HTGR Technology Course for the Nuclear Regulatory Commission

May 24 – 27, 2010

Module 6b

Pebble Bed HTGR Nuclear Design

Outline

- Pebble bed nuclear design characteristics
- Nuclear design considerations
- Analytical tools

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Pebble Bed Nuclear Design

Core Neutronics / Thermal Hydraulics

Analyze Neutronic Design for feedback to both engineering and safety

Steady-State (VSOP, MCNP) and Transient (TINTE) Analysis

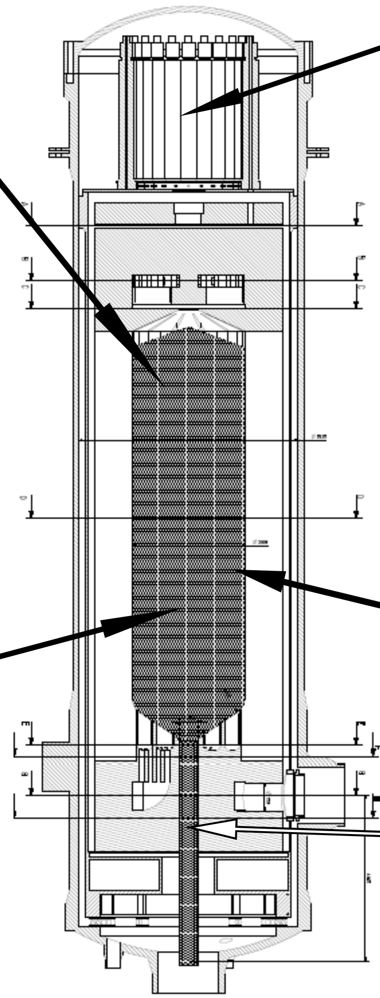
Input to engineering on core component temperatures, power profiles etc.

Input to safety on maximum fuel temperatures, control rod worth etc.

Fission Product Releases

Determine Fission Product Releases for both normal operation and accident scenarios

Input to the rest of the source term analysis chain



Shielding and Activation

Analyze Shielding and Activation of core structures and surrounding

Monte Carlo Analysis (MCNP) or simplified transport analysis (MicroShield)

Input to engineering on core component activities for maintenance / decommissioning

Input to safety for worker dose

Dust Generation and Activation

Graphite and metallic dust generation in the core and fuel handling system and activation of the dust

Fuel Source Term

Neutron and photon sources from spent and used fuel

Key Pebble Bed Nuclear Characteristics

- Continuous fueling provides core design flexibility to introduce different fuel cycles on-line
- Burnup measurement of each sphere instead of calculations reduces core design uncertainty
- No reload analyses are required and approach to criticality is only required for initial core loading or after reflector replacement is performed

Fuel Cycle Flexibility

- **Pebble bed can also be used for U-Th, Pu disposition and MOX**
- **AVR experience demonstrated core operation with between 4 and 14 different fuel elements**
  - Heavy metal loadings ranging from 5g to 20g
  - Enrichments ranging from 5% to 93% U-235
- **Different fuel cycle can be introduced on-line and the reactivity effect can be monitored continuously during the transition period**

