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Thermal-Hydraulic Modeling of MARVEL Microreactor

Idaho National Laboratory

Outline

- Microreactor Applications Research Validation and Evaluation (MARVEL) Microreactor Project
- RELAP5-3D Role
- Preliminary Transient Results
- Primary Coolant Test (PCAT) Experimental Facility
- Summary

MARVEL Projects Goals and Objectives

- **MARVEL: Microreactor Applications Research, Validation and Evaluation Project**

Project Goals:

- Rapid development of a small-scale microreactor that provides a platform to test unique operational aspects and applications of microreactors

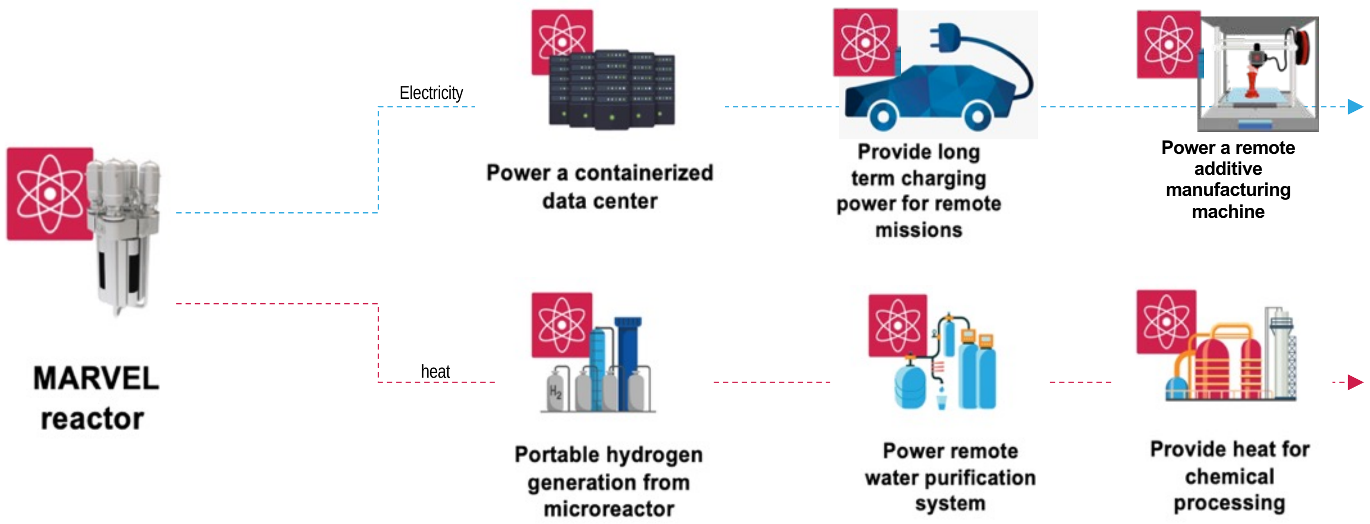
Primary Objectives:

- Project shall produce an operational microreactor in the most accelerated timeline possible
- Project shall result in an operational reactor that produces **combined heat and power (CHP)** to a functional **microgrid**
- ***DOE Sponsor Programs:*** MRP Microreactor Program, NRIC National Reactor Innovation Center

Microreactor Applications R&D

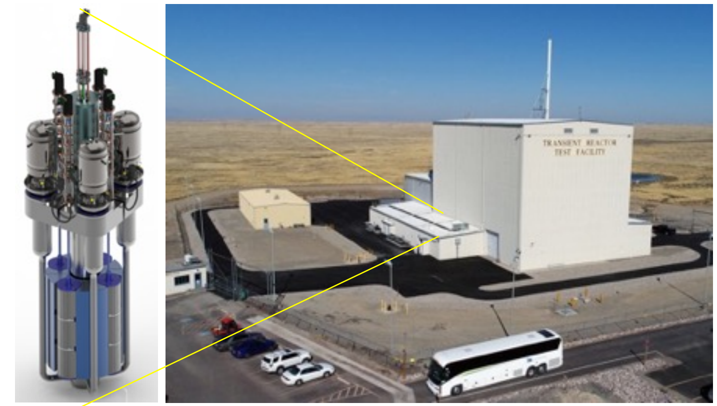
- Engage potential end user companies (B2B, B2C): interested in bringing application assets for testing and ultimate deployment
- End-users are actively being engaged to plan for integration tests

