

<https://www.anl.gov/nse/nuclear-systems-analysis>

<https://sai.inl.gov/>



REACTOR AND FUEL CYCLE ANALYSIS



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Argonne National Laboratory

May 20, 2026



CONTENT

- **Reactor Analysis Capabilities**
 - Introduction Reactor Analysis Tools
 - Sample reactor analyses
- **Nuclear Fuel Cycle and Economics Analysis**
 - Projection
 - Material flow
 - Cost estimation



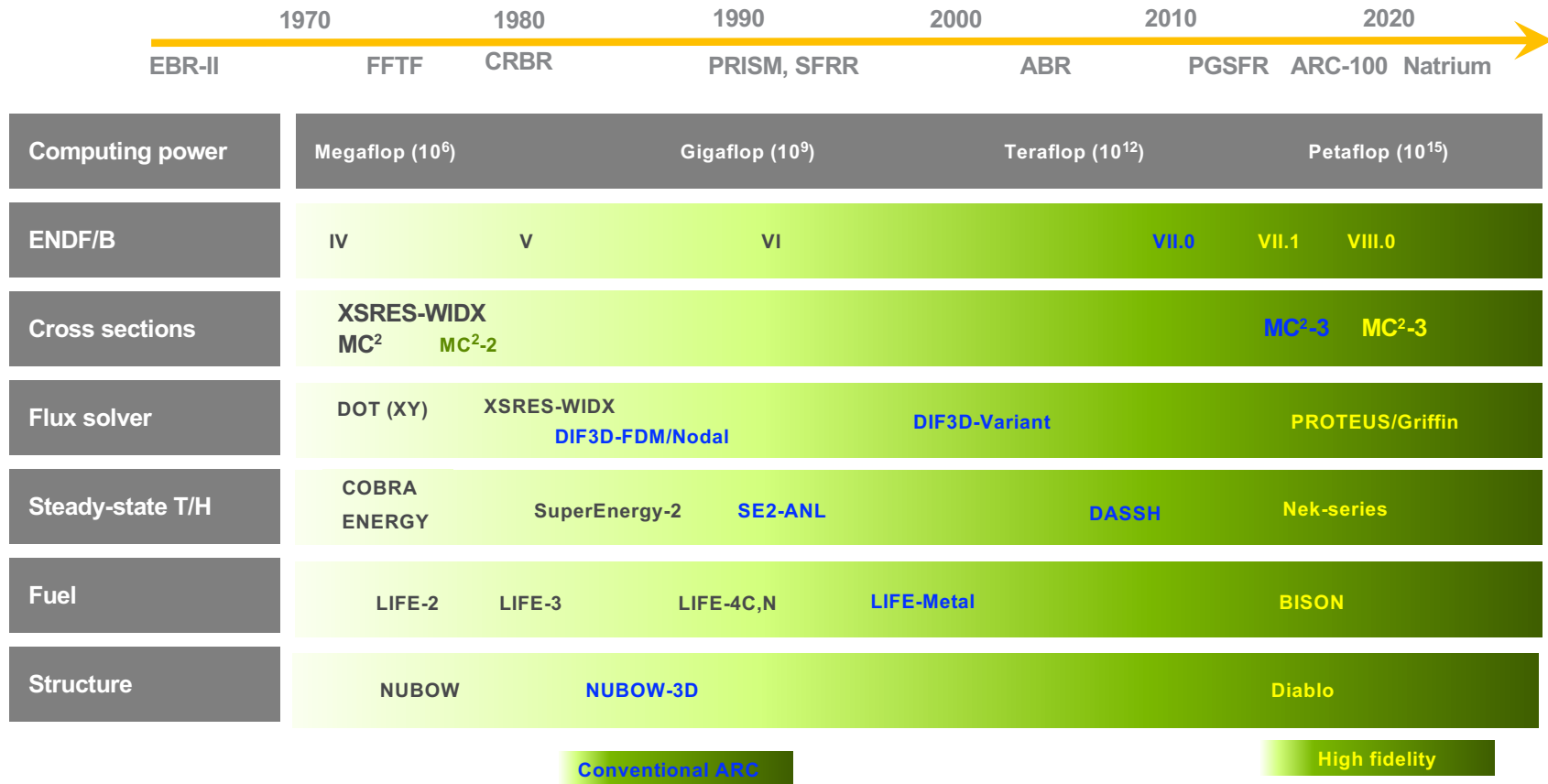
REACTOR ANALYSIS CAPABILITIES



U.S. DEPARTMENT OF
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U.S. Department of Energy laboratory
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NATIONAL LABORATORY | 1946–2021

Progress In Reactor Computation Capabilities



ANL M&S Tools for Advanced Reactor Analysis

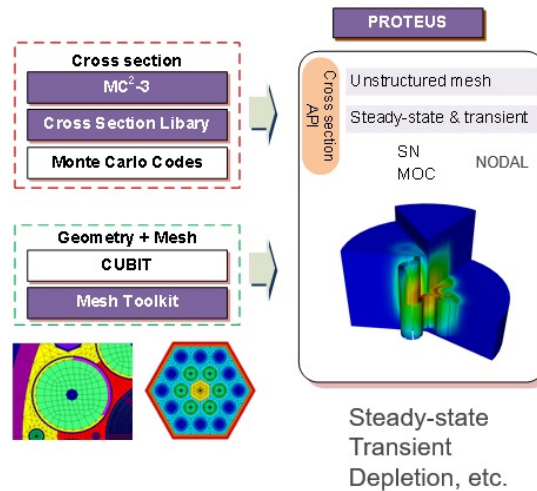
Conventional tool

ARC

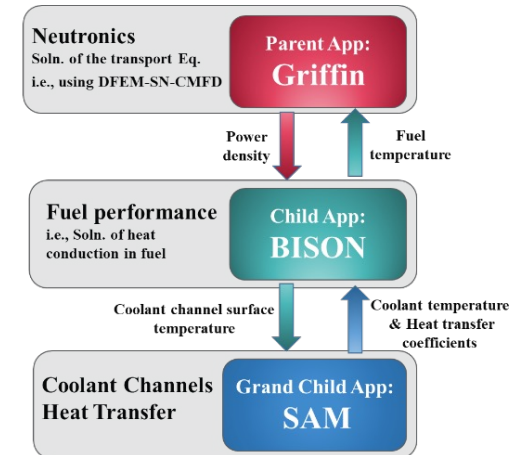


High-fidelity, advanced tools

PROTEUS/GRIFFIN



MOOSE-based tools



ARC Software

- **The ARC software provides a reactor and fuel cycle analysis**
 - Fuel fabrication and recycle, multiple fuel feeds, equilibrium operation, control rod burnup.
 - Thermal hydraulic and mechanics behavior of ducted fuel assemblies.
 - Many utility programs not listed here
- **Verification & validation of the codes**
 - ZPPR/ZPR, EBR-II, FFTF, etc.
 - Support software users for design licensing: VTR, ARDP, ART, etc.
 - Uncertainty quantification on software prediction for design margin determination
- **Working through Workbench/PyARC**
- **<https://www.anl.gov/nse/software>**

