Thermal-Hydraulic Analysis of a Gas-Cooled Test Reactor

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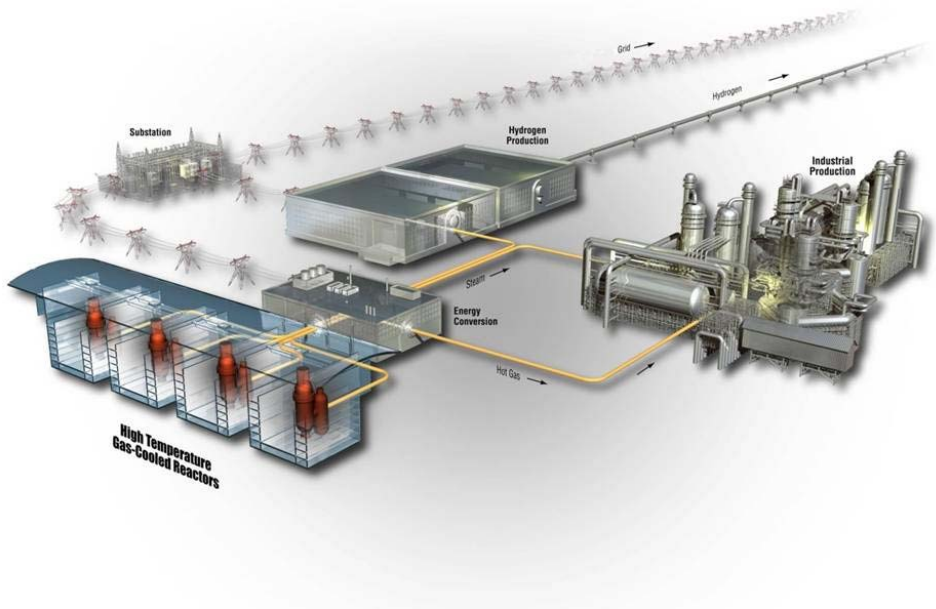


Overview

- *Point design objectives*
- *Reactor description*
- *Thermal-hydraulic assessment*

Missions

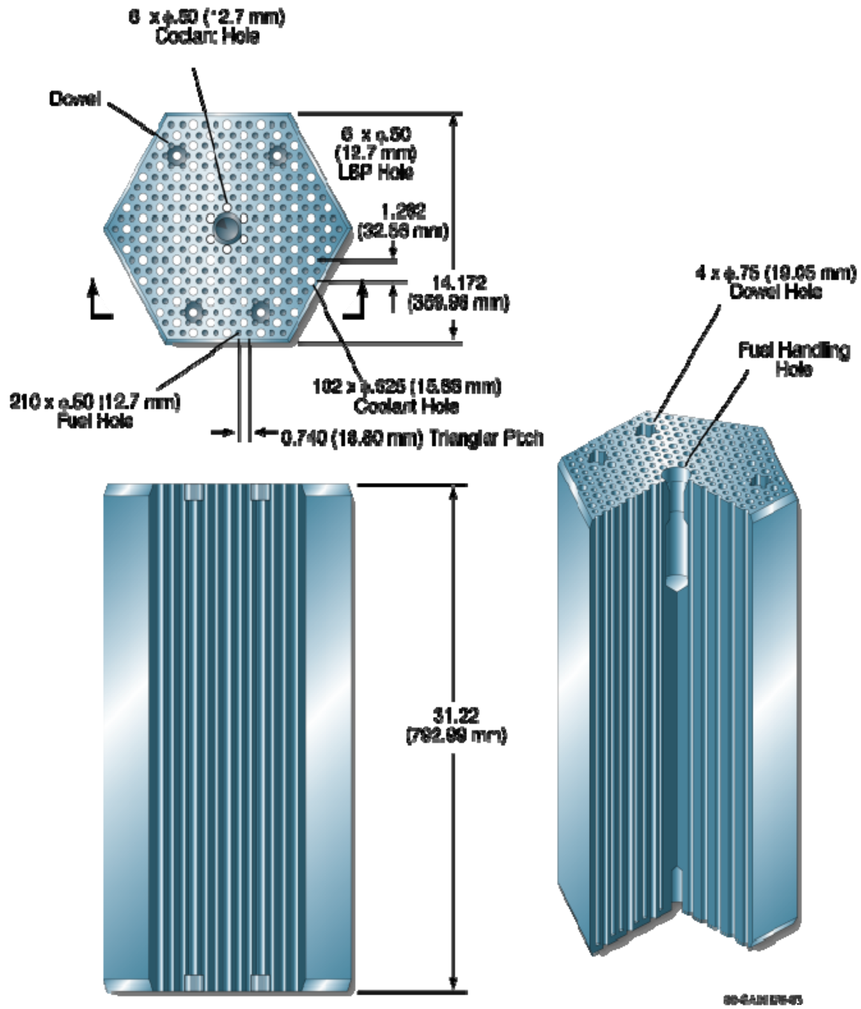
- Primary Mission: Irradiation of gas reactor technology test articles
  - Fuel samples, pins, assemblies
  - Instrumentation
  - Cladding, structural, control rod materials
  - Corrosion and compatibility behavior of structural materials in other fluids
    - Liquid sodium (Na)
    - Liquid salt (FLiBe)
    - High-pressure light water (H_2O)
    - High-pressure, high-temperature gases

- Secondary Missions:
  - Generation of electricity
    - Steam cycle
    - Option to increase outlet gas temperature to 750°C
    - Relatively long, stable power cycles
  - Production of commercial and medical isotopes
  - Production of high-temperature heat via secondary heat transfer loops
    - Hydrogen production
    - Chemical process testing
    - Heat exchanger testing

