MELCOR Development for HTGR Applications

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Background

- Energy Policy Act 2005
  - Demonstration HTGR to be built
  - NRC to license plant
- DOE/INL in design assessment stages
  - Experiments and models
- NRC/SNL preparing tools for safety and margins evaluation
  - Containment/confinement assessment
  - Fuel and FP release under accident conditions
  - MELCOR a principal tool

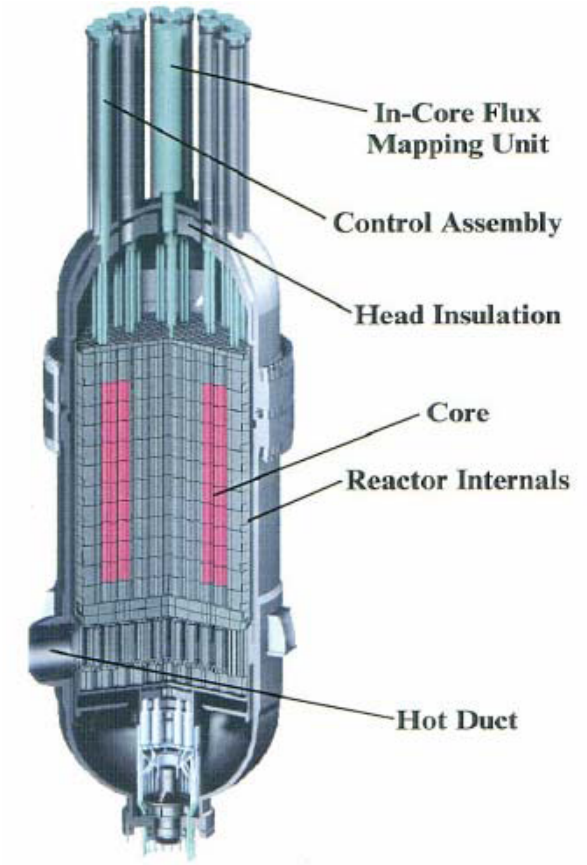
Accident Analysis Categories and Phenomena

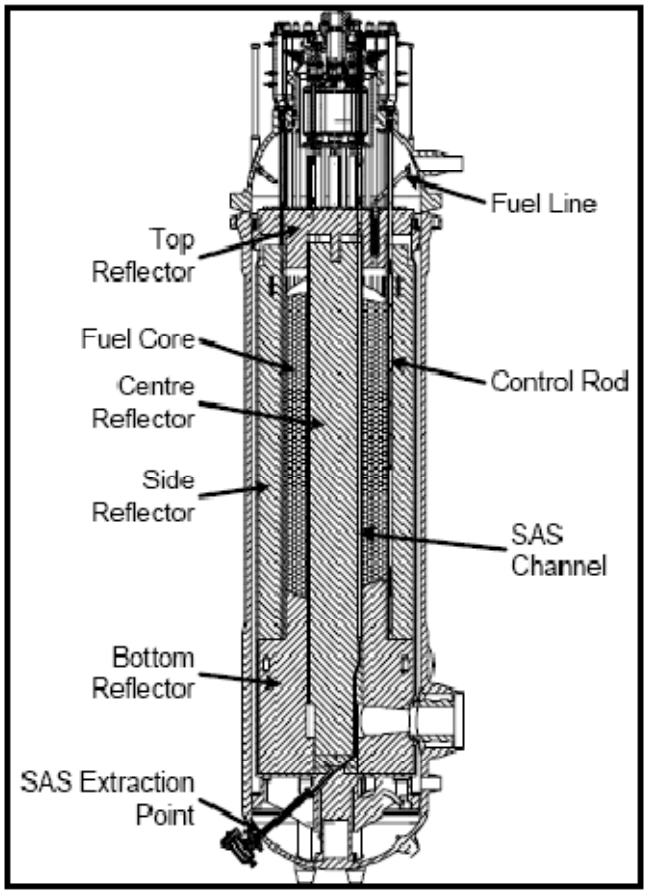
- HTGR PIRT performed by NRC
  - Identified basic accidents and modeling/data needs
- Loss of coolant flow at high pressure
- Depressurized loss of coolant/flow
- Air ingression and oxidation
- ATWS and reactivity insertions
- Cavity cooling system (ultimate heat rejection)