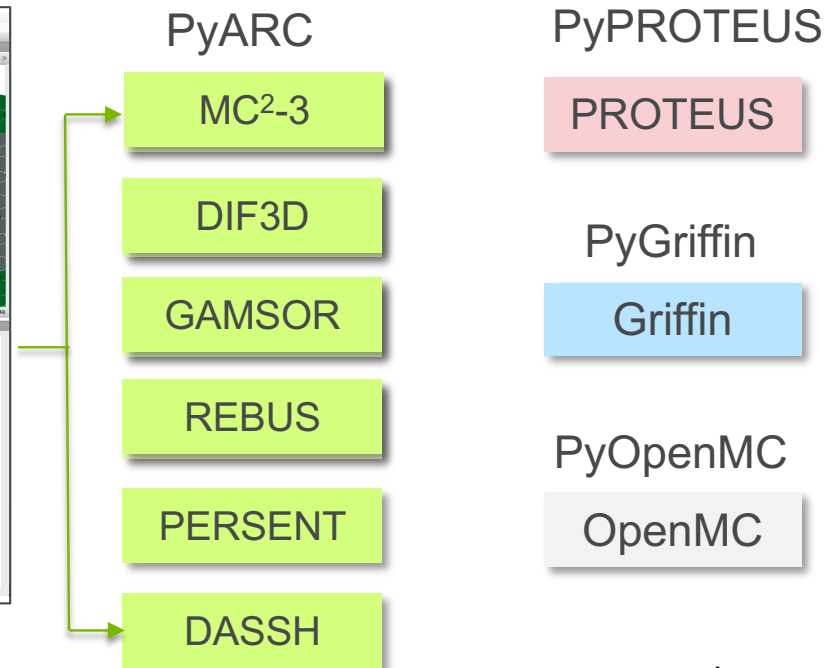


Workbench / PyARC

- Assist users in processing ARC inputs, workflow and post-processing (visualization)
- Open-source: <https://www.anl.gov/nse/pyarc>

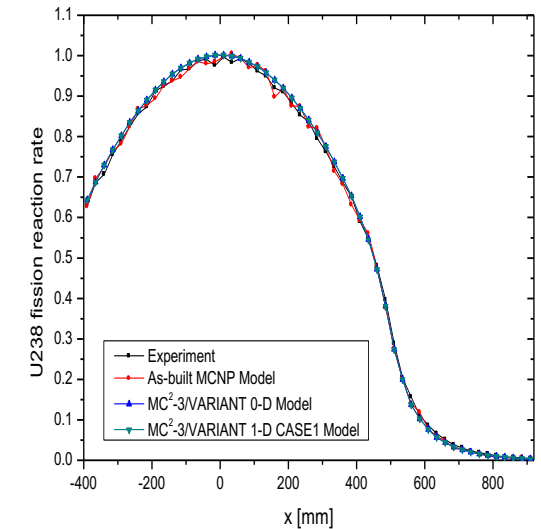
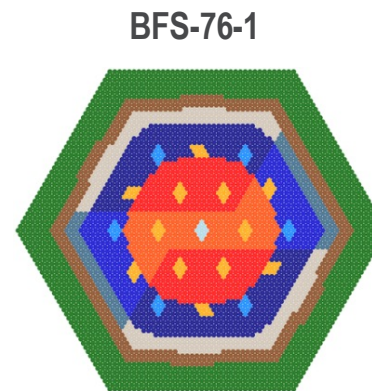
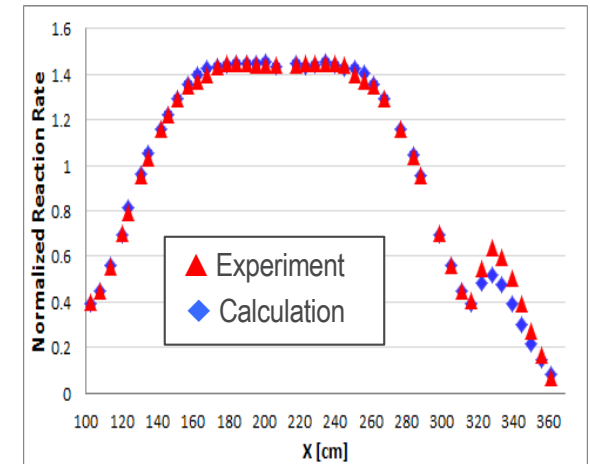
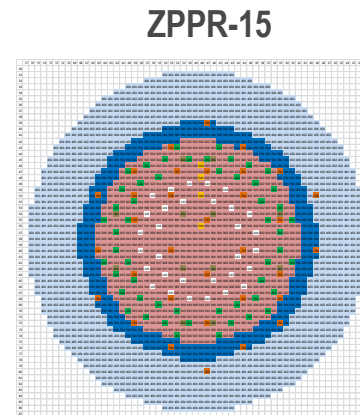
The screenshot displays the NEAMS Workbench interface with several key components highlighted:

- Workbench ARC input:** A code editor window showing the input script for the simulation, including parameters like power, geometry, and material properties.
- Post-processing of ARC code's results in summary tables:** A table window displaying simulation results, including columns for Assembly, Region, Index, Peak Strain, and Peak Fast Flux.
- Geometry Visualization:** A 3D model of the reactor core geometry, showing fuel elements and structural components.
- Results plotting:** A graph showing the neutron flux distribution over time, with curves for different simulation methods like US2D and US3D.
- 3D results visualization:** A 3D visualization of the neutron flux distribution within the reactor core geometry.



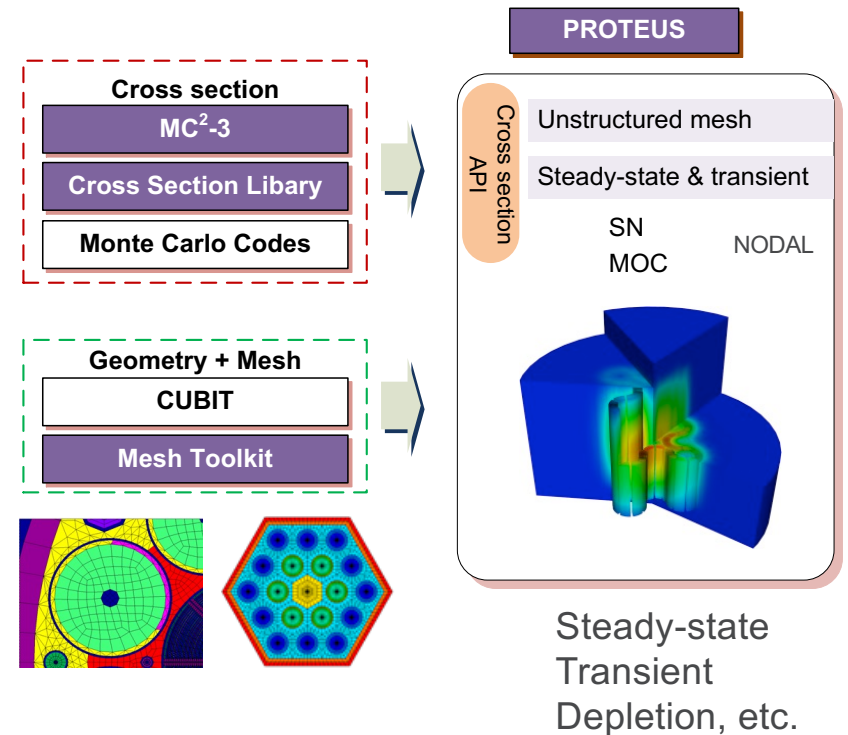
Validations

- ZPR / ZPPR-15 experiments
- FFTF experiments
- EBR-II experiments
- CEFR experiments
- Monju experiments
- JOYO experiments
- Phenix, Superphenix, BOR-60
- etc.

