INL/MIS-23-71634-Revision-0

Changing the World's Energy Future

INL Nuclear Thermal Propulsion: Project overview, status and future

March 2023

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Idaho National Laboratory

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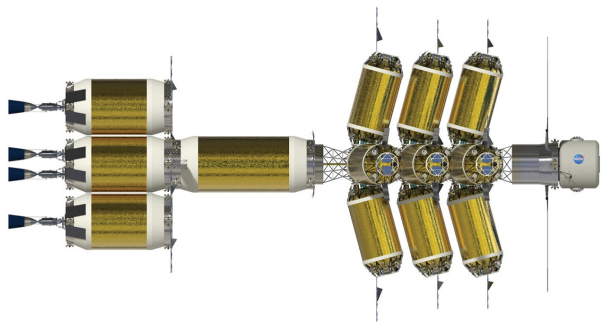
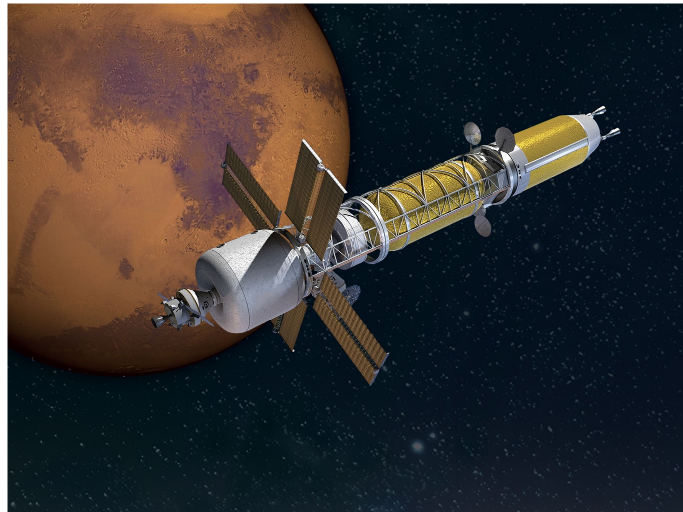
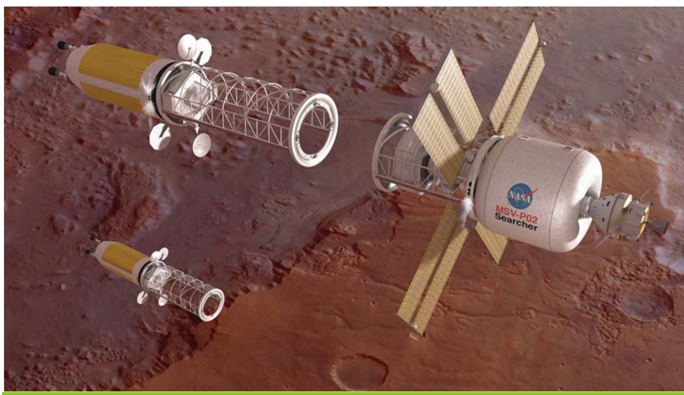




Mark DeHart, Sebastian Schunert and Vincent Labouré

Reactor Physics Methods and Analysis Department



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Georgia Institute of Technology

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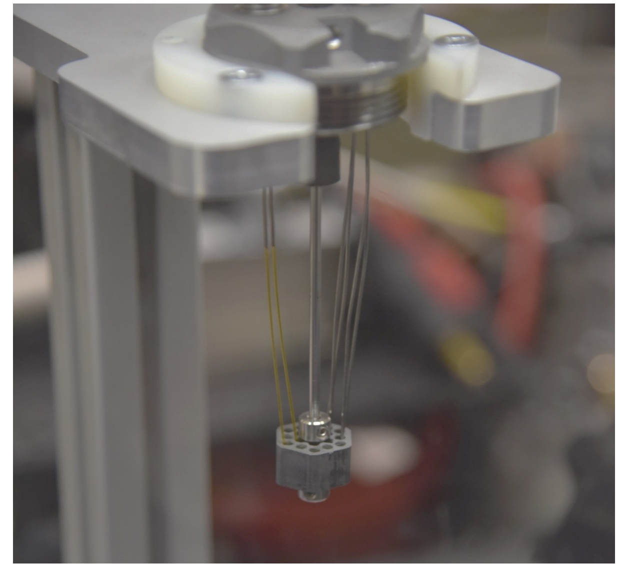
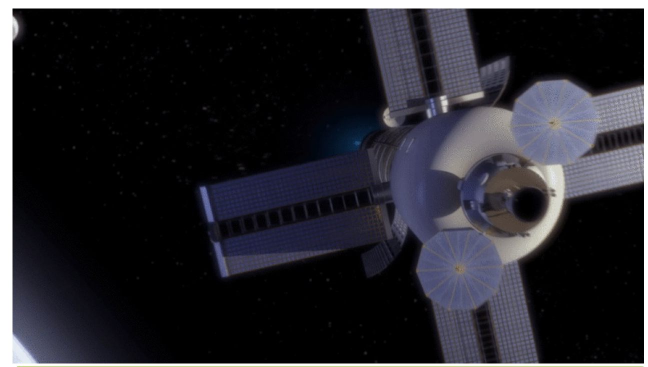
INL/MIS-23-71634

Overview

- Nuclear Thermal Propulsion Support at INL
- Cross Sections and Homogenization
- Full Core Model (Overview)
- Analysis Workflow
- Validation using SIRIUS measurements in TREAT
- Future of this project