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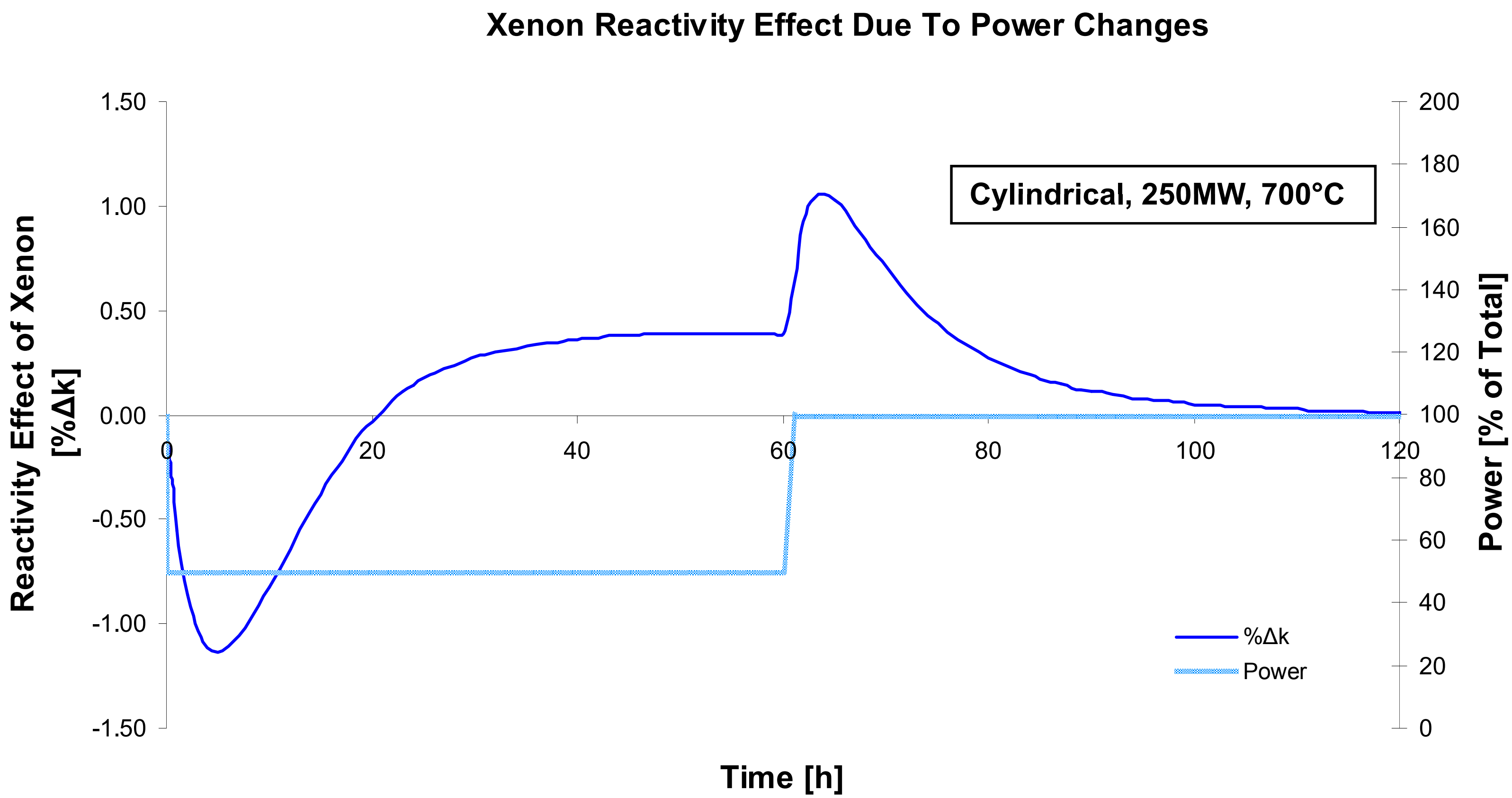
Key Considerations

- Equilibrium core parameters
- Excess reactivity
- Neutron control and shutdown
- Temperature coefficients
- Xenon stability
- Power distribution
- Neutron flux
- Fuel temperatures
- Burnup
- Decay heat

Typical Equilibrium Core Parameters

Description	Units	PBMR-400MW	PBMR-250MW
Thermal power	MW	400	250
Core diameter (inner/outer)	m	2.0/3.7	1.5
Core height (average)	M	11.0	10.5
Helium coolant temperatures (Inlet/Outlet)	°C	500/900	250/750
U-235 enrichment	wt%	9.6	7.8
Number of average fuel sphere cycles		6	15
Average residence time in core	Days	~ 930	~ 1080
Average discharge burn-up	MWd/t	91 450	81 565
Number of Fuel Spheres (FS)		~ 452 000	~ 400 300
Average number of fresh fuel spheres to be loaded per day		~ 486	~ 438
Average number of fuel spheres recirculated per day		~ 2 913	~ 6 566

Load Following Requirement



- Changes in reactor power causes Xe changes in core that affects the reactivity
- This lowering of reactivity following a power change needs to be compensated for by adding excess reactivity

Excess Reactivity

- The excess reactivity is the additional reactivity available in the core during operating conditions by the loading of a fuel mixture that is more reactive (less burned) than what is required to keep the reactor critical at the full power operational conditions (temperatures and equilibrium fission products)

- The excess reactivity is balanced by the insertion of the control rods to keep the reactor critical

