INL/MIS-25-84438

Svetlana Lawrence
RISA Pathway Lead

April 30, 2025

Larger Power Uprates – Opportunities, Challenges, and Enablers

Spring Program Review Meeting

Power Uprates - Unprecedented Opportunity

Near-term delivery of substantial amount of reliable baseload energy. Untapped available power (historical level of uprates):

- BWRs: ~ 1,800 GWe, equivalent to ~ 2 large LWRs, or ~ 15–20 small modular reactors
- PWRs: ~3,600 GWe, equivalent to ~ 3–4 large LWRs, or ~ 30–40 small modular reactors

Near-term, cost-efficient added power from existing nuclear fleet

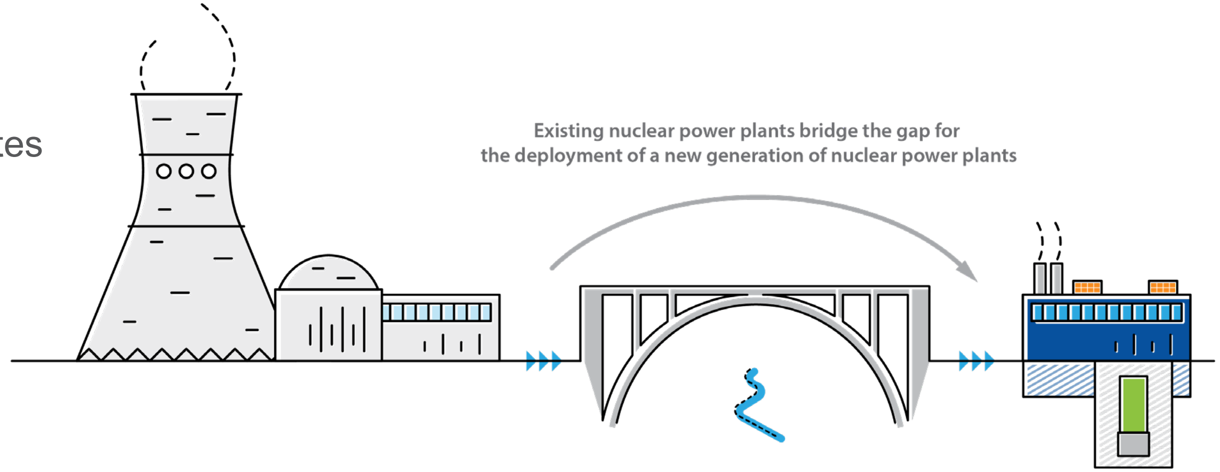
- Estimated costs of power uprates
  - Small uprates (MUR, < 2%): ~ $500 – $800 / kW
  - Medium uprates (SPU, 2%-7%) ~ $800 – $1,500 / kW
  - Extended power uprates (EPU, > 7%): ~ $1,500 – $2,500 / kW
  - Very large power uprates with large plant modifications: up to $5,000 / kW
    - Vogtle Units 3 & 4: ~ $11,000 /kW
    - New AP1000 estimates: $8,300–$10,375/kW, 6.5–8 years construction time[1]
- Improved economics of plant lifetime extension for another 20 years
- An opportunity to modernize

Added power to produce hydrogen

- Explicitly allowed for Inflation Reduction Act (IRA) §45V hydrogen production credit
- Hydrogen credits further strengthen the business case for power uprates

Bridging the gap to new nuclear

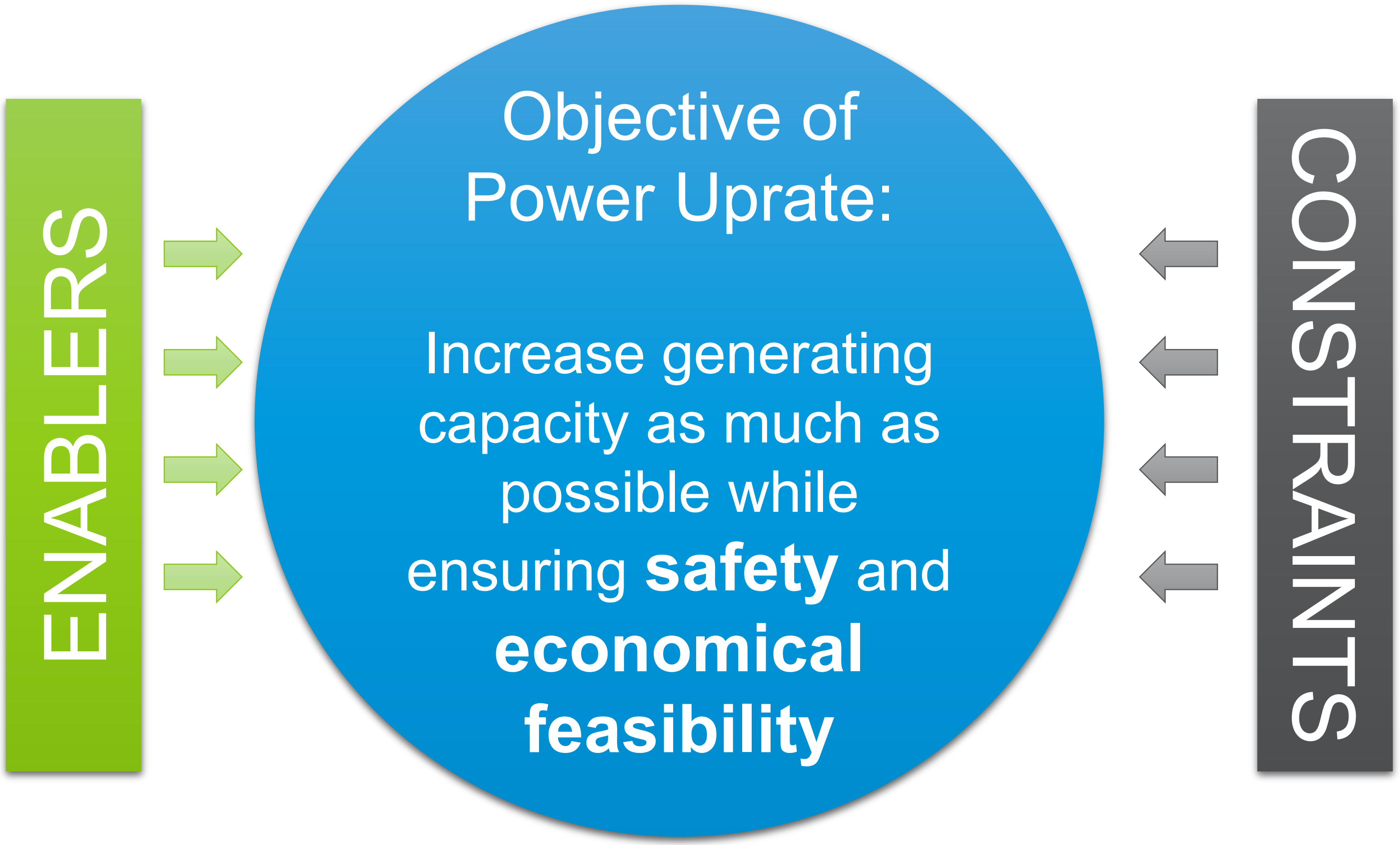
- U.S. nuclear energy to triple by 2050 – need to start with uprates
- Re-establishing U.S. nuclear capabilities and dominance:
  - Workforce
  - Supply chain for nuclear-grade systems and components
  - Scaled capacity of regulatory framework