MELCOR HTGR Development

- To prepare MELCOR for HTGR applications, we are performing some upgrades
  - Review gas properties for MELCOR
  - Review INL modifications to MELCOR 1.8.2
  - Expand oxidation models in MELCOR to include graphite
  - Update COR package with new reactor models for easier HTGR modeling
    - Thermal hydraulics, heat transfer (conduction/radiation)
  - Develop models for Cavity Cooling System
  - Implement fission product release and transport models
    - Fuel releases
    - Dust deposition and resuspension

PBR and PMR Core Designs





HTGR PMR Core

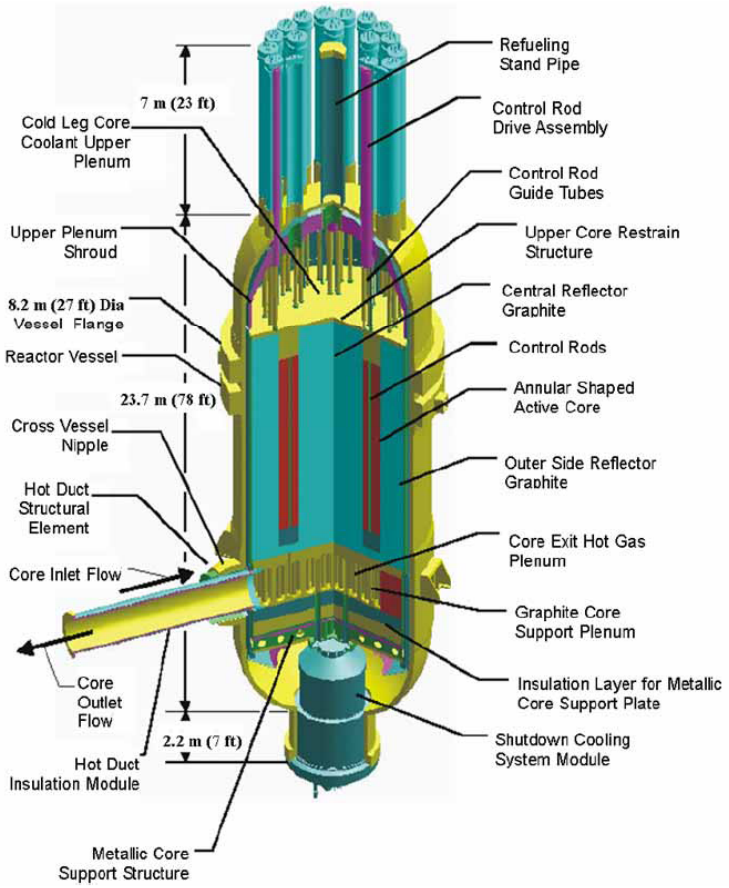
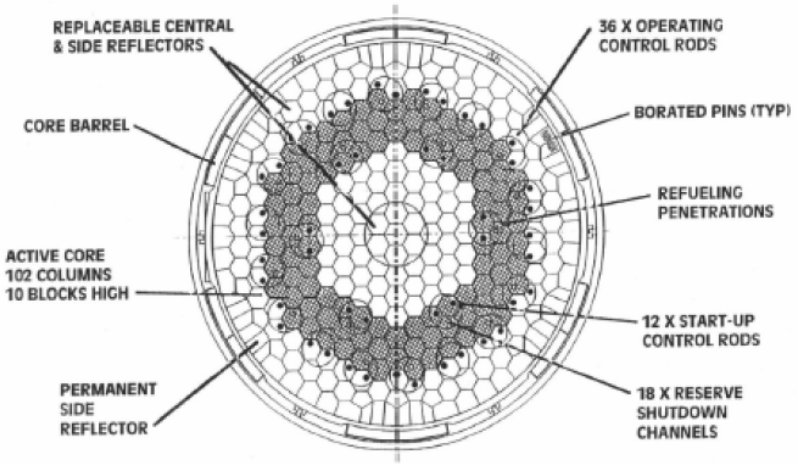
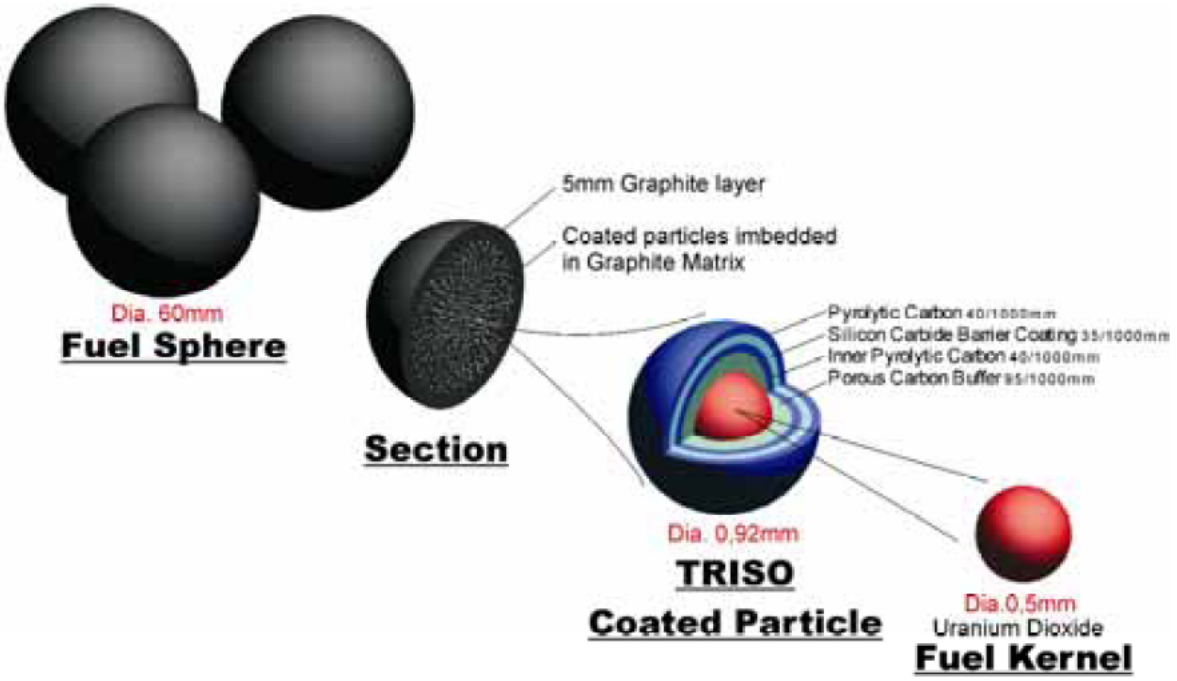


