MARVEL Technology Review: Thermal Hydraulics and Safety Basis

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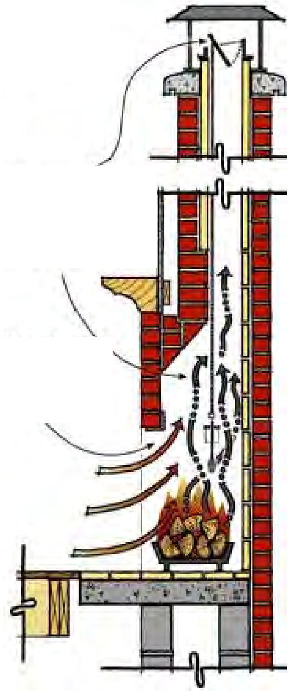
Overview

- Thermal-Hydraulic Characteristics
- Modeling Tools
- Simulation Results
  - Steady State
  - Shutdown / Startup
  - Load Following
  - Beyond Design Basis Accidents
- Primary Coolant Apparatus Test (PCAT)

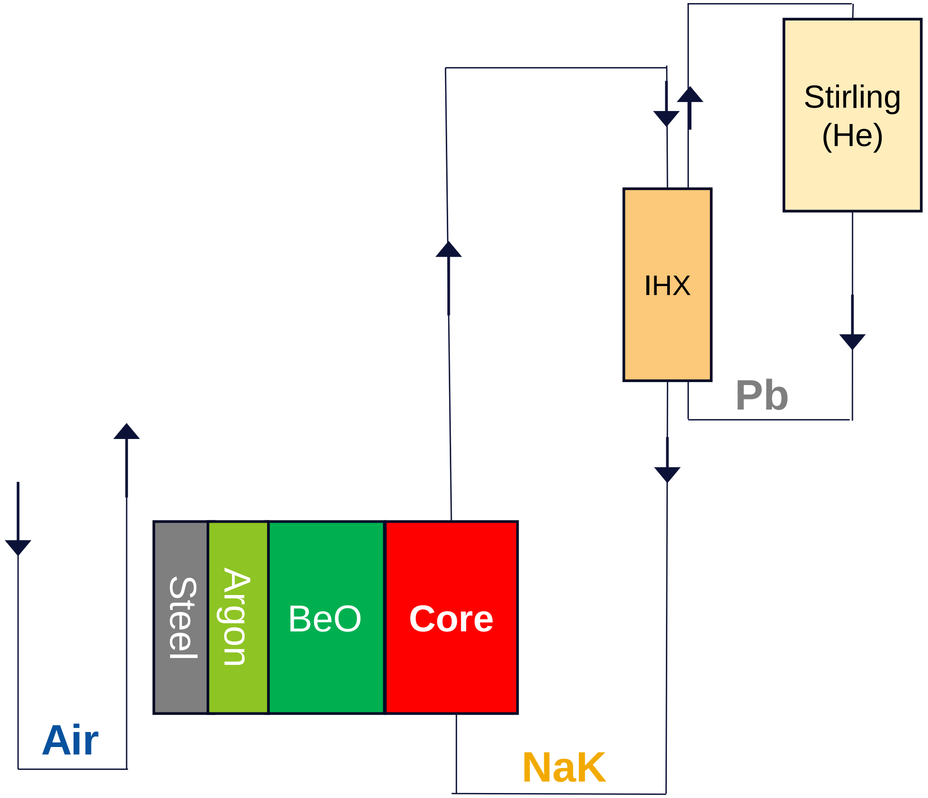
General Thermal-hydraulic characteristics

- **MARVEL microreactor thermal-Hydraulic (TH) characteristics** : liquid-metal-cooled, low-power density, closed loop, series-parallel coupled natural circulation system

MARVEL 3D CAD



Natural circulation



MARVEL natural circulation scheme

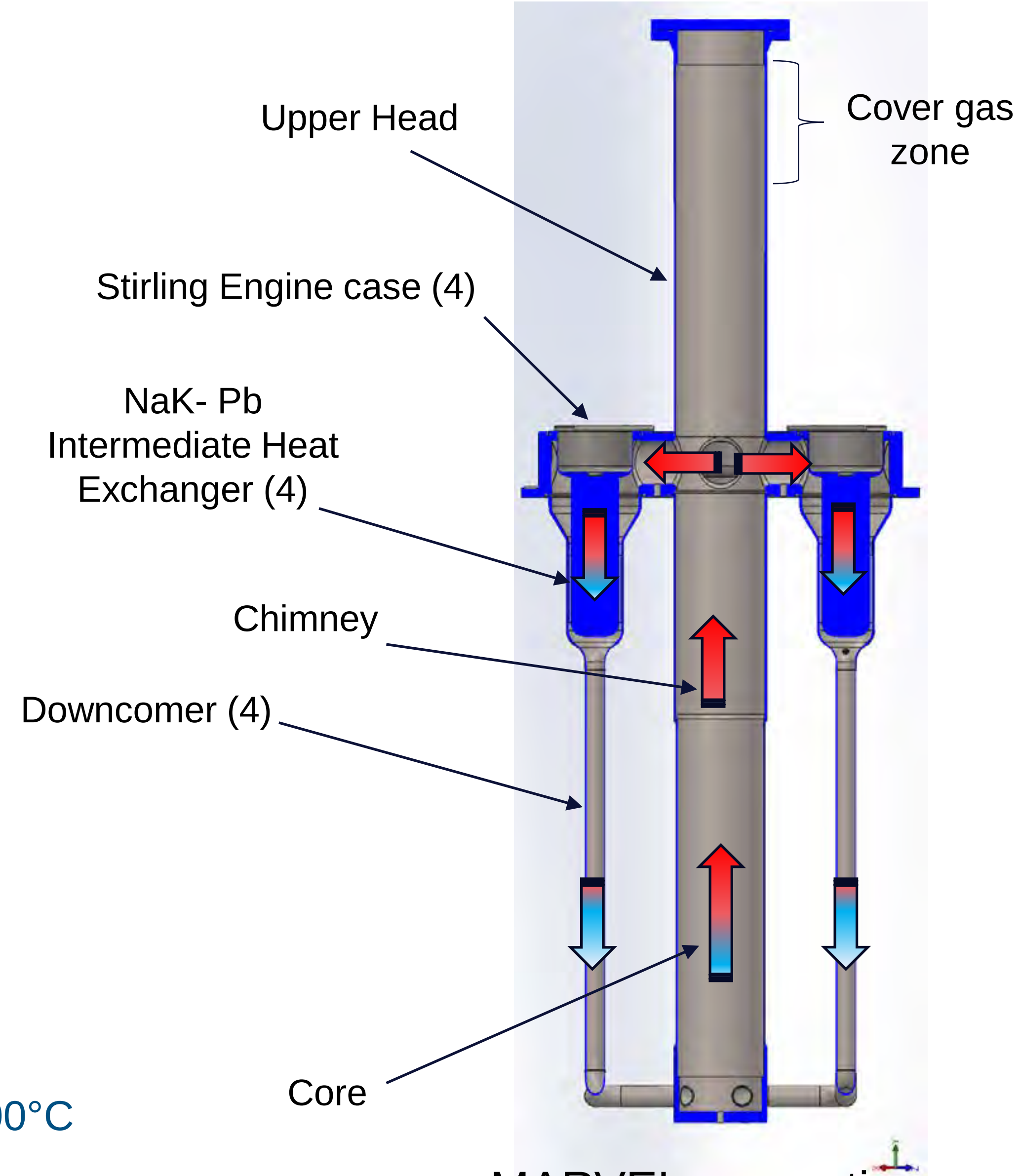
MRP Microreactor Program

Primary Loop Description

- **Key TH characteristics:**
  - Use of natural circulation
    - No pumps
    - Better flow distribution
    - Higher reliability
    - Simplicity
  - Four loops
  - Core power: 85 kW_{th}
  - Low power densities (average values):
    - 14.3 kW/liter
    - 0.03 MW/m^2
    - 3.72 kW/m
  - Elevation difference between thermal centers: 1.13 m
  - Minimization of circuit pressure drops
  - Total NaK mass flow: ~ 1.55 kg/s
  - Core average NaK temperature at hot full power (HFP): ~ 500°C
  - Operating pressure in the cover gas zone: ~ 2.87 atm gauge

$$\dot{m} = \left(\frac{2\beta_T Q g \Delta H}{\bar{c}_p R}\rho_0^2\right)^{\frac{1}{3}}$$

$$\Delta T_H = \left(\frac{R Q^2}{2\rho_0^2 \beta_T g \Delta H \bar{c}_p^2}\rho_0^2\right)^{\frac{1}{3}}$$