Examples of potential CHP applications



MARVEL Characteristics

- Will be the **53rd** reactor sited at INL
- To be installed at INL's Transient Reactor Test (TREAT) facility
- Pursuing Environmental Assessment (EA) for DOE Authorization (DOE/EA-2146)
  - First reactor to complete EA for National Environment Protection Act (NEPA) compliance, see [1]
  - Draft EA: January 11, 2021
  - FONSI (Finding of No Significant Impact): June 8, 2021
- Inspired by existing designs and technology
  - SNAP-10A space reactor
  - TRIGA fuel



MARVEL reactor at INL's TREAT facility

MARVEL Characteristics

Major Systems	Parameters	Value/Type
Core	Thermal Power	100 kWth
	Core Life	2 years
	Fuel Type	Uranium Zirconium Hydride ($UZrH_{1.6}$)
	Fuel Uranium Enrichment	<19.75 %U235
	Maximum Uranium in Core	<30kg U
Primary Circulation	Number of Loops	4
	Heat-Transfer Method	Liquid-Phase Natural Circulation
	Heat-Transfer Fluid	Sodium-Potassium Eutectic (NaK)
Secondary Circulation	Heat-Transfer Method	Liquid-Phase Natural Circulation
	Heat-Transfer Fluid	Lead-Bismuth Eutectic (PbBi)
Reactivity Controls	Reactivity Control Method 1	4 Vertical Control Drums
	Reactivity Control Method 2	Inherent Reactivity Feedback
Power Conversion	Power Conversion Technology	4 Frictionless, Free-Piston Stirling Engines
	Power Conversion Efficiency @500°C inlet temperature	20-25%
	Electrical Power	18-25 KWe

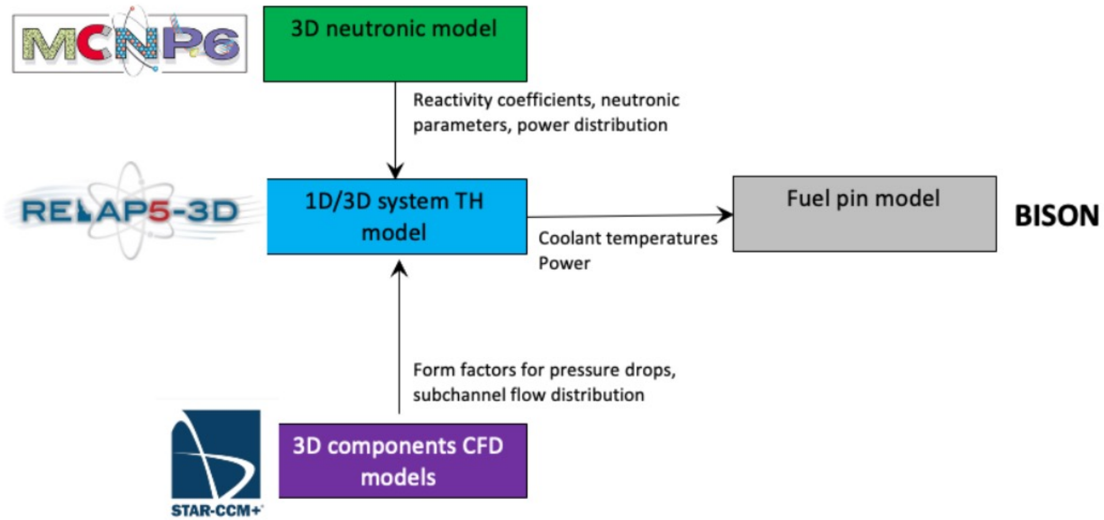
MARVEL 3D view

MARVEL Project

- **Main Steps**
  - **June 2020:** Reference Design Completed
  - **July–Sept. 2020:** Separate Effect Tests Performance
  - **Oct. 2020–Jan. 2021:** Integral Effects Test Facility (PCAT) Designed
  - **Oct. 2020–Jan. 2021:** Interim Design Reports Archived
- Reference & Interim Design included **thermal hydraulic analyses**
  - RELAP5-3D code reference thermal-hydraulic (TH) code

MARVEL M&S Strategy

- Modeling and simulation (M&S) strategy for design and safety analysis
  - Use **best-estimate** nuclear safety codes and commercial codes with an **extensive nuclear pedigree** and **well-proven reliability**
  - Introduce hot-channels factors for modeling **thermal-hydraulic/neutronic uncertainties**
  - Perform independent high-fidelity calculations using commercial CFD code for selected SSCs
  - Validate using 1:1 scale Integral Test Facility (being assembled)