SIRIUS-1 Fuel Test Specimen



Nuclear Thermal Propulsion Support at INL

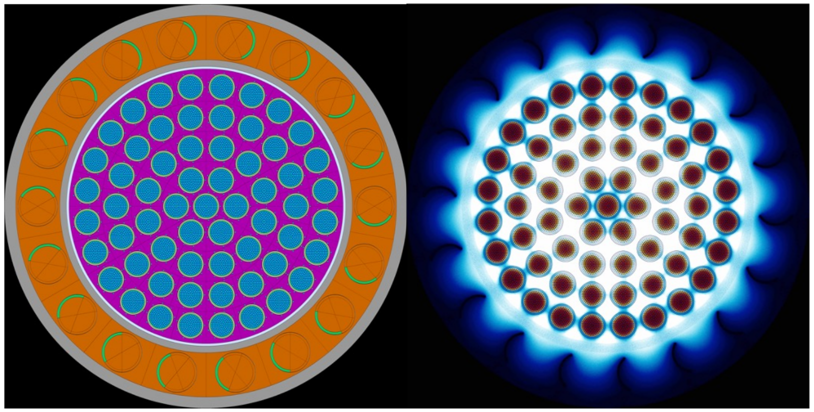
- INL support for NASA Marshall Flight Center and Glenn Research Center began in Spring 2020
  - Development of Griffin model NASA nominal plant design
    - 2D single assembly
    - 3D single assembly
    - 3D full core
    - Multiphysics simulations
      - Neutronics
      - Thermal-fluids
      - Heat transfer
      - Structural mechanics
      - Transient simulations
  - Simulation of SIRIUS series of experiments in TREAT

Cross Section Preparation with Serpent

Serpent Model

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

- 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

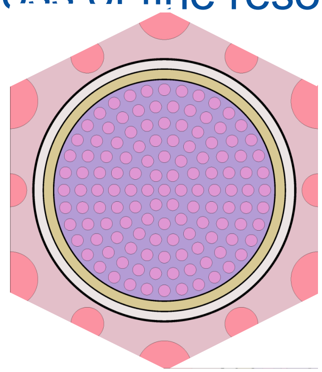


Serpent NTP core calculation

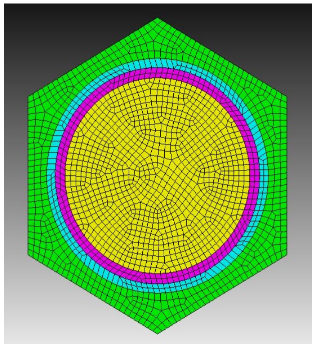
Mesh Generation for the Neutronics Model

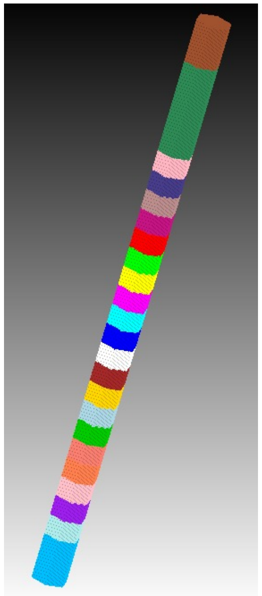
Mesh Generation

- 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



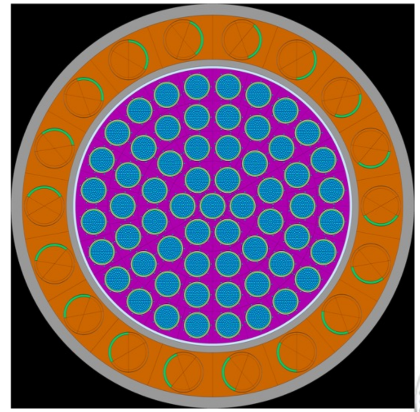
Geometry → Griffin



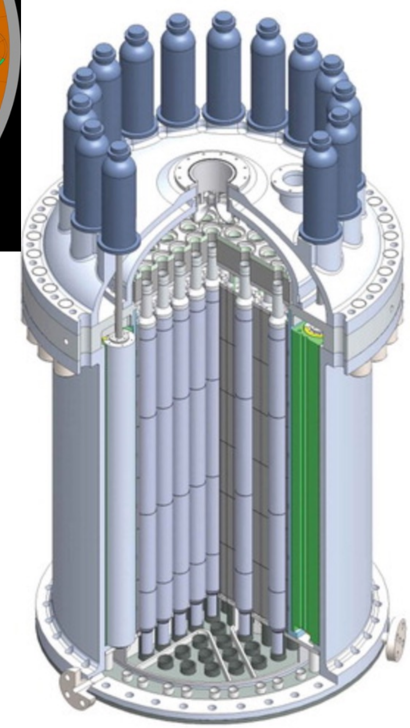


Axial homogenization

Full-Core Model Overview



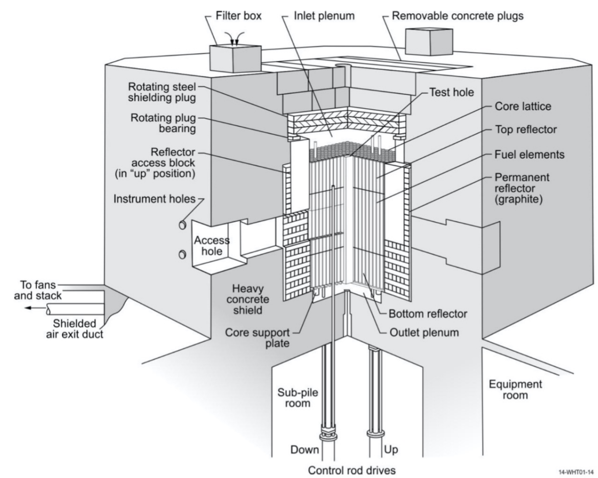
- 61 Fuel Elements in 5 rings
- 18 Control Drums in Be reflector to adjust reactivity/power
- Based on design supplied by BWXT
- Two models used in our analysis
  - Serpent model for generating multigroup cross sections
  - 3D FEM mesh for Griffin transient Multiphysics
- Griffin uses a cusping treatment that lets it rotate control drums in mesh and retain a smooth reactivity curve with angle (same treatment available for rods)*



