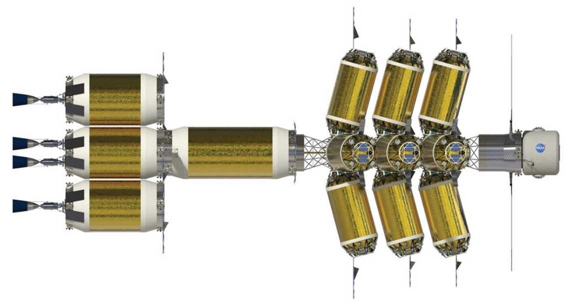
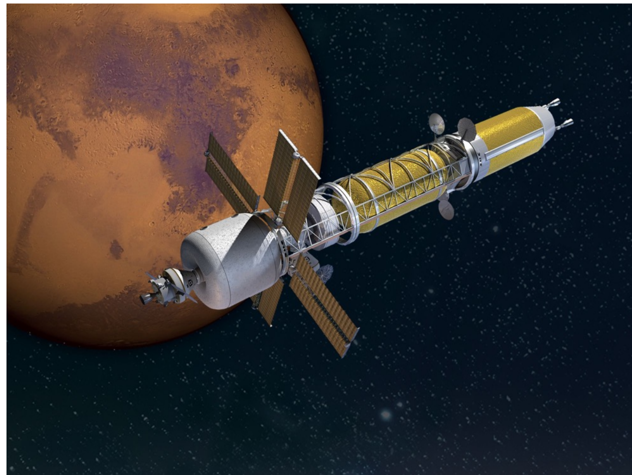


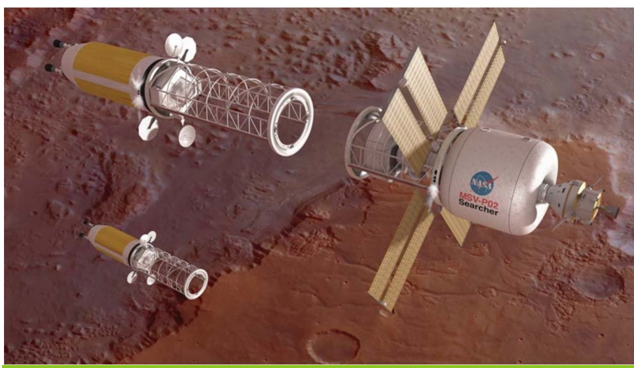


Mark DeHart ’84

Directorate Fellow

Nuclear Science &
Technology Directorate

Idaho National Laboratory



Multiphysics Modeling in Support of NASA Nuclear Thermal Propulsion Designs

Texas A&M University

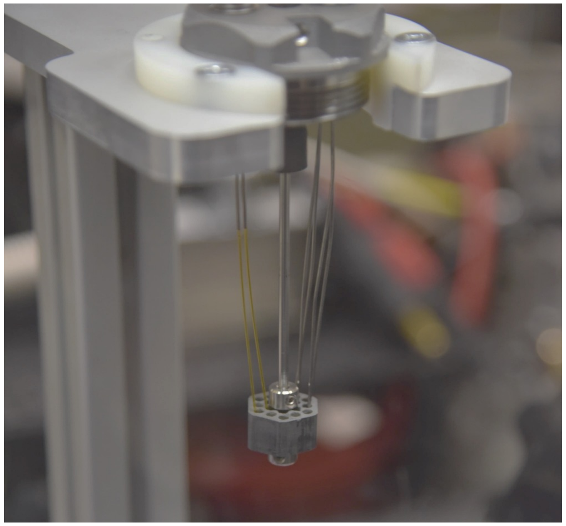
October 5th, 2022

Idaho National Laboratory

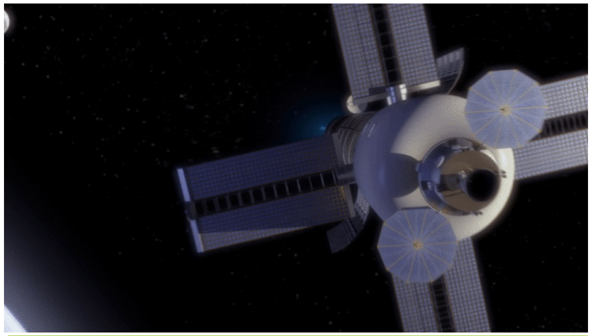
INL/MIS-22-69498

Overview

- Introduction to Idaho National Laboratory
  - Specific Work Opportunities of Potential Interest
- Nuclear Thermal Propulsion
- Background on Griffin
- Analysis Workflow
- Analysis Approach
  - Cross section generation
  - Mesh generation
  - Fuel element modeling
- Validation using SIRIUS measurements in TREAT (time permitting)
- Closing Remarks
- Internship Opportunities



SIRIUS-1 Fuel Test Specimen



National Laboratories

Addressing the world's most challenging problems

Nuclear S&T

- Nuclear fuels and materials
- Nuclear systems design and analysis
- Fuel cycle science and technology
- Nuclear safety and regulatory research
- Advanced Scientific Computing

Advanced Test Reactor Complex

- Steady-state neutron irradiation of materials and fuels
  - Naval Nuclear Propulsion Program
  - Industry
  - National laboratories and universities

Materials & Fuels Complex

- Transient testing
- Analytical laboratories
- Post-irradiation examination
- Advanced characterization
- Fuel fabrication
- Space nuclear power and isotope technologies

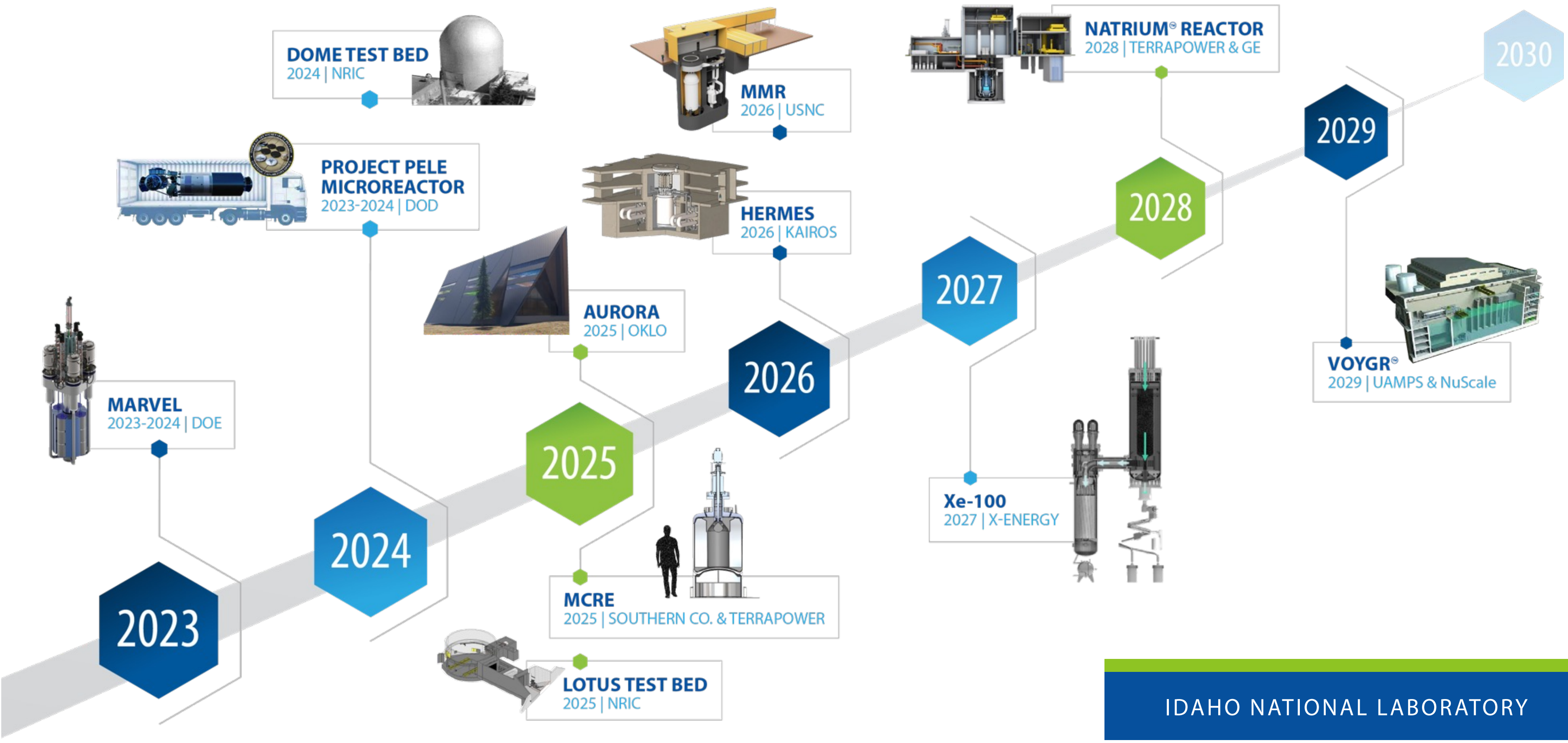
Energy & Environment S&T

- Advanced transportation
- Environmental sustainability
- Clean energy
- Advanced manufacturing
- Biomass