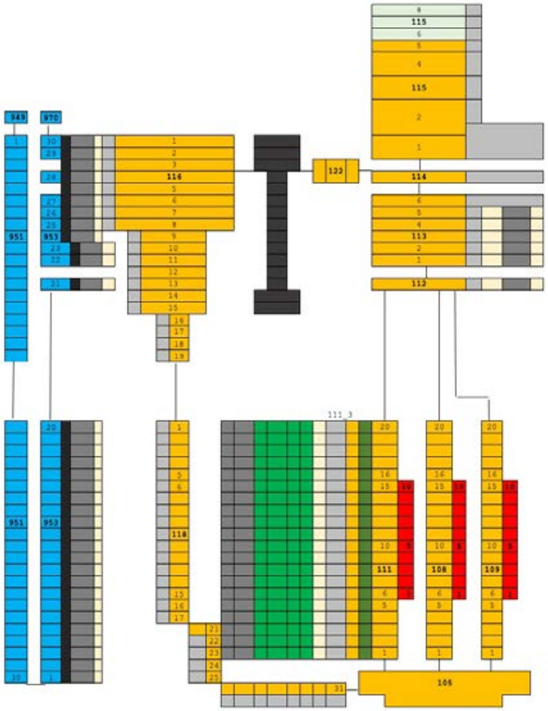


MARVEL Thermal-Hydraulic Design

- Use of INL's RELAP5-3D system thermal-hydraulic code as an M&S **workhorse**
- The RELAP series of codes have been developed at **INL** for over **50 years**
  - 1966: Idaho scientists began developing RELAP
  - RELAP5-3D is the **flagship** of nuclear reactor system analysis tools → most widely used nuclear reactor accident analysis code
  - Development ongoing (e.g., integration into INL's Multiphysics Object Oriented Simulation Environment (MOOSE) framework)
  - Capability to model liquid metal systems added in the 2000s
    - Several fluid property libraries available (Na, Na-K, Pb, Pb-Bi, Li)
    - <u>Specific correlations</u> for liquid-metal heat transfer (Seban-Shimazaki, Westinghouse)
    - 3D hydraulic components, 3D neutron kinetics

RELAP5-3D TH Modeling

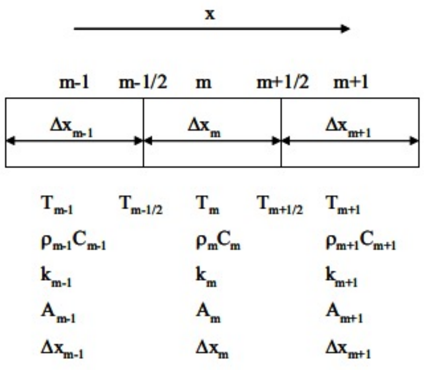
- RELAP5-3D thermal-hydraulic/neutronic model for transient analysis
- Includes primary & four secondary loops, guard vessel, shielding, air cooling riser
- Three independent TH systems using three different fluids:
  - NaK, PbBi, Air
- Core components include single sub-channel + hot channel factors
  - Five independent channels
- Reactivity coefficients for 0D neutronic module
- Component materials (e.g., BeO for side reflector)



MARVEL RELAP5-3D nodalization sketch

RELAP5-3D TH Modeling

- Special care for M&S of the following key points
  - **Pressure losses** → hand-calculated, verified by CFD analysis
  - **Axial heat conduction effects in the fluids**
    - Implemented control-variable based system for taking into account in primary and secondary system [2]
  - **Hot Spot Factors**
    - Quantify the safety margins including uncertainties
  - **Stirling Engine Feedback**
  - **Control Drums** system movement effect for power ramp simulation
    - Implemented using dedicated control-system