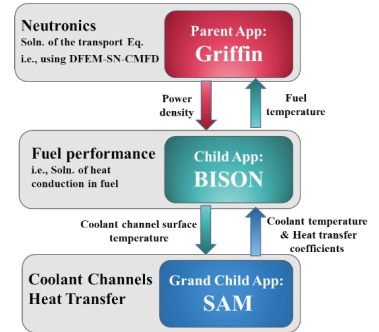
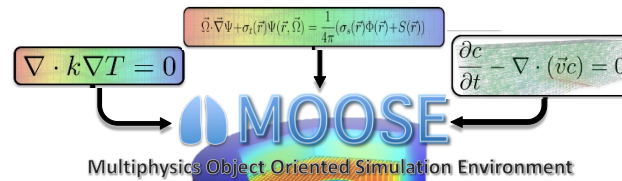


High-fidelity Codes: PROTEUS/Griffin

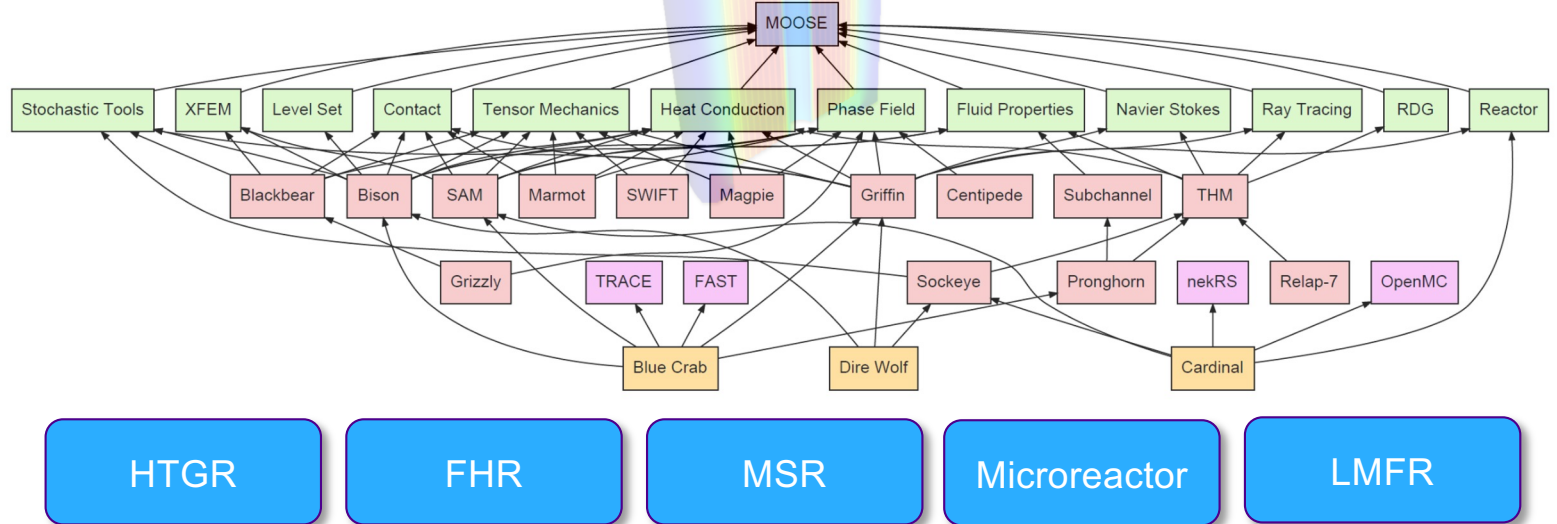
- Geometry flexibility using unstructured finite element meshes
- Multiple neutron transport solvers
- Massive parallelization with good scalability
- Cross section generation using external codes (MC²-3, Serpent, OpenMC) or the cross section API on the fly
- Internal thermal calculation routines
- Internal depletion routines
- In-house mesh generation toolkit for Cartesian and hexagonal geometry meshes
- Multi-physics coupling (SN) with Nek5000, Diablo, SAM
- Verified and validated using various benchmark problems and experiments (ZPR, EBR-II, TREAT, RCF, etc.)



High-fidelity Codes: MOOSE-based Software



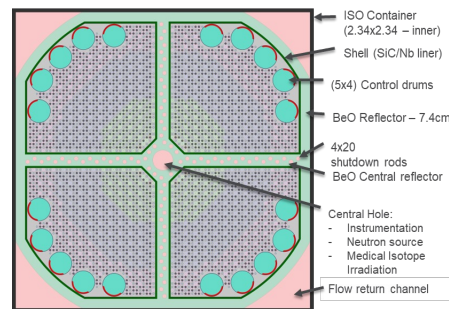
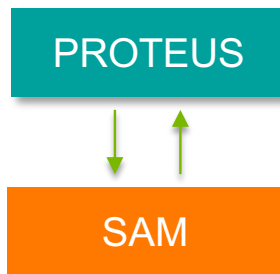
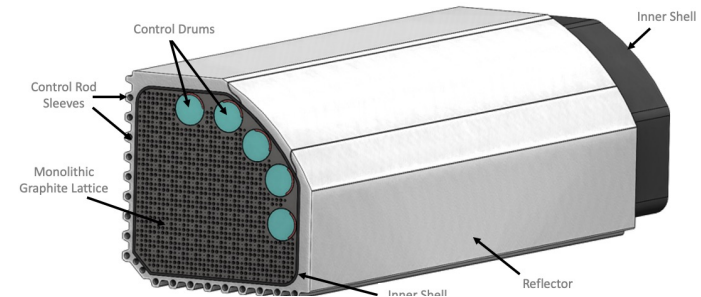
- MOOSE Framework
- MOOSE Modules
- MOOSE-Based Applications
- MOOSE-Wrapped Applications
- MOOSE-Coupling Applications



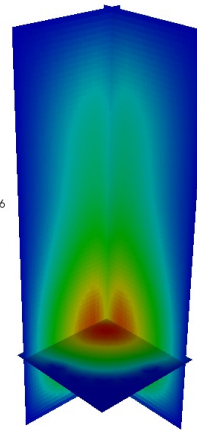
MOOSE enables multiphysics high-fidelity simulations

Simulation of HolosGen Micro Reactor

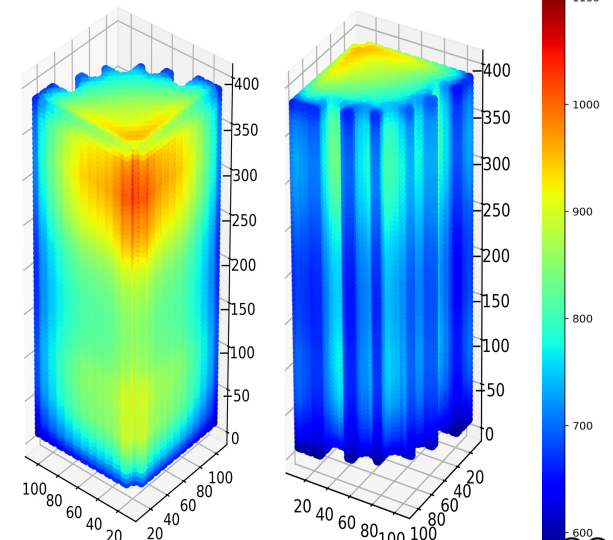
- High-temperature gas-cooled reactor concept using TRISO distributed in graphite hexagonal blocks, cooled with helium in a direct Brayton cycle independently executed by 4 Subcritical Power Modules (SPMs) fitted into a 40-foot ISO container
- Target core 22 MWt (10 Mwe) power and 7MPa with core outlet temperature of 850°C
- Multiphysics simulation with PROTEUS + SAM to support core design



Pseudocolor
Var: FX003
-246.4
-184.8
-123.2
-61.61
0.003946
Max: 246.4
Min: 0.003946



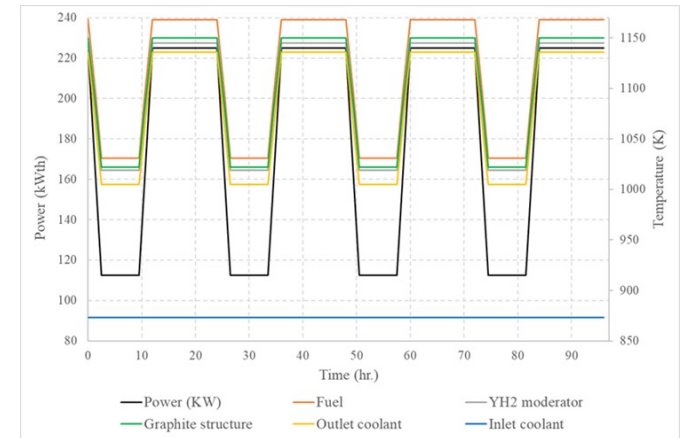
Thermal neutron flux



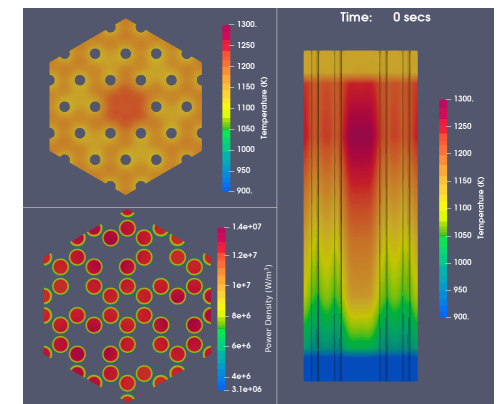
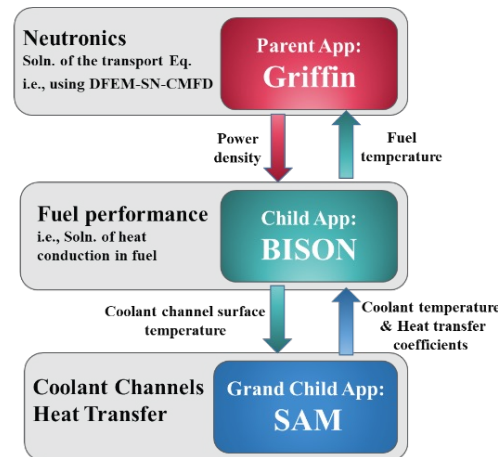
Temperature

