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Fausto Franceschini
Consulting Engineer
Westinghouse Italy

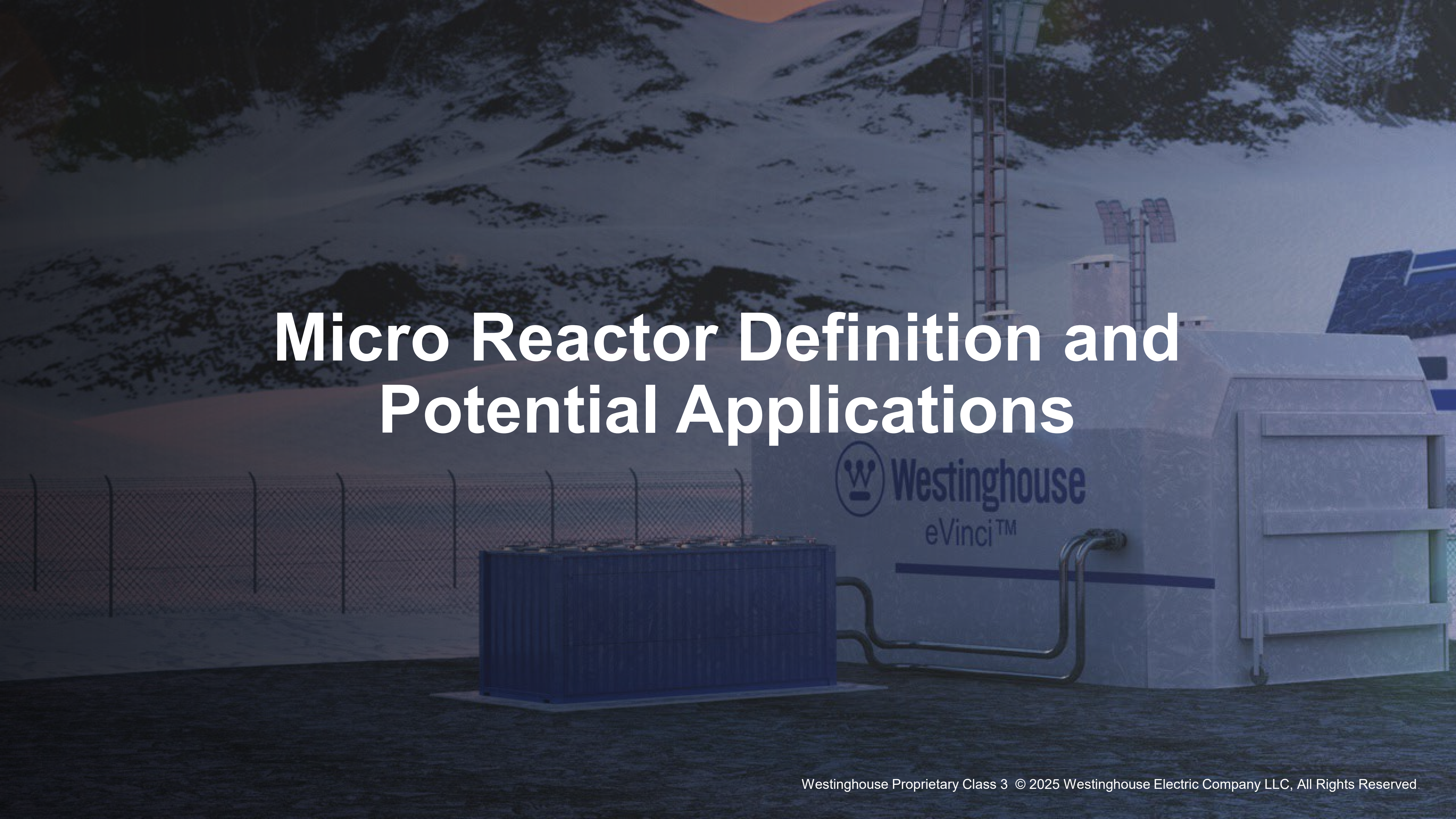
Micro Reactor
Application, Design and Analysis

IAEA-ICTP on SMR
April 14, 2026 Trieste

Outline

- What are micro reactors
  - Applications
  - Technology Options
  - Transportation
  - Economics
  - Manufacturing
  - Demonstration
  - Licensing
- Design and Analysis
  - Core Design and Analysis Approach
  - Transient and Safety Analysis
  - Fuel Rod Performance

Micro Reactor Definition and Potential Applications



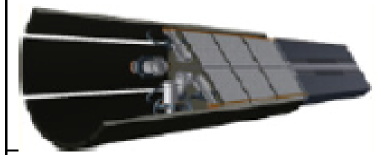
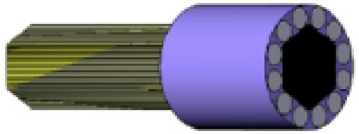
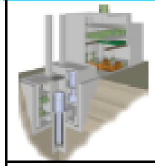
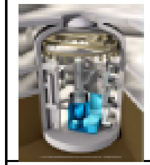
Micro Reactor Definition for U.S. Department of Energy

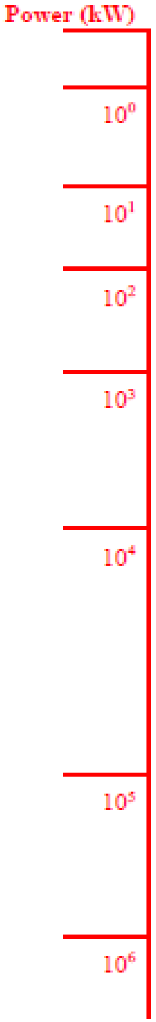
- A micro reactor is designed for use in unique applications where energy generation on the order of mega-watts is needed but otherwise unavailable or prohibitively expensive.
  - operate independently from the electric grid to supply highly resilient power for critical loads under normal and emergency conditions
  - Multiple configurations: stationary and mobile
- Micro Reactors generally produce less than 20 megawatt thermal (MWth):
  - manufactured and assembled in factory
  - easily transportable (e.g., truck, train, plane, or ship),
  - neutronically simple to enable semi- or fully-autonomous operation
- The use cases for the generated energy may call for electricity production, direct use of process heat, or both

Micro Reactor Key Benefits

- **Highly Resilient and Reliable**
  - Simplicity. Minimal moving parts. Passive safety
  - Long core life with highly reliable power conversion systems
- **Low Footprint and Environmentally Benign**
  - Can be located in close proximity to end-user due to small footprint
  - No greenhouse gases emitted
- **Flexible and On-Demand Operations**
  - Produce power on-demand. Load follow to match changes in demand.
  - Compatible with renewable and other intermittent sources of energy.
- **Electricity and Heat**
  - Heat can be used for industrial applications such as oil refining and chemical processing.
  - In colder climates, heat can be used for district heating
  - Water desalination and purification.
  - Hydrogen generation
- **Simple and Safe**
  - Simple to operate due to their small size, inherent level of safety and security, and the incorporation of advancements in technology
  - Many designs are semi-autonomous requiring very few human actions to operate.
- **Fast on-site installation**
  - Manufactured and assembled in factory and shipped to site for deployment
  - Quickly connected to the microgrid

Where do Micro Reactors Fit?

	Electric Power	Type	Application(s)
	500 W – 10 kW	Non-Light Water Reactor (LWR)	• Deep space power
	10 kW – 1 MW	Non-LWR	• Space propulsion • Planetary surface power • Military applications
	1 MW – 10 MW	Non-LWR	• Military bases • Remote locations • Disaster relief
	10 MW – 50 MW	Non-LWR	• Power to grid • Military bases • Process heat
	50 MW – 300 MW	LWR & Non-LWR	• Power to grid • Small cities • Burning of actinides
	1000 MW	Mostly LWR	• Power to grid



[a] The limit of 20 MW_{th} allows for classification of microreactors as Hazard Category 2 per 10 CFR 830, DOE-STD-1027.

Microreactor Market Applications

- Data Centers
- Critical Infrastructure
- Defense
- Remote Communities
- Remote Industry (Oil & Gas, Mining)
- Expanded Industry
- Maritime
- Universities & Research
- Disaster Relief & Recovery
- Space Missions

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Potential Applications: Remote Communities

- **Dependent on diesel generators for power, very far from any power grid, diesel supplied electricity is costly and hazardous**

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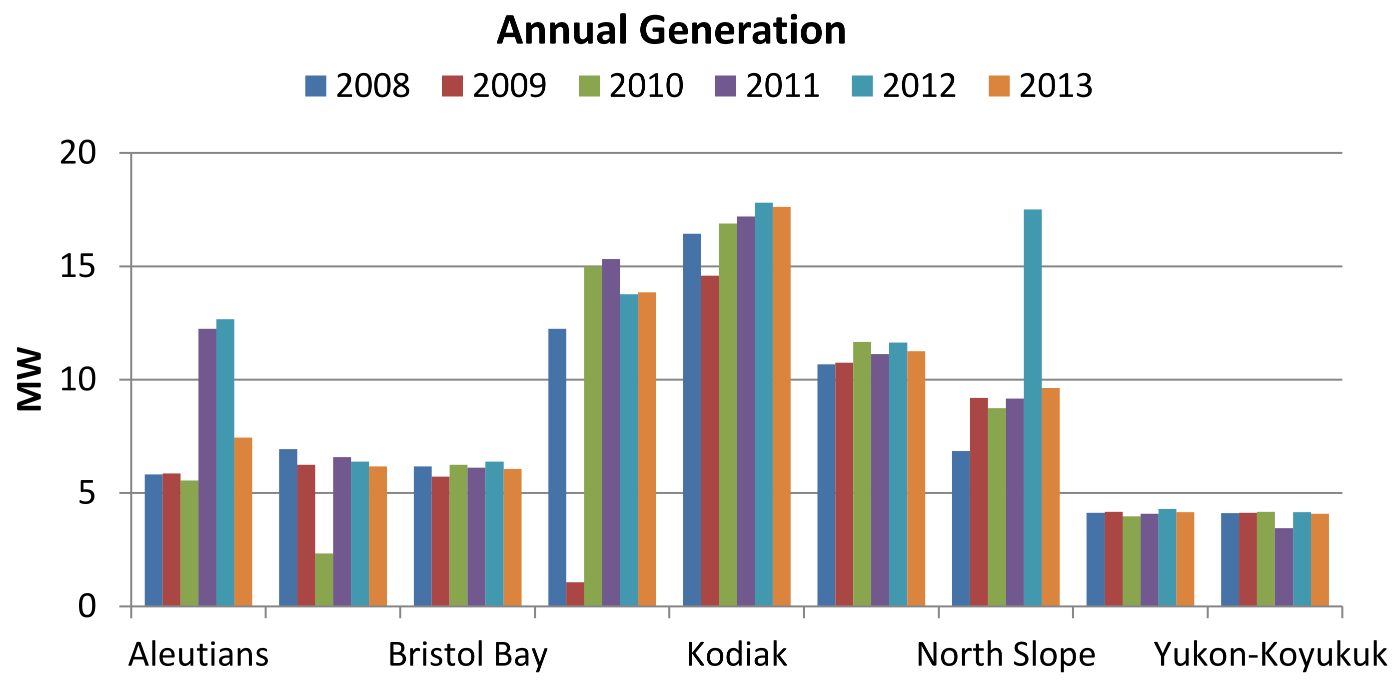
Case Study: Alaskan Remote Communities

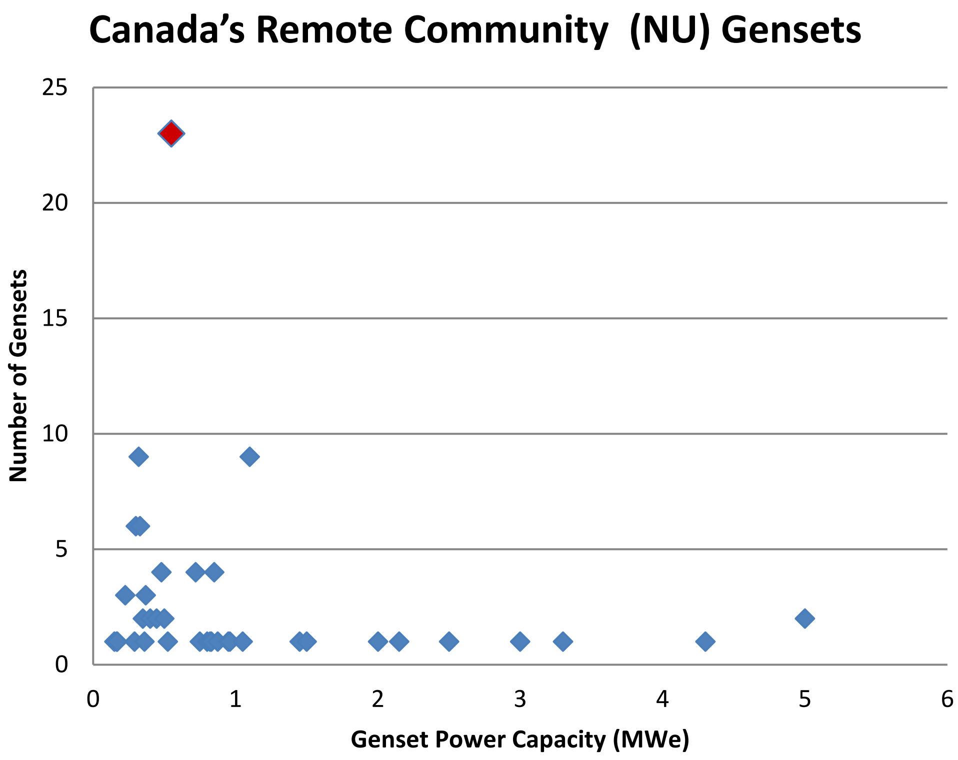
In rural Alaska, electric power cost varies between $0.50 - $1.50 kWh and heating fuel cost can vary between $1.40 - $10 per gallon.

- The harsh climate means there is a limited window for fuel to be delivered
- Diesel provides 90% of the electric power for rural areas.

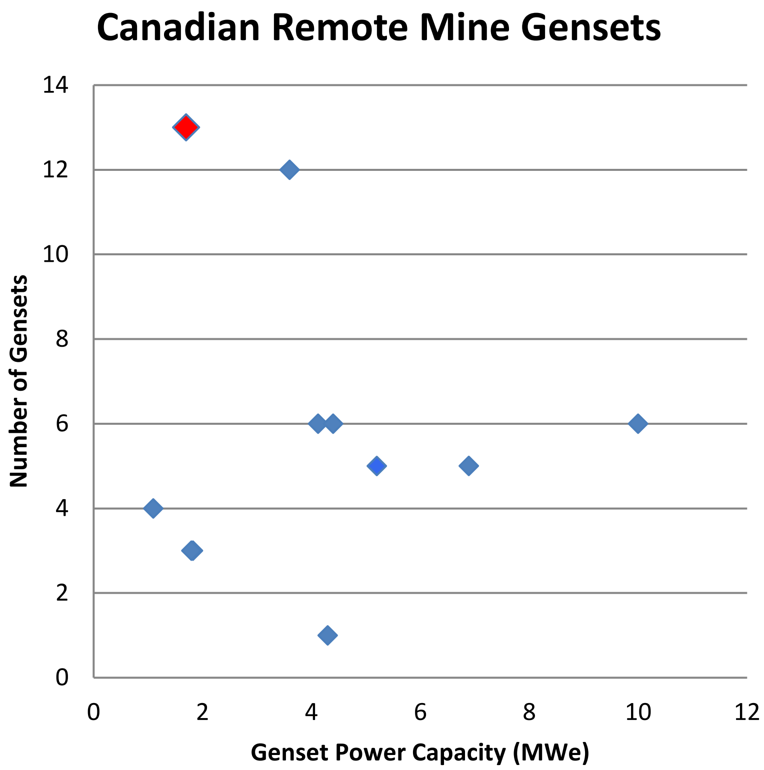


Source: Idaho National Laboratory, September 2018

Case Study: Canada's Diesel Generator Size Distribution



Average Genset Size ~ 0.79 MWe



Average Genset Size ~ 5 MWe

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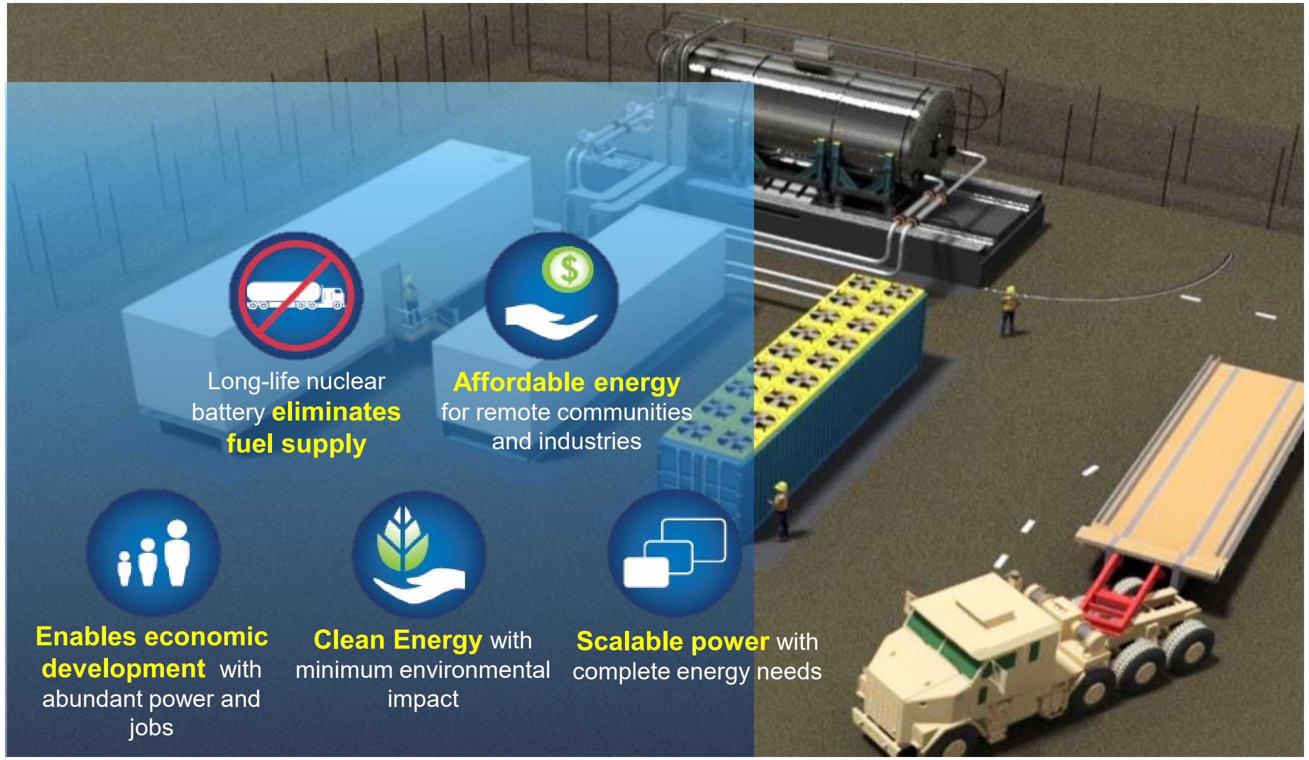
Potential Applications: Isolated Towns or Islands

- Special applications to utilities to extend presence in ‘off the grid’ conditions, or extended loss of power conditions
- Emergency backup power generation during or after natural disasters (hurricanes, et al) when major long term damage to grid is experienced.



Hurricane Maria striking Puerto Rico in 2017

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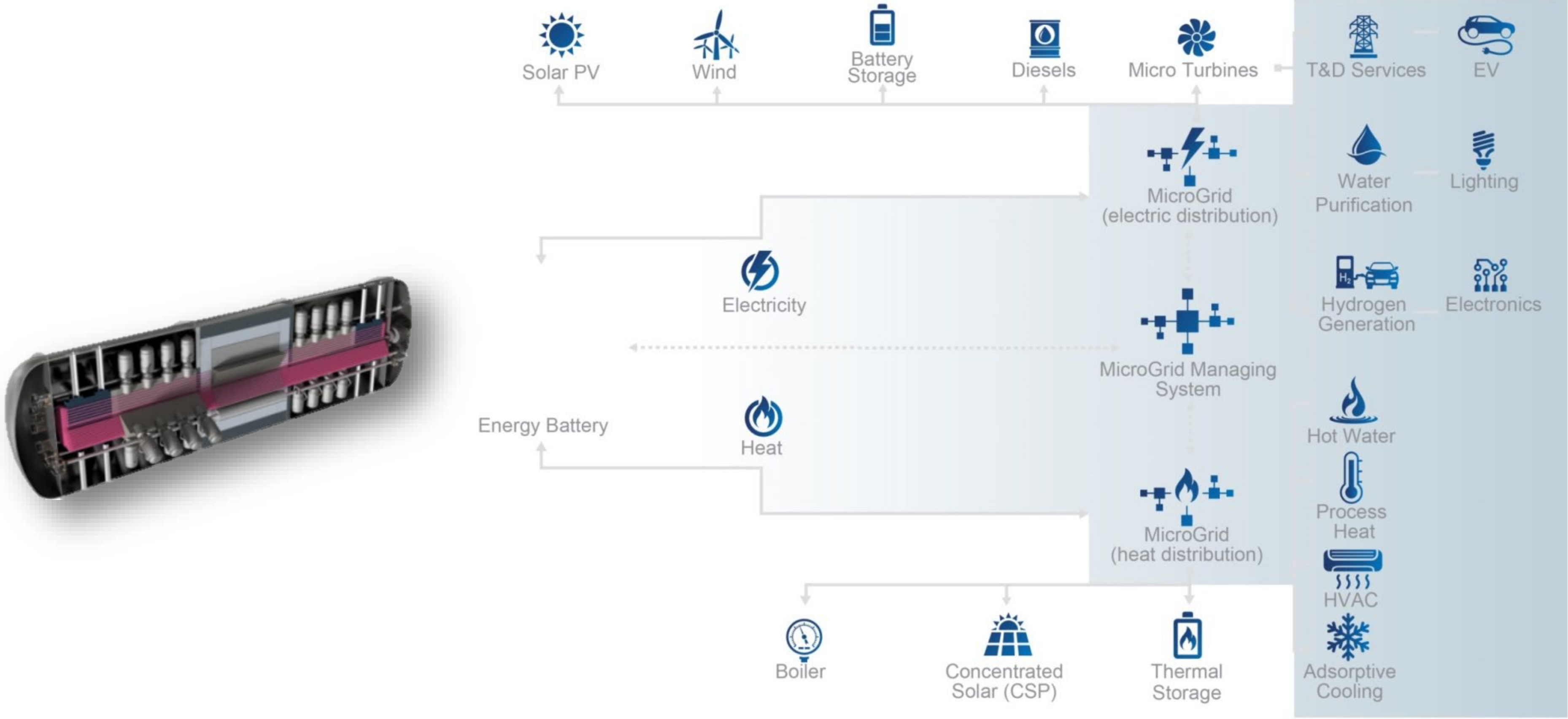
Potential Applications: Smart-Grids and Distributed Generation

- Micro Reactors provide the distributed generation market with an autonomous battery-type capability that meets the complete energy needs of the consumer



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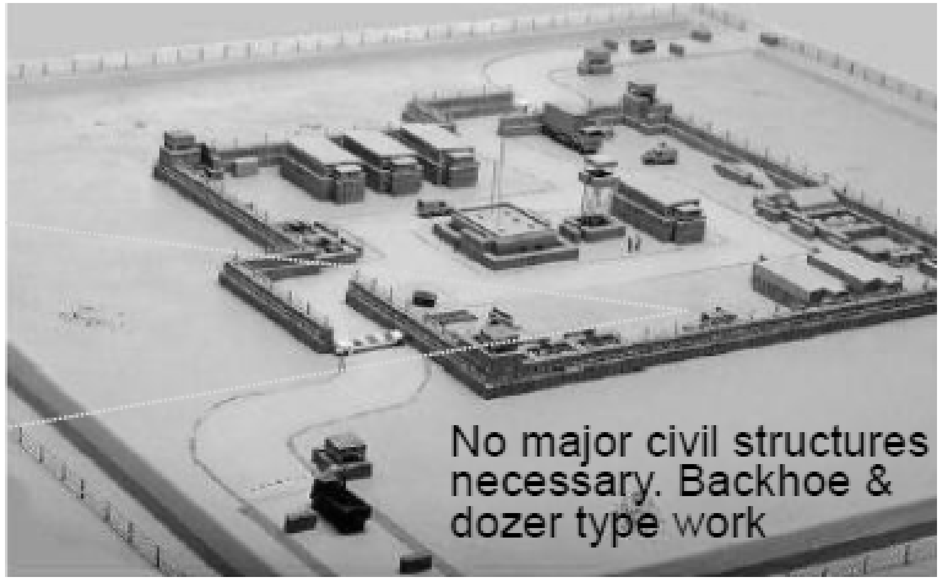
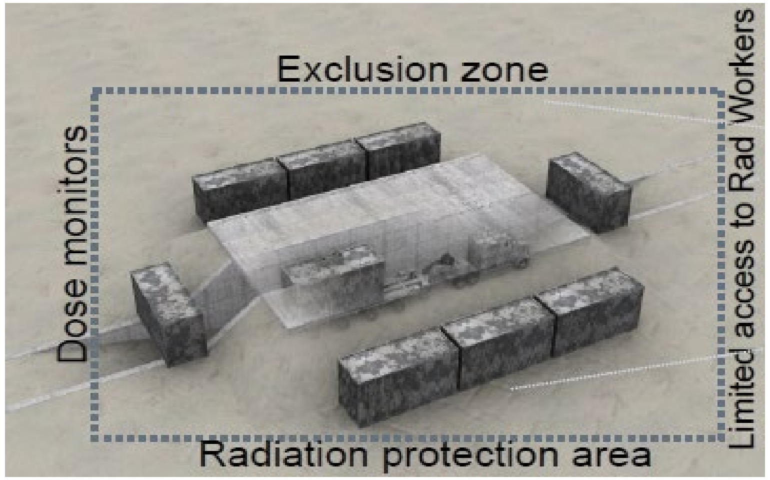
Potential Applications: Special Purpose Customer

- **An entity, company or community which has unique power consumption demands that are tailored to a safe, long term, highly reliable energy source**
- Examples are military bases





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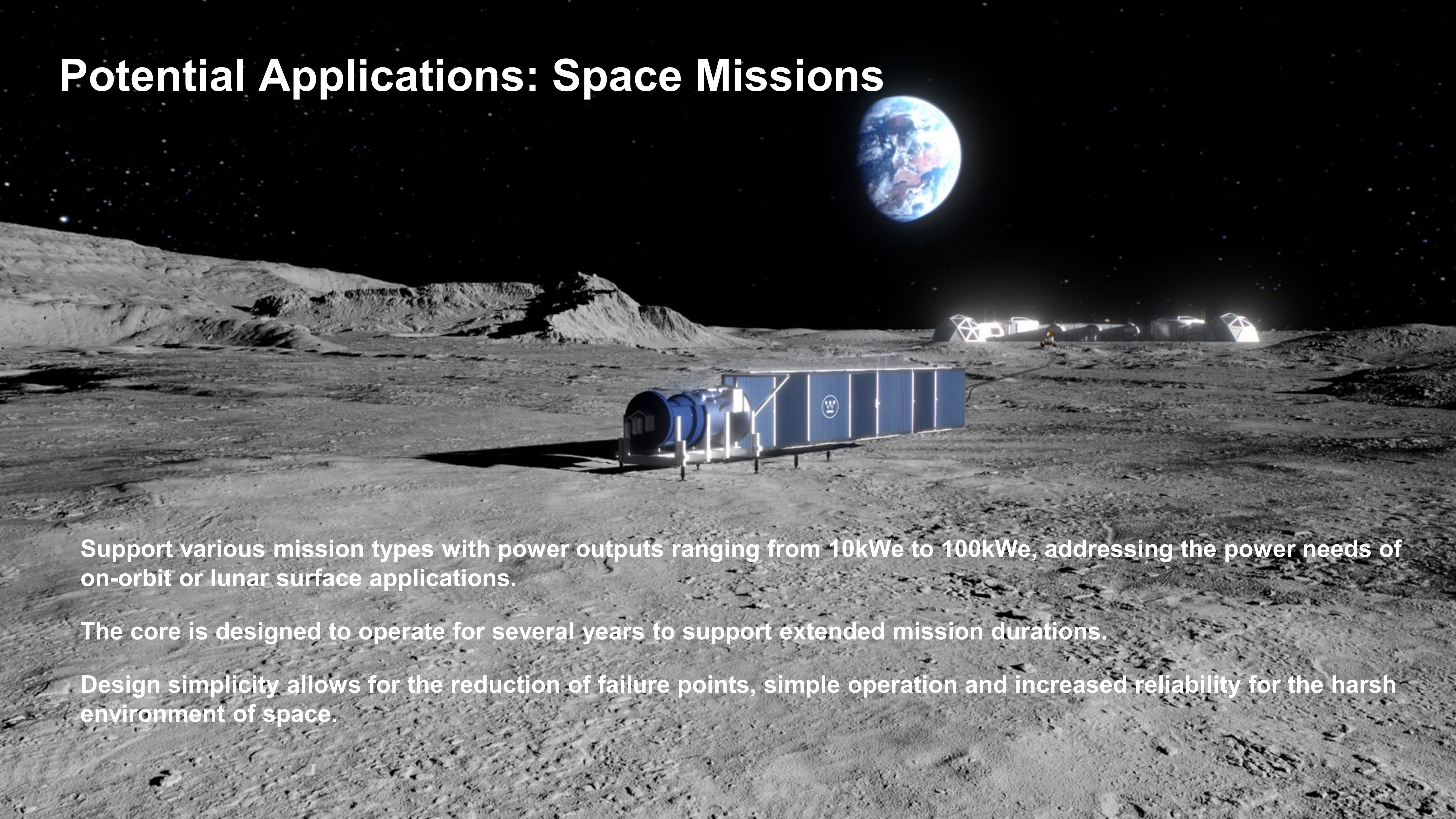
Potential Applications: Space Missions



- Support various mission types with power outputs ranging from 10kWe to 100kWe, addressing the power needs of on-orbit or lunar surface applications.
- The core is designed to operate for several years to support extended mission durations.
- Design simplicity allows for the reduction of failure points, simple operation and increased reliability for the harsh environment of space.

Technology Options

Reactor Types (1)

- **Heat Pipe Reactors:** These reactors typically use sodium (Na), potassium (K), or NaK heat pipes, which operate at high temperatures around the boiling point of the working fluid contained in the passive, self-regulating heat pipes

- **High-Temperature Gas Reactors** (HTGRs) using tristructural isotropic (TRISO) fuel. These reactors are typically designed to use forced circulation of helium for the primary coolant through the core

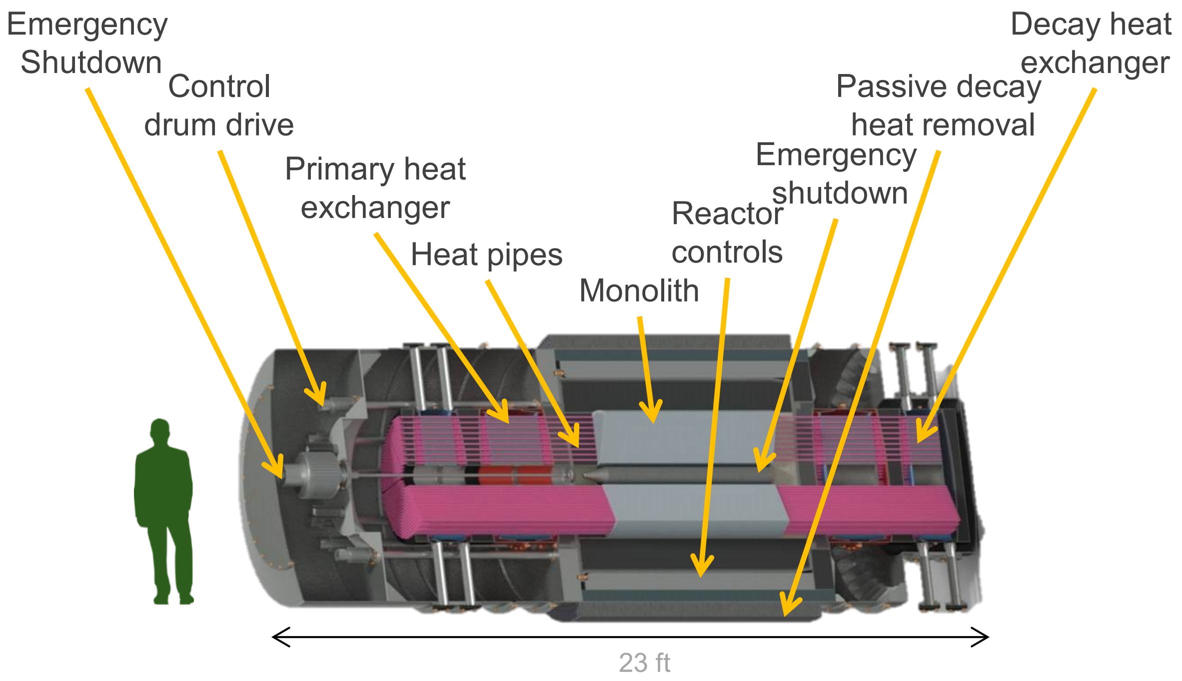
Reactor Types (2)

- **Liquid metal reactors** operate in a fast neutron spectrum and circulate molten sodium, lead or lead-bismuth as the primary coolant. The reactor coolant is nominally at low pressure and has a high boiling point. Higher corrosion concerns but elimination of boiling concerns for heavy liquid metal reactors, plus possibility to eliminate the intermediate circuit due to their compatibility with air/water/sCO2.

