MARVEL Technology Review
Thermal-hydraulic & Safety Basis

March 7, 2024

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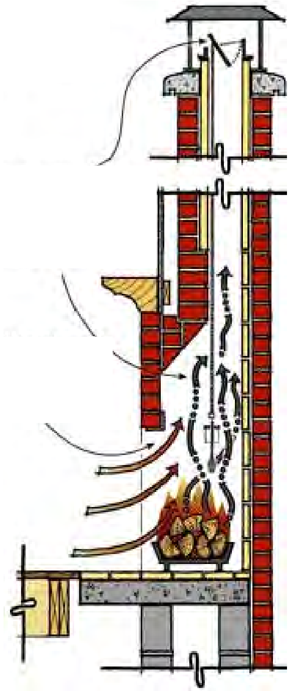
Overview

- MARVEL Thermal-hydraulics
- Modeling
- Boundary Conditions and Assumptions
- Acceptance Criteria
- Uncertainties and Hot Channel Factors
- Deterministic Safety Analysis Results

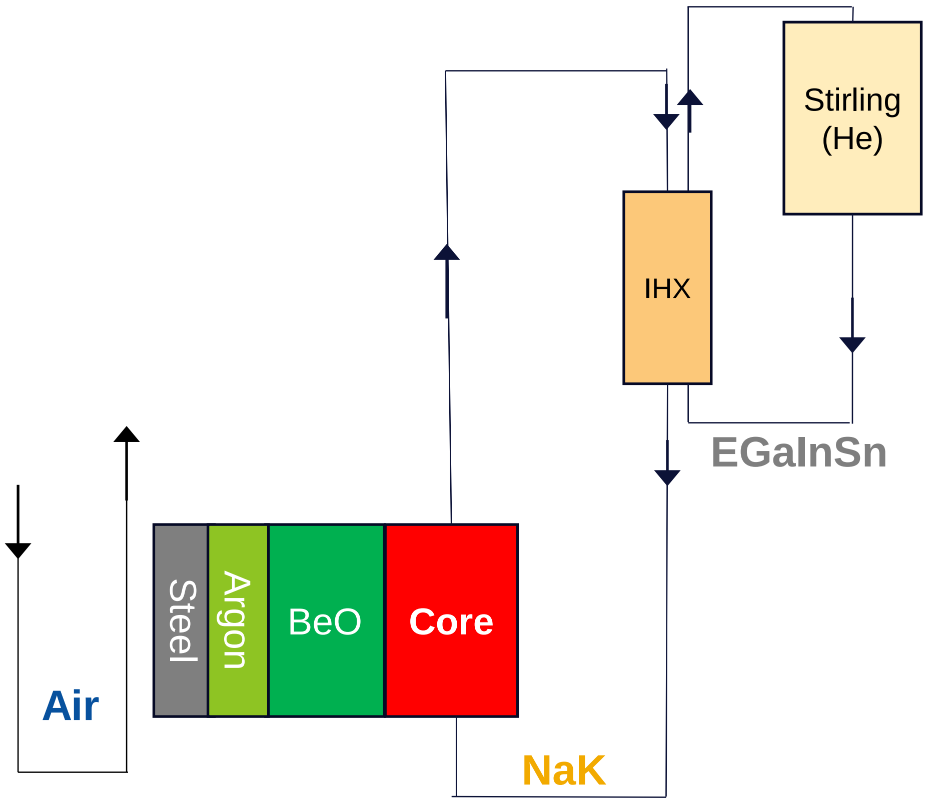
General Thermal-hydraulic Characteristics

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

MARVEL 3D CAD



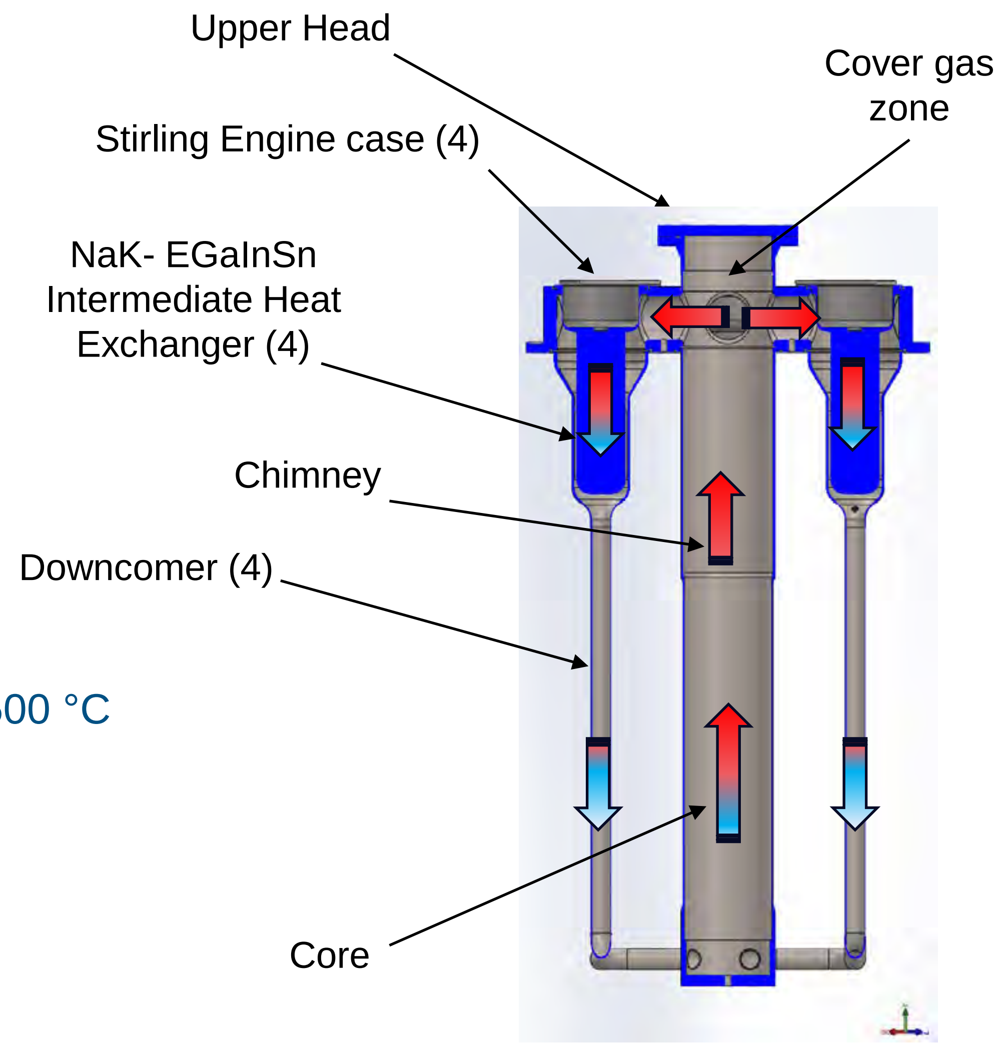
Natural convection



MARVEL natural circulation scheme

System Description

- **Key TH characteristics:**
  - Use of natural circulation on primary and secondary sides
    - No pumps
    - Better flow distribution
    - Higher reliability
    - Simplicity
  - 4 loops
  - Core power: 85 kW_{th}
  - Low power densities (average values)
  - Core average NaK temperature at Hot Full Power (HFP): ~ 500 °C
  - Operating pressure in the cover gas zone: ~ 3.2 atm