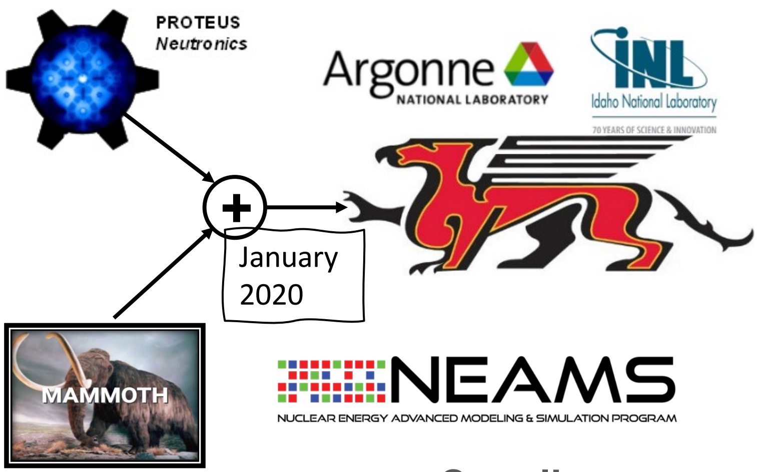
National & Homeland Security S&T

- Critical infrastructure protection and resiliency
- Nuclear nonproliferation
- Physical defense systems

Advanced reactors are coming – a key opportunity for reactor physics capabilities

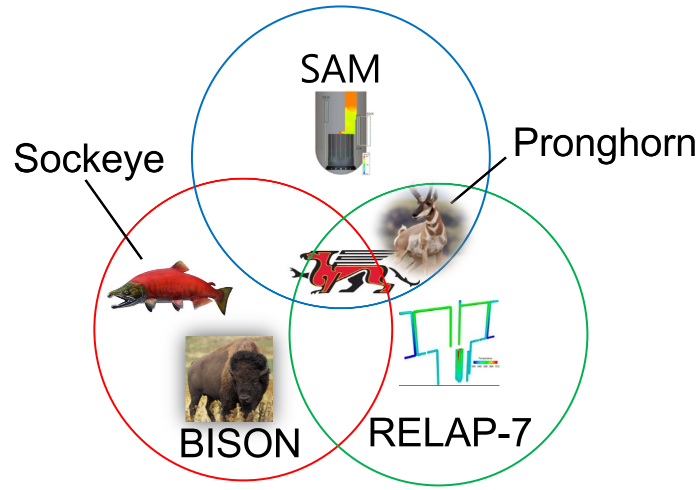


Griffin: Advanced Reactor Physics Tool
Workhorse of Reactor Physics Methods and Analysis Dept.



Opportunities:
Internships,
post-doc,
full-time

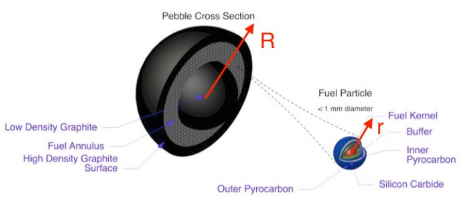
FHR, SFR, MSR



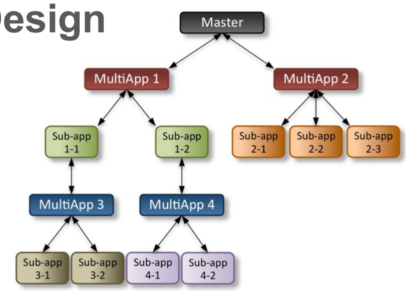
Micro-Rx **HTGR**

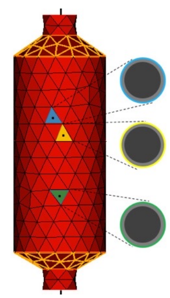
Coupling by Design

Strong Coupling



Multiapp





INL’s Thermal Fluids Methods and Analysis Department

RELAP5-3D

- Modeling air ingress scenarios in High Temperature Gas Reactor (HTGR)
- Simulating steam generator tube rupture and steam ingress in the primary side (HTGR)
- Sodium natural circulation during transients (SMR)

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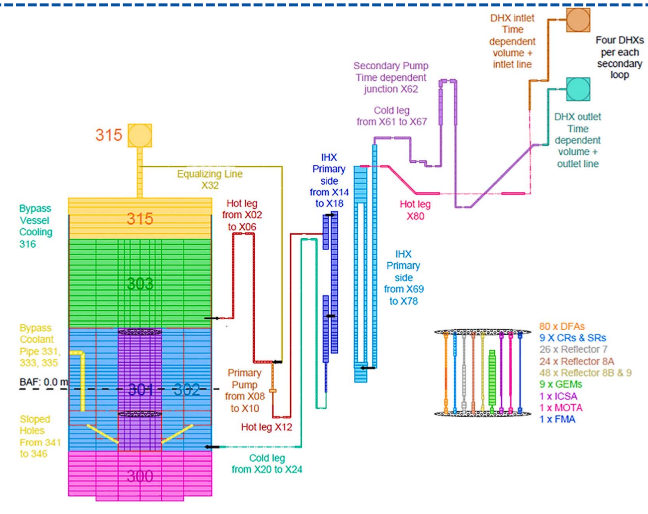
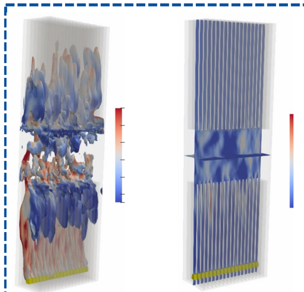
Connie.Stevens@inl.gov

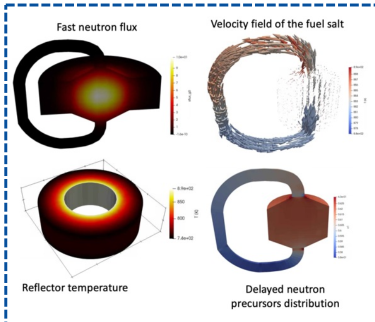


Three primary and secondary loops for a RELAP5-3D Model

V. Narcisi, et al., Nuclear Engineering & Design, 2021, Vol. 383



Modeling boiling in flow transition regime



Coupled model

Computational Fluid Dynamics

- Modeling coupled fluid flow and heat transfer including coupled effects such as oxide layer growth and nucleate boiling
- Simulating 3D flow induced vibration and analyzing risks of multi-axial mechanical fatigue
- Development of the INL CFD code

Multiphysics

- Modeling flow-accelerated corrosion and tracking species in Molten Salt Reactor (MSR)
- Coupled neutronics – thermal hydraulics – thermomechanics simulations (MSR & micro-reactors)
- Multiphysics analysis of bowing in liquid-metal cooled reactors involving thermomechanical deformation and coupled thermal hydraulics effects

Opportunities:
Internships, post-doc, full-time

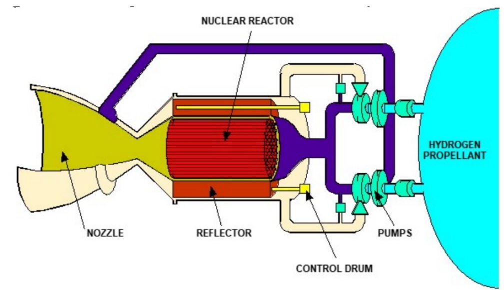
Code Development

- Code coupling to model dynamic and complex systems for advanced reactors
- Python scripting for material property generation, analytic solutions, and input/output processing

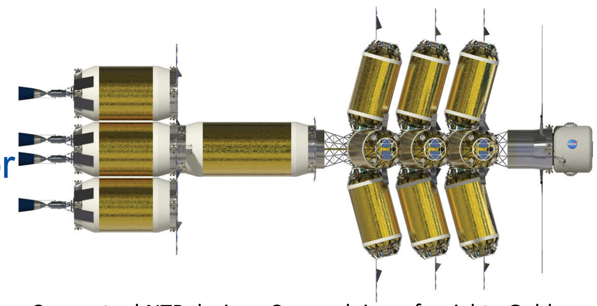
IDAHO NATIONAL LABORATORY

Nuclear Propulsion for Interplanetary Travel

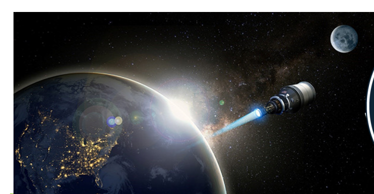
- NASA plans to launch a manned mission to Mars by the end of this decade.
  - Interplanetary travel will be fueled by nuclear propulsion – up to half the travel time
  - Two options are being considered:
    - Nuclear thermal propulsion (NTP), where hydrogen is heated to high (~3000 K) temperature to provide thrust directly.
    - Nuclear electric propulsion (NEP), where a nuclear reactor is used to generate electromagnetic fields to accelerate ions that are used to generate thrust.
    - NTP is more technically mature, and NASA is focused on it for rocket design.
- A mission to Mars will use a space or lunar base to assemble interplanetary engines and vehicles, nuclear engines will not launch from Earth.
- The US Department of Defense is also pursuing development of NTP engines for cis-lunar operations (Space Force) under the “Demonstration Rocket for Agile Cislunar Operations (DRACO)” project.