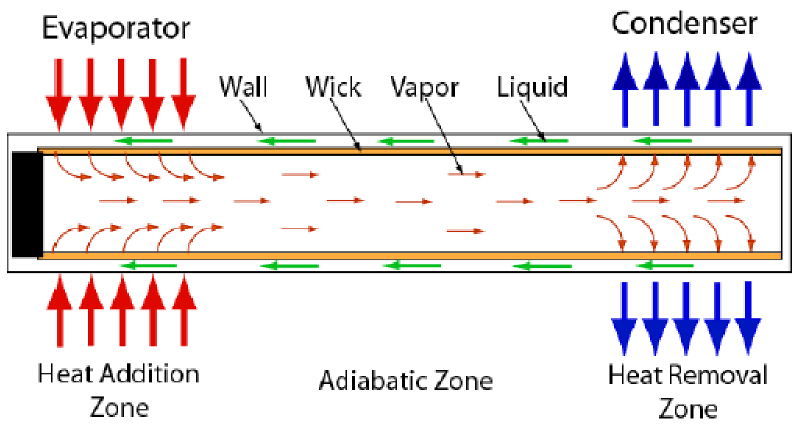
- **Molten Salt Reactors** based on chlorine salts or fluoride salts. The fuel can be circulating or not. These reactors typically use an intermediate heat exchanger (IHX) to transfer heat from the molten salt to the power conversion system, which is detrimental to plant compactness

Example of Heat Pipe Reactor –eVinci™

- Combined heat & power: 0.2-5 MWe, > 600ºC
- Fully factory built, fueled and assembled
- Up to 10-year fuel life
- < 1 month onsite installation
- Inherent safety
- Near Zero EPZ
- Autonomous load-follow capability
- Heat pipe technology
- Solid monolithic core block
- Minimal moving parts
- Greenfield decommissioning
- Small footprint



Heat pipe operation schematics



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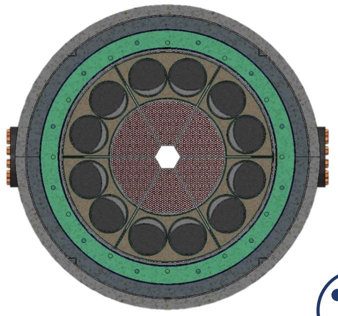
Reactor Control

- Minimum number of personnel on site is a requirement
- As a result, **a common goal for micro reactor developers is to target inherently safe self-regulating designs with a minimum number of components and limited need for maintenance**
- Use of “natural” means to control the reactivity: reactivity feedback effects such as Doppler, thermal expansion and negative moderator temperature coefficient; advanced cooling methods like using devices with high thermal conductance (heat pipes); and active methods like reactivity control drum rotation
- Load-following is an important feature of micro-reactors. It is achieved by a combination of feedback effects and active control based on monitoring certain reactor parameters

Reactivity control rotating drums →



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Core design

Specifics of micro-reactor core design:

- **Core life of 3-10 years. Typically single-batch designs**
- Small power density core facilitates long cycle lengths
- Solid core employed in heat-pipe designs
  - Reduction of the design complexity and increase in reliability by avoiding or minimizing use of moving elements in the core

Fuel Options

- **Micro-reactors can be very flexible in terms of fuel type utilization**
- The following fuel options are feasible for heat-pipe reactors: UO_2, UN, U_3Si_2, MOX, U-10Mo and TRISO at different enrichment levels.
  - TRistructural-ISOtropic (TRISO) fuel has high temperature radiation resistance and the ability to confine fission gases, and also has enhanced proliferation-resistant attributes
- Often High-assay low-enriched uranium (HALEU) fuel is required (^{235}U up to 19.9 w/o).
- The fuel selection is based on the reactor applications and selection of the materials used for other reactor components.

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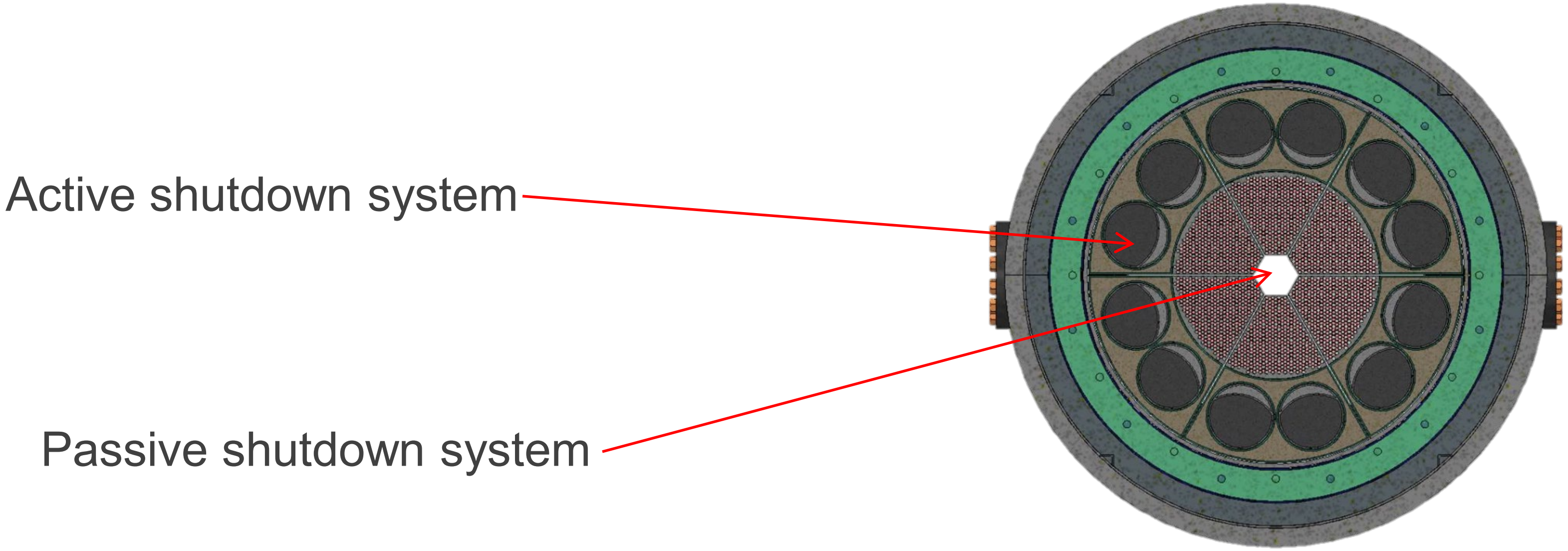
Shutdown Mechanisms

- Enhanced safety features of micro-reactors include use of reactivity feedback effects such as Doppler and thermal expansion, passive shutdown systems activated without I&C signals and shutdown methods using I&C signals.



Safety Approach

- **Level 1** – Prevention of abnormal operation and failures
- **Level 2** – Control of abnormal operation and detection of failures
- **Level 3** – Control of design basis accidents
  - Reactor shutdown
  - Passive decay heat removal
- **Level 4** – Control of severe plant conditions
- **Level 5** – Mitigation of radiological consequences
  - Procedures and Plans for Response

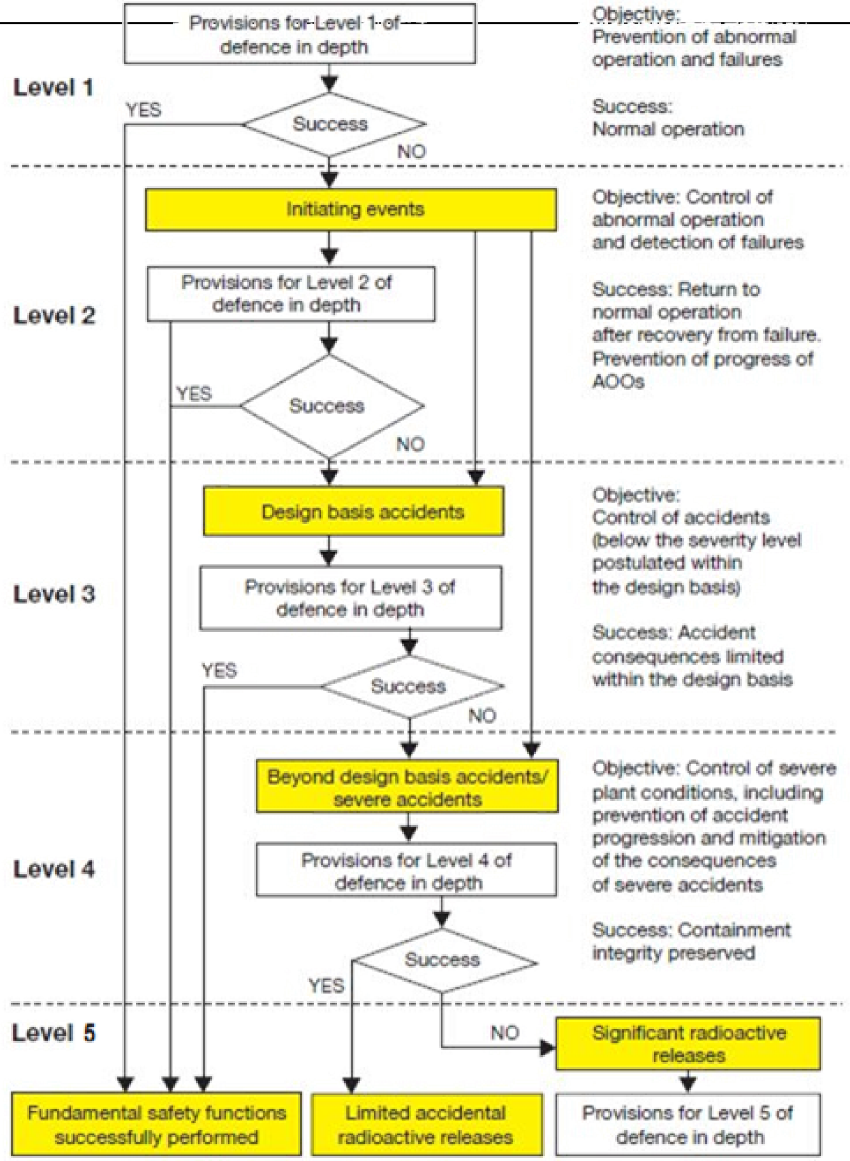
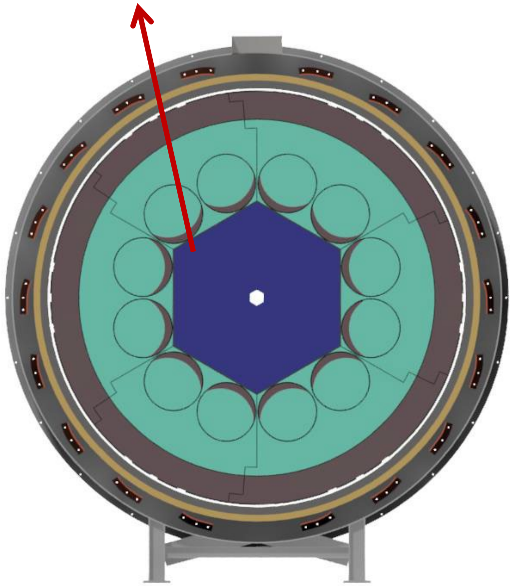


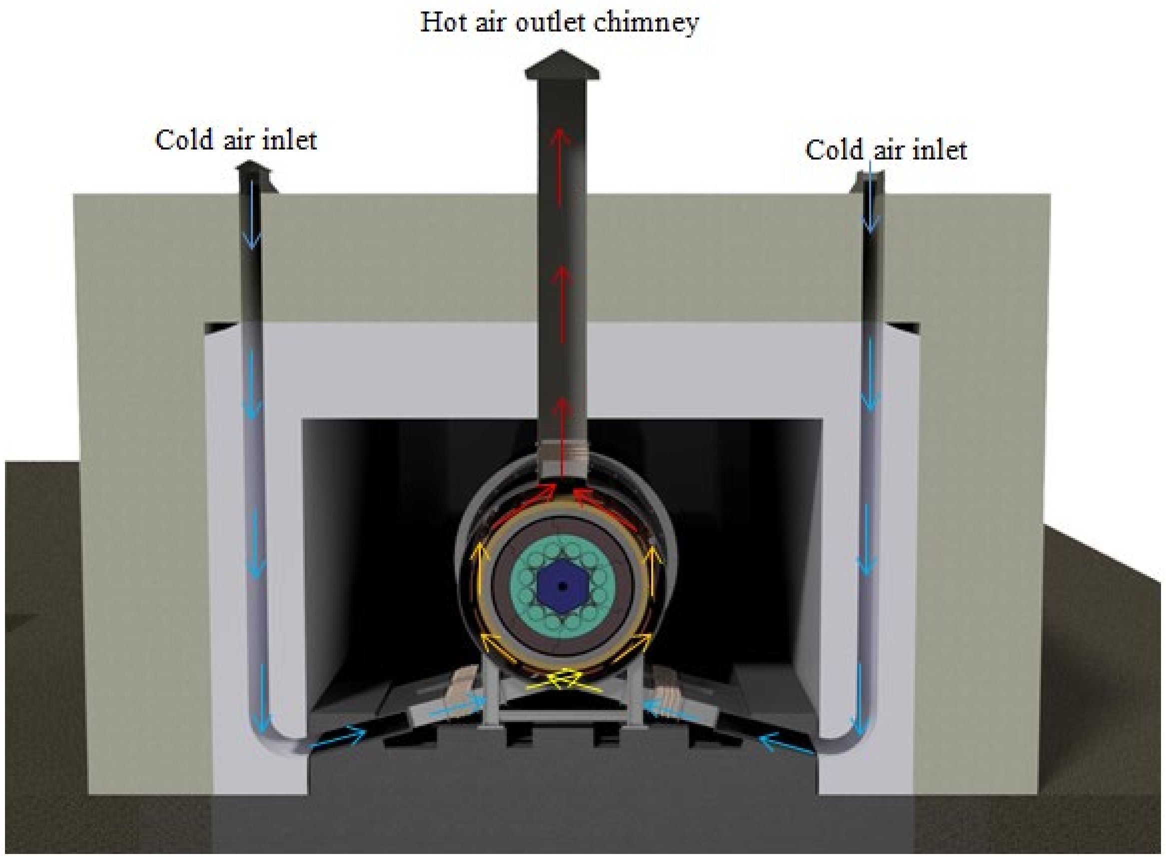
Fig. 1 of IAEA SRS-46 *Assessment of Defence in Depth for Nuclear Power Plants*

Passive Decay Heat Removal

- Air is typically the ultimate heat sink for decay heat removal in micro reactors

Decay heat pathway from reactor to outside of canister via conduction & radiative heat transfer





Power Conversion Systems of Micro Reactors

Goals

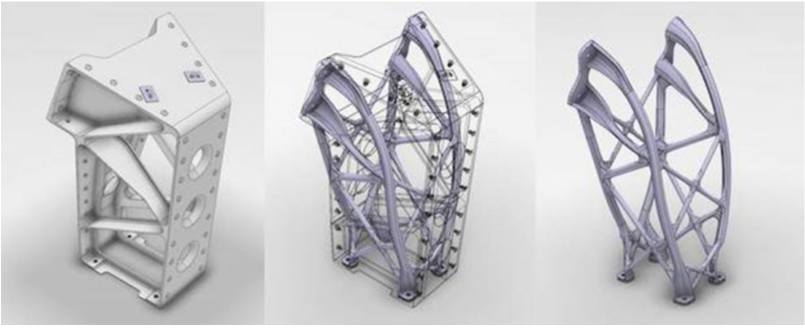
- Simple
- No Maintenance
- Reliable
- High Efficiency
  - Traditional cycles get less efficient with smaller size
- Compact
- Integrated: if possible
- Minimized Seals/Leak Points

Technology Options

- Brayton Cycle
- Organic Rankine Cycle
- Combined Cycles
- Supercritical CO2
- Free-Piston Stirling

Manufacturing Micro Reactors

- **Maximize in-factory fabrication, up to reactor manufacturing on an assembly line**
  - Suits the goals of rapid deployment and transportability
  - Reduces construction times and costs
  - Improves reliability and standardization
  - Reduces learning curve
  - Class “A” facility required as whole reactor with fuel is assembled in the factory
- Advanced manufacturing techniques are expected to play an important role in micro reactors→ smaller reactor components



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Transporting Micro Reactors: Conveyance Options

- Air Transport
- Land Transport
- Rail Transport
- Road Transport
- Sea Transport

Transportation Challenges of Micro Reactors

- **Appropriate transportation strategy to:**
  - **Reach remote communities**
  - **Rapid deployment on-site**
- Often micro reactor developers **express goal of transporting fueled reactor from assembly-line to the deployment site**
- For these reasons **transportation of micro reactors can be similar to fuel transportation** with related challenges from maintaining containment and ensure sub-criticality in case of accidents, plus weight/volume considerations come into play

Transportation Regulations - USA

NRC/DOT regulates shipments in US

- NRC
  - 10CFR71 establishes shipping standards and requirements
  - Approves the design, fabrication, use and maintenance of shipping containers for radioactive material
  - Regulates the physical protection of spent fuel during transit
- DOT
  - 49CFR171-178 relevant to shipment of radioactive material
  - Regulates shippers of hazardous (radioactive) materials
  - Oversees vehicle safety, routing, shipping papers, emergency response and shipper training
  - Authority for approving shipments outside US

Transportation Regulations - International

IAEA regulates international shipments

- IAEA Safety Standard SSR-6 establishes shipping standards and requirements
- 10CFR71 compatibility with IAEA
  - Currently compatible with the 2009 version of the IAEA safety standard [NRC-2008-0198]
  - Currently being updated to be consistent with the 2012 version of SSR-6 (ECD Dec 2020)*
- International transport of fissile material will require multilateral approval
- For international shipments, micro reactors will need to satisfy both the US and IAEA transportation requirements

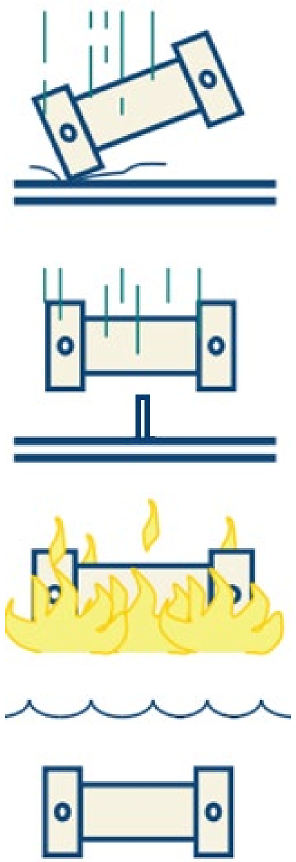
*Comparison of regulatory differences is provided in ORNL/TM-2014/658

Hypothetical Accident Conditions (HACs)

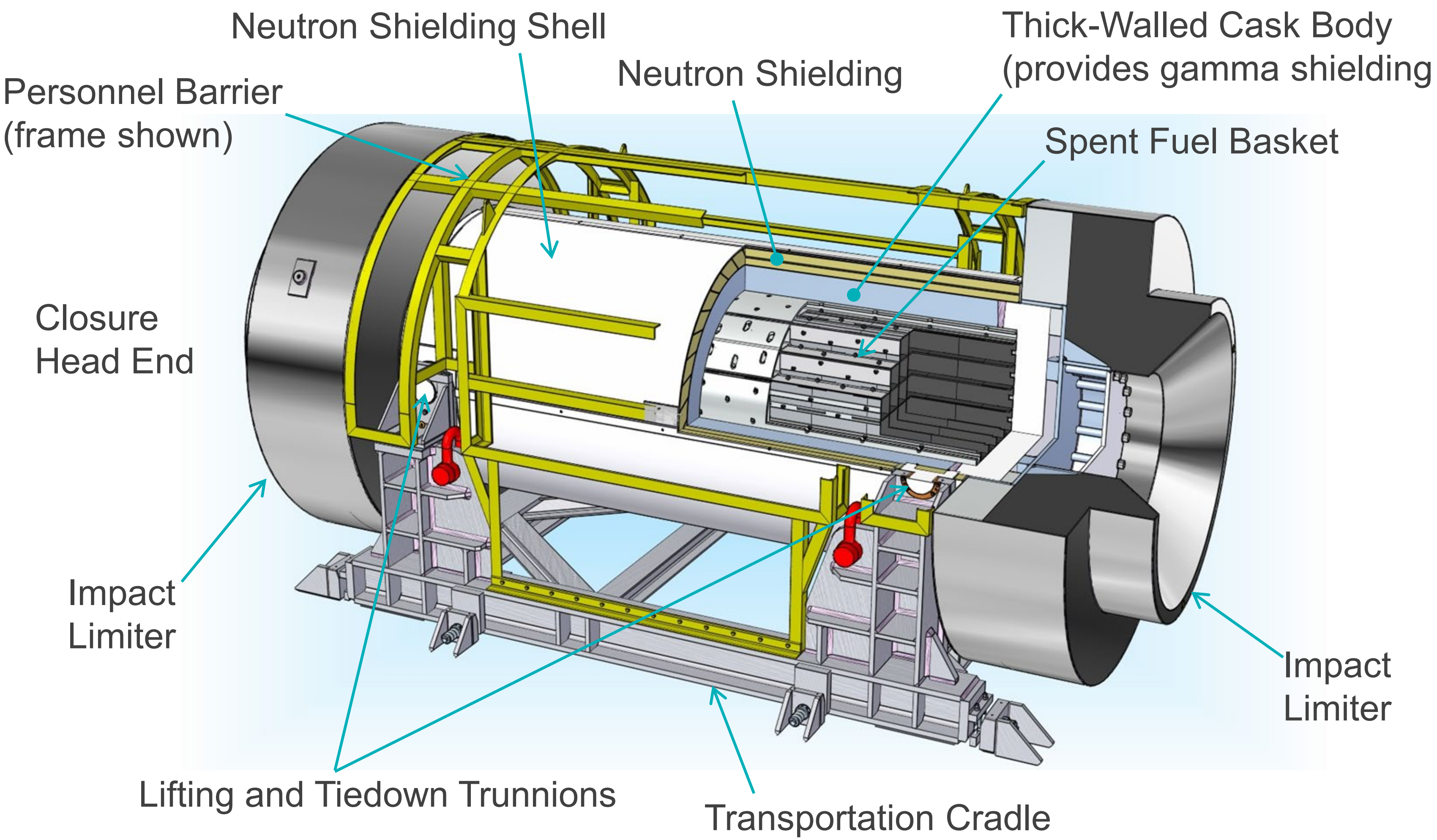
- HACs for fissile and Type B packages in 10CFR.73
- Evaluate the following in the sequence shown(1)
  1) 30-ft drop onto rigid target to maximize damage(2)
  2) 40-inch drop onto a 6-inch diameter steel puncture bar of sufficient length to produce maximum damage(2)
  3) 30-minute engulfing hydrocarbon fuel fire (1,475° F)
  4) Water immersion of damaged package
- The expected analysis content is described in NUREG-1617 and Regulatory Guide 7.9

(1) IAEA requires that the 30-foot drop and puncture test be sequenced to maximize cumulative damage leading into fire test

(2) Evaluate a series of drop orientations to determine worst case damage



Spent Fuel Shipping Container Features



ENSA ENUN 52B

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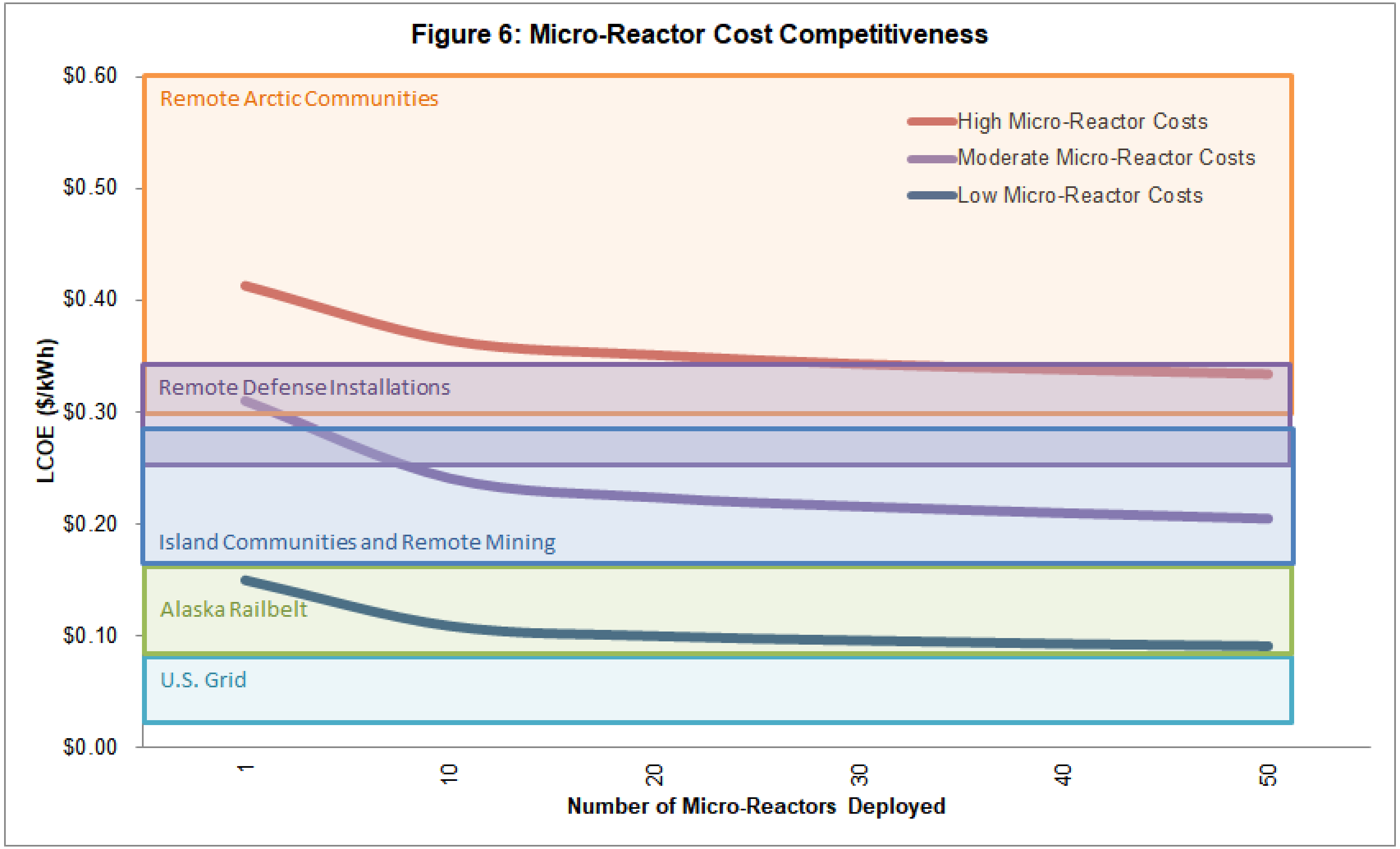
Economics Considerations on Micro Reactors

- Economics of large reactors is favored by smearing large fixed costs (with mild or no dependency on reactor size) over a relatively large power rating ("economy of scale") to obtain good LCOE. However a large initial investment is required plus long construction times and likelihood of delays penalize economics
- **Economics of micro reactors is favored by design simplification, factory manufacturing, economy of scale in production volume, shorter learning cycle, shorter construction time and minimal on-site construction**
- While it is unlikely that micro reactor will ever compete with large reactors on an LCOE basis, **they can penetrate markets with higher generating costs where energy resilience is at premium**

Micro Reactor Cost Competiveness



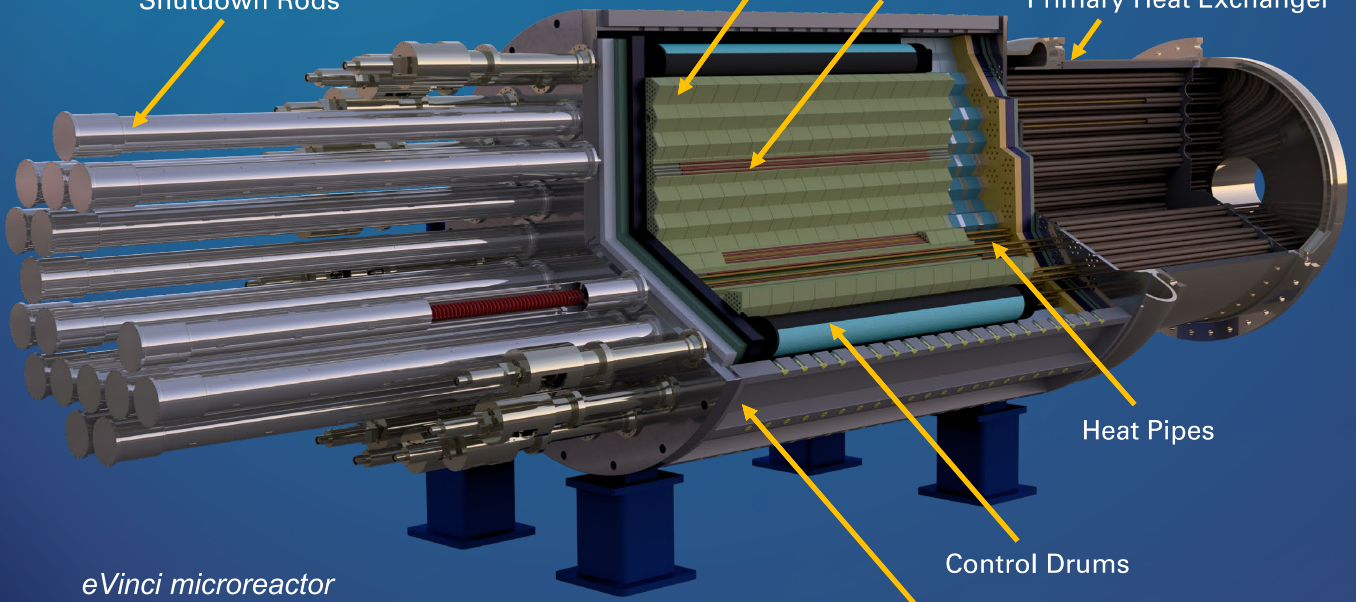
Source: NEI Technical Report Cost: "Competitiveness of Stationary Micro-Reactors for Enduring Locations" (NEI, April 2019)

Case Study: the eVinci Microreactor

Key Technologies & Components
Manufacturing
Design and Analysis
Demonstration
Licensing

THE EVINCI MICROREACTOR

HEAT PIPE TECHNOLOGY FOR THE WORLD'S FIRST 'NUCLEAR BATTERY'



eVinci microreactor

- Factory built, 5 MWe reactor with flexible heat and power capabilities
- Transportable for ease of delivery, installation & commissioning onto a small site footprint
- Elimination of spent fuel storage on site
- Digitalization