MARVEL x-z section

MRP Microreactor Program

System description

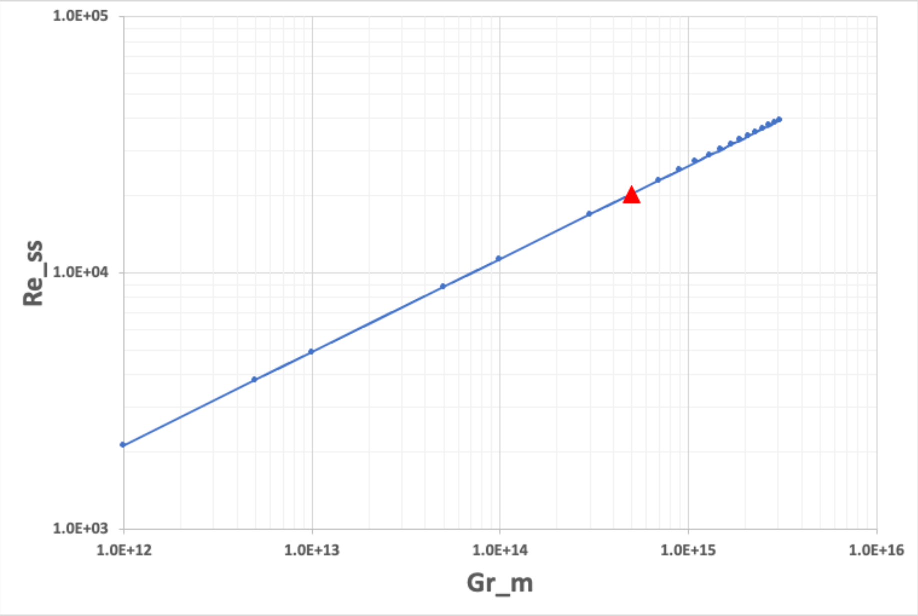
- Use of analytical models for preliminary system design and numerical code verification

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

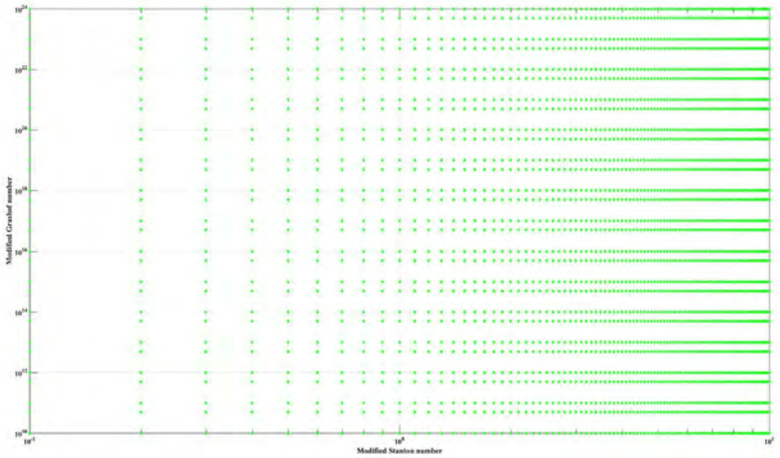
  - Elevation difference Δz_c between thermal centers: ~1.1 m
  - Minimization of circuit pressure drops R
  - Predicted total NaK mass flow at Hot Full Power: ~ 1.5 kg/s

- Non-dimensional analysis
  - for deriving steady-state maps
  - thermal-hydraulic stability studies

$$Re_{ss} = C\left[\frac{(Gr_m)_{\Delta z_c}}{N_G}\right]^r = 1.956\left[\frac{(Gr_m)_{\Delta z_c}}{4524}\right]^{0.3636}$$ [turbulent flow]



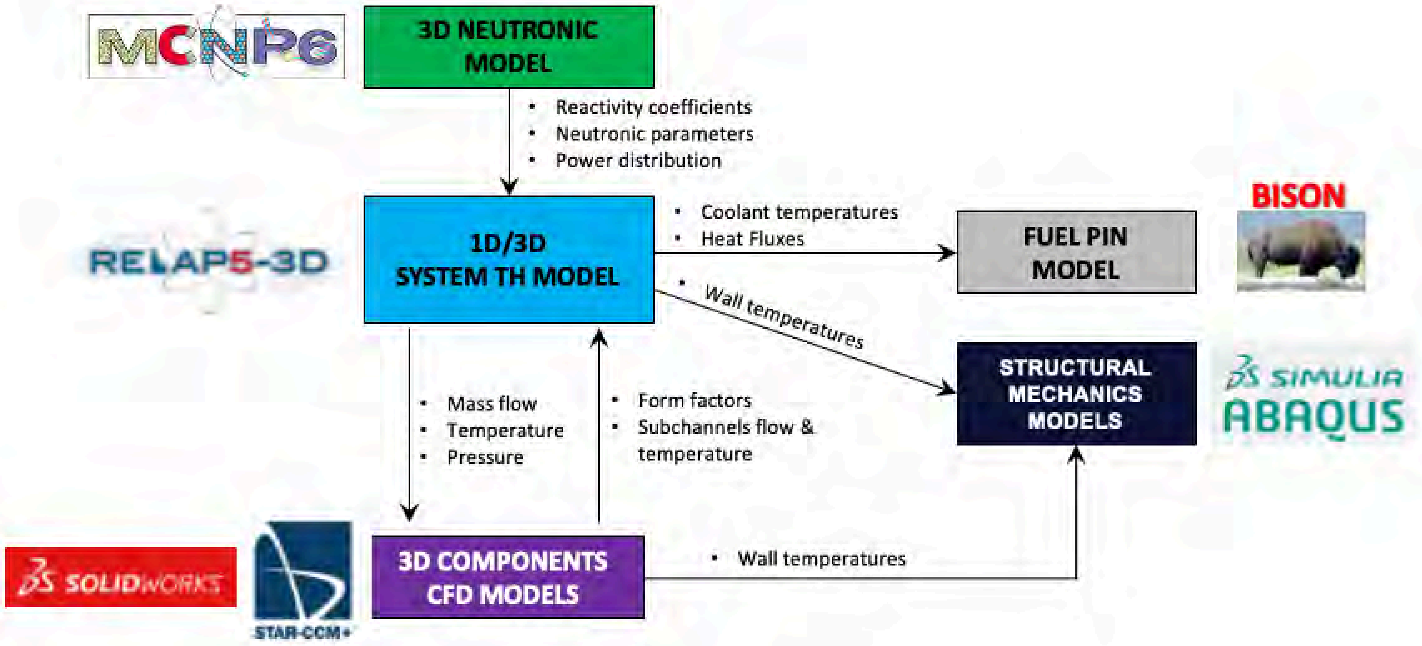
Steady state natural circulation for turbulent flow



Stability map

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

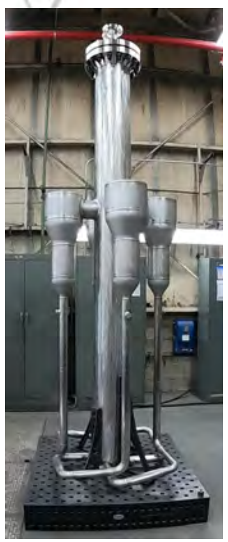


MRP Microreactor Program

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**
  - RELAP5-3D is the **flagship** of nuclear reactor system analysis tools → most widely used nuclear reactor accident analysis code
  - Development still ongoing (e.g., integration into INL's MOOSE framework)
  - Capability to model liquid metals systems
    - Several fluid properties libraries available
    - Specific correlations for liquid-metal heat transfer
    - 3-D hydraulic components, 3-D neutron kinetics
- TH model **validation** using MARVEL Integral Test Facility (ITF) **Primary Coolant Apparatus Test** (PCAT)

