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# Multiphysics Methods Development for High Temperature Gas Cooled Reactor Analysis

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# Outline

- Motivation
- Thermal Hydraulics Model
- Neutronics Model
- Cross Section models and coupling
- Verification studies;
  - Simulation of SANA experiment
  - PBMR-400 Benchmark problem
- Summary and Future Work

# Motivation

- To develop multiphysics methods in a **system analysis** code for;
  - calculating the **thermal-hydraulics** and **neutronics** parameters
  - predicting the transient behavior of the reactor **accurately** and **efficiently** under any anticipated accident conditions.

# Specific Research Objectives

- Development of a thermal-hydraulics computer code to calculate the **temperature** and **flow field**:
  - Use the porous media approach with pebble bed effective conductivity, resistance coefficient, and solid-to-fluid heat transfer coefficient (experimental data)
  - 3-D, Cylindrical coordinates
  - Steady-state, transient conditions

# Cont … (Specific Research Objectives )

- Modification of the existing 3-D cylindrical neutronics solver in PARCS code
  - implementation of new features
    - Anisotropic diffusion coefficients
    - Periodic boundary conditions for the azimuthal direction
  - Adjustments to perform the calculations of steady-state conditions for all anticipated transient scenarios

# Cont … (Specific Research Objectives )

- Development of methods to perform an efficient and accurate coupling of the thermal-hydraulics and neutronics solutions.

- Verification of methods by simulating Pebble Bed experiments and benchmark problems.

# T/H Codes for PBMR

- **THERMIX-KONVEK** & **THERMIX-DIREKT**

- THERMIX
  - Temperature calculation
  - Two-temperature porous media model
  - Steady-State and time dependent
  - 2-D (r-z) cylindrical coordinates

# Cont … (Current Codes)

- KONVEK
  - Flow field calculation
  - Porous media approach
  - **Steady-state (quasi-static)**
  - 2-D (r-z) cylindrical coordinates
- DIREKT
  - Flow field calculation
  - Porous media approach
  - **S.S. and time dependent**
  - 2-D (r-z) cylindrical coordinates

# Developed Methods

- PARCS/THERMIX-3D
  - Thermal/hydraulics Solver
    - 3-D cylindrical coordinates, porous media, time dependent & steady state
  - Neutronics
    - 3-D cylindrical coordinates, finite difference, neutron diffusion

# Thermal Hydraulics Model

## Mass Balance

$$\frac{\partial}{\partial t}(\varepsilon\rho_f) + \nabla.(\rho_f v_f) = 0$$

## Momentum Balance

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla.(\rho\vec{v}.\vec{v}) = -\nabla p + \nabla.\overline{\overline{\tau}} + \rho\vec{g}$$

## Energy Balance

Two-Temperature Model (next slide)

# Two-Temperature model

Solid Medium

$$\frac{\partial}{\partial t}\left[(1-\varepsilon)\rho_s c_{p_s} T_s\right] = \nabla.(1-\varepsilon)k_s \nabla T_s - \alpha(T_s - T_f) + Q$$

Fluid Medium

$$\frac{\partial}{\partial t}\left[\varepsilon\rho_f c_{p_f} T_f\right] + \nabla.(\rho_f c_{p_f} u T_f) = \nabla.\varepsilon k_f \nabla T_f - \alpha(T_f - T_s)$$

# Neutronics Model

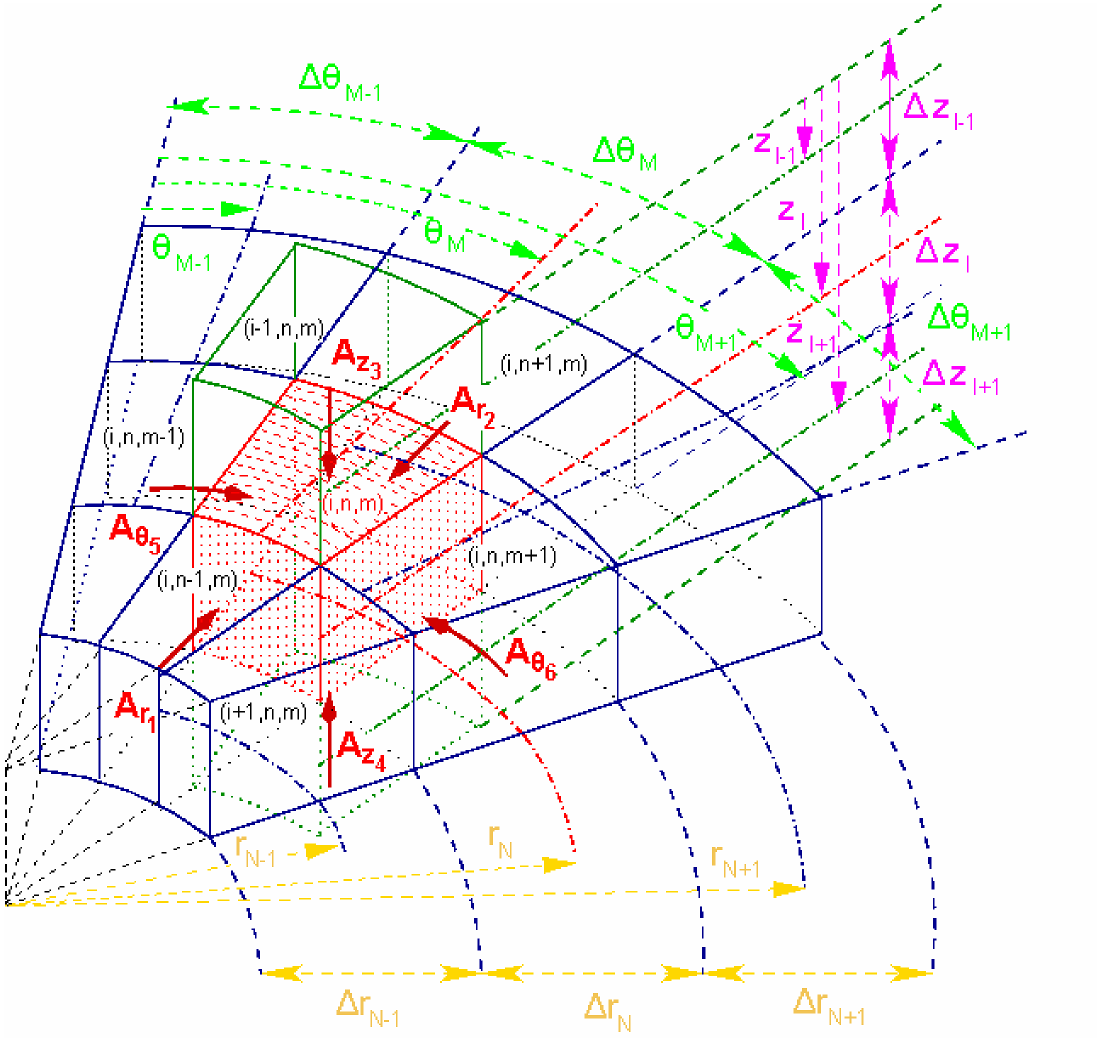
## Neutron Balance Equation

$$\frac{1}{v_g}\frac{d\phi_g}{dt} = \frac{\chi_{pg}}{k_{eff}}\sum_{g=1}^{G}\nu_{pg}\Sigma_{fg}\phi_g + \chi_{dg}\sum_{k=1}^{K}\lambda_k C_k + \sum_{g'=1(g'\neq g)}^{G}\Sigma_{sg'g}\phi_{g'} - \Sigma_{tg}\phi_g + \nabla.D_g\nabla\phi_g$$

## Precursor Concentration

$$\frac{dC_k}{dt} = \frac{1}{k_{eff}}\sum_{g=1}^{G}\nu_{dgk}\Sigma_{fg}\phi_g - \lambda_k C_k$$

# Control Volume



# Discretization Equation

- Spatial discretization
  - Finite volume
  - General Scheme for convective terms including, CD, UDS, Hybrid, Power Law and Exponential
- Temporal discretization
  - Theta method
    - 0 = fully explicit
    - 1 = fully implicit
    - 0.5 = Crank-Nicholson

# Discretization of the Energy Balance Equation

- Solid Energy Equation in Cylindrical Coordinates

$$\frac{\partial}{\partial t}\left[(1-\varepsilon)\rho_s c_{p_s} T_s\right] = \frac{1}{r}\frac{\partial}{\partial r}\left((1-\varepsilon)k_s r\frac{\partial T_s}{\partial r}\right) + \frac{1}{r}\frac{\partial}{\partial \theta}\left((1-\varepsilon)\frac{k_s}{r}\frac{\partial T_s}{\partial \theta}\right)$$

$$+ \frac{\partial}{\partial z}\left((1-\varepsilon)k_s\frac{\partial T_s}{\partial z}\right) - \alpha(T_s - T_f) + Q$$

# Final Form of The Solid Energy Equation

$$\left[(1-\varepsilon)_P(\rho c_p)_{s,P}\frac{\Delta V}{\Delta t}+\Theta(D_e+D_w+D_n+D_s+D_t+D_b+\alpha\Delta V)\right]T_{s,P}$$

$$-\quad \Theta D_e T_{s,E}-\Theta D_w T_{s,W}-\Theta D_n T_{s,N}-\Theta D_s T_{s,S}-\Theta D_t T_{s,T}-\Theta D_b T_{s,B}$$

$$=\quad (1-\varepsilon)_P^o(\rho c_p)_{s,P}^o\frac{\Delta V}{\Delta t}T_{s,P}^o+\Theta\Delta V(\alpha T_{f,P}+Q)$$

$$+\Big[D_e^oT_{s,E}^o+D_w^oT_{s,W}^o+D_n^oT_{s,N}^o+D_s^oT_{s,S}^o+D_t^oT_{s,T}^o+D_b^oT_{s,B}^o$$

$$-(D_e^o+D_w^o+D_n^o+D_s^o+D_t^o+D_b^o)T_{s,P}^o$$

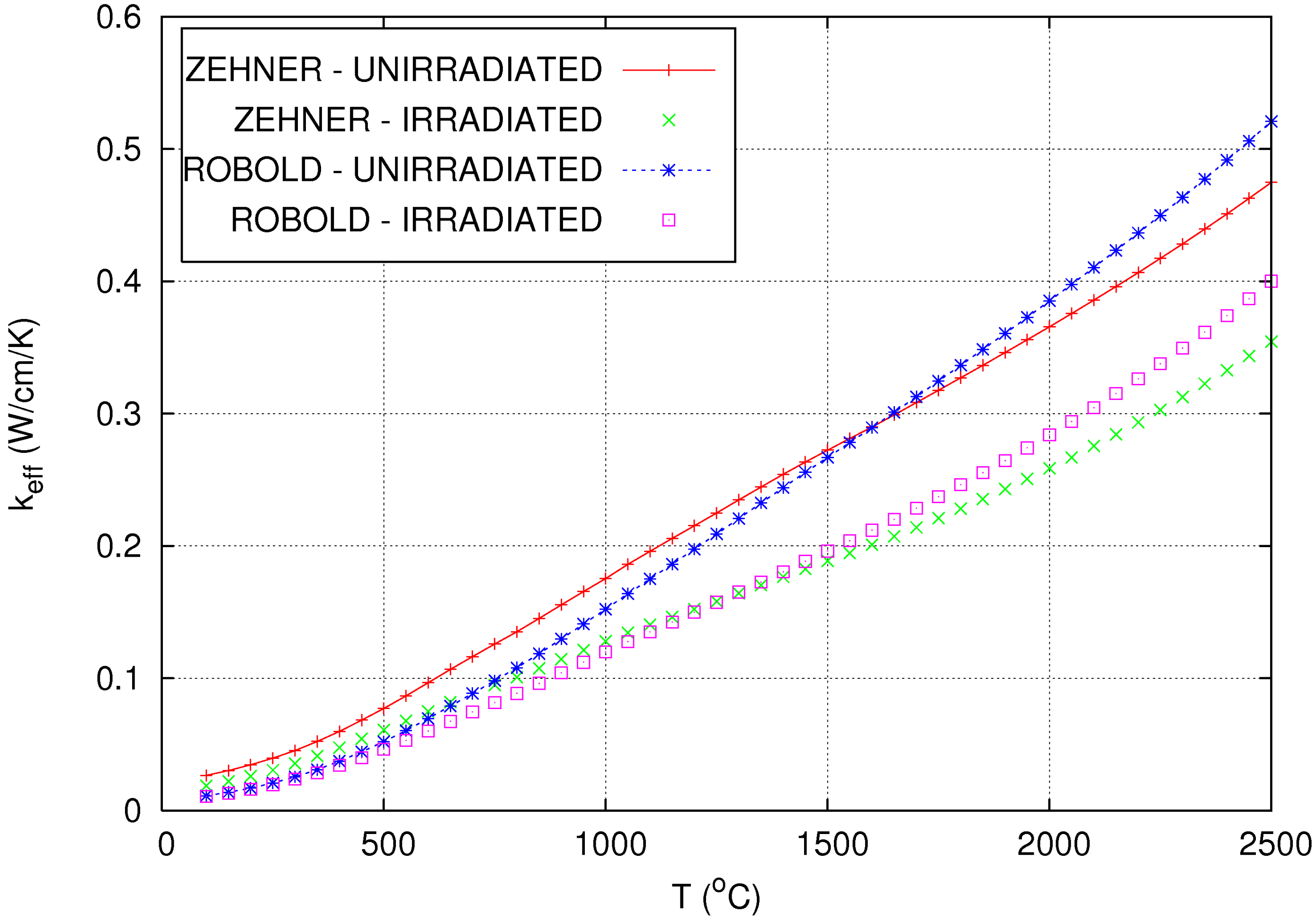
$$-\alpha^o(T_{s,P}^o-T_{f,P}^o)\Delta V+Q\Delta V\Big](1-\Theta)$$