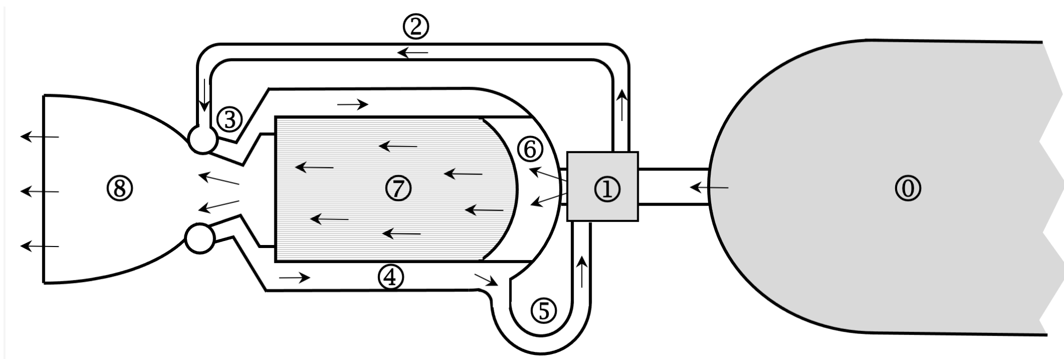
Major elements of a Nuclear Thermal Propulsion system.



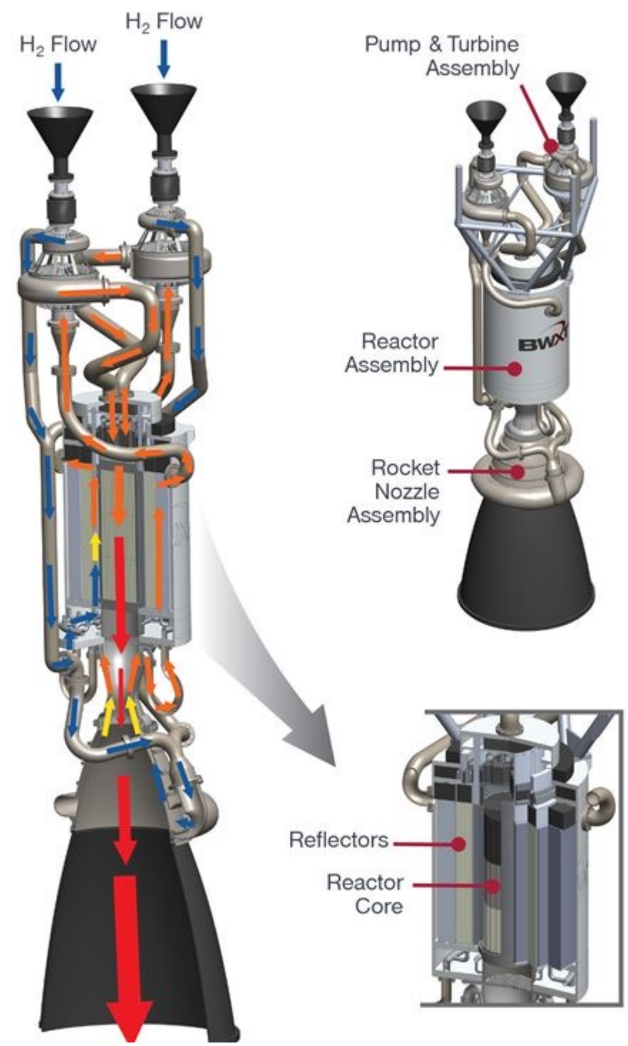
Conceptual NTP design. Crew cab is on far right. Golden tanks are for hydrogen, and most will be jettisoned during the mission.



Nuclear Thermal Propulsion Engine



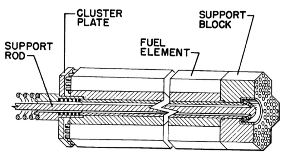
(0) Liquid hydrogen storage tank
(1) Pre-heated-hydrogen-driven turbopump
(2) Flow line from turbopump to nozzle
(3) Nozzle cooling
(4) Pressure vessel/reflector/control drum cooling
(5) Gaseous hydrogen feed to turbopump(s)
(6) Gas plenum above core
(7) Reactor core and hydrogen cooling
(8) Exhaust nozzle

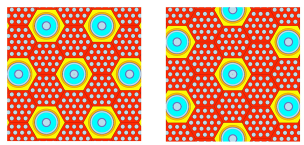


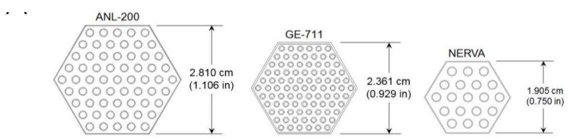
Why NTP?

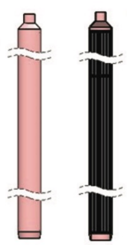
- The value of NTP was recognized in 1947 and large experimental programs pursued NTP engine design in the1950s and 1960s.
- NTP has several advantages over chemical $H_2 + O_2$ engines
  - First and foremost, a factor of 2-3 gain over performance (specific impulse, I_{sp}, analogous to MPG in a car).
    - The I_{sp} represents the time over which 9.81 kilograms (or one Newton of weight on Earth) of propellant can produce one Newton of thrust.
    - The larger the I_{sp}, the longer the engine can operate with a given mass of fuel.
    - For chemical engines the I_{sp} is about 450 s. For H_2 in an NTP engine, the ISP is about 900 s. This is related to the molecular mass of the propellent.
  - Can cut transit time to Mars in half (reduced radiation exposure)
  - Large abort window relative to chemical system
  - Potential for doubled payload (but with increased transit time)

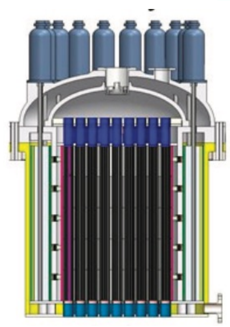
Nuclear Thermal Propulsion Support at INL







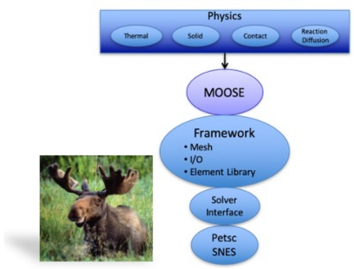




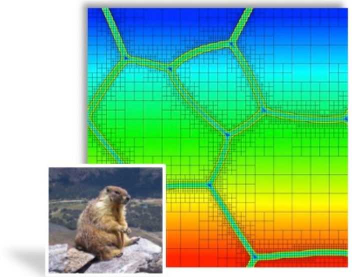
- INL support for NASA Marshall Flight Center and Glenn Research Center
  - Development of Griffin model NASA nominal plant design
    - 2D single assembly
    - 3D single assembly
    - 3D full core
    - Multiphysics simulations
      - Neutronics
      - Thermal-fluids
      - Heat transfer
      - Structural mechanics
      - Transient simulations
  - Simulation of SIRIUS series of experiments in TREAT

The MOOSE Herd

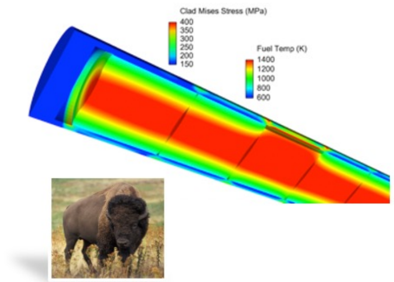
MOOSE
HPC Framework



Marmot
Mesoscale Materials

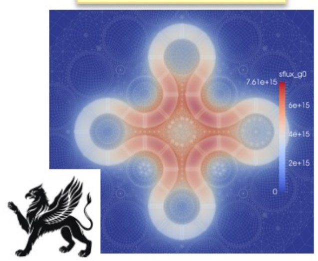


Bison
Nuclear Fuel Performance



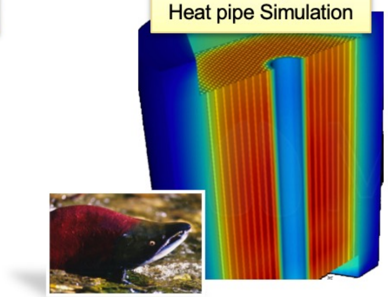
Grizzly
Structural Mechanics for Component Aging