*Sebastian Schunert, Yaqi Wang, Javier Ortensi, Vincent Laboure, Frederick Gleicher, Mark DeHart, Richard Martineau, "Control rod treatment for FEM based radiation transport methods," *Annals of Nuclear Energy*, Volume 127, 2019, Pages 293-302,

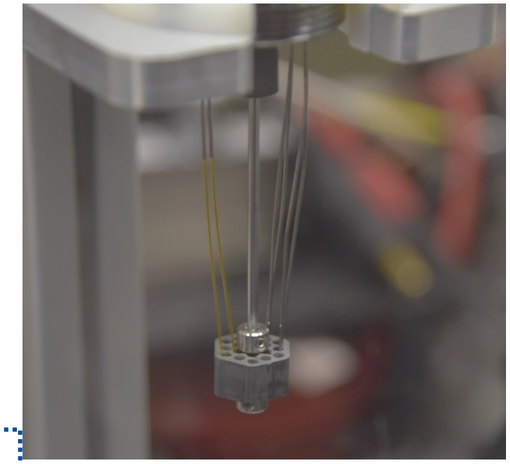
SIRIUS experiment series

- 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

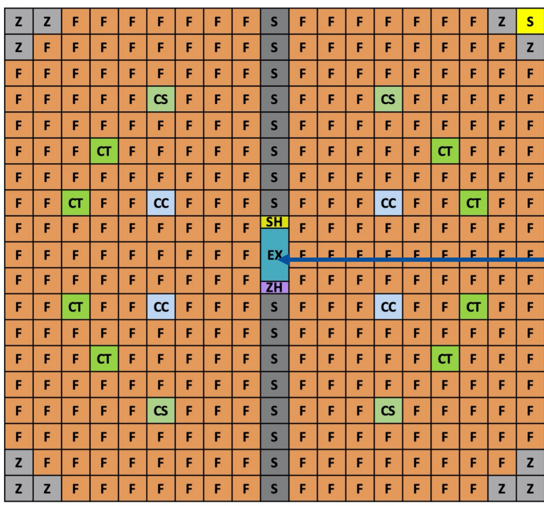


Multiphysics Simulations of SIRIUS-CAL

- Calibration experiment for SIRIUS-1

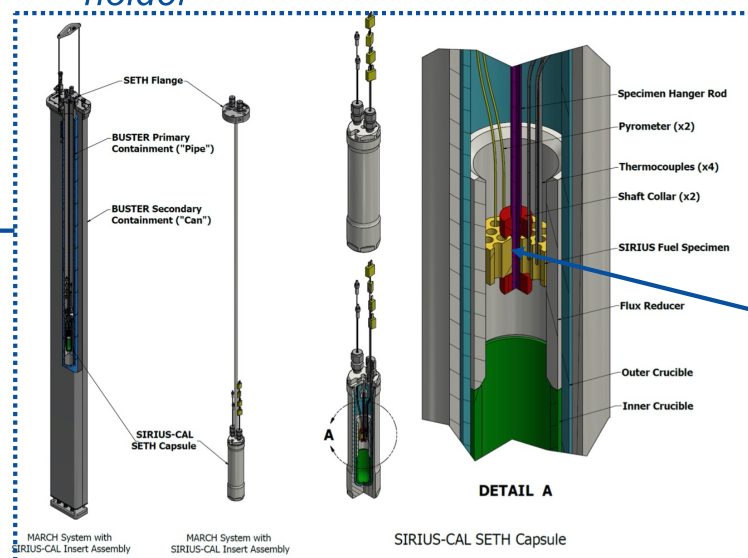


TREAT core configuration



- 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

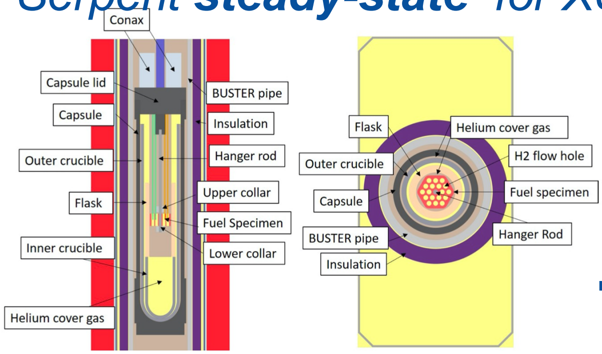


Sample (size of a quarter)