RELAP5-3D

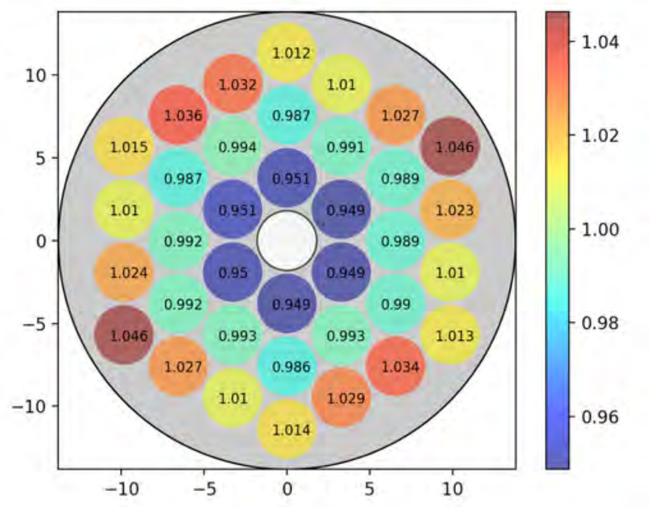


PCAT ITF

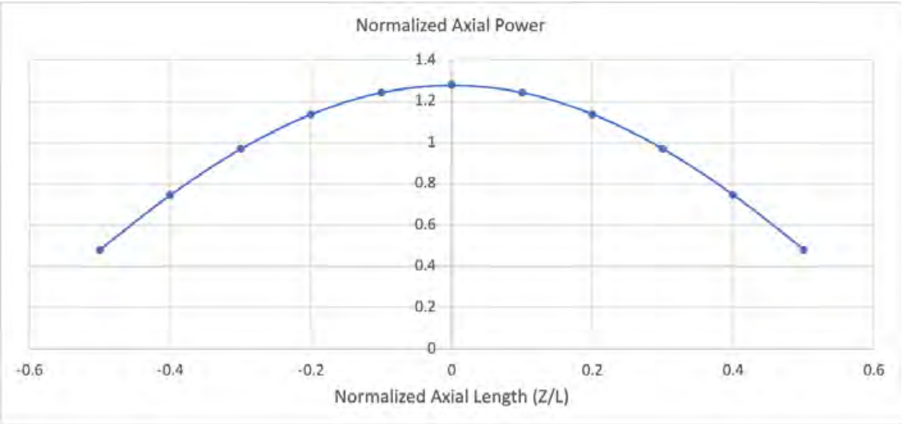
MRP Microreactor Program

Boundary Conditions and Assumptions 1/2

- Core conditions from MCNP code Monte Carlo calculations
    - Core at Beginning of Life (BOL)
    - ANS-05 decay standard
    - Reactivity coefficients vs. temperature
    - Pin power peaking factors
    - Axial power peaking factor



Pin Radial Peaking Factors



Axial Peaking Factor

MRP Microreactor Program

Boundary Conditions and Assumptions 2/2

- Conservative assumptions for Beyond Extremely Unlikely events (BEU)→ higher PCS and fuel temperatures
  - Gamma and neutron heating concentrated in the BeO
  - Other parameters

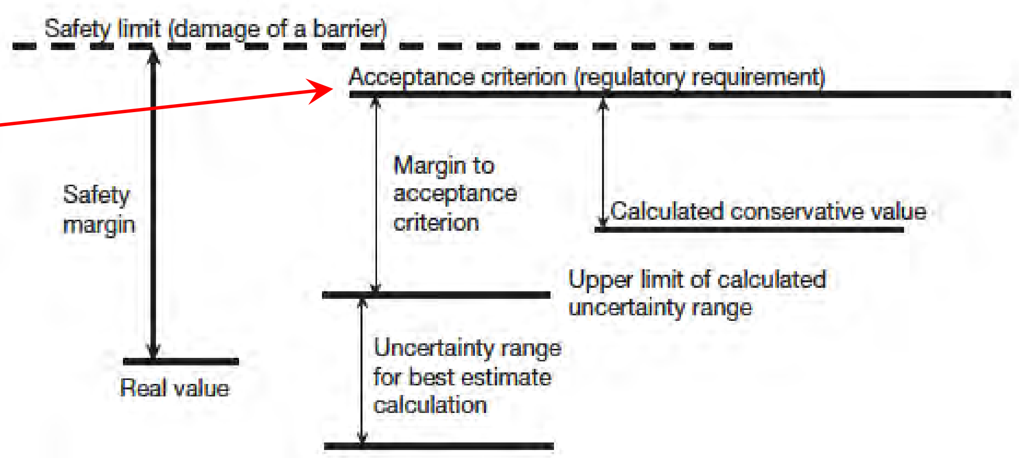
Parameters	Best-Estimate	Conservative
Overpower factor for the hot channel	1.0	1.15
Fuel heat transfer coefficient	Laminar/Turbulent	Laminar
Helium Stirling engine average temperature at HFP, °C	300	325

MRP Microreactor Program

Acceptance Criteria

- For Extremely Unlikely (EU) events, applied to Beyond Extremely Unlikely (BEU) events
  - Fuel: from fuel mechanics analysis
  - Clad: avoid localized boiling (surface temperature < NaK saturation temperature at atmospheric pressure)
  - Bulk coolant: protect PCS integrity
  - Core: qualitative, respected if criterion 2) achieved

Acceptance Criteria	
1	Peak fuel centerline temperature < 925 °C
2	Peak clad internal temperature < 764 °C
4	Bulk coolant < 704 °C
5	Core remains coolable



MRP Microreactor Program

Deterministic Analysis Options

- RELAP5-3D is a Best Estimate code (BE)
- Safety analysis strategy: using combination of options 2+3
- Conservative assumptions for systems availability, e.g.
  - No scram

Option	Computer code	Availability of systems	Initial and boundary conditions
1	Conservative	Conservative assumptions	Conservative input data
2	BE	Conservative assumptions	Conservative input data
3	BE	Conservative assumptions	Realistic input data with uncertainties
4	BE	Probabilistic safety analysis based assumptions	Realistic input data with uncertainties

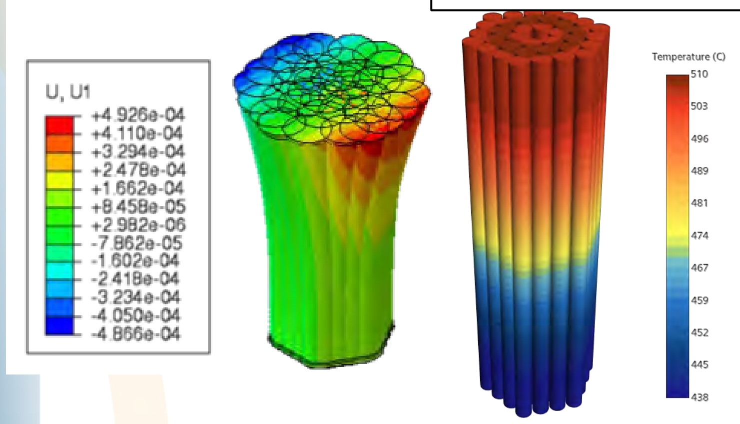
Options for Safety analysis
[from IAEA, SRS No. 52]

MRP Microreactor Program

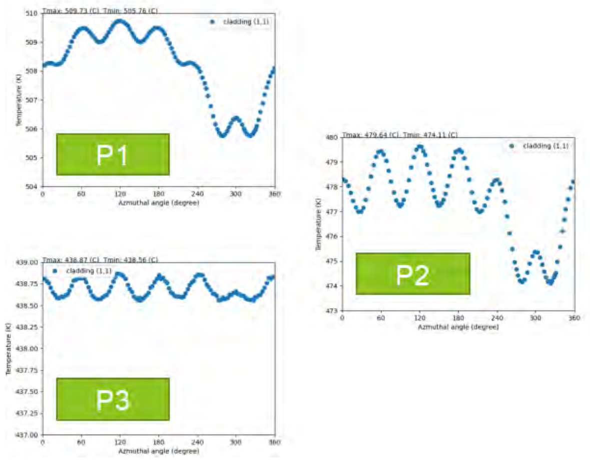
Uncertainties & Hot Channel Factors

- 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, analytical models, qualified references, high fidelity calculations
- HCF to be updated
  - using PCAT data
  - before going critical