Griffin
Radiation Transport

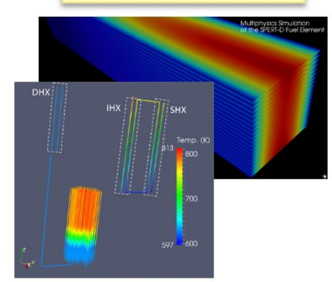


Pronghorn
Engineering Scale Flow

Sockeye
Heat pipe Simulation



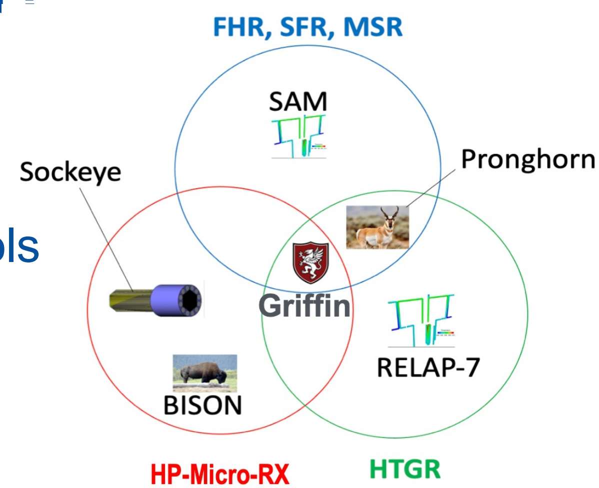
SAM and RELAP-7
Multiscale Multiphysics Systems Analysis



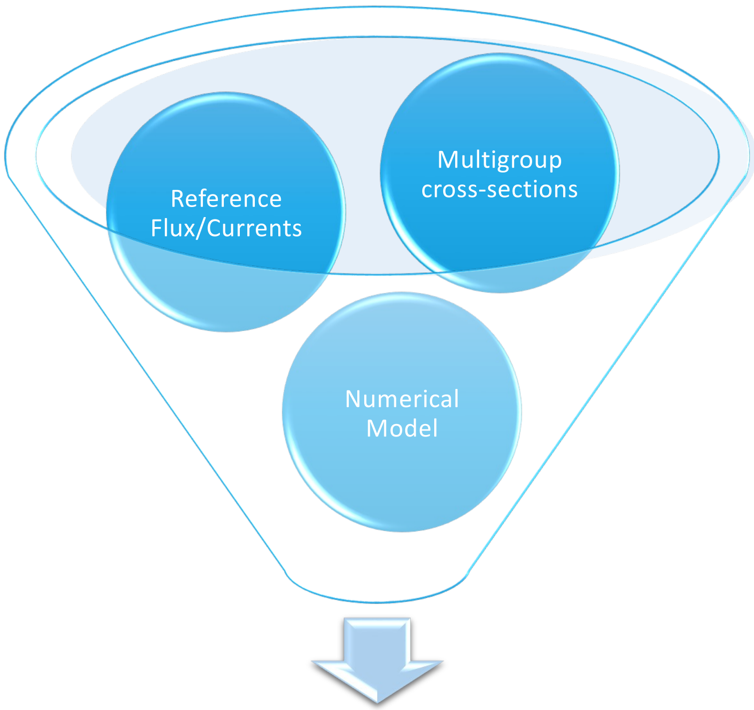
What is Griffin and Why is it important?

Griffin is a generalized tool for reactor physics for non-LWR reactors

- **Multiphysics-oriented**
  - Provides native coupling to all MOOSE-based tools
  - Takes advantage from common investment in framework
- **Flexible and Extendable**
  - Regular and unstructured geometries
  - Various types of calculations (variable fidelity)
  - Easy addition of functionality
- **Robust**
  - Consistent with NQA-1 process
  - Strict software development cycle
- **NRC's designated non-LWR neutronics code**
- **50/50 partnership between INL and ANL**



Homogenization Equivalence Methods 101

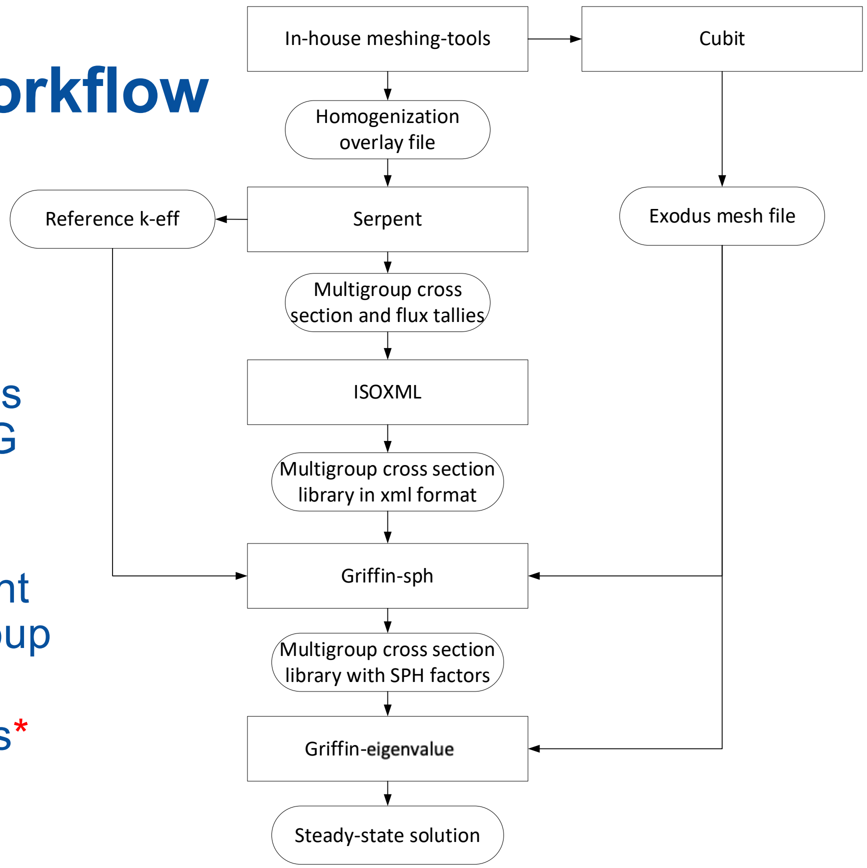


Equivalence-corrected library

Monte-Carlo corrected cross-sections to use an ***accurate*** diffusion scheme for ***transients***

NTP (and TREAT) Analysis Workflow

- Build mesh (Cubit) and Serpent model*
- Align detectors (tally regions) in Serpent model with corresponding regions in mesh for cross section assignment.*
- Calculate k_{eff} and fluxes in cross section regions with Serpent (reference solution) tallied over MG energy groups
- Perform a Super-Homogenization (SPH) calculation using Griffin to find energy-dependent correction (SPH) factors that will match multigroup fluxes.
- Update cross section library to add SPH factors*
- Repeat for each state point (typically temperature, control element position)*
- Run steady state calculation, confirm agreement with reference
- Run transient simulations



*These processes are largely automated

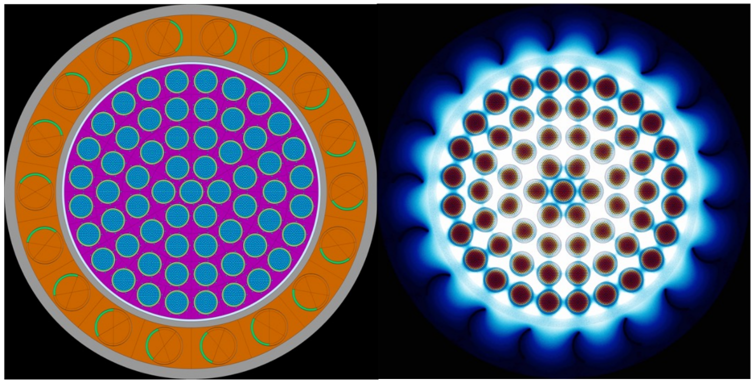
Cross Section Preparation with Serpent

Serpent Model

What is Serpent? A Monte-Carlo code created for reactor-physics calculations.

Bottom line: it creates nuclear cross sections for us!