Gas-cooled Micro Reactor (Assembly)

- A GC-MR assembly model developed gathering various modeling challenges for horizontal GC-MR
- Power is 225 kW thermal
- Multiphysics analysis of GC-MR for:
 - load-following transients (daily and frequency control)
 - accidental transients (loss of pressure, velocity, flow blockage, temperature transient)
- Multiphysics simulation using Griffin + BISON + SAM



Temperature and power during daily load-following transient (100-50-100% power)



Power and temperature evolution during channel blockage transient

Code Users

Conventional tool

ARC

ART, VTR, ORNL, INL, BNL, Airforce, etc.
 (Industries) TerraPower, Westinghouse, Oklo, ARC, etc.

(Universities) Berkley, MIT, Purdue, U Michigan, Georgia Tech, UT, NCSU, etc.

(International) KAERI, UNIST, SNU, JAEA

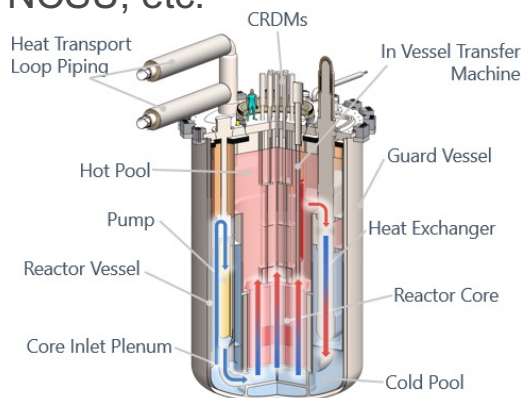
High-fidelity, advanced tools

PROTEUS/Griffin

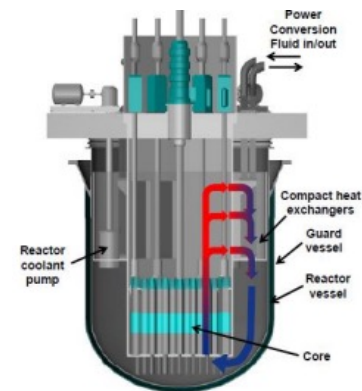
ART, TerraPower, Holos, Moltex, RPI, Purdue, Florida, Penn State, U Michigan, KSU, NCSU, etc.

MOOSE-based tools

INL, ORNL, LANL, NRC, many industries and universities, etc.



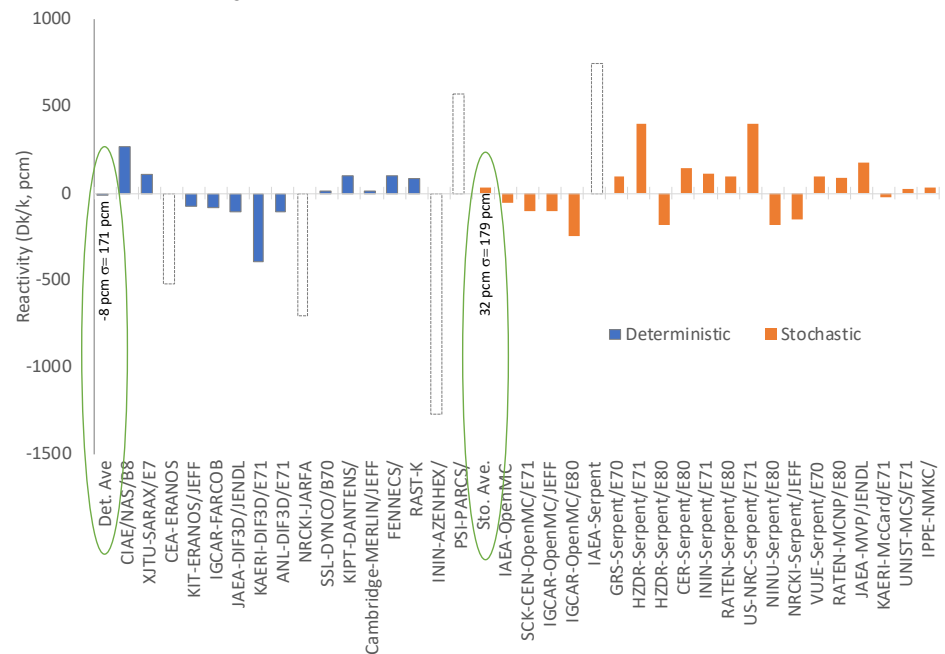
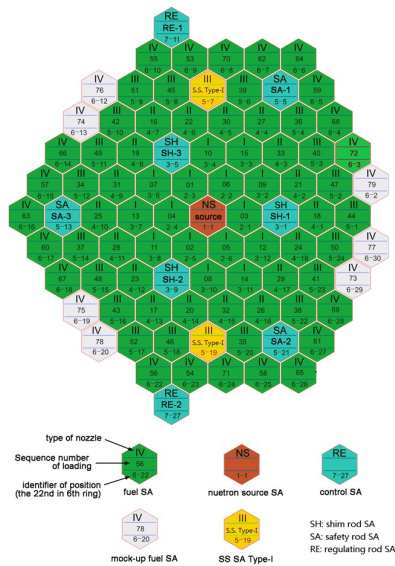
TP Natrium