Point Design Approach

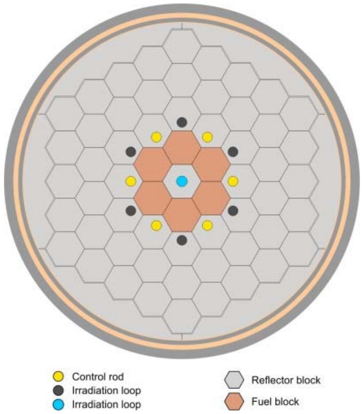
- Primary Goals
  - Maximize thermal and fast flux
  - Fuel cycle length ≥90 days
- Constraints
  - Peak fuel steady-state temperature (≤1250°C)
  - Use existing hexagonal block design
  - Accommodate 4-meter long test article
  - Prefer not to melt irradiation facilities
- Variables
  - Total core power (50-400 MW)
  - Number of fuel columns (6, 7, 12, 18)
  - Number of fuel blocks per column (4, 5, 6, 7, 8)
  - Arrangement of fuel columns in core

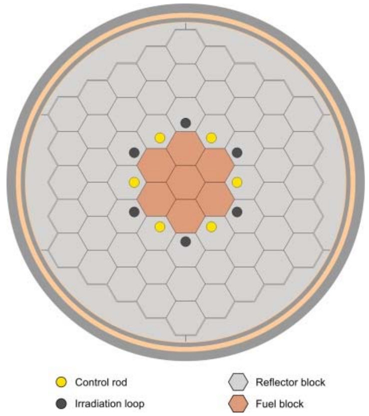
Fuel Block Description

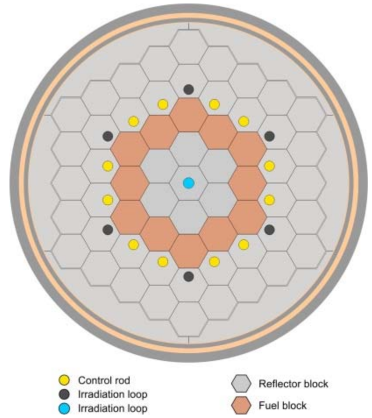


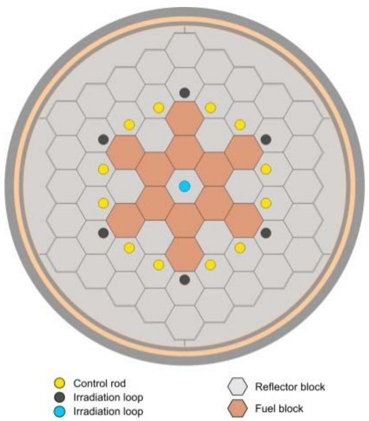
Fort Saint Vrain (FSV) fuel block.