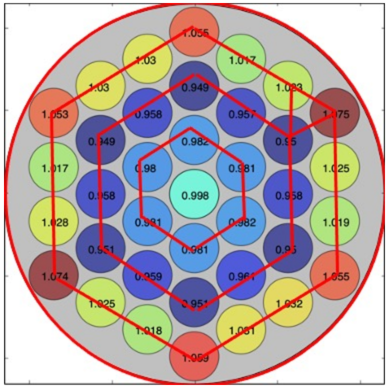


Nodalization diagram for the axial fluid heat conduction model

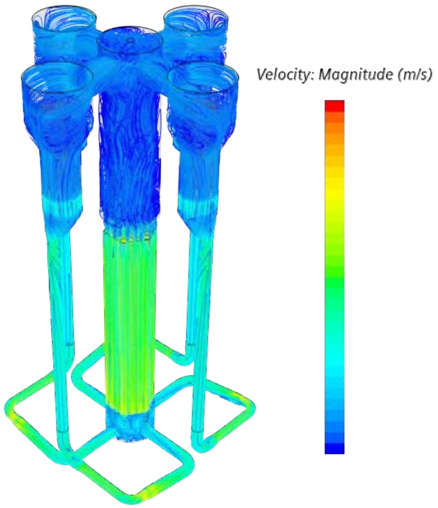
RELAP5-3D Results: Steady-State

- Steady-state results for 37-rod core
- Primary and secondary temperatures controlled for guaranteeing
  - respect of safety margins for fuel and structural materials
  - efficient operation of the Stirling Engines
- Steady-state model validation using MARVEL full-model STAR-CCM+ CFD simulations

Parameters - Primary & Secondary Side	Values
NaK Inlet Core Temperature, ºC	428
NaK Outlet Core Temperature, ºC	541
NaK Core Temperature Rise, ºC	113
Total Mass Flow, kg/s	1.07
IHX PbBi Minimum Temperature, ºC	409
IHX PbBi Maximum Temperature, ºC	489
IHX PbBi Mass Flow, kg/s	2.03



Core 37-rods TH model



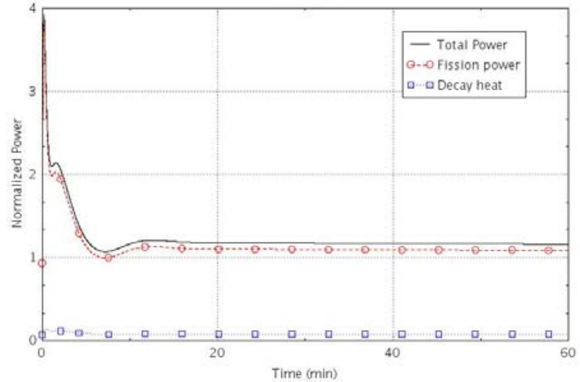
STARCCM CFD model for Validation

MARVEL Safety Analysis

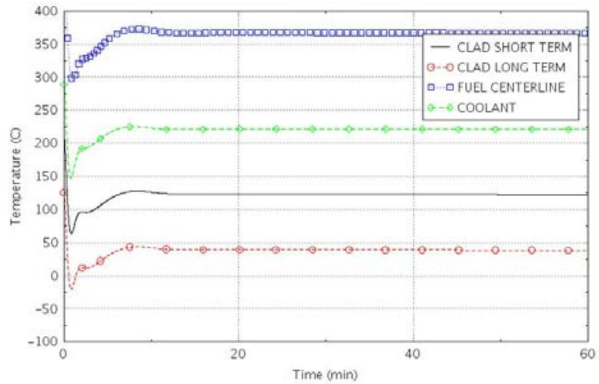
- Dedicated team of safety experts defining relevant transients/accidental scenarios for safety analyses
  - Use of PRA methods
- Safety analyses calculations will be part of TREAT Final Safety Analysis Report (FSAR) addendum
- MARVEL to be licensed by U.S. DOE
- Preliminary calculations part of the EA documents collection [3]
  - Show that the reactor is safe also during Beyond Extremely Unlikely Events (frequency of occurrence< 10^{-6} events/year)
  - Analyze unprotected events (failure of scram system)

MARVEL Preliminary Safety Analysis: UTOP

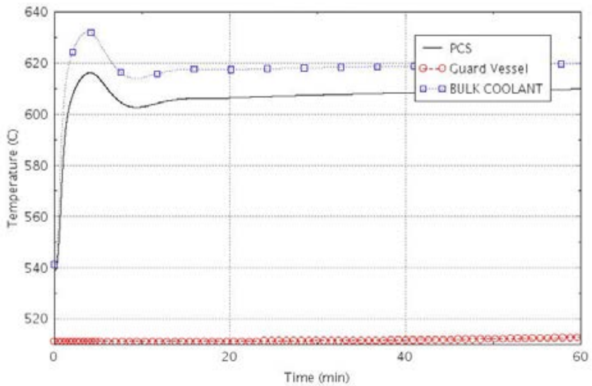
- Transient analyses: **unprotected transient overpower (UTOP)**
  - Step reactivity insertion → 1 CD out from critical position to the mechanical stops
  - No SCRAM
  - Negative reactivity feedbacks counter the power surge → system returns to a steady higher power and higher temperature
  - **No safety concerns** during 1-hr transient