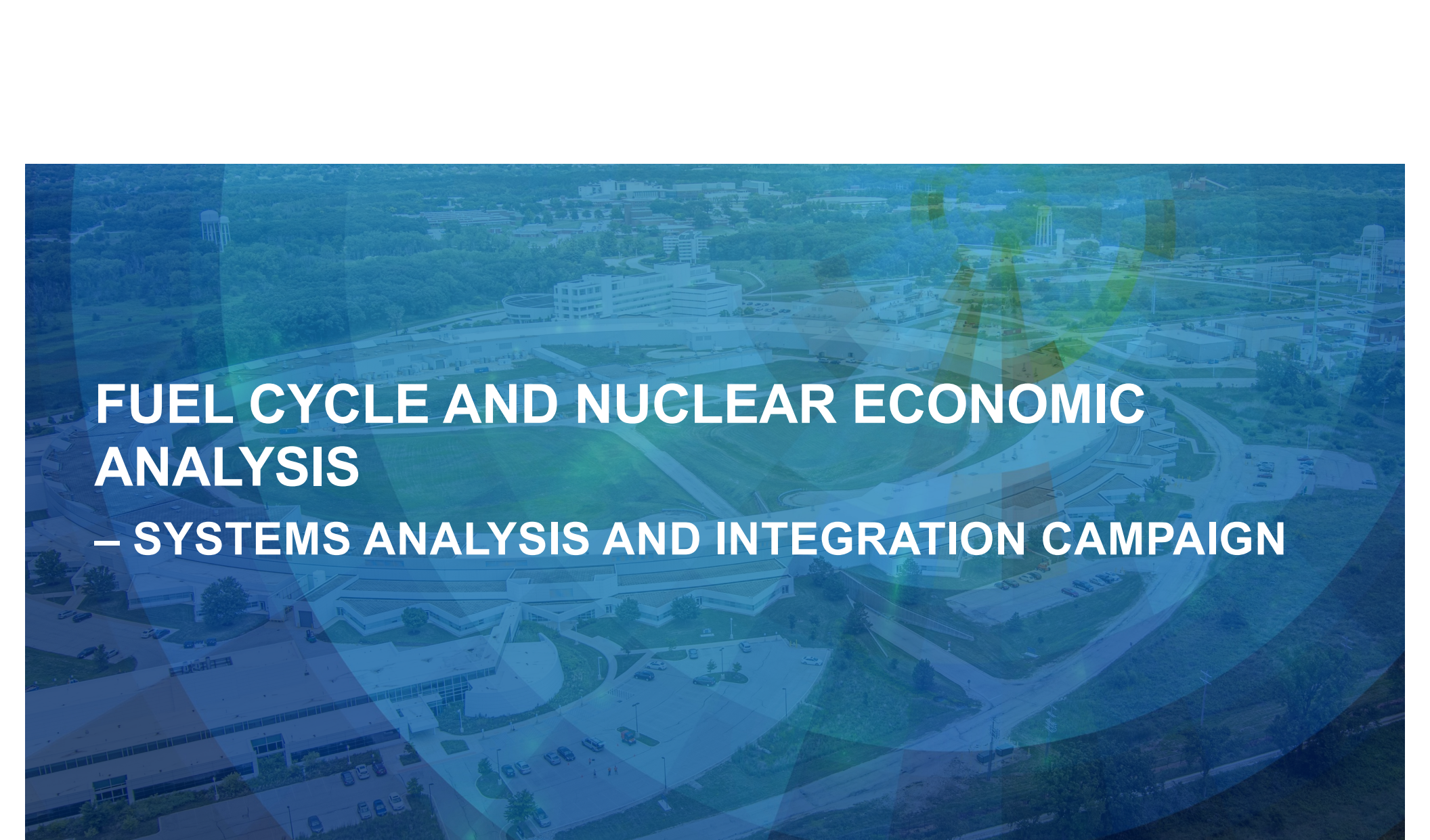


WEC LFR Argonne NATIONAL LABORATORY 1946-2025

CEFR BENCHMARK

- IAEA Benchmark was developed using CEFR start-up core physics test data
 - Clean core with measured material data (no uncertainties in compositions)
 - Criticality, CR worth, reaction rates, various reactivity coefficients were measured





FUEL CYCLE AND NUCLEAR ECONOMIC ANALYSIS

– SYSTEMS ANALYSIS AND INTEGRATION CAMPAIGN

SA&I CAMPAIGN MISSION

- **SA&I campaign is under NE-4 (Fuel Cycle Office) for strategic planning advanced fuel cycle deployment**
- **FY26 Budget Request Language**
 - SA&I activities include strategic planning and analysis as well as integrated evaluation of Fuel Cycle Laboratory R&D subprogram activities. Provide the critical capability needed to
 - analyze complex fuel cycle system options,
 - project nuclear energy demand under various scenarios,
 - assess overall nuclear technology readiness,
 - evaluate nuclear energy competitiveness and economic viability, and
 - improve understanding of the interdependencies between various subsystems and associated technologies

BASELINE SA&I AREAS

Fuel cycle analysis	Techno-economic analysis of nuclear systems	SA&I campaign competency and tools
<ul style="list-style-type: none"> Project nuclear energy demands, depending on energy policies and energy market status Assess reactor and fuel cycle facility deployment scenarios Evaluate the technology readiness level of nuclear systems Provide nuclear system information through the fuel cycle Catalog and Transmutation Library 	<ul style="list-style-type: none"> Evaluate costs of entire nuclear fuel cycle systems Assess nuclear energy markets and risks on deployment of advanced reactors Evaluate the economic readiness level of nuclear systems Develop nuclear energy market models 	<ul style="list-style-type: none"> Fuel cycle scenario analysis capability and tools (DYMOND, CYCLUS) Nuclear system information (Fuel Cycle Catalog, Transmutation Library) Long-term planning and energy market analysis tools (GCAM, A-LEAF, TIMES) Advanced fuel cycle cost analysis (ACCERT, NE-COST, Cost Basis Report, Cost reduction tool) Plant site assessment (OR-SAGE)

STRATEGIC ENGAGEMENTS

Stakeholders	Interests	Potential topics/areas of SA&I campaign
Federal and state administrations	<ul style="list-style-type: none"> - Quick and massive deployment of advanced reactor and fuel cycle facilities 	<ul style="list-style-type: none"> - Projection of nuclear demand for data center - Site assessment (C2N studies)
DOE NE-4	<ul style="list-style-type: none"> - Cost driver of advanced fuels (AFC) - Recycling impact on fuel cycle cost and disposal (MRWFD) - HALEU demand HALEU market (UFS) 	<ul style="list-style-type: none"> - Evaluation of fuel fabrication costs - Assessment of techno-economic impact of recycling technologies - Projection HALEU demand and future market
NE-5, NE-6, NE-7, NE-8, NRC, and Other DOE Offices	<ul style="list-style-type: none"> - Techno-economic assessment of advanced nuclear technologies - Deployment of adv. reactors 	<ul style="list-style-type: none"> - Cost reduction and first-mover risk mitigation strategies - TRL and ERL assessment of nuclear systems - Update of cost basis report (CBR)
Other Stakeholders (academia, industry, communities, etc.)	<ul style="list-style-type: none"> - Outreach and advertise campaign achievements 	<ul style="list-style-type: none"> - AP1000 lessons, nuclear site assessment - Improve awareness of SA&I activities/products
	<ul style="list-style-type: none"> - SA&I capabilities 	<ul style="list-style-type: none"> - Assess fuel cycle performance by Integrating capacities - Update cost base report (reactors) - Release the transmutation library and open the website
	<ul style="list-style-type: none"> - Contribution to international activities 	<ul style="list-style-type: none"> - NEA working parties (WRPS, WPFC), IAEA workshops on fuel cycle scenarios and nuclear economics, INPRO - Support TWOFCs and IEMPT conferences