Figure 1: VHTR Nuclear Heat Source based on prior U.S. DOE Prismatic Modular HTGRs



Source: "ANTARES: The HTR/VHTR Project at Framatome ANP", J. Gauthier et al., 2nd Int'l Topical Mtg on High Temperature Reactor Technology, Beijing, China, 2004.

HTGR Fuel and TRISO Particles



Source: "PBMR Project Status and the Way Ahead", D. Matzner, 2nd Int'l Topical Mtg on High Temperature Reactor Technology, Beijing, China, 2004.

PBR (Pebble Bed) Core Geometry

- Graphite “pebbles” containing TRISO microspheres
- Helium cooled
- Annular fuel region
  - Inside/outside radial reflectors
  - Top/bottom axial reflectors

PMR (Prismatic) Core Geometry

- Graphite cylindrical fuel "compacts" containing TRISO microspheres
- Fuel pins inserted in hexagonal graphite blocks
- Helium cooled
- Annular fuel region
  - Inside/outside radial reflectors
  - Top/bottom axial reflectors

New COR Models

- **Previous MELCOR modeling by Texas A&M (TAMU) adapted existing COR components**
  - **Used debris component as PBR fuel pebbles**
    - **Means decay heat is uniform, not scaled by reactor power shape**
    - **Debris component unavailable for real debris**
  - **Zr and Inconel redefined as Graphite/UO_2 mixture and pure Graphite, respectively**

