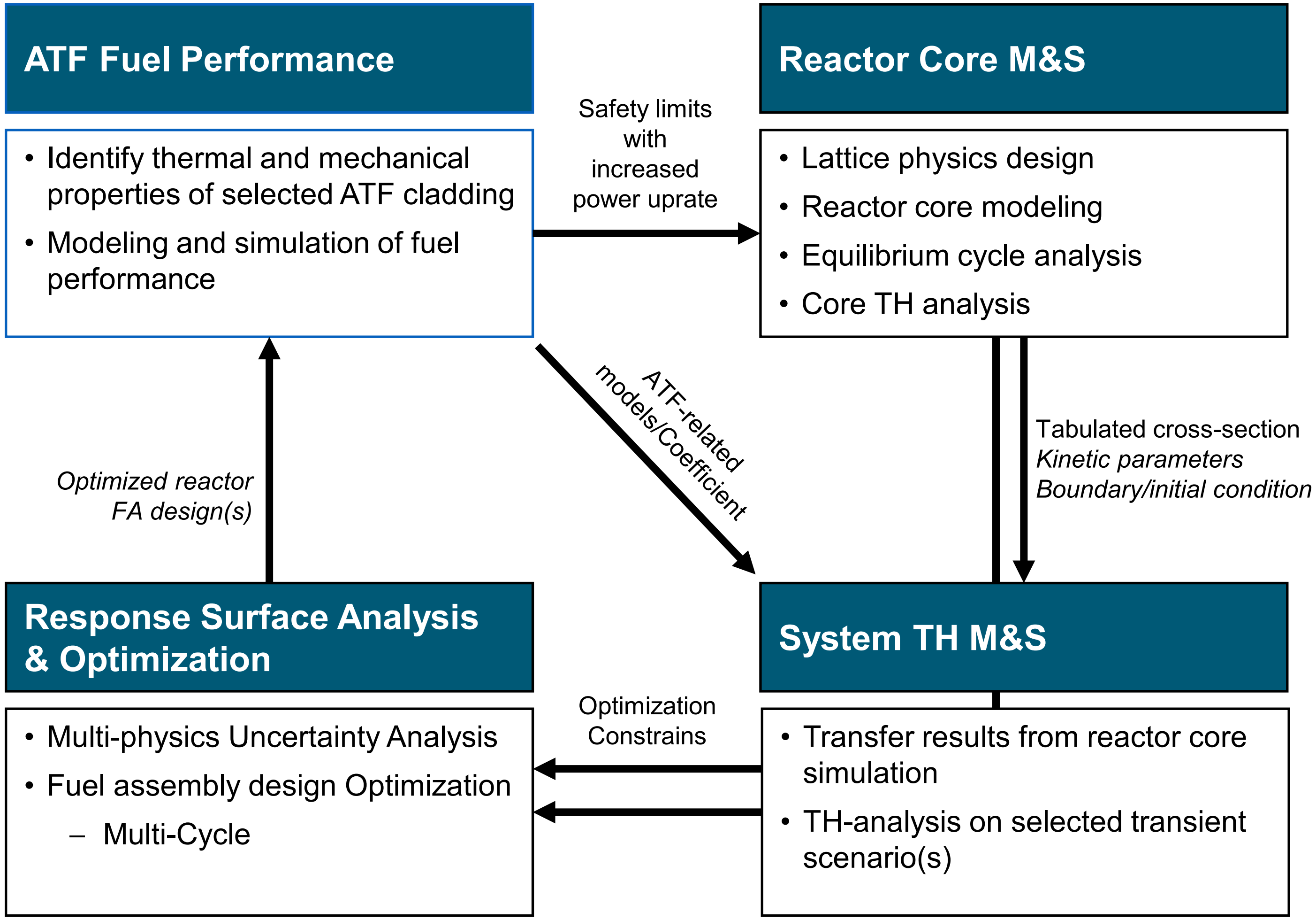
SEPTEMBER 20, 2024 · 1:40 PM ET

By C Mandler

LWRS Power Uprate Project Overview 2/2

Project Description

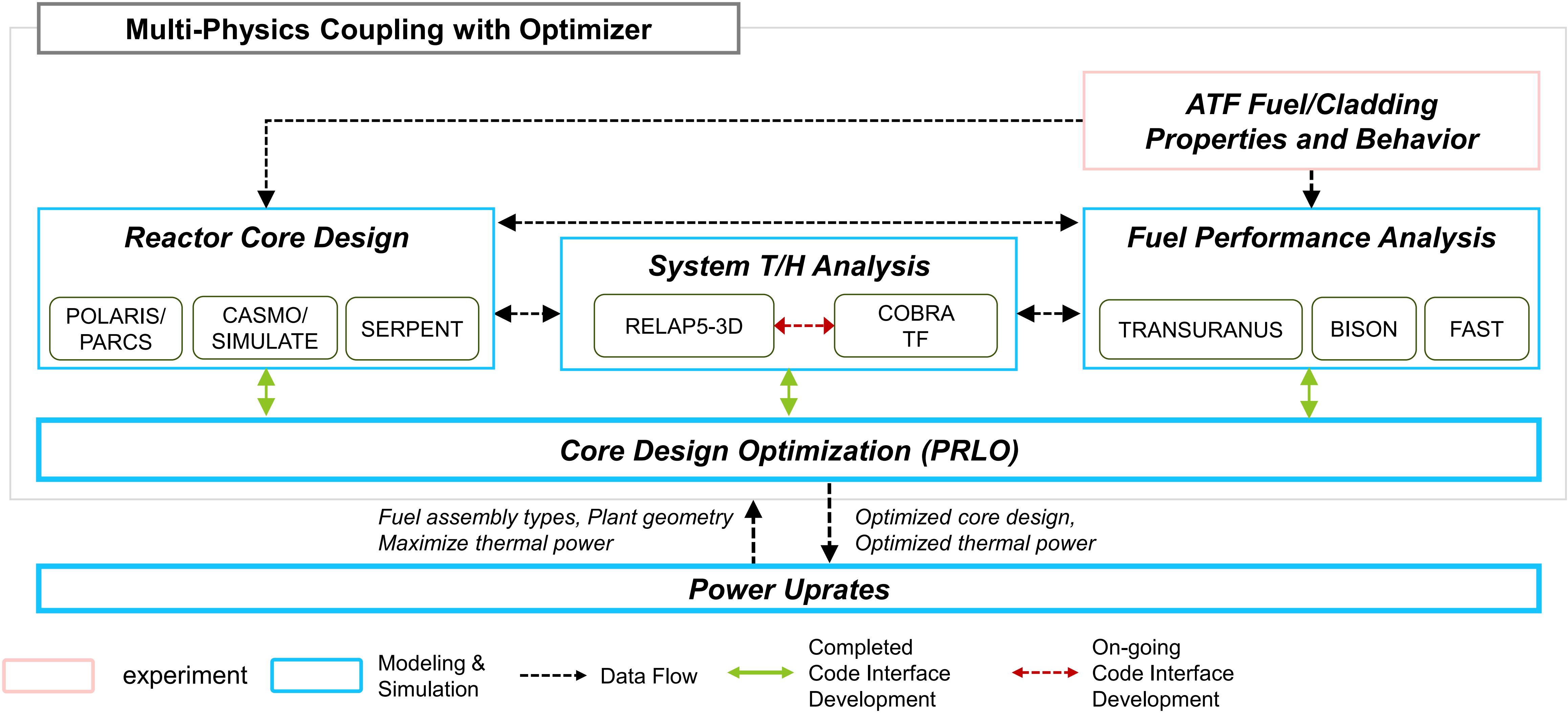
- Identify engineering design criteria of **ATF for power uprate**
- **ATF + Extended Enrichment + (possibly) HBU**
  - ATC can…
    - reduce oxidation kinetic
    - reduce hydrogen production & hydrogen pick up
    - improve post-quench ductility
    - improve corrosion resistance
  - Doped pellets has…
    - higher density
    - higher burnup support
    - higher plasticity at high temperature
    - better fission gas retention
    - improved PCI resistance
- Utilize **existing data/models/methods** first for ATF safety evaluation
  - Additional experiments in need can be performed