KEY DRIVERS FOR NEAR-TERM ACTIVITIES

EOs (14299 – 14302) and Secretary's Memorandum in Feb. 2025

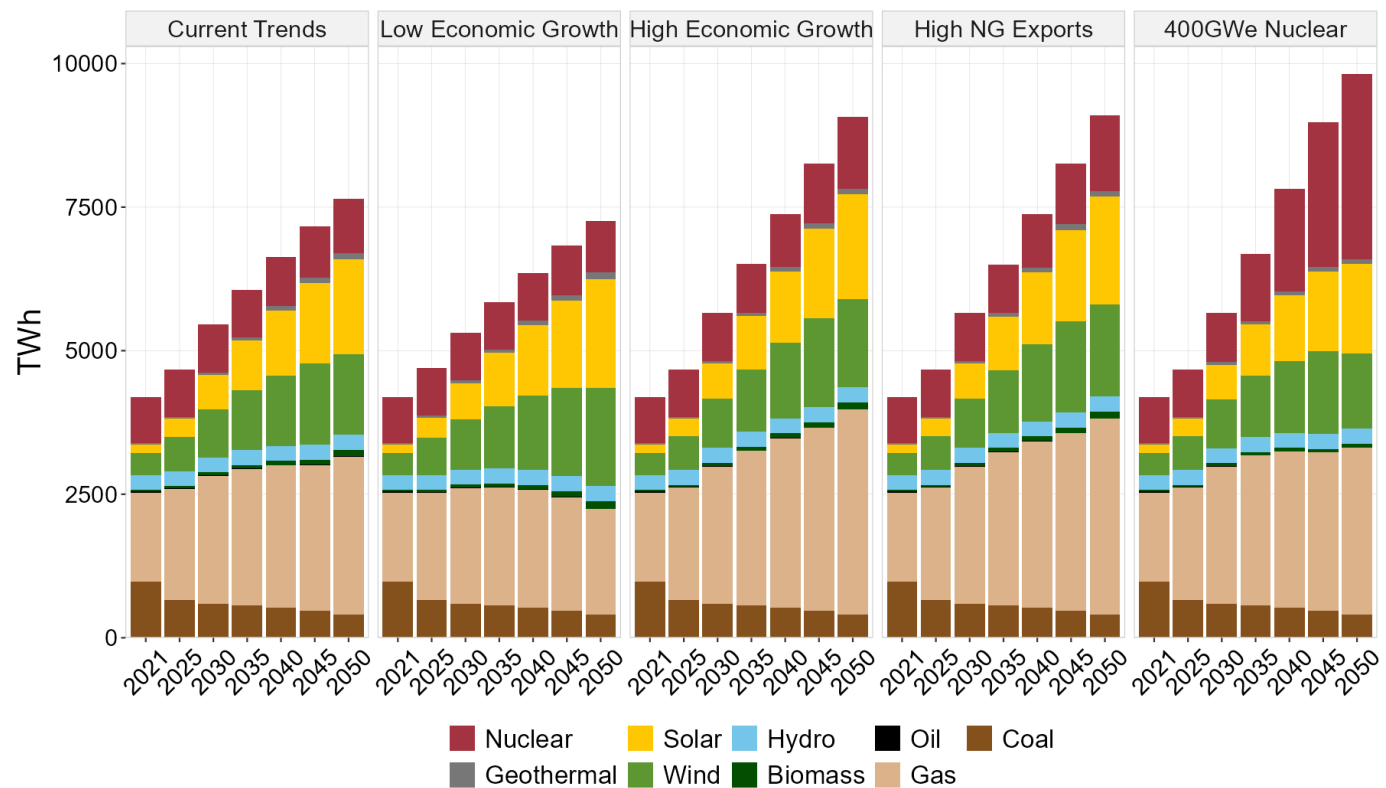
- Deployment of nuclear technologies (400 GWe by 2050) for national security through reforming the NRC and nuclear reactor testing using DOE's capabilities
- Reinvigoration of the nuclear industrial base and innovations for affordable, reliable, and secure energy technologies, including recycling and reprocessing of used nuclear fuels.

Key topics or questions

- Projection of nuclear energy demand and deployment scenarios of advanced nuclear systems
- How to achieve sustainable nuclear market for American energy dominance?
- What are reasonable costs of advanced nuclear systems and how to mitigate first-mover risks?
- Supply chain and fuel cycle capacity to meet nuclear demands and for deploying advanced nuclear systems
- Assessment of technology and economic readiness of advanced nuclear systems
- Working with INPRO to assess feasibility and strategic implications of deploying NPPs in Africa
- How many boreholes or repositories are needed, depending on fuel cycle options (once-through vs. recycling)?
- How to mitigate the nuclear cost by deployment rates?
- Fuel cycle cost if the U.S. utilizes (infinite capacity) uranium from seawater?
- The projection of nuclear fuel and demands if the current 35 pre-application reactors are commissioned?
- What are the technology and economic readiness level of the currently developing advanced reactors?

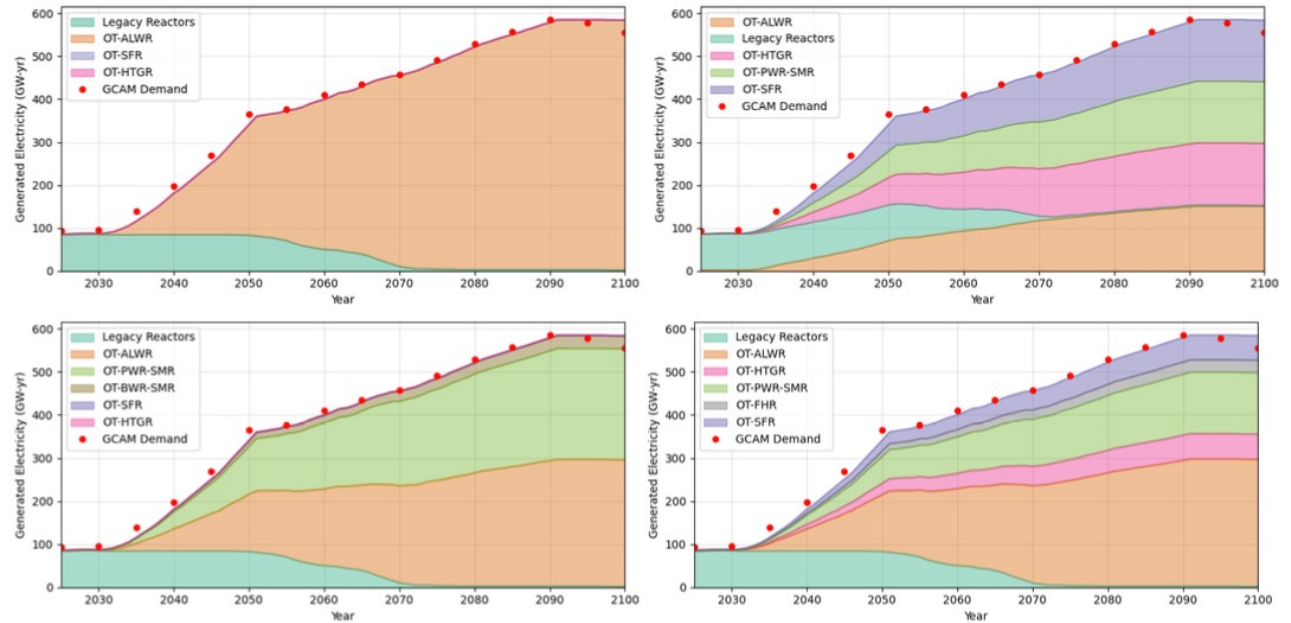
PROJECTION OF U.S. ELECTRICITY GENERATION BY FUEL TYPE (GCAM)

- Demand was projected by GCAM for various scenarios
- U.S. electricity generation ranges from 7,300–9,800 TWh across scenarios in 2050 (4,200 TWh in 2021)
- Growth is driven by data centers, light duty vehicles, and other end-use electrification
- Nuclear electricity accounts for 12–33% of total U.S. electricity generation across scenarios in 2050 (19% in 2021).



FUEL CYCLE SCENARIO STUDY (I)