Cladding Temperature Distribution



Thermomechanical analysis of fuel elements, S.J. Yoon, ECAR-7210



$$T_M = T_{in} + \sum_{m=1}^{M} F_m \Delta T_{m,nom}$$

Temperatures of Interest

MRP Microreactor Program

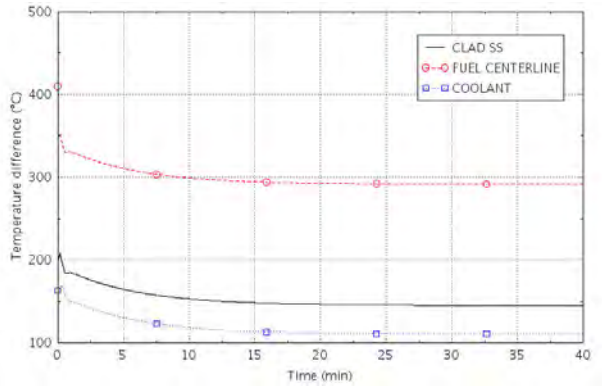
Uncertainties & Hot Channel Factors

- HCF treat in a conservative way (direct + statistical combination) uncertainties on:
  - Coolant mixing
  - Power & temperature measurements
  - Core heat transfer coefficient
  - Fuel geometry tolerances
  - Material physical properties (fuel, coolant, clad, gap)
  - Fuel nuclear properties
- Probabilistic treatment being considered for future uncertainty quantification (UQ) using RELAP5-3D/RAVEN code

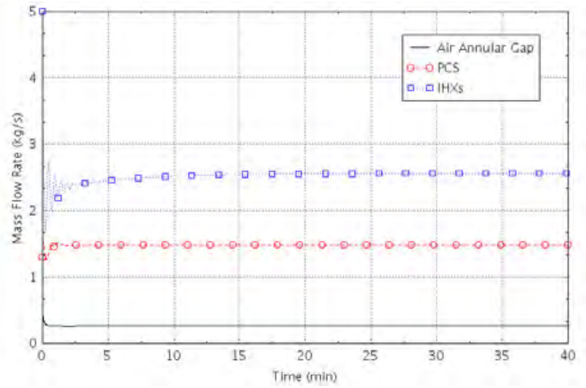
Normal Operation: Steady-State 1/2

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

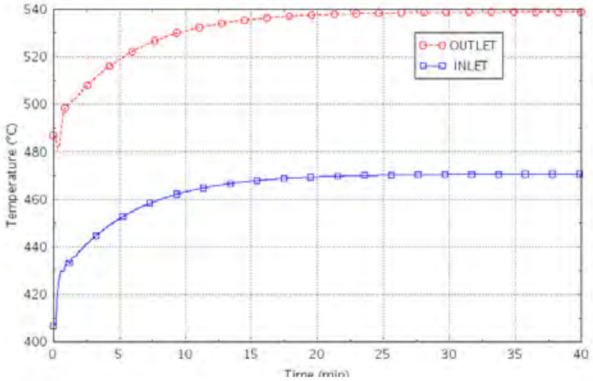
Parameters - Primary & secondary side	Values
NaK inlet core temperature, ºC	471
NaK outlet core temperature, ºC	540
NaK core temperature rise, ºC	69
Total mass flow, kg/s	1.49
EGaInSn minimum temperature, ºC	403
EGaInSn maximum temperature, ºC	425
EGaInSn temperature rise, ºC	22
IHX EGaInSn mass flow, kg/s	2.6



Temperature safety margins



Mass flows

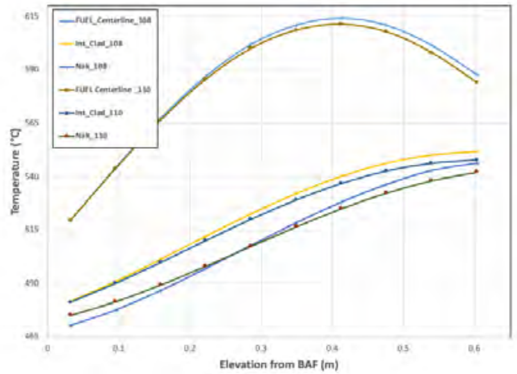


Core inlet/outlet temperatures

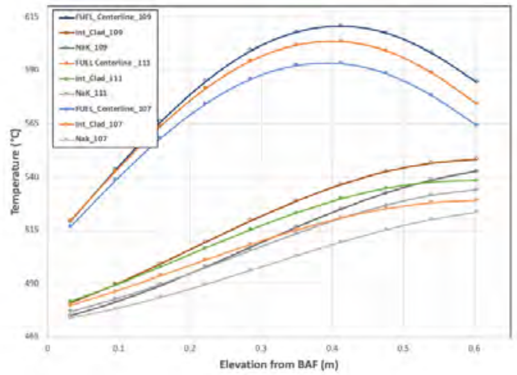
Normal Operation: Steady-State 2/2

- Other relevant parameters

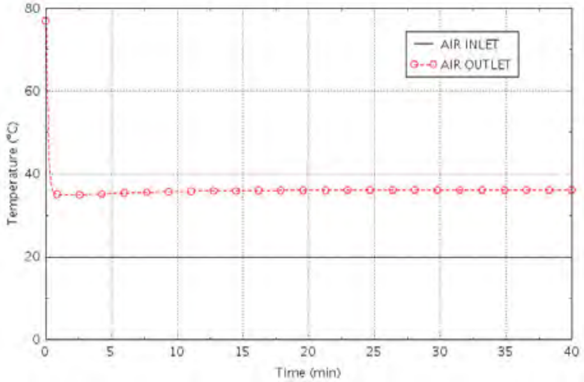
Parameters	Values
PCS pressure drop, Pa	160
BeO side reflector maximum temperature, ºC	519
PCS wall maximum temperature, ºC	540
PCS primary pressure, kPa	307
Guard vessel to air heat losses, kW	4.8
Air riser nominal inlet temperature, ºC	20
Air riser outlet temperature, ºC	36



Fuel and NaK core temperatures 1/2



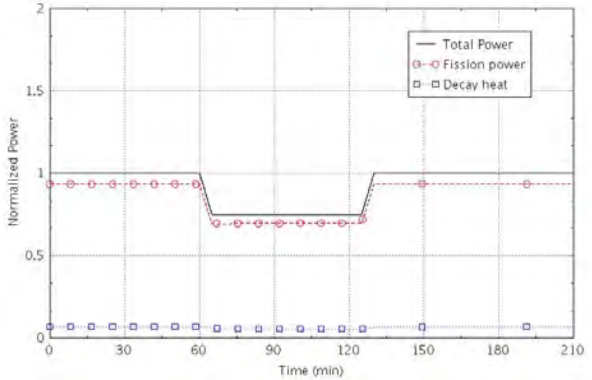
Fuel and NaK core temperatures 2/2



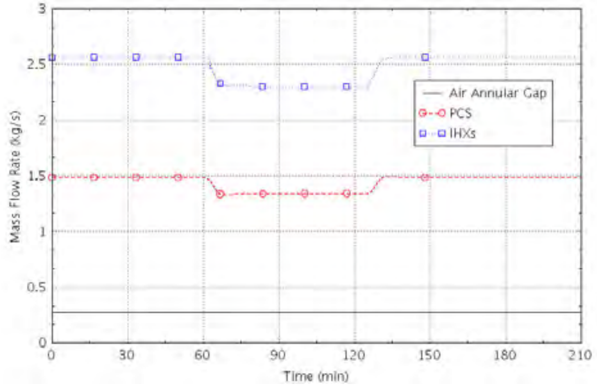
Air riser temperatures

Normal Operation: Load Following

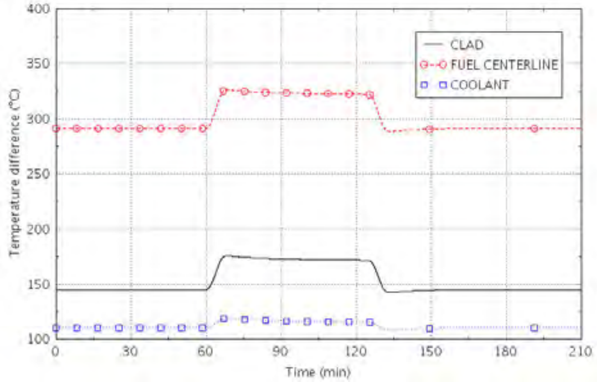
- **Load-follow**:
  - Simulate reaction to imposed power change: 100/75/100 % P_{nom} over ~2.5 hr period
  - All four Stirling engines in operation
  - Control system simulate reactivity insertion by control drums
    - Reactivity insertion vs. position
    - Drum rotation speed
  - Power changes imposed (simulate ±5% P_{nom}/min ramps)
    - PCS max temperature rate: ~0.91 ºC/min (~54.5 ºC/hour)
    - CD reactivity rate: ~+/-1.4 cents/min