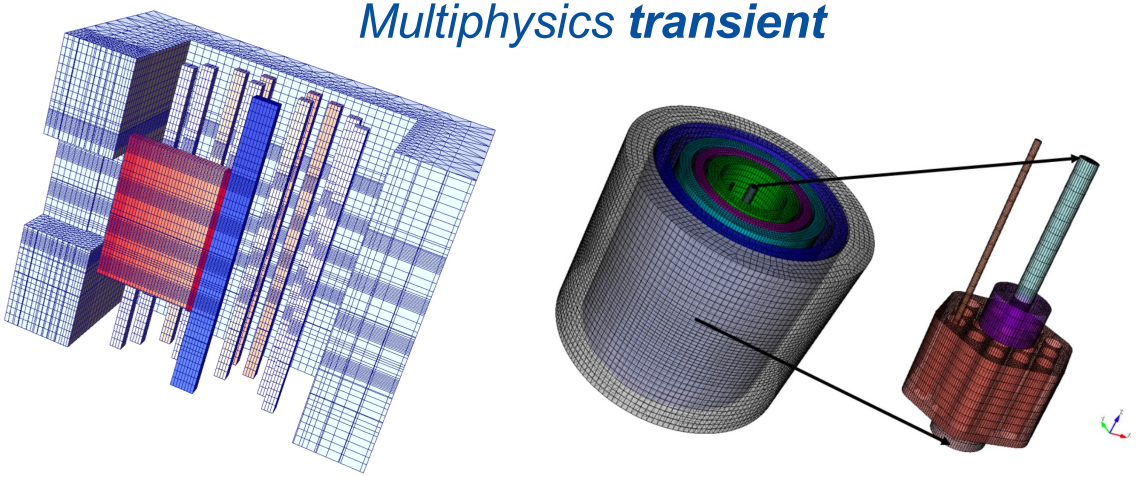
Multiphysics Model of SIRIUS-CAL

- 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***



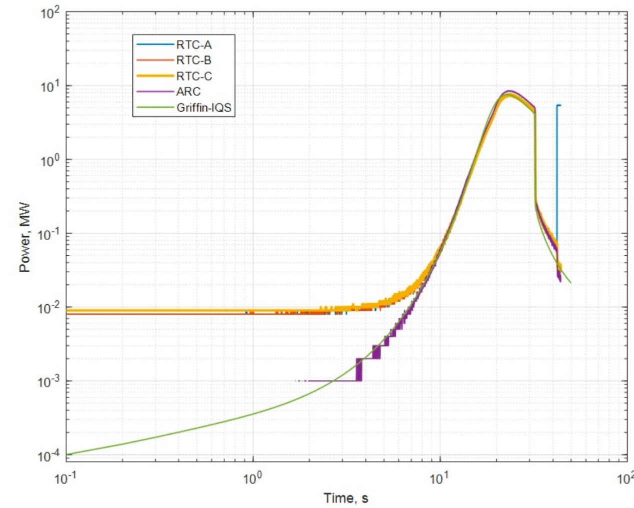
Neutronics

Thermal

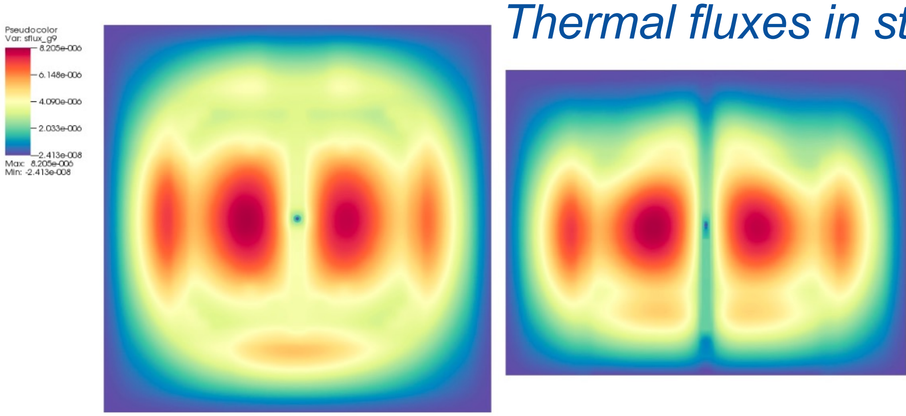
- Physics:
  - Neutronics
  - Structural mechanics
  - Heat transfer
    - Conduction
    - Convection
    - Radiation

SIRIUS-CAL Multiphysics Results

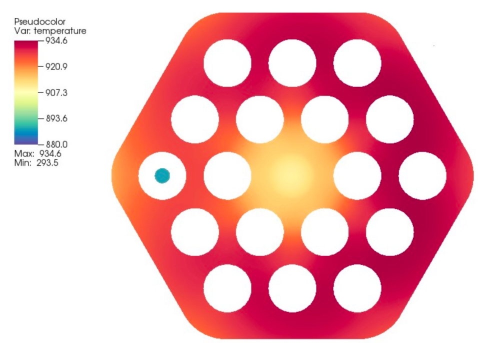
- SIRIUS-CAL reactivity insertion is 0.55% dk/k.
- Natural transient – C/Rs are pulled and remain out.
- We adjusted control rod motion to match TREAT initial peric – ongoing work to be fully predictive for TREAT transients
- Goal is validation for SIRIUS-CAL