New COR Models contd

- New reactor models (like present PWR, BWR)
  - PMR (prismatic)
  - PBR (pebble bed)
  - Are more transparent to user
  - Allow use of MELCOR fuel/clad components to represent HTGR fuel
  - Example MELCOR 2.0 input:
    - `COR_RT  PBR  ! Specify PBR (pebble bed) core geometry`

PBR COR Model

- Fueled part of pebble is fuel component
  - UO_2 with extra COR material as graphite
- Unfueled shell is clad component
  - Clad material becomes graphite
- Center reflector is Other Structure (OS) component
- Outer reflector is either OS or Shroud component
- Fuel radial temperature profile for sphere
  - Provides peak and surface pebble temperature
    - Better reactor simulation

PBR COR Model contd

- Radial cell-cell conductive/radiative heat transfer added
  - Uses effective bed conductivity (Zehner-Schlunder with modifications for thermal radiation)
- Axial cell-cell conduction modified to use effective bed conductivity
- Coolant friction factor is for pebble bed (Ergun equation) when PBR model is invoked
  - Achenbach correlation being investigated
- Coolant heat transfer uses pebble bed heat transfer coefficients

PMR COR Model

- More “rod-like”, requires fewer changes to COR
- Fuel compacts represented as fuel component
- Part of hex block associated with a fuel channel is “thick” clad component
  - Temperature gradient in clad as well as fuel
- Reflectors are Supporting Structure component
- Radial cell-cell conductive/radiative heat transfer added

Graphite Oxidation Models

- **Oxidation of graphite by steam and air**
  - **The air oxidation rate is implemented as (Richards, 1987)**

$$R_{OX} = 122.19 \exp\left(-\frac{20129}{T}\right) P^{0.5}$$

  - **The steam oxidation model is implemented as (Richards, 1988)**

$$R_{OX,steam} = \frac{k_4 P_{H_2O}}{1 + k_5 P_{H_2}^{0.5} + k_6 P_{H_2O}} \qquad k_i = K_i \exp\left(-\frac{E_i}{RT}\right)$$

Graphite Oxidation Models contd

- **Maximum rates limited by gaseous diffusion to surface**
- **Reaction Products**
  - **Currently, the air reaction produces CO**
  - **Steam reaction produces CO and H_2**
  - **The CO/CO_2 mole ratio is given by (Kim and NO, 2006)**