LWRS Power Uprate Project – Analysis Tools 1/4

- INL computational strategy for studying **power uprate options** centered around the use of **well-established** and **validated** codes
- Computational platform must be reliable and allow performing numerous computational analysis in reasonable time
- Analysis capabilities:
  - Performances of accident tolerant fuel
  - Time at temperature (T@T) phenomenon
  - High burnup effects
  - Perform selected transient analysis (e.g. loss of flow, rod ejection accident)
- Spatial resolution: fuel assembly & subchannel level

LWRS Power Uprate Project – Analysis Tools 2/4



LWRS Power Uprate Project – Analysis Tools 3/4

- **RELAP5-3D** is the world premiere system thermal hydraulic code for nuclear system analysis, including LWR and advanced reactors
  - Developed at INL
- **RELAP5-3D** leverages decades of validation and use in two phase thermal-hydraulic
  - 3D system TH code resolution, 2 phase, 2-fields
  - 0D and **3D neutronics** based on the **NESTLE code**
  - Fuel mechanics surrogate model based on **FRAP-T code**
    - Model metal/water reaction, clad deformation/rupture including subchannel flow are restriction
    - Validated for Zry clad / includes **ATF modeling features**
  - 2D heat transfer in heat structures
  - Coupling with subchannel codes (COBRA-TF) and MOOSE framework
  - Model AOO, DBA (LOCAs), ATWS

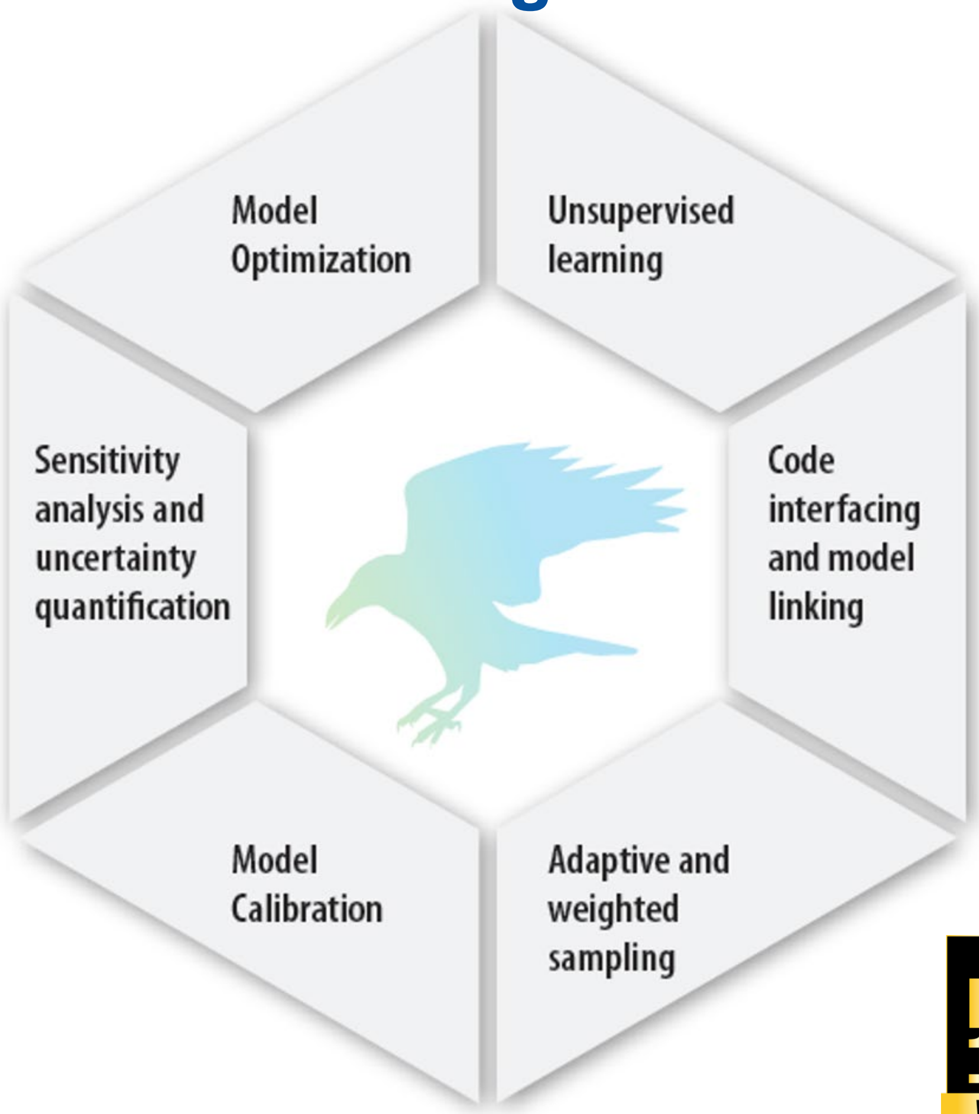
LWRS Power Uprate Project – Analysis Tools 4/4

Purdue Advanced Reactor Core Simulator (PARCS)

- **PARCS** v3.4.5
  - 3D reactor core simulator for solving multi-group neutron diffusion and low-order transport equations.
  - Used to provide **data for equilibrium cycle conditions and core depletion calculations** to RELAP5-3D under uprated conditions.
- **POLARIS**
  - 2D lattice physics code using method of characteristics (MOC) and the embedded self-shielding method (ESSM) for SCALE.
  - Used to compute few-group cross sections for use in **PARCS**.
- **GenPMAXS** v6.3
  - Used to process tabulated neutron cross sections between **POLARIS** ('.t16') and **PARCS** ('.PMAXS') file formats.