Larger Uprates Faster – the Urgent Need

R&D goals:

- Enable larger-size uprates
- Demonstrate safety of power uprates
- Support economic feasibility by efficiency gains

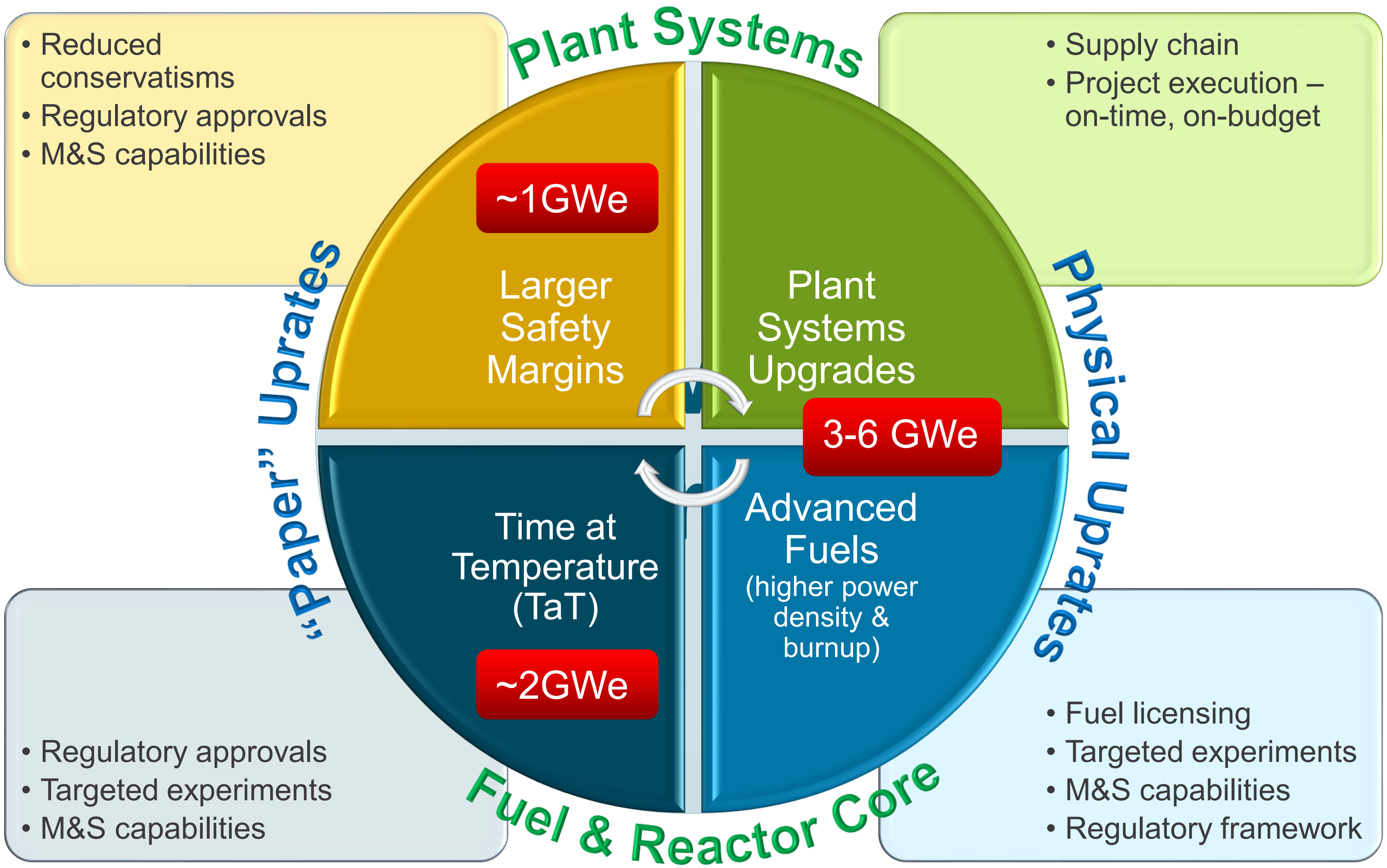


LWRS
LIGHT WATER REACTOR SUSTAINABILITY

Larger Uprates Faster → SYSTEMS INTEGRATION

R&D AREAS:

- Enhanced modeling and simulation tools
  - Systems analyses
  - Fuel performance analyses
- Demonstration of adequate safety margins
  - Reducing conservatisms
  - Detailed analyses
  - Reducing uncertainties
- Artificial Intelligence and Machine learning (AI/ML) technologies
- Risk-informed licensing pathways
- Feasibility assessments
- Demonstrated case studies

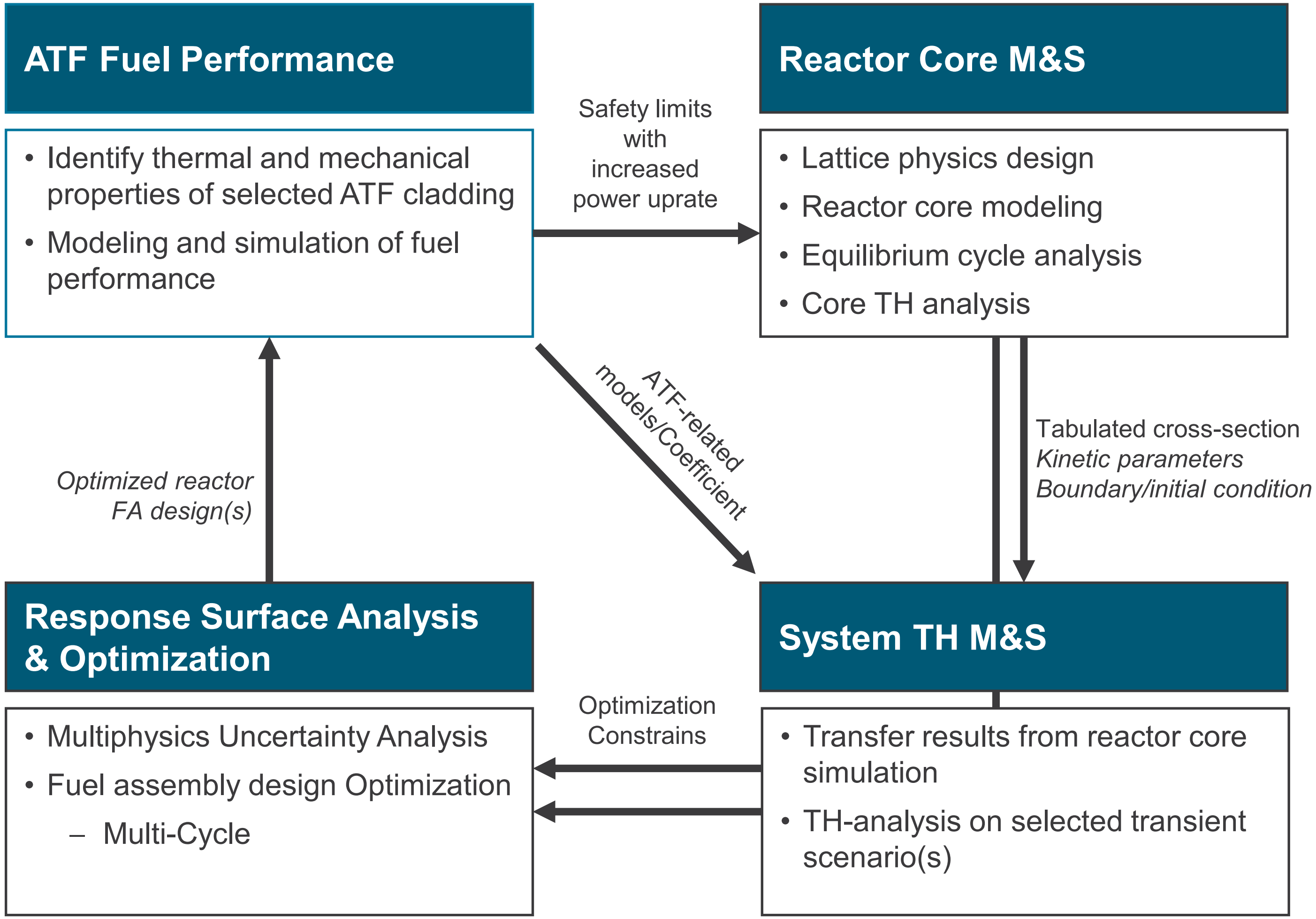


LWRS
LIGHT WATER REACTOR SUSTAINABILITY

Power Uprates – Assessment of Reactor Core Capabilities

Project Description

- **Identify engineering design criteria of Accident-Tolerant Fuel (ATF) for power uprate**
- **ATF + Extended Enrichment + (possibly) High-Burnup (HBU)**
  - ATF can…
    - reduce oxidation kinetic
    - reduce hydrogen production & hydrogen pick up
    - improve post-quench ductility
    - improve corrosion resistance
  - Dopped Pellets fuel 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
LIGHT WATER REACTOR SUSTAINABILITY