Variable Porosity and Effective Thermal Conductivity

ε = f(r,θ,z)

k = f(T,D)    D: Fast Neutron Dose

# Effective Thermal Conductivity of Pebble Bed



# Fluid Energy Equation in Cylindrical Coordinates

$$\frac{\partial}{\partial t}\left[(\varepsilon\rho_f c_{p_f} T_f\right] = -\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho_f c_{p_f} u_r T_f\right) - \frac{1}{r}\frac{\partial}{\partial \theta}\left(\rho_f c_{p_f} u_\theta T_f\right) - \frac{\partial}{\partial z}\left(\rho_f c_{p_f} u_z T_f\right)$$

$$+\frac{1}{r}\frac{\partial}{\partial r}\left(\varepsilon k_f r\frac{\partial T_f}{\partial r}\right) + \frac{1}{r}\frac{\partial}{\partial \theta}\left(\varepsilon\frac{k_f}{r}\frac{\partial T_f}{\partial \theta}\right)$$

$$+ \quad \frac{\partial}{\partial z}\left((1-\varepsilon)k_s\frac{\partial T_s}{\partial z}\right) - \alpha(T_f - T_s)$$

# Final Form of The Gas Energy Equation

$$
\begin{aligned}
&\left[\varepsilon_P(\rho c_p)_{f,P}\frac{\Delta V}{\Delta t}+\Theta(A_E+A_W+A_N+A_S+A_T+A_B+\alpha\Delta V)\right]T_{f,P}\\
-\;&\Theta(A_E T_{f,E}+A_W T_{f,W}+A_N T_{f,N}+A_S T_{s,S}+A_T T_{f,T}+A_B T_{f,B})\\
=\;&\varepsilon_P^o(\rho c_p)_{f,P}^o\frac{\Delta V}{\Delta t}T_{f,P}^o+\Theta\Delta V\alpha T_{s,P}\\
+\;&\Big[A_E^o T_{f,E}^o+A_W^o T_{f,W}^o+A_N^o T_{f,N}^o+A_S^o T_{f,S}^o+A_T^o T_{f,T}^o+A_B^o T_{f,B}^o\\
&-(A_E^o+A_W^o+A_N^o+A_S^o+A_T^o+A_B^o)T_{f,P}^o\\
&-\alpha^o(T_{f,P}^o-T_{s,P}^o)\Delta V\Big](1-\Theta)
\end{aligned}
$$

# Coefficients

$$A_E = D_e A(|P_e|) + [\![ -F_e, 0 ]\!] \qquad A_W = D_w A(|P_w|) + [\![ F_w, 0 ]\!]$$

$$A_S = D_s A(|P_s|) + [\![ -F_s, 0 ]\!] \qquad A_N = D_n A(|P_n|) + [\![ F_n, 0 ]\!]$$

$$A_T = D_t A(|P_t|) + [\![ -F_t, 0 ]\!] \qquad A_B = D_b A(|P_b|) + [\![ F_b, 0 ]\!]$$

| **Scheme** | **Expression for A(\|P\|)** |
|---|---|
| Central difference | 1-0.5\|P\| |
| Upwind | 1 |
| Hybrid | [\| 0, 1-0.5\|P\| \|] |
| Power Law | [\| 0, $(1-0.5\|P\|)^{0.5}$ \|] |
| Exponential | \|P\|/[exp(\|P\|)-1] |

$$P = \frac{D}{F} \quad \text{: Peclet Number}$$

# Flow Field Calculation

- The resistance term is introduced into the momentum equation using a simplification in the momentum equation. (applied in TINTE, THERMIX-KONVEK and THERMIX-DIREKT)

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla.(\rho\vec{v}.\vec{v}) = -\nabla p + \nabla.\overline{\overline{\tau}} + \rho\vec{g}$$

$$\nabla.(\rho\vec{v}.\vec{v}) - \nabla.\overline{\overline{\tau}} = W.\rho\vec{v}$$

# Simplified Momentum Equation

$$\frac{\partial(\rho\vec{v})}{\partial t} = -W.\rho\vec{v} - \nabla p + \rho\vec{g}$$

$$W = \zeta\frac{(1-\varepsilon)}{\varepsilon^3}\frac{1}{d_p}\frac{|\rho v|}{2\rho}$$

$\varepsilon =$ porosity

$d_p =$ particle diameter

$\zeta =$ resistance cofactor (experimentally determined)

$$\zeta = \frac{320}{(\mathrm{Re}/(1-\varepsilon))} + \frac{6}{(\mathrm{Re}/(1-\varepsilon))^{0.1}} \quad \text{(for pebble bed)}$$

# Discretization of the Momentum Equation

$$\frac{\partial(\rho\vec{v})}{\partial t} = \frac{1}{A}\frac{\partial \dot{m}}{\partial t}$$

$$\frac{1}{A_{r1}}\frac{d\dot{m}_1}{dt} = -\frac{W_1}{A_{r1}}\dot{m}_1 - \frac{\Delta p_1}{(r_N - r_{N-1})}$$

$$\frac{1}{A_{r2}}\frac{d\dot{m}_2}{dt} = -\frac{W_2}{A_{r2}}\dot{m}_2 - \frac{\Delta p_2}{(r_{N+1} - r_N)}$$

$$\frac{1}{A_{z3}}\frac{d\dot{m}_3}{dt} = -\frac{W_3}{A_{z3}}\dot{m}_3 - \frac{\Delta p_3}{(z_I - z_{I-1})} + \rho_3 g$$

$$\frac{1}{A_{z4}}\frac{d\dot{m}_4}{dt} = -\frac{W_4}{A_{z4}}\dot{m}_4 - \frac{\Delta p_4}{(z_{I+1} - z_I)} - \rho_4 g$$

$$\frac{1}{A_{\theta 5}}\frac{d\dot{m}_5}{dt} = -\frac{W_5}{A_{\theta 5}}\dot{m}_5 - \frac{1}{r_N}\frac{\Delta p_5}{(\theta_M - \theta_{M-1})}$$

$$\frac{1}{A_{\theta 6}}\frac{d\dot{m}_6}{dt} = -\frac{W_6}{A_{\theta 6}}\dot{m}_6 - \frac{1}{r_N}\frac{\Delta p_6}{(\theta_{M+1} - \theta_M)}$$

# Temporal Discretization

$$\frac{(r_N - r_{N-1})}{A_{r1}} \frac{\dot{m}_1^{k+1} - \dot{m}_1^k}{\Delta t} = (1-\Theta)(-\frac{(r_N - r_{N-1})}{A_{r1}} W_{r1}\dot{m}_1 - \Delta p_{r1})^k$$

$$+\Theta(-\frac{(r_N - r_{N-1})}{A_{r1}} W_{r1}\dot{m}_1 - \Delta p_{r1})^{k+1}$$

$$\frac{(r_N - r_{N+1})}{A_{r2}} \frac{\dot{m}_2^{k+1} - \dot{m}_2^k}{\Delta t} = (1-\Theta)(-\frac{(r_N - r_{N+1})}{A_{r2}} W_{r2}\dot{m}_2 - \Delta p_{r2})^k$$

$$+\Theta(-\frac{(r_N - r_{N+1})}{A_{r2}} W_{r2}\dot{m}_2 - \Delta p_{r2})^{k+1}$$

- 
- 
- 

# Cont..

If we extract the $\dot{m}^{k+1}$ terms

$$\dot{m}_1^{k+1} = \frac{\left(\frac{1}{\Delta t} - (1-\Theta)W_{r1}^{k}\right)}{\left(\frac{1}{\Delta t} + \Theta W_{r1}^{k+1}\right)} \dot{m}_1^{k} - \frac{A_{r1}}{(r_N - r_{N-1})} \frac{(1-\Theta)\Delta p_{r1}^{k} + \Theta \Delta p_{r1}^{k+1}}{\left(\frac{1}{\Delta t} + \Theta W_{r1}^{k+1}\right)}$$

$$\dot{m}_2^{k+1} = \frac{\left(\frac{1}{\Delta t} - (1-\Theta)W_{r2}^{k}\right)}{\left(\frac{1}{\Delta t} + \Theta W_{r2}^{k+1}\right)} \dot{m}_2^{k} - \frac{A_{r2}}{(r_N - r_{N+1})} \frac{(1-\Theta)\Delta p_{r2}^{k} + \Theta \Delta p_{r2}^{k+1}}{\left(\frac{1}{\Delta t} + \Theta W_{r2}^{k+1}\right)}$$

# Cont …

Expansion of the dm/dt for a gas yields:

$$\frac{dm}{dt} = V.\frac{\partial \rho}{\partial t}$$

$$\frac{\partial \rho}{\partial t} = \left.\frac{\partial \rho}{\partial T}\right|_{p=const.} \frac{\partial T}{\partial t} + \left.\frac{\partial \rho}{\partial p}\right|_{T=const.} \frac{\partial p}{\partial t}$$

By the use of the ideal gas law or equation of state

$$\rho = \frac{p}{RT}$$

$$\rho_{He} = \frac{48.14\,\frac{p}{T}}{1.0 + 0.4446\,\frac{p}{T^{1.2}}}$$

# Discrete form of the continuity

$$V\frac{\Delta\rho}{\Delta t}=(1\text{-}\Theta)\sum_{j=1}^{6}\dot{m}_j^{k}+\Theta\sum_{j=1}^{6}\dot{m}_j^{k+1}$$

If we insert the $\dot{m}^{k+1}$ we derived from momentum and express the density terms considering ideal gas law or equation of state, we can come up with an expression for the pressure

# Cont…

$$p^{k+1}_{I,N,M}\left\{C'_1+\Theta^2\left(\frac{A_{r1}}{(r_N-r_{N-1})}\frac{1}{\left(\frac{1}{\Delta t}+\Theta W^{k+1}_{r1}\right)}+\cdots\right\}-p^{k+1}_{I,N-1,M}\Theta^2\left(\frac{A_{r1}}{(r_N-r_{N-1})}\frac{1}{\left(\frac{1}{\Delta t}+\Theta W^{k+1}_{r1}\right)}\right)$$

$$-p^{k+1}_{I,N+1,M}\cdots-p^{k+1}_{I-1,N,M}\cdots-p^{k+1}_{I+1,N,M}\cdots-p^{k+1}_{I,N,M-1}\cdots-p^{k+1}_{I,N,M+1}\cdots$$

$$=\Theta^2\left(\frac{A_{z3}}{(z_I-z_{I-1})}\frac{(\rho_3 g\Delta z_3)^{k+1}}{\left(\frac{1}{\Delta t}+\Theta W^{k+1}_{z3}\right)}-\frac{A_{z4}}{(r_{I+1}-r_I)}\frac{(\rho_4 g\Delta z_4)^{k+1}}{\left(\frac{1}{\Delta t}+\Theta W^{k+1}_{z4}\right)}\right)+\Theta\left(\frac{\left(\frac{1}{\Delta t}-(1-\Theta)W^{k}_{r1}\right)}{\left(\frac{1}{\Delta t}+\Theta W^{k+1}_{r1}\right)}\dot{m}^{k}_{1}+\cdots\right.$$

$$+\Theta(1-\Theta)\left[-\frac{A_{r1}}{(r_N-r_{N-1})}\frac{\Delta p^{k}_{r1}}{\left(\frac{1}{\Delta t}+\Theta W^{k+1}_{r1}\right)}-\cdots\right]$$

$$+(1-\Theta)(\dot{m}_1+\dot{m}_2+\dot{m}_3+\dot{m}_4+\dot{m}_5+\dot{m}_6)^{k}+p^{k}_{I,N,N}.C'_2+C'_3$$