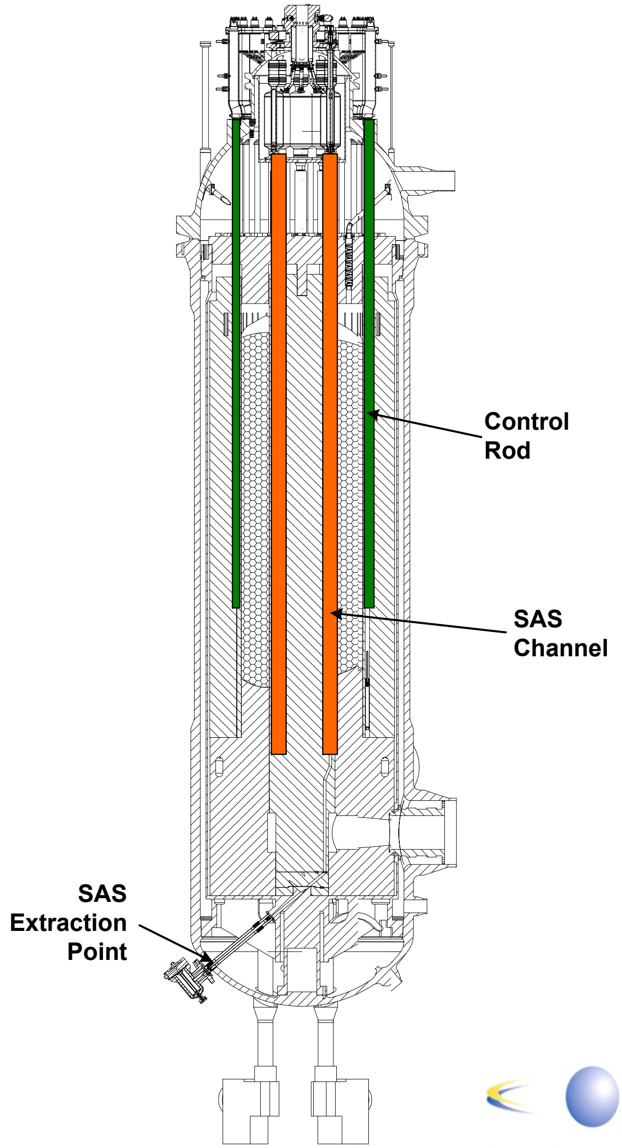
- The excess reactivity can be changed by changing the position of the control rods and the adjusting loading of fresh fuel into the core

Neutron Control and Instrumentation Requirements

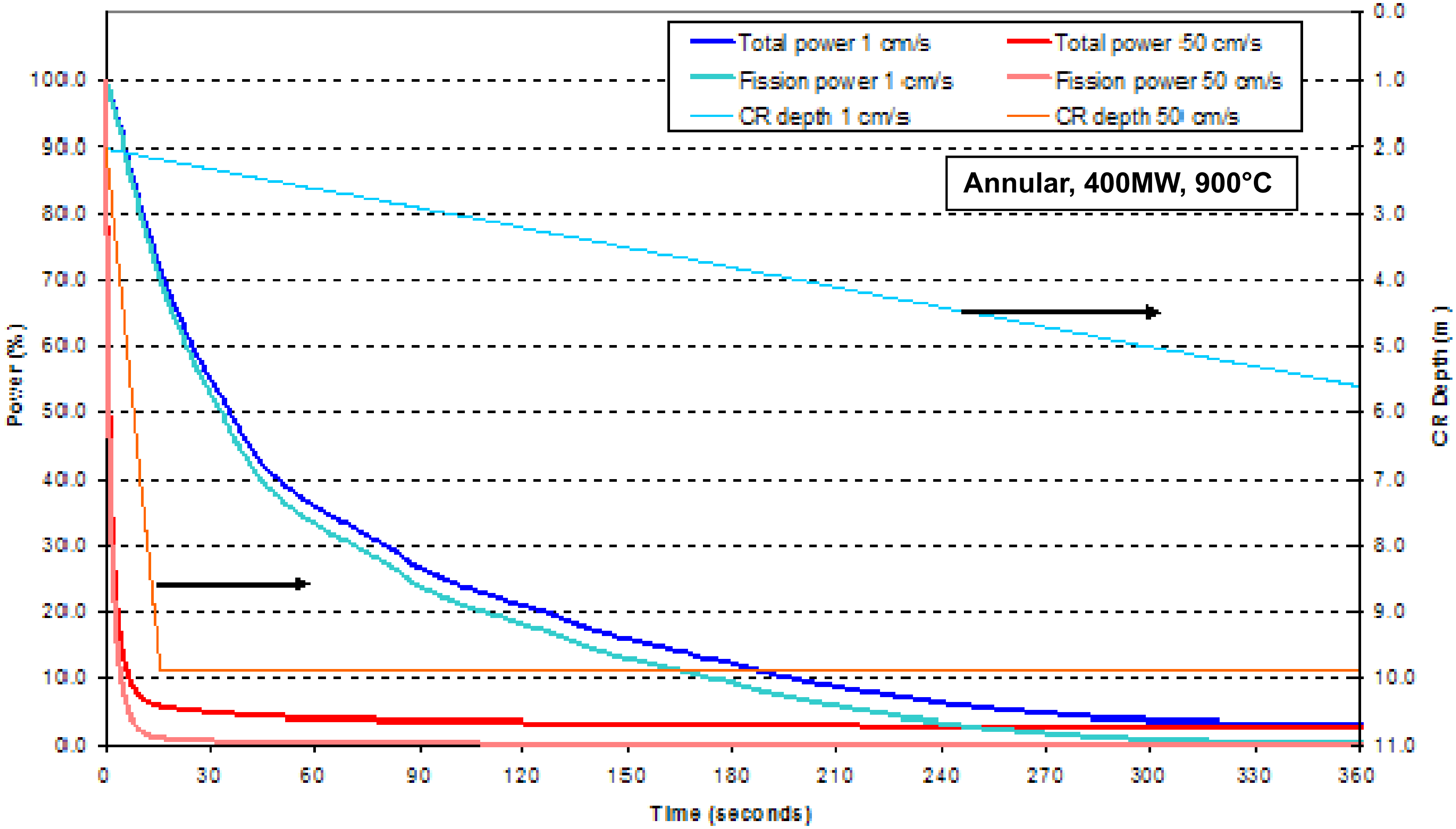
- Provide two independent and diverse systems of reactivity control for reactor shutdown
- Each system shall be capable of maintaining hot subcriticality
- One system shall be capable of maintaining cold shutdown
- Provide neutron flux (low, intermediate and high range) and axial profile measurements