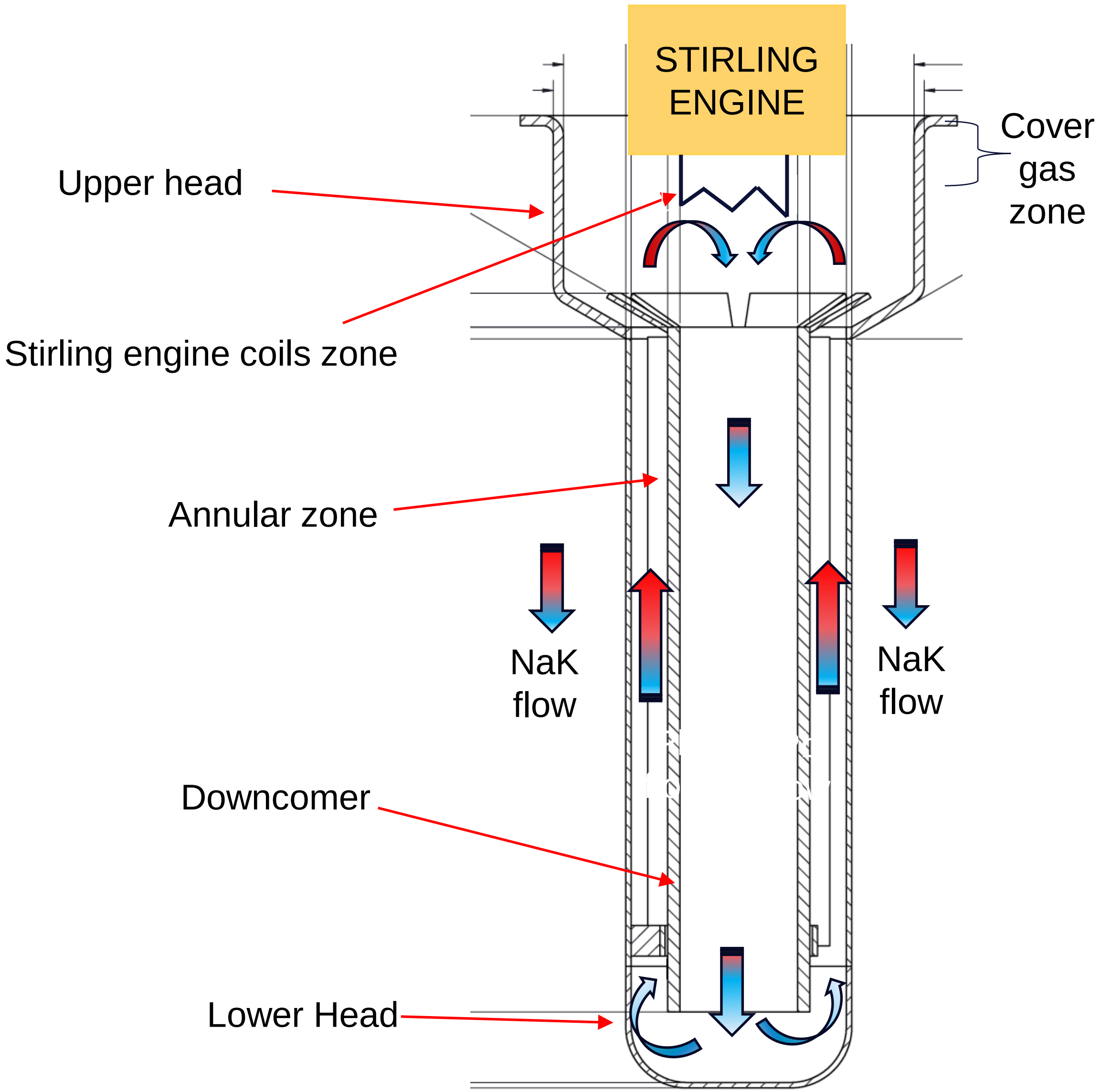


MARVEL x-z section

MRP Microreactor Program

Secondary Loop Description

- Key TH characteristics:
  - Four intermediate heat exchangers (IHX)
  - Removed power: ~20 kW_{th} each
  - Double head, annular section
  - Single double-wall thermally insulated downcomer
  - Elevation difference between thermal centers : ~ 0.28 m
  - Minimization of circuit pressure drops
  - Pb mass flow: ~ 5.2 kg/s
  - Average Pb temperature at HFP: ~ 396°C

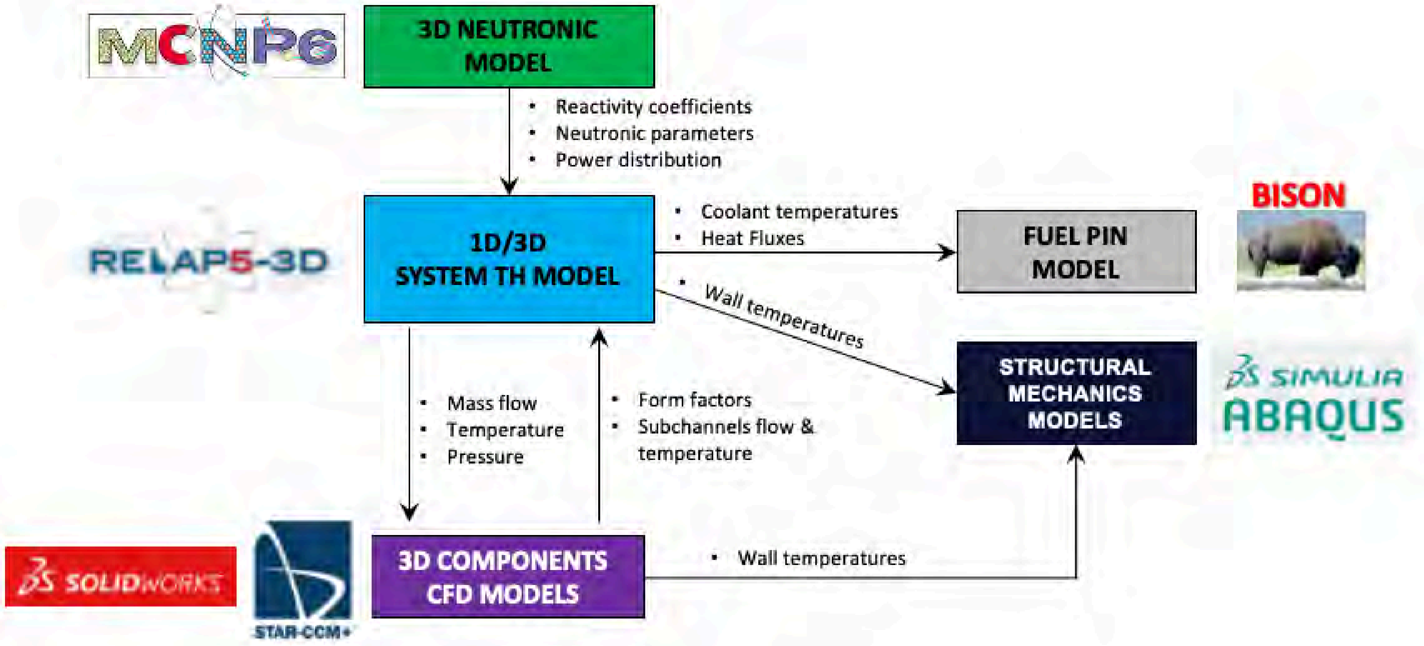


NaK-Pb IHX

MRP Microreactor Program

Thermal-hydraulic Modeling & Simulation Tools

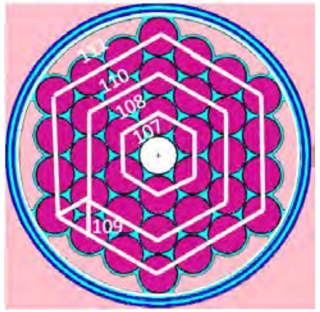
- Modeling and simulation (M&S) strategy for safety analysis
  - Use **best-estimate** nuclear safety codes and commercial codes with **extensive nuclear pedigree** and **well-proven reliability**
  - Perform independent **high-fidelity** calculations using commercial computational fluid-dynamic (CFD) codes for selected system, structure, components (SSCs) for design validation
  - TH model validation using MARVEL Integral Test Facility (ITF) PCAT