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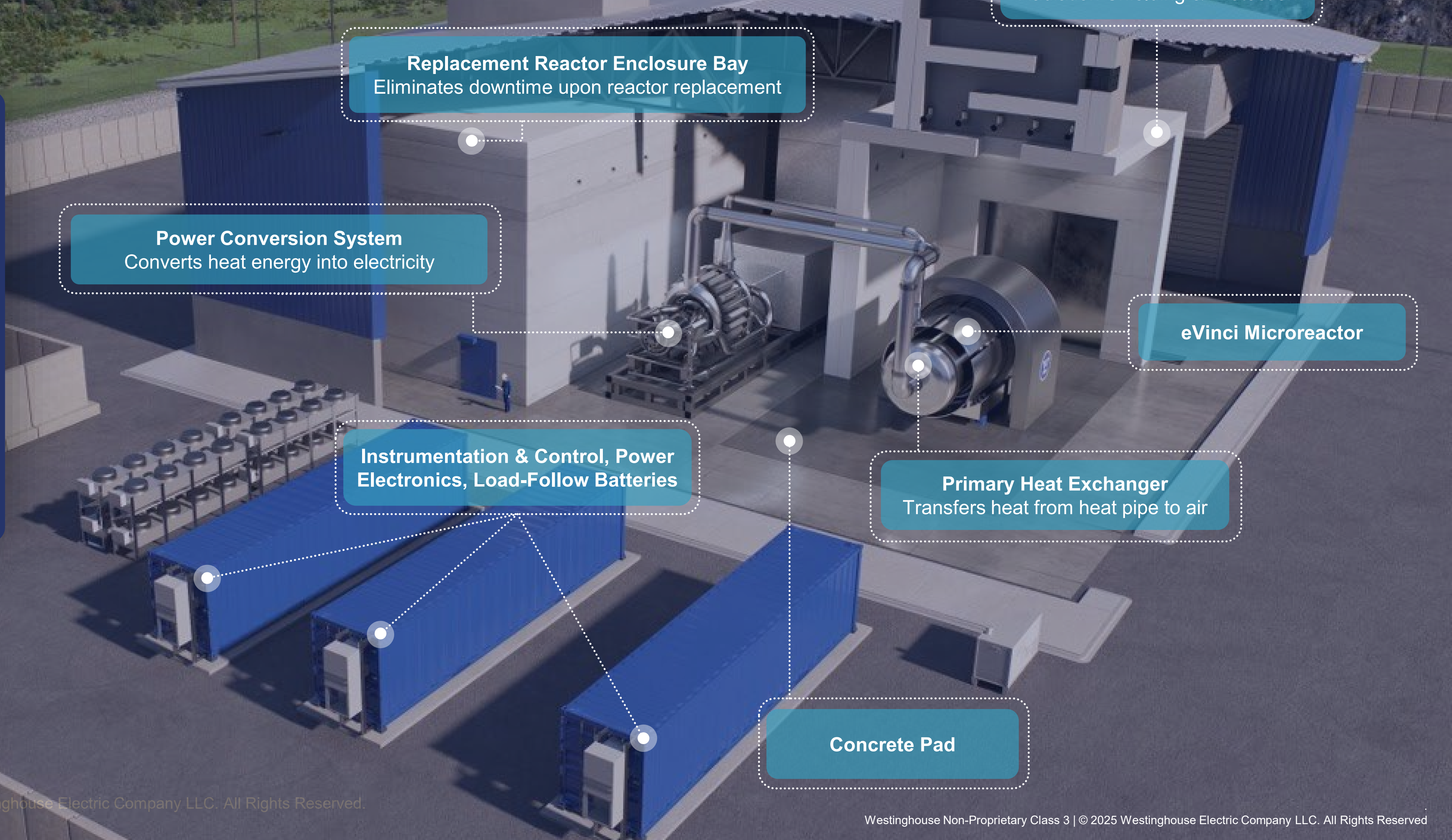
Example Layout of an eVinci Microreactor Facility

Key Attributes

- **Minimal personnel** needed for operation & security
- **Option to modify** the facility to accommodate multiple eVinci microreactors



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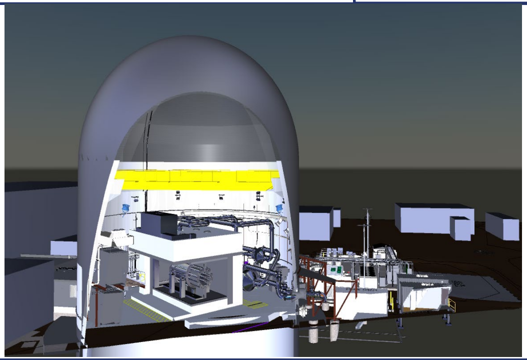
Deployment & Fuel Lifecycle

1

Test reactor for safety feature performance demonstration

Nuclear Test Reactor



2

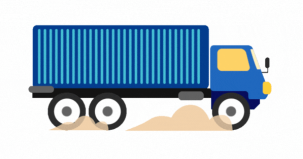
eVinci licensing approval

Scaled test program – supports licensing thru code V&V

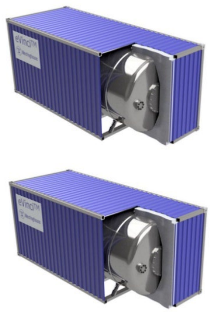
eVinci Microreactor Deployment

3 Assemble in factory

4 Transport to site



5 Install and operate at site



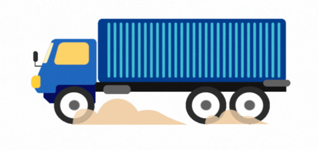
Primary reactor

Replacement reactor

Remote monitoring station

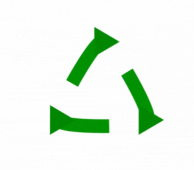
Limited site staff with remote monitoring

6 Transport away from site



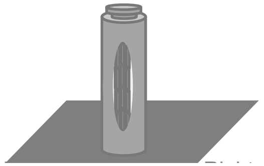
Depleted reactor

7 Refuel/refurbish

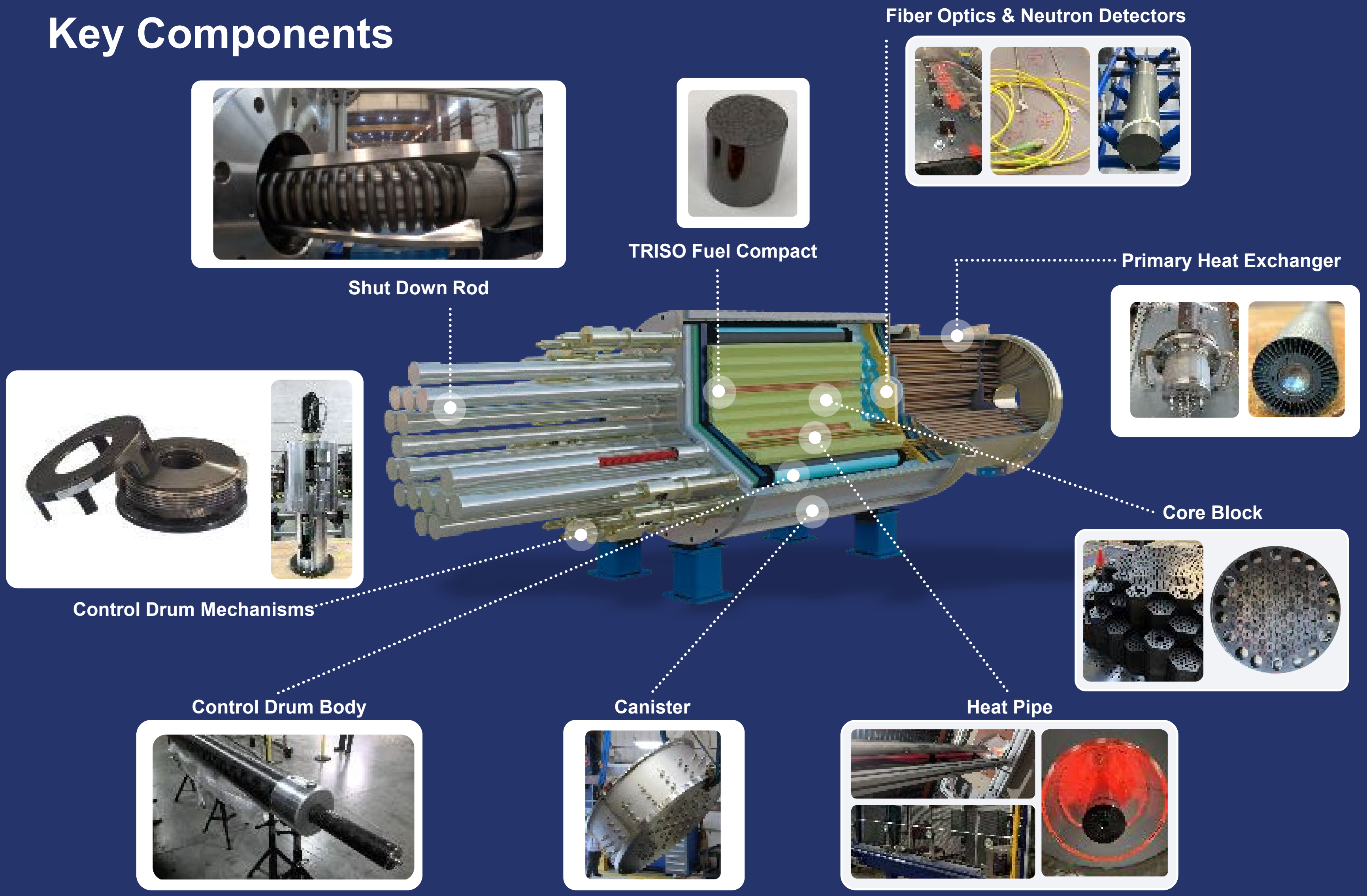


or decommission

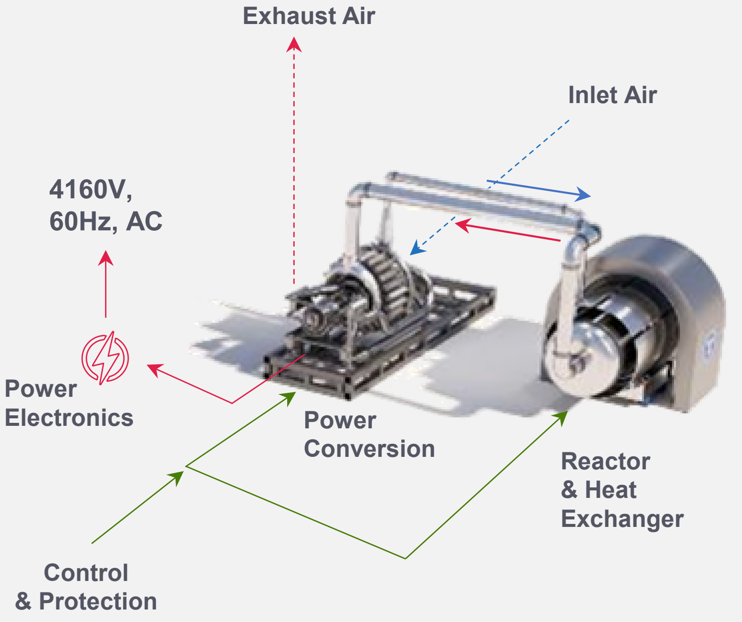
8 Fuel storage facility



Key Components

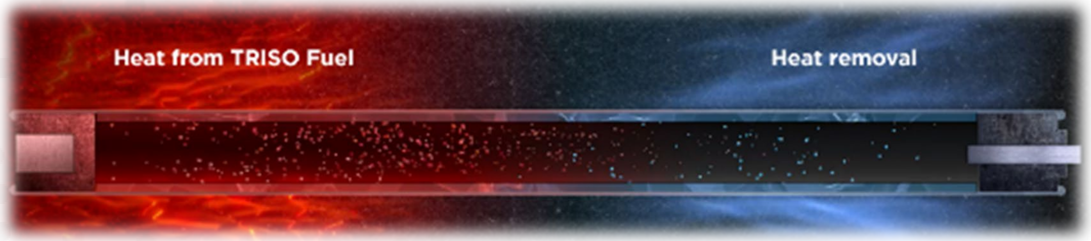


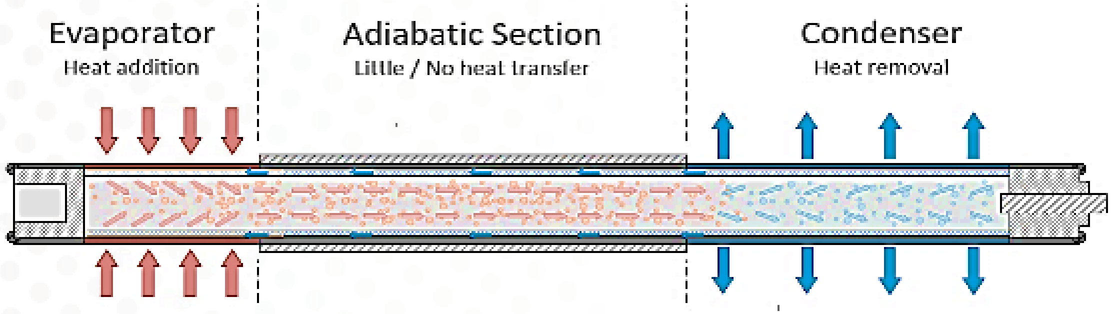
General Arrangement

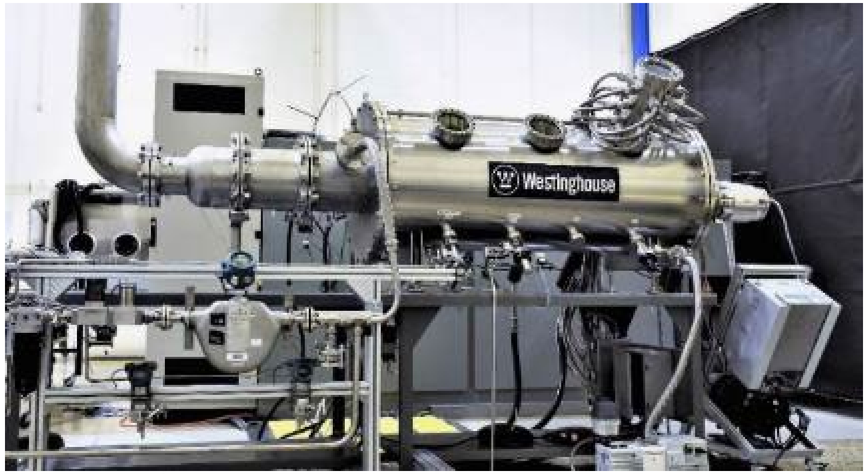


Heat Pipe Technology

Sodium filled, low pressure heat pipes enable passive heat removal







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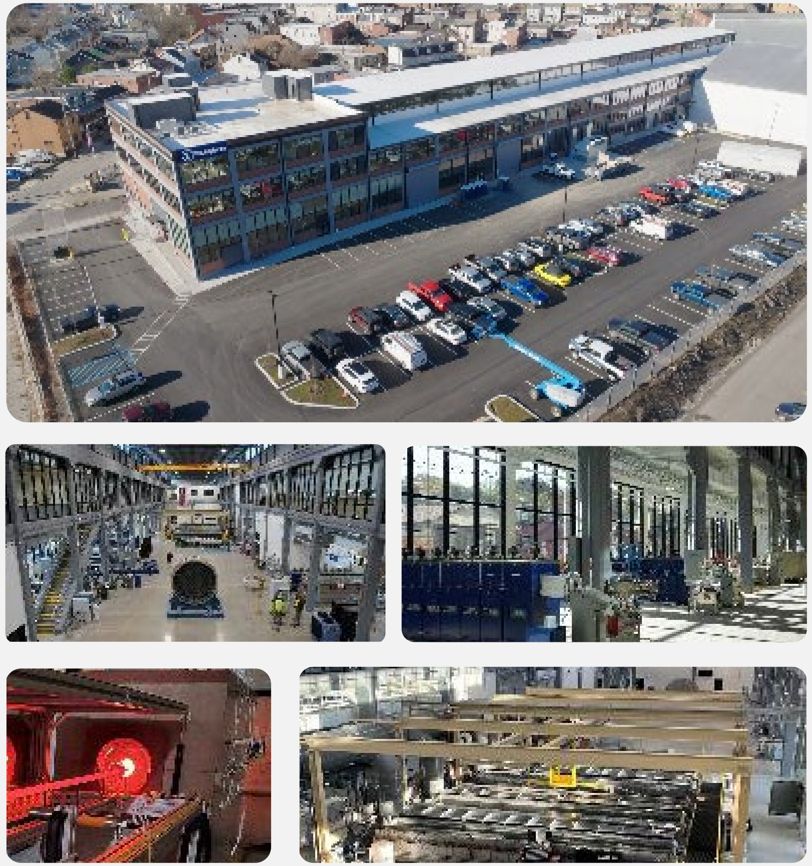
Heat Pipe Manufacturing In Action

Facility Features

- 87,000 ft^2 building with modern office space & high-tech shop
- Close proximity to Westinghouse Global Headquarters and access to world-class talent

Site Capabilities

- Heat pipe production & QA certifications
- Material Laboratory
- Component testing and Machine Shop
- Instrumentation & Control Lab
- Operator training facilities that include simulators



Westinghouse Manufacturing Facilities Supporting eVinci Microreactor

Newington, NH
Reactor subcomponent assembly

250,000 ft^2 facility

Shoreview, MN
Reactor subcomponent assembly

90,000 ft^2 facility

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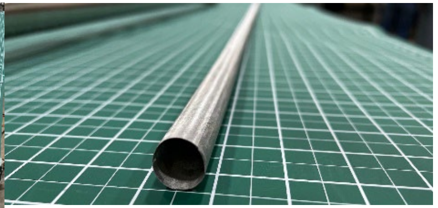
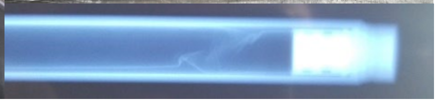
Heat Pipe Development and Testing





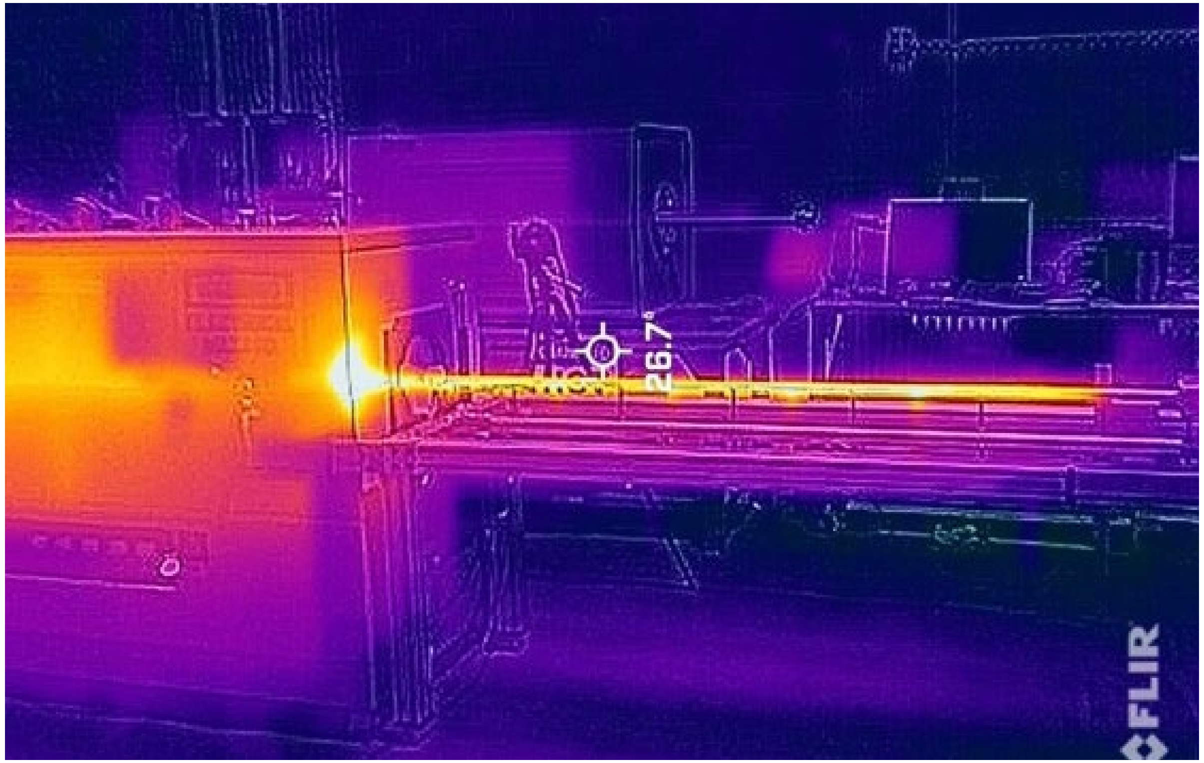






Heat Pipe Demonstration

- Westinghouse engineers successfully tested 12' heat pipes, a key demonstration milestone
- Heat pipes are designed to operate at temperatures exceeding 850C



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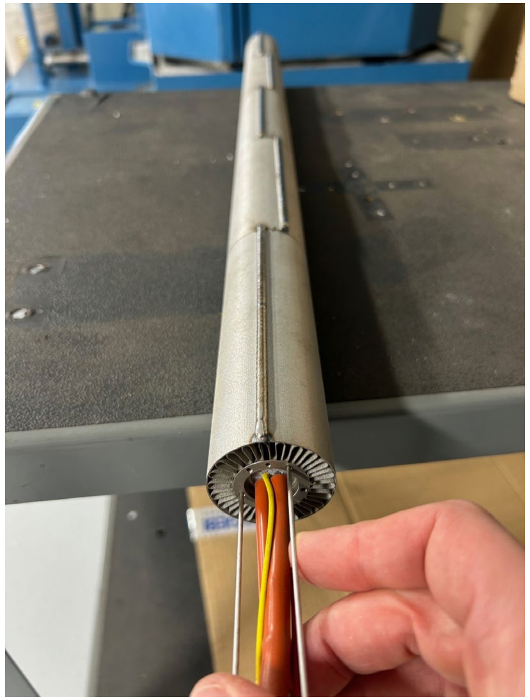
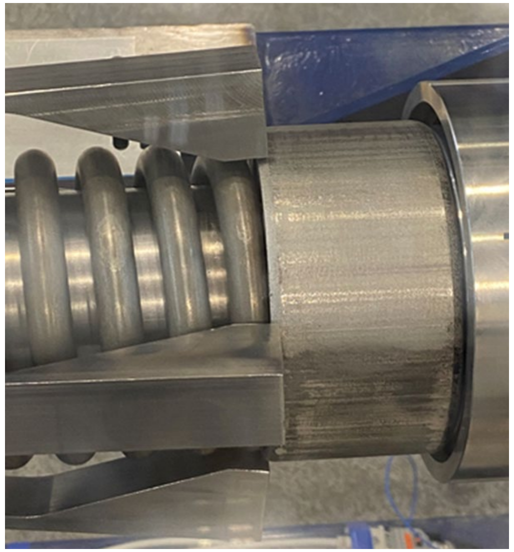
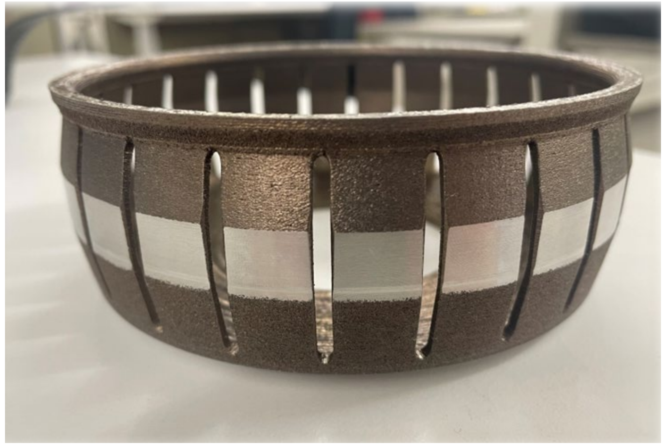
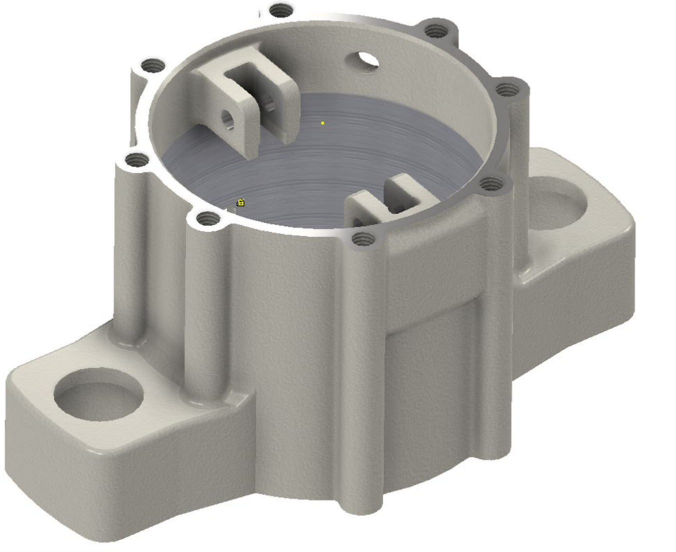
Additive Manufacturing Development





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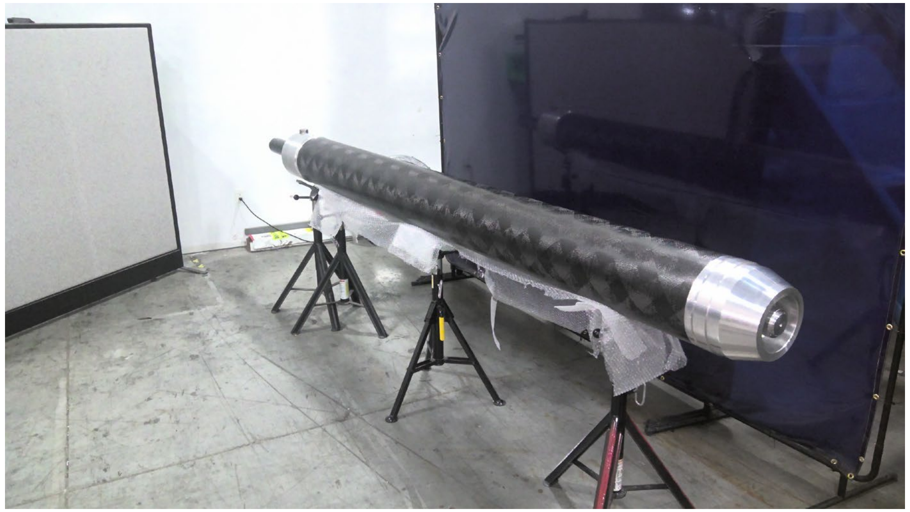
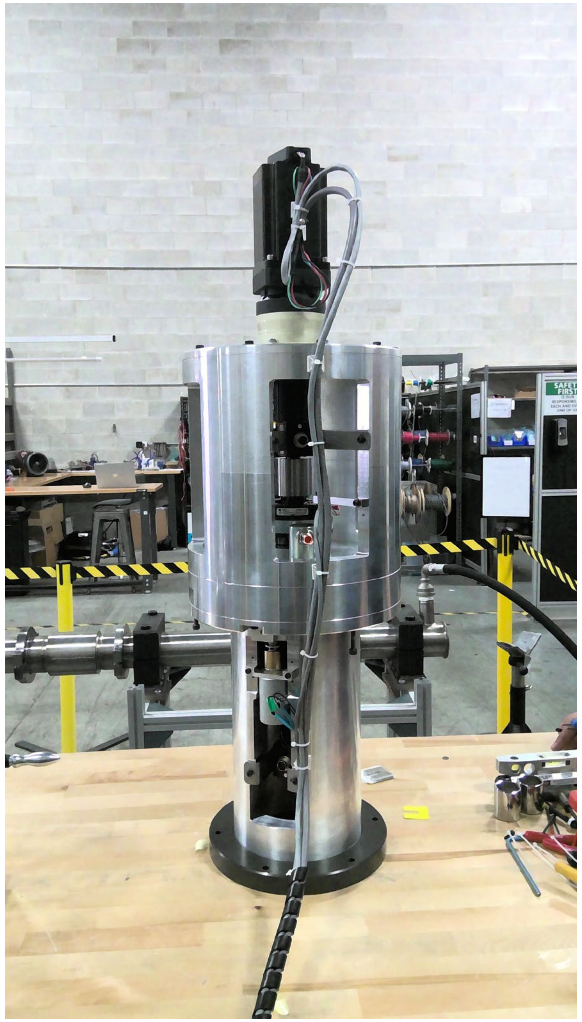
Control Drum Manufacturing Demonstration and Testing





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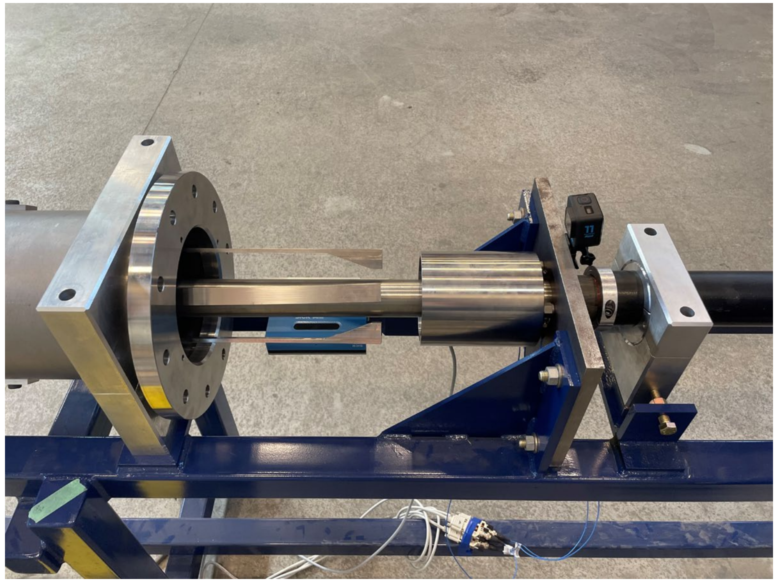
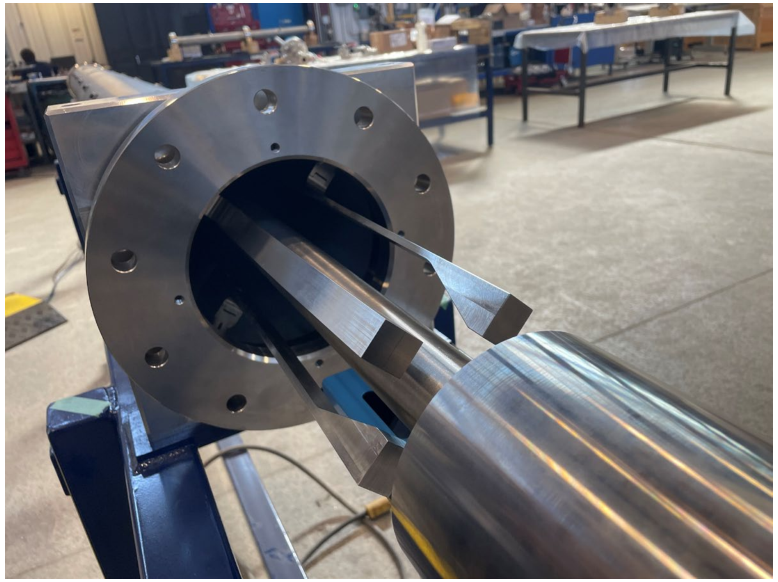
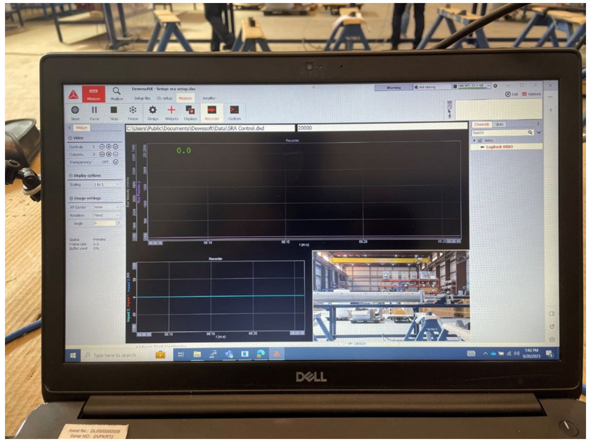
Shutdown Rod Manufacturing Demonstration and Testing





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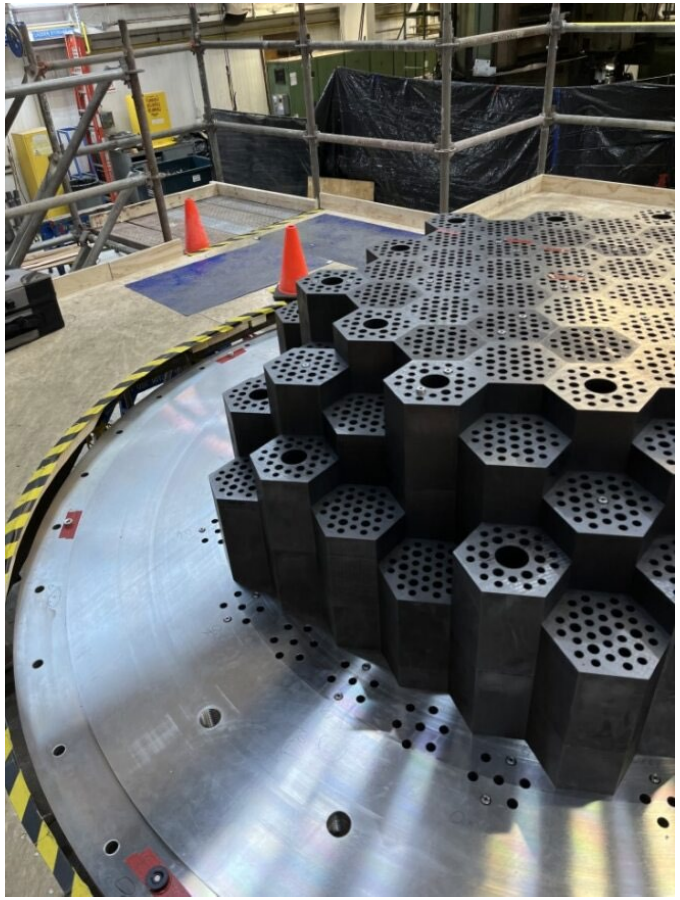
Manufacturing Demonstration Units (MDUs)

The MDUs were fabricated and assembled to drive learning of the interfaces and assembly process of the reactor components.