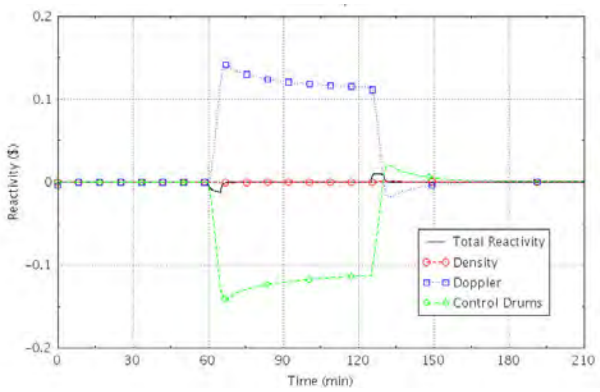
Reactor power



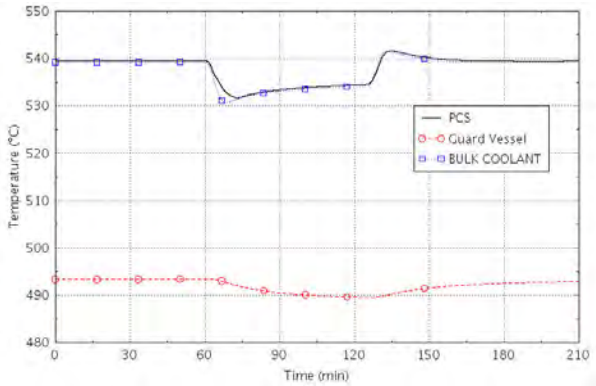
System mass flows



Temperature safety margins



Reactivity

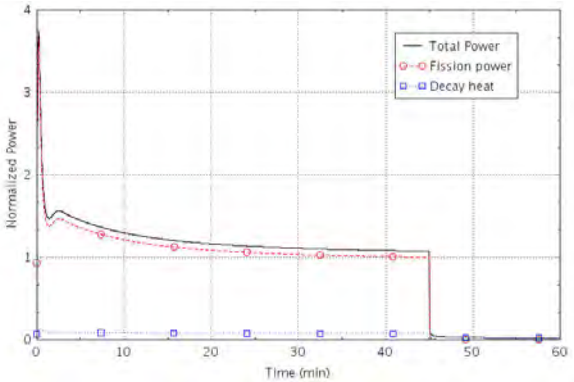


PCS & guard vessel temperatures

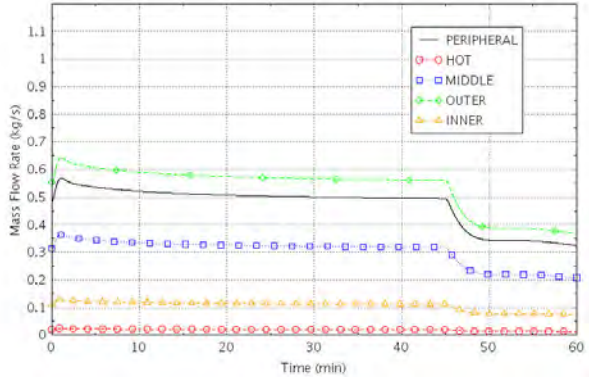
MRP Microreactor Program

Postulated Accident Conditions: UTOP at HFP, w/ Stirling engines

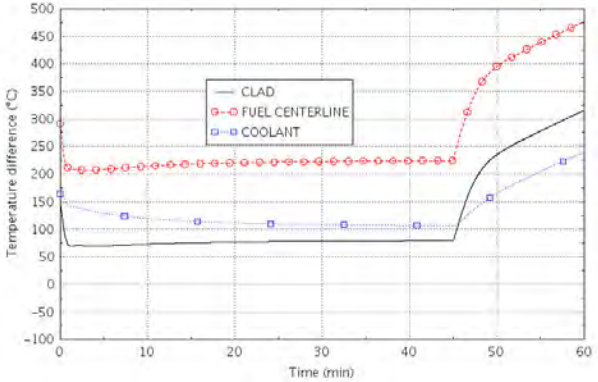
- **Unprotected Transient Overpower**
  - Step reactivity insertion (0.4$) → 1 CD out from critical position to the mechanical stops
  - No SCRAM
  - Stirling engines on → maximize energy release to the fuel
  - Reactor power peaks ~3.74 P_{NOM} (318 kW) at t = 12 s
  - Negative reactivity feedbacks counters the power surge → system back to a steady higher power and higher temperature by t = ~ 20 min
  - **No safety concerns** until scram (not needed)