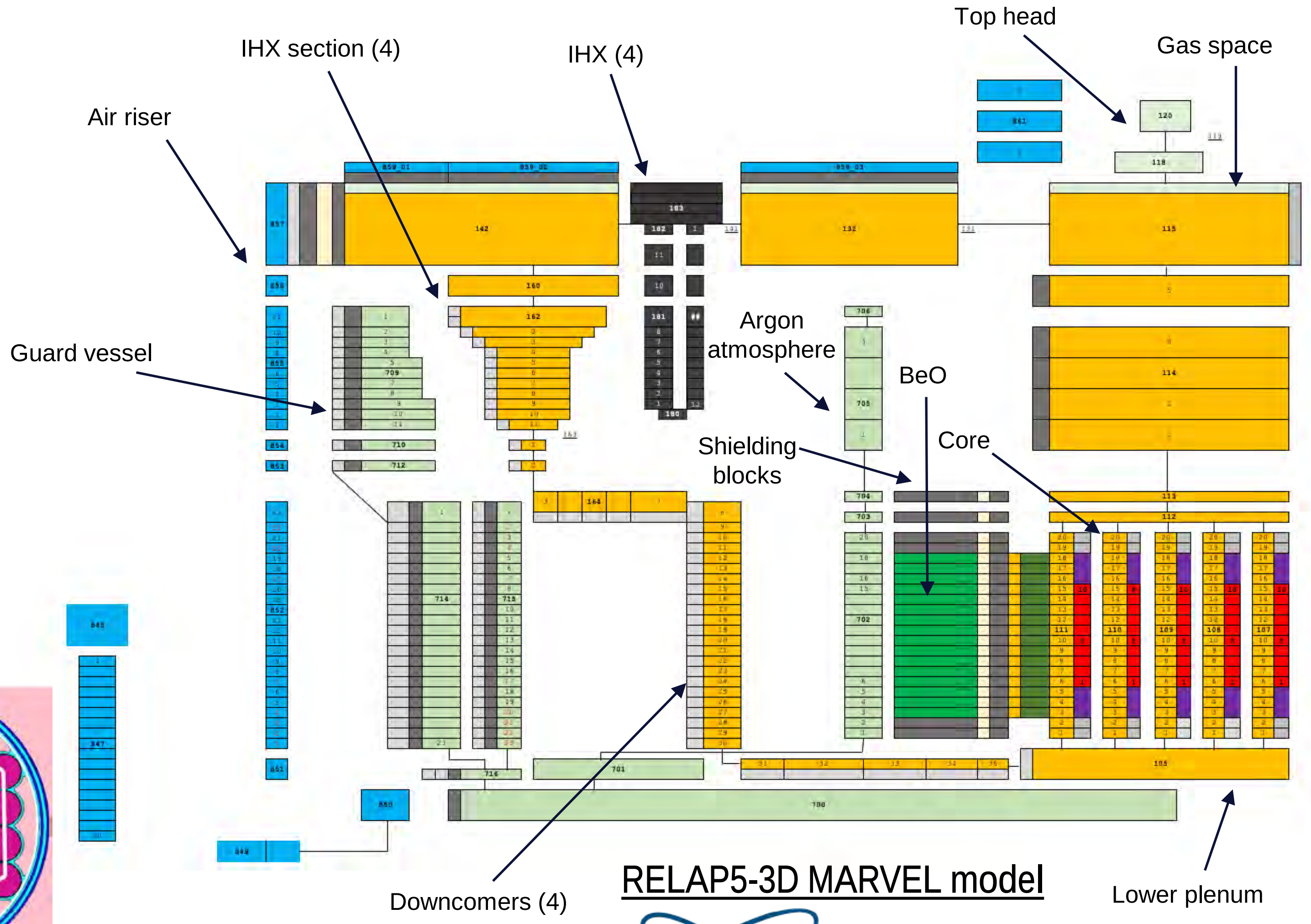
MRP Microreactor Program

Thermal-Hydraulic Modeling & Simulation Tools

- RELAP5-3D thermal-hydraulic and neutronic model for **steady-state & transient analysis**
  - Includes primary & four secondary loops, guard vessel, shielding, air cooling riser
  - Core components: single sub-channel + hot channel factors & four channels (different rings)
  - Reactivity coefficients for 0D neutronic module
  - Component materials (BeO, Be, C-steel, ZrH, etc.)
  - Control & protection systems for power ramps and scram



Core 36-rods TH model



RELAP5-3D MARVEL model

MRP Microreactor Program

Design Limits

- Acceptance criteria based on
  - Fuel and coolant temperature
  - To be verified by RELAP5-3D
- Stress and strain in the clad verified by dedicated thermo-mechanical analysis by RELAP5-3D-BISON coupled calculations

<table>
<tr><th>Design Criteria</th><th colspan="4">Design Basis Events</th></tr>
<tr><th></th><th>Normal Operation</th><th>Anticipated Events</th><th>Unlikely Events</th><th>Extremely Unlikely Events</th></tr>
<tr><td>1</td><td>Peak fuel centerline temperature < 700°C</td><td></td><td></td><td></td></tr>
<tr><td>2</td><td></td><td colspan="3">Peak fuel centerline temperature < 1050°C</td></tr>
<tr><td>3</td><td colspan="2">Bulk coolant < 650°C</td><td></td><td></td></tr>
<tr><td>4</td><td colspan="2">Peak clad internal temperature < 650°C</td><td></td><td></td></tr>
<tr><td>5</td><td></td><td></td><td>Peak clad internal temperature < 704°C</td><td>Peak clad internal temperature < 704°C (long term), <788°C (short term)</td></tr>
<tr><td>6</td><td></td><td></td><td colspan="2">Bulk coolant < 704°C</td></tr>
<tr><td>7</td><td colspan="4">Core remains coolable</td></tr>
</table>

MRP Microreactor Program

Hot Channel Factors

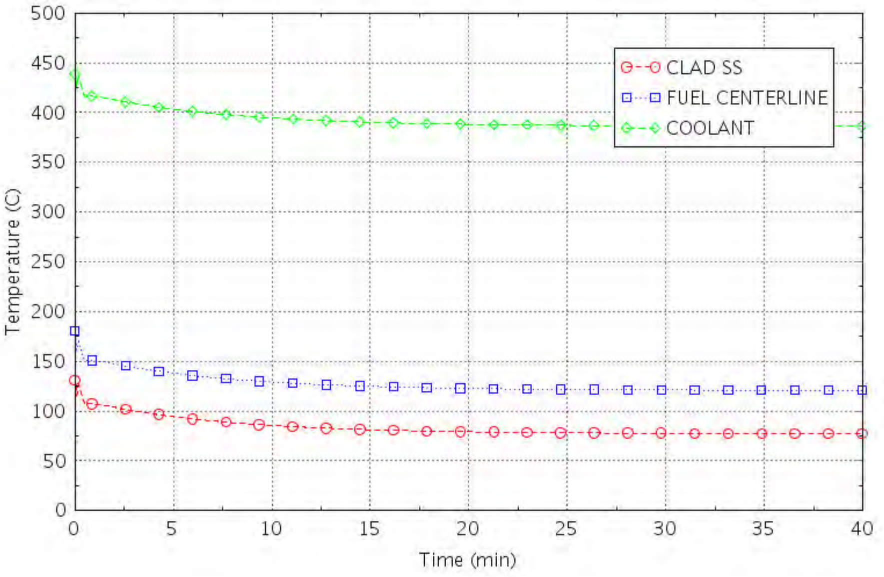
- Hot channel factors (HCF) implemented in RELAP5-3D as safeguards against **uncertainties** (minimize margins)
  - Protect fission product barriers (fuel, clad, PCS)
- HCF derived from references based on past experiences and sensitivity analysis
- HCF to be updated
    - Using data from ITF PCAT
    - Before going critical
- Probabilistic treatment being considered for future uncertainty quantification (UQ) using **RELAP5-3D** and **RAVEN** codes

MRP Microreactor Program

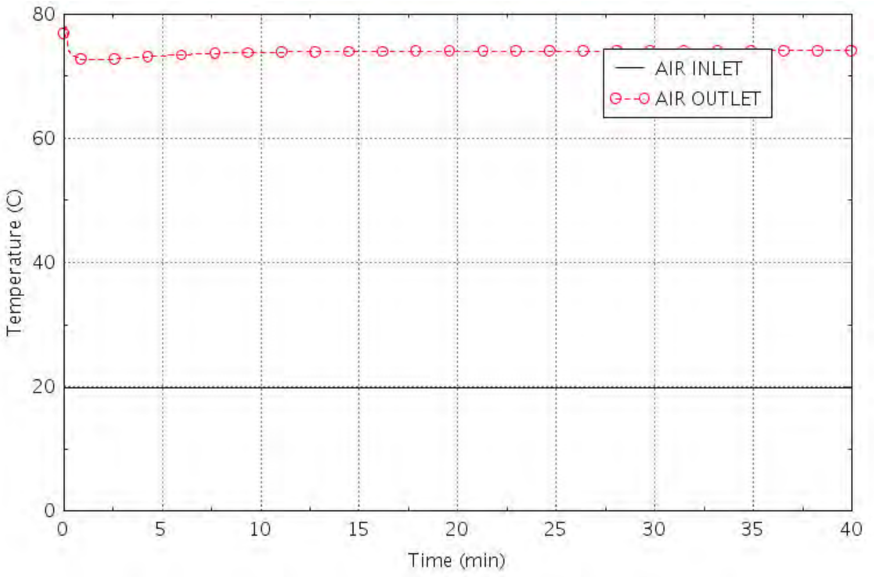
Normal Operation: Steady-State

- Steady-state results for 36 TRIGA fuel rods, 1.414 in. OD (3.59 cm), 25 in. (63.5 cm) tall active core
- Reactor power: 85 KW_{th}
- All structures in thermal equilibrium
- Good steady-state temperature margins

Parameters - Primary & Secondary Side	Values
NaK inlet core temperature, ºC	465
NaK outlet core temperature, ºC	532
NaK core temperature rise, ºC	67
Total mass flow, kg/s	1.55
IHX Pb minimum temperature, ºC	386
IHX Pb maximum temperature, ºC	411
Pb temperature rise, ºC	25
IHX Pb mass flow, kg/s	5.2