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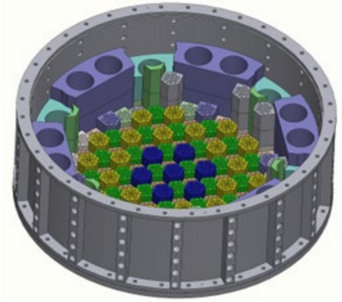
Deployment Approach



Phase 0

- Manufacturing development
- Prototyping
- Test articles
- Vendor development
- Strategy development

Phase 1

- Nuclear Test Reactor (NTR) manufacturing
- eVinci manufacturing facility development
- Start commercial unit long lead procurement

Phase 2

- FOAK commercial units
- eVinci manufacturing facility construction and licensing

Phase 3

- NOAK commercial units
- Production scale manufacturing in eVinci manufacturing facilities

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Licensing Approach

- Staged licensing approach
  - Pre-application regulatory engagement
  - Nuclear Demonstration Unit (NDU) licensing
  - Commercial unit licensing
- Pre-application regulatory engagement
    - Familiarization of regulatory staff with design
    - Address regulatory policy issues / other topics for early consideration
      - Identification of intended exemption requests with design specific approach
      - Presentation of select analytical approaches

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Nuclear Demonstration Unit Licensing

- Atomic Energy Act Section 104c [10CFR50.21(c)] license application using NUREG-1537 used to develop safety case
  - Use of Licensing Modernization Program (NEI 18-04 / DG-1353)
    - Risk Informed, Performance Based Systematic Method (See next slide)
  - Electrical Demonstration Unit, Integral Effects Test and Separate Effects Tests used as supporting evidence
- Phased increase in operating risk state
  - Develop experiment to demonstrate actual plant response
    - Apply restraints to prevent exceeding limit
  - Demonstrate plant response in agreement with code results prior to continuing to higher risk state.
  - Repeat as necessary until at highest operational risk state (for example, full power)

US Commercial Licensing

- Submittal will be prepared using same guidance as NDU (NUREG-1537) to achieve the Part 50/52 license
- Leverage data obtained during NDU operation to further safety case
- Request risk informed, performance based exemptions

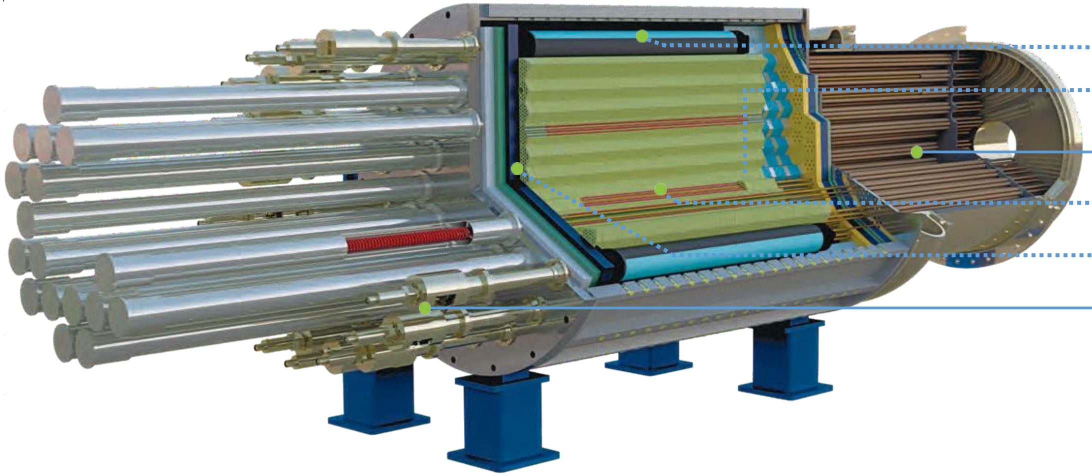
Design and Analysis Approach

eVinci Microreactor

Facility & non-reactor infrastructure capable of 40-year operation, including operations, maintenance, sustainment and refueling activities as needed to meet electricity production, capacity factor, and reliability objectives.

Technical Description	Heat pipe cooled, TRISO fueled microreactor utilizing open air Brayton cycle power conversion system
Capacity	5 MWe *Or Only Heat Option ~13.5 MWt @ >1,300F*
Capacity Factor	99+%
Fuel (% U^{235})	TRISO[(1)] in a Graphite Compact *19.75% U235*
Cooling Method	Passive Heat Pipes with Sodium Working Fluid
Shutdown Features	Control Drums with independent passive shutdown Shutdown Rods Passive Cooling - radiation & natural air convection
Reactor Pressure	~1 atm
Neutron Moderator	Graphite
Refueling Cycle	8+ years
Installation Time	< 30 days from Reactor Arrival to Commercial Operation
Footprint	Site: <3 acres Building: 0.4 acres Nuclear Concrete Basemat: 200 sq ft

(1) TRi-structural ISOtropic particle fuel.



The eVinci Microreactor Advantage | 5MWe Electrical Power

- ✓ No water or oil systems
- ✓ No pressurization needed
- ✓ No active cooling
- ✓ Fault-tolerant – capable of operating through heat pipe failures
- ✓ No pressure to disperse fission products
- ✓ Less instrumentation
- ✓ No flow-induced effects (corrosion & vibration)
- ✓ No coolant filtration or online radwaste control
- ✓ Reduced risk of pressure induced leaks
- ✓ No chemistry changes or foreign material
- ✓ Less inspection and maintenance without a pressure vessel
- ✓ Black start capable
- ✓ Operation connected to grid or in islanded mode
- ✓ Transportable for reduced site work and simplified decommissioning

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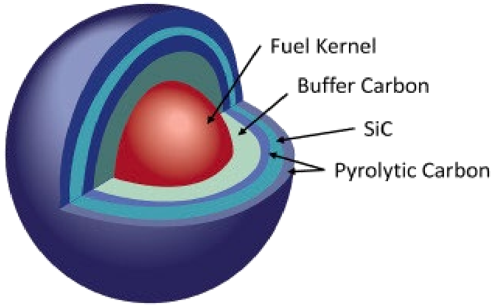
TRISO Fuel for Containment & HALEU for Performance

Why TRISO?

- The eVinci safety case credits the TRISO particle layers as a functional containment barrier which combined with our atmospheric reactor pressure, lowers the consequence and probability of radiological dose impacting the public in severe accidents
- TRISO fuel is the only high temperature fuel that has regulatory acceptance and extensive qualification basis. eVinci fuel is within the bounds of the NRC-approved Advanced Gas Reactor ("AGR") fuel qualification parameters



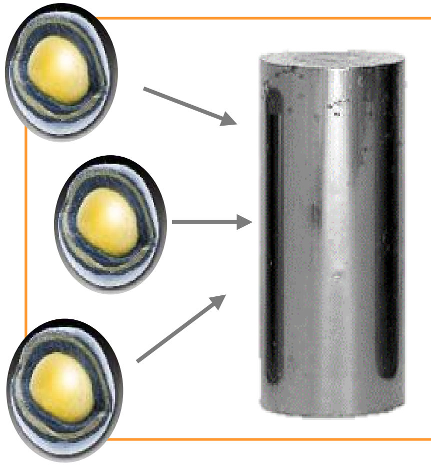
Why HALEU?

- More 235U atoms are in each fuel compact compared to current nuclear fuel products
- Translates to longer core life, higher power output, and higher fuel burnup

Fuel Supply for Testing

✓ DOE committed 45 kgU HALEU oxide to eVinci for our one fuel qualification test in addition to our reactor criticality experiment being performed in collaboration with LANL at the NCERC Facility

✓ DOE is prioritizing HALEU for test reactors

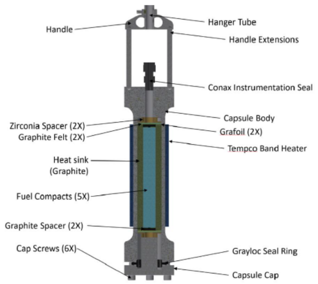


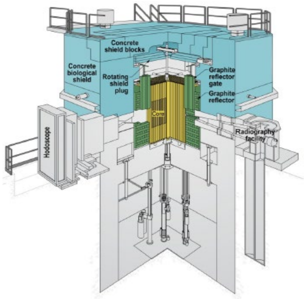
UCO HALEU TRISO coated particles are compacted in graphite pellets

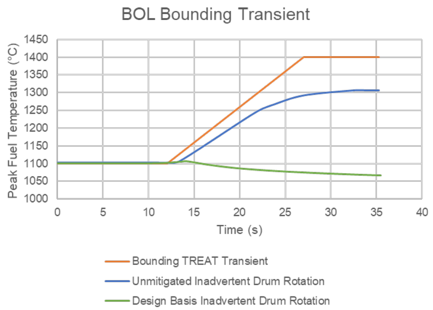
19.75wt% ^{235}U

UCO = Uranium Oxycarbide.

Westinghouse plans to perform one fuel capsule test in INL's TREAT reactor







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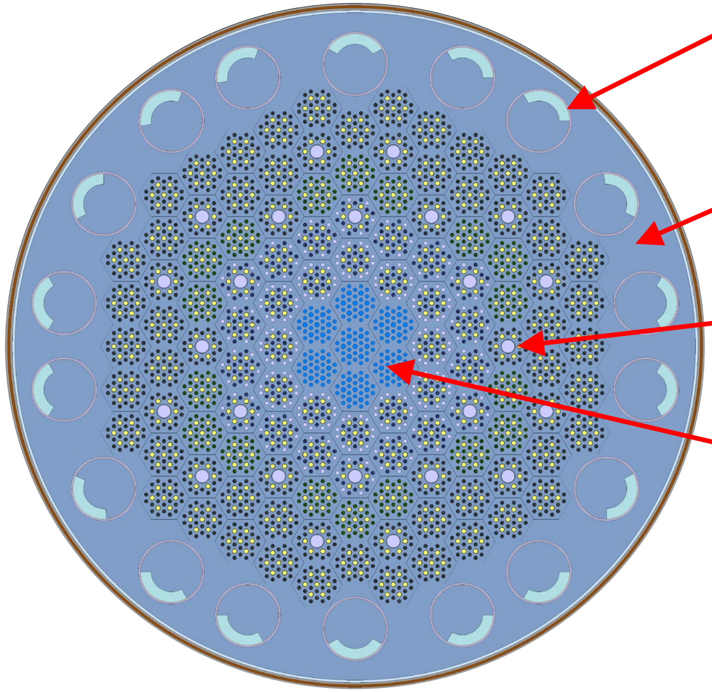
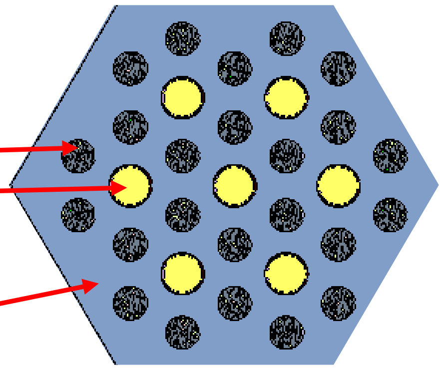
Core Analysis:
Monte-Carlo Based Approach

Core Design

Graphite, Heat Pipes, & Fuel





- Monte Carlo code used as basic neutronic tool for core design and analysis
  - MC continuous energy and general geometry capabilities enable to cope with high degree of heterogeneity, spatially and spectrally, of HP micro reactors cores
  - Used for steady-state analysis and to generate XS for downstream transient analysis (with Griffin/Direwolf)
  - Also used to perform coupled neutronics and thermo-mechanical analysis (e.g. coupled with OpenFOAM/OFFBEAT or with Moose tools)
- **Serpent-2 is the main MC code employed for eVinci**
  - Other MC options exist (e.g. openMC) and can be applied with pros and cons
- Deterministic approaches also possible (with pros and cons)
  - For eVinci whole-core direct simulation capabilities using MPACT under development

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Serpent-2 Applications in eVinci

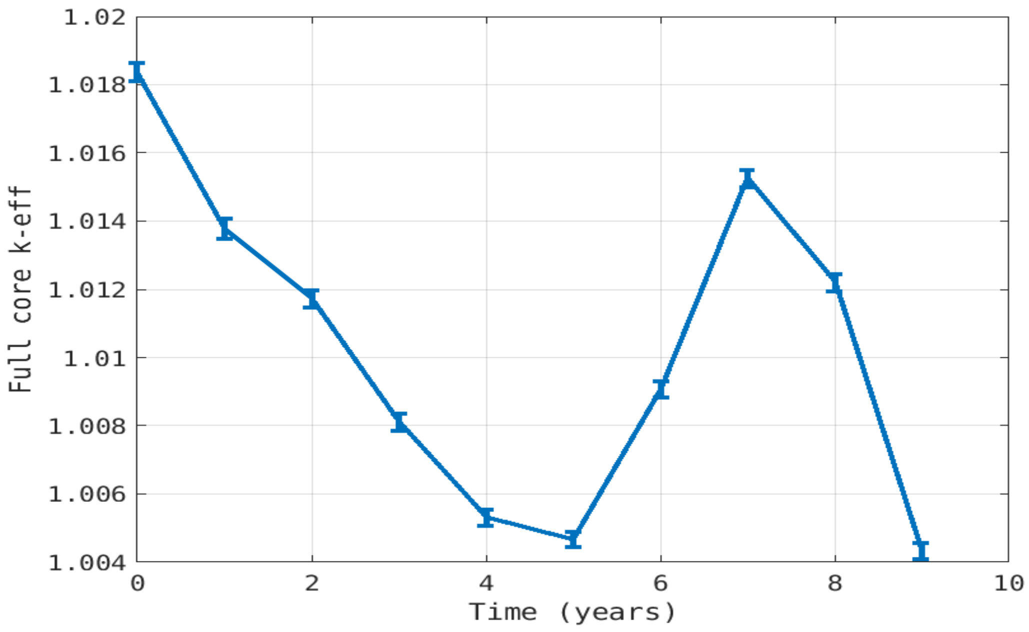
- Generation of steady-state core depletion results
  - High-fidelity model, including control drum critical search
  - Determination of core loading pattern, unit cell design parameters, U enrichment and TRISO packing fraction distribution, BA location etc.
  - Reactivity coefficients, shut-down margin calculations
- Generation of cross-section for downstream transient analyses with Griffin
- OpenFOAM-OFFBEAT coupling for high-fidelity neutronic-thermo-mechanical analyses
- Streamlined core design optimization through connection with DAKOTA/WATTS
- Generation of fission source distribution for shielding analysis
- HPC at DOE/INL available for computational intensive simulations

Serpent-2 Applications in eVinci (1)

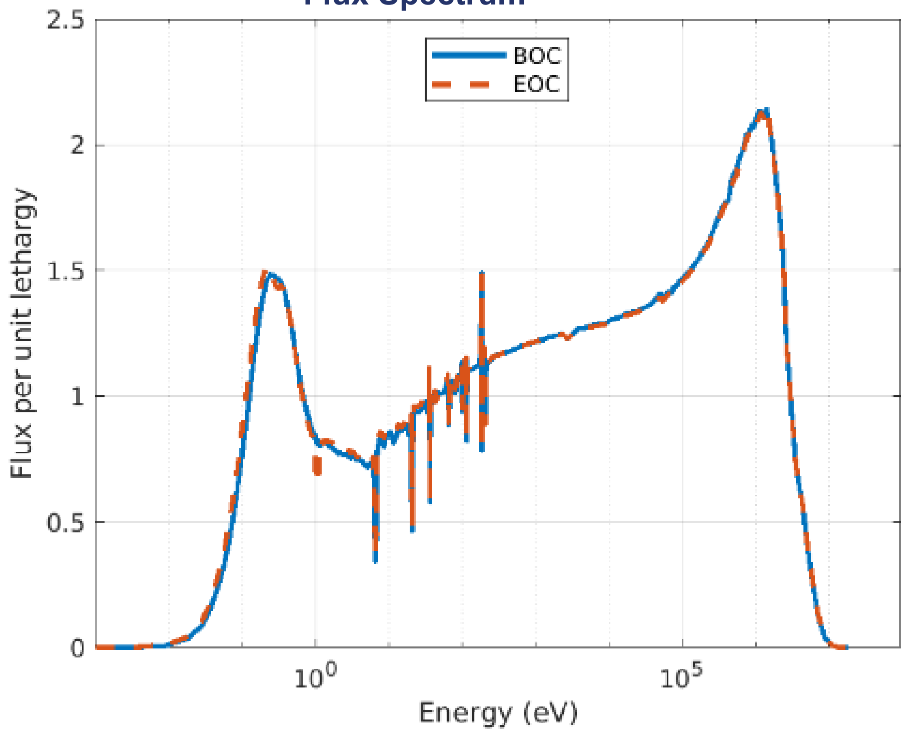
Generation of steady-state high-fidelity depletion results

- Detailed modeling of all relevant components inside/outside the core
- Determination of core loading pattern, unit cell design parameters, U enrichment and TRISO packing fraction distribution, BA location etc. to achieve energy requirements and main safety limits
- Reactivity coefficients, shut-down margin calculations
- Control drum critical search/depletion

Reactivity vs. Time



Flux Spectrum



Serpent-2 Applications in eVinci (2a)

Generation of cross-section for Griffin multi-physics analysis

- Griffin is a reactor physics code within MOOSE
  - Stead-state and transient capabilities
  - Various solvers and fidelity levels
  - Equivalence methods (SPH and DFs) available
  - Streamlined multi-physics capabilities
- Griffin relies on cross-section tables pre-generated with Serpent-2
  - Branches to cover various operating and transient conditions
  - Geometry homogenization and diffusion employed to reduce computational burden, with SPH from Serpent-2 heterogeneous results to restore accuracy

Table 6-2. Eigenvalue Results from Griffin for the 3-D Assembly

Solver	Eigenvalue	Time [sec] (12 proc)	Δk pcm	Pin % RMS	Pin % Max	Pin % Min
Serpent 2	1.14084 +/- 9.3E-6	-	-	-	-	
SPH-Diffusion[1]	1.14086	71.1	0.0	0.0000	0.0000	0.0000
SPH-Diffusion[2]	1.14086	71.1	0.0	0.0620	0.1352	-0.1470

[1] Reaction rates based on cross sections and SPH reference fluxes.
[2] Reaction rates from direct tallies.

Table 6-3. Eigenvalue Results from Griffin for the 2-D Core with CD In

Code/Solver	Eigenvalue	Time [sec] (40 proc)	Δk pcm	Pin % RMS	Pin % Max	Pin % Min
Serpent 2	1.14519 +/- 5.4E-6	-	-	-	-	
SPH-Diffusion[1]	1.14519	172	0.0	0.0024	0.0056	0.0000
SPH-Diffusion[2]	1.14519	172	0.0	0.5636	1.1342	-1.0610

[1] Reaction rates based on cross sections and SPH reference fluxes.
[2] Reaction rates from direct tallies.

Table 6-4. Eigenvalue Results from Griffin for the 2-D Core with CD Out

Code/Solver	Eigenvalue	Time [sec] (40 proc)	Δk pcm	Pin % RMS	Pin % Max	Pin % Min
Serpent 2	1.17242 +/- 5.1E-6	-	-	-	-	
SPH-Diffusion[1]	1. 17242	154	0.0	0.0001	0.0002	0.0000
SPH-Diffusion[2]	1. 17242	154	0.0	0.6114	1.3945	-1.2575

[1] Reaction rates based on cross sections and SPH reference fluxes.
[2] Reaction rates from direct tallies.

Assessment of the Griffin Reactor Multiphysics Application Using the Empire Micro Reactor Design Concept
July 31, 2020

ANL/NSE-20/23

Serpent-2 Applications in eVinci (2a)

Generation of cross-section for Griffin multi-physics analysis

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  - Various solvers and fidelity levels
  - Equivalence methods (SPH and DFs) available
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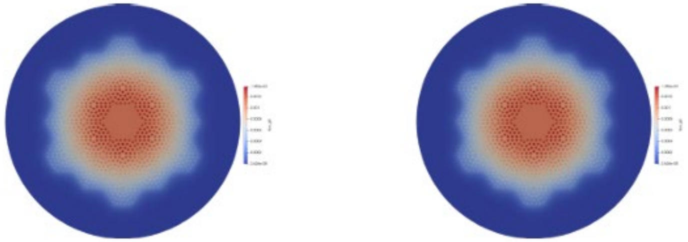
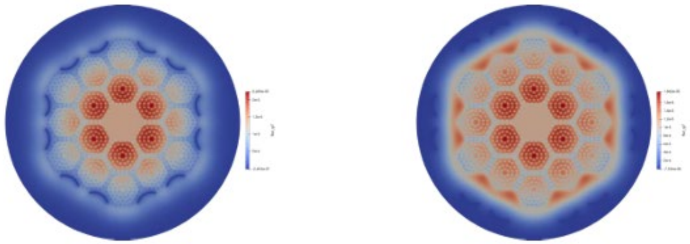


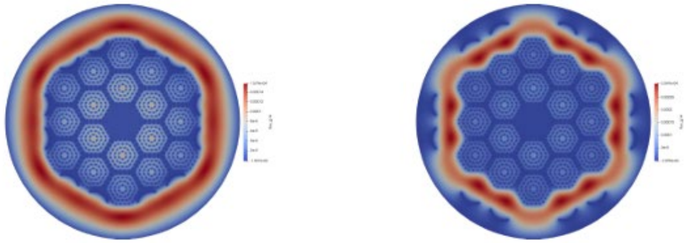
(a) CD In (b) CD Out

Figure 6-1. Flux Distribution from SPH-Diffusion [8.21E+05 – 2.00E+07 eV]



(a) CD In (b) CD Out

Figure 6-2. Flux Distribution from SPH-Diffusion [3.3 – 4.0 eV]



(a) CD In (b) CD Out

Figure 6-3. Flux Distribution from SPH-Diffusion [1.0E-05 – 3.0E-02 eV]

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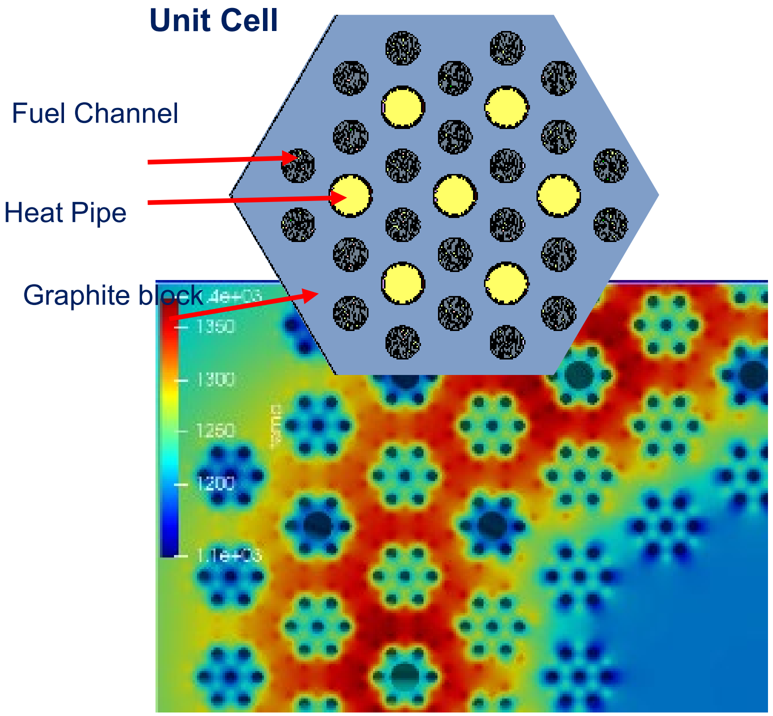
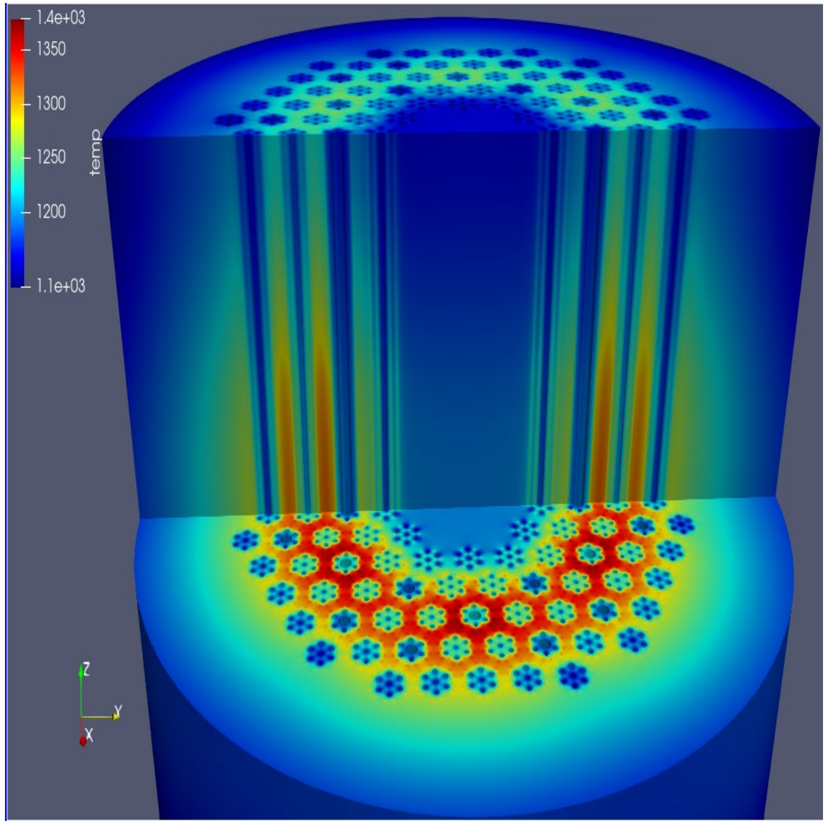
Transient analyses with Griffin

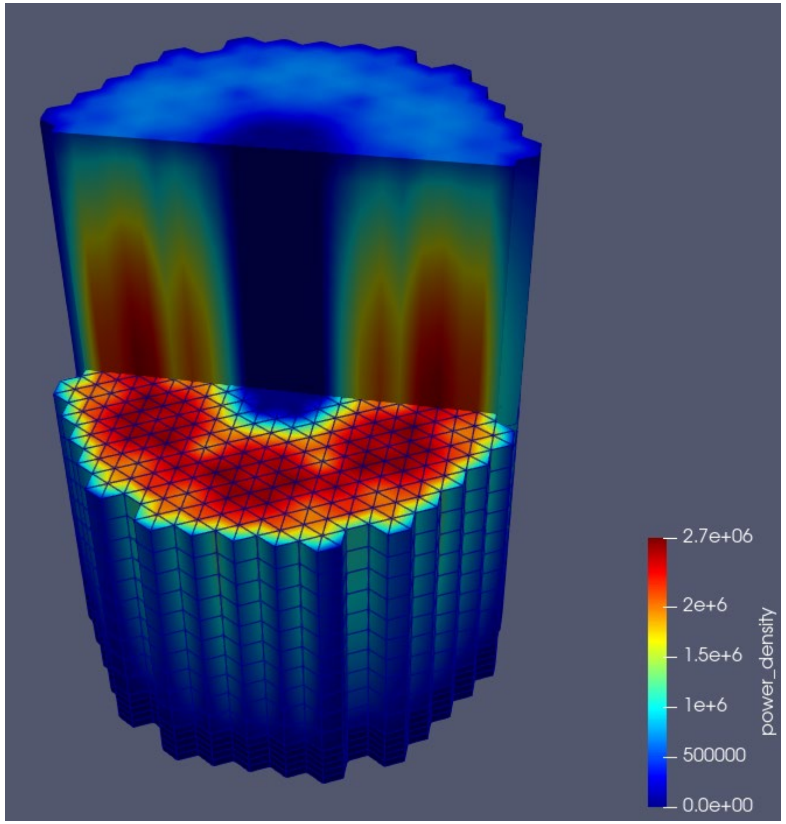
- Griffin is then coupled with Moose to perform transients analyses with thermal feedback



Temperature Distribution



Power Density



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Serpent-2 Applications in eVinci (3)
OpenFOAM-OFFBEAT coupling

- **Thermo-mechanical-neutronics coupled simulations performed with Serpent-2 coupled to OFFBEAT**
  - Enable to account for thermal and mechanical interaction from solid state reactor components
  - Including dimensional changes due to expansion and evolution with irradiation
- **OFFBEAT is an Open-FOAM based fuel performance code**
  - Coupling relies on Serpent multiphysics interface that allows running Monte Carlo gamma-neutron transport on Open-FOAM unstructured meshes enabling direct cell-by-cell exchange of density, temperature, and power density data
  - A dedicated heat-pipe model was implemented in OFFBEAT, in which the heat-transfer mechanism within the heat pipes is approximated using an equivalent heat-conduction approach.
  - Temperature-dependent models for the thermal conductivity of both the moderator block and the fuel incorporated
  - Evolution of heat transfer across gaps as mesh deformation progresses handled

- **Framework enables high-fidelity quantification of individual contributions to reactivity feedback**

Reactivity Feedback

- Temperature
- Displacement
  - Gap Conductance
  - Leakage
  - Volumetric Fractions

Evolution of Thermo-Mechanical Response

Irradiation-Induced:

- Dimensional changes
- Creep
- Degradation of thermo-mechanical properties

Serpent-2 Applications in eVinci (4)

Core design optimization through connection with DAKOTA/WATTS

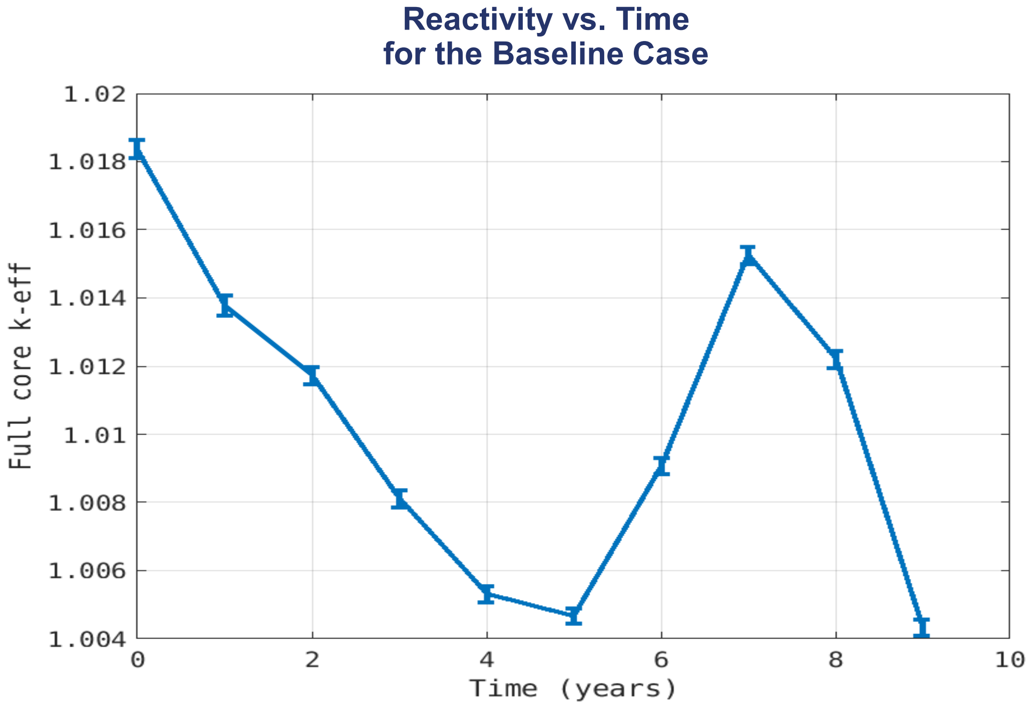
- WATTS: Manages workflow with multiple codes with information exchanged at a coarse level
  - Open-source MIT license: https://github.com/watts-dev/watts
  - Plugins available for SERPENT and DAKOTA
- DAKOTA Optimization solver
  - MOGA: multicriteria optimization genetic algorithm
- Design parameters automatically varied to converge to optimal design configurations with respect to the optimization objectives
  - Within allowed range of variation and respecting design or safety constraints

eVinci core design optimization workflow applied to burnable absorber optimization