# Neutron Diffusion Equation in Discrete Form

$$
\begin{aligned}
&-D_{grL}\,S_{rL}\,\overline{\phi}_{grL}-D_{grR}\,S_{rR}\,\overline{\phi}_{grR}\\
&-D_{g\theta L}\,S_{\theta L}\,\overline{\phi}_{g\theta L}-D_{g\theta R}\,S_{\theta R}\,\overline{\phi}_{g\theta R}\\
&-D_{gzL}\,S_{zL}\,\overline{\phi}_{gzL}-D_{gzR}\,S_{zR}\,\overline{\phi}_{gzR}\\
&+\left(\begin{aligned}&D_{grL}\,S_{rL}+D_{grR}\,S_{rR}+D_{g\theta L}\,S_{\theta L}\\ &+D_{g\theta R}\,S_{\theta R}+D_{gzL}\,S_{zL}+D_{gzR}\,S_{zR}\\ &+\left(\Sigma_{ag}+\sum_{g\neq g'}\Sigma_{sg'g}\right)V^{l}\end{aligned}\right)\overline{\phi}_{g}\\
&=\left(\sum_{g\neq g'}\Sigma_{sgg'}+\frac{\chi_g}{k_{eff}}\sum_{g'}\nu\Sigma_{fg'}\right)\overline{\phi}_{g'}V^{l}
\end{aligned}
$$

# Cross Section Model

- Native Format

$$\Sigma(\alpha, Tf, Tm, Dm, Sb) = \Sigma^{r} + \alpha\Delta\Sigma^{cr} + \frac{\partial\Sigma}{\partial\sqrt{Tf}}\Delta\sqrt{Tf} + \frac{\partial\Sigma}{\partial Tm}\Delta Tm + \frac{\partial\Sigma}{\partial Sb}\Delta Sb + \frac{\partial\Sigma}{\partial Dm}\Delta Dm + \frac{\partial^2\Sigma}{\partial Dm^2}(\Delta Dm)^2$$

- 5-D Interpolation for the PBMR
  - Fuel and Moderator Temperatures
  - Fast and Thermal bucklings
  - Xenon concentration

# Anisotropic Diffusion Coefficients

- Treatment of the void regions in PBR
- Use of radial and axial diffusion coefficients
- Obtained from analytical optimization process
- For a reactor with a height-to-radius ratio above 1

$$D_r = 0.1R$$

$$D_z = 0.5R$$

# Linear System Solvers

- PARCS linear system solver
  - Preconditioned Conjugate Gradient (PCG)
  - MILU (Modified Incomplete LU) preconditioner

- Other solvers investigated from the IMSL library
  - DPCGRC: Jacobi Preconditioned Conjugate Gradient
  - DGMRES: Generalized Minimum Residual
  - DLSLXG: Sparse system with Gauss Elimination
  - DLSLRG: Gauss Elimination

# PARCS/THERMIX-3D Coupling

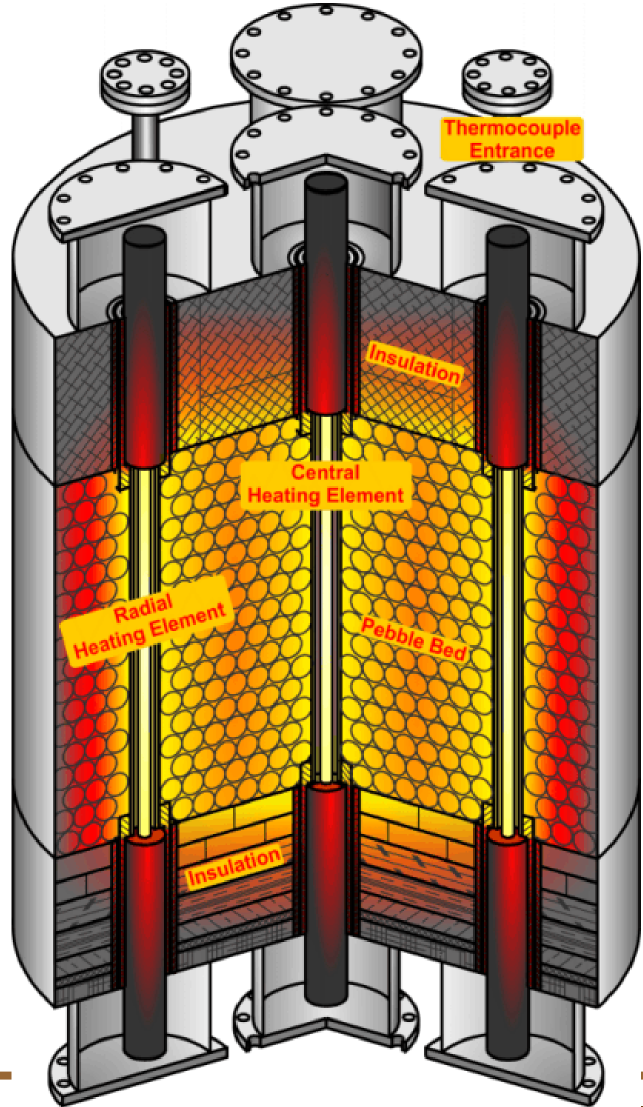
- Thermix is merged into PARCS source.
- Called as a subroutine when T/H feedback is required.
- Uses same coarse mesh structure
- Mapping is performed automatically

# VERIFICATION STUDIES

- SANA experiment
  - Standalone Thermal-Hydraulics
- PBMR-400 benchmark problem
  - Standalone Neutronics
  - Standalone Thermal-Hydraulics
  - Couple Neutronics/ Thermal-Hydraulics

# SANA Test Facility

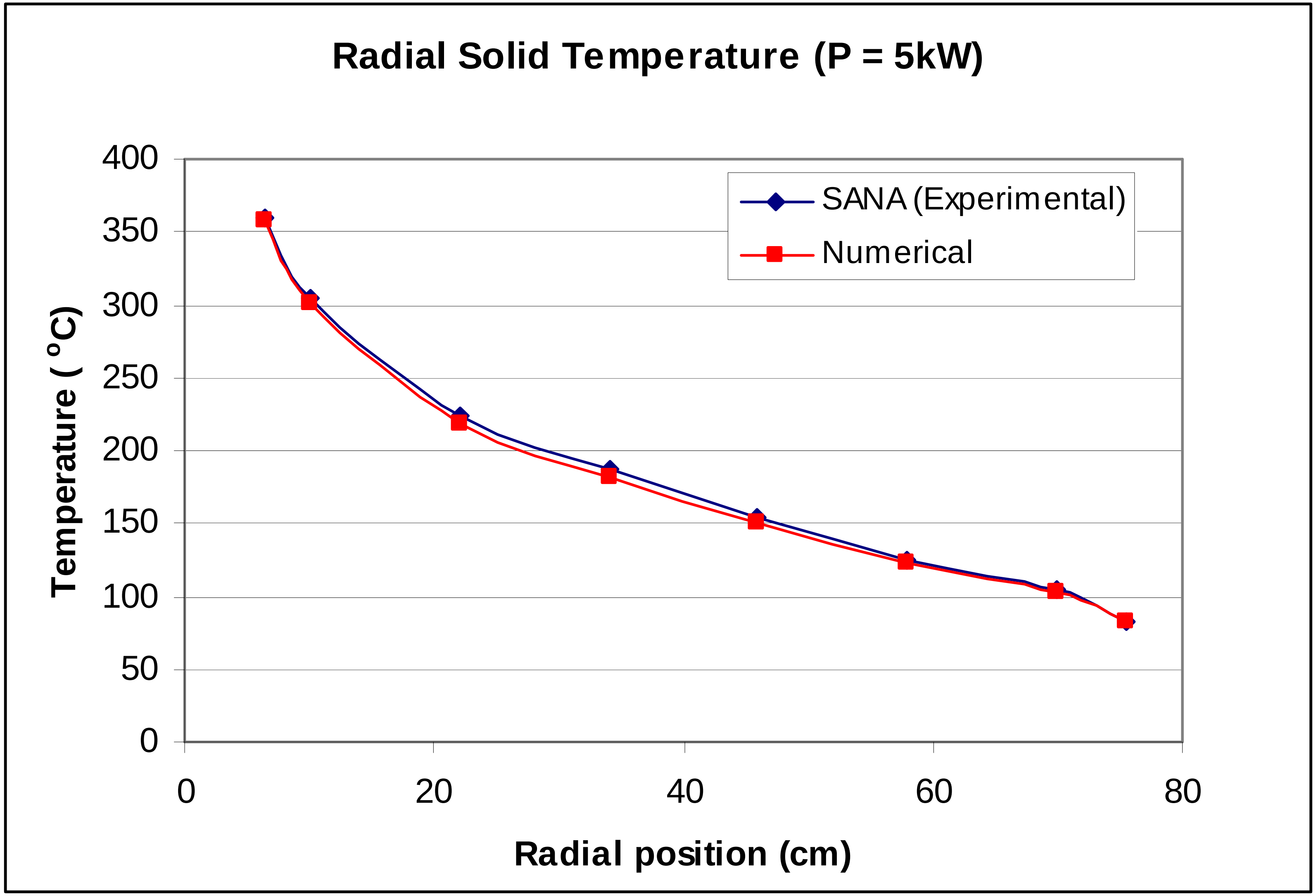
- Bed of graphite pebbles in a cylindrical arrangement.
- Diameter of 1.5 m and a height of 1 m
- Approximately 9500 graphite pebbles with a diameter of 6 cm
- Heat is produced by the 4 electrical resistance heating element



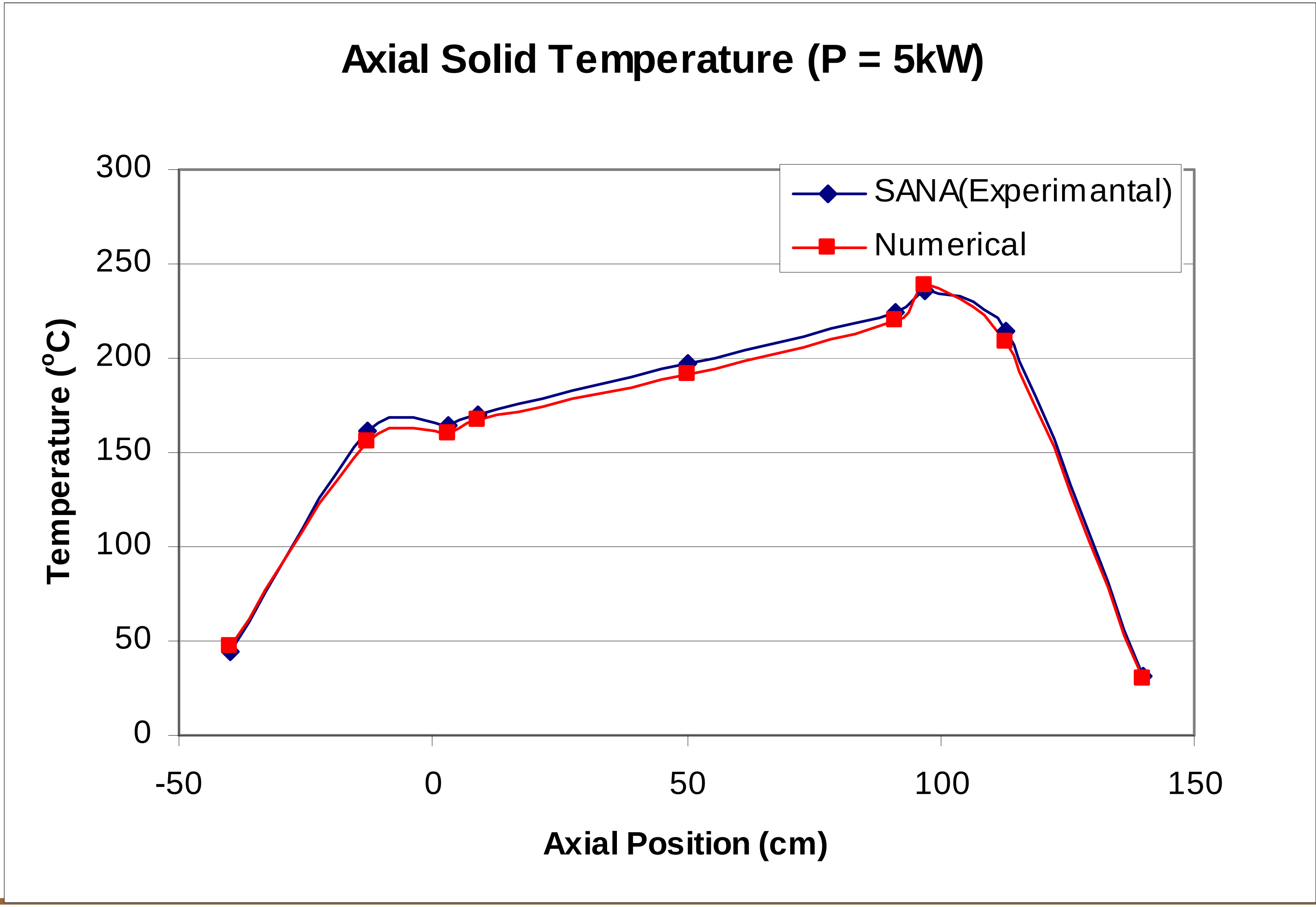
# Test-1&2

- Steady State
- Long heating element in the centre
- 6 cm diameter pebbles
- Cooled by helium
- **Test-1** with **5kW power**
- **Test-2** with **30kW power**