- Monte Carlo method:
  - Stochastic transport method
  - Highly accurate in energy resolution
  - Slow & mostly limited to steady-state
- Griffin:
  - Deterministic transport method
  - Uses few-group cross sections
  - Designed for multiphysics transients
- We use Serpent's built-in cross section tallying, energy collapsing and spatial homogenization to generate cross sections in a user-specified group structure

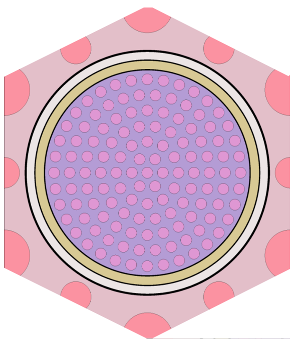


Serpent NTP core calculation

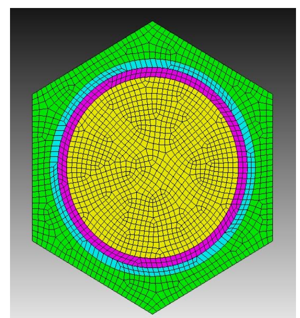
Mesh Generation for the Neutronics Model

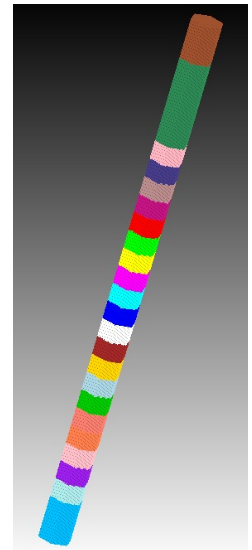
Mesh Generation

- Needs to occur before developing Serpent models to define homogenization zones in Serpent
- **Homogenization**: Average nuclear cross sections over heterogeneous regions
  - Pro: Saving in computational resources
  - Con: Loss of fine resolution
- Often thermal-hydraulics drive uncertainties despite homogenization
- Homogenization equivalence and reconstruction mitigate loss of fine resolution



Geometry → Griffin





Axial homogenization

Coupled Fuel Element - Overview

- Neutronics geometry: 90-degree, fuel + axial reflectors
- Heat conduction: active fuel region, 30-degree
- Thermal-hydraulics: representative fuel and moderator flow channels

Neutronics

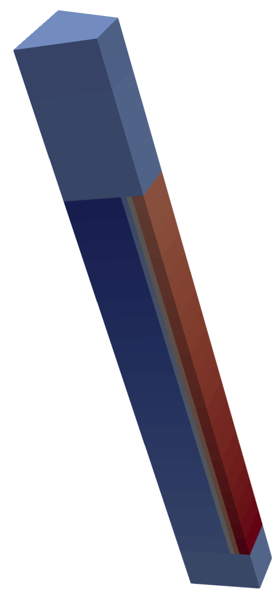
power density ↓ ↑ T_m, T_f

Heat Conduction

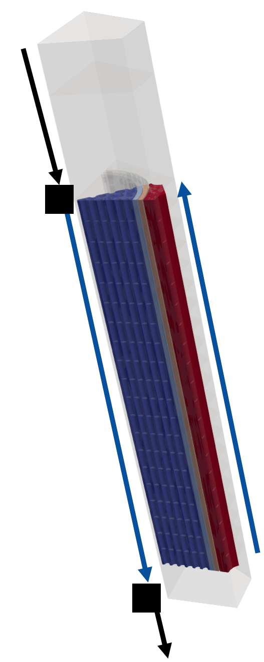
T_w ↓ ↑ T_H, htc

Thermal-hydraulics

Neutronics: primary app



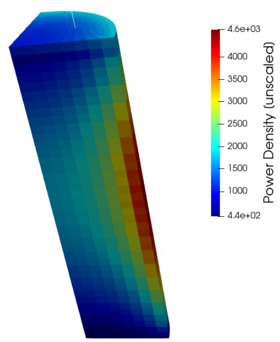
Heat conduction: sub-app 1
TH channels: sub-app 2

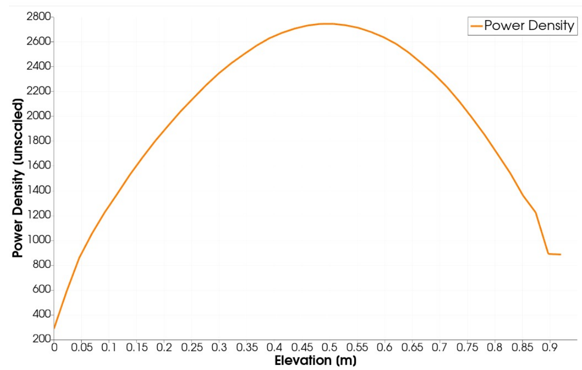


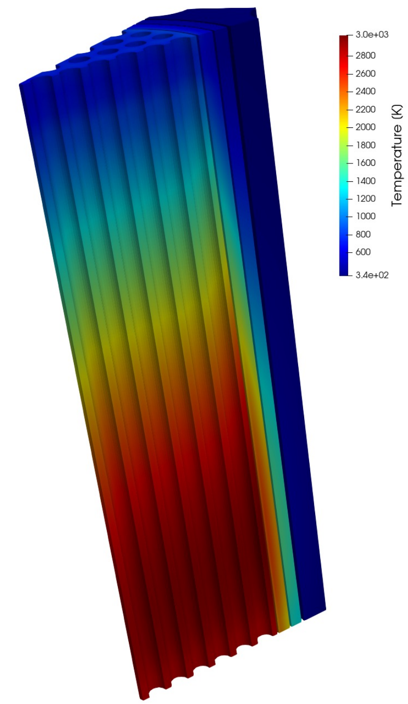
Serpent XS & Fluxes → SPH correction → Match eigenvalues → **Griffin multiphysics**

Coupled Fuel Element Steady-state – Results

Quantity	Value
Av. Fuel T [K]	2188
Inlet Moderator T [K]	410
Max. T [K]	3033
Outlet Moderator T [K]	2656





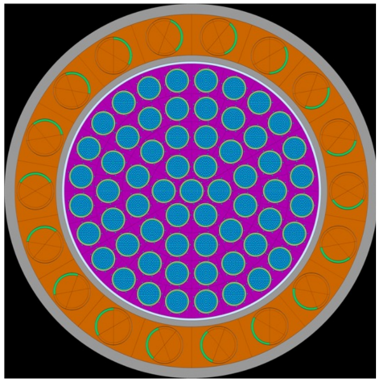


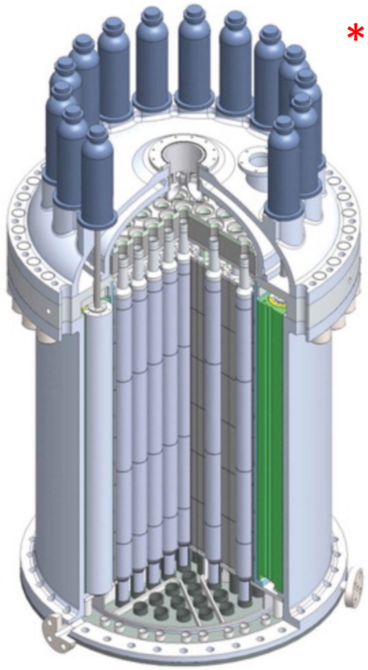
- Neutronics: Griffin
- Heat Transfer: Griffin (MOOSE Heat Conduction module)
- Structural Mechanics: Griffin (MOOSE Tensor Mechanics module)
- Convection Cooling: Griffin (MOOSE Thermal Hydraulics Module)

Full-Core Model Overview

New CERMET/CERCER NASA/BWXT NTP concept

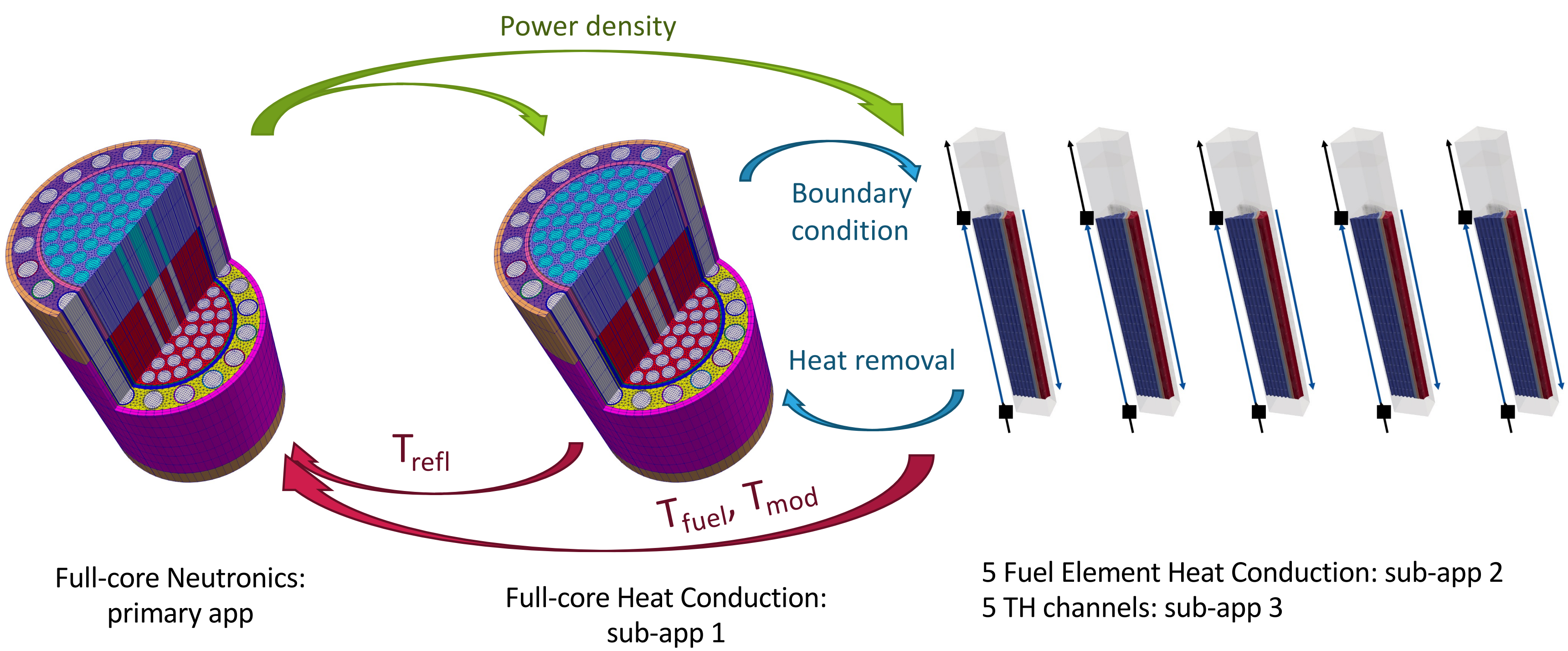
- 61 Fuel Elements in 5 rings
- 18 Control Drums in Be reflector to adjust reactivity/power
- In most current simulations all the drums are simultaneously rotated with the same rotation angle
- Griffin allows independent drum rotation (e.g., for a simulated reactivity insertion accident)