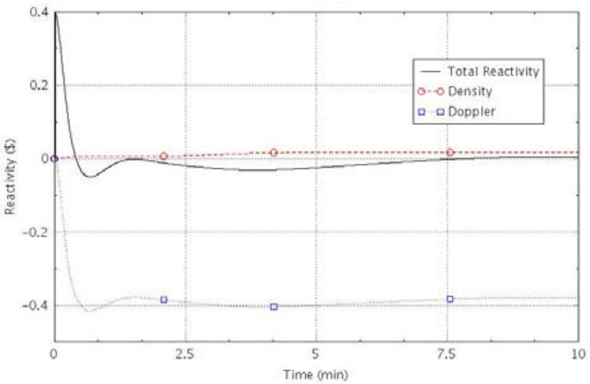
Reactor Power



Temperature Safety Margins

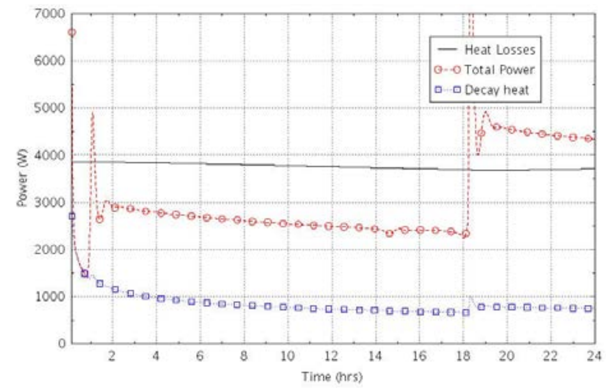


PCS & SCS Temperatures



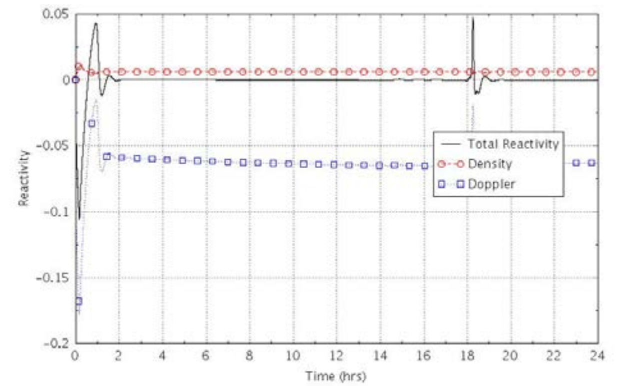
Reactivity

MARVEL Preliminary Safety Analysis: ULOHS

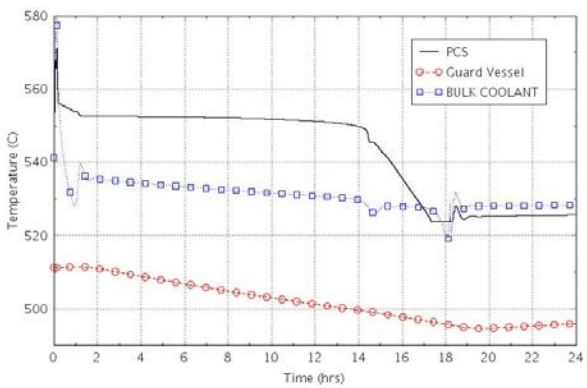


Reactor Power & Heat Losses

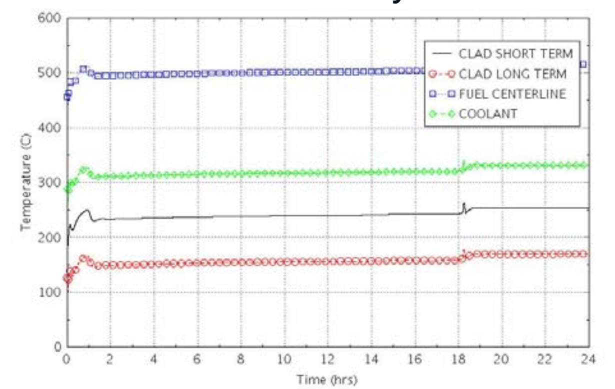
- Transient analyses: **unprotected loss of heat sink (ULOHS)**
  - All four Stirling-engines heat removal capabilities lost at t = 1.0 s
  - No SCRAM
  - Reactor cooled solely by **heat losses** via the guard vessel only
  - Reactor shutdown due to intrinsic negative reactivity
  - Return to power caused by
    - Fuel cooldown
    - Natural-circulation restart
    - Power < guard vessel heat losses for ~18 hr