# Results of Test 1&2

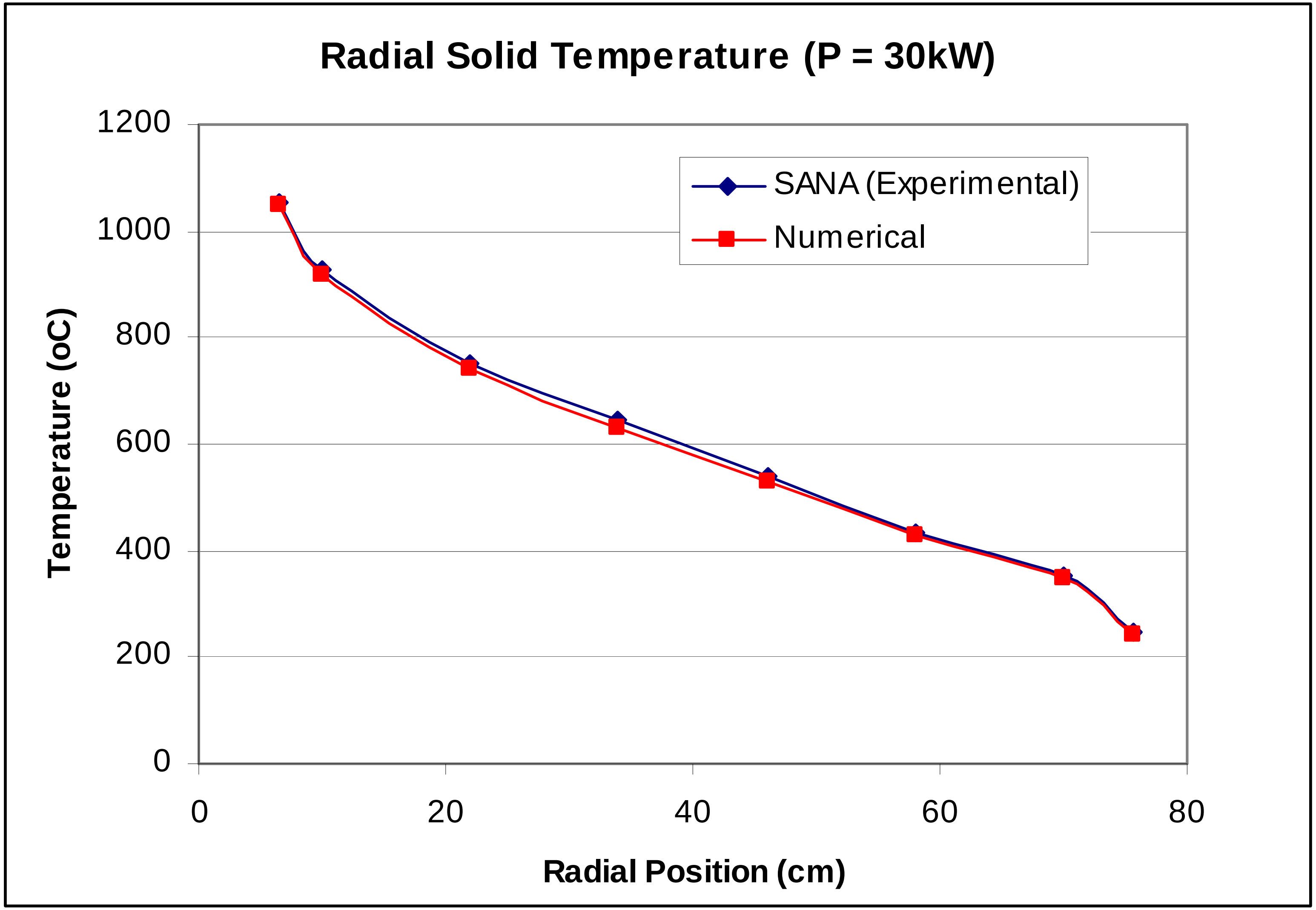


# Cont …



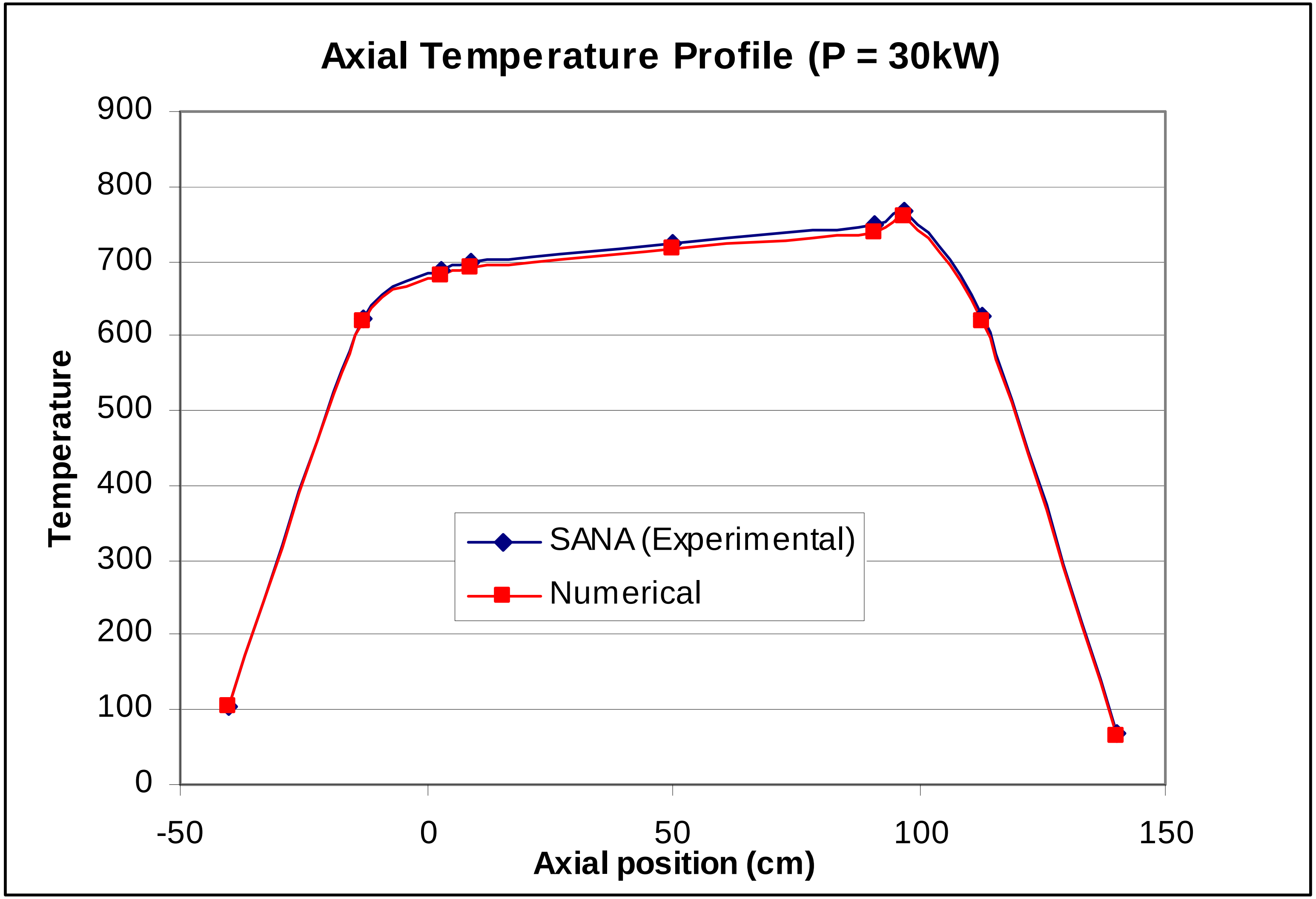
Axial Solid Temperature (P = 5kW)
300
250
200
150
100
50
0
-50
0
50
100
150
Temperature (°C)
Axial Position (cm)
SANA(Experimantal)
Numerical

# Cont …



Radial Solid Temperature (P = 30kW)
SANA (Experimental)
Numerical
Temperature (oC)
0
200
400
600
800
1000
1200
0
20
40
60
80
Radial Position (cm)

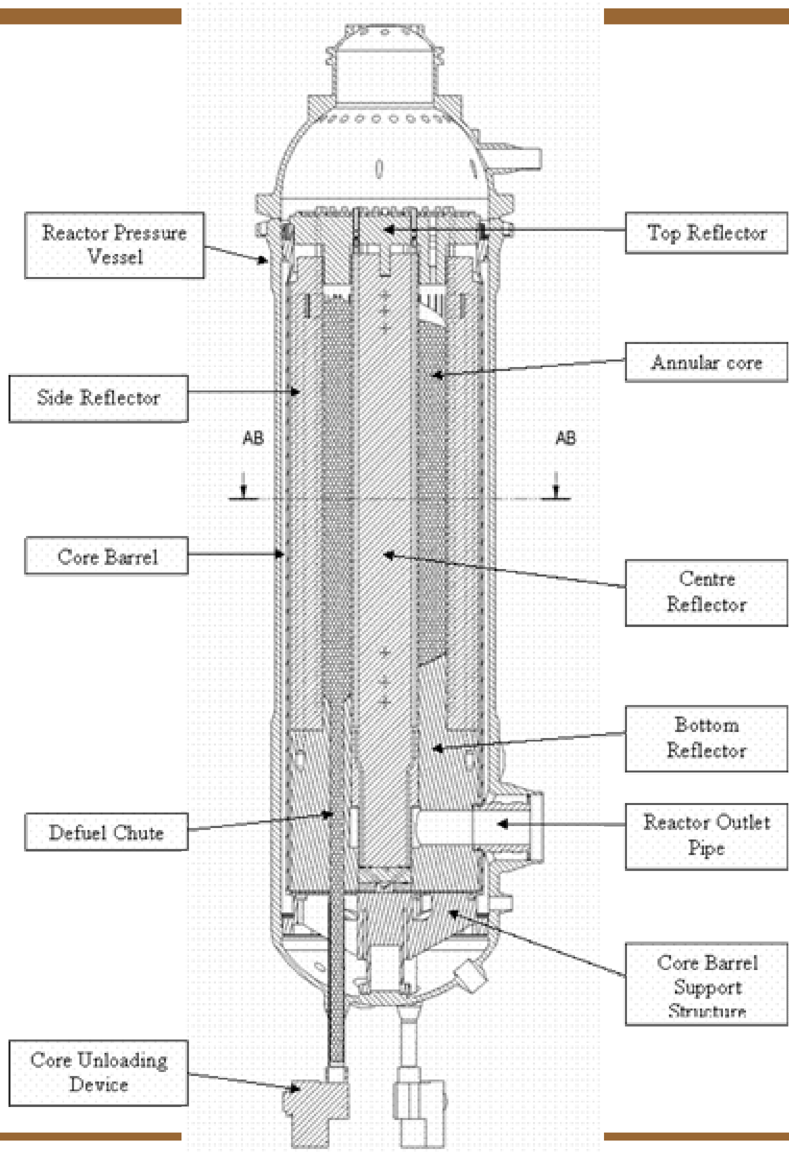
# Cont …



Axial Temperature Profile (P = 30kW)
900
800
700
600
500
400
300
200
100
0
Temperature
-50
0
50
100
150
Axial position (cm)
SANA (Experimental)
Numerical