Temperature safety margins

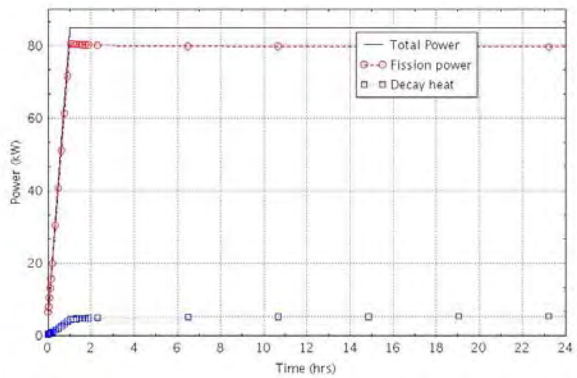


Air riser temperatures

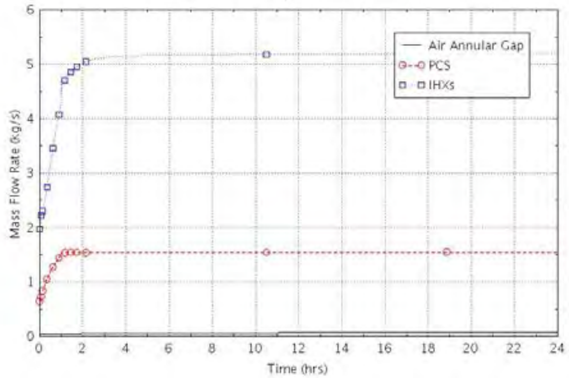
MRP Microreactor Program

Normal Operation: Start-Up

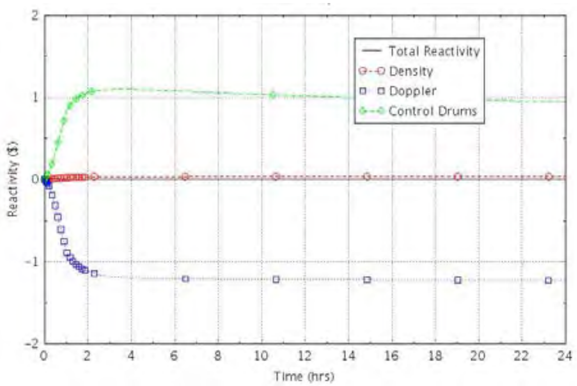
- Tentative **start-up** sequence:
  - Heat the system above the Pb melting point (T_{SYS} > 327.5ºC)
  - System steady state at reactor power = 7 kW, T_{avg} = 340ºC
  - Perform power ascension to 85 kW in ~ 1 hr
    - 1.3 kW/minute
      - Max PCS temperature rates: ~2.1ºC/min
      - Control Drums (CDs) reactivity rate: ~1.3 cents/min
    - Stirling generators sink temperature adjusted after ~ 1 hr



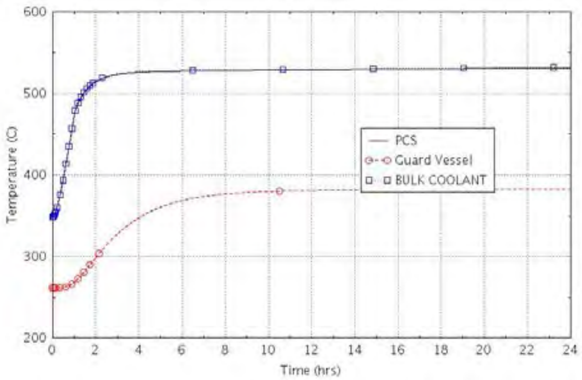
Reactor power



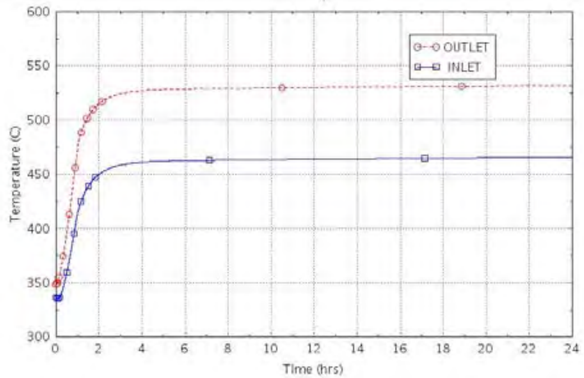
Core, IHX and air riser mass flows



Reactivity



PCS & guard vessel temperatures

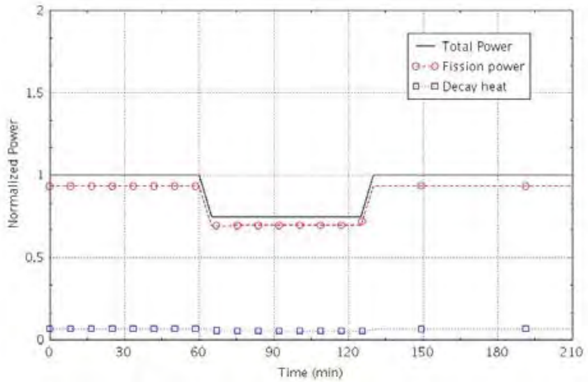


NaK temperatures

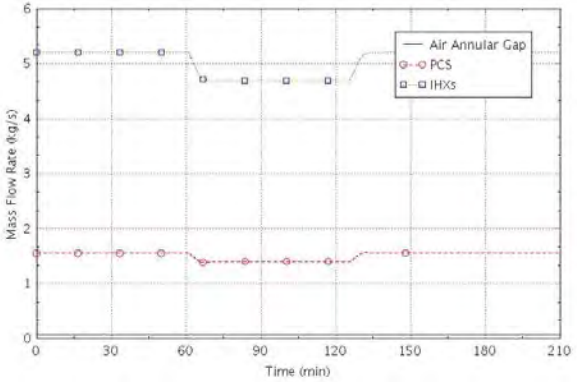
MRP Microreactor Program

Normal Operation: Load-Follow

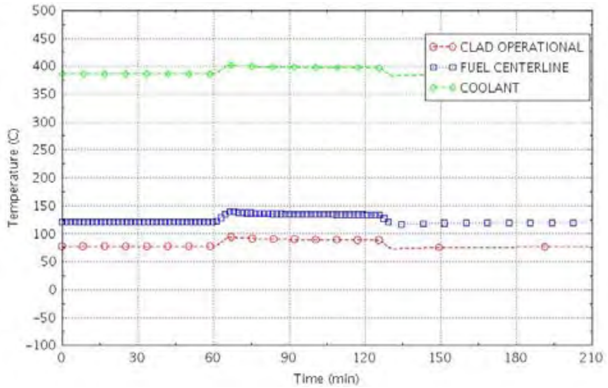
- **Load-follow**:
  - Simulate reaction to imposed power change: 100/75/100% P_{nom} over ~2.5 hr period
  - All four Stirling engines in operation
  - Control system simulate reactivity insertion by control drums
    - Reactivity insertion vs. position
    - Drum rotation speed
  - Assumption: “turbine follow” mode → Stirling engines react to remove power produced by the reactor
  - Power changes imposed (simulate ± 5% P_{nom}/min ramps)
    - PCS max temperature rate: ~2.0ºC/min
    - CD reactivity rate: ~+/-1.4 cents/min