Core design optimization through connection with DAKOTA/WATTS

Objective

- B4C-based burnable absorber employed in the core for reactivity hold-down and power shaping
- Objective functions:
  - minimization of radial power peaking (MRPP) - heat-pipe safety related
  - minimization of power peaks (MTIPP) - peak fuel temperature safety related
  - maximization of discharge burnup - core economics related
- Constraints:
  - Core-lifetime > 8 years
  - Shut-down margin met
- Two-step optimization:
  - BA axial/radial concentrations
  - fuel/BA radius and lengths



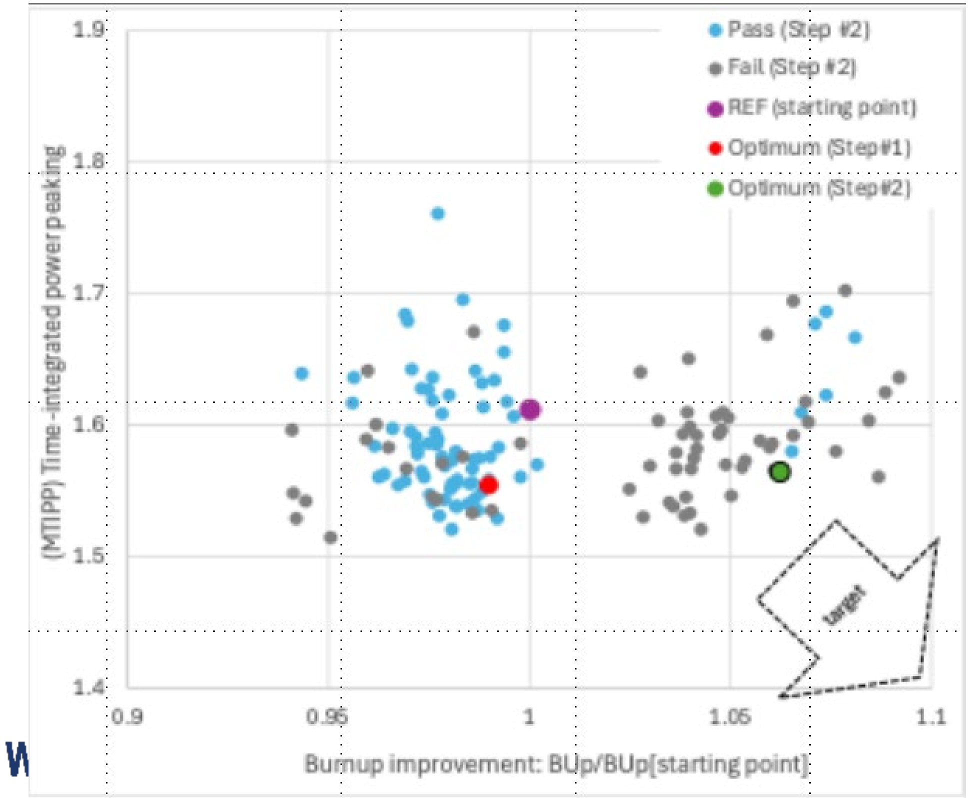
	Ref. (starting point)
Fuel mass	Ref.
Core lifetime [year]	8.43
Discharge burnup	Ref.
Max. radial power peaking	1.585
Max. time-integrated power peaking	1.611

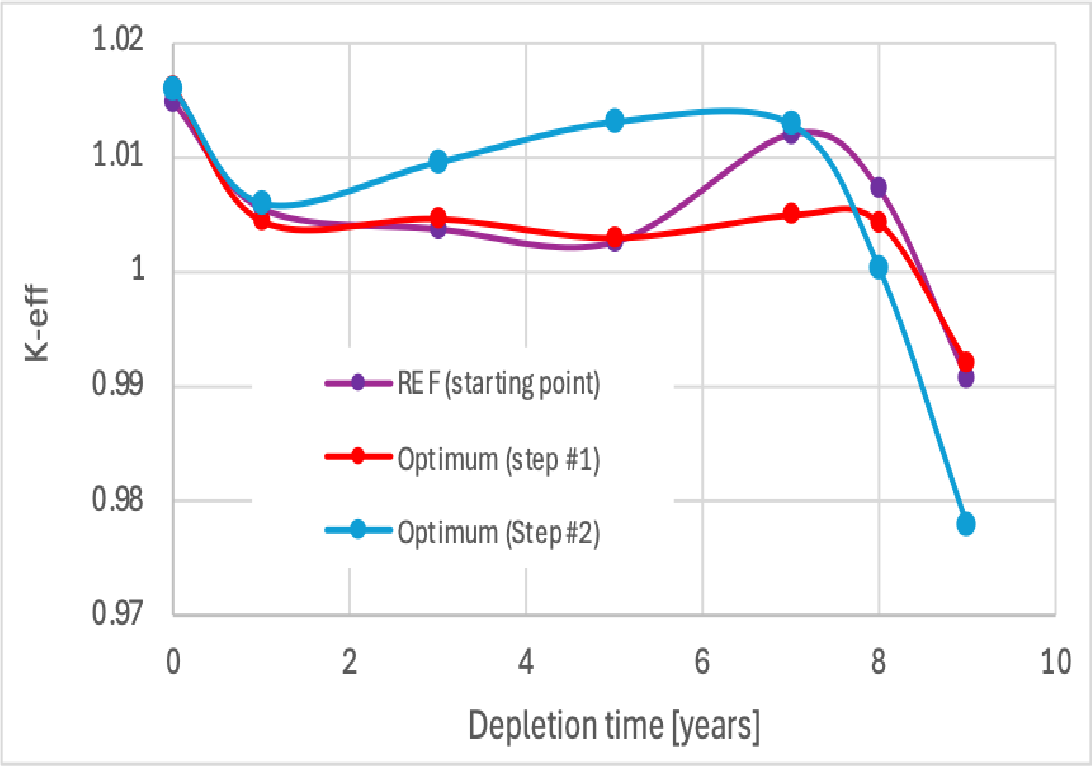
Core design optimization through connection with DAKOTA/WATTS

Results

- 6% Improvement in fuel utilization
- Reduced power peaks
- Top-level safety criteria met

	Ref. (starting point)	Opt. (Step #1)	Opt. (Step#2)
Fuel mass reduction factor	Ref.	Ref.	0.89
Core lifetime [year]	8.43	8.35	8.01
Discharged burnup improvement	Ref.	0.99	**1.06**
(MRPP) Max. radial power peaking	1.585	**1.545**	**1.517**
(MTIPP) Max. time-integrated power peaking	1.611	**1.555**	**1.564**





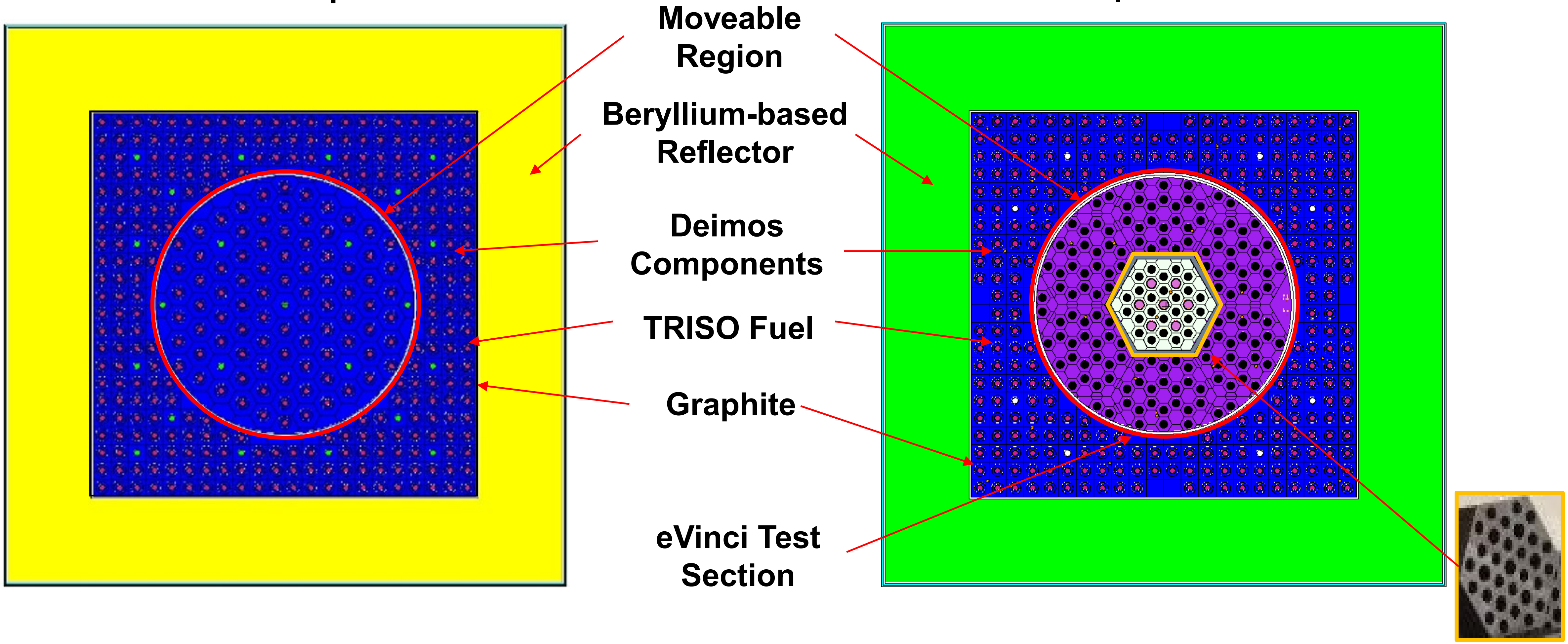
Nuclear Data Validation

- NCERC facility used to fill gaps in nuclear data to support computer code validation
  - Serpent
  - Griffin
- Critical system setup similar to eVinci
  - Materials
  - Geometry
  - Operating conditions

- Data of Interest:
  - **Neutron multiplication factor**
  - **Neutron spectrum**
  - **Prompt neutron lifetime**
  - **Effective delayed neutron fraction**
  - **Reactivity coefficients**
  - **Reactor period**
  - **Radial and axial neutron flux/power distributions including the location of hot spots**
  - **Depletion rates of burnable absorbers**
  - **Length of the fuel cycle**
  - **Control drum worth**
  - **Shutdown rod worth**

Criticality Test

Deimos Experiment | **Deimos Experiment + eVinci**



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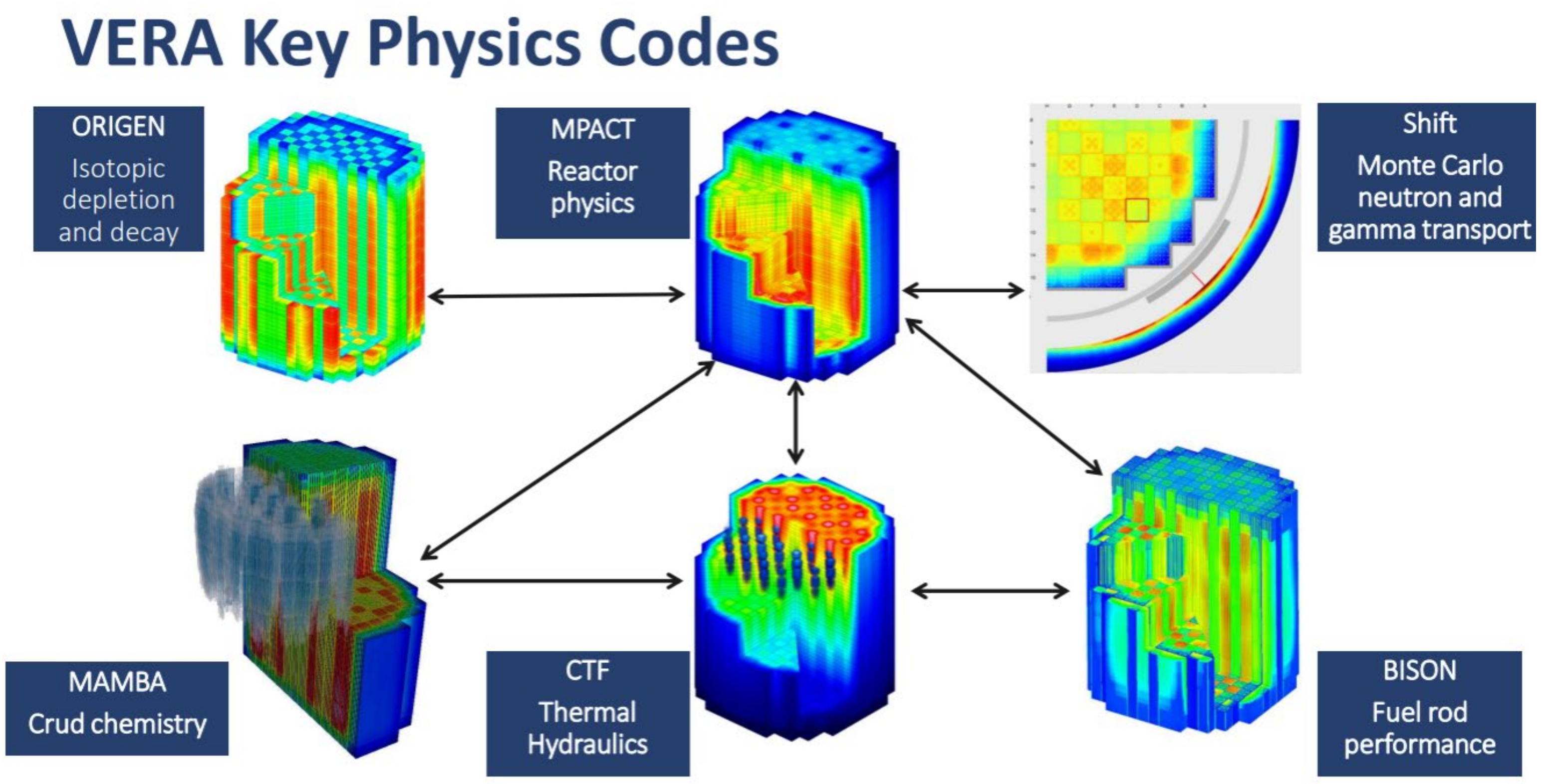
Core Analysis Tools: Deterministic Approach

Work Performed in Collaboration with S. Choi and B. Kochunas (University of Michigan)

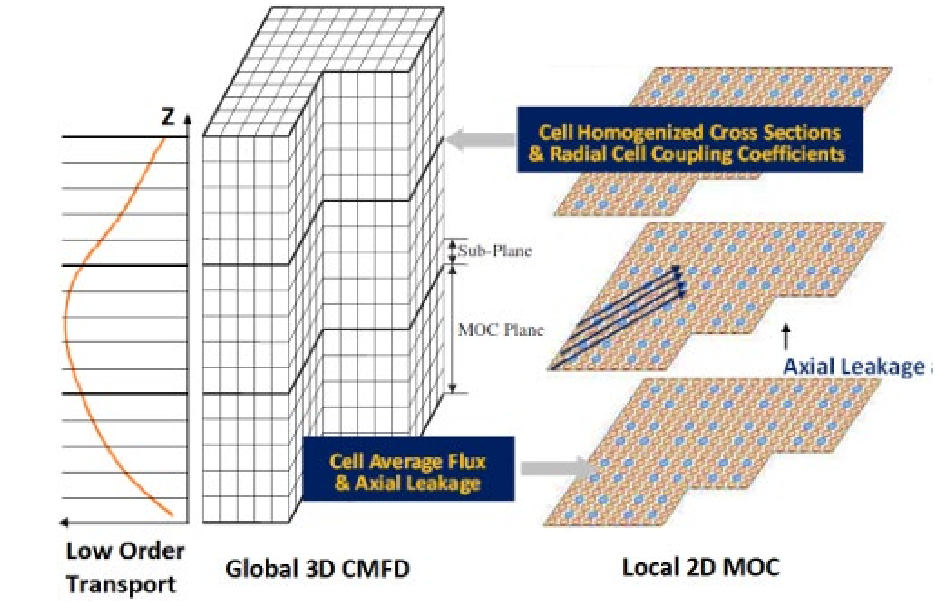
Deterministic Tools

- Deterministic tools can also be applied to heat-pipe micro-reactor analysis to reduce computational burden and facilitate implementation of thermal feedback
- Traditional core design tools geared on LWR core analysis are challenged by extension to micro-reactors, due to highly heterogeneous design with large flux gradient and spectral variations, significantly higher impact of core leakages and modeling needs from new fuel/core features (e.g. TRISO fuel, control drum outside the active core)
  - Two-step approaches with pre-generated cross-section generation and few-group nodal diffusion at the core levels may not be appropriate and require ad hoc modifications
- More general higher fidelity approaches with on-the-fly cross-section generation and whole-core direct transport calculations are favored for extension to micro-reactor core analysis
  - Still require customized thermo-mechanical internal feedback, or coupling to external thermo-mechanical tools
  - Can be appropriate also to model transients if featuring kinetic capabilities
- One such tool is the MPACT code, developed under the DOE Consortium for Advanced Simulation of LWRs within the Virtual Environment for Reactor Applications (VERA)
  - Significant application and validation basis to LWR core analysis

MPACT within VERA



MPACT 2D/1D Neutron Transport



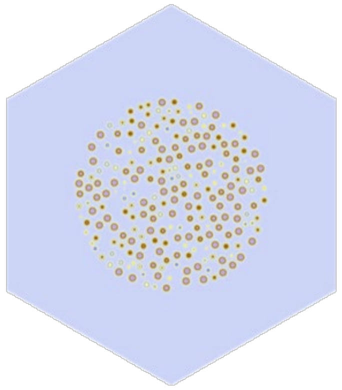
The 2D/1D method with the subplane scheme used for the 3D CMFD and 1D axial calculations.

MPACT Key Features

- MPACT is a pin-resolved, high-fidelity reactor physics solver integrated within the Virtual Environment for Reactor Applications (VERA)
  - MPACT has been rigorously validated against LWRs
  - Recently, MPACT has broadened its scope to encompass non-LWR systems, including heat-pipe microreactors
- New features implemented
  - TRISO fuel modeling based on the Sanchez-Pomraning (S-P) method
  - Enhanced geometry modeling for hexagonal geometry and microreactor
  - Novel correction for the 2D/1D method that improves both the accuracy and stability of problems with axial void regions
  - Simplified Multiscale Thermal-fluid (SMTF) Solver to handle thermal feedback in heat-pipe microreactors

TRISO fuel modeling

- Challenges in TRISO fuel modeling
  - The fuel compact containing randomly dispersed TRISO fuel particles is commonly referred to as doubly heterogeneous fuel (fuel kernel and compact)
  - The double-heterogeneity challenges for resonance self-shielding and neutron transport methods.
  - Simply homogenizing the fuel compact via volume weighting can result in significant errors, often amounting to a few thousand pcm in graphite-moderated systems
- Sanchez-Pomraning (S-P) method implemented in MPACT
  - The method is a robust technique successfully applied in various transport codes to address self-shielding in particulate fuels.
  - The S-P method has already been incorporated into various transport codes, including HELIOS, DeCART, APOLLO, Dragon, ALPHA, demonstrating promising results for both steady-state and depletion calculations.



TRISO Fuel Modeling in MPACT vs. Monte Carlo

- Monte Carlo
  - Require random generation and explicit modeling of all individual TRISO particles
  - More computationally intensive and complex setup
- MPACT
  - Only requires TRISO particle properties and packing fraction
  - Can easily handle multiple TRISO particle types within the same compact/stochastic region
  - Does not require explicit modeling of every particle
- Successful validation against Monte-Carlo (Serpent-2) results

Microreactor Geometry Modeling in MPACT

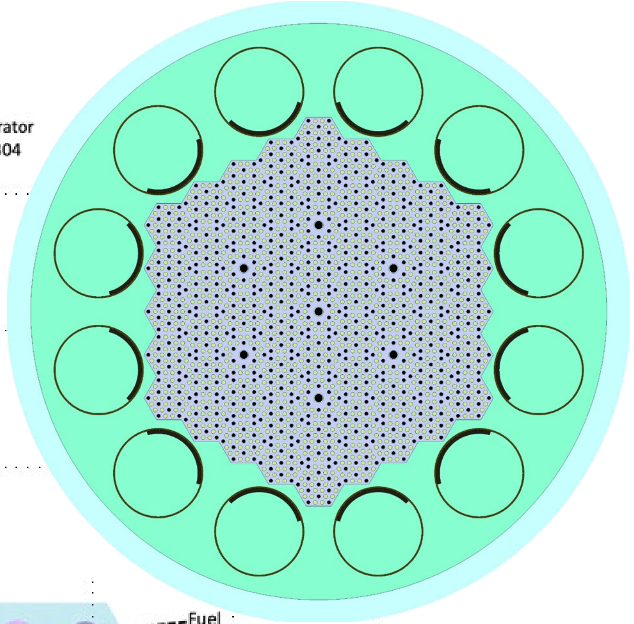
- CAD-based modeling with UM²
  - UM² – External library for enabling MOC/CMFD calculations on CAD models and automatically generated unstructured polygon meshes
    - https://github.com/KyleVaughn/UM2
  - **Works with any geometry** as long as a CAD model is available.
  - **CAD is inefficient for modeling repeated, structured geometries** like lattice cores.
  - **Geometry must be provided in CAD format** or via an external geometry modeling tool.

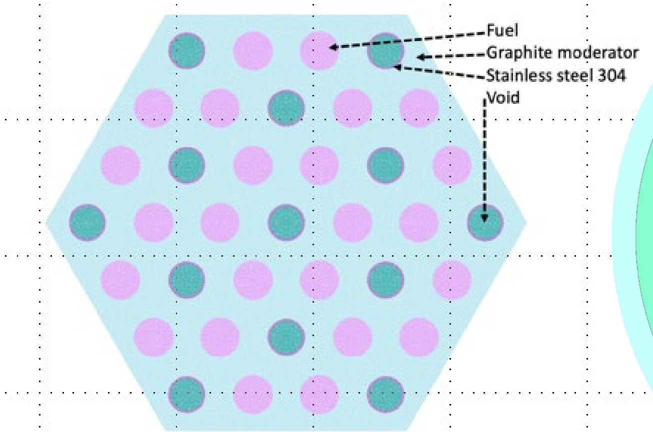
✓ **Structured geometry input in MPACT**
  - Define problems with standardized input decks (e.g., pin cell, assembly, core) using minimal information
  - **Easy to use** as long as the desired geometry type is supported in MPACT.
  - Simple, parameterized input is much more **efficient for modeling repeated reactor geometries**
  - **Limited to predefined geometries.**
  - **Requires implementation** of specific geometry feature (e.g. Control Drums)

Verification of MPACT Micro-reactor Predicting Capabilities

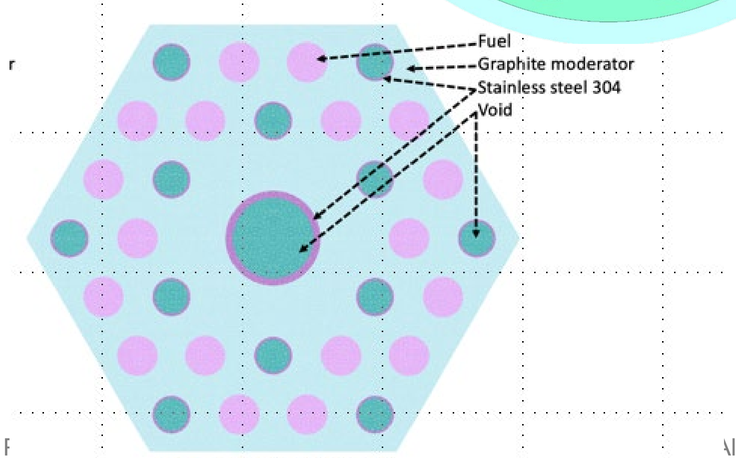
- Public eVinci^{TM} Motivated Design (EMD) used
  - D. Price, et. al. “Thermal Modeling of an eVinci™-like heat pipe microreactor using OpenFOAM.” NED-415, p. 112709 (2023).
- Verification problems
  - 2D fuel assembly problems
  - 2D full core problems with varying drum rotations
  - UCO TRISO fuel with 40% Packing Fraction at 19.75% U-235
  - Reference: Serpent2

eVinci^{TM} Motivated Design





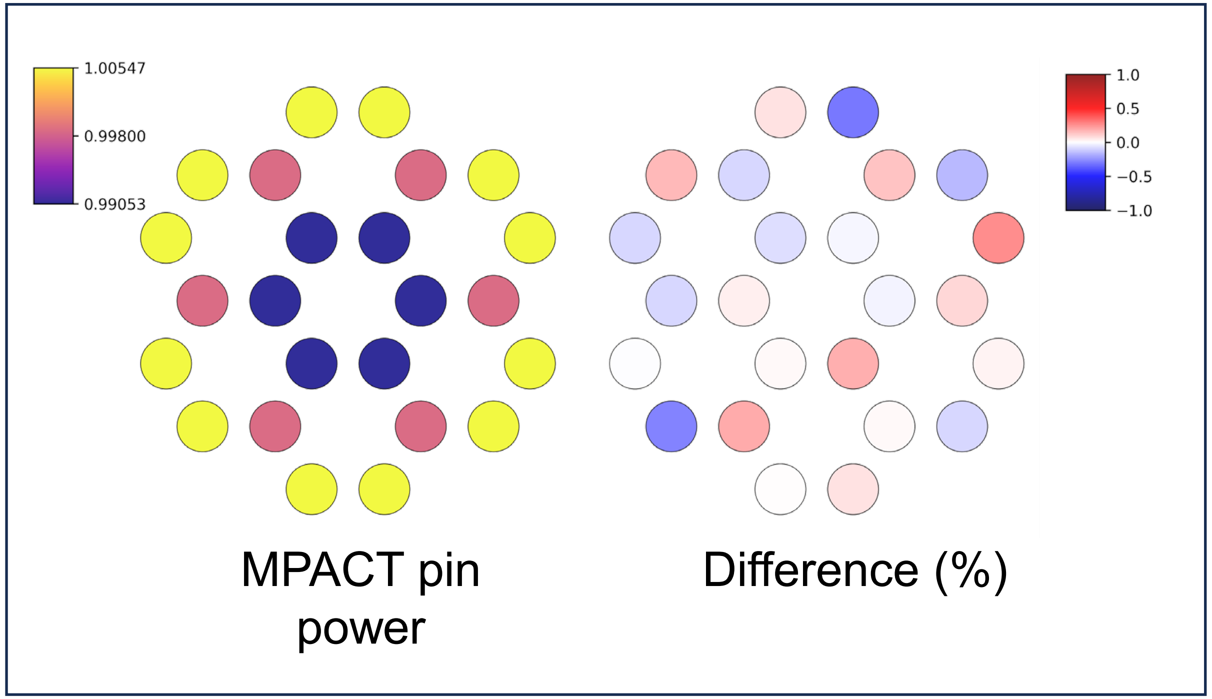
Assembly Type 1



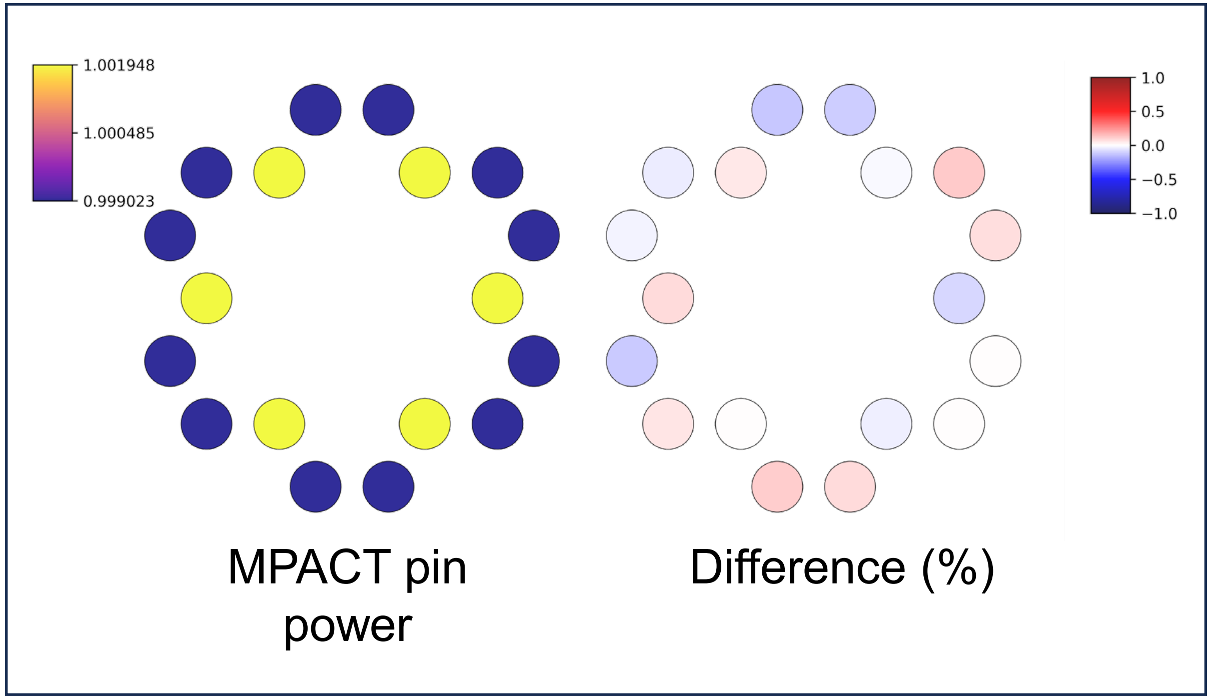
Assembly Type 2

2D Fuel Assembly Problem Results

Assembly Type 1



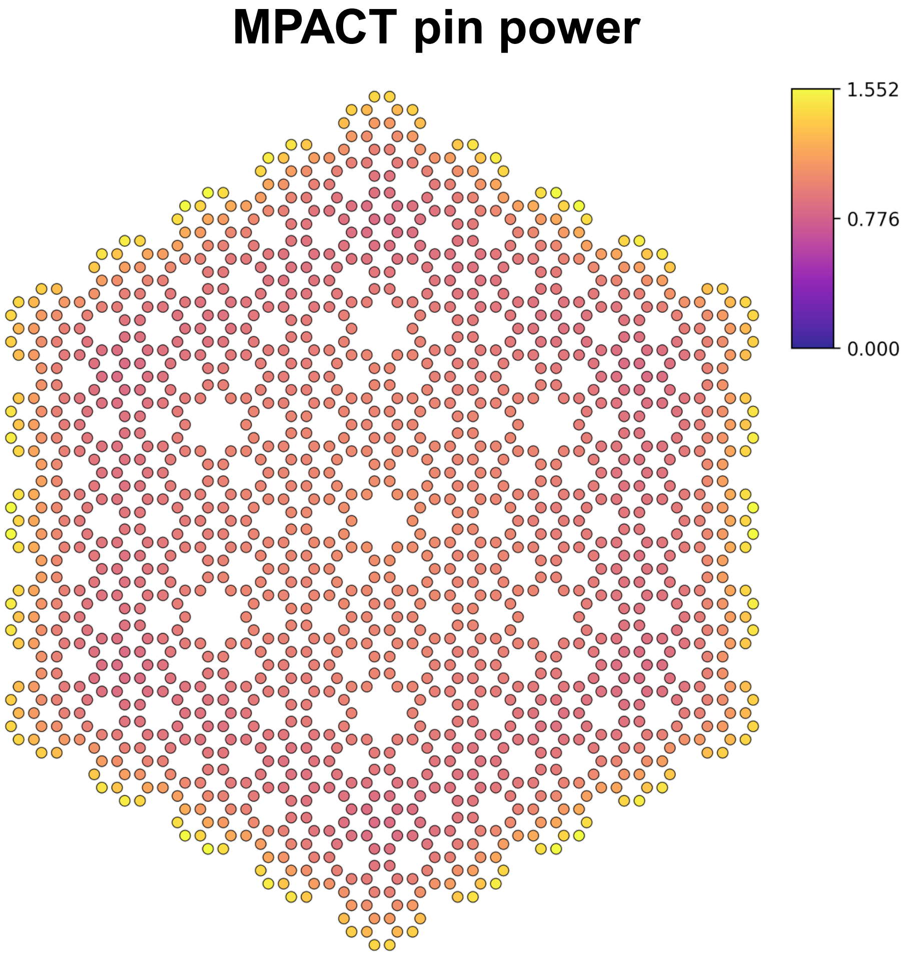
Assembly Type 2

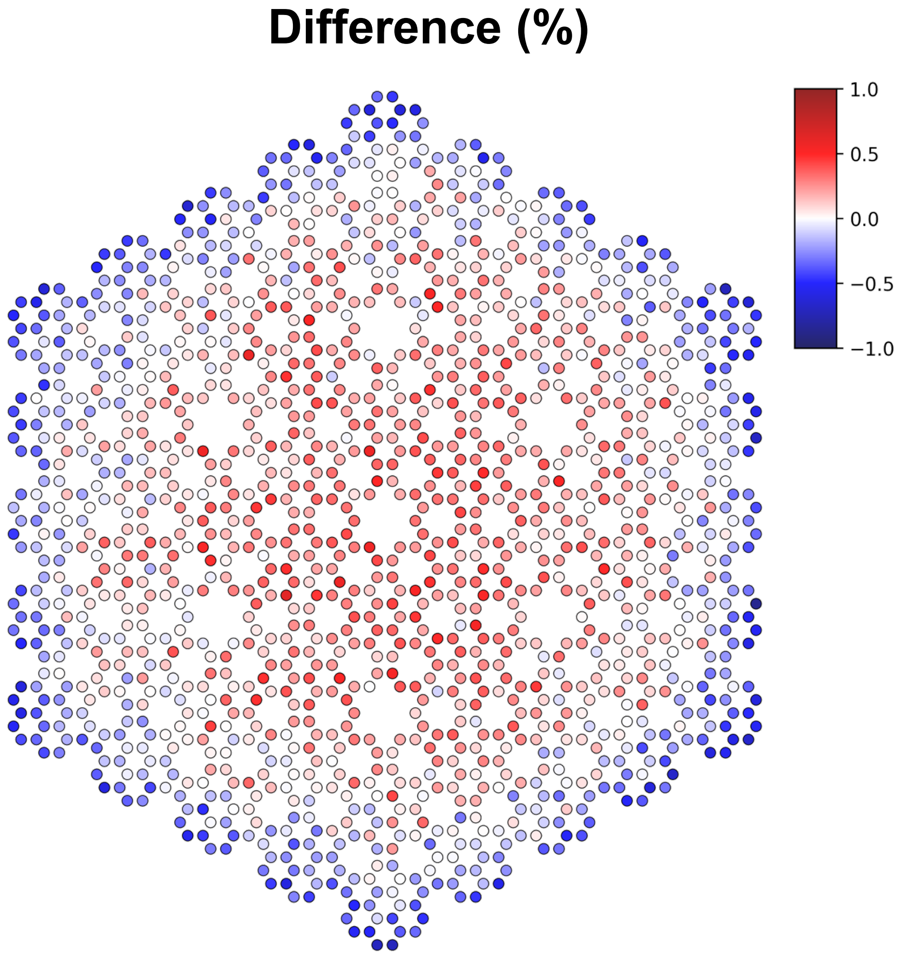


Problem	Code	Description	k_{eff}	Difference (pcm)	Pin power distribution RMS(%)	Pin power distribution Max(%)	Run-time (Core-minutes)
Assembly type 1	Serpent	Reference	1.24292	±17*	±0.157	±0.166	148.1
	MPACT	252g, TCP_0, FS	1.24271	-21	0.136	0.309	0.8
Assembly type 2	Serpent	Reference	1.13370	±18	±0.145	±0.152	159.7
	MPACT	252g, TCP_0, FS	1.13198	-172	0.146	0.270	0.9

* Values with the symbol ± represent statistical errors.