$$f_{CO/CO_2} = 7396e^{-69604/RT}$$

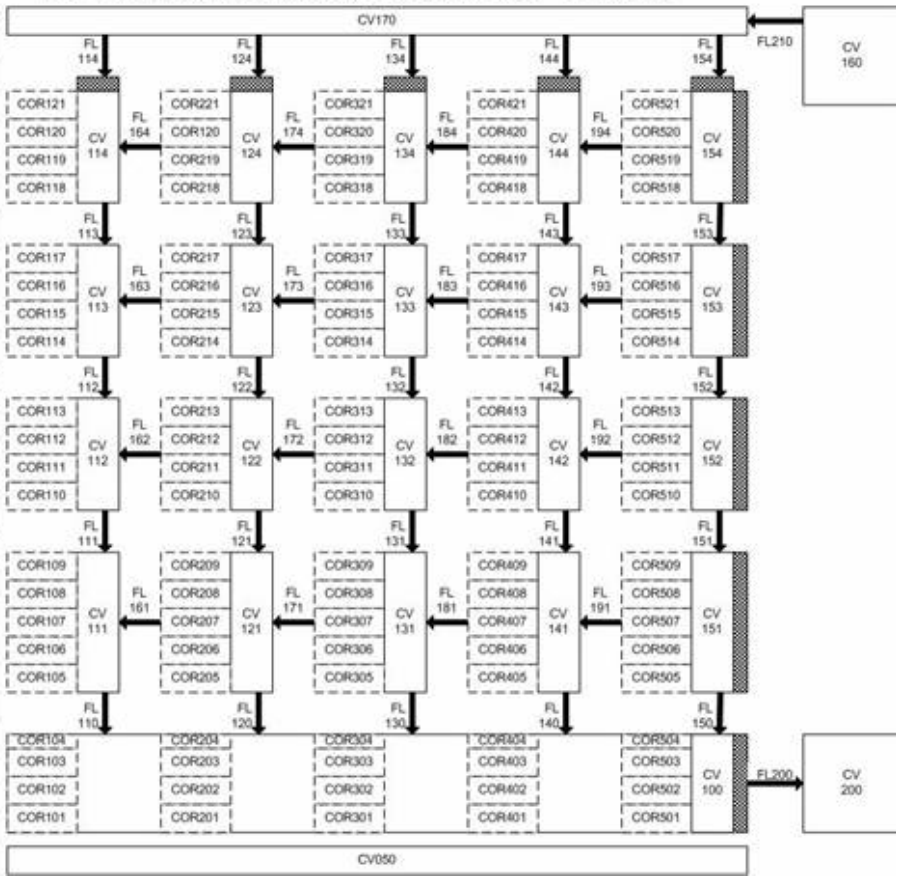
Point Kinetics Model

- Point kinetics for operating reactor applications
  - Model developed by UNM
    - Stable over wide range of timesteps
  - Temperature-dependent reactivity feedback from COR components
    - Fuel/Moderator/Reflector generalized weighting for spatially averaged feedback
  - External reactivity insertion via control functions
    - Generalized and flexible

HTGR COR Model Testing

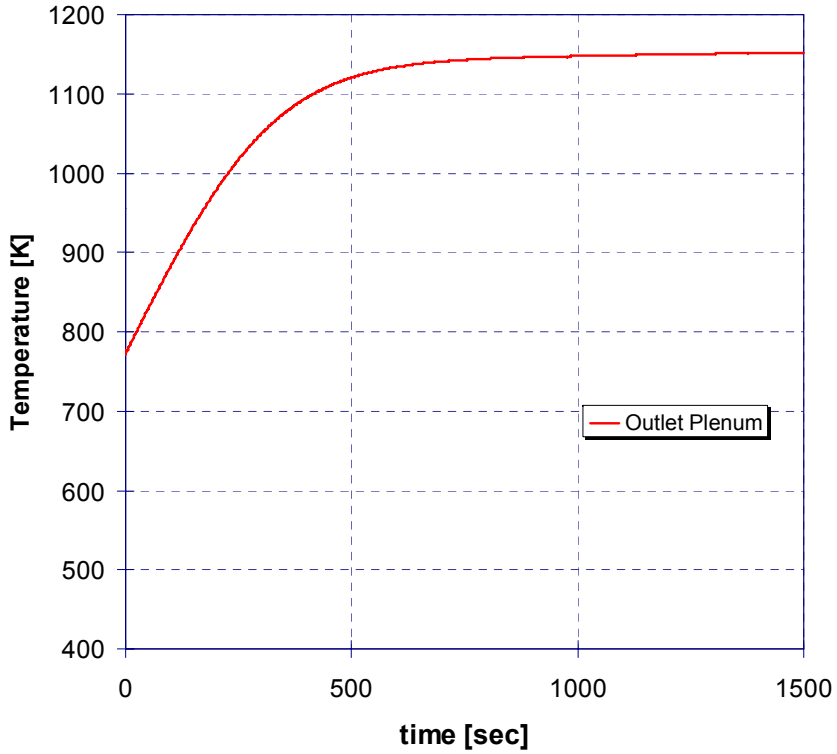
- PBR Testing of new COR model
- Deck adapted from Texas A&M PBR deck
  - Pebbles represented as fuel/clad components instead of debris
  - Steady state problem
    - 268 MW reactor power
    - Run to 1500 s
  - Reactor is older Pty Ltd design as in Reitsma (2006)