# PBMR-400 Benchmark Problem

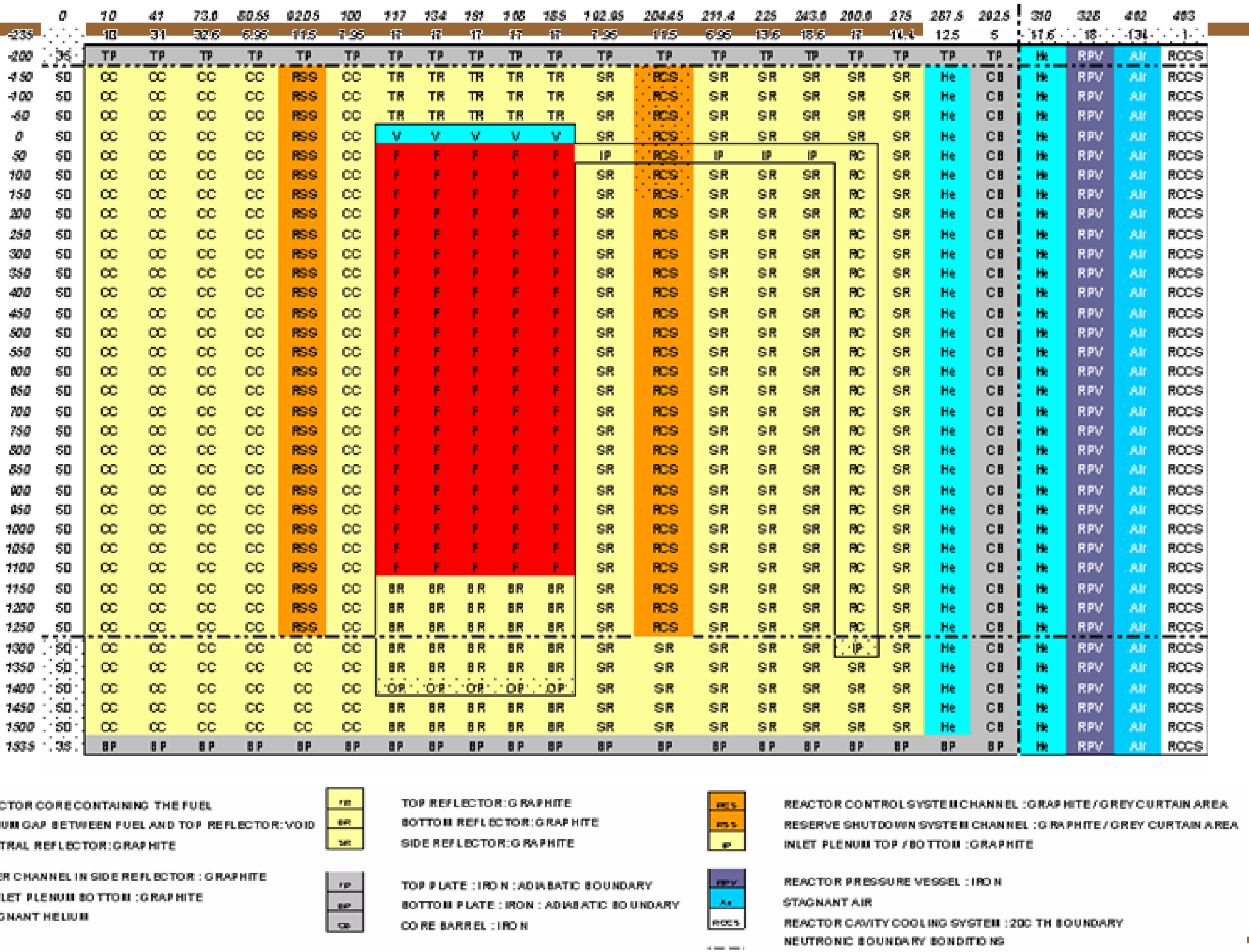
| PBMR Characteristic | Value |
|---|---|
| Thermal Power | 400 MW |
| Core configuration | Vertical with fixed centre graphite reflector |
| Outer diameter | 3.7 m |
| Core Height | 11 m |
| Reactor pressure | 9MPa |
| Mass flow rate | 192.5 kg/s |
| Core inlet temperature | 500°C. |



# Benchmark Specification

- 2-D (r-z) for all cases except control rod ejection (requires 3-D)
- flattened pebble bed's upper surface and bottom cones
- pebble flow is in parallel channels and at equal speed.
- Use of 5-D cross section.

# Core Layout


REACTOR CORE CONTAINING THE FUEL
HELIUM GAP BETWEEN FUEL AND TOP REFLECTOR: VOID
CENTRAL REFLECTOR: GRAPHITE
RISER CHANNEL IN SIDE REFLECTOR : GRAPHITE
OUTLET PLENUM BOTTOM : GRAPHITE
STAGNANT HELIUM
TOP REFLECTOR: GRAPHITE
BOTTOM REFLECTOR: GRAPHITE
SIDE REFLECTOR: GRAPHITE
TOP PLATE : IRON : ADIABATIC BOUNDARY
BOTTOM PLATE : IRON : ADIABATIC BOUNDARY
CORE BARREL : IRON
REACTOR CONTROL SYSTEM CHANNEL : GRAPHITE / GREY CURTAIN AREA
RESERVE SHUTDOWN SYSTEM CHANNEL : GRAPHITE / GREY CURTAIN AREA
INLET PLENUM TOP / BOTTOM : GRAPHITE
REACTOR PRESSURE VESSEL : IRON
STAGNANT AIR
REACTOR CAVITY COOLING SYSTEM : 20C TH BOUNDARY
NEUTRONIC BOUNDARY CONDITIONS

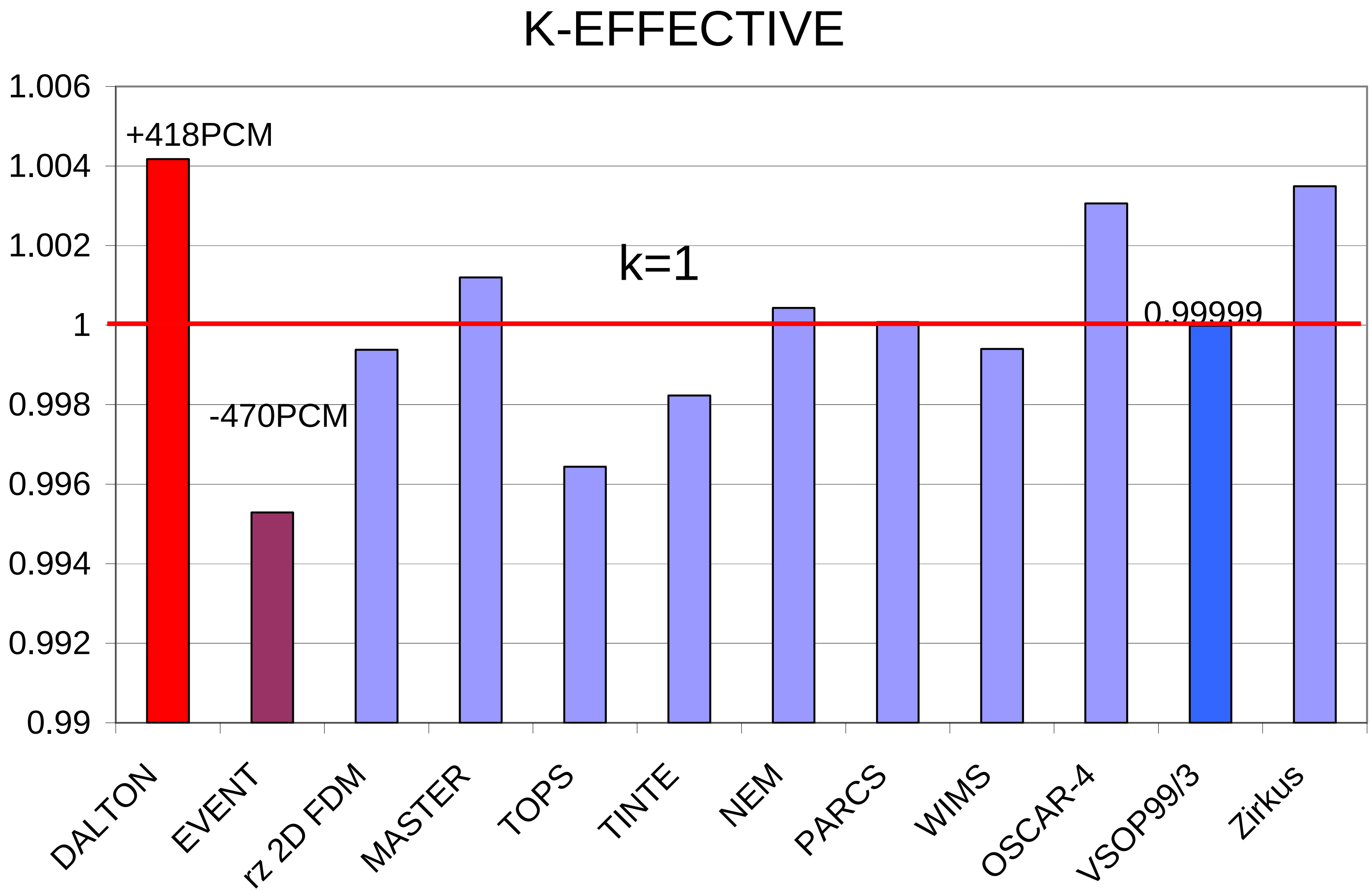
# Cases Analyzed

- Steady-State cases;
  - **Case S-1**: Neutronics Solution with Fixed Cross Sections
  - **Case S-2**: Thermal Hydraulic solution with given power / heat sources
  - **Case S-3**: Combined neutronics thermal hydraulics calculation – starting condition for the transients
- Transient Cases;
  - **Case T-5**: Control Rod Ejection: All 24 control rods are ejected in 0.1 sec.