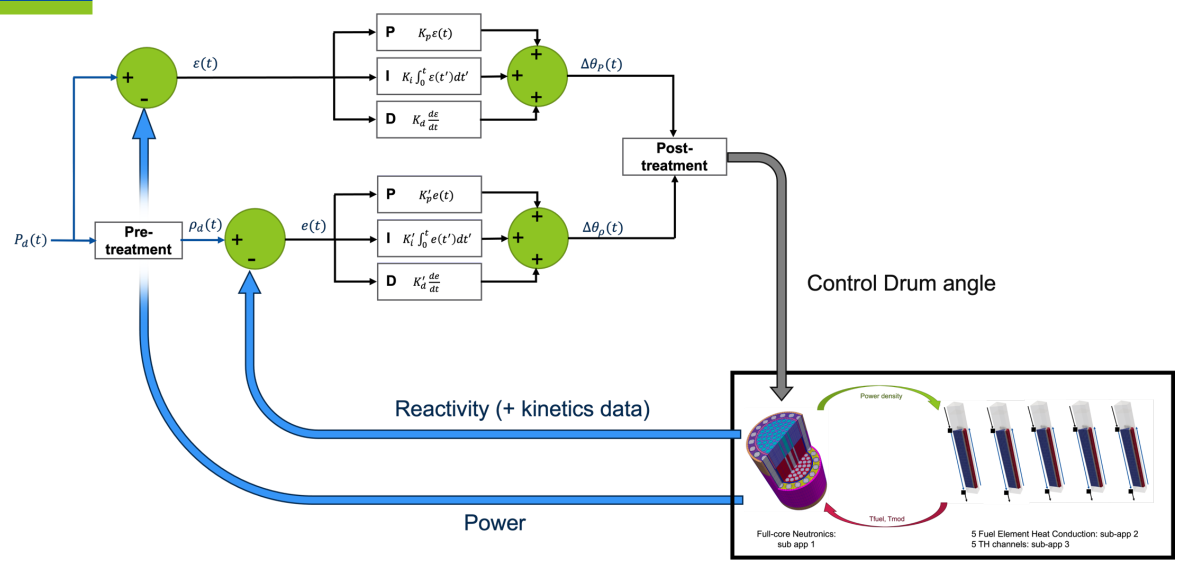


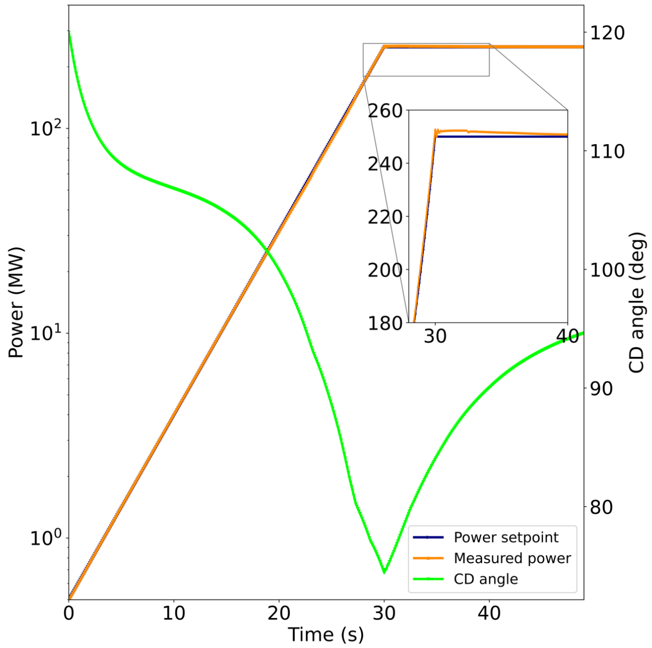
*

Coupled NTP Full-Core Model



PID Control of Drums

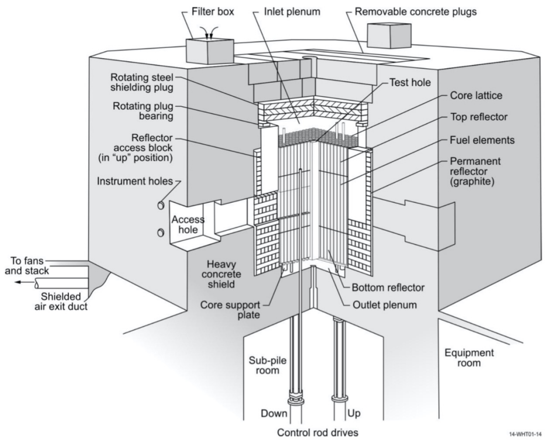




- Using MOOSE control logic, we have created a software proportional–integral–derivative (PID) controller
- Requires less trial and error than manual control
- Currently ignores any limitation on drum rotation (speed, etc.)

SIRIUS experiment series

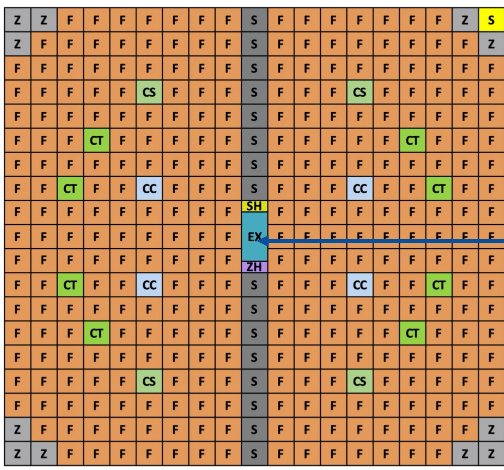
- Experimental campaign for transient testing of new NTP Fuel candidates: UN-CERMET & UN-CERCER
- Experiments are performed in TREAT
- Challenges of NTP fuel:
  - Very hot: 2600-2850 K
  - Fast heat rates: 100 K/s
  - Strong temperature gradient (~25 K/cm)
- SIRIUS series progresses in complexity:
  - SIRIUS-1: UN-CERMET – proof of principle
  - SIRIUS-2: Series of different materials, fab. processes, CERMET (and a CERCER experiment in the works)
  - SIRIUS-3: Stack of 16 fuel specimens with 7 gas channels
  - SIRIUS-4: first hydrogen-cooled experiment, 10 stacked specimens of CERMET
  - SIRIUS-5: second hydrogen-cooled experiment, CERCER stack of specimen