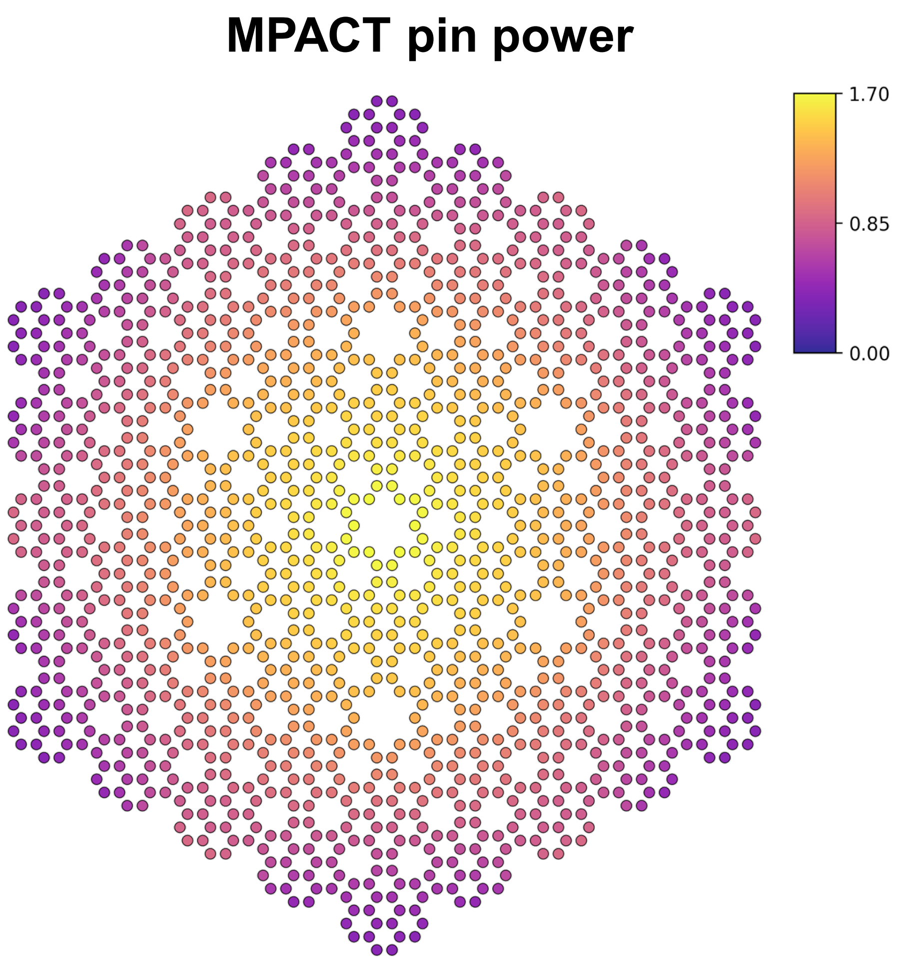
2D Core All Drums Out Problem Results

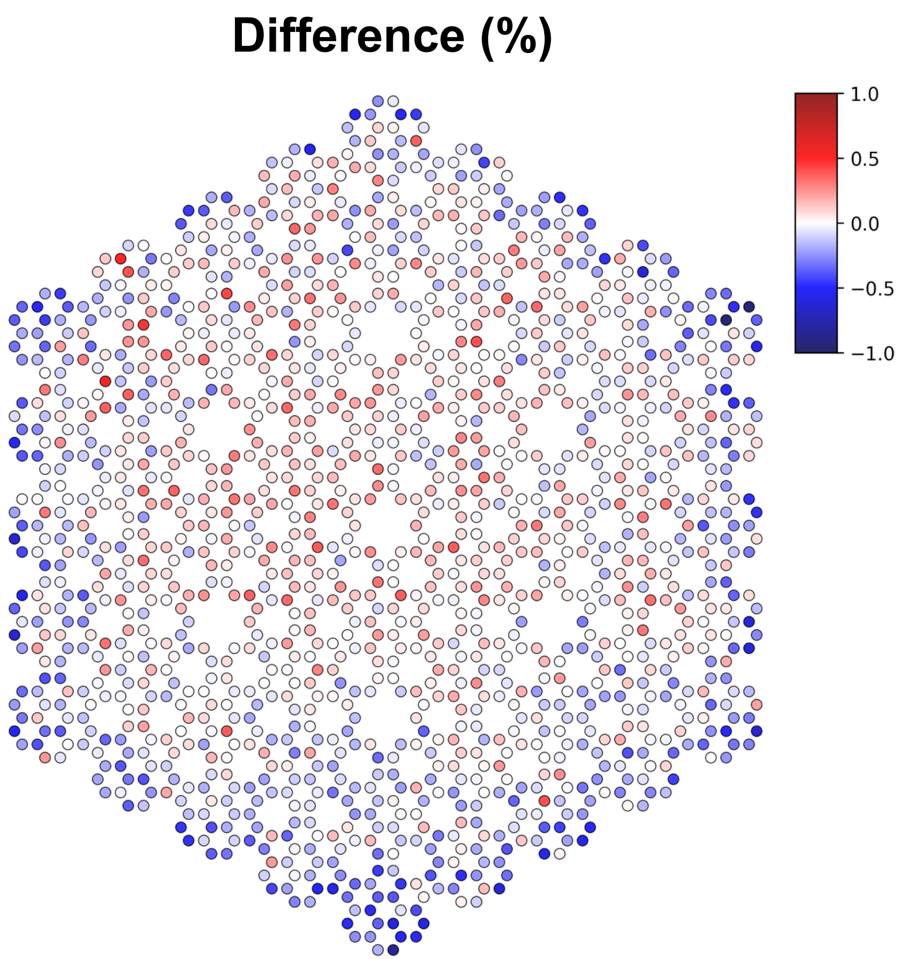




Code	k_{eff}	Difference (pcm)	Pin power distribution		Run-time (Core-hours)
			RMS(%)	Max(%)	
Serpent	1.13941	±2	±0.134	±0.147	1145.6
MPACT	1.13843	-98	0.257	0.861	6.2

2D Core All Drums In Problem Results





Code	k_{eff}	Difference (pcm)	Pin power distribution RMS(%)	Pin power distribution Max(%)	Run-time (Core-hours)
Serpent	0.97644	±3	±0.148	±0.235	894.4
MPACT	0.97622	-22	0.195	0.935	8.0

3D Assembly with Void Region and Improved 2D/1D Method

Problem Cases	Method	k_{eff}	k_{eff} diff. (pcm)	1D RMS diff. (%)[a]	1D Max diff. (%)[b]	2D RMS diff. (%)[c]	3D RMS diff. (%)[d]
Tube r=1.4 cm	OpenMC	1.09897	±13	±0.19	±0.23	±0.19	±0.19
	2D/1D	1.09892	-5	0.54	1.30	0.04	0.58
	2D/1D with Σ_L	1.09940	43	0.18	0.49	0.04	0.25
Tube r=1.7 cm	OpenMC	1.07886	±13	±0.19	±0.23	±0.19	±0.19
	2D/1D	1.06398	-1488	16.76	43.09	0.04	16.75
	2D/1D with Σ_L	1.07927	40	0.26	0.62	0.04	0.30
Tube r=2.0 cm	OpenMC	1.05884	±13	±0.19	±0.23	±0.19	±0.19
	2D/1D	1.04454	-1430	16.64	42.97	0.04	16.64
	2D/1D with Σ_L	1.05953	68	0.13	0.34	0.03	0.22
Graphite filled tube	OpenMC	1.08353	±13	±0.19	±0.22	±0.19	±0.19
	2D/1D	1.08467	114	0.13	0.36	0.02	0.21
	2D/1D with Σ_L	1.08468	114	0.14	0.38	0.02	0.22

[a] RMS error for the radially integrated axial pin fission rate distribution, calculated using absolute differences.

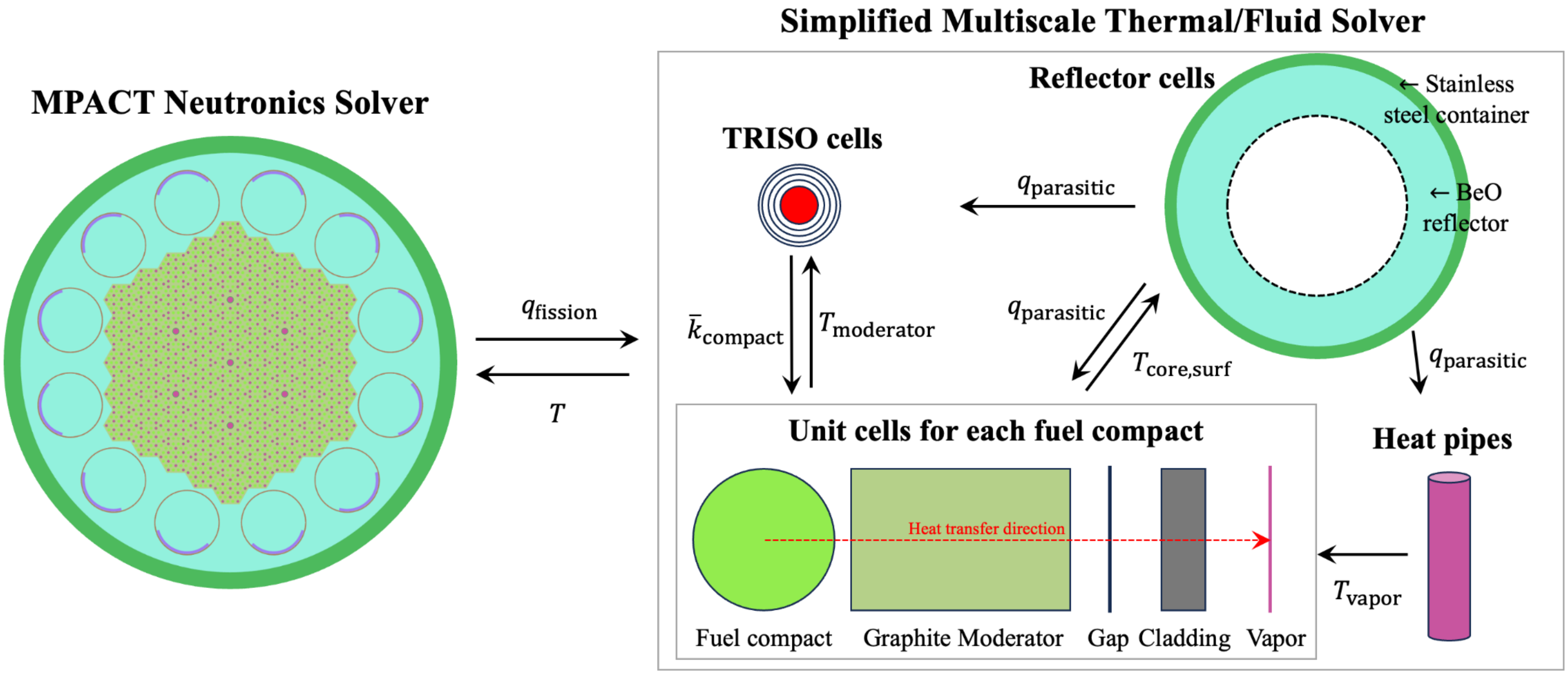
[b] Maximum error for the radially integrated axial pin fission rate distribution.

[c] RMS error for the axially integrated radial pin fission rate distribution.

[d] RMS error for the 3D pin fission rate distribution.

∗ Integrated standard deviations are estimated from pin-wise values.

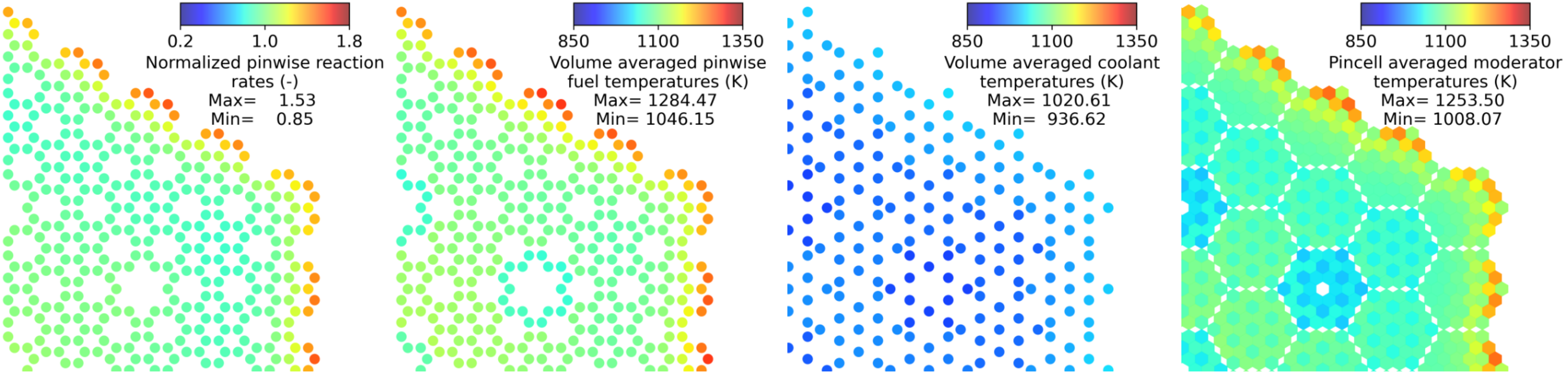
MPACT multiphysics coupling for Microreactors



MPACT multiphysics coupling for Microreactors

- **Unit cell solver**: Defined for each fuel compact, this solver calculates heat transfer through the fuel compact, graphite moderator, and heat pipe vapor.
- **Heat pipe solver**: Applied to each axially integrated fuel compact, this solver calculates heat transfer from the heat pipes in the core to the heat exchanger, determining the resulting heat pipe vapor temperature.
- **TRISO solver**: Defined for subregions within fuel compacts, this solver determines the temperature within the TRISO regions and computes the homogenized thermal conductivity of the fuel compact.
- **Reflector solver**: Assigned to each axial level, this solver calculates the reflector temperature and parasitic heat loss to account for heat loss directly from the outer vessel.
- **All solvers are iteratively solved and tightly coupled to neutronics solver**

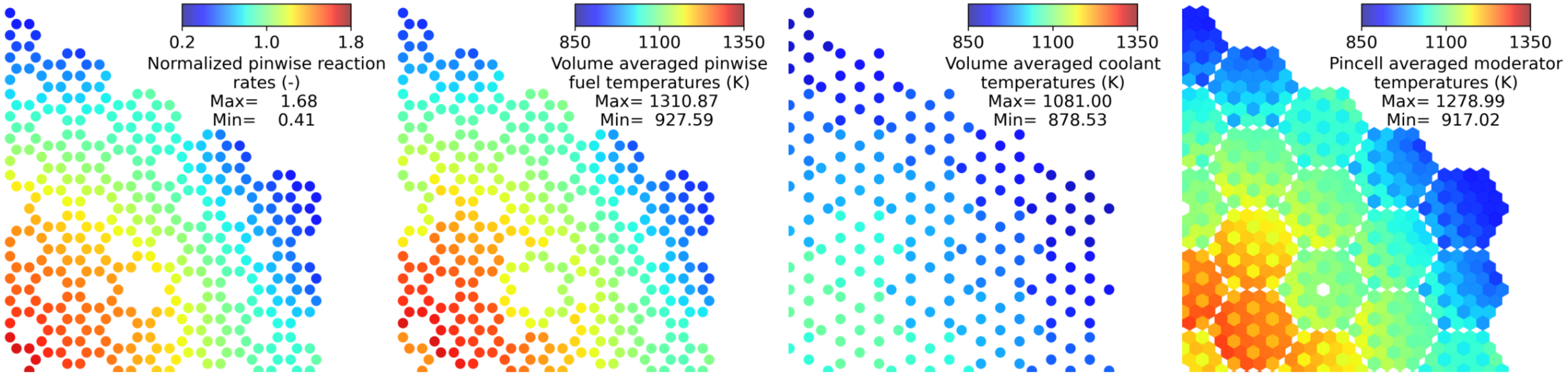
2D Full Core Results – All Drums Out Case



(a) Pin fission reaction rate *(b) Fuel temperature* *(c) Pipe vapor temperature* *(d) Moderator temperature*

- keff: 1.12900; total power iterations: 26
- Simulation time: 5min with 16 MPI
  - SMTF solver time: 0.35 sec

2D Full Core Results – All Drums In Case



(a) Pin fission reaction rate *(b) Fuel temperature* *(c) Pipe vapor temperature* *(d) Moderator temperature*

- keff: 0.96626; total power iterations: 21

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Core Analysis Tools: Advanced Neutronic and Thermo-mechanical Coupling

Work Performed by Chiara Genoni in Collaboration with C. Fiorina (Texas A&M University)

Motivation

- Solid state systems characterized by a **strong thermo-mechanical-neutronics coupling**
- Limited experimental data call for development of **high-fidelity multiphysics frameworks**

Reactivity Feedback

- Temperature
- Displacement
  - Gap Conductance
  - Leakage
  - Volumetric Fractions

KRUSTY was found to have 85% of reactivity feedback coming from fuel expansion.

Evolution of Thermo-Mechanical Response

Irradiation-Induced:
- Dimensional changes
- Creep
- Degradation of thermo-mechanical properties

State-of-the-Art Modeling

Develop and Apply a deformation-aware simulation workflow that is based on integrating

Serpent 2
Monte Carlo Code

OFFBEAT
Fuel Performance Code

Key Features
Evolution of gap conductance with geometry variations
Capability of treating mechanical contact without mesh overlapping
Spatial resolution of all the coupled fields (especially in neutronics)
Include models for material behavior under neutron irradiation
Good parallel scalability to reduce the compute time

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Work Performed by Chiara Genoni in Collaboration with C. Fiorina (Texas A&M University)

Approach

1. Computational Tools Choice

2. OFFBEAT Library Extension

3. Simulation Workflow

The workflow will be tested on a core design based on the **eVinci heat-pipe cooled microreactor:**

- Graphite solid matrix
- Sodium heat-pipes
- TRISO as fuel (40% packing factor)

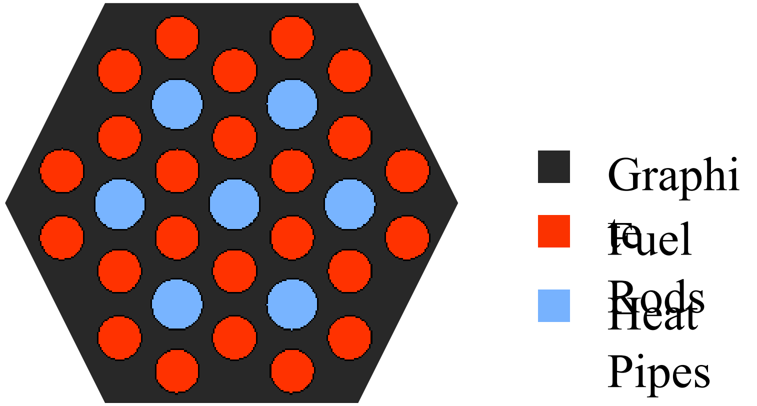

Figure 4. Schematic representation of the eVinci unit cell.

Unit Cell Parameters	
Linear Power	70 kW/m
Fuel OD	0.90 cm
Heat-Pipes OD	1.05 cm
Fuel Gap	500 microns
Heat Pipe Gap	200 microns
Pin Pitch	2.7 cm
Unit Cell Pitch	17 cm

Westinghouse Work Performed by Chiara Genoni in Collaboration with C. Fiorina (Texas A&M University)

Approach: Computational Tools Choice

SERPENT 2	
Provided of a multiphysics interface for coupling with any OpenFOAM based solver	→ Capturing local Effects
Simulation of gamma-neutron transport on an OpenFOAM unstructured mesh	
Material properties and tallies at a cell-by-cell level	→ Achieving high spatial resolution
Based on delta Woodstock tracking routine	→ Limiting the computational requirements
On-the-fly generation of temperature dependent cross section	

Work Performed by Chiara Genoni in Collaboration with C. Fiorina (Texas A&M University)

Approach: Computational Tools Choice

OFFBEAT
OpenFOAM-based Solver
Open source, Object Oriented
Models for material behavior under neutron irradiation
Model for variation in gap conductance
Semi-Implicit method for mechanical contacts, prevents meshes from overlapping

→ Coupling with Serpent 2

→ Straightforward implementation of new correlations for graphite

→ Fundamental for multi-body problems

Westinghouse Work Performed by Chiara Genoni in Collaboration with C. Fiorina (Texas A&M University)

Approach: Library Extension

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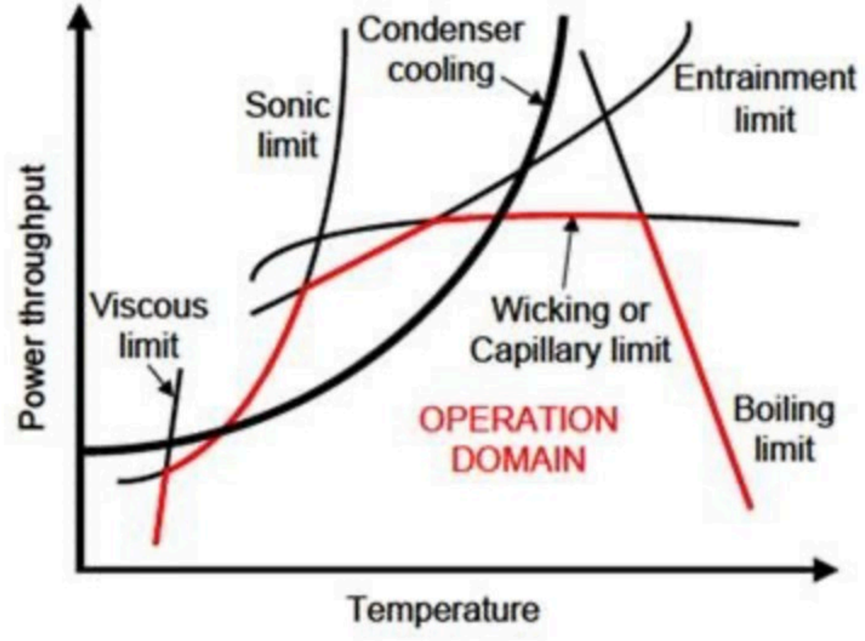
Heat-Pipe Model: Effective Heat Conduction

- Computationally cheap.
- Captures transition from free-molecular to viscous flow during start-up.
- Suitable when heat-pipes are operating within the safety margins.
- Based on the similarity between:
  - Mass Diffusion (Fick's Law)
  - Fourier's Law



Approach: Simulation Workflow

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Mapping of coupled fields across differently refined meshes generated using SALOME.

- **Coarse mesh** → Serpent 2 to tally gamma-fission energy deposition, fast flux.
- **Fine mesh** → OFFBEAT to solve temperature, stress distribution, displacement.

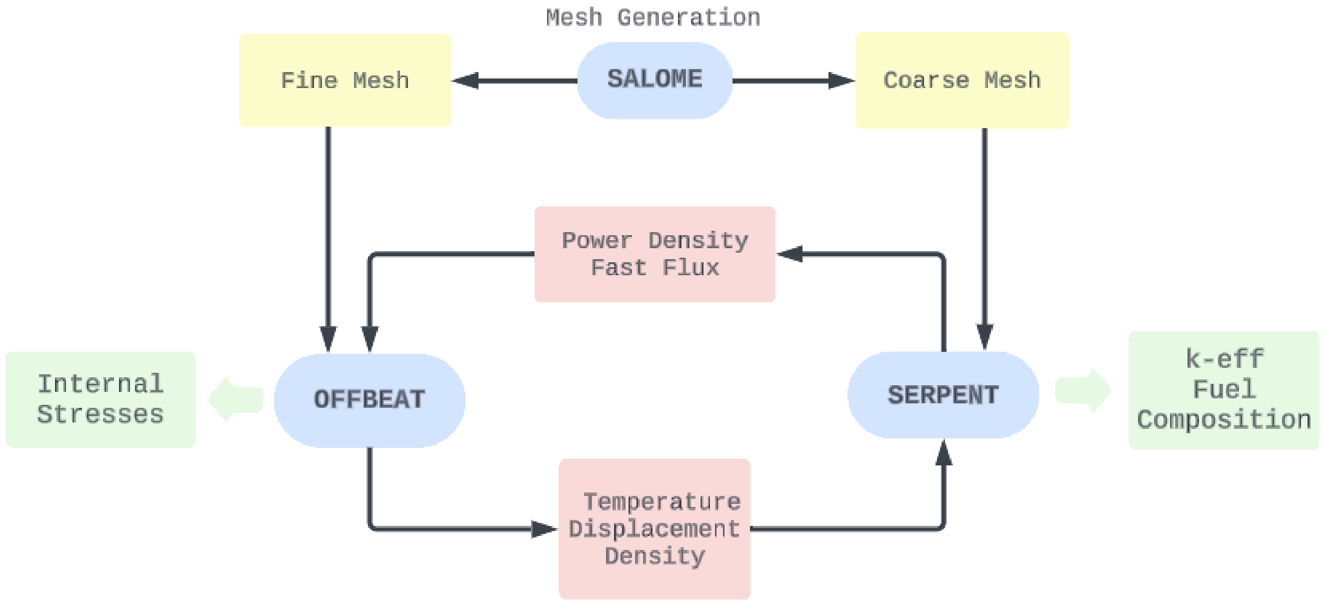

Figure 5. Schematic representation of the simulation workflow.

Exchange of coupled fields through **Picard iterations**

- **Heat Deposition, Fast Flux**
  SERPENT → OFFBEAT
- **Temperature, Displacement**
  OFFBEAT → SERPENT

Preliminary Results

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Benchmarking against Cardinal (OpenMC + MOOSE)

- Verification of our workflow.
- Support of the computational tools' choice.

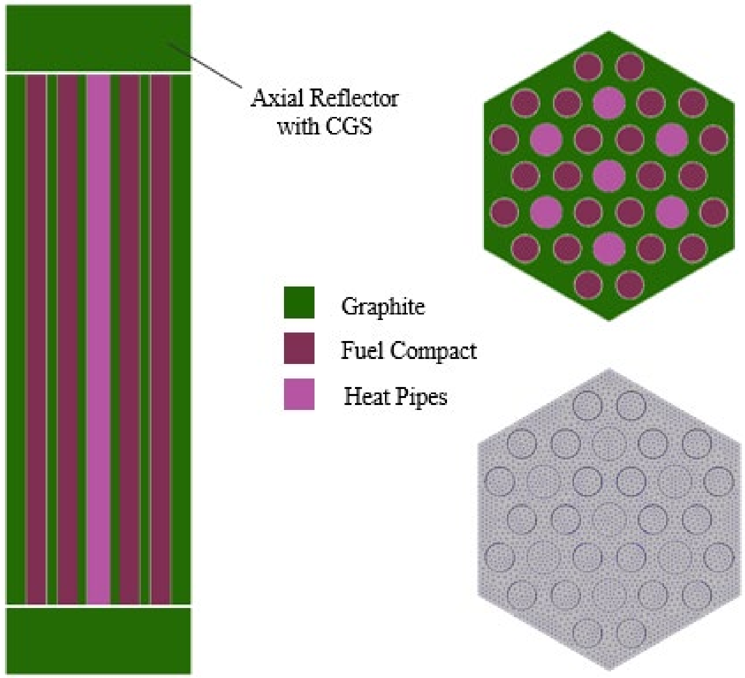

Figure 6. Schematic representation of the eVinci unit cell.

Relevant Differences	
OFFBEAT/SERPENT 2	**CARDINAL**
FVM Solver for thermo-mechanics	FEM Solver for thermo-mechanics
Woodstock delta tracking routine in Serpent 2	Surface tracking routine in OpenMC

Preliminary Results

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Benchmarking against Cardinal (OpenMC + MOOSE)

	k_{eff} Cold Uniform	k_{eff} Hot Non Uniform
Serpent 2	1.14120 +/- 0.00021	1.06096 +/- 0.00021
OpenMC	1.14230 +/- 0.00021	1.06128 +/- 0.00022 – 10 temperature bins 1.06420 +/- 0.00021 – 20 temperature bins

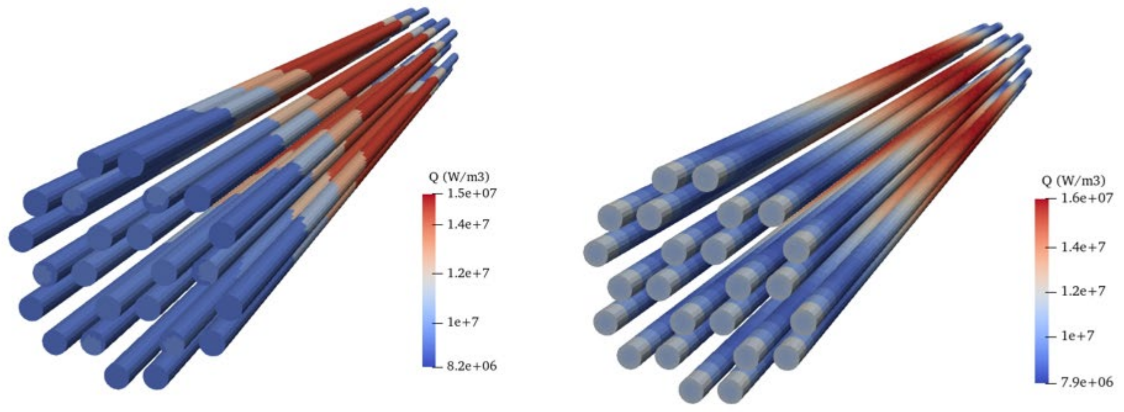

Figure 7. Power density distribution in OpenMC (left) and Serpent 2 (right).