Overall Approach for Sizable PWR Power Uprates

- **Approach:** ATF + EE (extended enrichment) + (possible) HBU
- **Near-term ATF concepts:** existing data, models, and methods can be used for its safety evaluations
  - (Primarily) Cr-coated Zr cladding
    - Significantly reduced oxidation kinetic
    - Significantly reduced hydrogen production and hydrogen pick up
    - Improved post-quench ductility
    - Improved corrosion resistance
  - (Optionally) Doped pellets
    - Higher density, can support higher burnup
    - Higher plasticity at high temperature
    - Better fission gas retention
    - Improved PCI resistance

LWRS-Developed Framework (cont'd)

Two possible approaches to evaluation of power uprates:

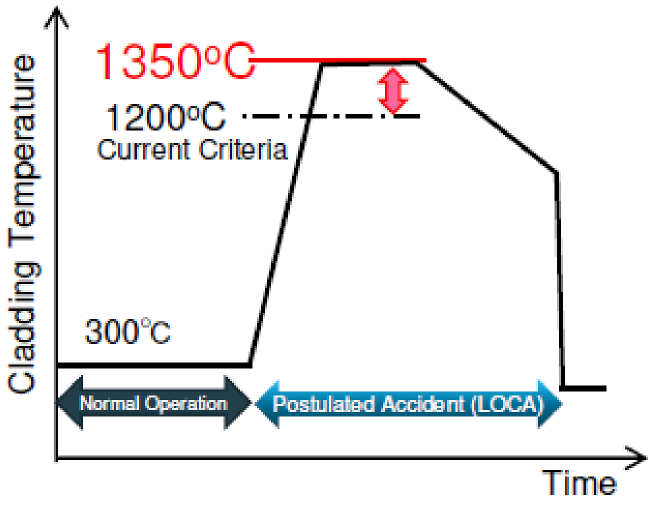
1. **Staged optimization approach ✓**
   - Core → system, steady-state → transient, single-physics → multiphysics
   - Pros: computationally efficient; no complicated coupling scheme
   - Status: multi-objective optimization of core design has been demonstrated; working on core-to-system informing scheme
   - Needs:
     - Relatively accurate surrogate safety limit (e.g., hot channel factors Fq & FΔH)
2. **Holistic multiphysics optimization approach**
   - Pro: incorporation of experimentally determined safety limits (e.g., peak temp. during transient); avoid use of surrogate limits
   - Needs:
     - Experimentally determined safety limits
     - ML surrogate model to accelerate optimization

Reactor Core and System Design Problem

- **Design objectives:**
  - Sizable (~20%) power uprates for a generic PWR plant with minimal increase in fuel cost
- **Design variables**
  - Core reloading scheme
  - Fuel assembly (enrichment, rod dimension, lattice configuration, etc.) and control rod design
  - Plant operating conditions: flowrate, temperature, etc.
- **Design constraints**
  - Safety: hot channel factors, critical boron concentration, reactivity feedback coefficients, shutdown margin, etc.
  - Performance: burnup, enrichment, etc.
  - Economics: reloading cycle length, component upgrade, etc.

Connections to Ongoing R&D Activities (cont.)

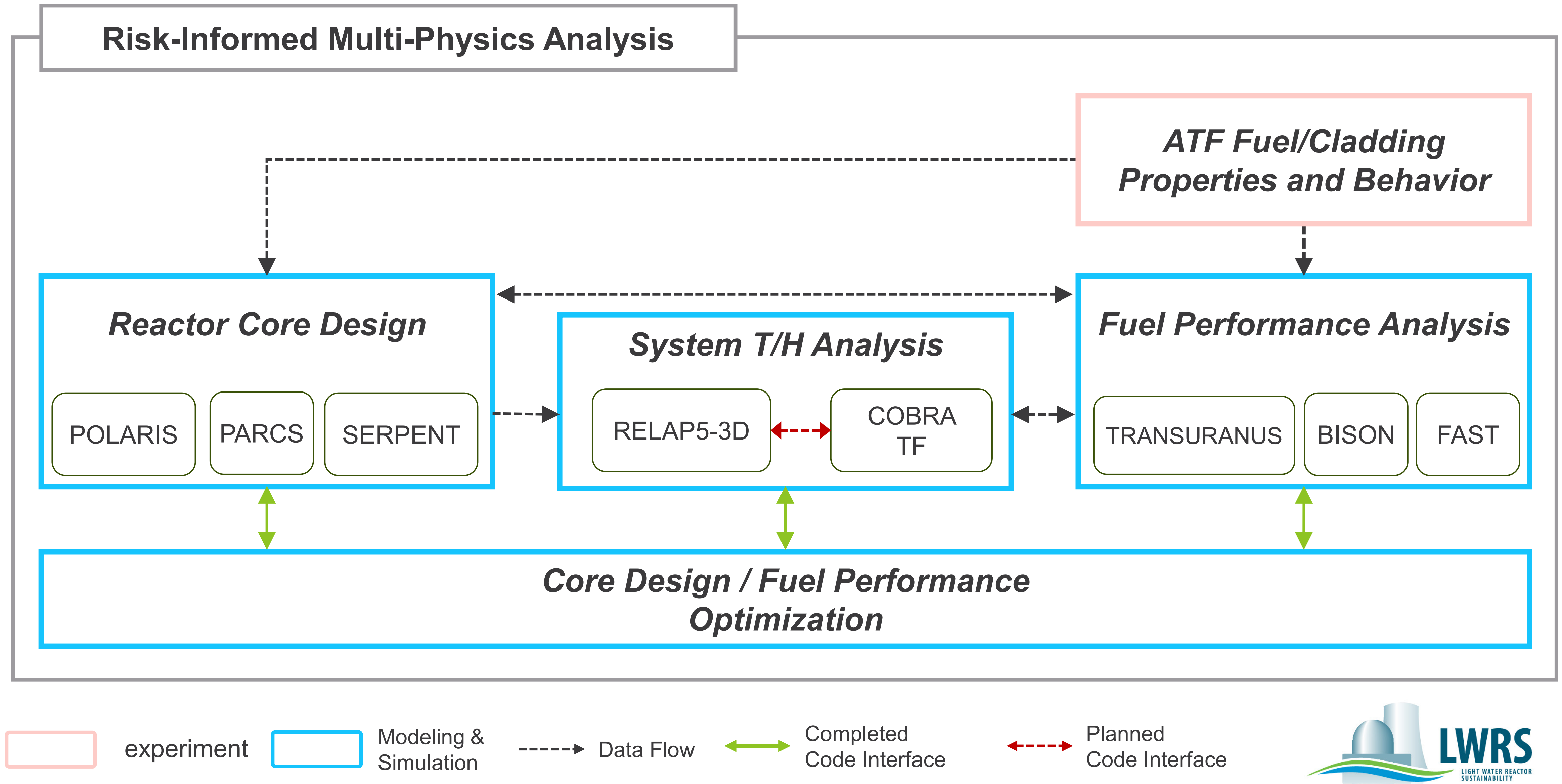
- **Need input from ATF (and HBU) experimental campaign**
  - Obtain and update correlations used in fuel performance code
  - How to translate new thermal and mechanical limit of ATF failure to constraints used in core optimization
  - For example:
    - Increase power output leads to reduced margin for hot channel factors (Fq & FΔH)
    - ATF can help maintain the margin due to elevated temperature criterion
    - How to correlate temperature criterion during loss of coolant accident (LOCA) with linear heat generation rate (LHGR) and hot channel factors?