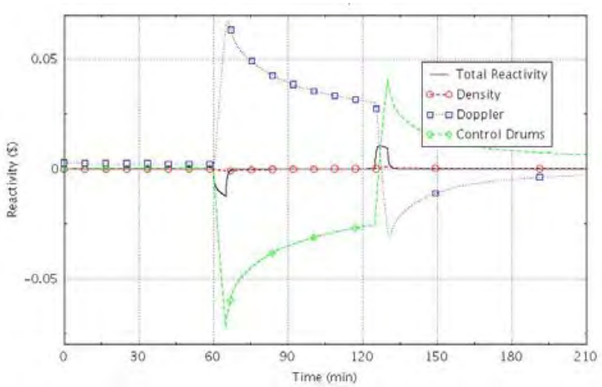
Reactor power



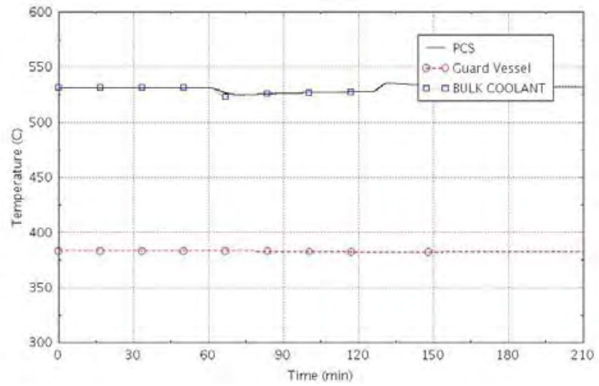
Core mass flows



Temperature safety margins



Reactivity

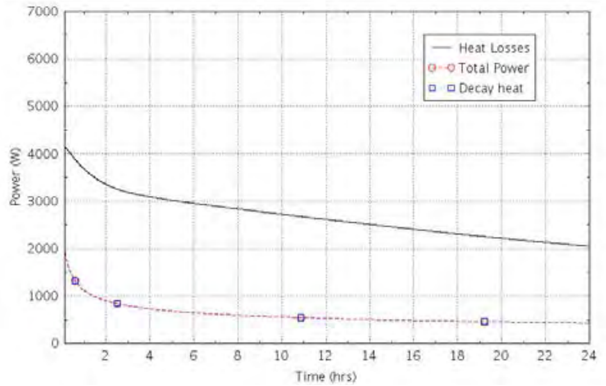


PCS & guard vessel temperatures

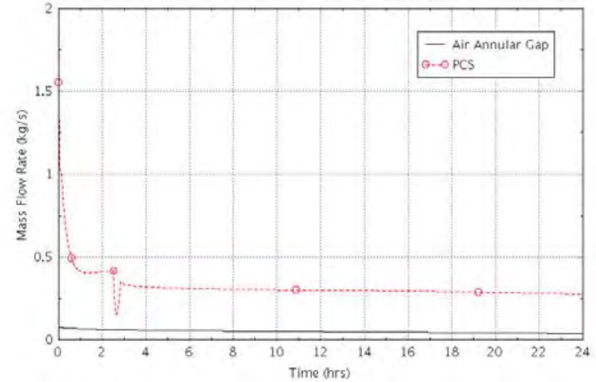
MRP Microreactor Program

Normal Operation: Normal Shutdown

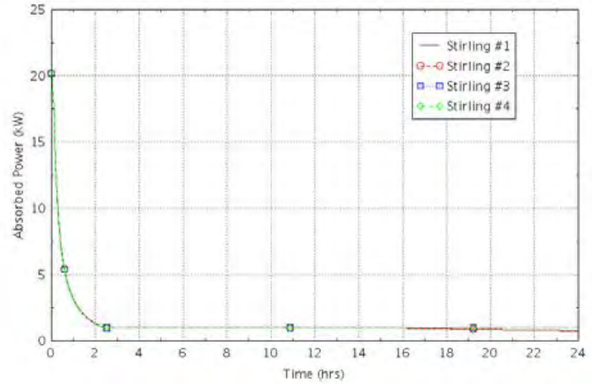
- Simulation of **Normal Shutdown**:
  - Reactor operating at HFP
  - Shutdown of four Stirling engines at t=60.0 sec
  - Decay heat removed via
    - Air riser (natural convection ~ 4.16 kWth)
    - Stirling engines (forced H_2O circulation and heat losses ~ 4 kWth total)
  - System cooldown characteristics
    - Max rate: ~ 1.63ºC/min (98.7ºC/hr)
    - Structures max temperature reaches ~300ºC at t = +24 hr
    - Estimated time for hot standby condition (340ºC): ~2.5 hr



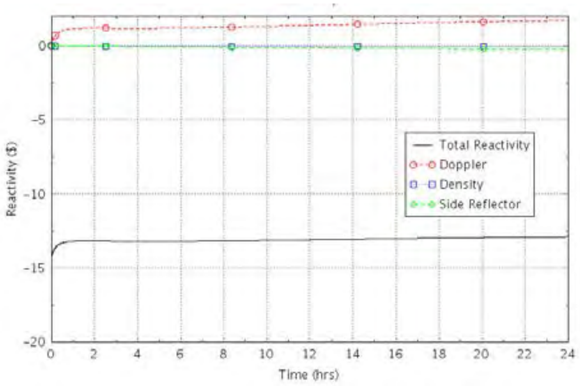
Reactor power & heat losses



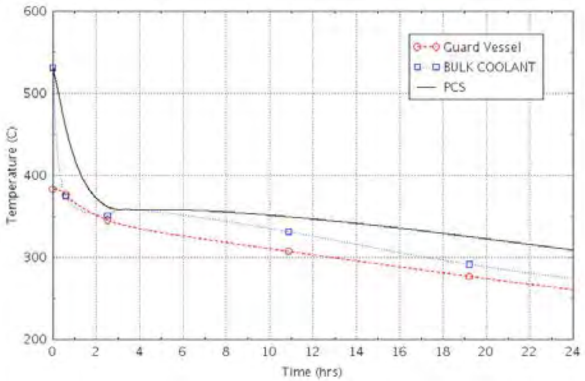
PCS and air riser mass flows



Stirling engines power



Reactivity

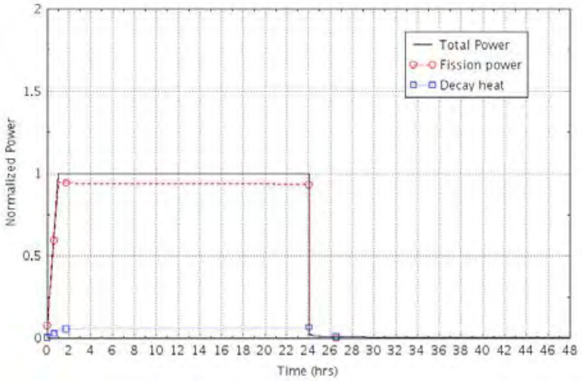


PCS & guard vessel temperatures

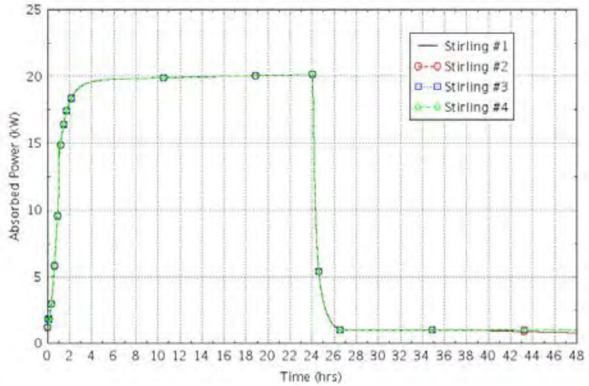
MRP Microreactor Program

Start-Up & Shutdown

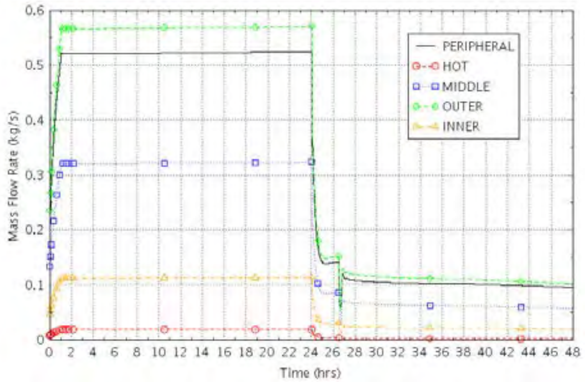
- Simulation of possible MARVEL operation during a weekend
- Start-up, operate for 24 hr, then shutdown