Relevant Differences	
OFFBEAT/SERPENT 2	**CARDINAL**
Woodstock Delta Tracking routine in Serpent 2	Surface tracking routine in OpenMC

Monte Carlo Code	Run Time (core-hours)	Total Cells
Serpent2	280	500,000
OpenMC	250	1,500 20 temperature bins

Cardinal provides an algorithm that groups the mesh elements into macro-regions
over which the coupled fields are spatially averaged.

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Preliminary Results

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Simulation workflow tested
on a **full-size eVinci-like microreactor** for:

- Structural analysis on the solid matrix
- Temperature reactivity feedback

Modeling Assumptions

- One twelfth rotation symmetry.
- Solid matrix represented as a single block.
- Reflector was included through CSG.
- No control drums/rods.
- Fuel density homogenization.

Core Parameters	
Power	15 MWth
Core Active Length	1.6 m
Core Radius	1.12 m
Core H/R Ratio	1.42
Reflector Thickness	0.2 m
Fuel Enrichment	19.75 w/o

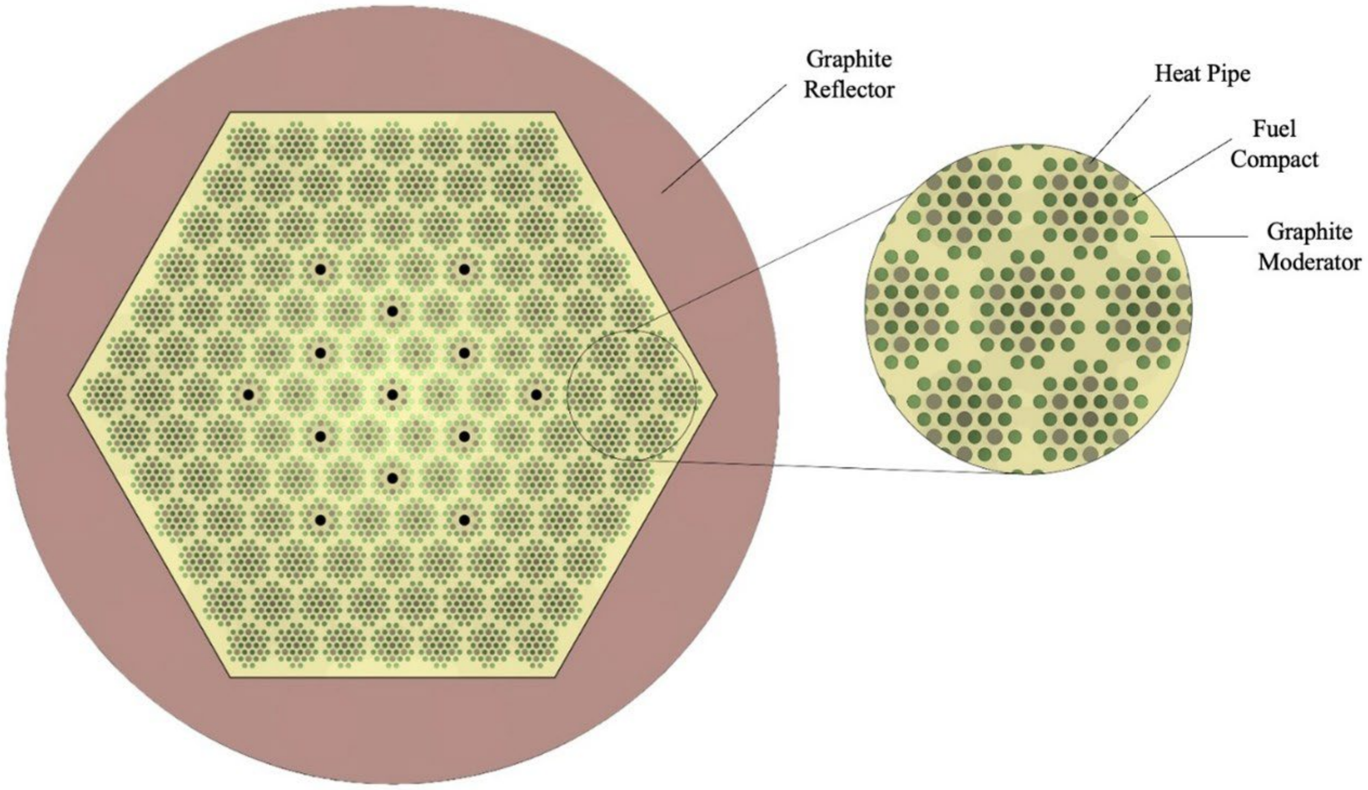

Figure 8. Schematic representation of the eVinci microreactor core.

Preliminary Results

Thermo-Mechanics Boundary Conditions:

- Coupled boundary conditions for **gap conductance** and **mechanical contact**.
- **Free displacement** and **Zero Temperature Gradient** for graphite, fuel rods.
- **Positive Normal Displacement** constrained, fixed temperature at the heat-pipe condenser side.

Simulation	Cell Size	Core-hours
Thermo-Mechanics	35 million	7500
Monte Carlo Tally	4 million	3000
Monte Carlo k-eigenvalue	8 million	1000 (~10 pcm)

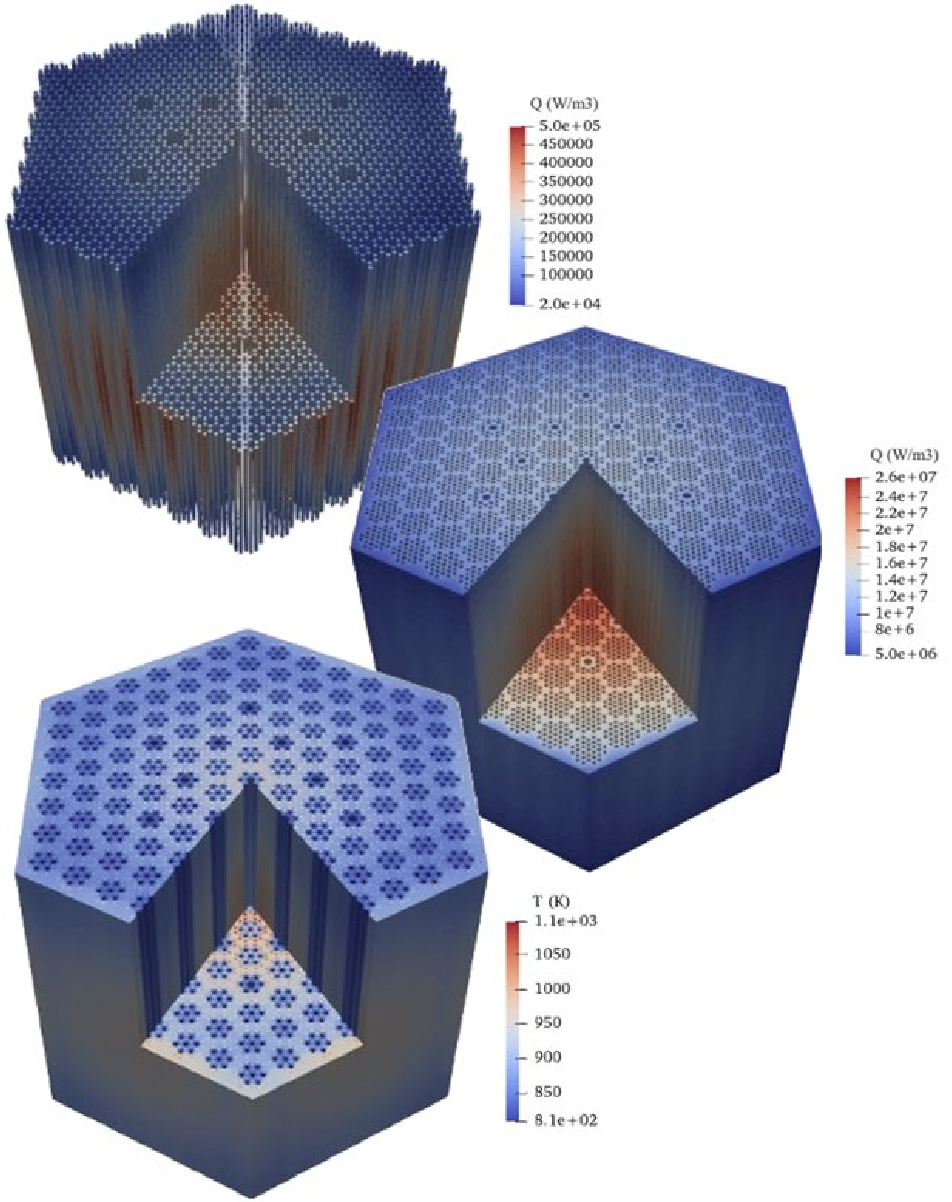

Figure 9. Power density and temperature distribution.

Preliminary Results

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Multiplication factor for each k-eigenvalue calculation to access temperature reactivity feedback.

Configuration	Temperature	Geometry	Densities	k_{eff}
Cold Zero Power	uniform 300 K	undeformed	uniform cold	1.14287
Hot Zero Power	uniform 800 K	deformed	cell-by-cell	1.08950
Case 1	cell-by-cell	undeformed	uniform cold	1.07990
Case 2	averaged by material	undeformed	uniform cold	1.08156
Case 3	averaged by mesh region	undeformed	uniform cold	1.07897
Case 4	cell-by-cell	deformed	cell-by-cell	1.08038
Case 5	uniform 300 K	deformed	uniform cold	1.14363

Cross-Sections

MCPLIB03 Photon Data Library
ENDF/B-VII.0 Nuclear Data Library

Preliminary Results

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Temperature Reactivity Feedback

- Comparison between cold case and the case representative of operational conditions (temperature + deformation)
- Majority of the **negative reactivity feedback** comes from temperature effects (~ 6000 pcm)

Configuration	Temperature	Geometry	Densities	k_{eff}
Cold Zero Power	uniform 300 K	undeformed	uniform cold	1.14287
Hot Zero Power	uniform 800 K	deformed	cell-by-cell	1.08950
Case 1	cell-by-cell	undeformed	uniform cold	1.07990
Case 2	averaged by material	undeformed	uniform cold	1.08156
Case 3	averaged by mesh region	undeformed	uniform cold	1.07897
Case 4	cell-by-cell	deformed	cell-by-cell	1.08038
Case 5	uniform 300 K	deformed	uniform cold	1.14363

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Preliminary Results

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Thermal Expansion Reactivity Feedback

- Comparison between cold case with and without deformation
- **Positive reactivity feedback** ~ 75 pcm
- In contrast with diffusion theory which predicts negative reactivity feedback

Configuration	Temperature	Geometry	Densities	k_{eff}
Cold Zero Power	uniform 300 K	undeformed	uniform cold	1.14287
Hot Zero Power	uniform 800 K	deformed	cell-by-cell	1.08950
Case 1	cell-by-cell	undeformed	uniform cold	1.07990
Case 2	averaged by material	undeformed	uniform cold	1.08156
Case 3	averaged by mesh region	undeformed	uniform cold	1.07897
Case 4	cell-by-cell	deformed	cell-by-cell	1.08038
Case 5	uniform 300 K	deformed	uniform cold	1.14363

Preliminary Results

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Effects of temperature spatial resolution:

- Comparison between hot case with and without deformation
- **Positive reactivity feedback** ~ 50 pcm
- In contrast with diffusion theory which predicts negative reactivity feedback

Configuration	Temperature	Geometry	Densities	k_{eff}
Cold Zero Power	uniform 300 K	undeformed	uniform cold	1.14287
Hot Zero Power	uniform 800 K	deformed	cell-by-cell	1.08950
Case 1	cell-by-cell	undeformed	uniform cold	1.07990
Case 2	averaged by material	undeformed	uniform cold	1.08156
Case 3	averaged by mesh region	undeformed	uniform cold	1.07897
Case 4	cell-by-cell	deformed	cell-by-cell	1.08038
Case 5	uniform 300 K	deformed	uniform cold	1.14363

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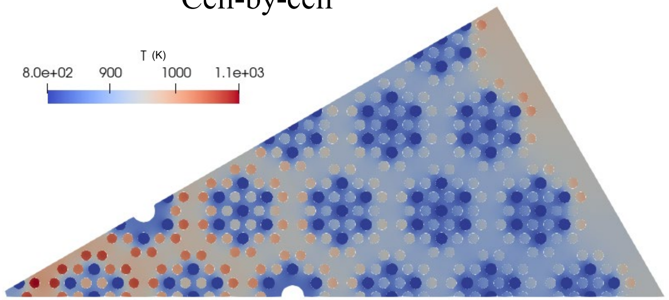
Preliminary Results

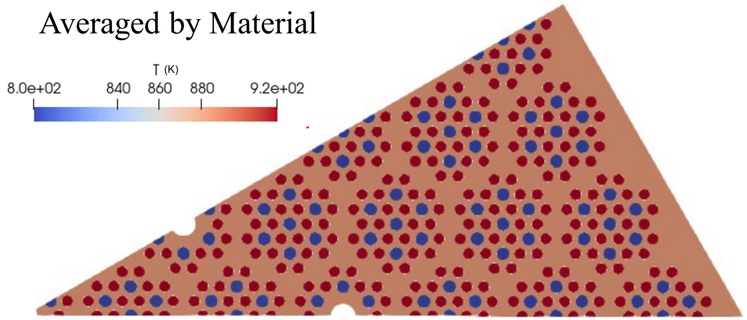
Effects of temperature spatial resolution

Configuration	Temperature	Geometry	Densities	k_{eff}
Cold Zero Power	uniform 300 K	undeformed	uniform cold	1.14287
Hot Zero Power	uniform 800 K	deformed	cell-by-cell	1.08950
Case 1	cell-by-cell	undeformed	uniform cold	1.07990
Case 2	averaged by material	undeformed	uniform cold	1.08156
Case 3	averaged by mesh region	undeformed	uniform cold	1.07897
Case 4	cell-by-cell	deformed	cell-by-cell	1.08038
Case 5	uniform 300 K	deformed	uniform cold	1.14363

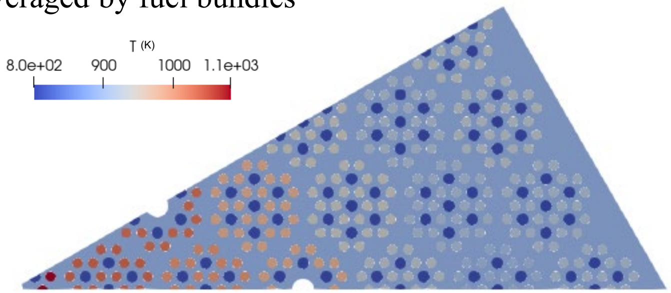
Cell-by-cell



Averaged by Material



Averaged by fuel bundles



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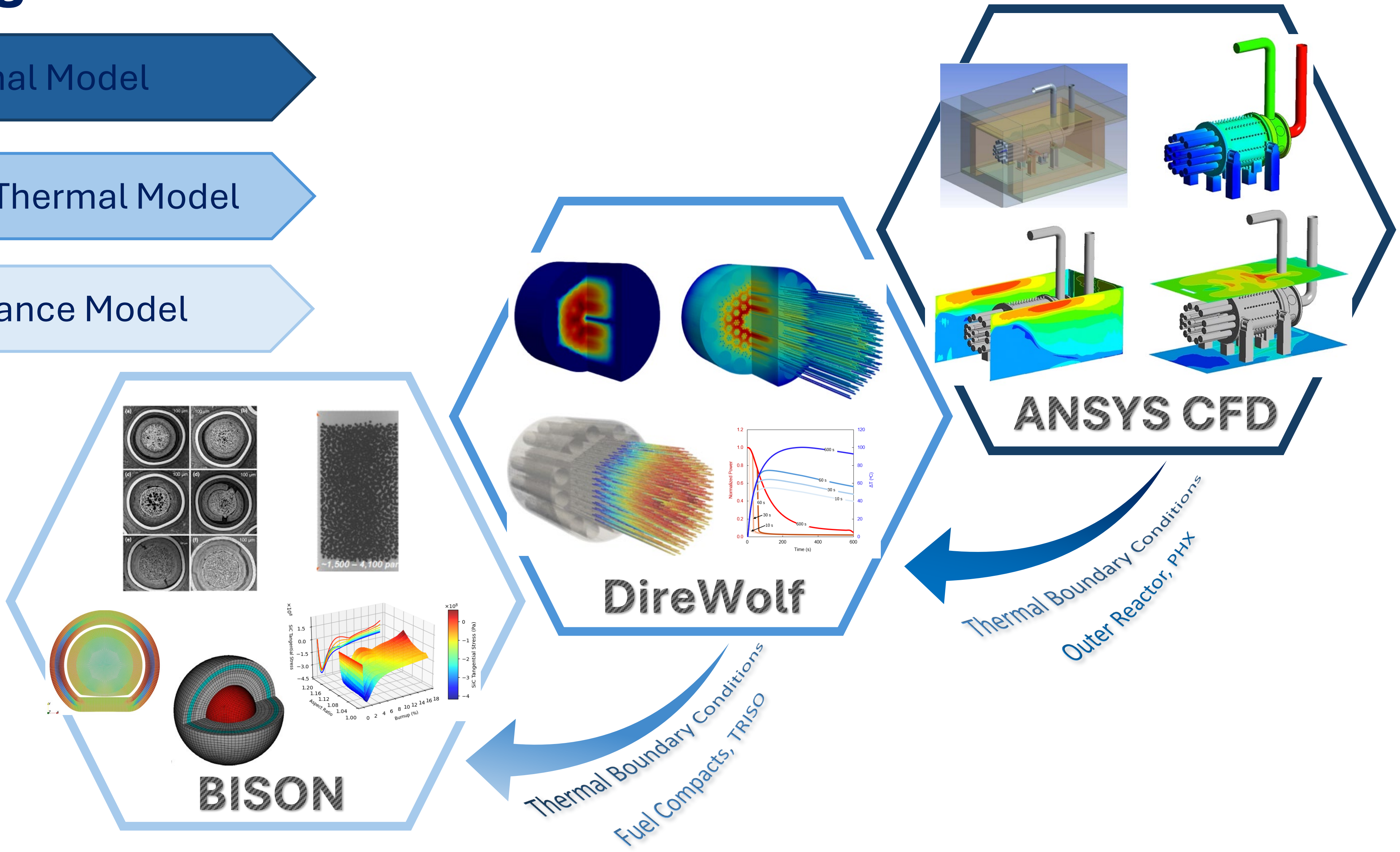
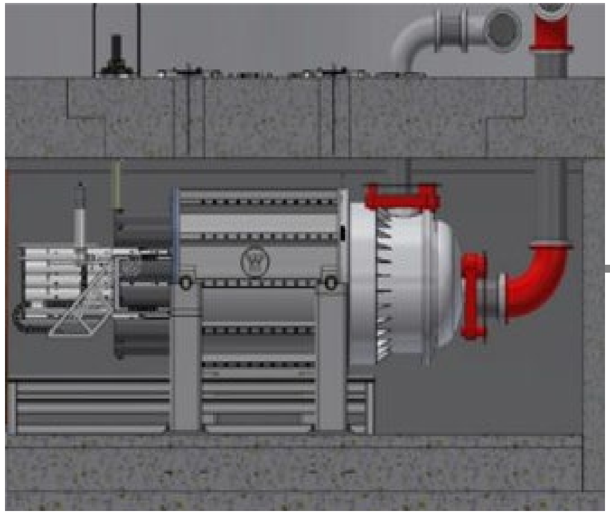
MOOSE-based Tools - Transient and Accident Analysis (DireWolf)

eVinci Integrated M&S Platform

- Multi-System Thermal Model
- Reactor Neutronic-Thermal Model
- TRISO Fuel Performance Model

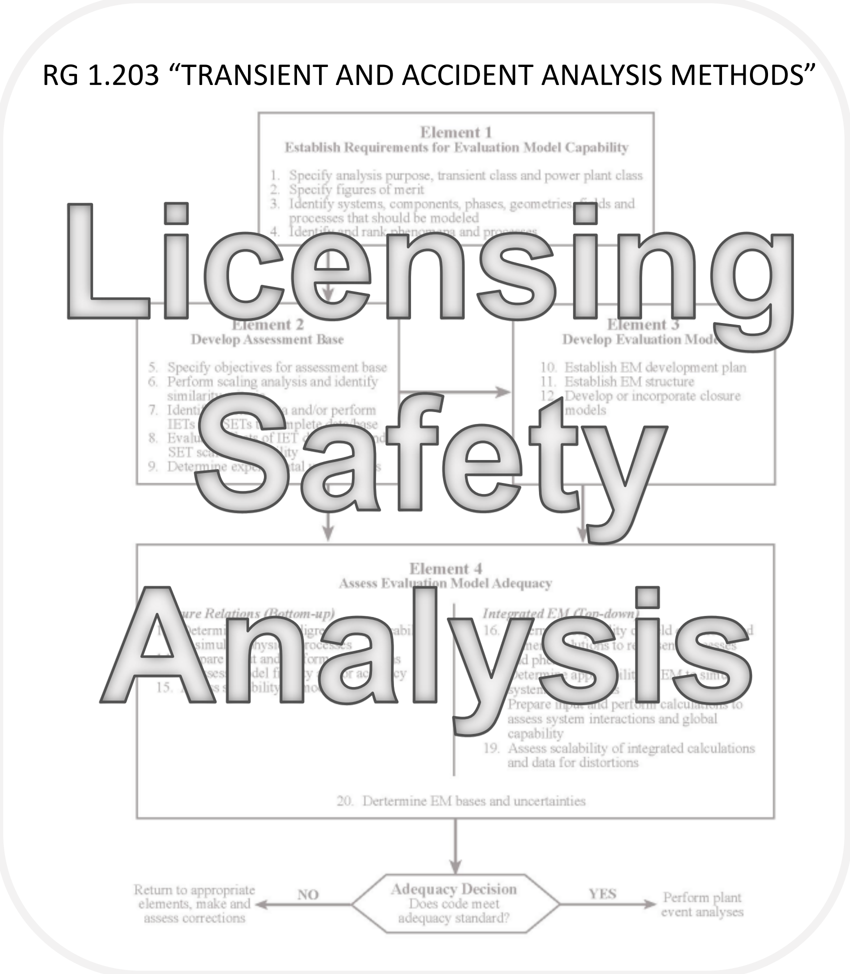


Transient and Accident Analysis (DireWolf)



- Normal Operation
- Operational Transient
- Anticipated Operation Occurrence
- Design Basis Accident
- Beyond Design Basis Accident *

RG 1.203 “TRANSIENT AND ACCIDENT ANALYSIS METHODS”



Beyond Design Basis Accident is currently not analyzed by MOOSE-based code in Westinghouse

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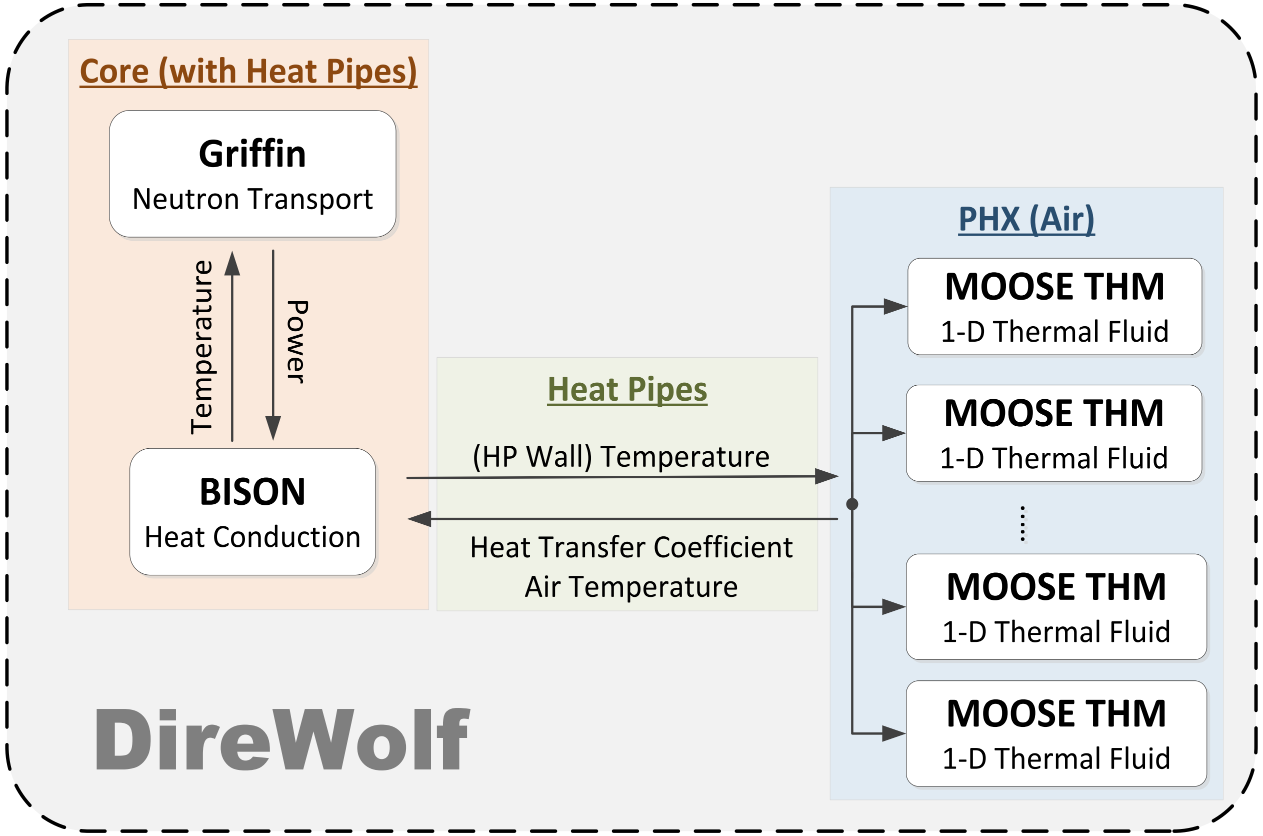
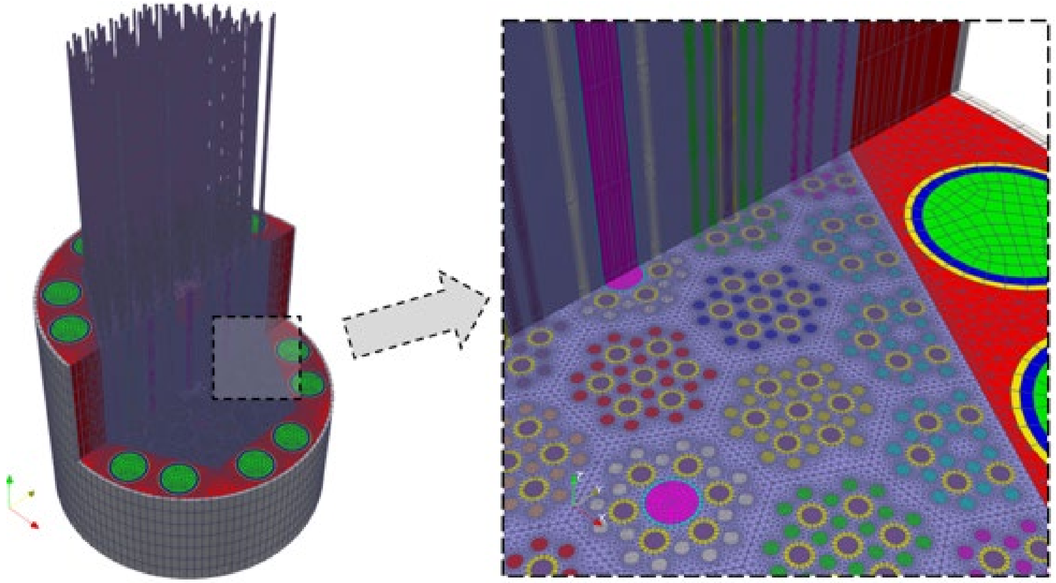
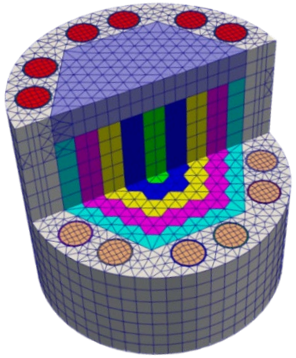
Transient and Accident Analysis (DireWolf)

Computer Codes and Input Models

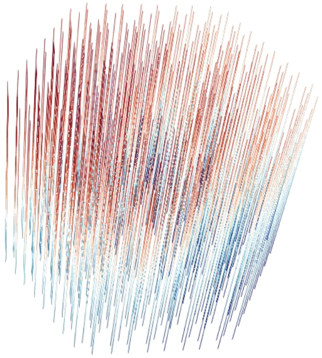




BISON Thermal Model



Griffin Neutronics Model

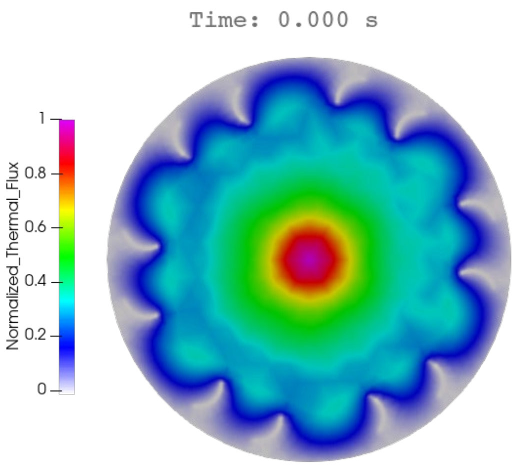


MOOSE THM Flow Model

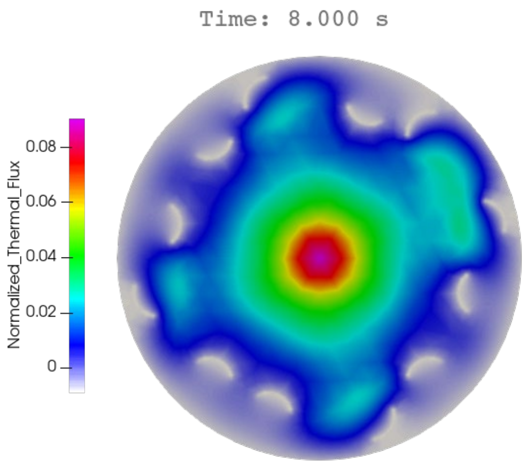
Transient and Accident Analysis (DireWolf)

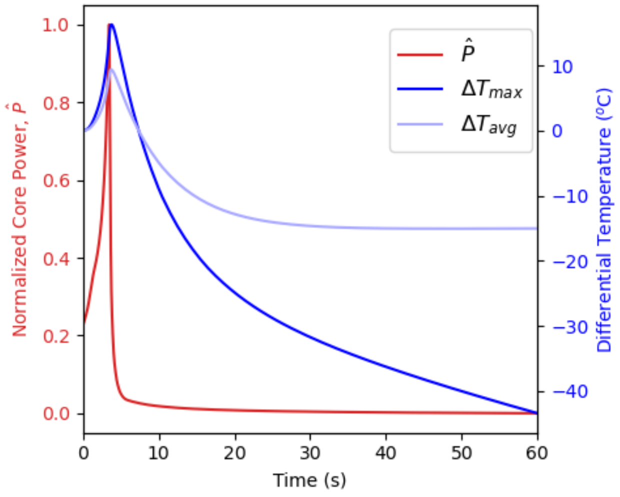
Safe Shutdown in Reactivity Insertion Accident