Typical Pebble Bed Neutron Control Systems

- Control rods are used for operational (ROT) control and hot shutdown
- Small absorber spheres (SAS) are used to achieve cold shutdown
- Control rods and SAS are located in reflectors (SR/SR or SR/CR)
- Control rods can be operated in banks

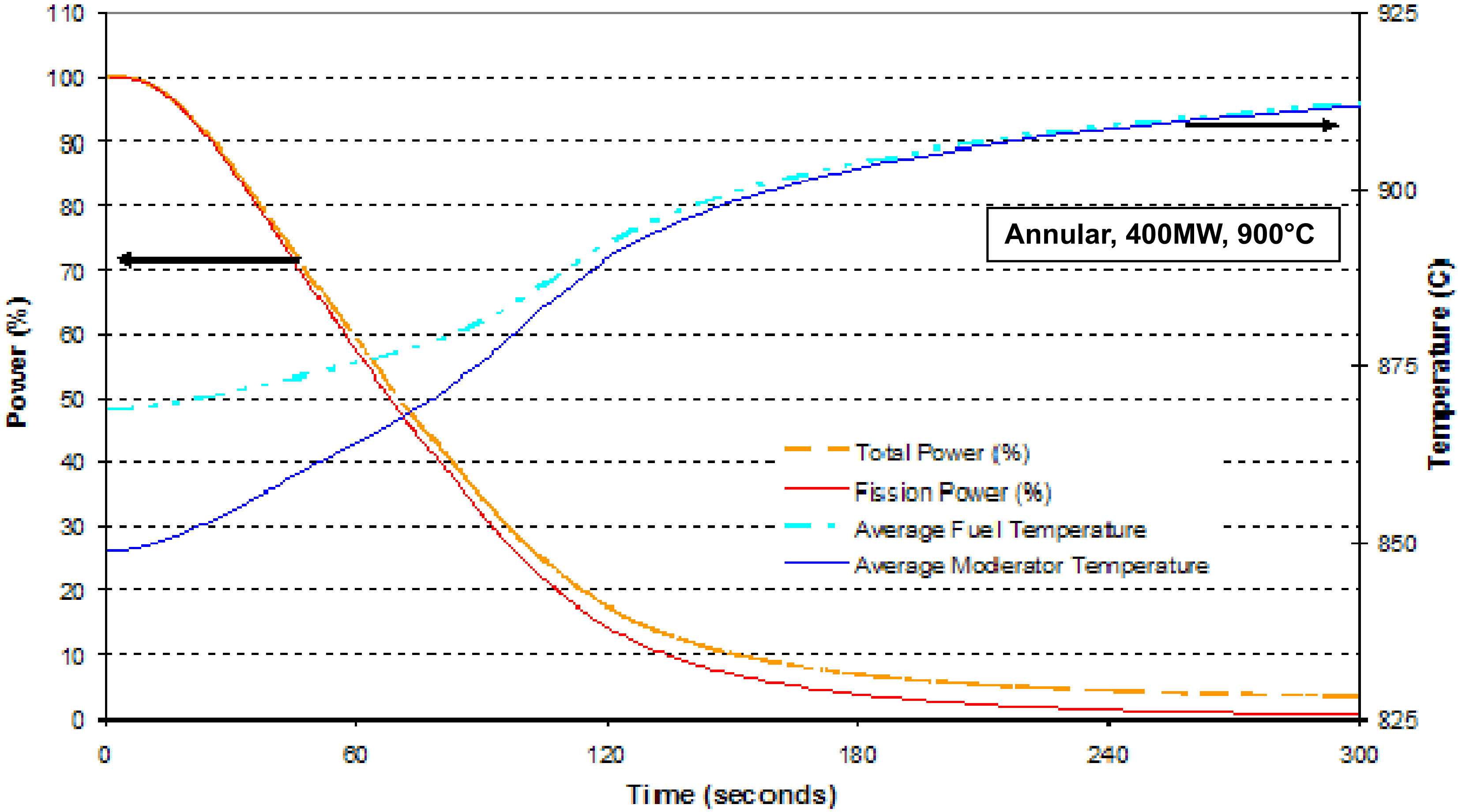


Reactor Shutdown with Control Rods



- Rapid shutdown of reactor for two different control rod speeds
- 1 cm/s is the normal controlled insertion
- 50 cm/s is the scram speed when the power is cut to the CRDMs

Shutdown by Interruption of Coolant Flow