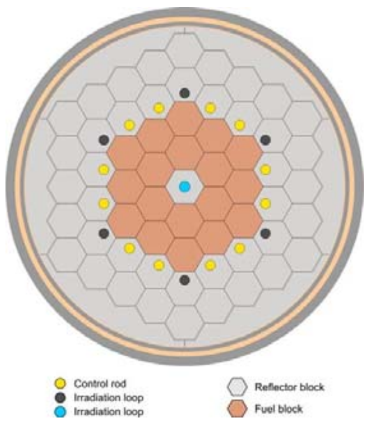
Core Arrangements Considered







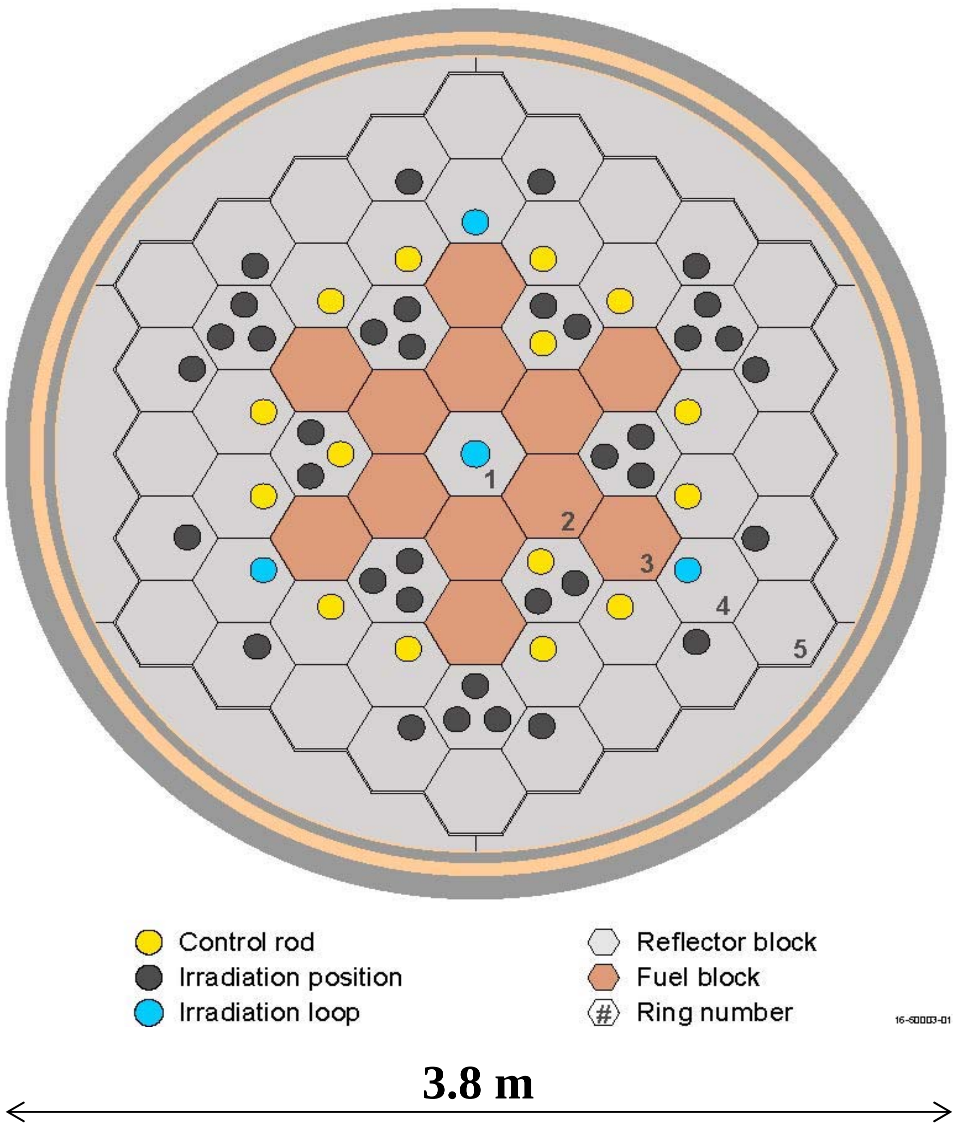


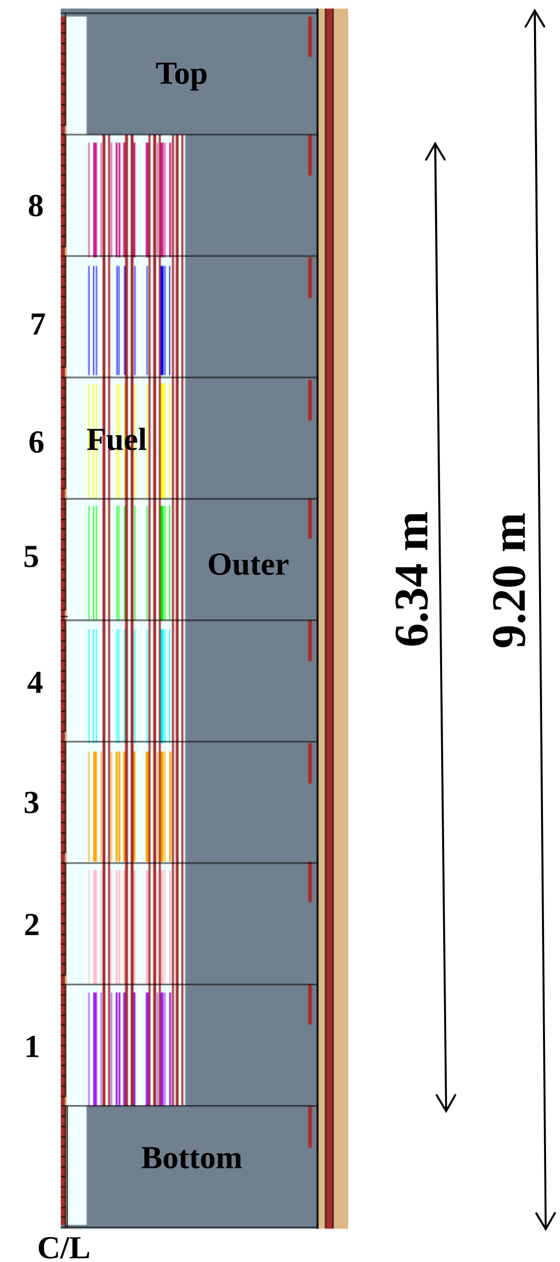


Test Reactor Point Design Features

- High-temperature gas-cooled reactor technology
- 200 MW
- High-pressure helium gas coolant (7 MPa, 650°C outlet)
- Prismatic graphite blocks (fuel + reflector)
- 5 rings of hexagonal blocks + permanent side reflector (PSR)
- 12 fuel columns
- 8 fuel blocks per column
- Core height = 9.2 m
- Core diameter = 3.4 m
- Large number of irradiation facilities (large volumes and lengths)

Core Description





HTGR Test Reactor Facilities

Hex Ring No.	No. of Loops	No. of Tubes	Test Diameter (cm)	Test Length (m)	Test Volume per facility (liters)	Total Test Volume (liters)
1	1	0	5.4	6.34	14	14
2	0	0	----	----	----	----
3	0	15	8.0	6.34	30	450
4	3	9	5.4/8.0	6.34	14/30	42/270
5	0	12	8.0	6.34	30	360
Total	4	36				1136

Thermal-Hydraulic Assessment Overview

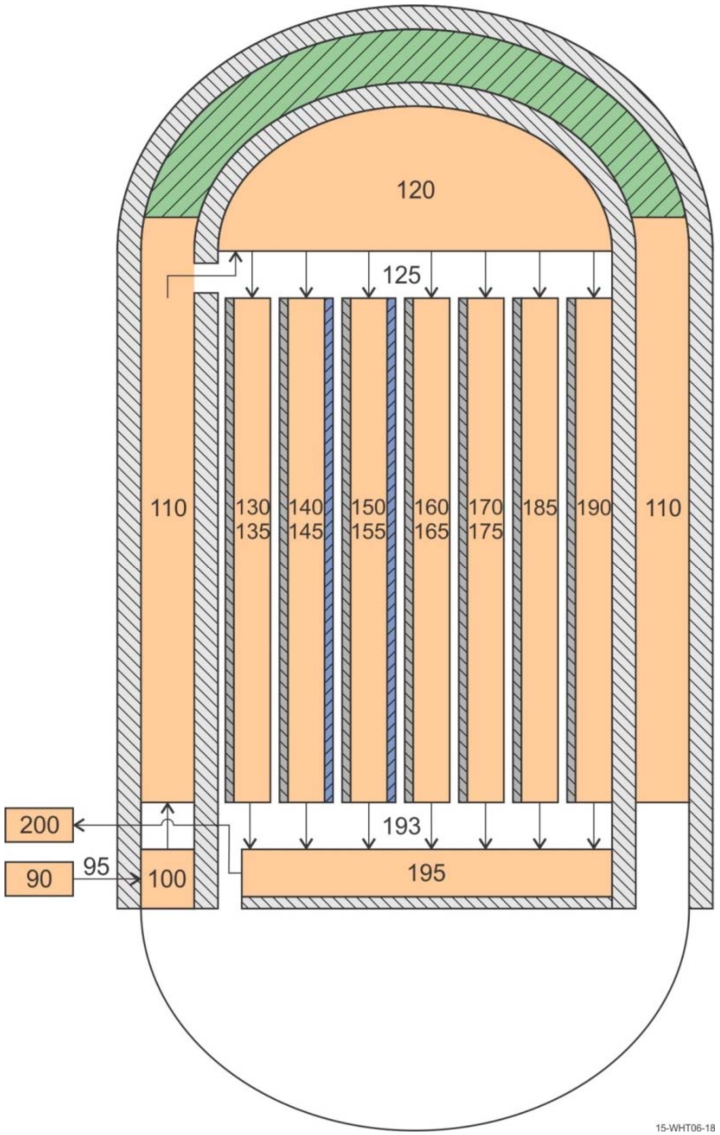
- RELAP5-3D model description
- Steady state conditions
- Safety features
- Accident simulation results