Murakami (2023)*

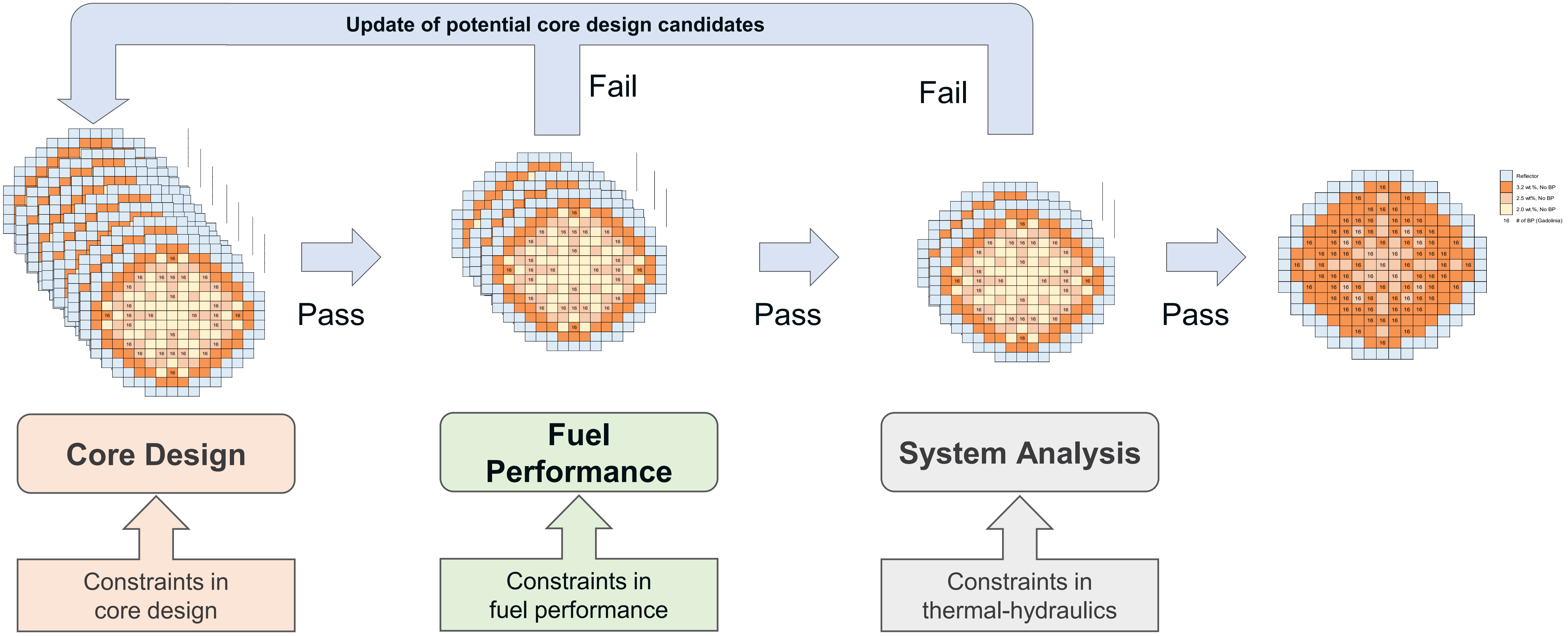
* Murakami (2023) Development of Cr coated zirconium alloy fuel cladding: Progress in 2022. Annual EPRI/DOE/INL Joint Combined Workshop on Accident Tolerant Fuel and Higher Burnup. April 2023.