- When the coolant flow is stopped through the core, the sphere temperatures increase and the reactor is shutdown, even with no movement of the control rods
- This temperature coefficient effect has been successfully demonstrated in the AVR and HTR-10

Temperature Coefficients

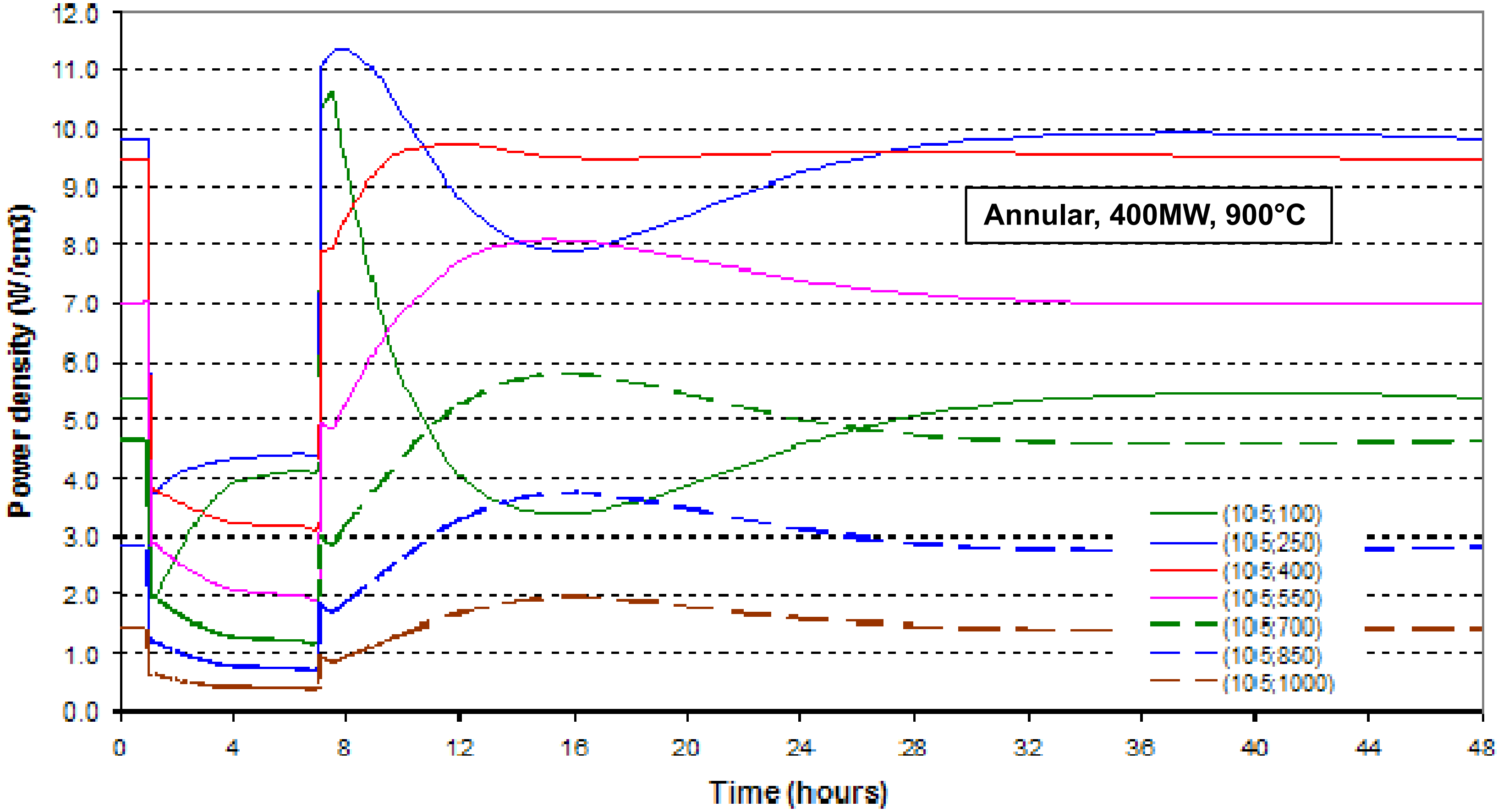
Temperature Coefficients	Unit	Annular, 400MW, 900°C At Operating Conditions
Fuel (Doppler coefficient of mainly ^{238}U)	$\Delta\rho$/°C	- 4.4 $x10^{-5}$
Moderator	$\Delta\rho$/°C	- 1.0 $x10^{-5}$
Reflector regions (all together)	$\Delta\rho$/°C	+ 1.8 $x10^{-5}$
TOTAL	***$\Delta\rho$/°C***	***- 3.6 $x10^{-5}$***