Measured and simulated power traces



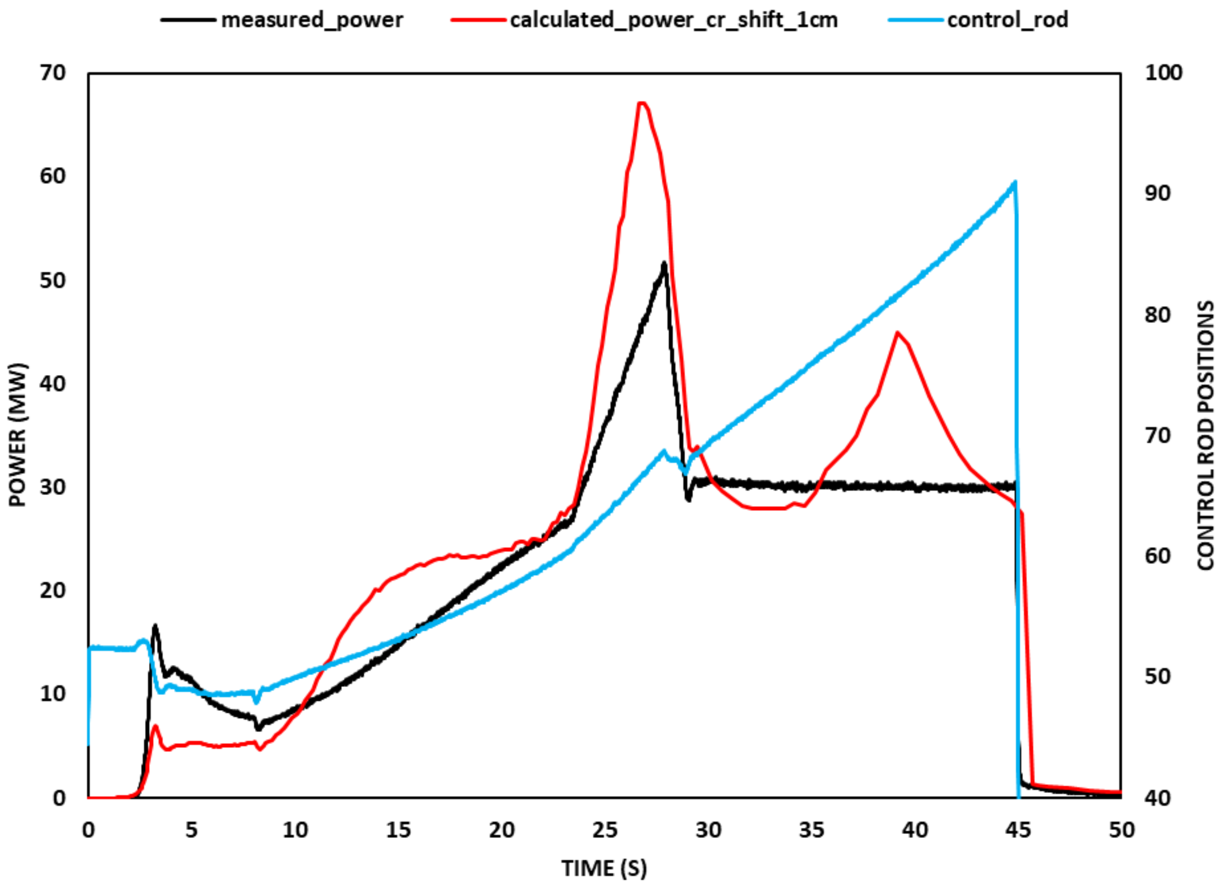
Thermal fluxes in steady-state



Temperature distribution in the specimen

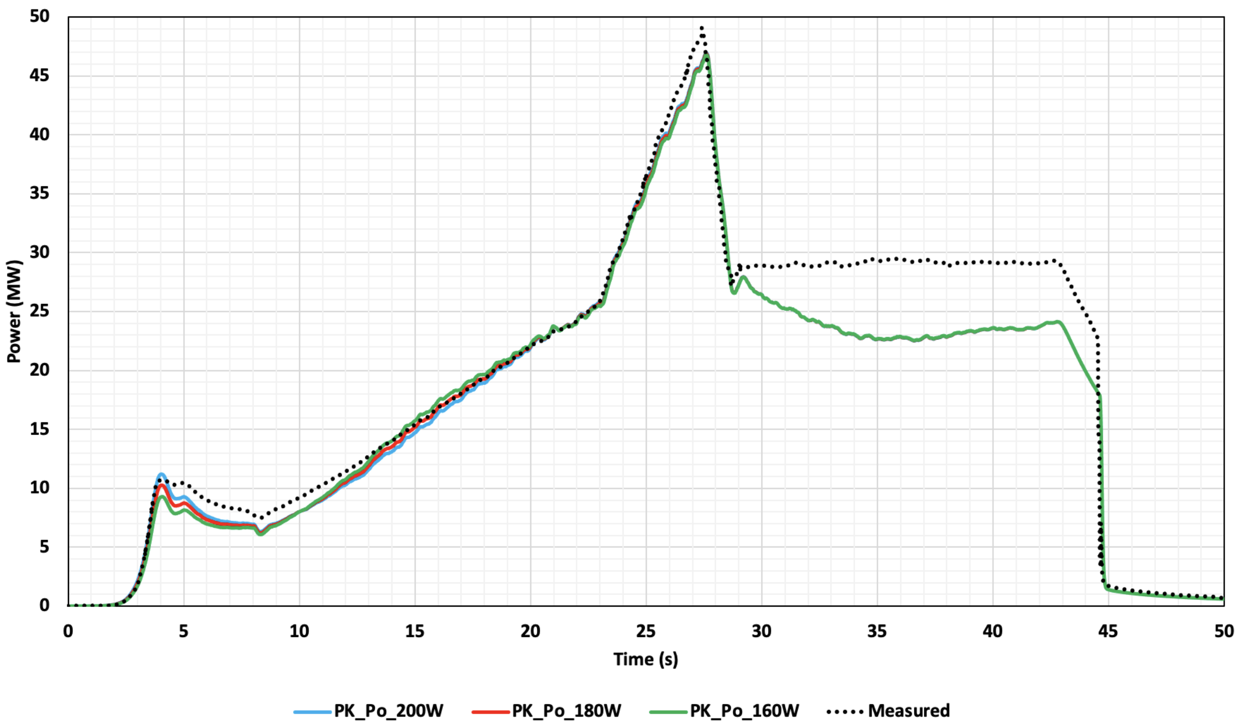
Jing T, Schunert S, Labouré VM, DeHart MD, Lin C-S, Ortensi J. Multiphysics Simulation of the NASA SIRIUS-CAL Fuel Experiment in the Transient Test Reactor Using Griffin. *Energies*. 2022; 15(17):6181. https://doi.org/10.3390/en15176181