MELCOR PBR Noding

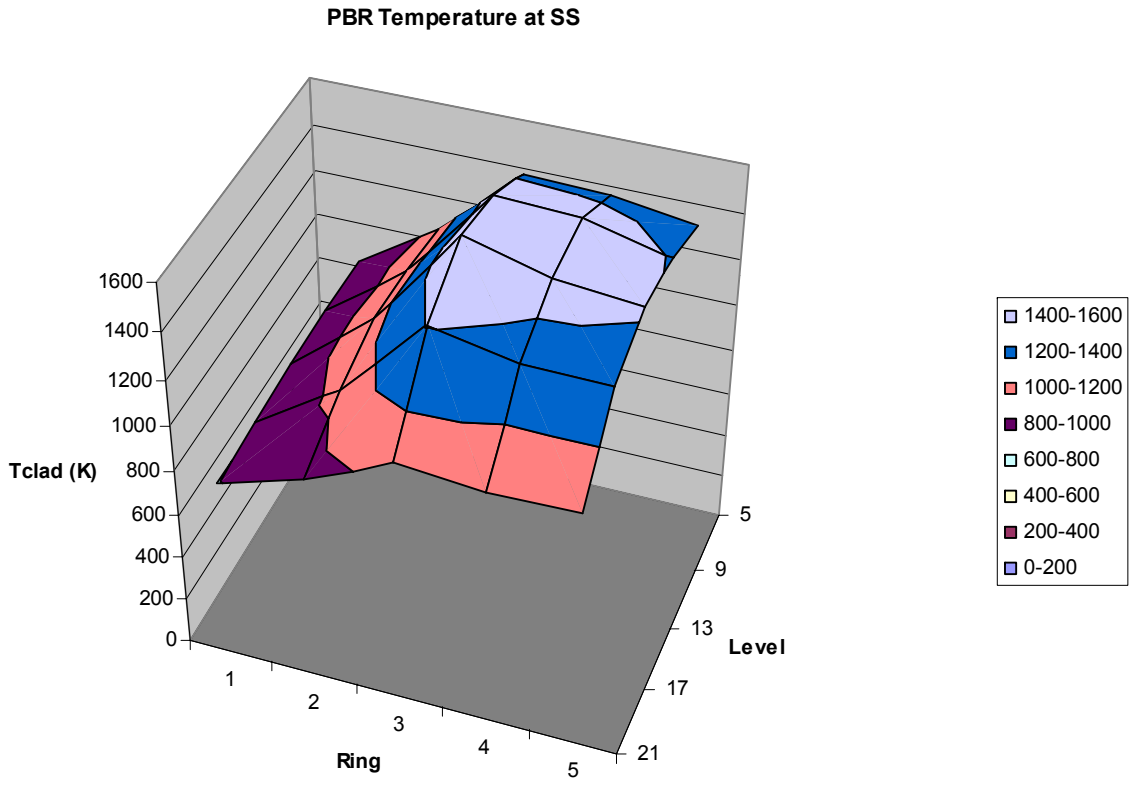


From Vierow, MELCOR Modeling of a Pebble Bed Modular Reactor (2007)