RELAP5-3D Input Model

- Reactor vessel
- Water-cooled, natural convection reactor cavity cooling system (RCCS) for decay heat removal during accidents
- Fixed coolant inlet temperatures
- Primary flow rate adjusted to get desired coolant outlet temperature
- Irradiation loop coolant flow through center facility
- Helium coolant flow (not primary coolant) in gap between irradiation loop and pressure boundary tube

Reactor Vessel Nodalization

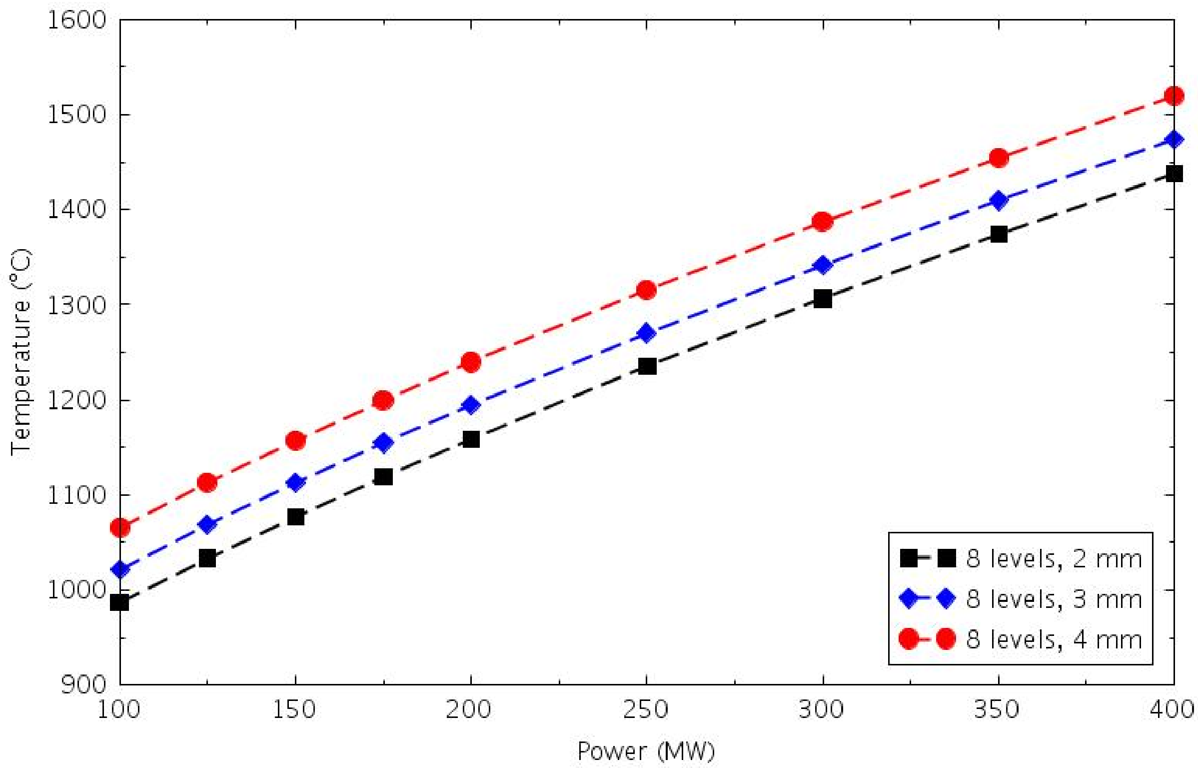
- Each ring modeled
- Fuel and reflector blocks in Ring 3 modeled separately
- Flow paths
  - Through coolant holes
  - Between blocks
  - Around control rods
  - Around irradiation positions
  - Crossflow between rings
- Axial and radial conduction
- Radial radiation



Steady state conditions

Parameter	2-mm gaps	3-mm gaps	4-mm gaps
Coolant inlet temperature (°C)	325	325	325
Coolant outlet temperature (°C)	650	650	650
Coolant flow rate (kg/s)	117.2	117.3	117.3
Effective core bypass at core outlet (%)	27	31	35
Peak fuel temperature (°C)	1159	1194	1240
Center reflector peak temperature (°C)	648	645	651
Ring 3 reflector peak temperature (°C)	585	567	558
Ring 4 reflector inner peak temperature (°C)	562	550	548
Ring 4 reflector outer peak temperature (°C)	392	383	380
Ring 5 reflector peak temperature (°C)	357	348	343
PSR peak temperature (°C)	336	332	331
Core barrel peak temperature (°C)	329	328	328
Reactor vessel peak temperature (°C)	317	317	317
RCCS heat removal (MW)	0.44	0.44	0.44