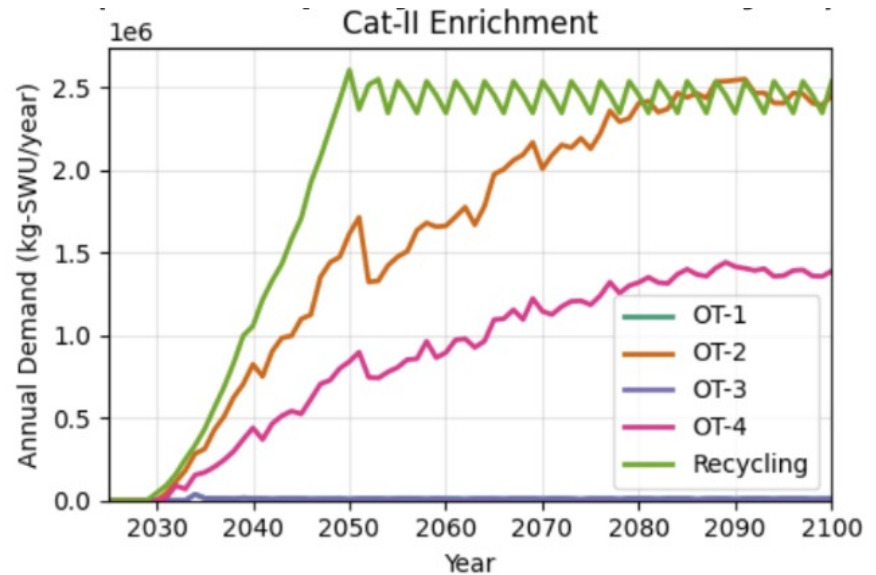
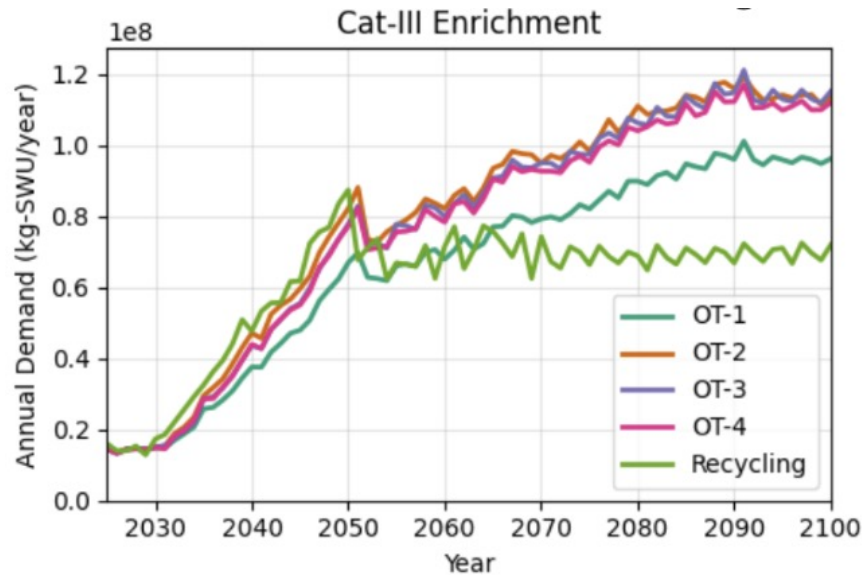
- Demands of front-end and back-end fuel cycle capacities were evaluated with 4 once-through fuel cycles and 1 recycling fuel cycle
 - OT fuel cycle variations with reactor types
- Items to be evaluated
 - Material demand flow (when, how much, cost)
 - Optimum deployment strategies (large in-front for economies of sale or many small size facilities)
 - Learning curve effect
 - Market model and validation



Deployment scenarios for 4X by 2050

FUEL CYCLE SCENARIO STUDY (II) - ENRICHMENT

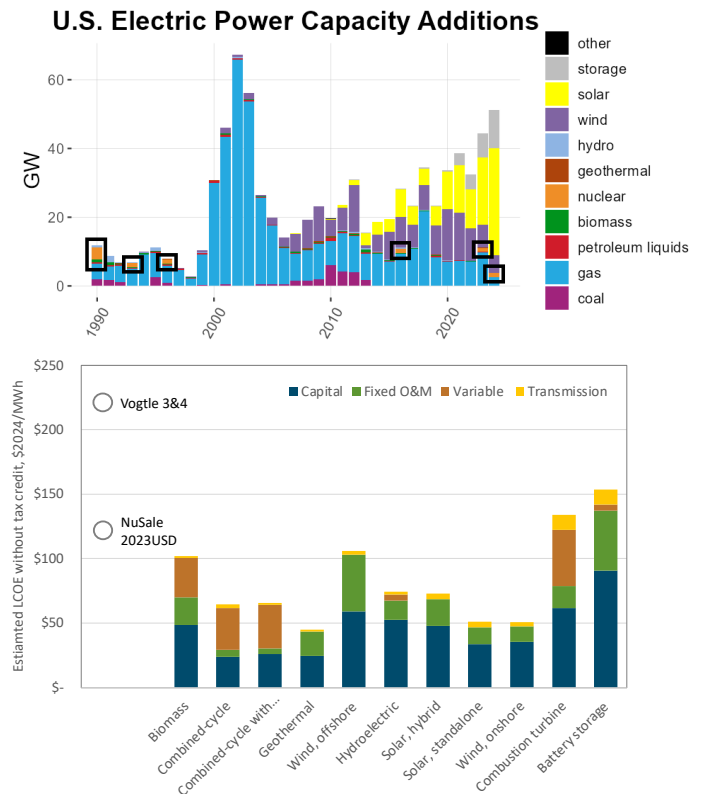
- Currently, U.S. required about 15 million SWU (approximately 80% of SWU from foreign-sourced in 2024)



Preliminary results for fuel cycle scenarios for 4X by 2050

POWER MARKET STRUCTURES IN THE U.S.

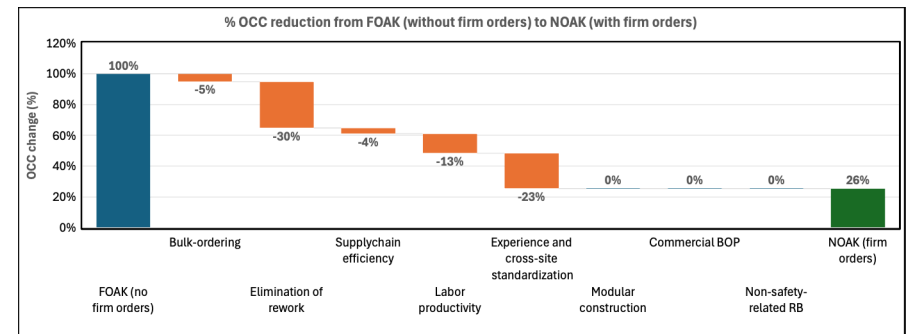
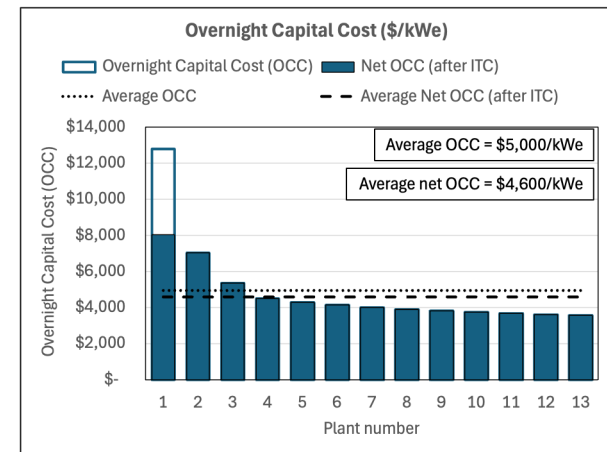
- Deregulation through legislation in the mid 1990s**
 - This led to a transition from vertically integrated utilities to competitive wholesale power markets.
 - Roughly two-thirds of U.S. electricity demand is now provided in competitive wholesale electricity markets.
 - Competitive electricity markets favor technologies with lower CAPEX, smaller unit sizes, and faster deployment (e.g., gas turbines, solar PV, onshore wind turbines, energy storage).
- New nuclear power plants built in the U.S. since deregulation are Watts Barr 2 and Vogtle 3 & 4**
 - All three plants are located in the Southeast, which remains a traditionally regulated electricity market and has relatively higher electricity demand and demand growth than other areas of the country
- FOAK nuclear is still much expensive than other baseload technologies**



Preliminary results

RECOMMENDATION FOR MASSIVE DEPLOYMENT

- **Quick movement to NOAK from FOAK is the largest cost reduction lever**
- **Mitigation of first mover risks**
 - Adopt inherently safe features in the advanced reactor design
 - Complete and standardize reactor design before construction
 - Develop stable, universal, and flexible regulatory frameworks
- **Cost Reduction through Quick Movement to NOAK**
 - To achieve significant cost reduction through learning-by-doing, support or develop large-order-book projects; develop at least 10 construction projects through three-party consortium (vendor, customer, and government)
 - Accelerate design certifications of advanced reactors
 - Develop flexible front-end fuel cycle product lines
- **Cost Reduction through Economies of Scale**
 - Develop efficient licensing process for reactor scaled-up
 - Develop a large order book for factory fabrications



Preliminary results

Systems Analysis and Integration

Latest Reports

January 26, 2026

Analysis of Stakeholder Involvement in Nuclear Power Plant Cost Overruns and Implications for Contract Structuring

This study introduces a novel framework to model cost overruns associated with four key stakeholders in nuclear power plant construction: equipment suppliers, construction subcontractors, the design and management team, and creditors.