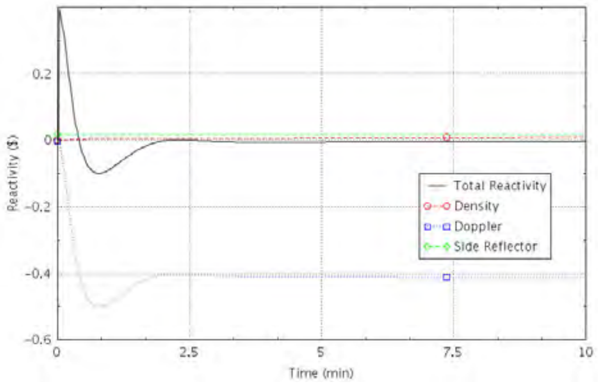
Reactor power



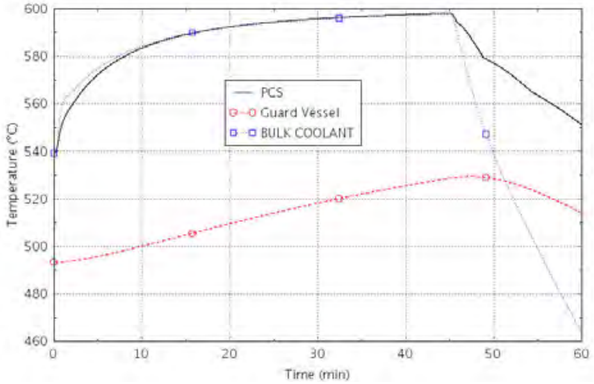
Core mass flows



Temperature safety margins



Reactivity

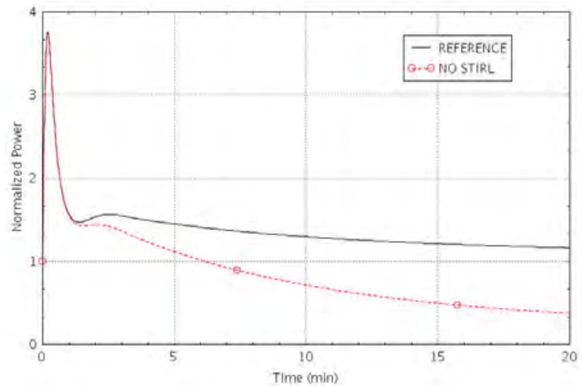


PCS & guard vessel temperatures

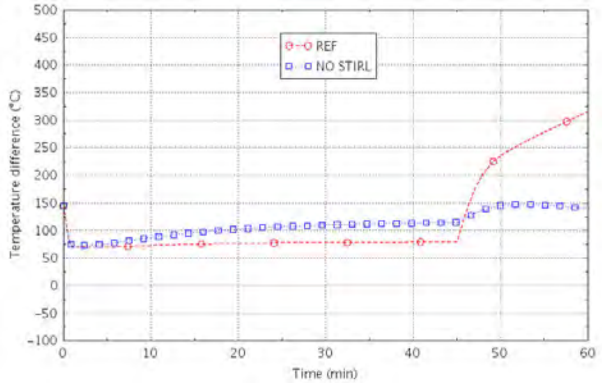
MRP Microreactor Program

Postulated Accident Conditions: UTOP at HFP, w/o Stirling engines

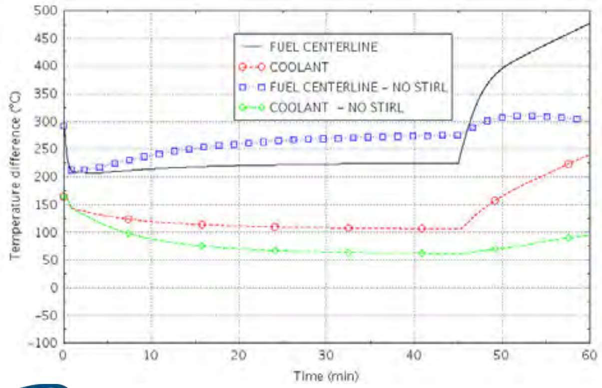
- **Unprotected Transient Overpower**
  - Step reactivity insertion (0.4$) → 1 CD out from critical position to the mechanical stops
  - No SCRAM
  - Stirling engines off → maximize PCS temperature and pressure
  - Used for ASME D-section calculations
  - **No safety concerns** until scram (not needed)



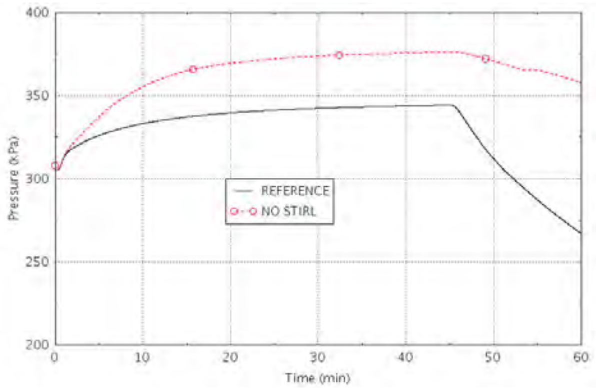
Reactor power



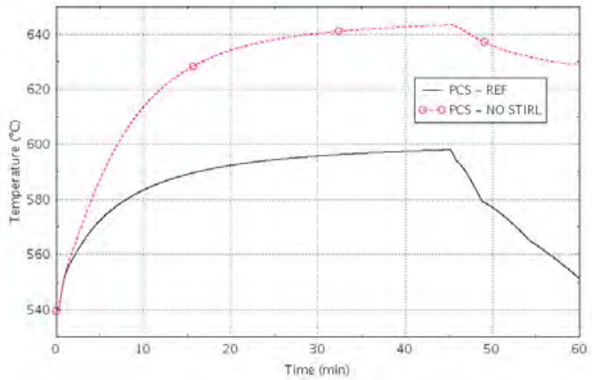
Clad safety margins



Fuel/coolant safety margins



Primary pressure comparison

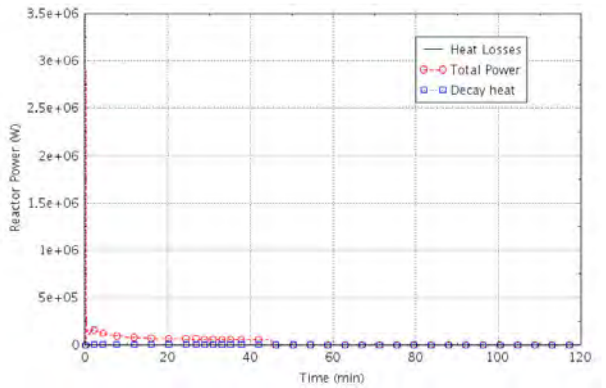


PCS & guard vessel temperatures comparison

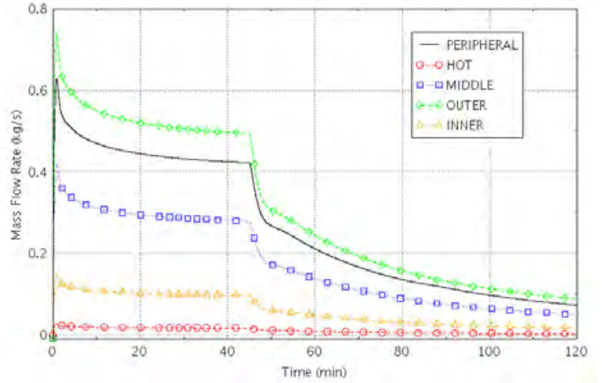
MRP Microreactor Program

Postulated Accident Conditions: UTOP at CZP

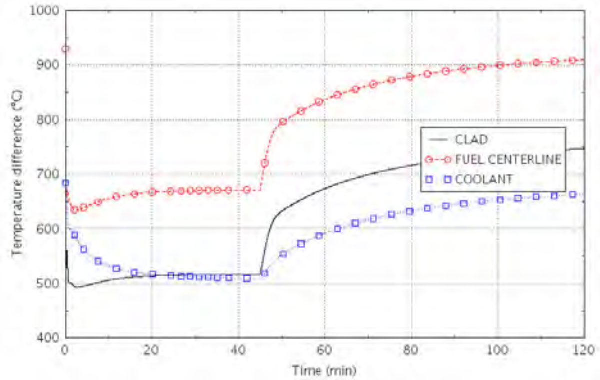
- **Unprotected Transient Overpower at Cold Zero Power (20 ºC)**
  - Step reactivity insertion (1.3$) → 1 CD out from critical position to the mechanical stops
  - No SCRAM
  - Reactor power peaks ~34 P_{NOM} (2.9 MW) at t = 2 s
  - Negative reactivity feedbacks counters the power surge
  - **No safety concerns** during first 5 minutes, reasonably also later
    - Temperatures stay safely low
  - Fast temperature ramp rate (~ 11 ºC/min), but max PCS temperature < 200 ºC