Multiphysics Simulations of SIRIUS-CAL

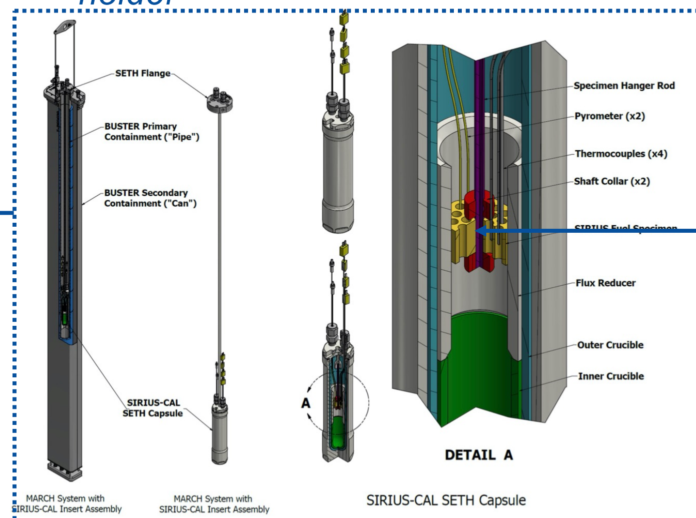
- Calibration experiment for SIRIUS-1

TREAT core configuration

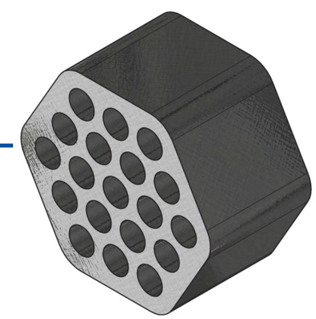


F	Fuel element
CT	Fuel element containing transient control rod
CS	Fuel element containing safety control rod
CC	Fuel element containing compenstation control rod
S	Non-fueled source element
Z	Zirc-clad non-fueled graphite element
S	Zirc-clad slotted graphite block
EX	Experiment region
SH	Half-width zirc-clad slotted element
ZH	Half-width zirc-clad non-fueled graphite element

Experiment vehicle and sample holder



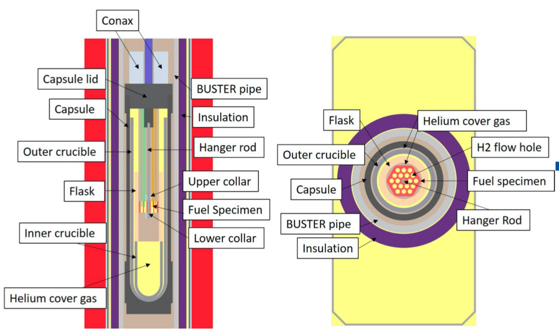
Sample (size of a quarter)



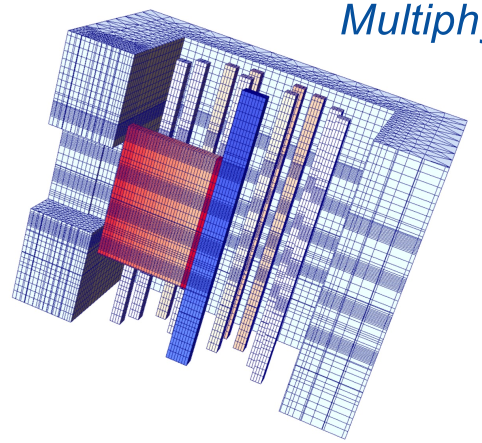
Multiphysics Model of SIRIUS-CAL

- Multiphysics model uses 2-step process: Serpent cross section, Griffin diffusion with SPH equivalence
- Transient is a coupled Griffin neutronics + thermal model

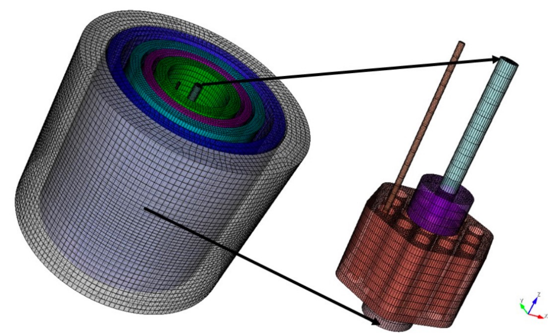
*Serpent **steady-state** for XS*



Griffin (Diffusion + SPH)
*Multiphysics **transient***



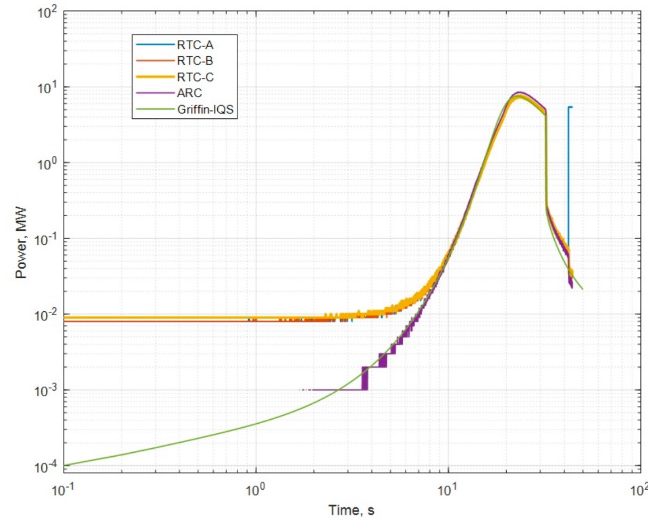
Neutronics



Thermal

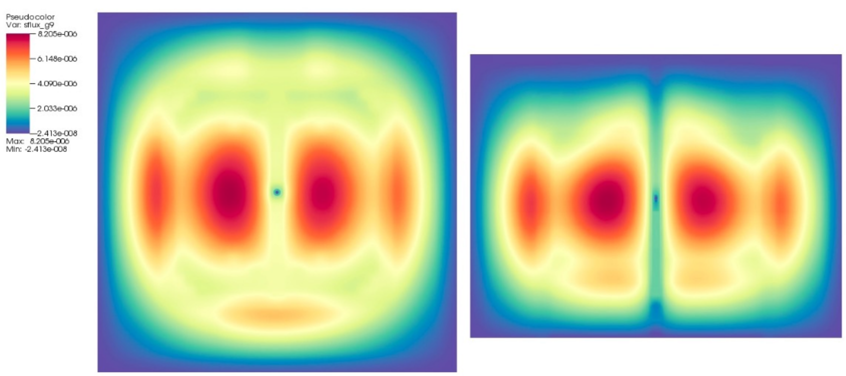
SIRIUS-CAL Multiphysics Results

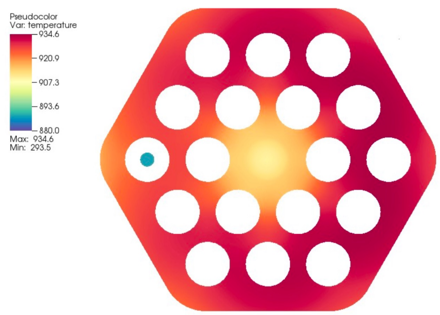
- SIRIUS-CAL reactivity insertion is 0.55% dk/k
- We currently adjust control rod motion to match TREAT initial period – ongoing work to be fully predictive for TREAT transients
- Goal is validation for SIRIUS-CAL



Measured and simulated power traces

Thermal fluxes in steady-state





Temperature distribution in the specimen

System Description

SIRIUS-2
SIRIUS-2a: UN CERMET
SIRIUS-2a: UN CERMET

Purpose: Investigate impacts of temperature ramp rate and operating temperature on cermet fuel performance

Specimen Geometry:
- Single 0.5” thick fuel wafer
- Hexagonal geometry
- Cermet: Mo-30W matrix
- Angular uncoated kernels
- 7 flow channels
- No flow tubes

Test Environment: Static safe gas

SIRIUS-3
UN CERMET

Purpose: Investigate impacts of temperature ramp rate and operating temperature on subscale fuel element

Specimen Geometry:
- 8” long stack of 0.5” wafers
- Unbonded wafers
- Circular geometry
- Uncoated angular or spherical fuel kernels
- 19 flow channels
- Unbonded Mo flow tubes

Test Environment: Static safe gas

SIRIUS-4 (PRIME-1)
UN CERMET
Flowing H_2

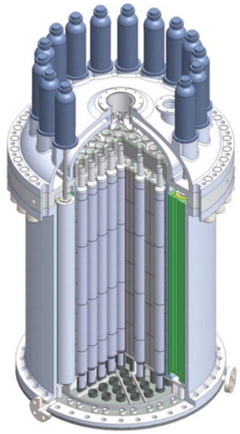
Purpose: Investigate integrity of cermet fuel + moderator unit cell in flowing hydrogen

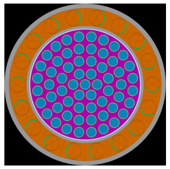
Specimen Geometry:
- 20” long stack of 0.5” wafers
- Unbonded wafers
- Circular geometry
- Fuel, moderator, and insulator materials
- Coated spherical fuel kernels
- 19 flow channels

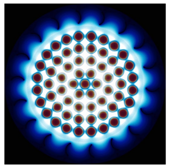
Test Environment: Flowing hydrogen

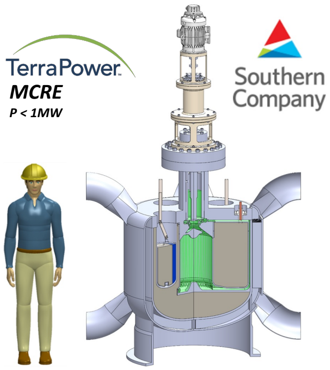
Closing Remarks

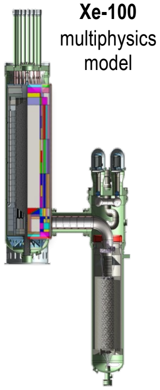
- INL is the nation's premier nuclear science and technology laboratory
- The reactor multiphysics team works at the forefront of solving some of the most challenging modeling problems for advanced reactors
- Our work relates directly to the nation's energy future via ARDPs, private/public partnerships, & reactor demonstrations
- I only talked about nuclear thermal propulsion systems, but this team is engaged in many types of advanced reactor analysis
- Which is a perfect segue to…











Technology maturation with Marvel

Modeling autonomous fission batteries

Internships

- Paid opportunities available in a wide range of STEM and other fields for both undergraduate and graduate students
- Internship opportunities enable collaboration with experienced scientists and engineers to develop innovative solutions for challenging, real-world projects

80%	**20%**
of time spent working on projects and applying what you learned in the classroom to solve real work-related challenges	of time spent participating in enrichment & professional development activities *(workshops, networking, etc.)*

2021 Top 100 Internships




The East Idaho Lifestyle

- Enjoy unparalleled access to the region’s world-class skiing, hiking, camping, climbing, mountain biking, hunting, fishing, and much more
- Live close to some of the country’s greatest natural wonders: Yellowstone National Park, Grand Teton National Park, Craters of the Moon National Monument, Jackson Hole, Glacier National Park and more

Want to learn more?