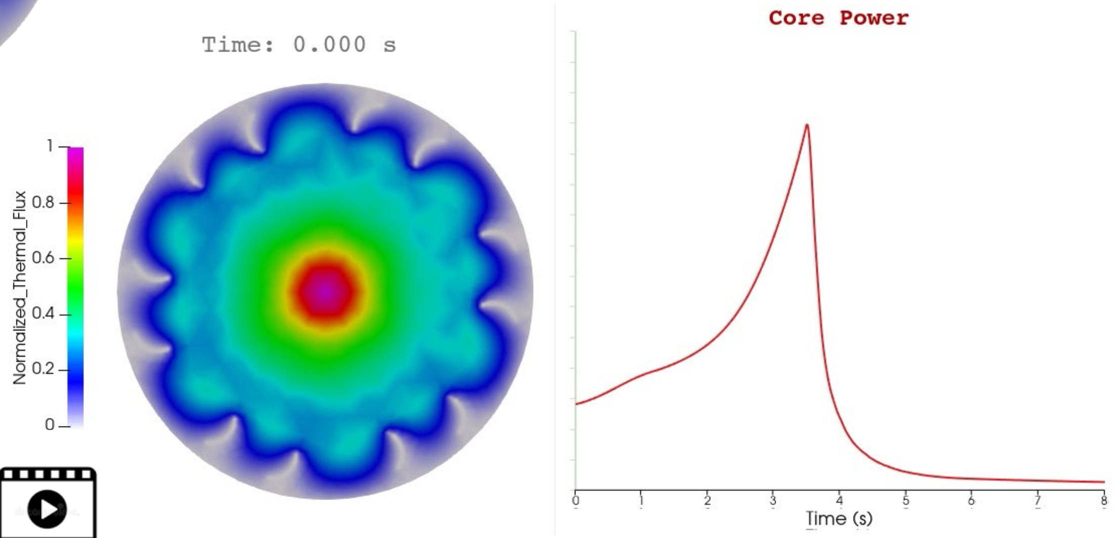
Accident Initiated



Accident Mitigated



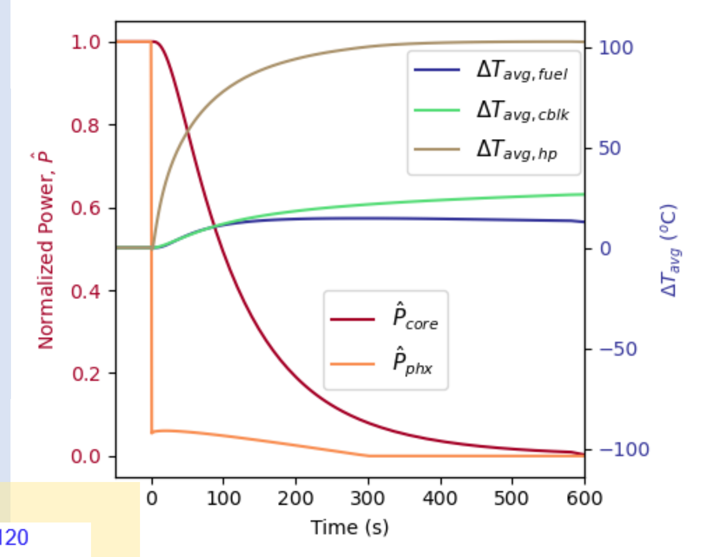




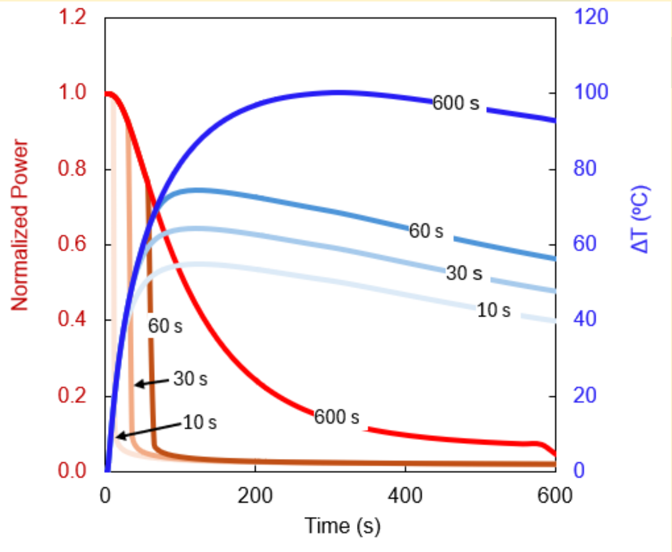
Transient and Accident Analysis (DireWolf)

Safe Shutdown in Loss of PHX Accident

- Core temperature increases after losing primary heat removal path in the accident
- Reactor is shut down automatically in ~10 min. after core temperature starts to increase



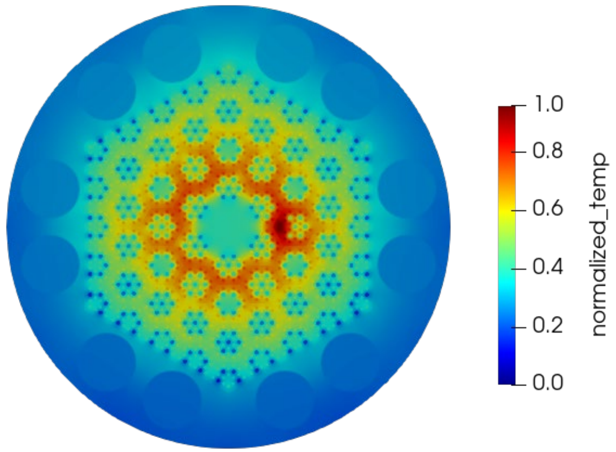
- Enhanced safety margin with earlier reactor trip via protection system

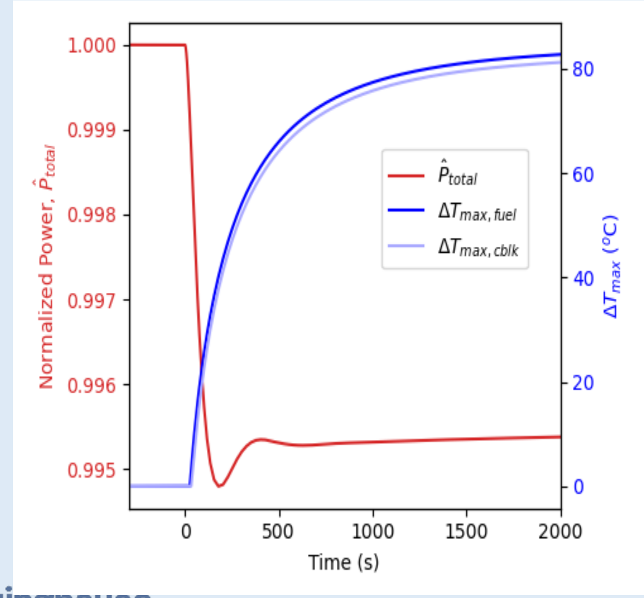


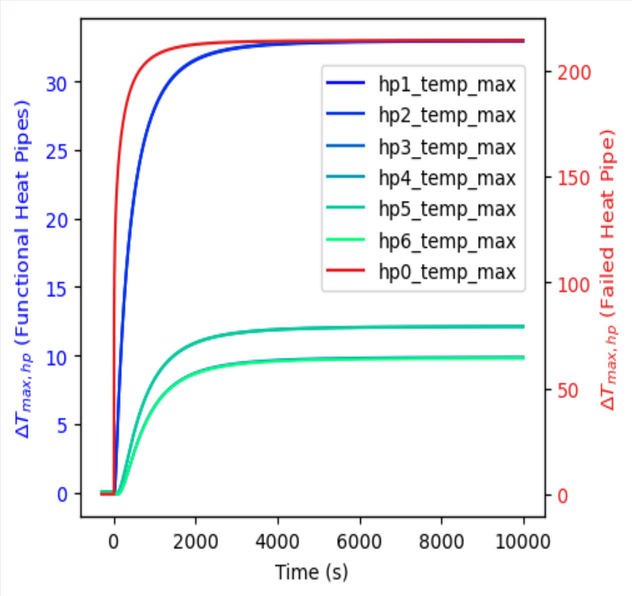
Transient and Accident Analysis (DireWolf)

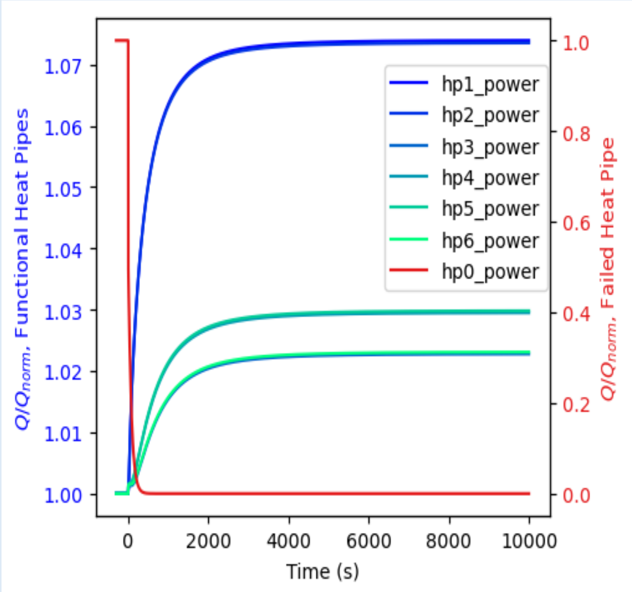
Isolated Effects in Single HP failure Accident

- Localized heat-up (Fuel, Core Block, Heat Pipe) with trivial effects beyond adjacent regions and global **core power**
- Insignificant thermal effects to neighboring heat pipes
- Extra protection can be implemented to trip the reactor on component overheat setpoints









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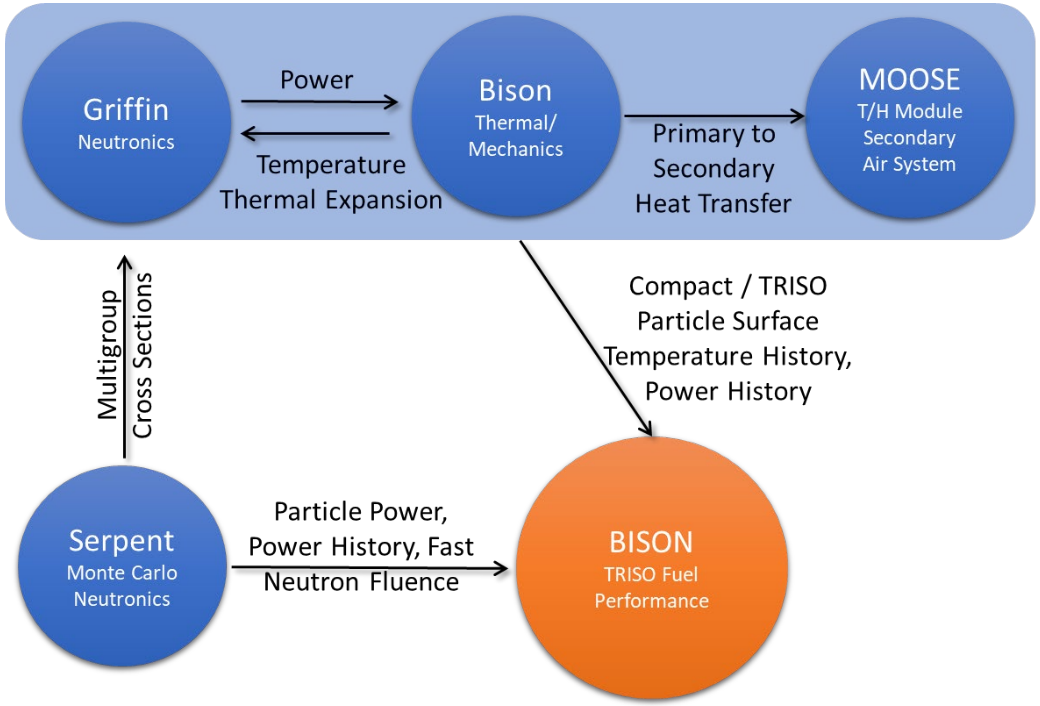
MOOSE-based Tools - TRISO Fuel Performance (BISON)

eVinci Microreactor TRISO Fuel Performance Methodology

Robust Methodology using NEAMS Based Tools and Statistic Models

- Evaluate thermo-mechanical performance, failure probability, and fission product release rates during normal operation, AOOs and DBAs
- Support the development, testing, and licensing of the eVinci microreactor



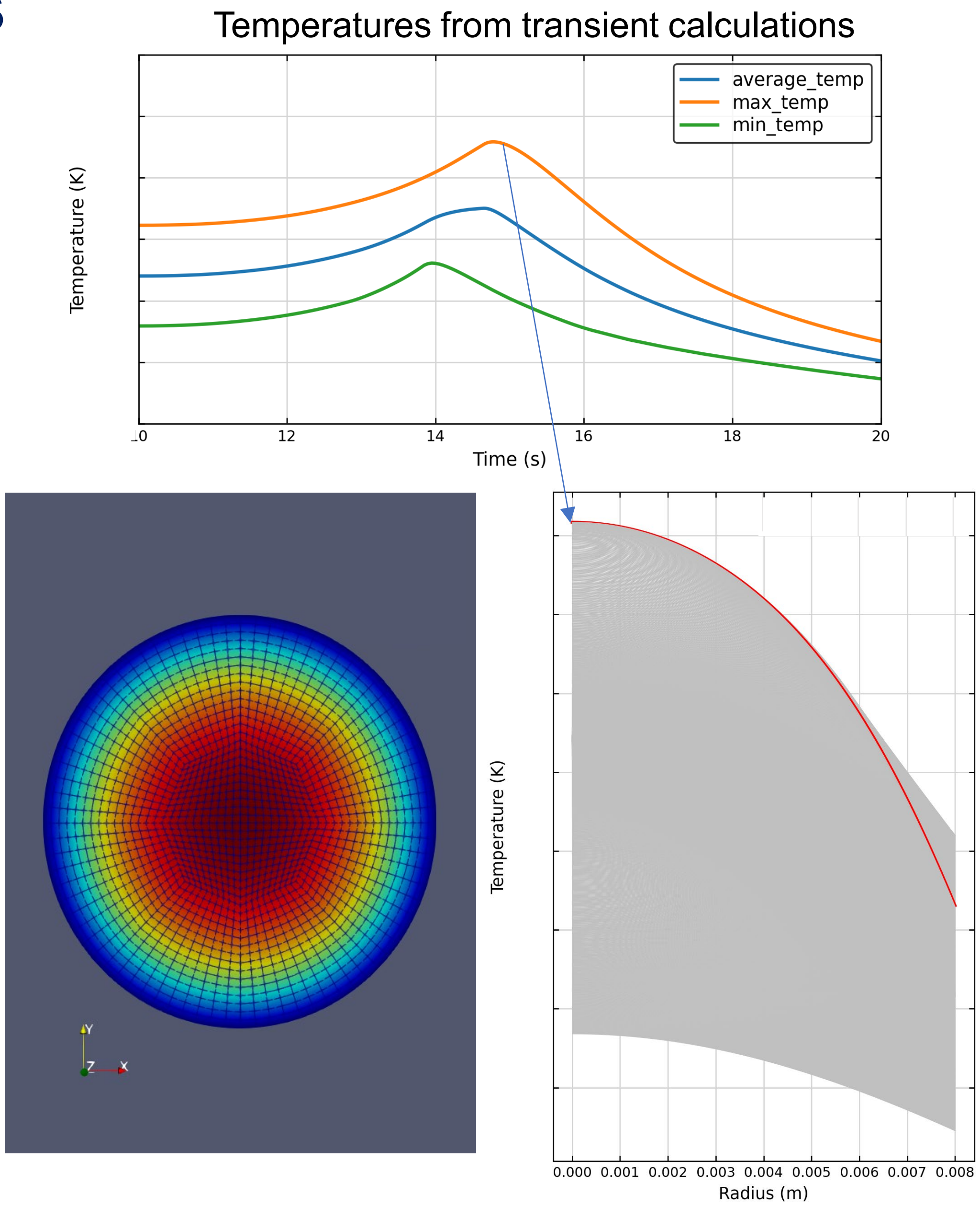
Fuel models are included to describe temperature and burnup dependent thermal properties, fission product swelling, densification, thermal and irradiation creep, fracture, and fission gas production and release.

Bison Thermo-Mechanical Evaluations
Fuel Compact Level

- Compact thermo-mechanical behavior during normal operation, anticipated operation occurrences (AOOs), and design basis accidents (DBAs)

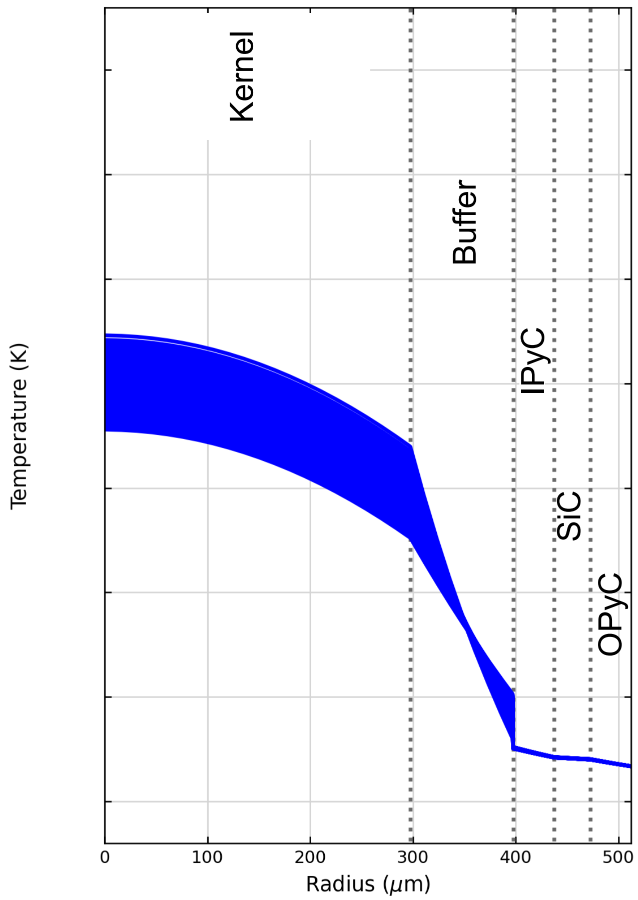
- Analysis Inputs:
  - Irradiation conditions from core design and transient calculations.
  - Compact surface temperature (thermal boundary condition)
  - Fast neutron fluence

Calculated max temperature is used as boundary condition on the particle level



Bison Thermo-Mechanical Evaluations
TRISO Particle Level

- Thermo-mechanical behavior during during normal operation, anticipated operation occurrences (AOOs), and design basis accidents (DBAs)
- Bison thermal, mechanical, and species models to predict the fission gas production/release/diffusion, distributions of temperatures and stresses / strains in the TRISO particle layers
- Analysis Inputs:
  - Particle surface temperature (Thermal boundary condition)
  - Fission rate (for burnup, heat generation, and fission product inventory)
  - Fast neutron fluence

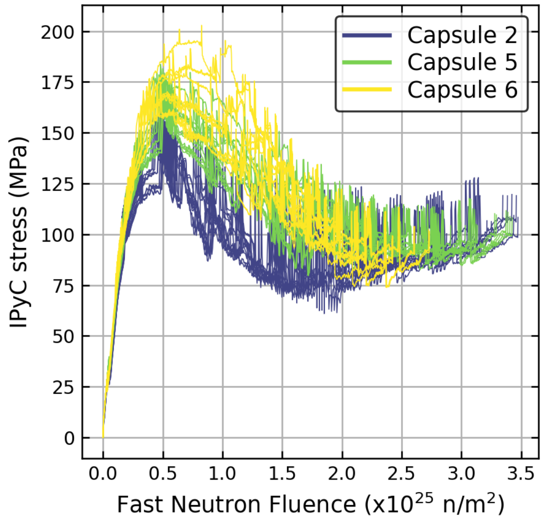


Calculated temperatures and stresses are then checked against criteria to determine particle failure and fission product release.

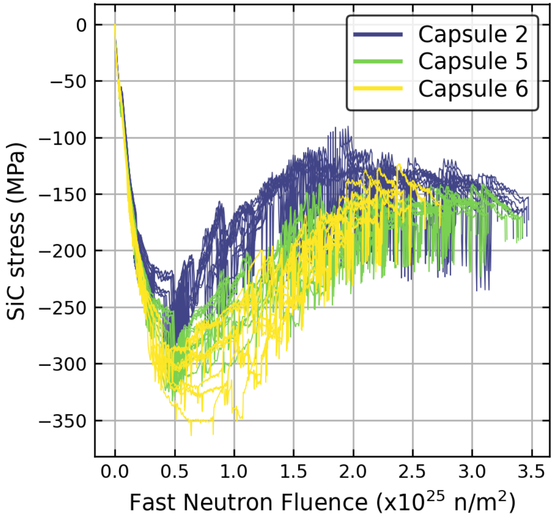
Tangential Stresses in IPyC, SiC, and OPyC Layers

AGR-2 UCO Capsule 2, 5, and 6 Compacts

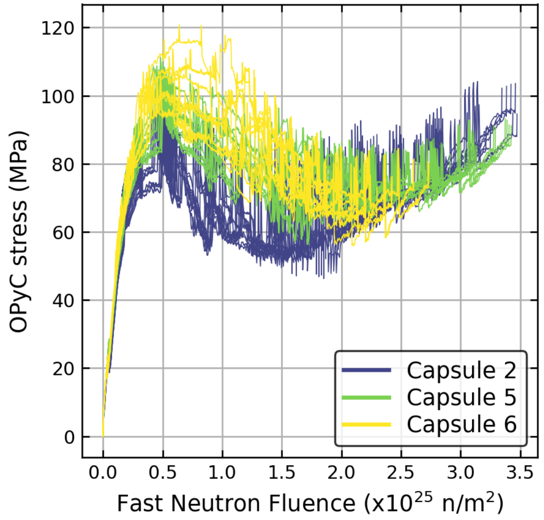
IPyC Layer

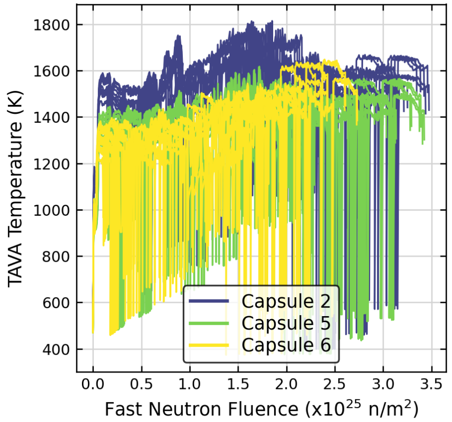


SiC Layer



OPyC Layer



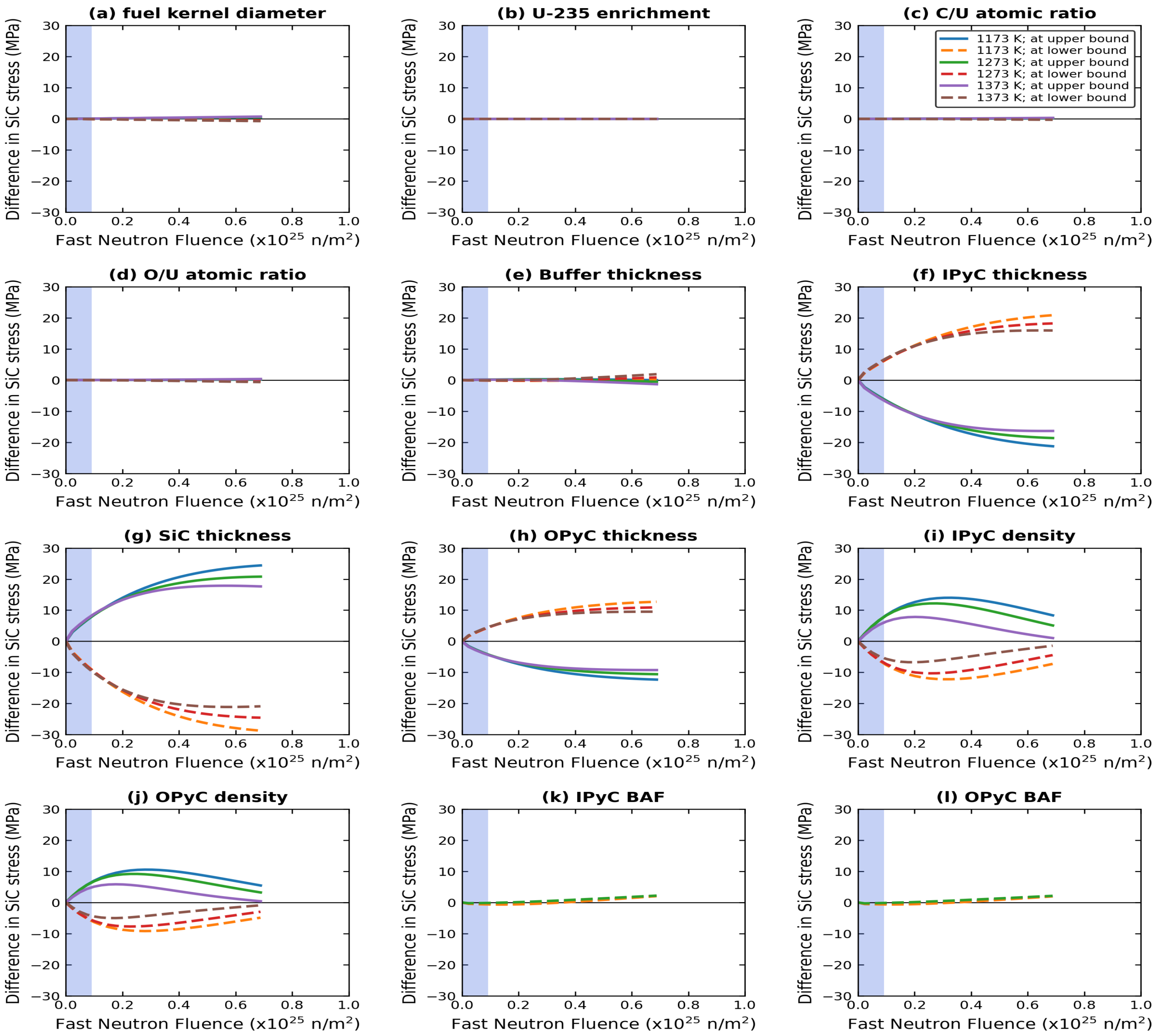


The spikes observed in the stress profiles are primarily attributed to fluctuations in the daily temperature histories.

Parametric Sensitivity Study

Parameters:

- Fuel kernel diameter (μm)
- U-235 enrichment (wt.%)
- CU atomic ratio (-)
- OU atomic ratio (-)
- Buffer thickness (μm)
- **IPyC thickness (μm)**
- **SiC thickness (μm)**
- **OPyC thickness (μm)**
- **IPyC density (g/cm3)**
- **OPyC density (g/cm3)**
- IPyC Bacon anisotropy factor (-)
- OPyC Bacon anisotropy factor (-)



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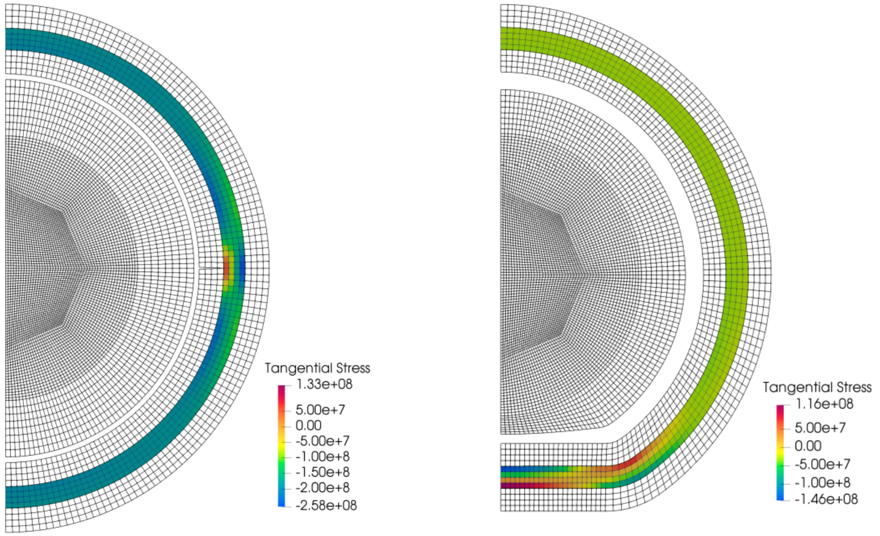
Particle Failure Probability Analysis

Built-in MOOSE Tools for Failure Probability Analysis

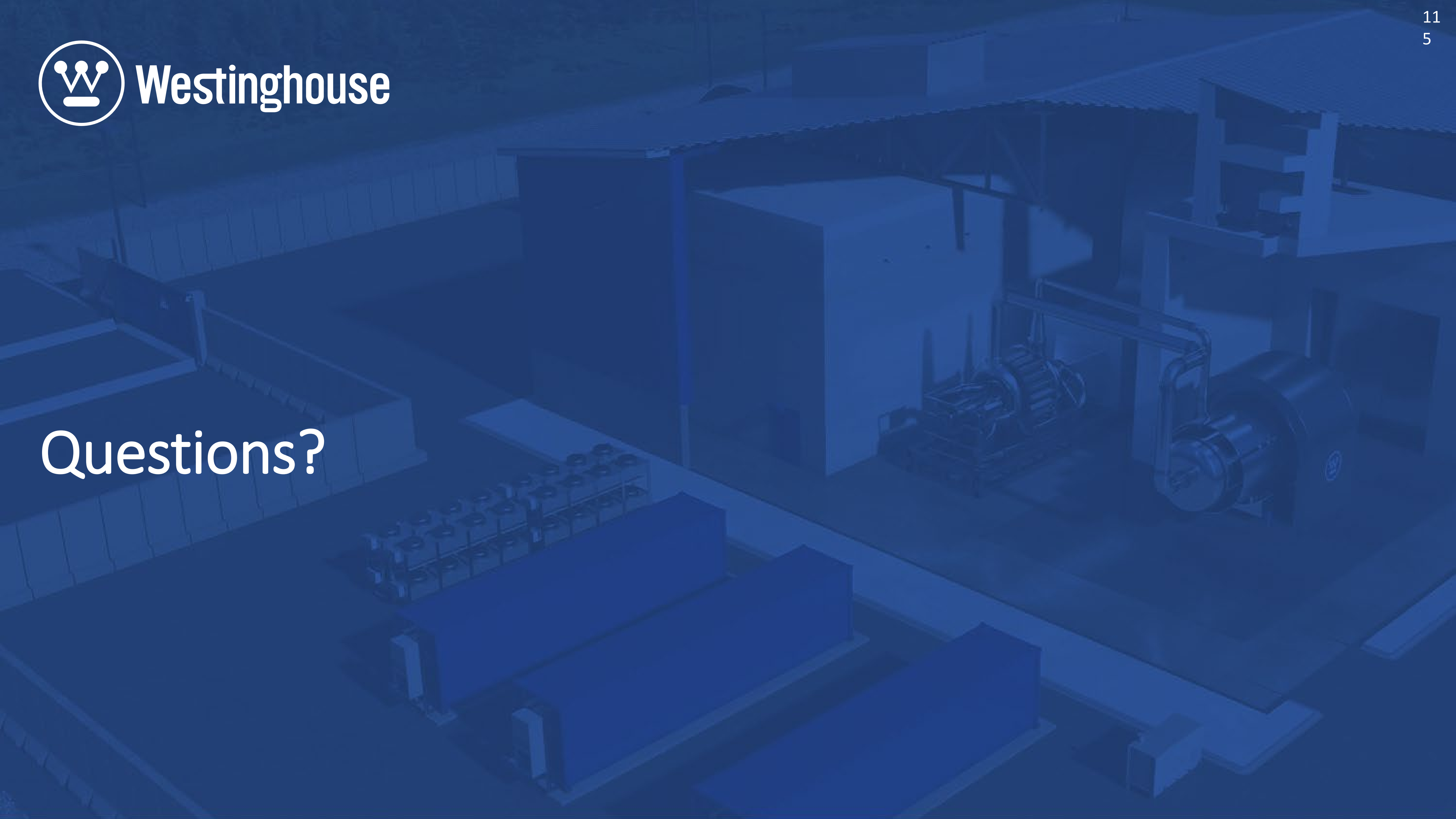
- Automatic statistic sampling
- Automatic sample execution
- Monte Carlo and Direct Integration probability models



Applicable Failure Models Available in Bison

- Pressure vessel failure (including aspherical effects)
- IPyC/OPyC crackings leading to SiC failure
- Pd penetration
- IPyC- SiC debonding
- SiC failure due to debonding

Weibull failure criterion: The maximum stress σ_c is compared to a strength sampled from a Weibull distribution featuring mean strength σ_{ms} and Weibull modulus m. Failure occurs when σ_c exceeds the sampled strength



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Questions?