Steady state peak fuel temperatures



Safety features

- Passively safe design
- Tristructural isotropic (TRISO) fuel
- Inert coolant
- Large thermal capacity in core and reflectors
- Long, slow transients
- No energized systems required for decay heat removal
  - Conduction
  - Radiation
  - Natural convection of water and gas
- Fuel temperature guidelines
  - 1250°C maximum during steady state operation
  - Within Advanced Gas Reactor time-at-temperature envelope during accidents and transients

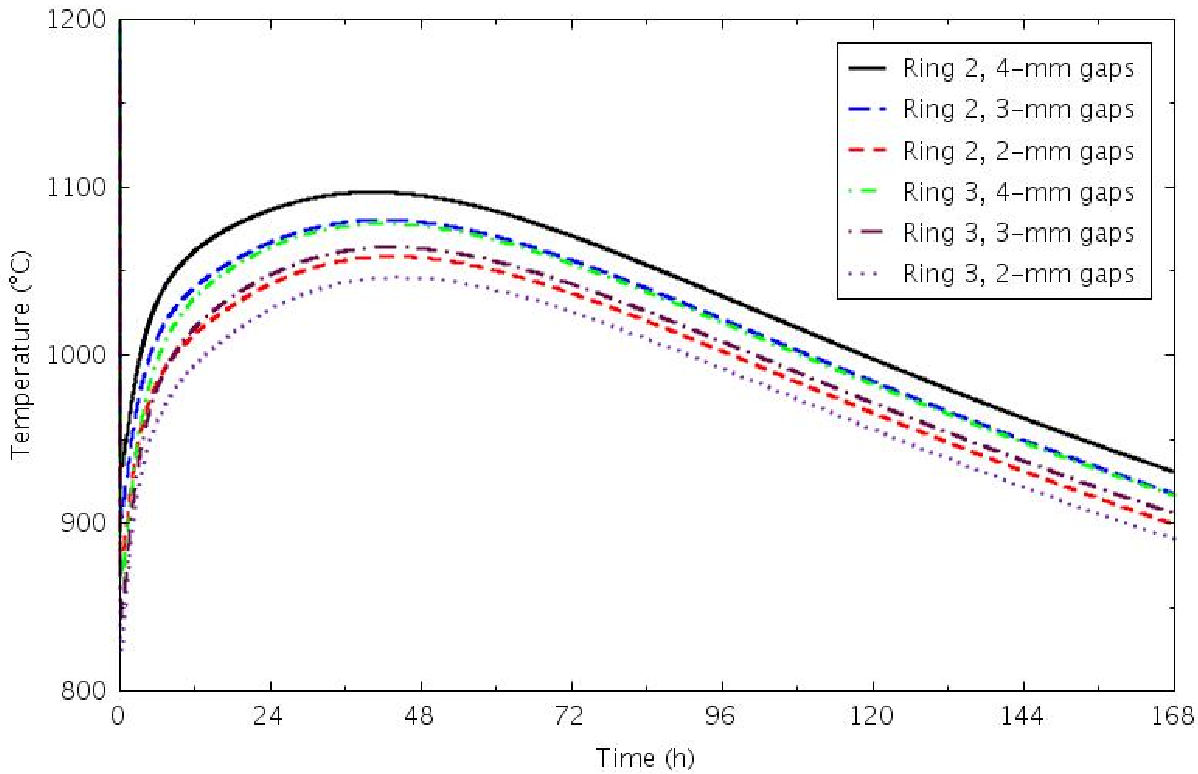
Accident analyses

- Loss-of-forced convection cooling is primary event
  - Depressurized conduction cooldown (DCC)
    - PCS pressure boundary breached
    - Expected to be limiting case for fuel temperatures
  - Pressurized conduction cooldown (PCC)
    - PCS pressure boundary intact
- Boundary conditions
  - Reactor scram at transient initiation
  - Primary coolant and irradiation loop flow coastdown
    - 1 s for DCC
    - 5 s for PCC
  - 1-s depressurization imposed for DCC