- **The Doppler temperature coefficient acts promptly and stabilizes the nuclear chain reaction.**
- **The moderator coefficient acts promptly when temperature change of the moderator is the primary event, and causes a response in the neutron flux and fission rate.**
- **The reflector temperature changes are not so strongly coupled to power changes in the fuel. The side reflector temperature is dominated by the coolant temperature in the riser channel and combined with the large heat capacity will cause a considerable delay of effect of the reflector temperature coefficient.**

Xenon Stability

- **Xenon stability refer to the degree to which the spatial flux distribution varies for a specific reactor design due to spatial xenon dynamics**
- **The main question is whether the change in xenon concentration with time exhibits a damped or un-damped oscillatory behavior**
- **Previous studies on HTGR-specific xenon stability reported the following conclusions:**
  - Un-damped axial xenon oscillations only occurred for HTR cores when the core height was increased to larger than 8 m, with a simultaneous power density increase to more than 20 MW/m3
  - No un-damped radial xenon oscillations were observed for cylindrical cores of up to 6.4 m in radius

Xenon Oscillation Results from 100%-40%-100% Power Variation

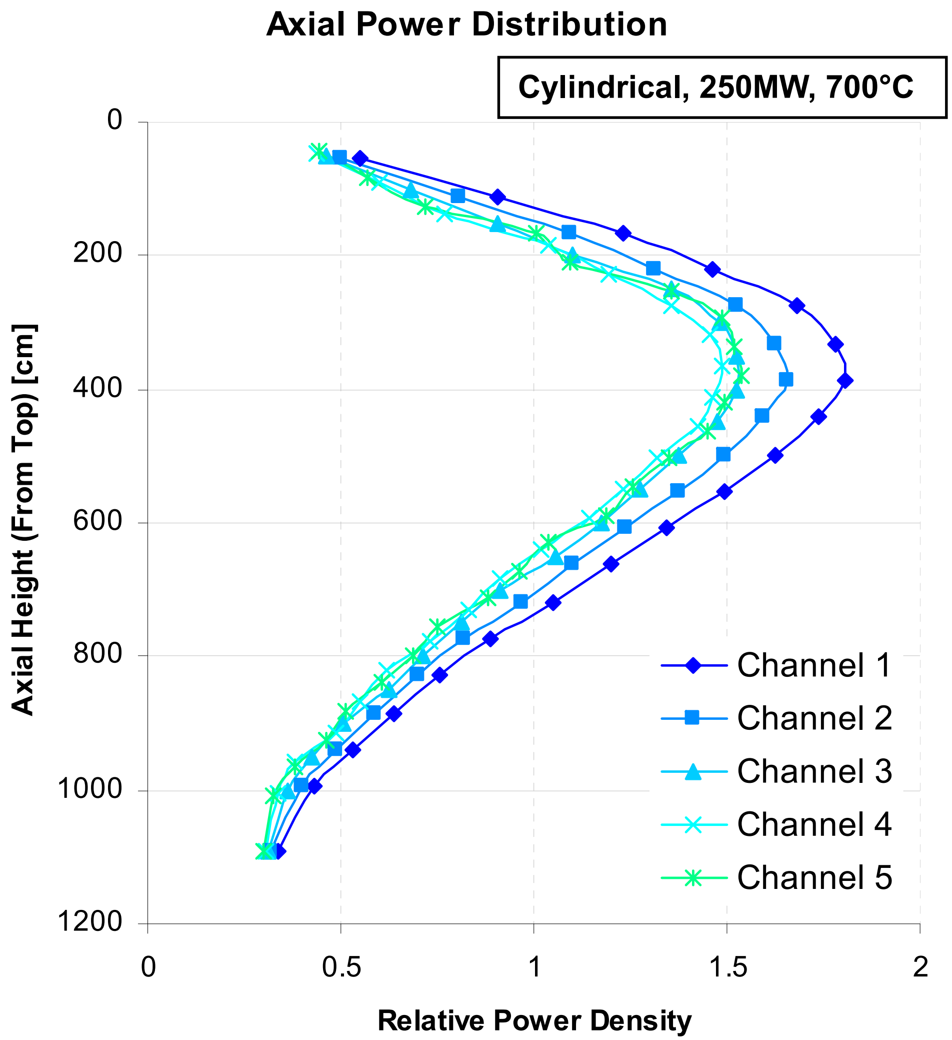


- **Legend refers to different heights in the core with 100 being near the top of the bed and 1000 being at the bottom of the bed**

Power Shaping

- Pebble beds do not have to use fuel loading or burnable poison to affect power shaping
- Fuel can be circulated faster through the core to flatten the axial power profile
- Once equilibrium conditions are established control rods do not need to be moved to compensate for burnup

Axial Power Distribution



- **The power profile is biased towards the top of the core due to the lower fuel temperatures and fresh fuel**
- **The top of the power profile is depressed due to the partially inserted control rods**
- **Since no burnable poisons are used with on-line refueling, this power profile is representative of the greater part of plant operation**

Note: channels are not physical but represent sphere flow regions for modeling with channel 1 towards the centre of the core and channel 5 towards the outside of the core

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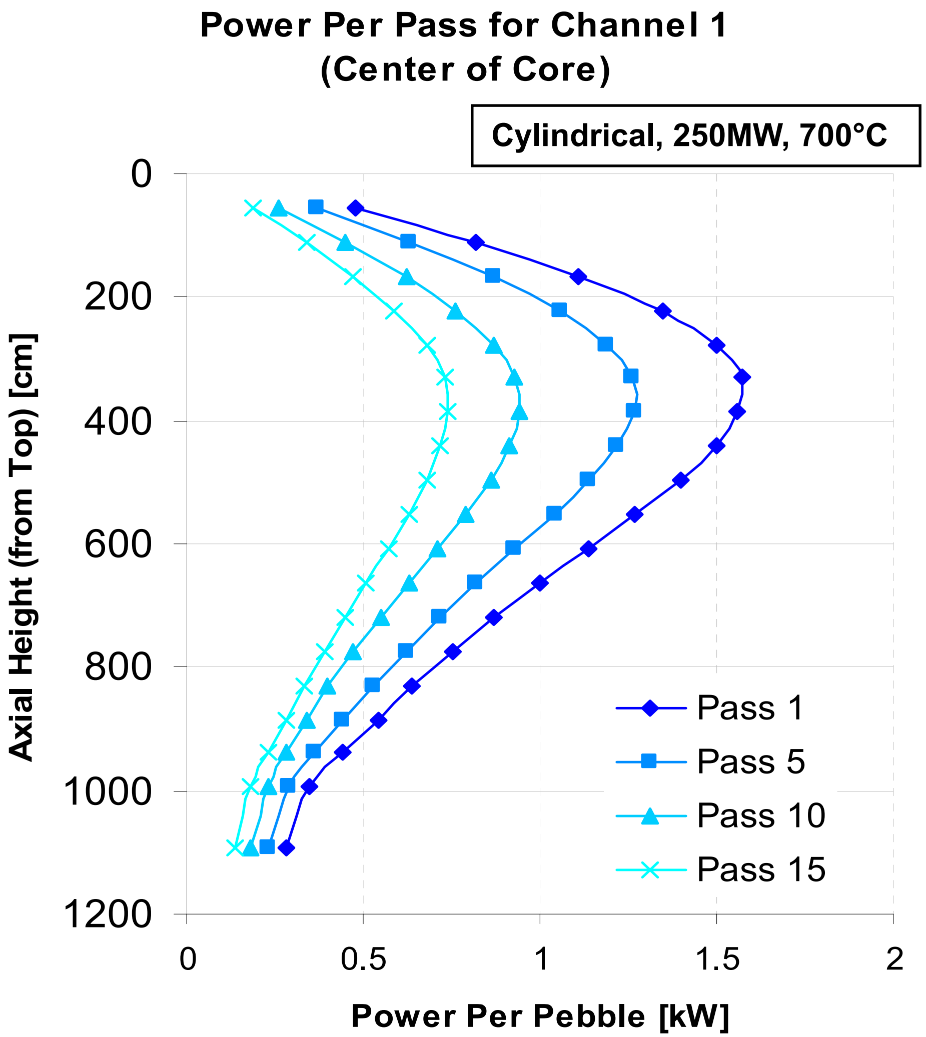
Power Distribution per Pass



