Multiphysics Modeling in Support of NASA Nuclear Thermal Propulsion Designs

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Mark D DeHart
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Mark D DeHart

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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The Ohio State University
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Overview

- Introduction to Idaho National Laboratory
- The Reactor Multiphysics Team
- MOOSE Background
- Griffin
- Nuclear Thermal Propulsion
- Analysis Workflow
- Analysis Approach
  - Cross section generation
  - Mesh generation
  - Fuel element modeling
  - Validation using SIRIUS measurements in TREAT
  - Full Core Modeling
- TREAT experiment simulations (time permitting)
- Closing Comments
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
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, and more
The Reactor Multiphysics Team (RMT)

- Primary development of the Griffin (neutronics) and Pronghorn (coarse mesh TH) codes within the DOE/NE Nuclear Energy Advanced Modeling and Simulation (NEAMS) program

- Partnering with several companies on GAIN vouchers and Advanced Reactor Demonstration Project (ARDP) awards

- Advises the US NRC on multiphysics tools for analysis of advanced reactors

- Funded by US NRC, NASA, NEAMS, Nuclear Reactor Innovation Center (NRIC), DOE/NE Advanced Reactor Technology (ART), INL Strategic Thermal Irradiation Program.

- Scope runs the gamut from algorithm development, implementation, to reactor analysis

- Reactors we work on: PBRs, FHRs, MSRss, NTPs, prismatic VHTRs, micro-Rx, and INL’s Transient Test Reactor (TREAT), Advanced Test Reactor (ATR) and the Neutron Radiography (NRAD) Reactor
\[ \nabla \cdot k \nabla T = 0 \]

\[ \nabla \cdot D \nabla u + b = 0 \]

\[ \frac{\partial c}{\partial t} - \nabla \cdot (\vec{v} c) = 0 \]

MOOSE Enables Multiphysics Simulation
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
Flexibility by MultiApps

- Master app owns a sub-app
- Recursive: sub-app can own its own sub-app tree
- Information transfer via flexible MOOSE transfers
- Different meshes & dimensionality (different length scales)
- Sub-cycling (different time scales)
- Mixing eigenvalue & transients
- Picard Iterations

- MOOSE supports loose coupling (operator split) & Picard via MultiApps
- MOOSE supports strongly coupled solves
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
Nuclear Thermal Propulsion (NTP) 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/reflectors/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 the 1950s 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
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
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 $k_{\text{eff}}$ 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

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 & 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

- 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
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
Coupled Fuel Element Steady-state – Results

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Av. Fuel T [K]</td>
<td>2188</td>
</tr>
<tr>
<td>Inlet Moderator T [K]</td>
<td>410</td>
</tr>
<tr>
<td>Max. T [K]</td>
<td>3033</td>
</tr>
<tr>
<td>Outlet T [K]</td>
<td>2656</td>
</tr>
</tbody>
</table>

- Neutronics: Griffin
- Heat Transfer: Griffin (MOOSE modules)
- Structural Mechanics: Griffin (MOOSE modules)
- Convection Cooling: RELAP-7
Full-Core Model Overview

- 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 rotation (e.g., for a simulated reactivity insertion accident)
Control Drum Worth with Griffin Cusping & SPH

- At state points (0, 60, 120, 180), eigenvalue and power profile exactly reproduced
- Between state points, cusping treatment from Griffin is utilized
- Bias between -40 and +60 pcm
- Series of eigenvalue calculation in both Serpent and Griffin are in good agreement.
Coupled NTP Full-Core Model

Full-core Neutronics: primary app

Full-core Heat Conduction: sub-app 1

Power density

Boundary condition

Heat removal

$T_{\text{refl}}$, $T_{\text{fuel}}$, $T_{\text{mod}}$

5 Fuel Element Heat Conduction: sub-app 2
5 TH channels: sub-app 3
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.)
Start-up Transient with PID

Startup with PID control of the drums

- Power (W)
- Temperature (K)

Startup with PID control of the drums

- Power (W)
- Reactivity ($)
SIRIUS experiment series

- Experimental campaign for transient testing of new Nuclear Thermal Propulsion Fuel: 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 (~25K/cm)
- SIRIUS series progresses in complexity:
  - SIRIUS-1: UN-CERMET – proof of principle
  - SIRIUS-2: Series of different materials, fab. processes, CERMET & CERCER
  - SIRIUS-3: Stack of 20 fuel specimens
  - SIRIUS-4: first hydrogen-cooled experiment, 10 stacked specimens CERMET
  - SIRIUS-5: second hydrogen-cooled experiment, CERCER stack of specimen
Multiphysics Simulations of SIRIUS-CAL

- Calibration experiment for SIRIUS-1

TREAT core configuration

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

Thermal fluxes in steady-state

Measured and simulated power traces

Temperature distribution in the specimen
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% of time spent working on projects and applying what you learned in the classroom to solve real work-related challenges

20% of time spent participating in enrichment & professional development activities (workshops, networking, etc.)
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
Start-up Transient Assumptions

- **Goal:** go from low power to full power in a few minutes

- Currently, we assume 100% H2 flow rate established at the beginning of the transient

- Assume initial temperature:
  - $T_{\text{fuel}} = 500$ K
  - $T_{\text{mod}} = 270$ K
  - $T_{\text{rrefl}} = 300$ K

- Initial power: 610 kW (10 kW/fuel element)

- Initial CD angle $\theta_i = 120^\circ$

- Final CD angle $\theta_f = 60^\circ$

- Drum rotation determined by PID controller
PID Control of Drums

- Requires less trial and error than manual control
- For now, ignores any limitation on drum rotation (speed, etc.)
• If only proportional term is included in PID:
  \[ K_p = \frac{\Delta \theta}{\Delta \rho} \]

• For the CD angle between 60° to 120°, CD worth ~ 25-30 pcm/° or 24-30 °/$

• \( K_p = 25 \, °/$ should be reasonable

• Direct correlation between reactivity and CD angle: this is why we choose to rotate drums based on reactivity and not power (time delay between reactivity and power)
Start-up Transient with PID: $K_p = 25, K_i = K_d = 0$
Changing $K_i$

- Increasing temperature creates negative feedback not captured by ‘proportional-only’ PID
- Integral term can capture the persistent lag behind the setpoint
- During the early stages the transient,

$$
\int_0^t e(\tau)d\tau \approx 100 - 200 \text{ s}
$$

- Thus, we pick: $K_i = \frac{K_p}{100} = 0.25^{\circ}/(\text{s})$
Start-up Transient with PID: $K_p = 25$, $K_i = 0.25$, $K_d = 0$