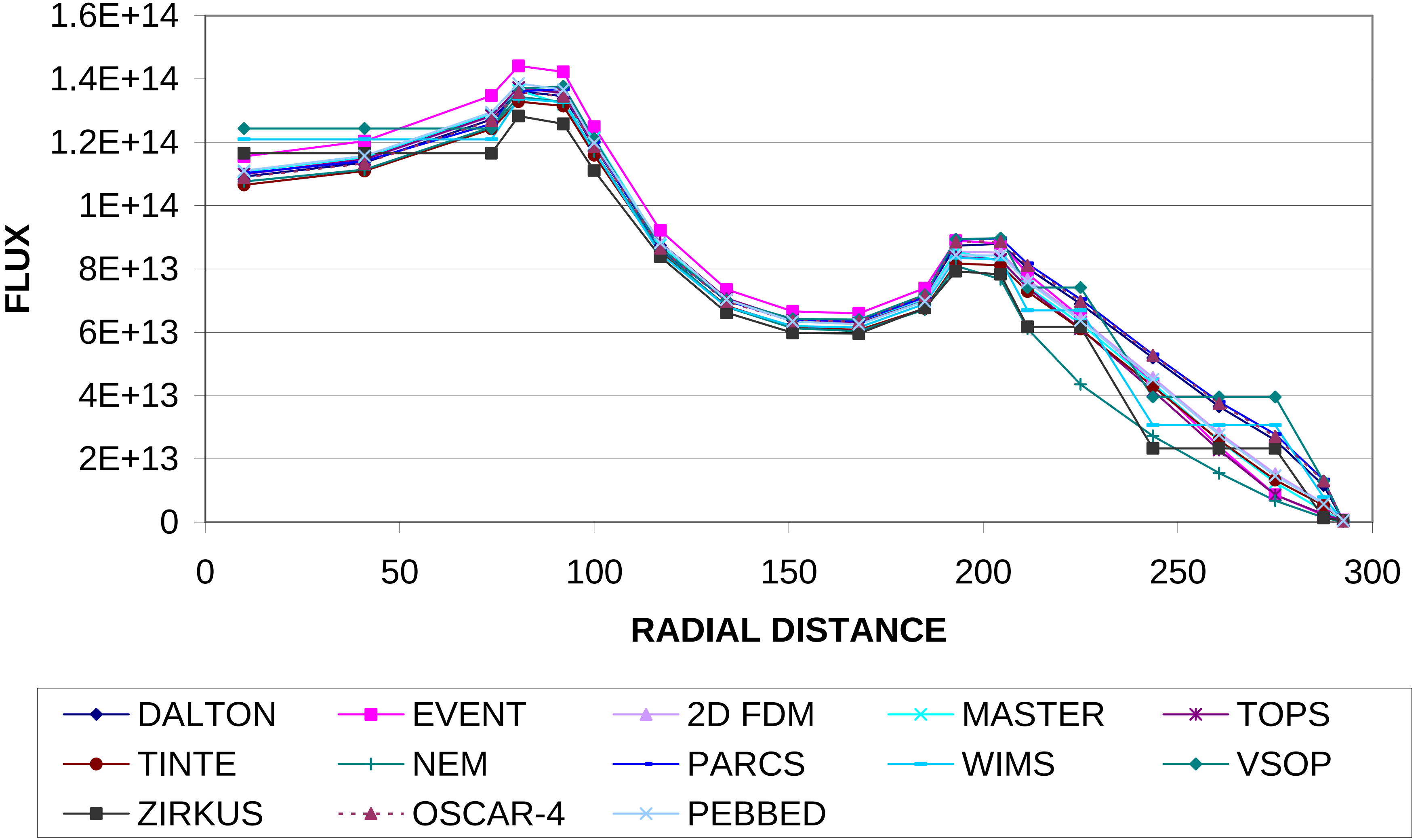
# PARTICIPANTS

| | | | |
|---|---|---|---|
| Delft-Diffusion | B.Boer | the Netherlands | 3D Diffusion code (used in R-Z mode) |
| Delft-EVENT | B.BOER, C. DE OLIVEIRA | the Netherlands, USA | EVENT |
| KAERI-FDM | Hyun Chul Lee (KAERI) | KOREA | rz 2D FDM |
| KAERI-MASTER | Hyun Chul Lee, Jae Man Noh (KAERI) | KOREA | MASTER |
| KAIST | Nam Zin Cho (KAIST) | Republic of Korea | TOPS |
| PBMR-TINTE | PBMR | RSA | TINTE |
| PSU-INL | The Pennsylvania State University & Idaho National Laboratory | U.S.A | NEM |
| Purdue University | Purdue University | USA | PARCS & DIREKT |
| Serco Assurance | Serco Assurance | UK | WIMS |
| NECSA | NECSA | South Africa | OSCAR-4 |
| Serco Assurance | Serco Assurance | UK | WIMS |
| PBMR-VSOP | PBMR | South Africa | VSOP99/3 |