Visit inl.gov/inl-initiatives/education/

For Internships, Postdocs & INL Graduate Fellowships: academic@inl.gov

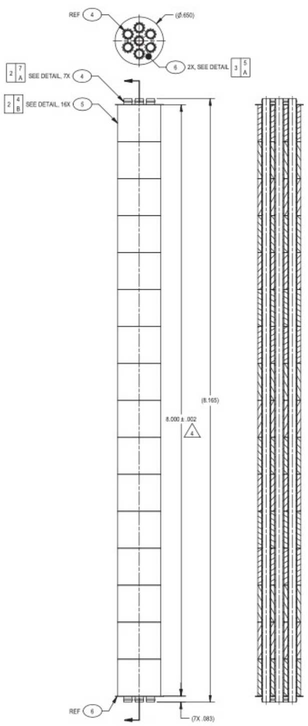
For Full-time Careers: careers@inl.gov

Drop your email address in the event chat

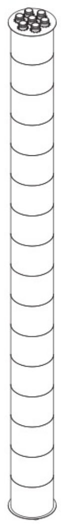
Idaho National Laboratory

WWW.INL.GOV

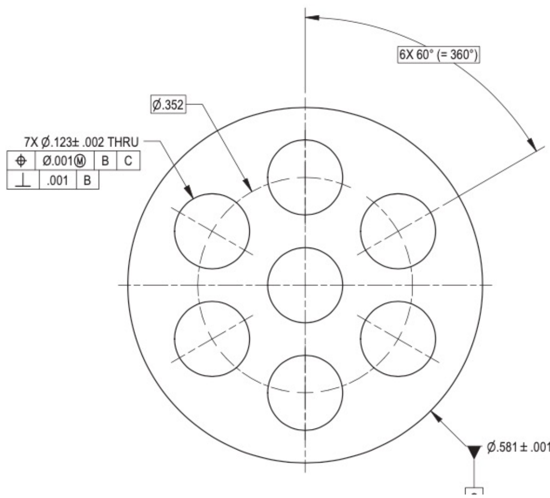
SIRIUS-3: Heat Transfer Challenges



-1 ASSEMBLY
SCALE: 2/1



-1 ISOMETRIC
REFERENCE ONLY
SCALE: NONE



-5 ISOMETRIC

Griffin Capabilities

Cross Sections

- Serpent
- MC^2-3
- Online cross section

Transport Solver

- P_N, SAAF-S_N, Diffusion, S_N
- MOC, Nodal
- Multi-scheme, Hom. Equiv.
  Pebble Tracking Transport

Mesh generation

- CUBIT
- ANL mesh-kit
- MOOSE inline meshing,
  Python Meshing Tools

Physics

- Neutron
- Depletion: CRAM,
  ORIGEN data;
  Radiative transfer,
  Multiphysics coupling
- PBR equilibrium core
  Photon (X/gamma-ray)

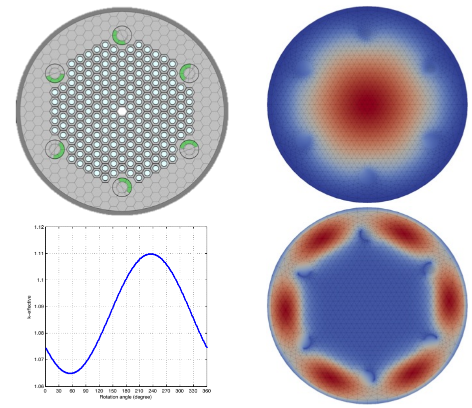
Ported from both

Ported from PROTEUS

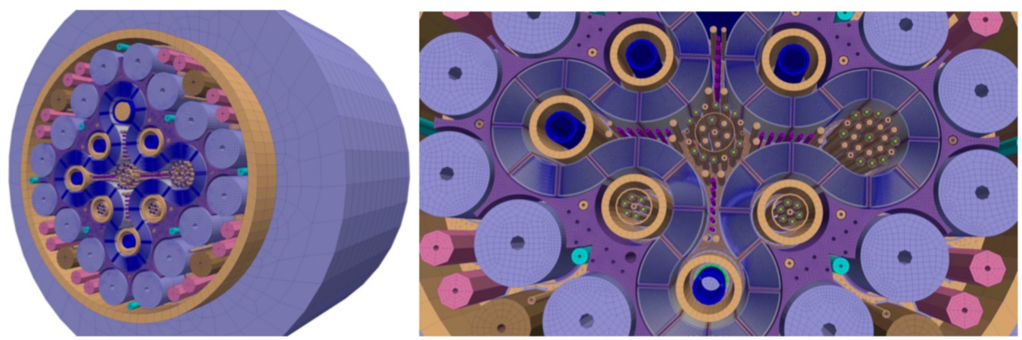
Ported from MAMMOTH

New development

Micro-reactors



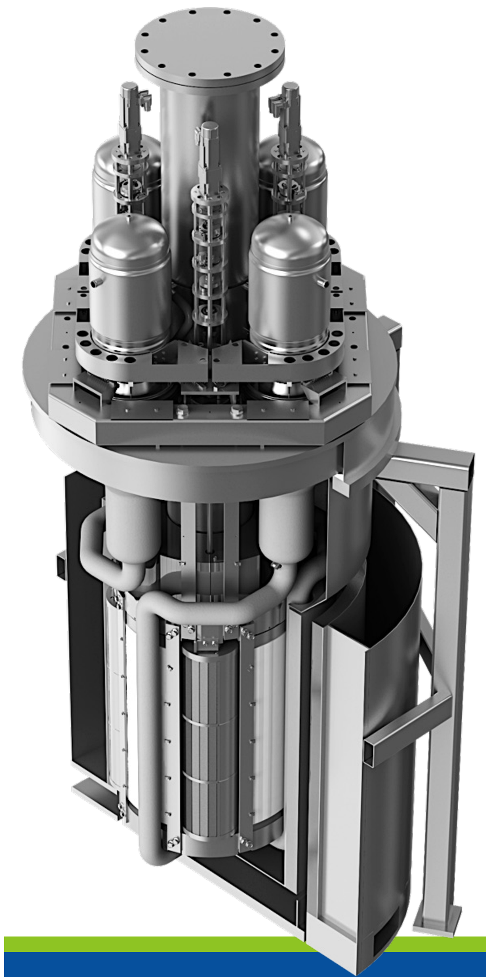
Advanced Test Reactor (ATR)



MARVEL - Test Microreactor

Microreactor Application Research, Validation and EvaLuation Project

Key Design Features	
Thermal Power	100 kW
Electrical Power	20 kWe (QB80 Stirling Engines)
Weight	< ~10 US ton
Primary Coolant	Sodium-Potassium eutectic
Intermediate Coolant	Lead-Bismuth eutectic
Coolant Driver	Natural Convection, single phase
Fuel	HALE(UZrH), 304SS clad, end caps
Moderator	Hydrogen
Neutron Reflector	Graphite, Beryllium (S200), Beryllium oxide
Reactivity Control	Radial Control Drums, Central Absorber
Primary Coolant Boundary	SS316H



IDAHO NATIONAL LABORATORY

Molten Chloride Reactor Experiment (MCRE)

Parameter	MCRE
Rated Thermal Power	200 kW
Fuel Salt Mass Flow Rate Range	25-100 kg/s
Fuel ΔT	10°C
Nominal Fuel Temperature	650°C
Design Temperature	700°C
Design Pressure	500 kPa
Fuel Salt Composition	NaCl-UCl_3 (67-33mol%)
Fuel Salt Mass	1225 kg
HEU Mass	630 kg
Heat Removal Method	Gas-Cooled Vessel