RAVEN/PRLO: Optimization of Reactor Core Design 1/2

- RAVEN: multi-purpose stochastic platform
- **Methods/capabilities**
  - Uncertainty propagation
  - Machine learning
  - Optimization
  - Data analysis
- **Language**: designed for applying these methods and capabilities to user-provided simulation models
- Development began in early 2012, supported by:
  - Light Water Reactor Sustainability (LWRS) program
  - Nuclear Energy Advanced Modeling and Simulation Program (NEAMS)
  - Nuclear-Renewable Hybrid Energy Systems (NHES)

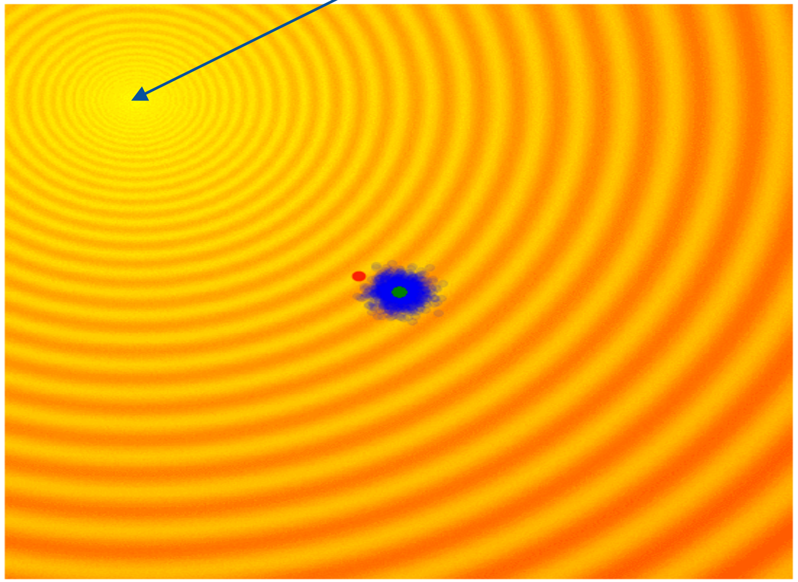


2023 R&D 100 WINNER

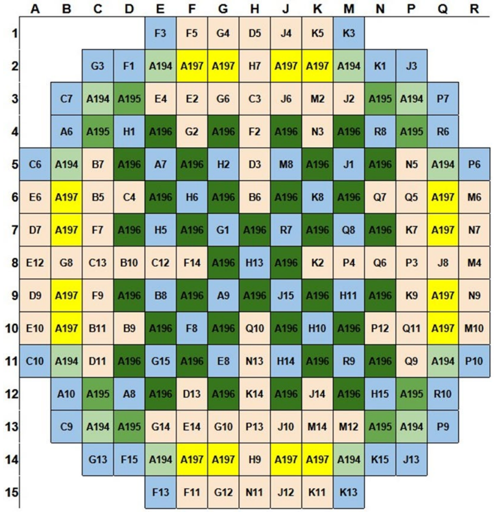
RAVEN/PRLO: Optimization of Reactor Core Design 2/2

- Balance between economics and safety
  - Optimize fuel batch for economic benefits
  - Multiple “safety” parameters to be considered
  - Flexible for computational tools
- Looking for wide applications
  - LEU+, ATF, HBU, power-uprate, flexible operation
  - Non-LWRs or advanced nuclear systems

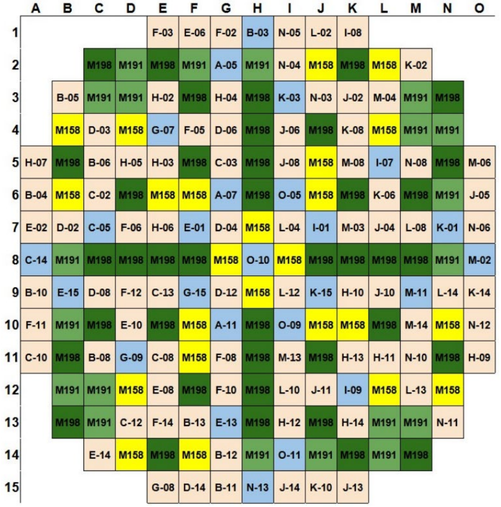
Optimal Solution



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



Key	Description
A194	4.2 w.t.% + 64 IFBA
A195	4.2 w.t.% + 104 IFBA
A196	4.2 w.t.% + 128 IFBA
A197	4.6 w.t.% + 128 IFBA
OB	Once burned
TB	Twice burned



Key	Description
M158	7.50 w.t.% + M8
M191	7.95 w.t.% + M1
M198	7.95 w.t.% + M8
OB	Once burned
TB	Twice burned

RAVEN/PRLO: Multi-objective Optimization 1/2

- NSGA-II performs multi-objective optimization by sorting solutions using dominance and crowding distance for diversity.
- Why NSGA-II?
  - Lower computational complexity than NSGA-I
  - Population diversity is guaranteed.
  - One of the multi-objective evolutionary computation benchmarks