LWRS Power Uprate – Workflow



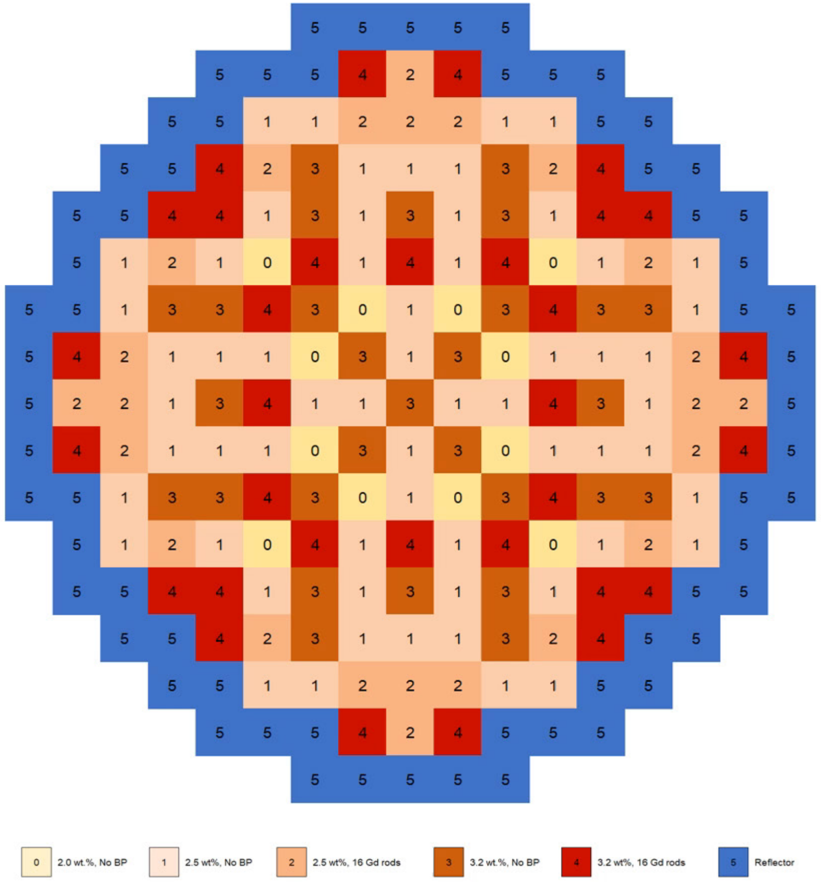
Enabling R&D

Optimization of Reactor Core Design

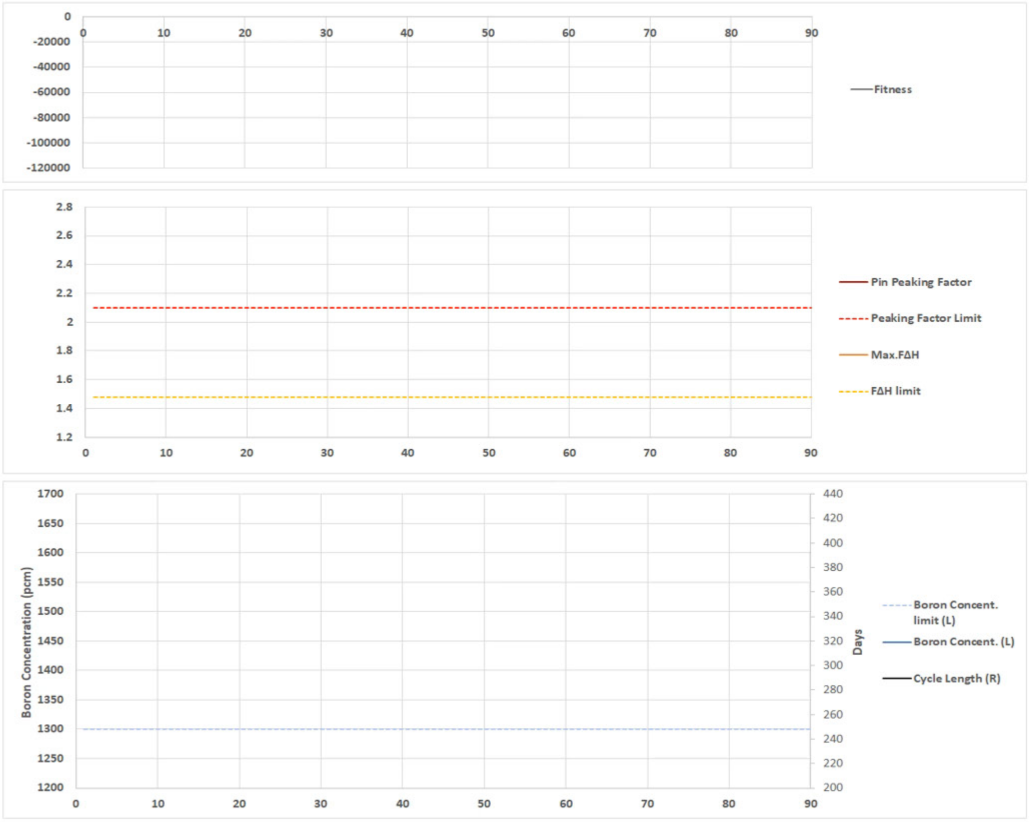