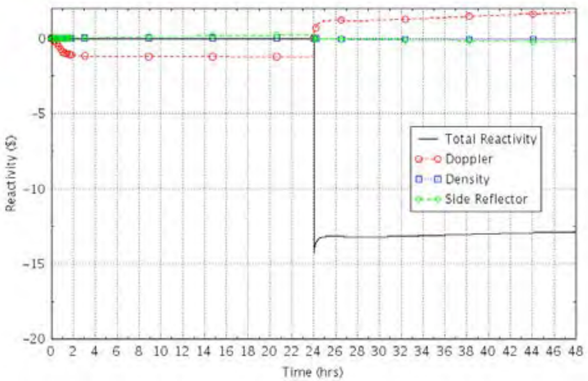
Reactor power



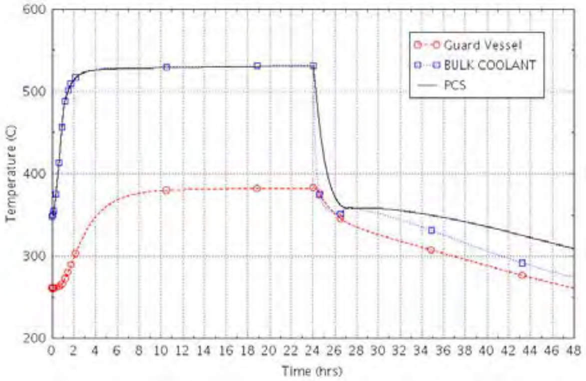
Stirling engines power



Core mass flows



Reactivity

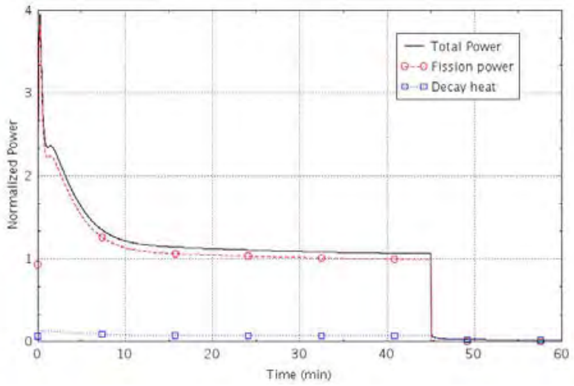


PCS & guard vessel temperatures

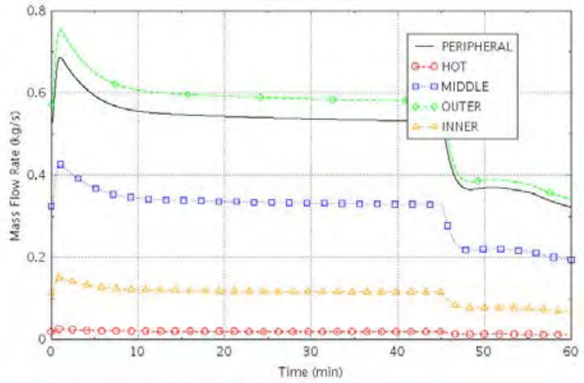
MRP Microreactor Program

Postulated Accident Conditions: UTOP at HFP

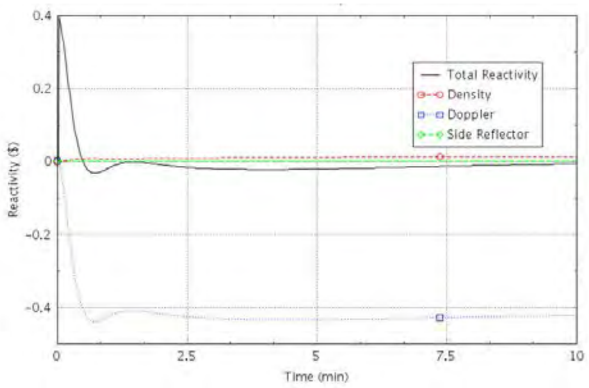
- **Unprotected Transient Overpower (UTOP)**
  - Step reactivity insertion (0.4$) → 1 CD out from critical position to the mechanical stops
  - No scram
  - Reactor power peaks ~4 P_{NOM} (340 kW) at t = 14 s
  - Negative reactivity feedbacks counters the power surge → system back to a steady higher power and higher temperature by t = ~ 15 min
  - **No safety concerns** until scram (not needed)



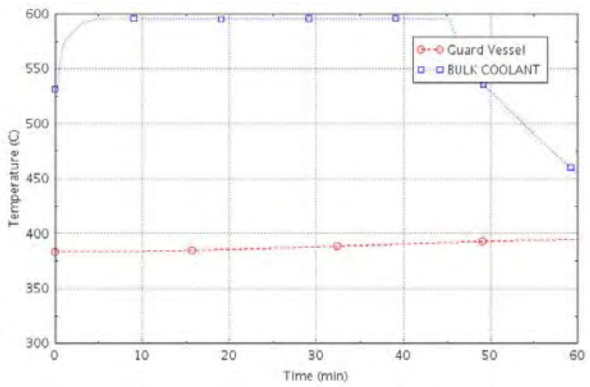
Reactor power



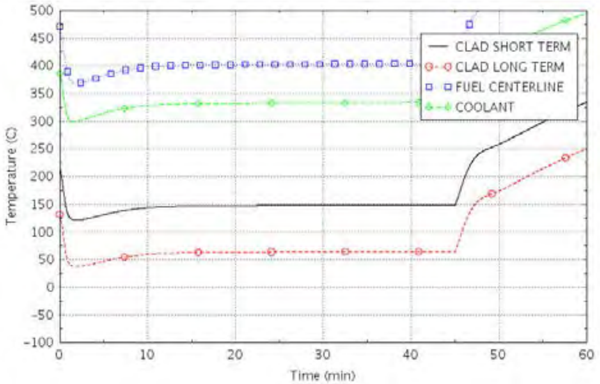
Core mass flows



Reactivity



PCS & guard vessel temperatures

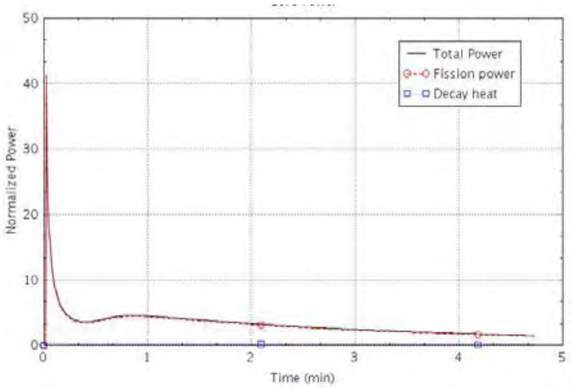


Temperature safety margins

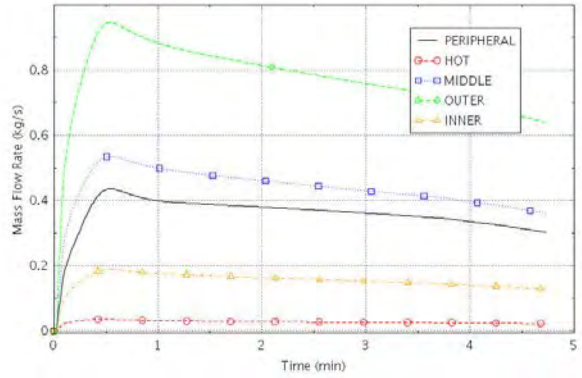
MRP Microreactor Program

Postulated Accident Conditions: UTOP at CZP

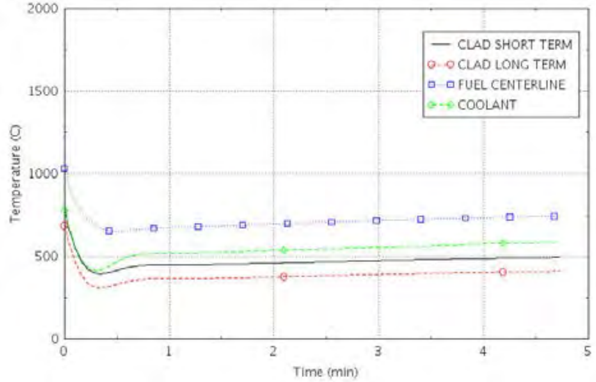
- **Unprotected Transient Overpower at Cold Zero Power (CZP), 20ºC**
  - Step reactivity insertion (1.3$) → 1 CD out from critical position to the mechanical stops
  - No SCRAM
  - Reactor power peaks ~40 P_{NOM} (3.4 MW) at t = 2 s
  - Negative reactivity feedbacks counters the power surge
  - **No safety concerns** during first 5 minutes, reasonably also later
    - Temperatures stay safely low
    - Mechanical effects of fast temperature ramp rate being verified



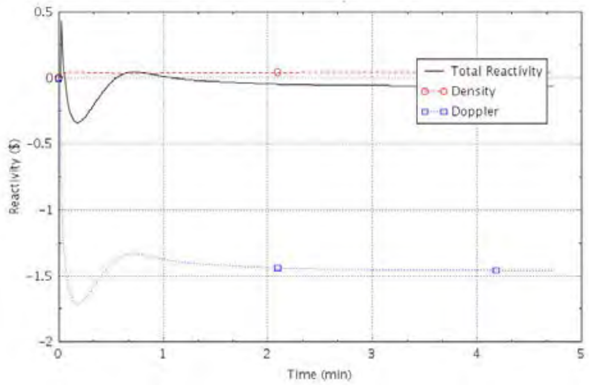
Reactor power



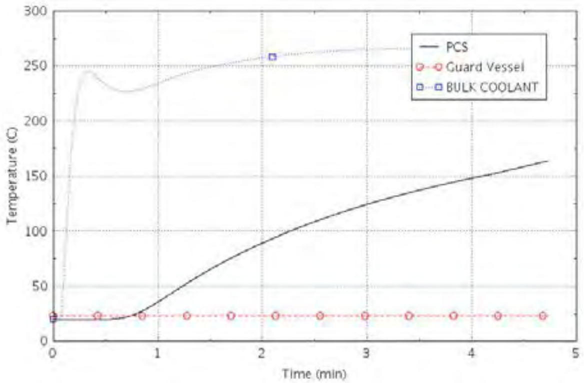
Core mass flows



Temperature safety margins



Reactivity

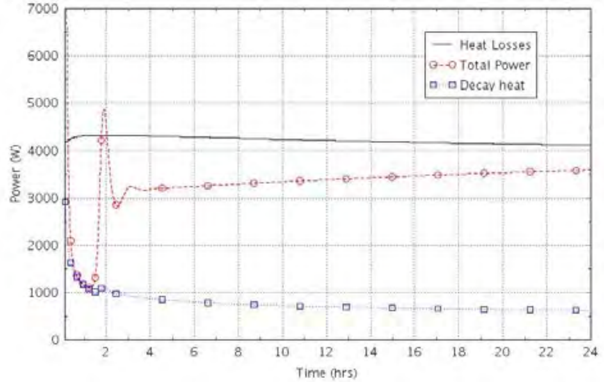


PCS & guard vessel temperatures

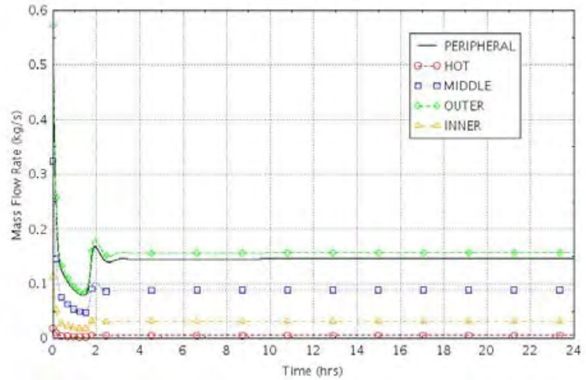
MRP Microreactor Program

Postulated Accident Conditions: ULOHS

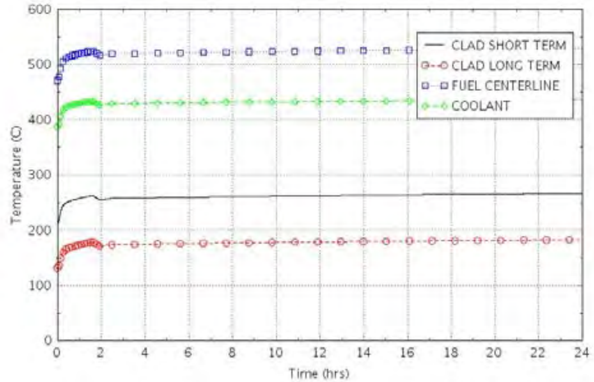
- **Unprotected Loss of Heat Sink (ULOHS)**
  - All four Stirling engines heat removal lost at t = 1.0 s
  - No scram
  - Reactor cooled only by **heat losses** through guard vessel only (~4.1 kW) → conservative assumption
  - Reactor shutdown by intrinsic negative reactivity
  - Return to power caused by fuel cooldown
  - Core power < guard vessel heat losses for first 24 hr
  - **No safety concerns** during at least first 24 hr
  - Beyond 24 hr, reactor power = heat losses (new equilibrium)