  - **No safety concerns** during at least the first 24 hr



Reactivity



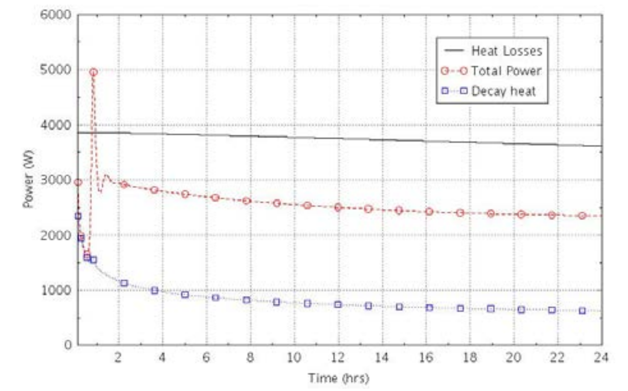
PCS & SCS Temperatures



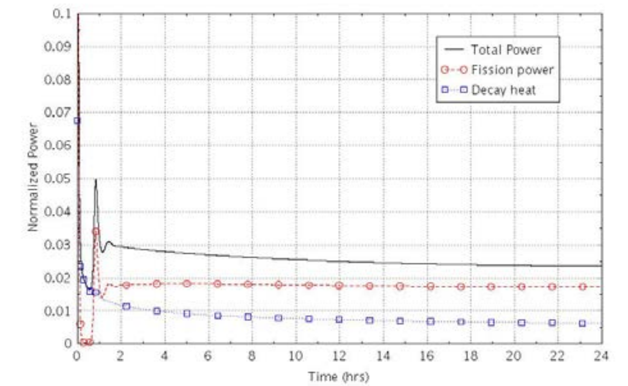
Temperatures Safety Margins

MARVEL Preliminary Safety Analysis: ULOF

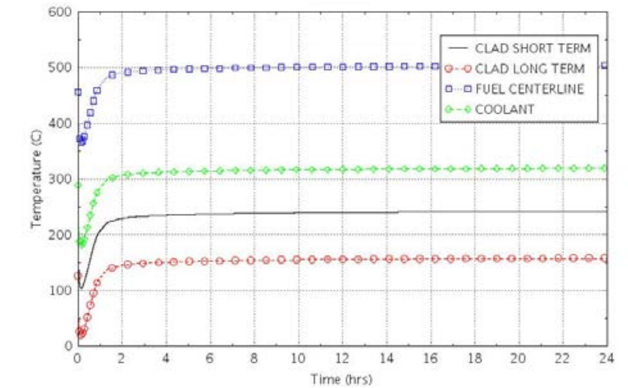
- Transient analyses: **unprotected loss of flow (ULOF)**
  - Total blockage of all four downcomers at t = 0.0 s (assuming four IHX damages)
  - No SCRAM
  - Loss of secondary-side (IHX) heat removal capabilities
  - Reactor **only** cooled by heat losses through the guard vessel
  - Reactor power self-reduced
  - Hot-spot clad temperature not a safety concern, due to the reactor's self shut-down features
  - **No safety concerns** during at least the first 24 hr