PBR COR Model Testing: Outlet Gas Temperature



PBR COR Model Testing: Steady State Core Temperature



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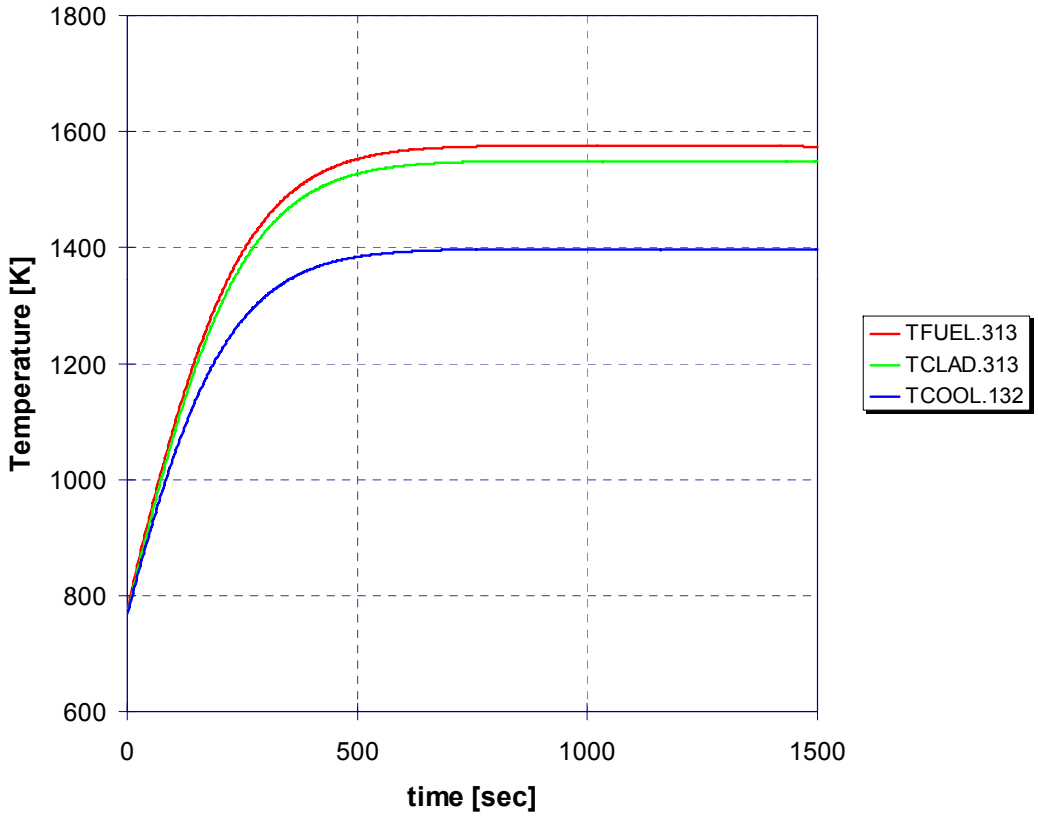
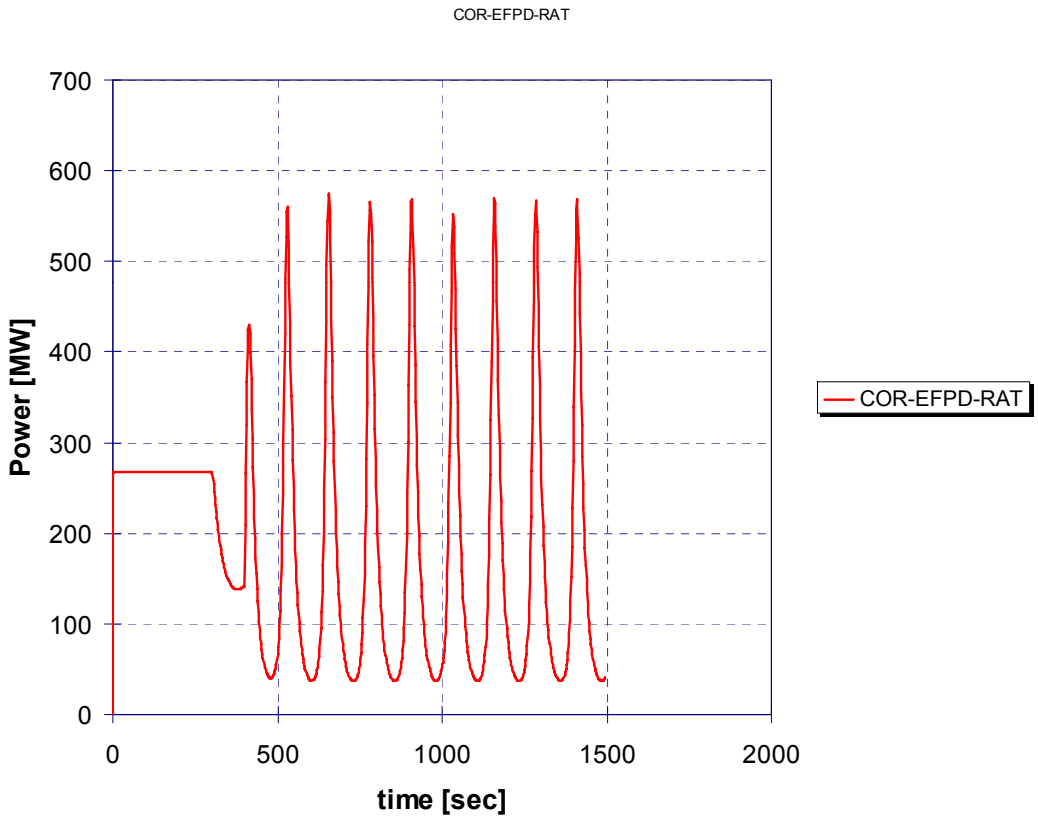
PBR COR Model Testing: Core Temperatures at Max Location