Single Cycle Optimization | Single Objective

Reactor Core Fuel Pattern

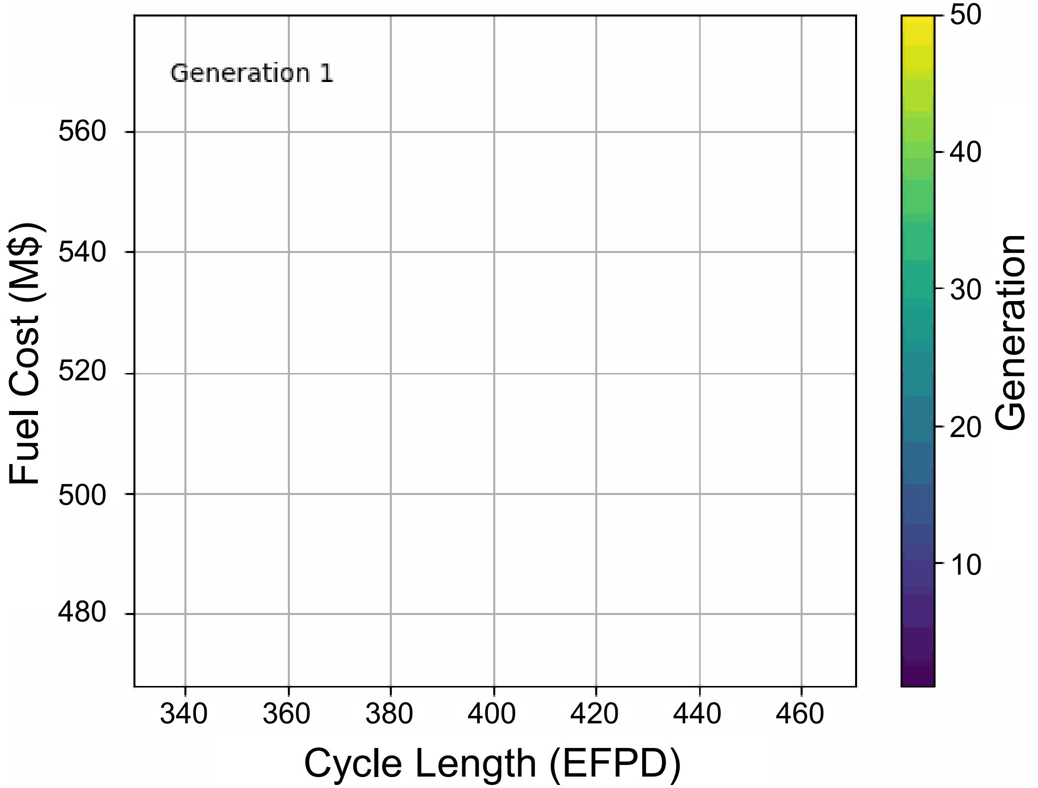


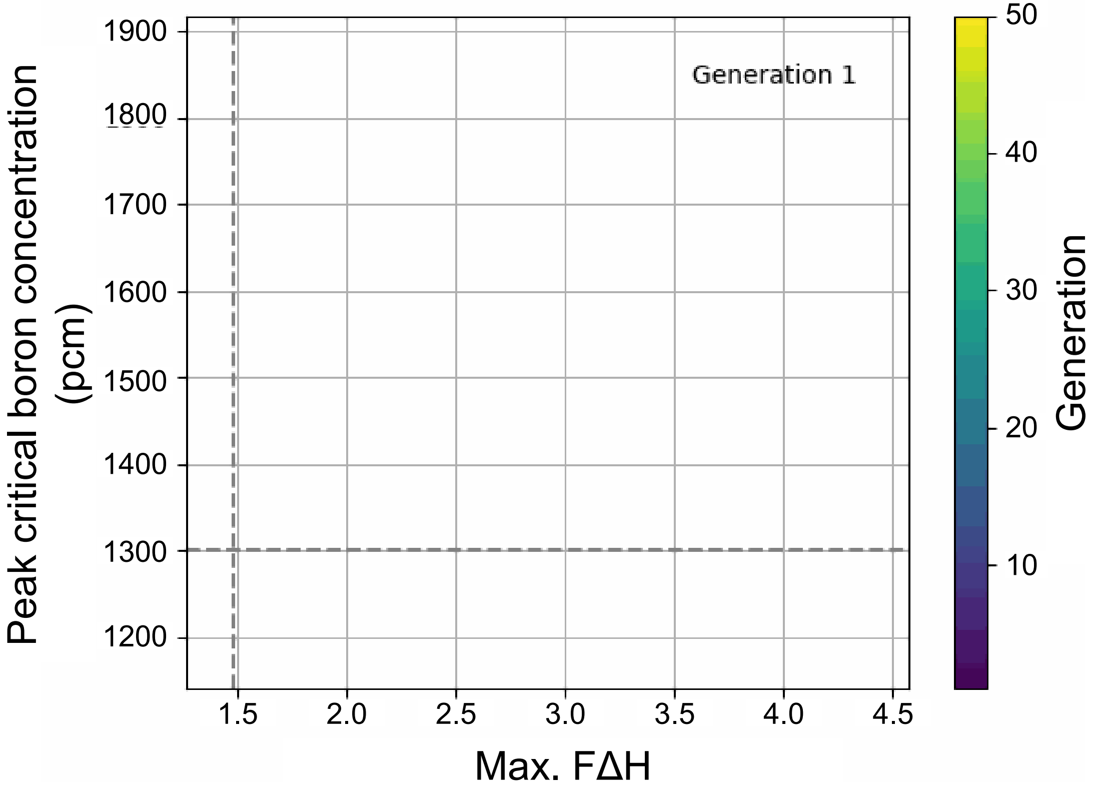
Fitness of Pattern, Constraints, Objective