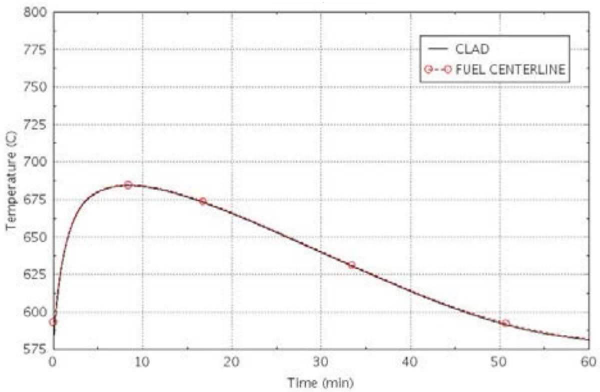
Reactor Power & Heat Losses



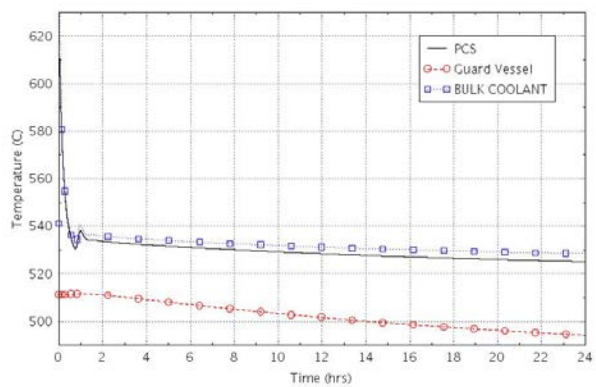
Reactor Power



Temperatures Safety Margins



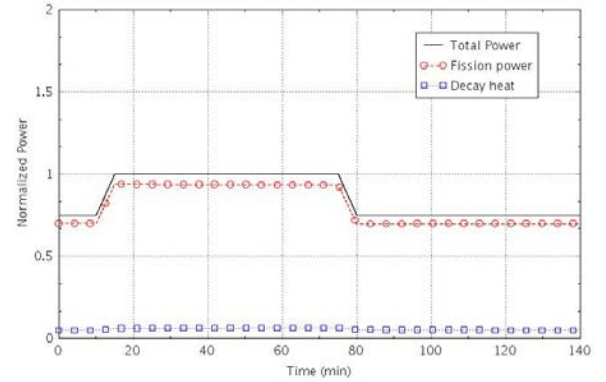
Hot Spot Temperatures



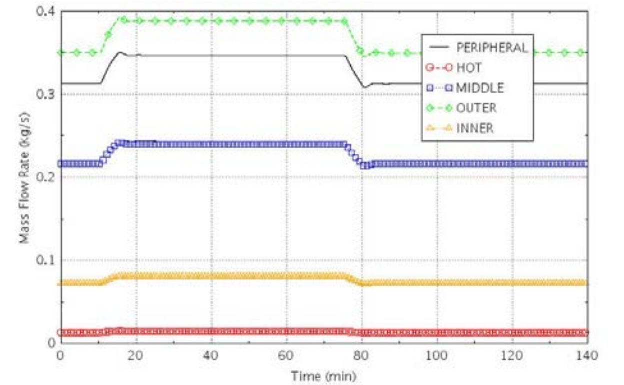
PCS & SCS Temperatures

MARVEL Power Ramps Simulation

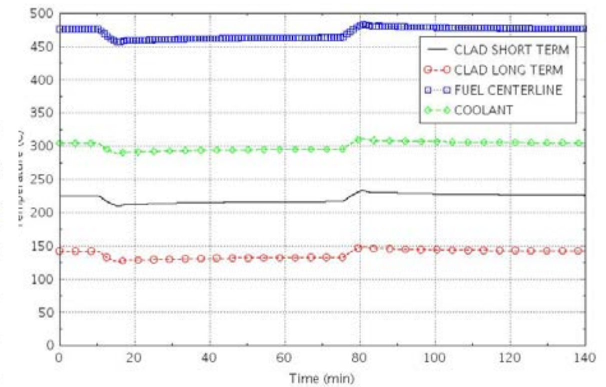
- Transient Analyses: **power ramps**
  - Simulate reaction to imposed power change: 75/100/75 % P_{nom}
  - All four Stirling engines in operation
  - Control system simulate reactivity insertion by CD
    - Reactivity insertion vs position
    - Drum rotation speed
  - Assumption: “Turbine follow” mode → Stirling engines reac remove power produced by the reactor
  - Power changes imposed (simulate ±5% P_{nom}/min ramps)
    - PCS temperature rates: ~1.2ºC/min
    - CD reactivity rate: ~1.2 cents/min