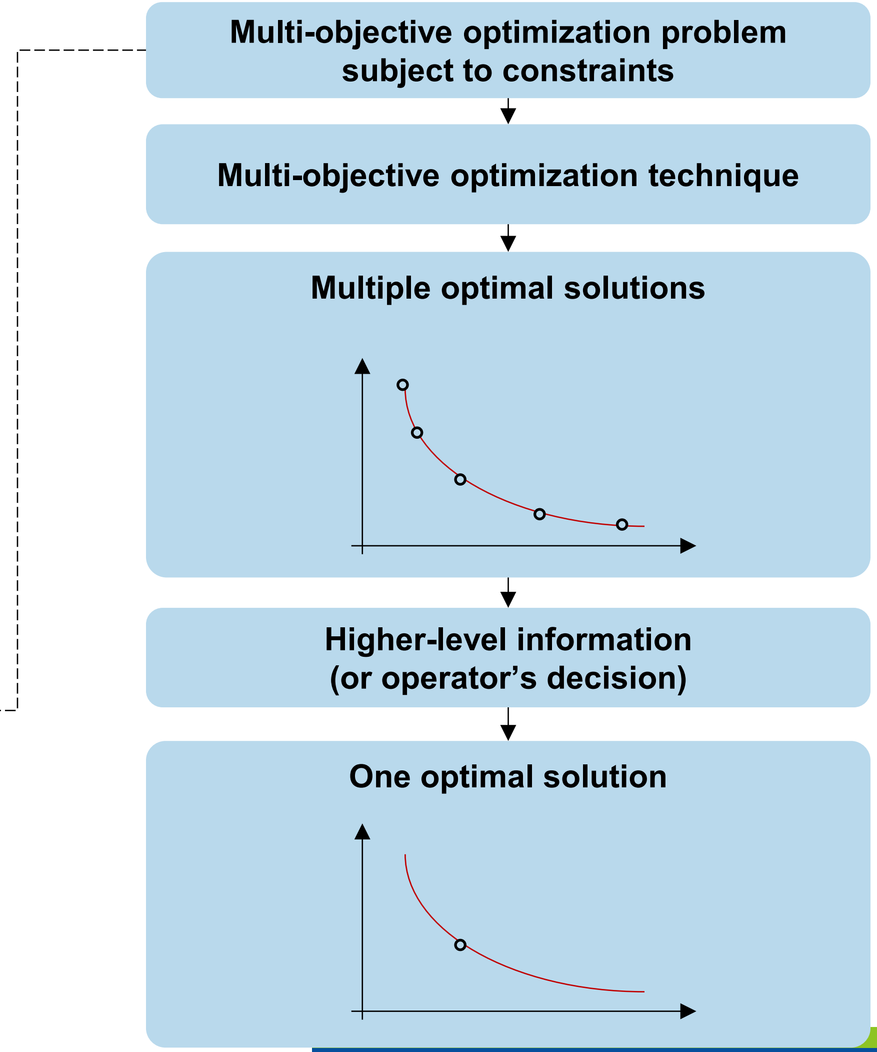
A multi-objective optimization problem can be written as

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

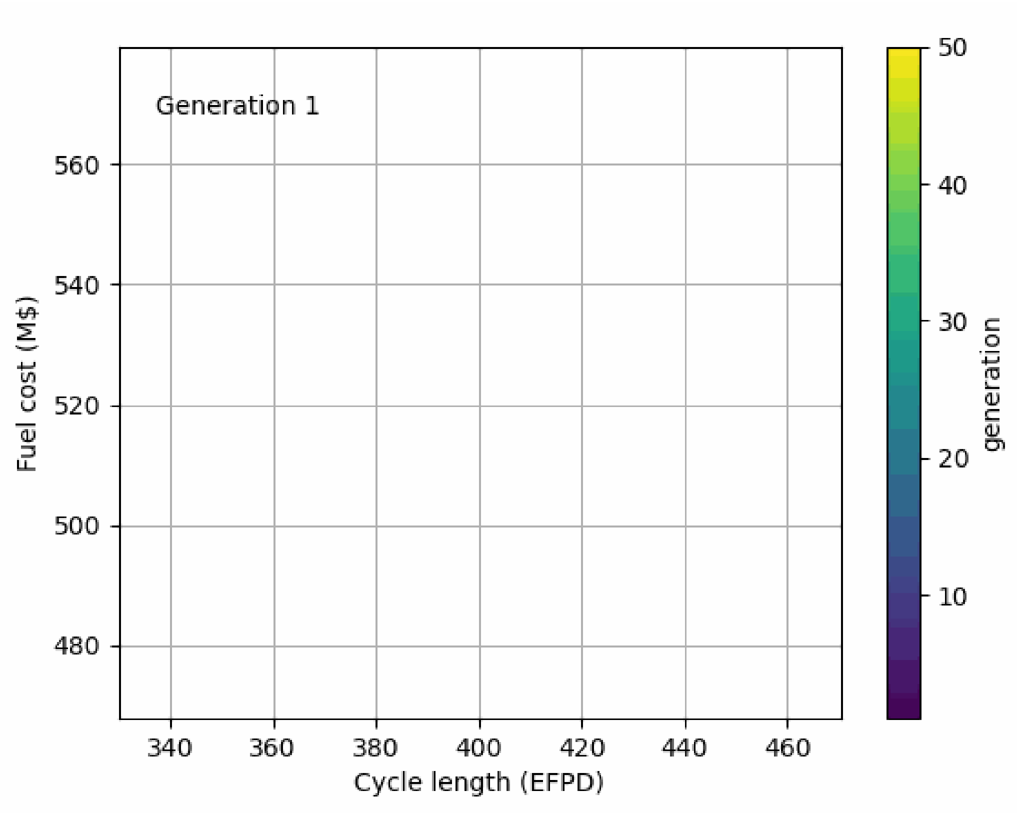
Subject to

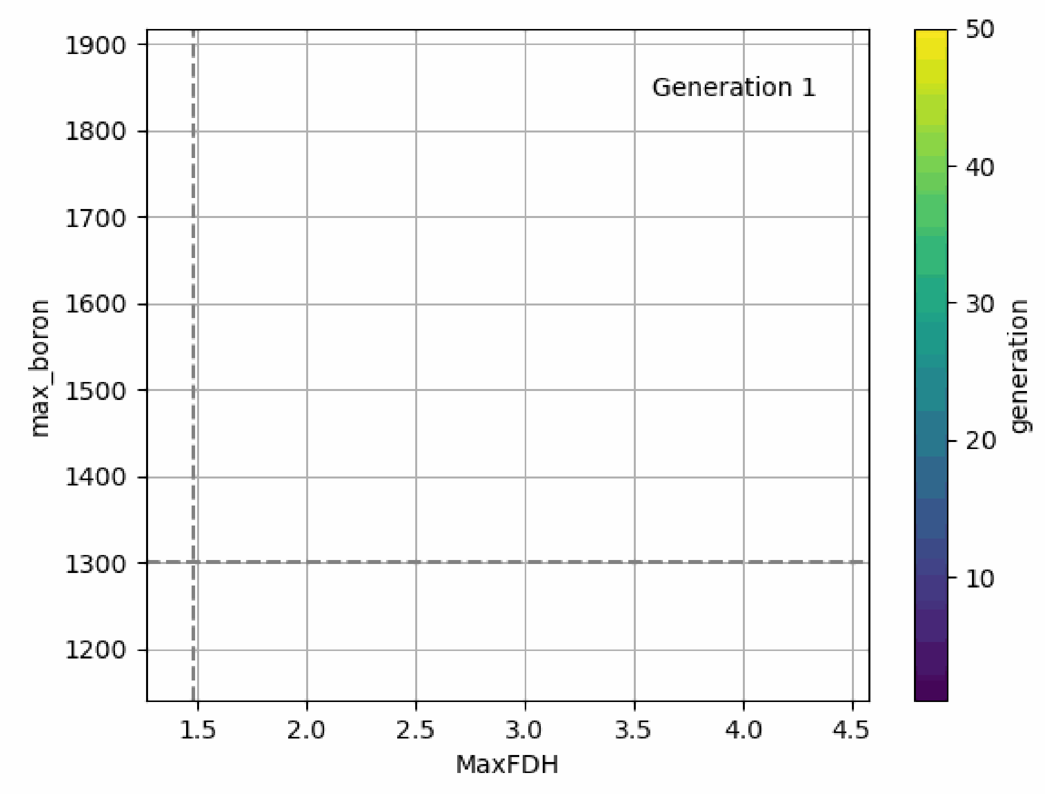
$$\mathrm{g_j(x)} \geq (\mathrm{or}\ \leq)\ 0$$
$$\mathrm{h_k(x)} = 0$$
$$x_i^{(L)} \leq x_i \leq x_i^{(U)}$$