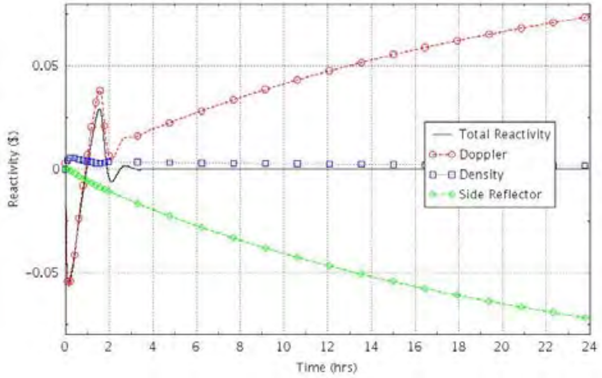
Reactor power & heat losses



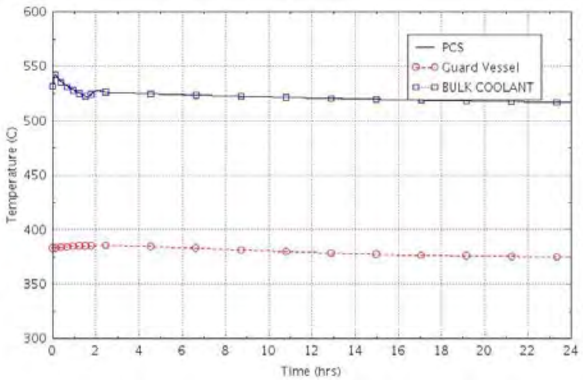
Core mass flowrate



Temperature safety margins



Reactivity

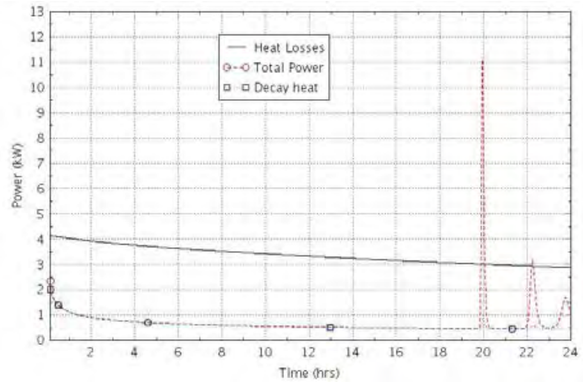


PCS & guard vessel temperatures

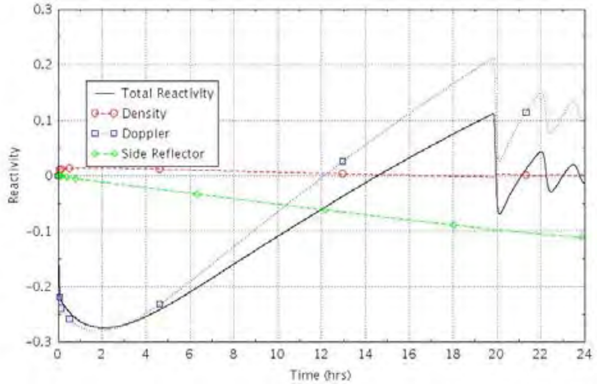
MRP Microreactor Program

Postulated Accident Conditions: ULOF

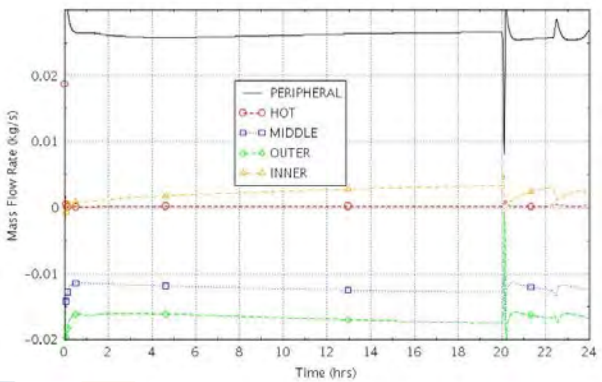
- **Unprotected Loss of Flow (ULOF)**
  - Total blockage of all 4 downcomers at time t = 0.0 s (assume catastrophic damage of all four IHXs) →
    - **Not credible event** (see structural mechanics presentation)
    - Bounding **partial loss of flow** events (intermediate design review comment)
  - No scram
  - Loss of secondary side (IHX) heat removal capabilities
  - Reactor cooled **only** by heat losses through guard vessel
  - Reactor power self-reduced
  - Hot spot clad temperature not of safety concern due to the reactor self-shutdown features
  - **No safety concerns** : data shown for the first 24 hr, beyond that reactor power = heat losses (new equilibrium)



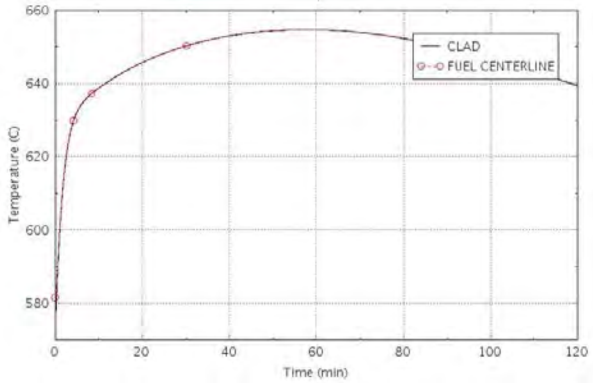
Reactor power & heat losses



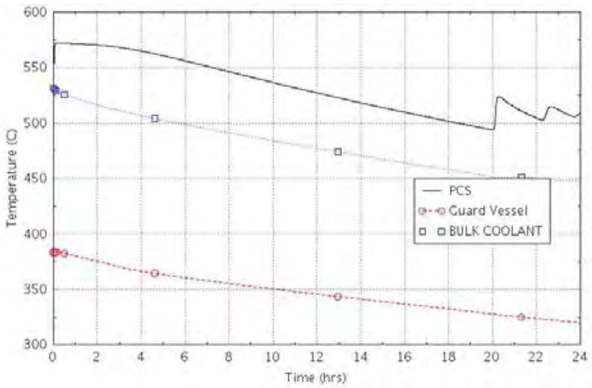
Reactivity



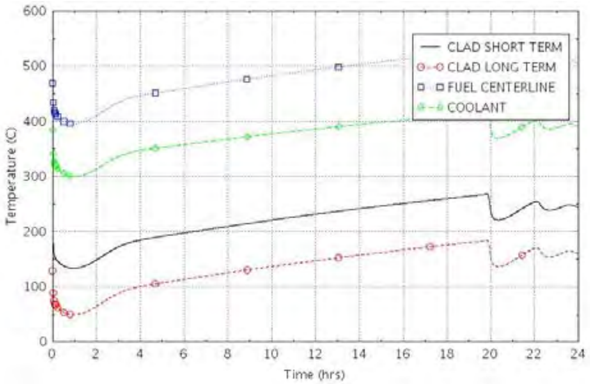
Core mass flow



Hot spot temperature



PCS & guard vessel temperatures



Temperature safety margins

MRP Microreactor Program

Postulated Accident Conditions: ULOCA

- **Unprotected Loss of Coolant Accident (ULOCA)**
  - MARVEL reactor avoids by design the NaK level drop below the top of the core (core never uncovered) also during the break of the low-elevation components (downcomer, lower plenum)
  - Decay heat removal capabilities bounded by ULOF calculations