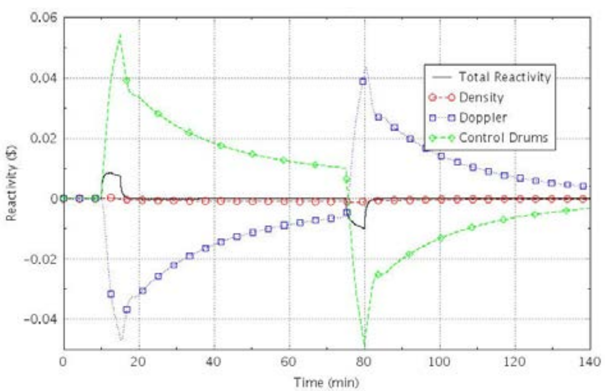
Reactor Power



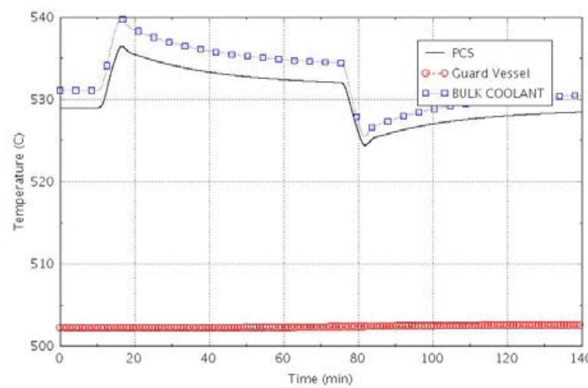
Core Mass Flows



Temperatures Safety Margins



Reactivity



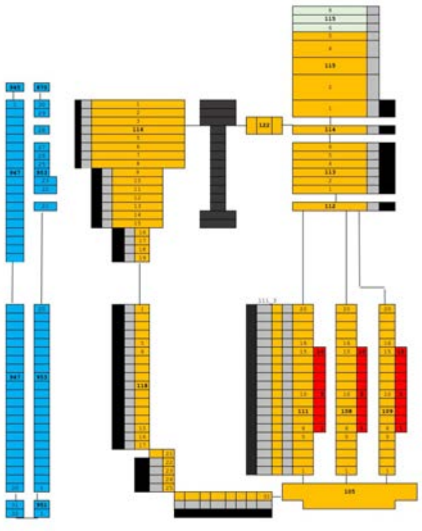
PCS & SCS Temperatures

MARVEL Preliminary Safety Analysis Summary

- Primary safety analysis did not identify **safety concerns**
  - UTOP 0.4$ limiting case, but no safety threshold violated
  - ULOF → corrected conservative BC, lower temperatures obtained → to be rerun in the future with axial conduction effects → further safety margins increase expected
  - ULOHS → no safety concerns
- First “load follow” case simulated: 75/100/75% P_{nom}
  - Reactivity insertion rates and PCS temperature rates seems acceptable

MARVEL Integral Test Facility PCAT

- RELAP5-3D used to design the MARVEL integral test facility PCAT
- Full power (100 KW_{th}), 1:1 electrically heated facility
- “Made in INL” → fabrication completed; assembly ongoing
- RELAP5-3D used for facility pre-test and design
  - Leveraged reactor model
- PCAT will provide data for
  - RELAP5-3D model **validation**
  - Streamline manufacturing methods
  - Component testing
  - Investigation of operational procedures/operator training



RELAP5-3D PCAT model

PCAT components at INL MFC

Next Steps

- RELAP5-3D MARVEL-related activities for FY-22
  - Analyze PCAT experimental results
  - Calculate TH operational transients
  - Finalize FSAR calculations
- Looking forward to FY-23 (MARVEL fuel load, criticality,..)

Summary

- MARVEL project is a pioneering effort to develop a small microreactor that would work as testbed for the next generation nuclear technology
  - 53rd INL reactor, first after many decades
- RELAP5-3D is the **reference TH code** for MARVEL
  - Demonstrated its versatility and robustness in M&S of this novel technology

References

[1] NEPA. N. d. "DOE/EA-2146: Microreactor Applications Research, Validation and Evaluation (MARVEL) Project; Idaho National Laboratory." https://www.energy.gov/nepa/doeea-2146-microreactor-applications-research-validation-and-evaluation-marvel-project-idaho.

[2] C. B. Davis. 2007. "*Evaluation of the Use of Existing Relap5-3D Models to Represent the Actinide Burner Test Reactor.*" INL/EXT-07-12228, Idaho National Laboratory. https://doi.org/10.2172/911901.

[3] C. Parisi. 2021. "Primary Coolant and Decay Heat Removal System", INL-EXT-21-61284, Idaho National Laboratory.