- $f_m(x)$ 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



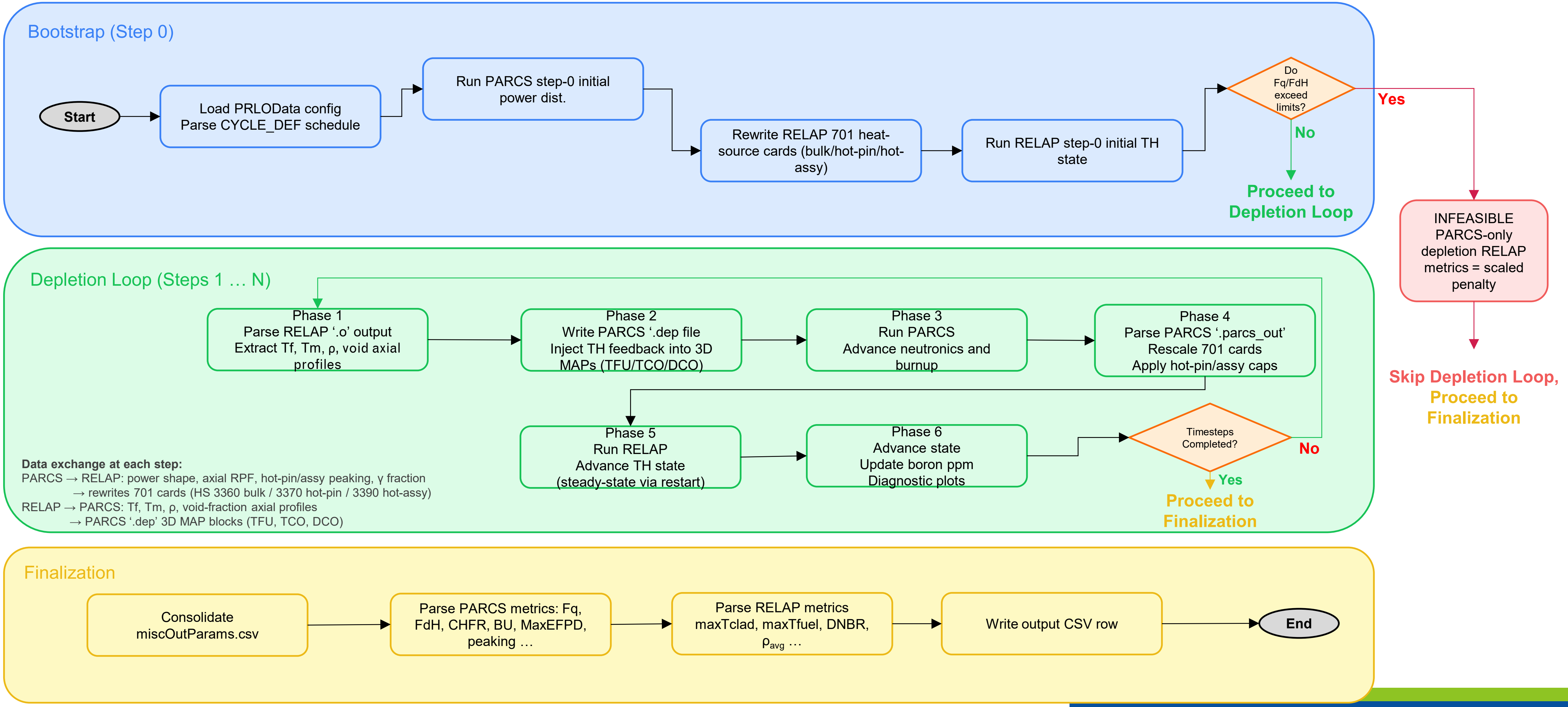
RAVEN/PRLO: Multi-objective Optimization 2/2