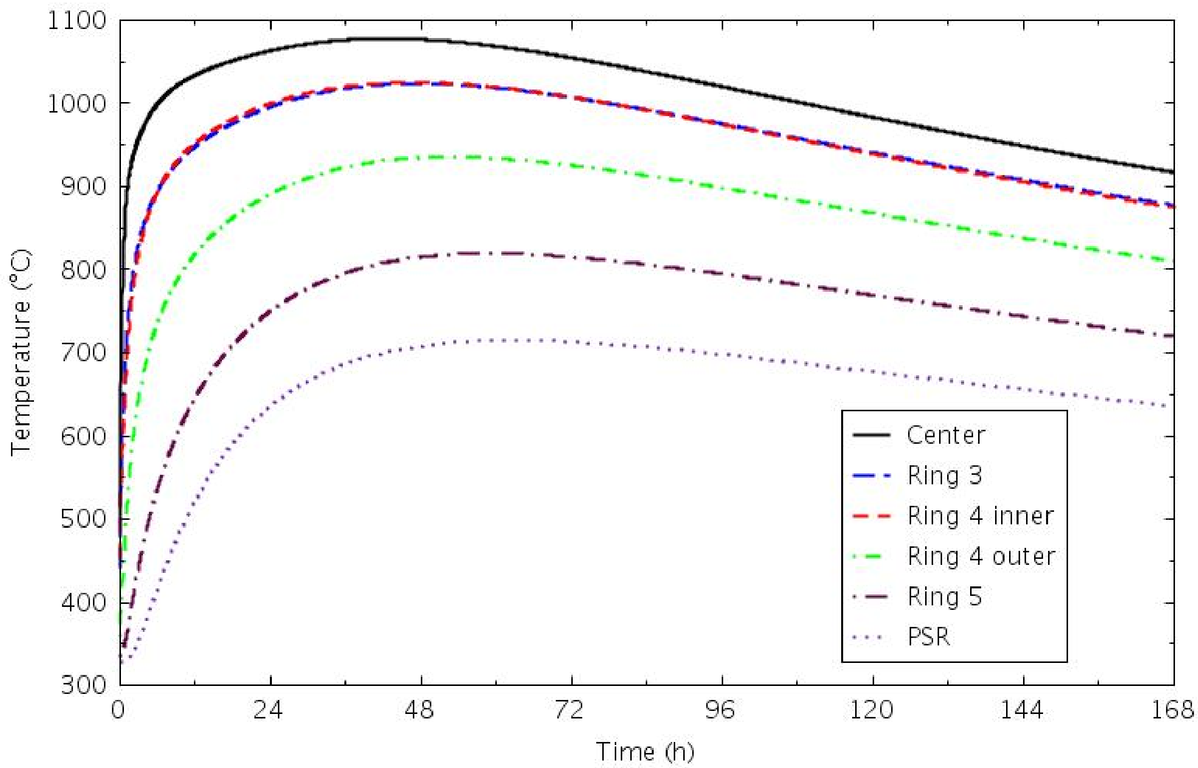
Sensitivity studies

- Axial power shape (cosine vs. flat)
- Scram delay (1 s or 10 d)
- Increased operating temperatures (350/750°C)
- Maintain cooling flow to center irradiation loop
- Blocking some core bypass flow paths
- Temperature of helium entering through break