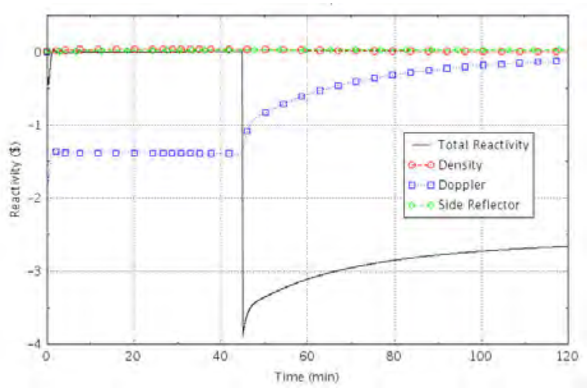
Reactor power



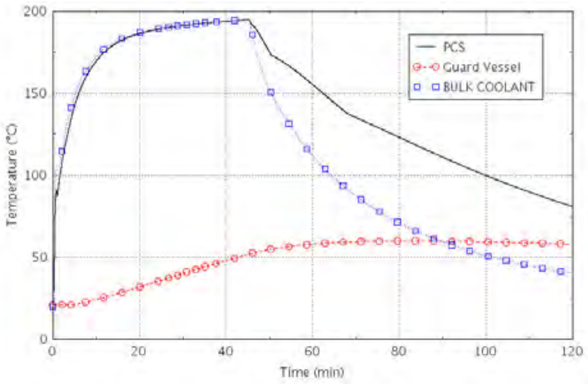
Core mass flows



Temperature safety margins



Reactivity

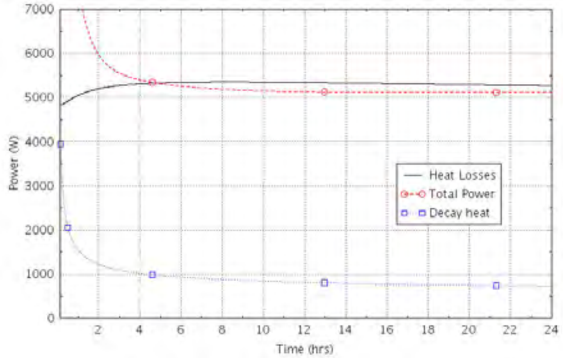


PCS & guard vessel temperatures

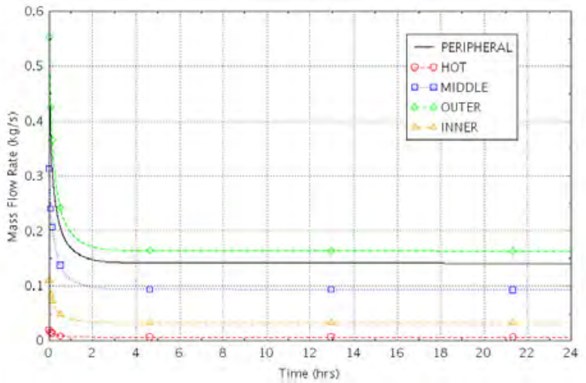
MRP Microreactor Program

Postulated Accident Conditions: ULOHS

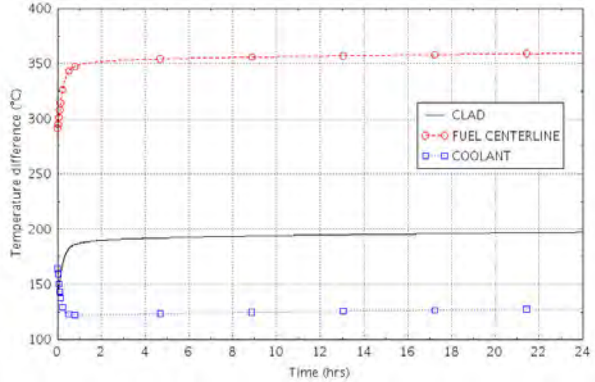
- **Unprotected Loss of Heat Sink**
  - All 4 Stirling engines heat removal lost at t = 1.0 s
  - No SCRAM
  - Reactor cooled only by **heat losses** through guard vessel only (~4.8 kW) → conservative assumption
  - Reactor shutdown by intrinsic negative reactivity
  - Return to power caused by fuel 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)



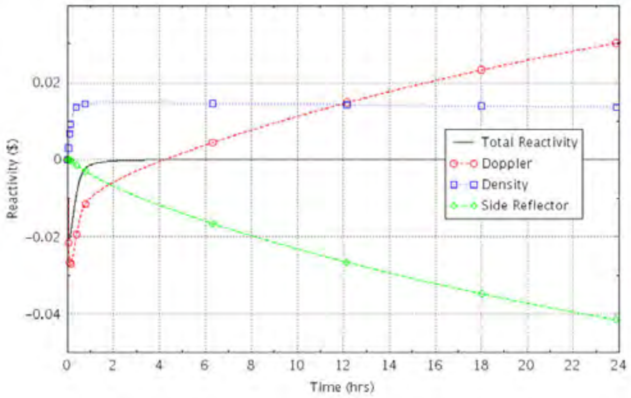
Reactor power & heat losses



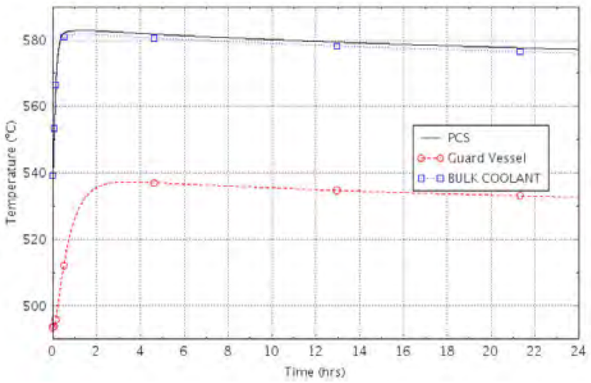
Core mass flowrate



Temperature safety margins



Reactivity

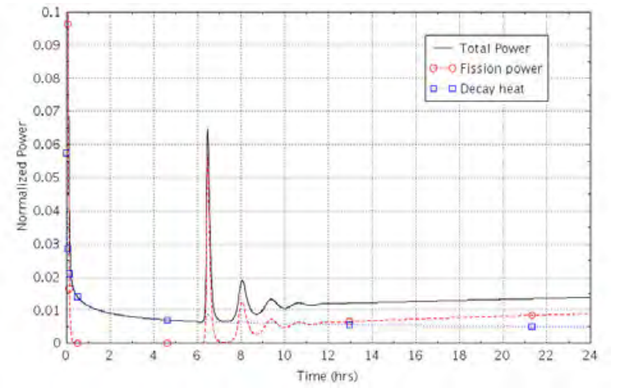


PCS & guard vessel temperatures

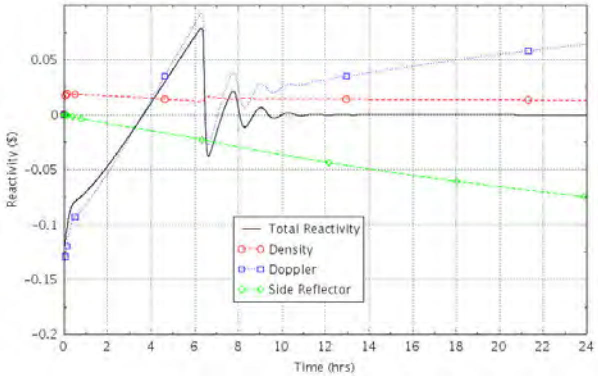
MRP Microreactor Program

Postulated Accident Conditions: ULOF

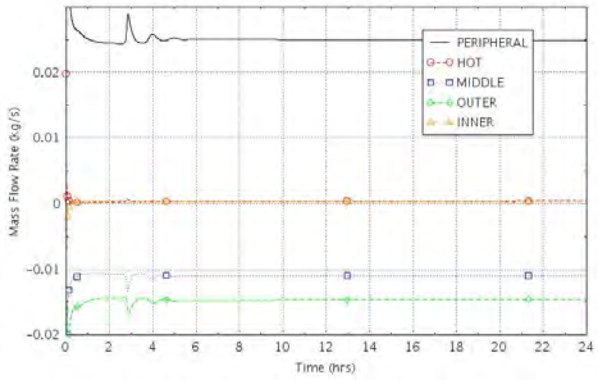
- **Unprotected Loss of Flow**
  - Total blockage of all 4 downcomers at time t = 0.0 s (assume catastrophic damage of all 4 IHXs) →
    - **not credible event**
    - bounding **partial loss of flow** events
  - no SCRAM
  - Loss of secondary side (IHX) heat removal capabilities
  - Reactor cooled **only** by heat losses through guard vessel
  - Reactor power self-reduced
  - Hot spot clad temperature not of safety concern due to the reactor self shut-down features
  - **No safety concerns** : data shown for the first 24 hrs, beyond that reactor power = heat losses (new equilibrium)