SIRIUS-1: Control Rod Motion During Transient



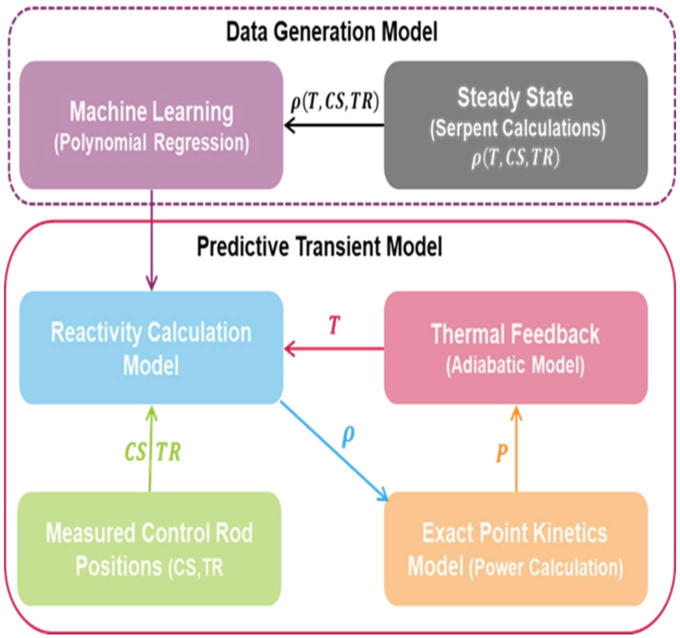
- First “realistic” transient for SIRIUS testing.
- Rod model has problems; small differenced give big errorts

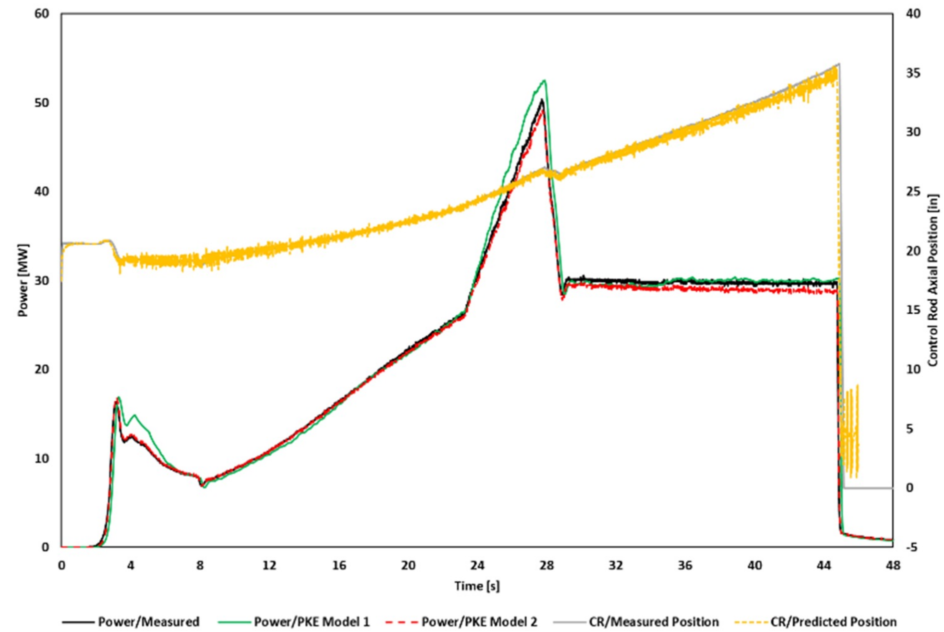
SIRIUS-1: Control Rod Motion During Transient



- Improved model
  - Smaller timestep in kinetics AND thermal solvers
  - Finer discretization of cross section tabulation
  - Still challenged with larger rod motion
- Not acceptable, and at this point we don't know why we don't get rod reactivities right.