HTGR Point Kinetics Testing

- Initial power level is 268 MW
- Control Function used to insert $0.50 reactivity oscillation
  - Period is $2\pi/0.05 = 125$ s
- Doppler feedback from fuel and moderator
- PK Model turned on at 300 s
- Oscillation started at 400 s
  - Initial power drop from 300-400s because reactor is still heating up

HTGR PK Testing 2



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HTGR Ongoing Work

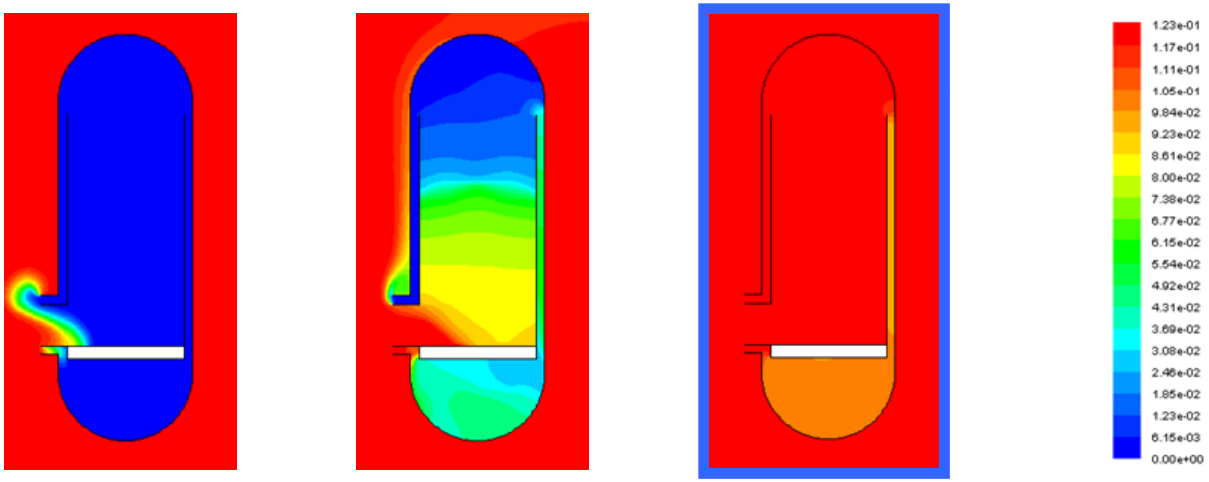
- Fission product release and transport from HTGR fuel
  - Release
    - Review PARFUME models
    - Devise simplified MELCOR model (Booth?)
  - Transport
    - Plate out
    - Surface sorption
    - Dust liftoff
- Plant demonstration calculations
  - Use of point kinetics for accidents w/o SCRAM
  - Consider coupling of 2D neutronics (ie PARCS) with COR

HTGR Ongoing Work contd

- Stratified flow for air ingress
  - Original scenario was that air entered by diffusion
    - 10hr timescale
  - CFD simulation shows that air enters via stratified flow and circulation (Kim, 2008)
    - 260s timescale

CFD Air Ingress Simulation

Snap Shots of Simulation (Air Mole Fraction) from "NRC/INL Meeting on Methods for VHTRs", E. Kim, C. Oh, R. Schultz, INL (2008)



1.0 sec **16.0 sec** **256.0 sec**

HTGR Ongoing Work contd

- HTGR RCCS model
  - Removal of heat from vessel
- Plant components
  - Gas turbine
  - Heat exchangers
  - Helium circulator

MELCOR HTGR Development Summary

- **Models being added/upgraded to allow HTGR Plant Simulation**
  - **New COR models**
  - **Flow/Heat transfer models**
  - **Point Kinetics**
  - **Fission product release**