A generic 17x17 PWR reactor core is used for the demonstration

RELAP-PARCS Coupling Method

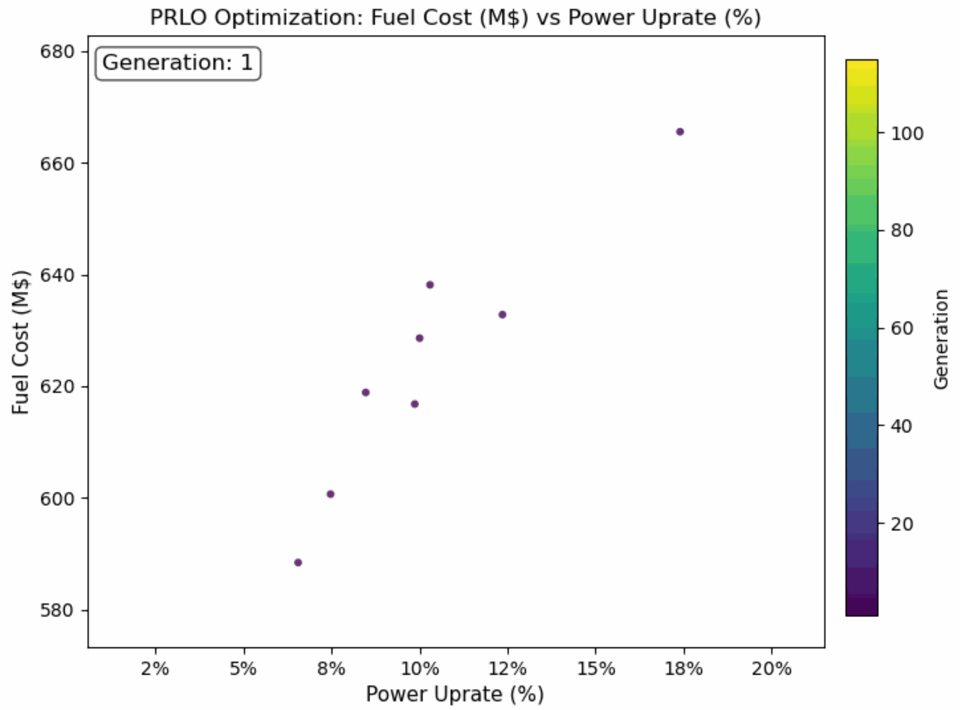


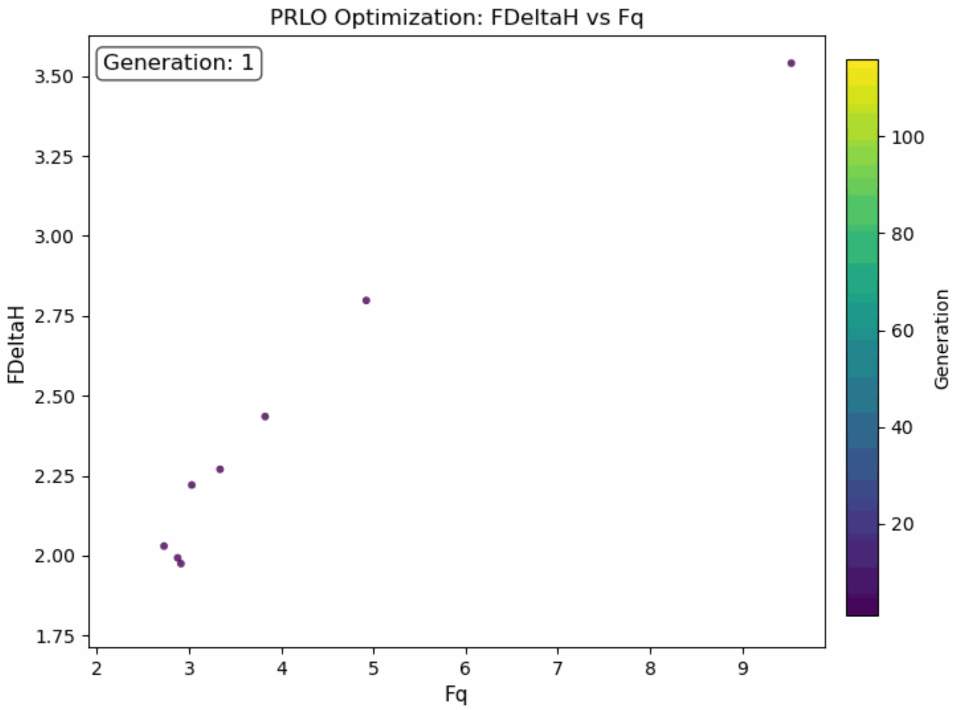
Reference Reactor: Vogtle 1

- Vogtle 1 is a Westinghouse Pressurized Water Reactors (PWR)
- Location: Waynesboro, GA
- Nominal power: 3626 MW_{th} (1280 MWe)
- Westinghouse 4-loop PWR
- Maximize reactor thermal power
  - LEU+ fuel
  - Reactivity control: IFBA, WABA, soluble boron
  - Multi-objective optimization problem
  - Transient behavior with coupled RELAP analysis
  - DEGB-LOCA on cold leg (downstream of RCP)

Vogtle 1 & 2 NPP

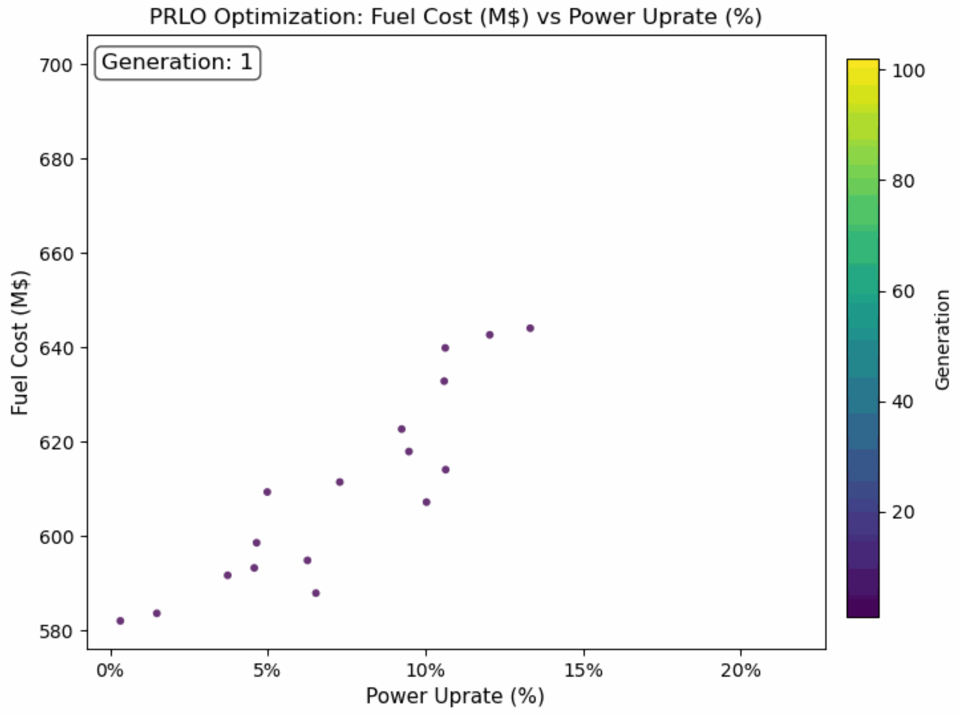
PRLO Optimization Example: RELAP-PARCS Coupling 1/2