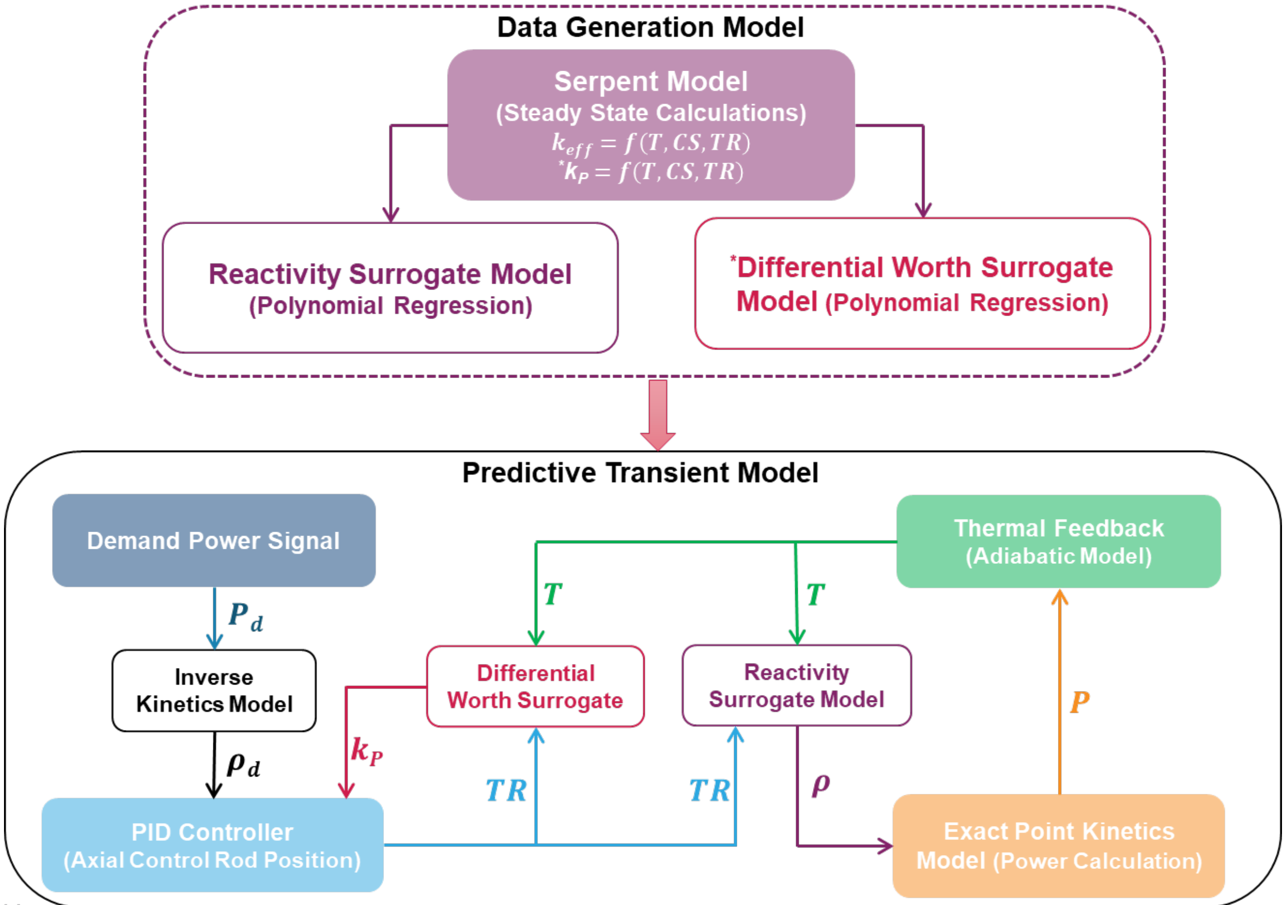
Solution: Predictive Point Kinetics Algorithm





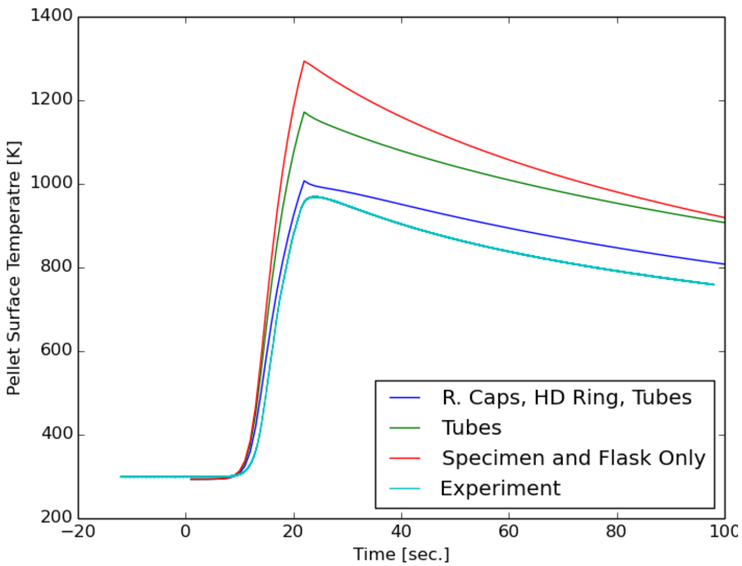
The first predictive transient model (Model 1) used measured C/R positions and calculated core average temperature to estimate total reactivity for transient calculations. Further improvements were made to the initial predictive model and a more sophisticated model was developed with ability to solve inverse problems to predict C/R axial position and inserted reactivity from C/R movement to fulfill a demand power signal during the transient (Model 2).