Report Overview

August 31, 2025

Preliminary Analysis of Nuclear-Powered Data Center Scenarios

August 30, 2025

Assessment of Uranium Isotope Impacts

July 30, 2025

Assessment of Deep Burnup HALEU Fuel Impact and Requirements

June 12, 2025

Potential Cost Reduction in New Nuclear Deployments Based on Recent AP1000 Experience

NOTABLE SA&I CAMPAIGN REPORTS

- Nuclear Fuel Cycle Evaluation and Screening Report (2014)
- Technology and System Readiness Assessment Process for R&D Evaluation (2016)
- Estimated HALEU Requirements for Advanced Reactors to Support a Net-Zero Emissions (2021)
- Nuclear Waste Attributes of SMRs Scheduled for Near-Term Deployment (2022)
- Pros and Cons Analysis of HALEU Utilization in Example Fuel Cycles (2022)
- Benefits and Challenges of Converting Coal Plants into Nuclear Plants (2022) and guidebook (2023)

- Evaluation of nuclear and coal power plant sites for new nuclear capacity (2024)
- Quantifying Capital Cost Reduction Pathways for Advanced Nuclear Reactors (2024)

- The value of Recovered Uranium from HALEU used nuclear fuels (2025)
- Potential Cost Reduction in New Nuclear Deployments Based on Recent AP1000 Experience (2025)
- Fuel Cycle Cost Analysis by Integrating Fuel Cycle Scenario and Economic Tools and Data (2025)

- Nuclear outlook in the United States and globally (2026)
- Summary assessment of the pathway toward massive nuclear energy deployment (2026)
- Case studied on nuclear energy for datacenter (2026)
- HALEU market model and V&V (2026)

FUEL CYCLE EVALUATION & SCREENING STUDY

▪ Objectives

- Evaluated a comprehensive set of technology-neutral nuclear fuel cycle options (once-through, limited recycling, and continuous recycling) and identified promising nuclear fuel cycles (FY10 - 14)
- DOE provided evaluation criteria, and the campaign developed screening metrics (e.g., waste mass, activity, proliferation risk, material security, safety, utilization, LCOE, etc.)

▪ Campaign capabilities utilized

- Knowledge of various nuclear systems, reactor physics, and fuel cycle options and evaluation of evaluation metrics

▪ Key outcomes

- Conclusion on Promising Fuel Cycle Options
- Nuclear system information and evaluated metrics: ~90 nuclear systems, technologies, isotopic data, fuel cycle options
- Fuel cycle Catalog and database

Nuclear Fuel Cycle Evaluation and Screening – Final Report

Fuel Cycle Research & Development

*Prepared for
U.S. Department of Energy*

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T. Taiwo, ANL

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M. Todosow, BNL

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R. Jubin, ORNL

J. Buelt, PNNL (retired)

S. Stockinger, DOE-NV

*K. Jenni, Insight Decisions LLC/
TechSource*

B. Oakley, Scully Capital Services, Inc.

October 8, 2014

FCRD-FCO-2014-000106



FUEL CYCLE FACILITY REQUIREMENTS FOR DEPLOYMENT OF DEMONSTRATION REACTORS AND POTENTIAL FUTURE FUEL CYCLES

Report on Fuel Cycle Facility Requirements for Deployment of Demonstration Reactors and Potential Evolutionary Fuel Cycle Scenarios

Nuclear Fuel Cycle and Supply Chain

Objectives

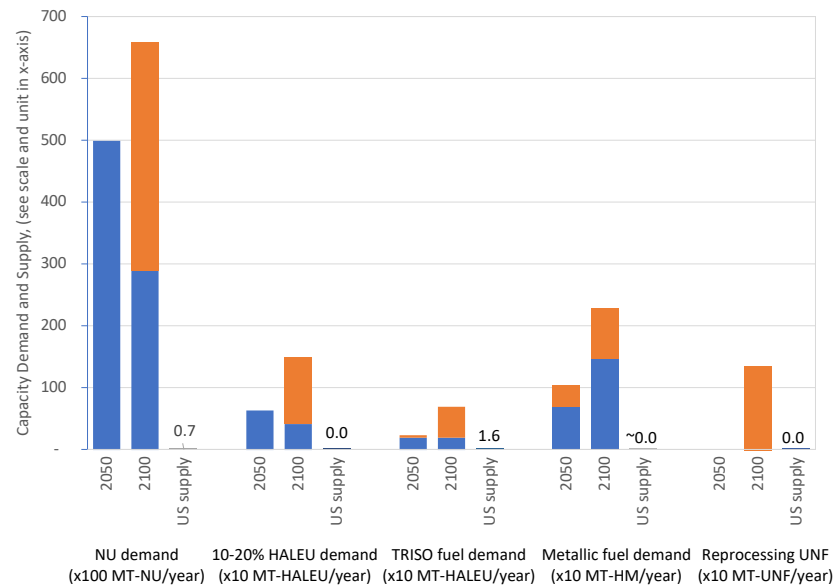
- Assessment of fuel cycle facility requirements to support the large-scale deployment of demonstration reactors and potential fuel cycle options (once-through and recycle)

Campaign capabilities utilized

- Protection of nuclear demand (GCAM)
- Fuel cycle simulation tools (DYMOND, CYCLUS)
- Reactor physics for generating data for fuel cycle scenario analyses

Key outcomes

- Projections of fuel cycle demand (NU, HALEU, TRISO, Metal fuel)
- Projection of required nuclear fuel cycle facilities (recycling, UNF, storage, etc.)



Prepared for
U.S. Department of Energy
Systems Analysis and Integration
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November 28, 2022
ANL/NSE-22/39



EVALUATION OF NUCLEAR WASTE OF NEAR-TERM DEPLOYABLE SMRS

- **Objective**
 - Evaluation of Nuclear waste attributes of Small Modular Reactors (SMRs) scheduled for deployment within this decade and comparison with a reference large Pressurized Water Reactor (PWR).
- **Campaign capabilities utilized**
 - Reactor physics expertise
 - Advanced reactor information and E&S study data
- **Key outcomes**
 - Given the analysis results in this study, there appear to be no major challenges to the management of SMR wastes compared to the reference LWR wastes.

Nuclear Waste Attributes of SMRs Scheduled for Near-Term Deployment

Nuclear Fuel Cycle and Supply Chain

Table E-2 Comparison of nuclear waste metric values calculated in this study

	Ref. PWR	VOYGR™ a)	Natrium a)	Xe-100 a)
DU mass, t/GWe-year	179	220 (1.23)	209 (1.17)	174 (0.97)
SNF mass, t/GWe-year	21.7	23.9 (1.10)	6.10 (0.28)	5.41 (0.25)
SNF volume, m ³ /GWe-year	9.58	10.4 (1.08)	5.56 (0.58)	118 (12.3)
SNF activity (Ci/GWe-year) compared to Ref PWR @ 10 ¹ , 10 ² , 10 ³ , 10 ⁴ , 10 ⁵ years		(1.07, 1.08, 1.04, 1.05, 1.08)	(0.63, 0.71, 0.63, 1.40, 1.17)	(0.79, 0.80, 0.45, 0.38, 0.58)
SNF decay heat, kW/GWe-year				
@ 10 years	40.6	42.2 (1.04)	24.5 (0.60)	32.2 (0.79)
@ 100 years	9.76	10.3 (1.05)	4.65 (0.48)	6.36 (0.65)
SNF radiotoxicity, x10 ⁸ Sv/GWe-year				
@ 10,000 years	1.21	1.27 (1.06)	1.78 (1.47)	0.413 (0.34)
@ 100,000 years	0.0860	0.0912 (1.06)	0.127 (1.48)	0.0406 (0.47)
Decommissioning LLW volume				
Classes A, B, and C, m ³ /GWe-year	645.3	573 (0.9)	N/A ^{b)}	N/A ^{b)}
GTCC, m ³ /GWe-year	0.13	0.72 (5.7)	0.0 – 0.55 (0.0 – 4.4)	0.0 – 24.5 (0.0 – 193.1)

a) Values in parentheses indicate the ratio of a waste metric to that of the reference PWR.
 b) Not available because the open information is insufficient to calculate the LLW volume.

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