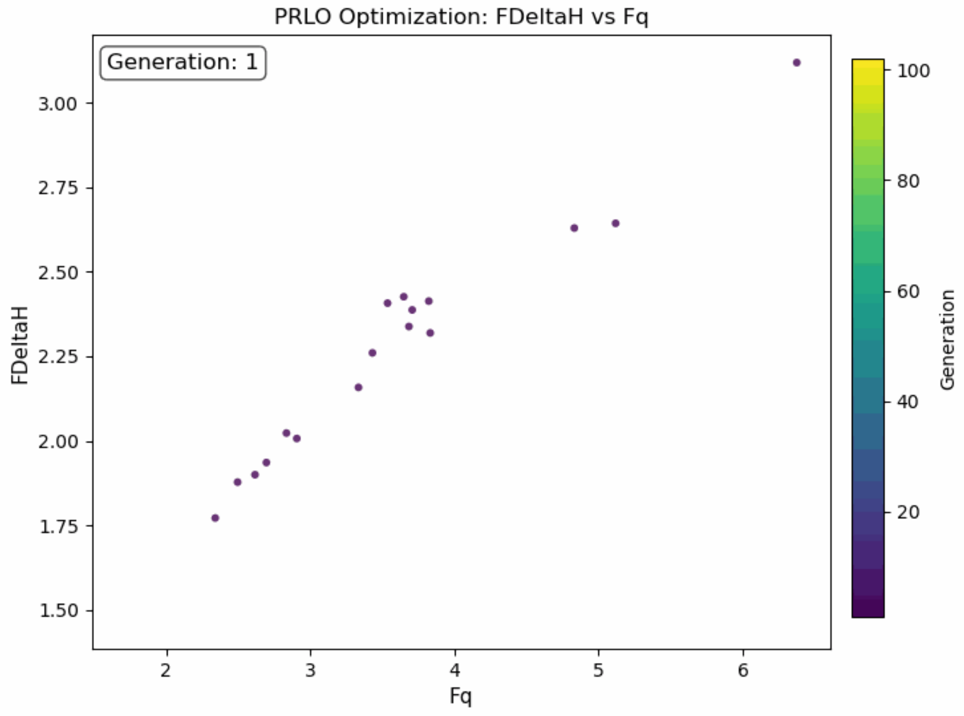




- Multi-objective optimization with RELAP-PARCS coupling and DEGB-LOCA transient feedback
  - Objective: maximize power uprate, minimize fuel cycle cost.

PRLO Optimization Example: RELAP-PARCS Coupling 2/2





- Multi-objective optimization with PARCS depletion ONLY.
  - Objective: maximize power uprate, minimize fuel cycle cost.

Conclusions and future works

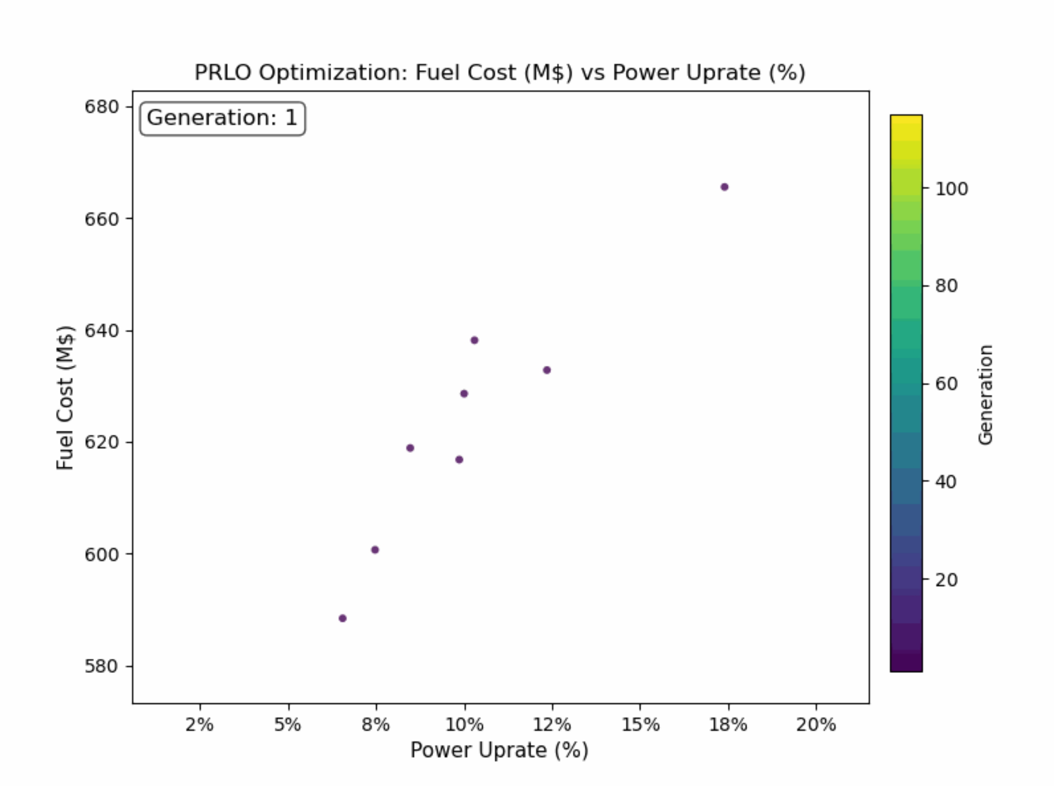
- A RELAP-PARCS coupling scheme has been created and implemented in the RAVEN/PRLO reactor optimization workflow with support for DBA transient analysis.
- Data-driven optimization for PWR power uprates has been demonstrated replacing power peaking safety parameters with material performance during DBA transients.
- Future works
  - RELAP-PARCS tight coupling by adapting the same optimization workflow
  - Non-coupled feedback from fuel performance calculations (FAST, BISON)