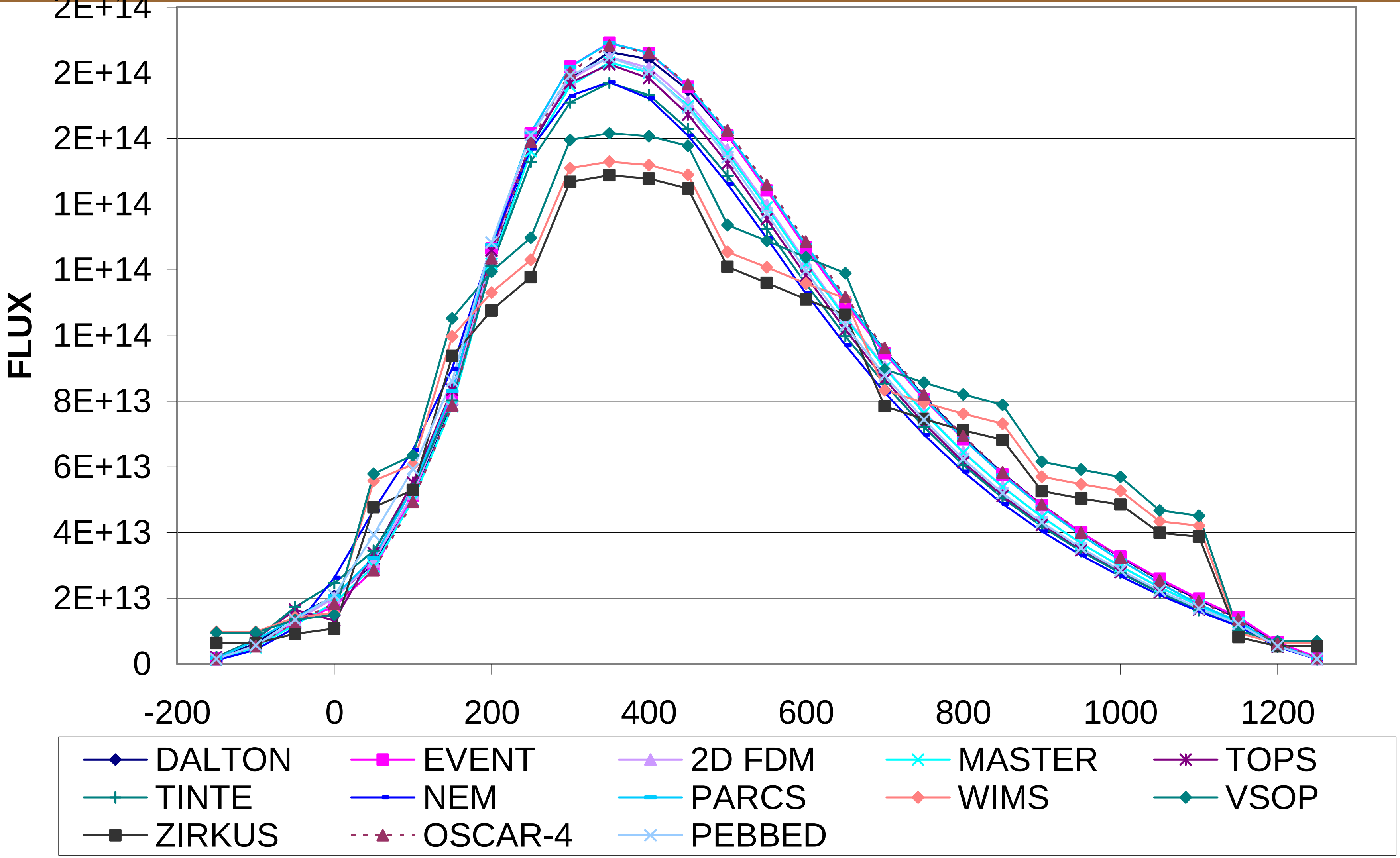
# Case S-1 Results



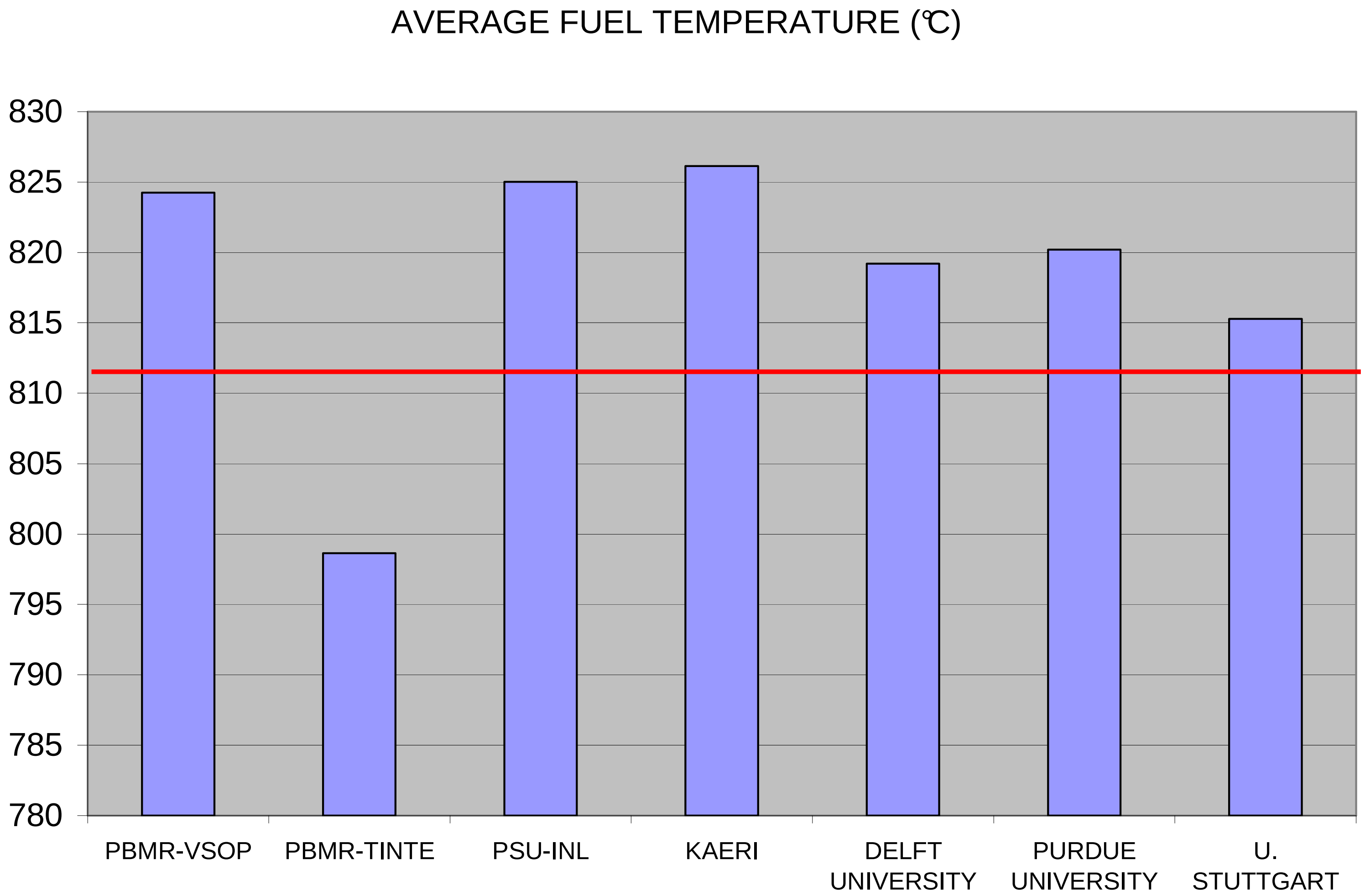
# RADIAL THERMAL FLUX



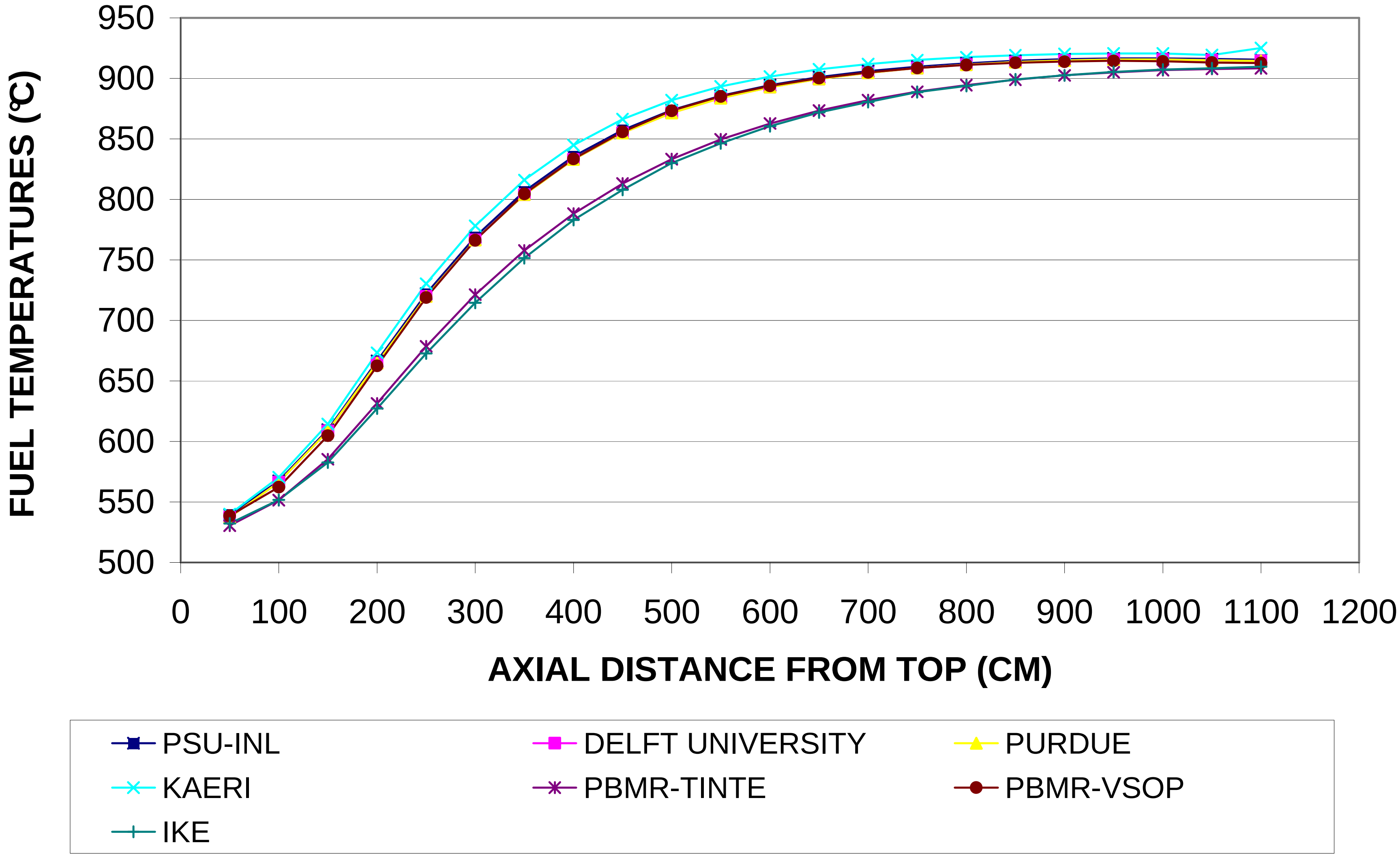
# AXIAL THERMAL FLUX

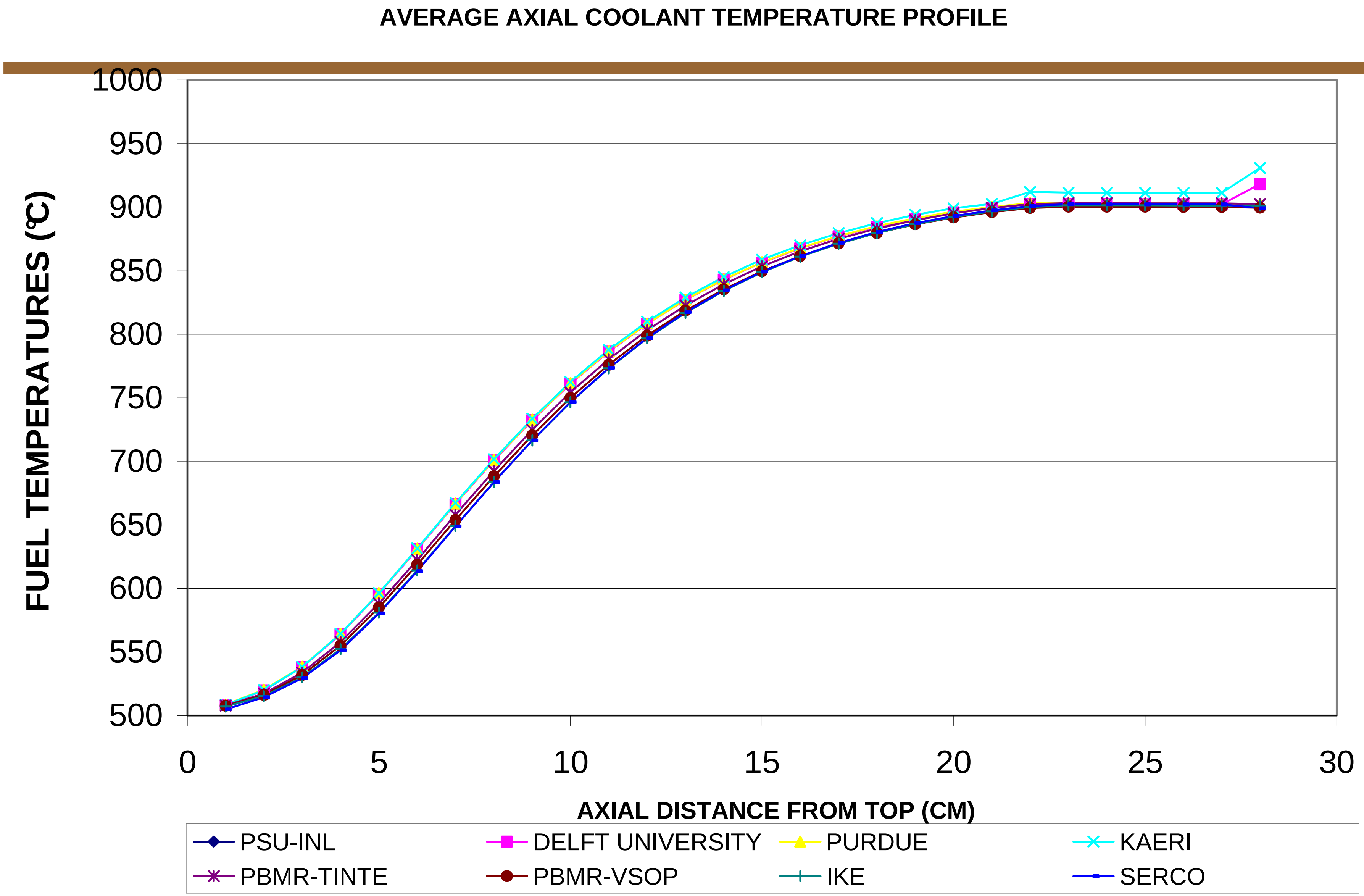


# Case S-2 Results



## AVERAGE AXIAL FUEL TEMPERATURE PROFILE

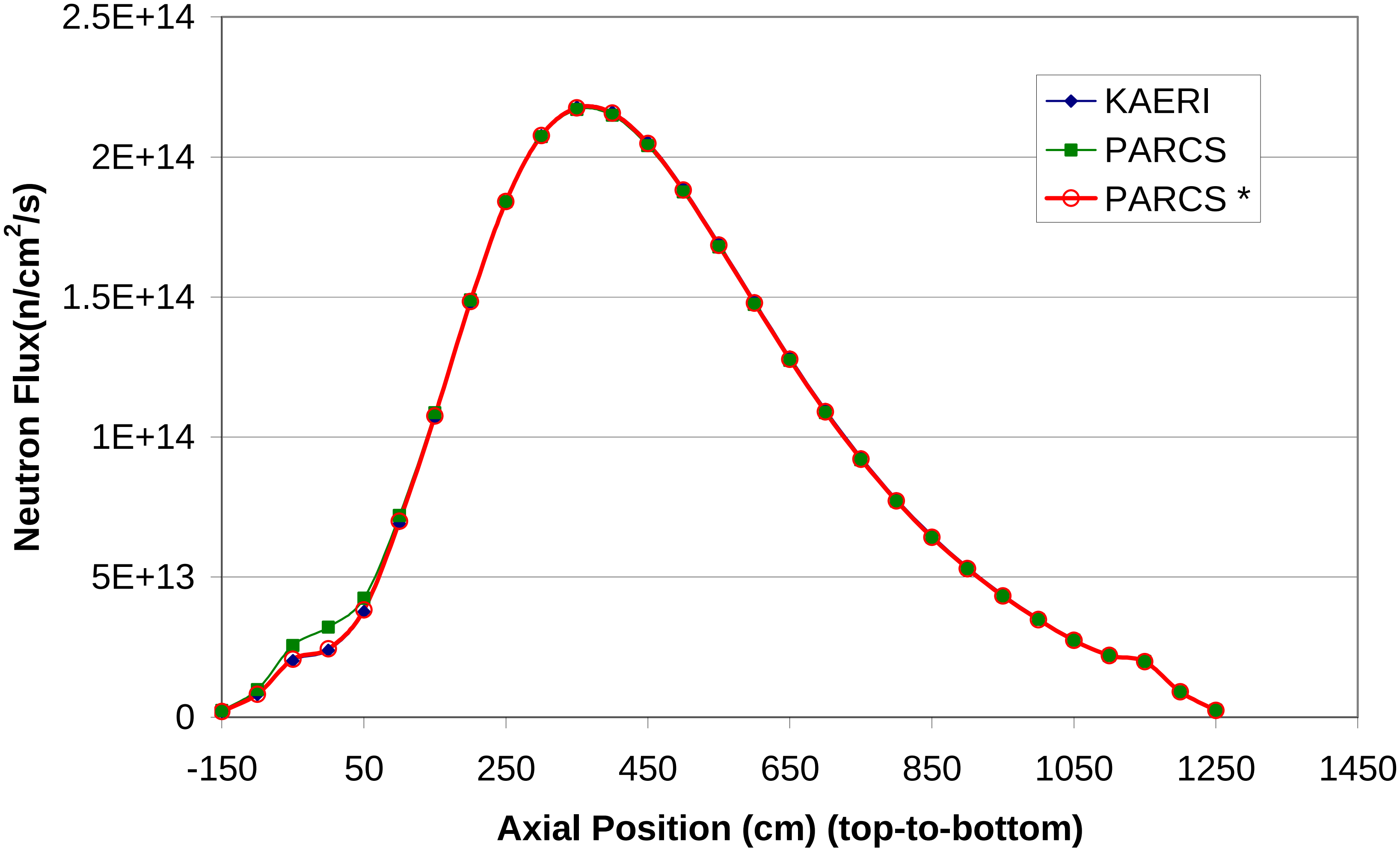



AVERAGE AXIAL COOLANT TEMPERATURE PROFILE
FUEL TEMPERATURES (℃)
1000
950
900
850
800
750
700
650
600
550
500
0
5
10
15
20
25
30
AXIAL DISTANCE FROM TOP (CM)
PSU-INL
DELFT UNIVERSITY
PURDUE
KAERI
PBMR-TINTE
PBMR-VSOP
IKE
SERCO

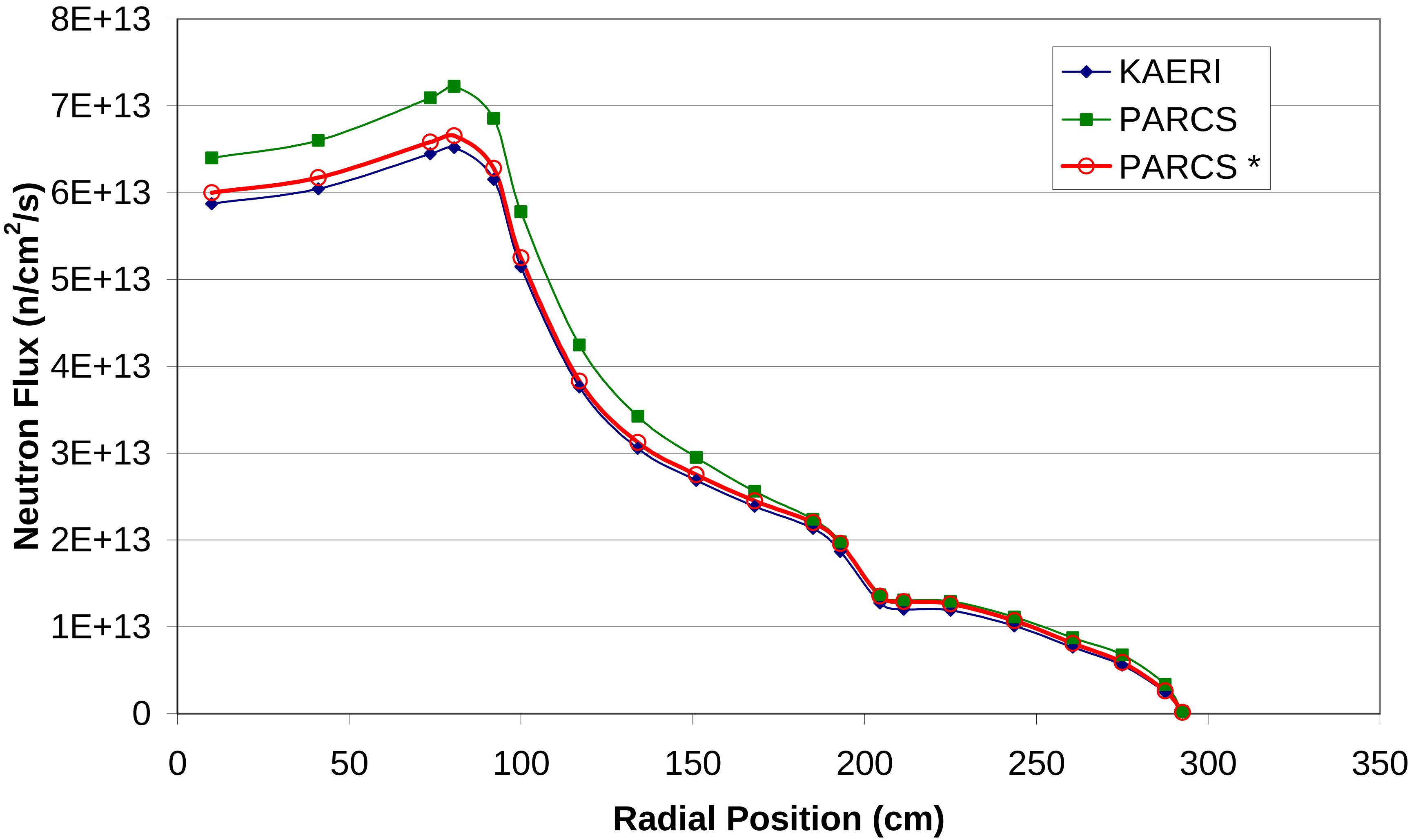
# Case S-3 Results

| CODE | keff |
|---|---|
| CAPP/MARS | 0.99270 |
| PARCS | 0.99283 |
| PARCS * | 0.99282 |
| | **keff (at zero power)** |
| PARCS * | 1.04099 |
| KAERI | 1.04090 |
| ** Calculation with single diffusion coefficient* | |