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

Single Cycle Optimization | Multi-Objective





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

Upcoming Research - Cycle-by-Cycle Optimization | Multi-Objective

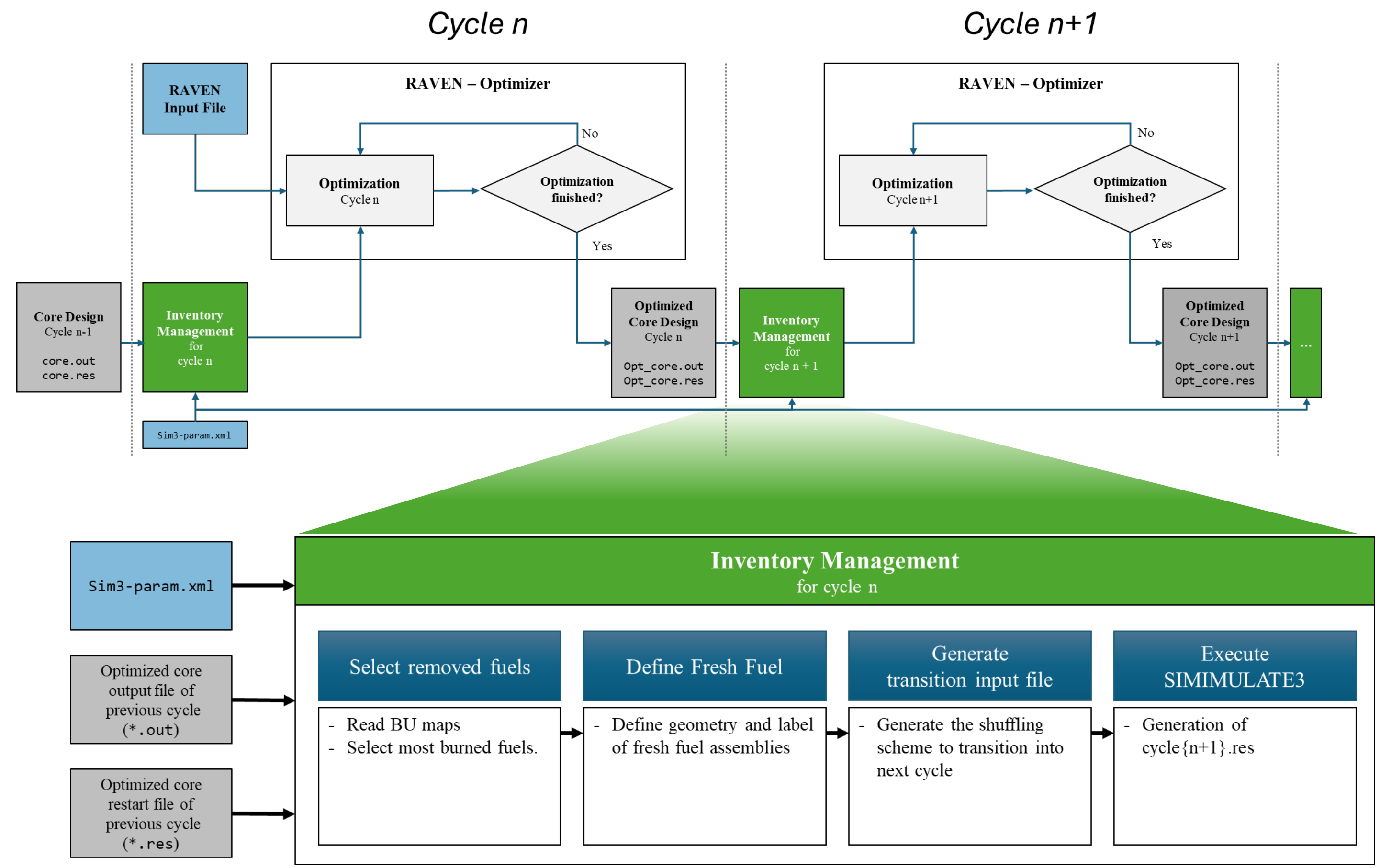
Fuel Inventory Management

Key Challenges of Multicycle Optimization

- Very Large Design Space
- Different irradiation histories of each FA
- Multi-Unit Fuel Inventory Management

Cycle n optimization is linked to Cycle n+1 optimization through the Inventory Management

Cycle-by-Cycle Optimization Process in the PRLO Framework



Core Optimization Technology Roadmap

	Phase 1 (FY19–20) Methodology Development	Phase 2 (FY21–22) Framework Development for PWR	Phase 3 (FY22–23) Framework Enhancement for PWR	Phase 4 (FY24–25) Framework Demonstration for PWR	Phase 5 (FY26–27) Framework Development for BWR *(Planned)*
Multiphysics Analysis & Coupling	Set plant-based scenarios	Apply risk-informed approach	Uncertainties quantification	Fast responding ROM for Fuel Depletion (Neutronics)	A genetic BWR core modeling
	Simulate DBA and Evaluate safety margin				Subchannel modeling
Framework Development	Setup tools & methods	Code interface (CASMO/SIMULATE)	Multi-objective optimization algorithms	optimization acceleration methods	Code Interface (POLARIS/PARCS)
		Single-objective optimization algorithms		Multicycle optimization	Framework (plug-in) release
Demonstration			Single-cycle optimization of a genetic PWR core	Multicycle optimization of a genetic PWR	Application to recent Cycle optimization for PWR
				PWR Benchmark Study with Historical Reference	
Stakeholder Engagement			NDA with a utility company for PWR Optimization	Data/Knowledge Transfer with a utility company	Data/Knowledge Transfer with a vendor company
				NDA with a vendor company for BWR Optimization	

LWRS

LIGHT WATER REACTOR SUSTAINABILITY

Sustaining National Nuclear Assets

lwrs.inl.gov