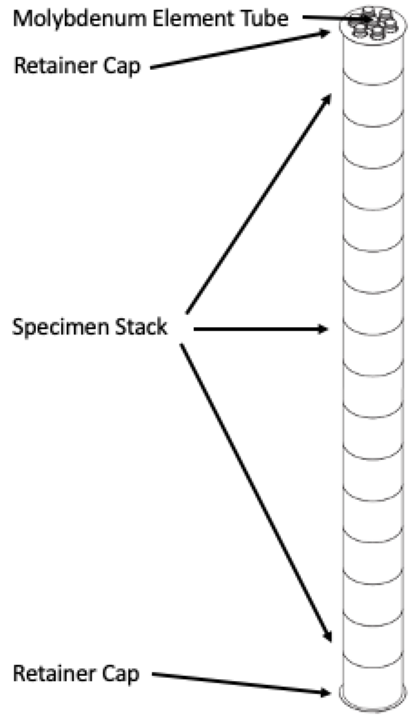
Improved Predictive PKE Algorithm

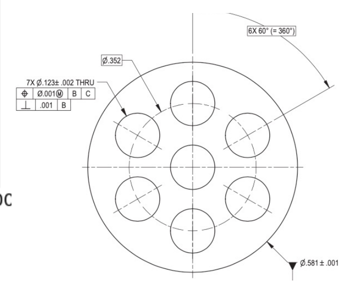


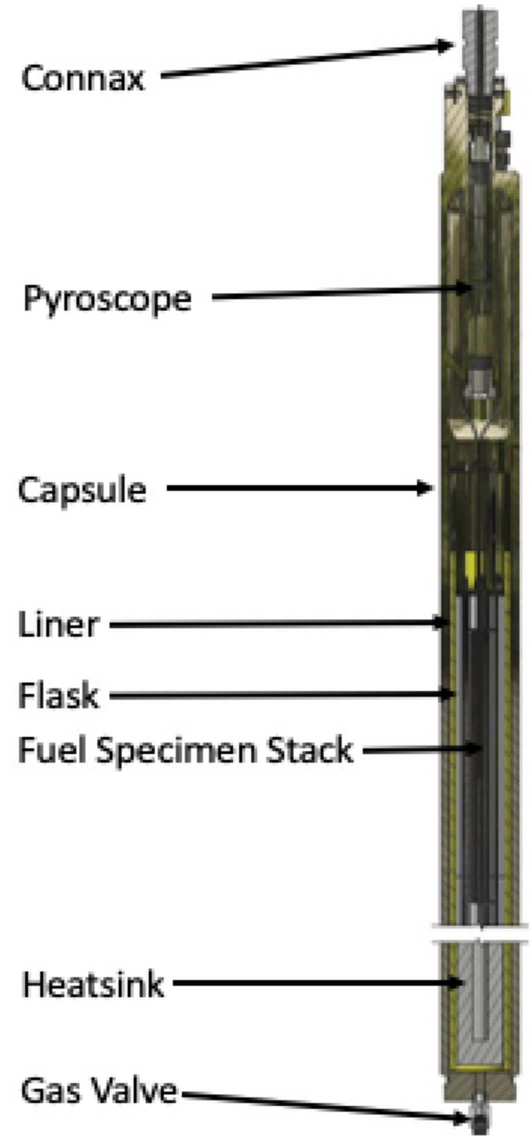
Mustafa K. Jaradat, Sebastian Schunert, Frederick N. Gleicher, Vincent M. Labouré, and Mark D. DeHart, “A Predictive Transient Model of the TREAT-SIRIUS Experiments”, Nuclear and Emerging Technologies for Space (NETS 2023), Idaho Falls, ID, May 7-11, 2023

SIRIUS-3 Experiment Simulation



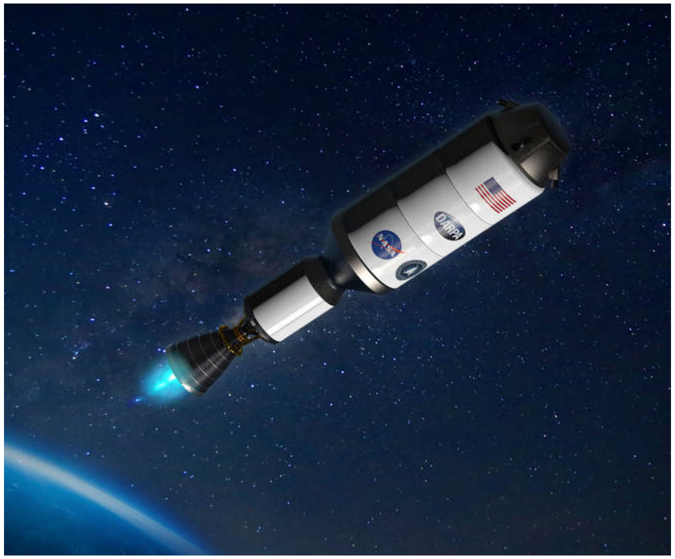






Newsflash: Future of the Project

- *Jan 24, 2023*: **NASA, DARPA Will Test Nuclear Engine for Future Mars Missions**
- NASA and the Defense Advanced Research Projects Agency (DARPA) announced Tuesday a collaboration to demonstrate a nuclear thermal rocket engine in space, an enabling capability for NASA crewed missions to Mars.
- NASA and DARPA will partner on the Demonstration Rocket for Agile Cislunar Operations, or DRACO, program. The agreement designed to benefit both agencies, outlines roles, responsibilities, and processes aimed at speeding up development efforts.
- The U.S. Space Force has signaled its support for DRACO with the intent to provide the launch for the demonstration mission.



DARPA Collaboration Fallout

- NASA is moving most of the funding currently provided to DOE to DOD/DARPA
- Most of the existing programs are being put on hold
  - SIRIUS experiments
  - Fuel fabrication research
  - Advanced modeling and simulation
- On the positive side, DARPA fully intends to launch and startup an NTP engine by 2027 (or “as soon as” depending what you read)
  - “We will conduct several experiments with the reactor at various power levels while in space, sending results back to operators on Earth, before executing the full-power rocket engine test remotely,” said Dodson. “These tests will inform the approach for future operation of NTR engines in space.”
  - DARPA does not require a 900s specific impulse; high temperature operation is not required
  - NASA must pick up efforts for fuel development efforts
  - Some funding may come back to DOE in next 2-4 years

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