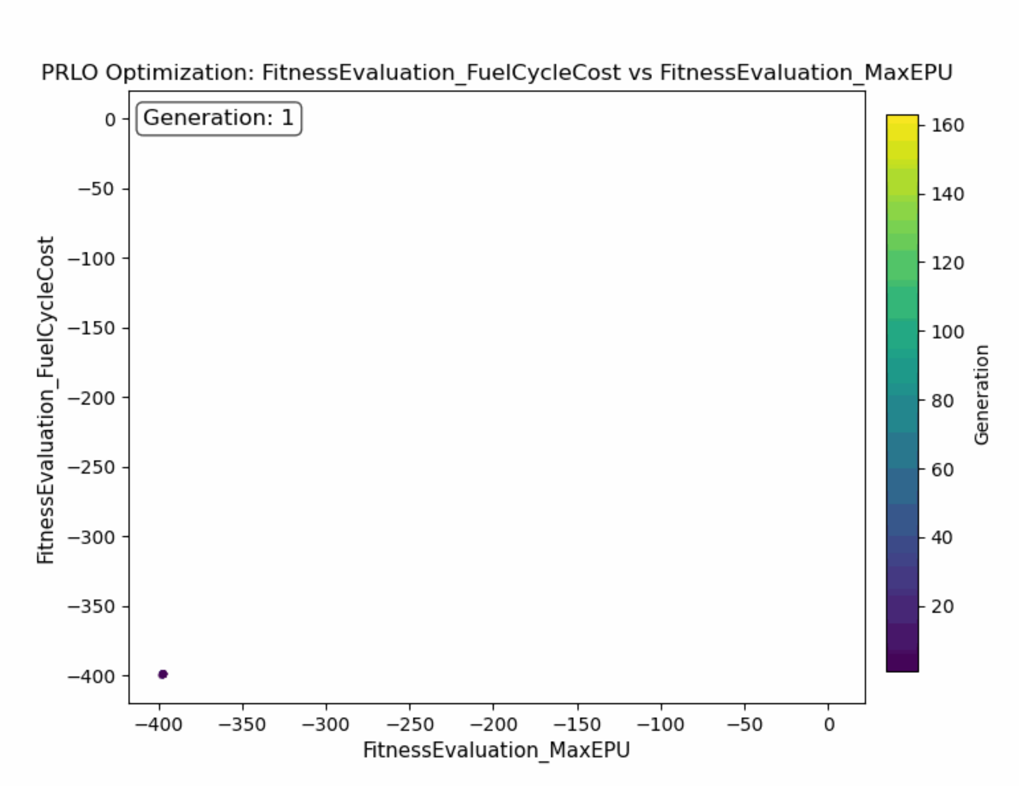
Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.

Backup Slides

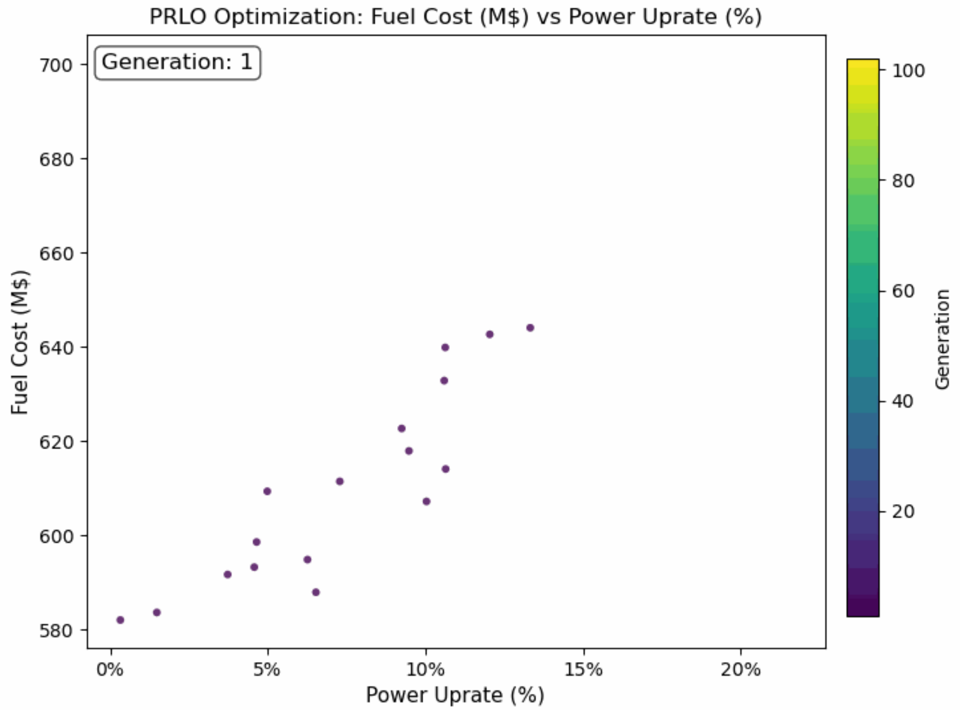
PRLO Optimization Example: RELAP-PARCS Coupling 1/2

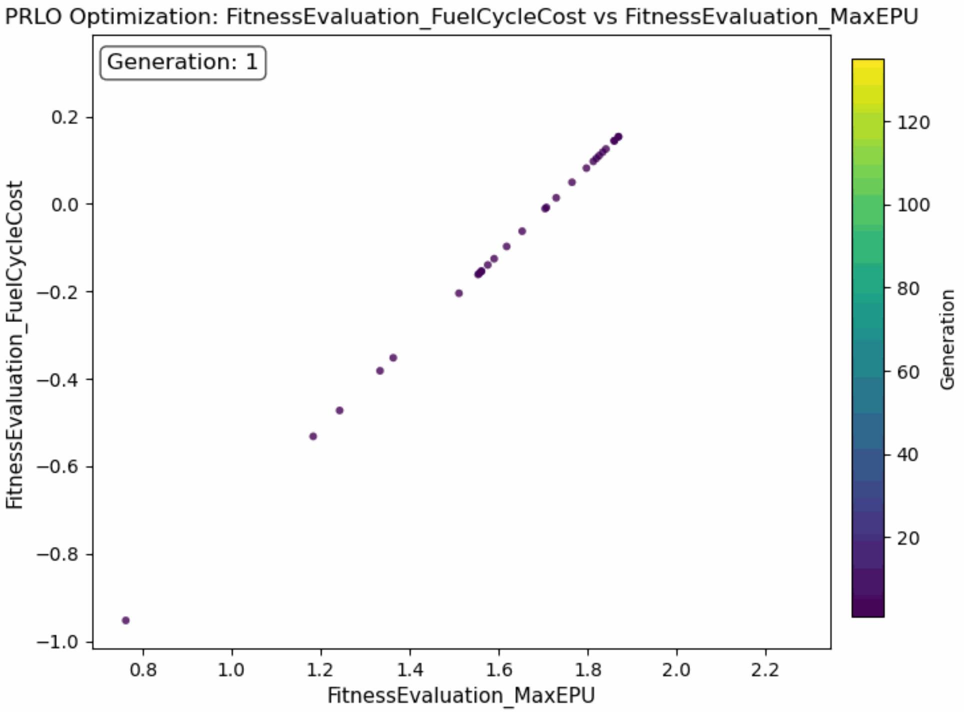




- Multi-objective optimization with RELAP-PARCS coupling and DEGB-LOCA transient feedback
  - Objective: maximize power uprate, minimize fuel cycle cost.

PRLO Optimization Example: RELAP-PARCS Coupling 2/2





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