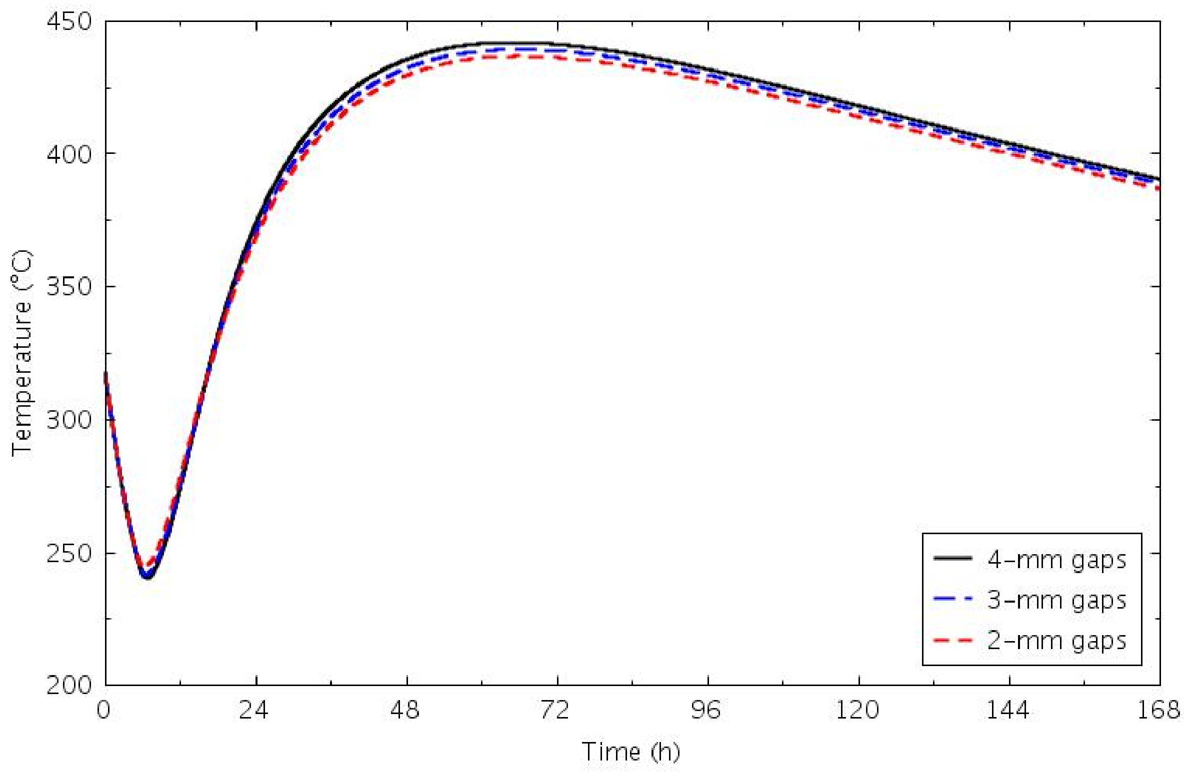
DCC peak fuel temperatures



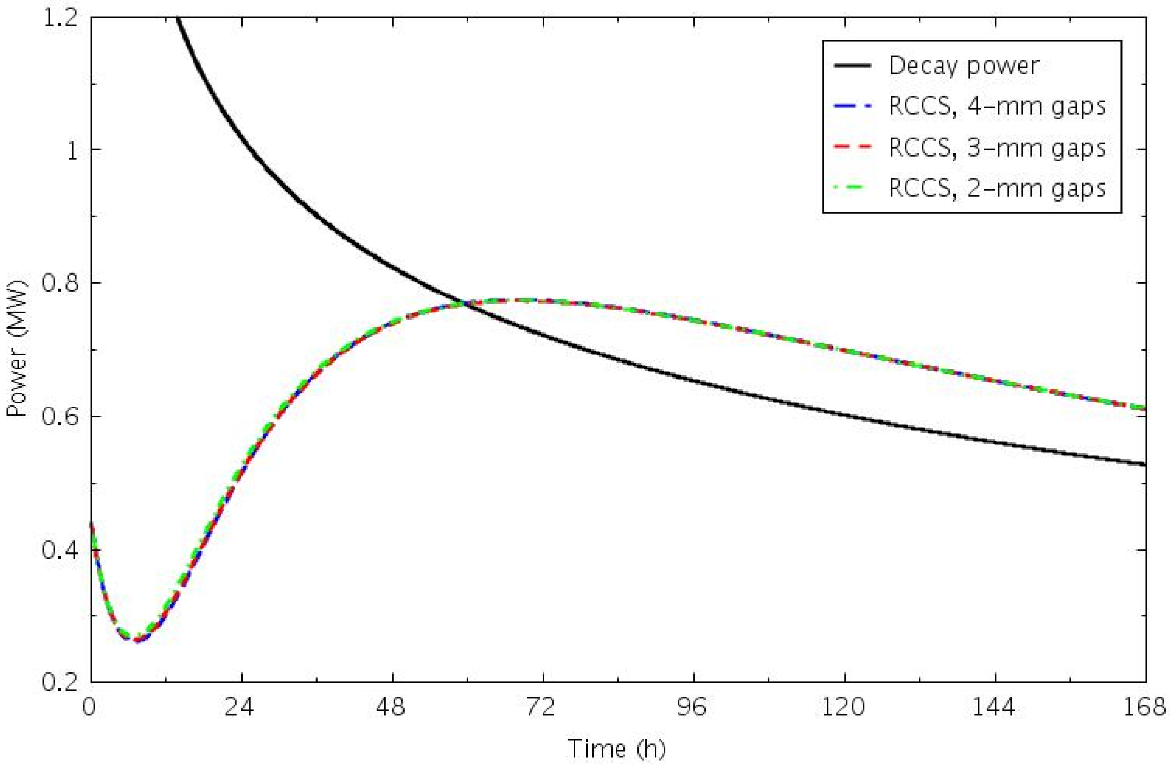
DCC reflector axial average temperatures (4-mm gaps)