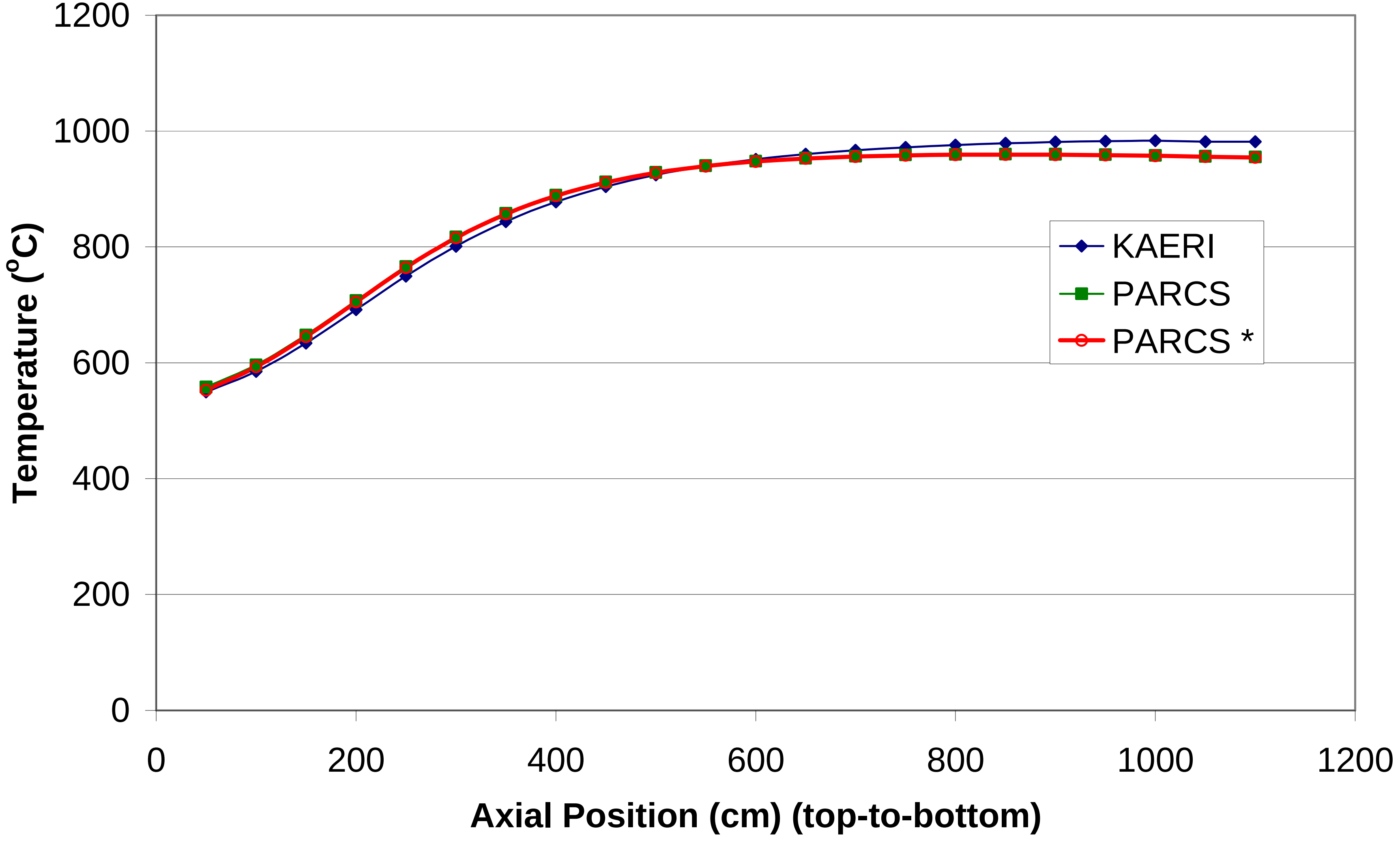
# Axial Thermal Flux



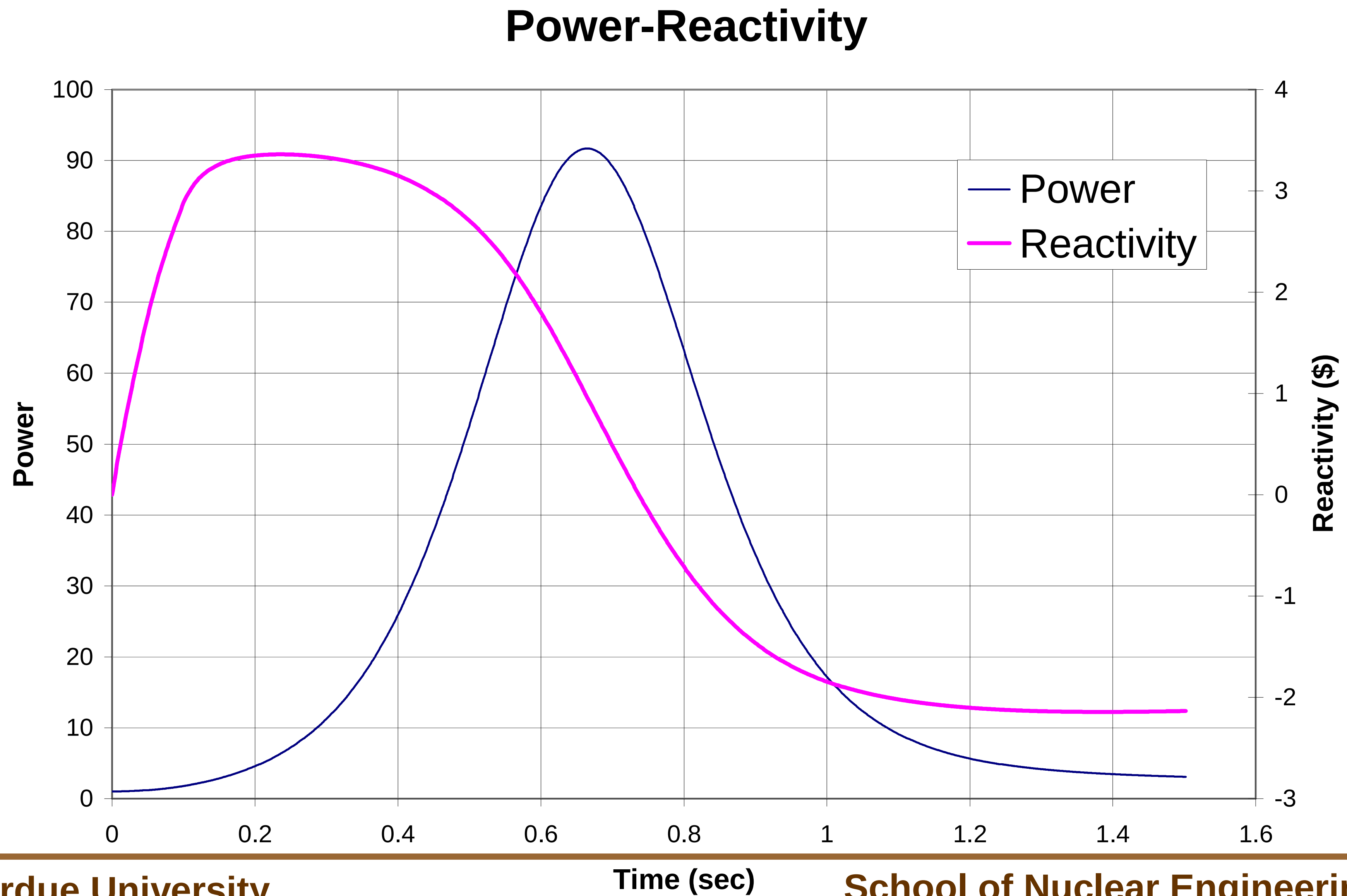
# Radial Thermal Flux (Top plane)



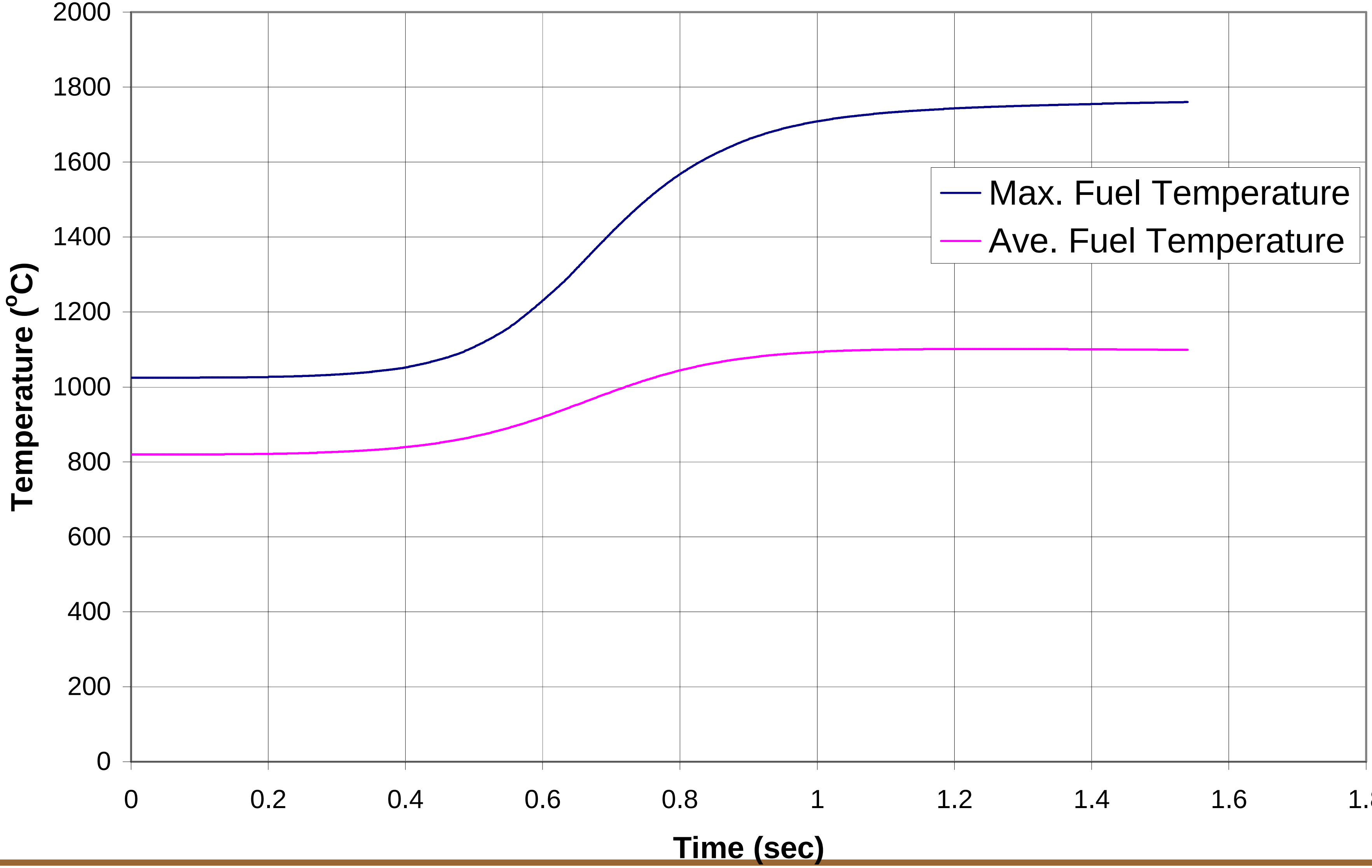
# Doppler Temperature



# CASE T-5 Results



# Fuel Temperatures



# Summary And Future Work

- A 3-D thermal hydraulic solver for PBRs is developed.
- A 3-D neutronics solver is developed by utilizing finite difference neutron diffusion equation.
- Verification of the standalone codes by simulating several experiments and benchmark problems has also been performed.
- Further analysis and validation is being performed for the transient conditions using the OECD/NEA PBMR-400 Benchmark