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Summary of MARVEL Analysis

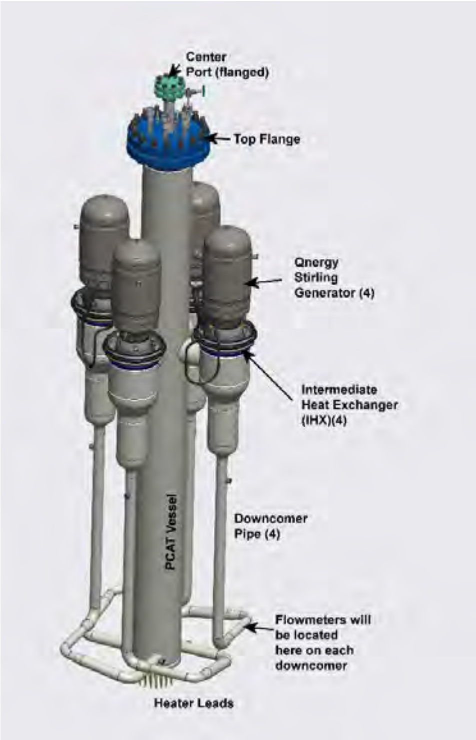
- RELAP5-3D system analysis shows reliable and stable MARVEL performances during start-up, normal operation and load following and shutdown
- **Very conservative** accident analysis shows that all **minimum safety margins are > 0**

Transient	Minimum Margins (ºC)		
	Clad (short / long terms)	Fuel Centerline	Coolant Boiling
UTOP - HFP	121 / N/A	368	298
UTOP - CZP	394 / N/A	651	413
ULOHS	213 / 129	470	385
ULOF	134 / 50	395	300

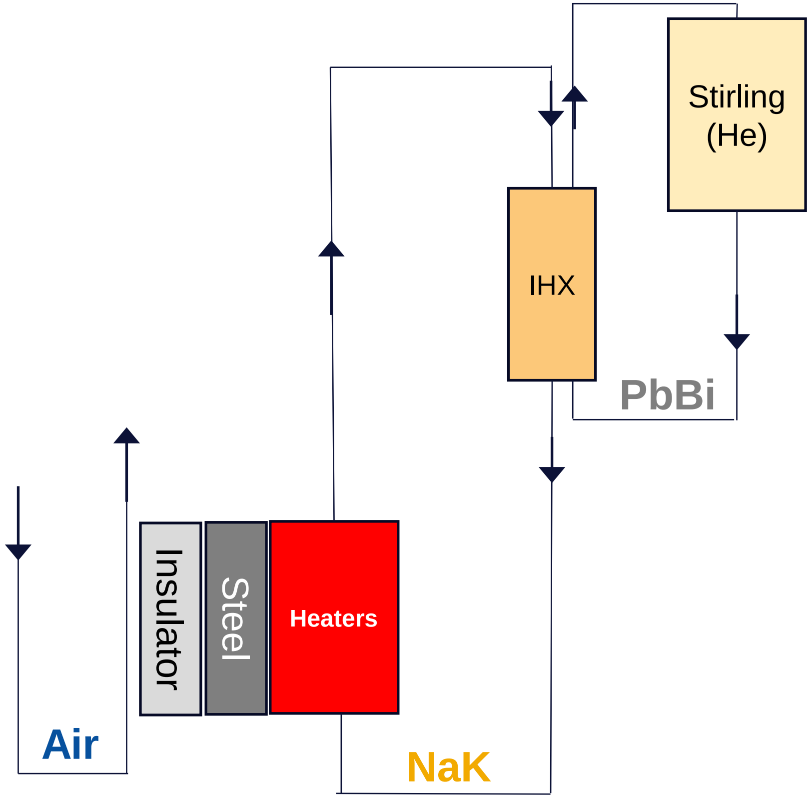
MRP Microreactor Program

PCAT General Thermal-Hydraulic Characteristics

- PCAT is the electrically-heated test loop of MARVEL
  - **Full scale** (1:1 elevation, power)
- General TH characteristics are similar to MARVEL : liquid-metal-cooled, low-power density, four closed loop, series-parallel coupled natural circulation system



PCAT 3D CAD



PCAT natural circulation scheme

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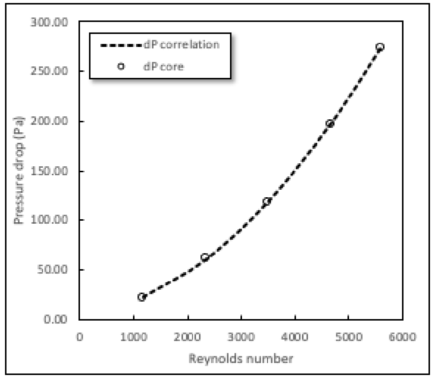
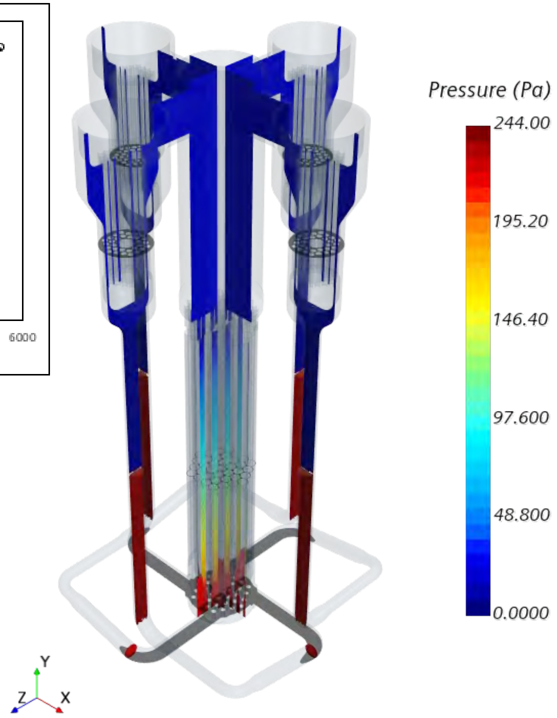
Rationale for PCAT

- Capability of RELAP5-3D in modeling single-phase natural circulation well assessed by different projects and publications performed by several research institutions
  - PCAT RELAP5-3D analysis independently validated by high-fidelity tools (CFD analysis by S. Yoon, J. Kim) and first-principle independent calculations
- Rationale for PCAT:
  - Reduce the uncertainties in the modeling assumptions
    - Heat transfer coefficients (HTC) in core, IHX
    - Pressure drops at different Reynolds number
    - Heat losses at the Stirling engines
  - Combined systems dynamic (three coupled loops)
    - IHX performance
    - Stirling engines operation





PCAT CFD simulation

$$\Delta P_{fric} = \Delta P_{boyancy}$$

$$\frac{\beta g q_{co} L_{th}}{\rho_l a_c C_{pl} u_{co}^3} = \sum_{i=1}^{N} \left\{ \frac{1}{2} \left(\frac{fl}{d_h} + K \right)_i \left(\frac{a_c}{a_i} \right)^2 \right\}_o$$

Analytical model for natural circulation

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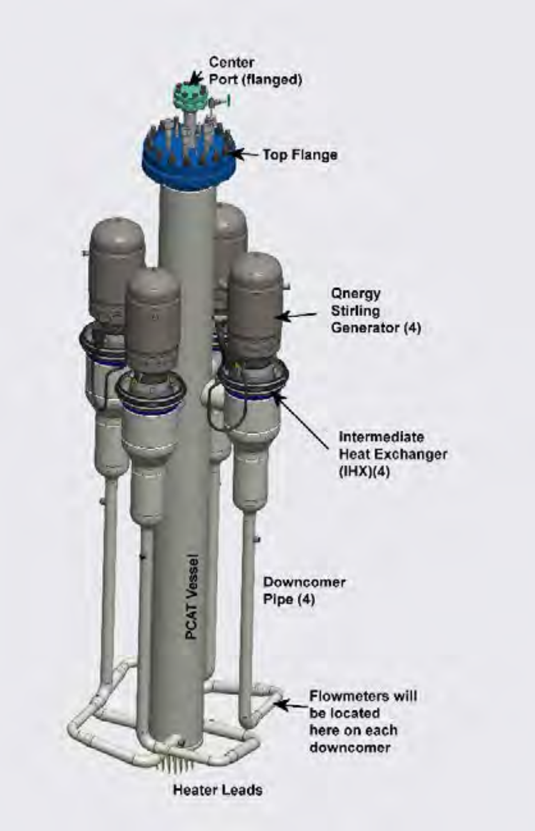
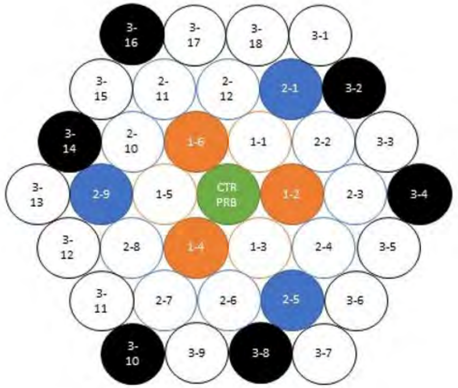
Rationale for PCAT

- PCAT is heavily instrumented to allow **validation of the TH model** and **extrapolate MARVEL TH performances**
  - Three thermocouples (TC) per each heater
  - Three TC for core barrel
  - Three TC per loop
  - Fine temperature distribution measurement in the lower plenum
  - Five TC per IHX
  - One Flowmeter per loop
- PCAT in operation by beginning of calendar year 2023





Core heaters and TC

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