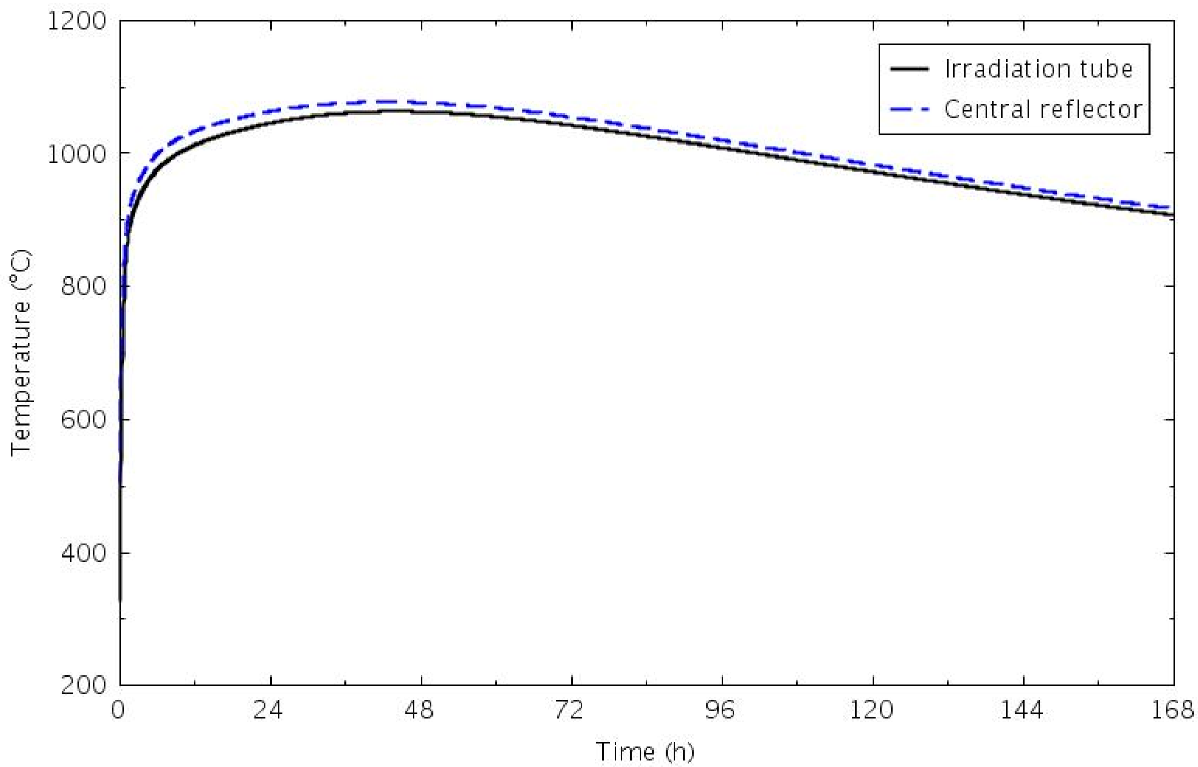
DCC reactor vessel peak temperature



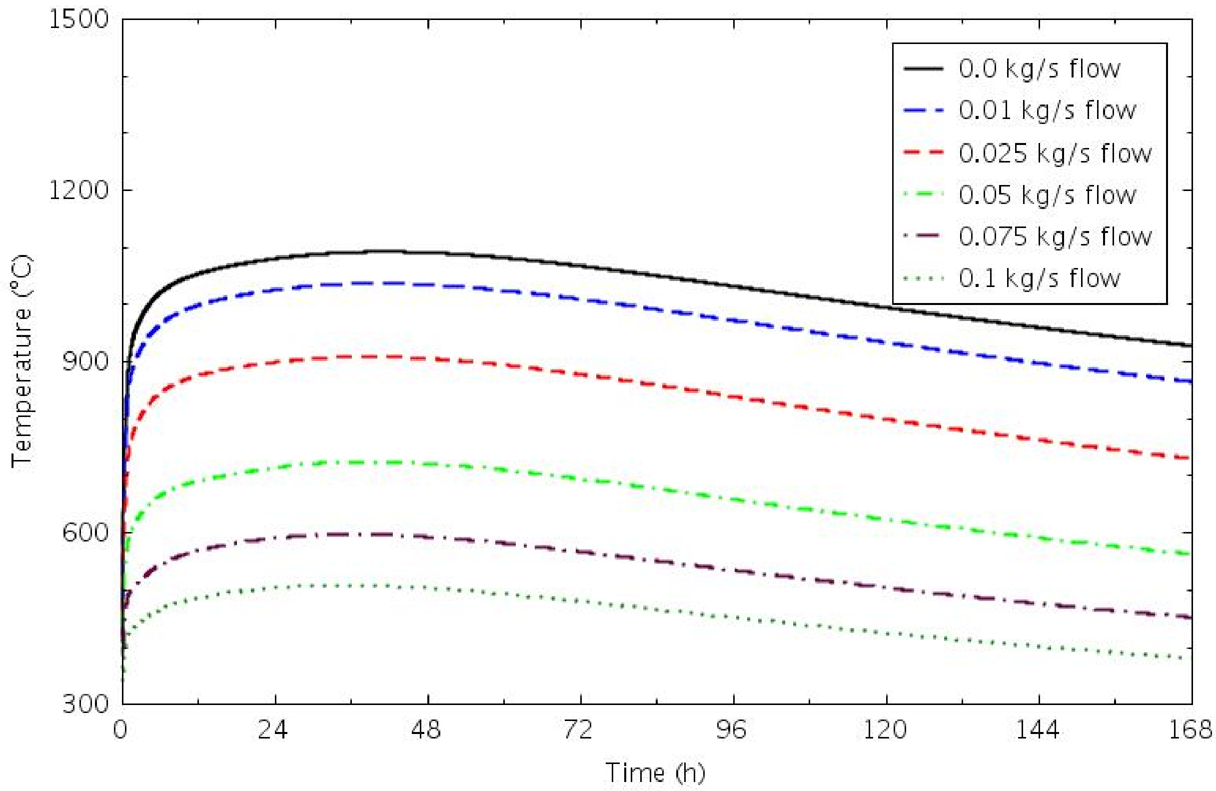
DCC decay heat and RCCS heat removal



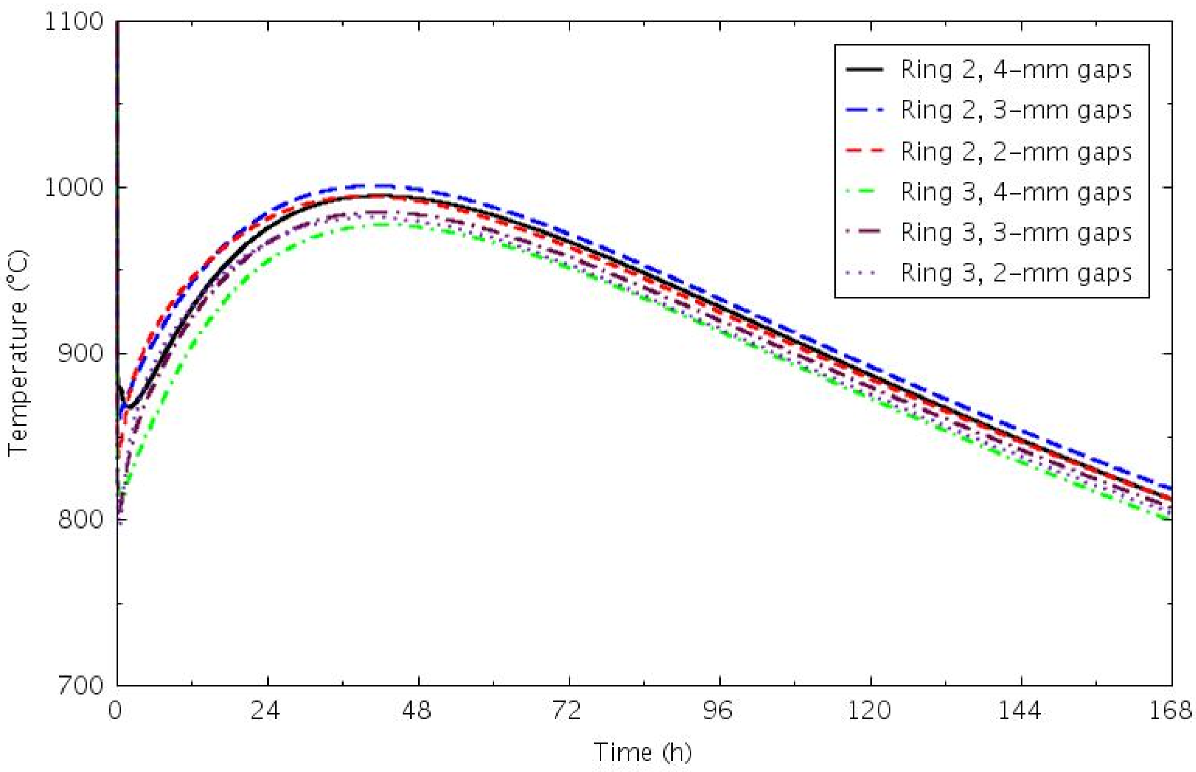
DCC central reflector and irradiation tube axial average temperatures



DCC central reflector and irradiation tube axial average temperatures with helium cooling flow



PCC peak fuel temperatures



HTGR Test Reactor Accident Analysis Summary

- Peak fuel temperatures during the conduction cooldown transients were 150-250°C below steady state temperatures.
- Irradiation loop tube temperatures will likely be above code design limits, though well below the melting point, unless sufficient internal cooling can be maintained.
- Irradiation tubes for drop-in experiments (cooled by primary coolant flow) can be made of high melting temperature materials (titanium, molybdenum) as they will not be pressure boundaries.