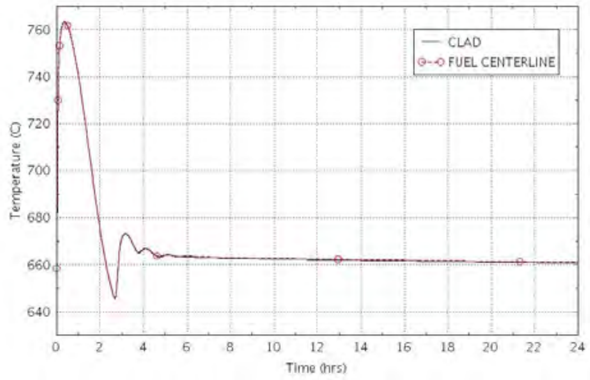
Reactor power & heat losses



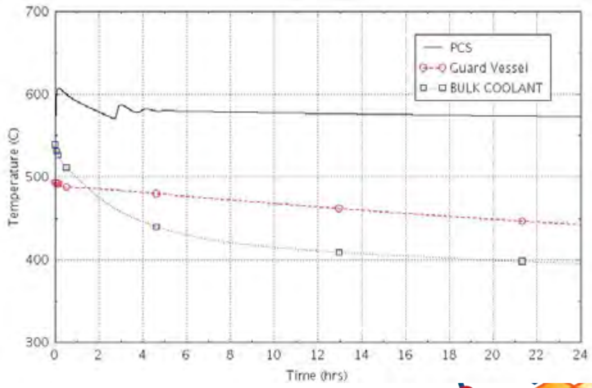
Reactivity



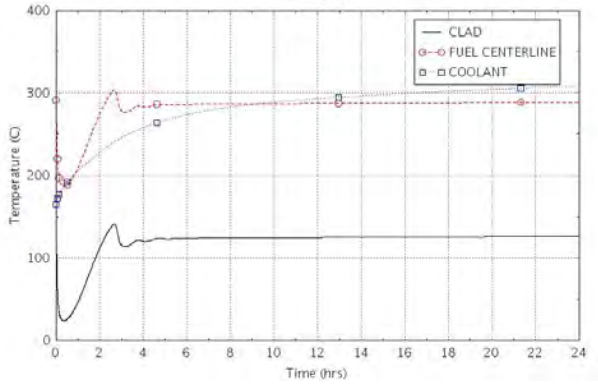
Core mass flow



Hot spot temperature



PCS & guard vessel temperatures

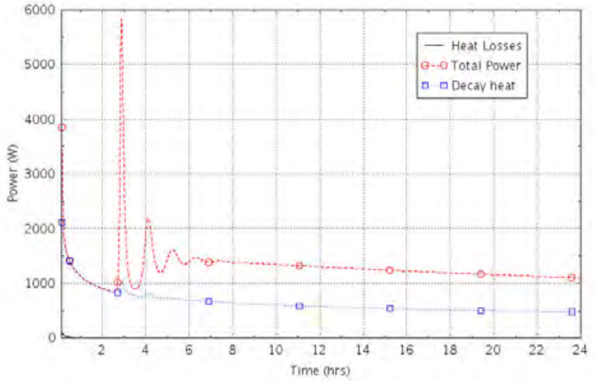


Temperature safety margins

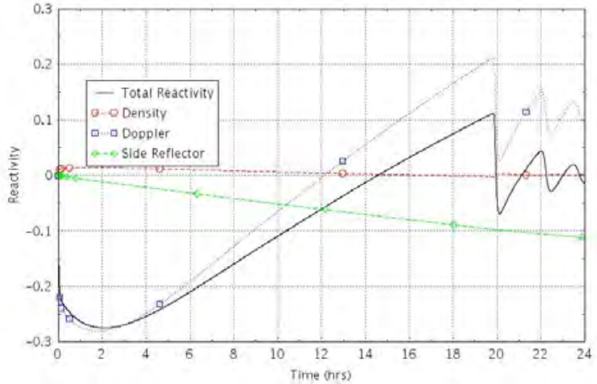
MRP Microreactor Program

Postulated Accident Conditions: ULOF, no DHRAC

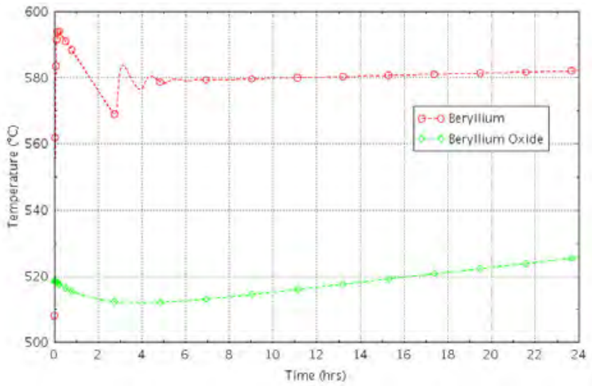
- **Unprotected Loss of Flow and blockage of Decay Heat Removal Air Channel (DHRAC)**
  - Loss of secondary side (IHX) heat removal capabilities
  - Total loss of cooling
  - Reactor power self-reduced
  - Hot spot clad temperature not of safety concern due to the reactor self shut-down features
  - **No safety concerns** for the first 24 hrs



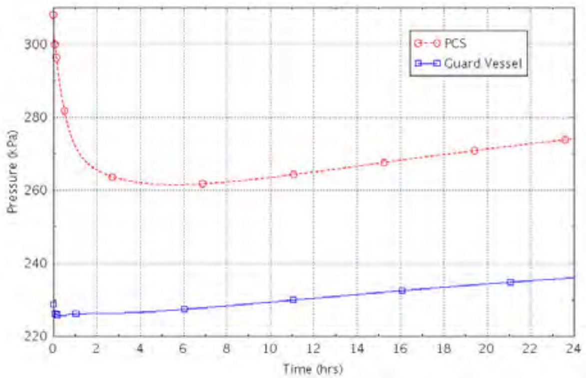
Reactor power & heat losses



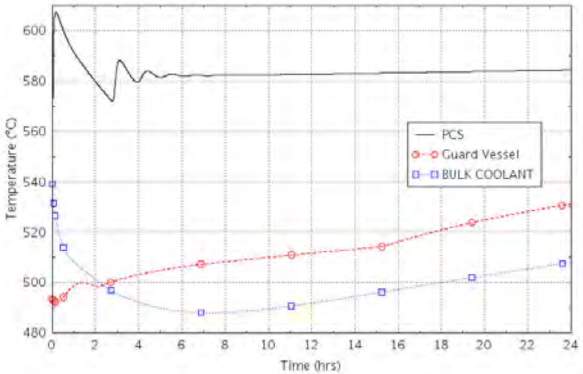
Reactivity



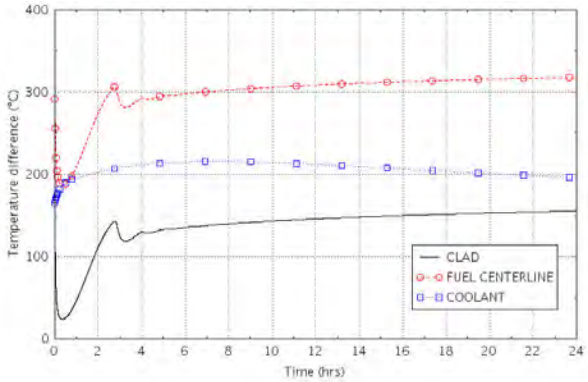
Be and BeO temperatures



System pressures



PCS & guard vessel temperatures



Temperature safety margins

MRP Microreactor Program

Postulated Accident Conditions: ULOCA

- **Unprotected Loss of Coolant Accident**
  - 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

MRP Microreactor Program

Summary

- RELAP5-3D system analysis shows reliable and stable MARVEL performances during operational transients and selected BEU transients
- **Very conservative** accident analysis shows that all **minimum safety margins are > 0**

Transient	Minimum margins (ºC)		
	Clad	Fuel centerline	Bulk Coolant
UTOP- HFP	18	201	100
UTOP - CZP	470	620	505
ULOHS	118	291	125
ULOF	9	190	160

MRP Microreactor Program

MRP Microreactor Program

Questions?