- **The power produced per fuel sphere reduces with each pass through the core**

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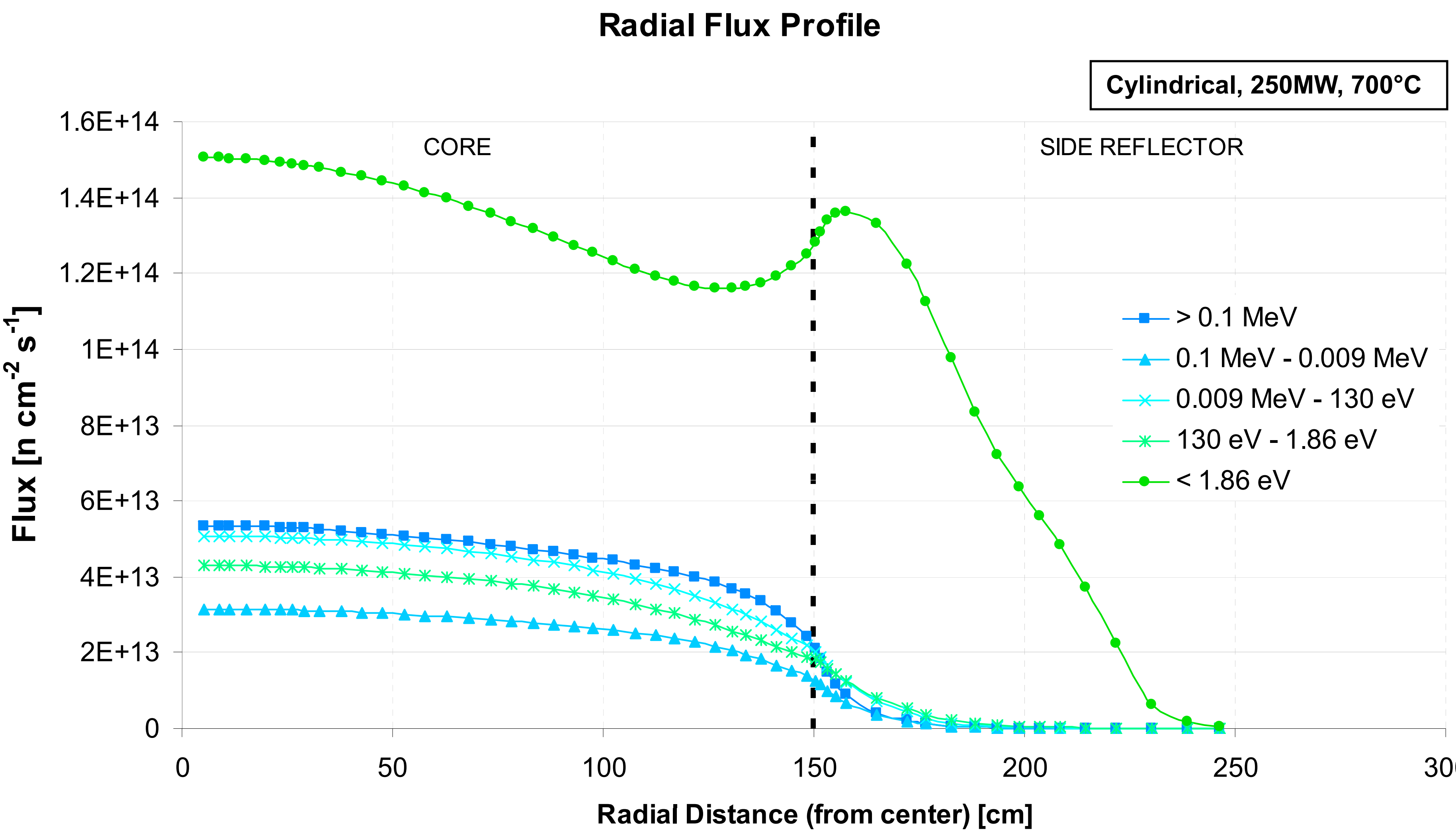
Neutron Flux Distribution (Radial)



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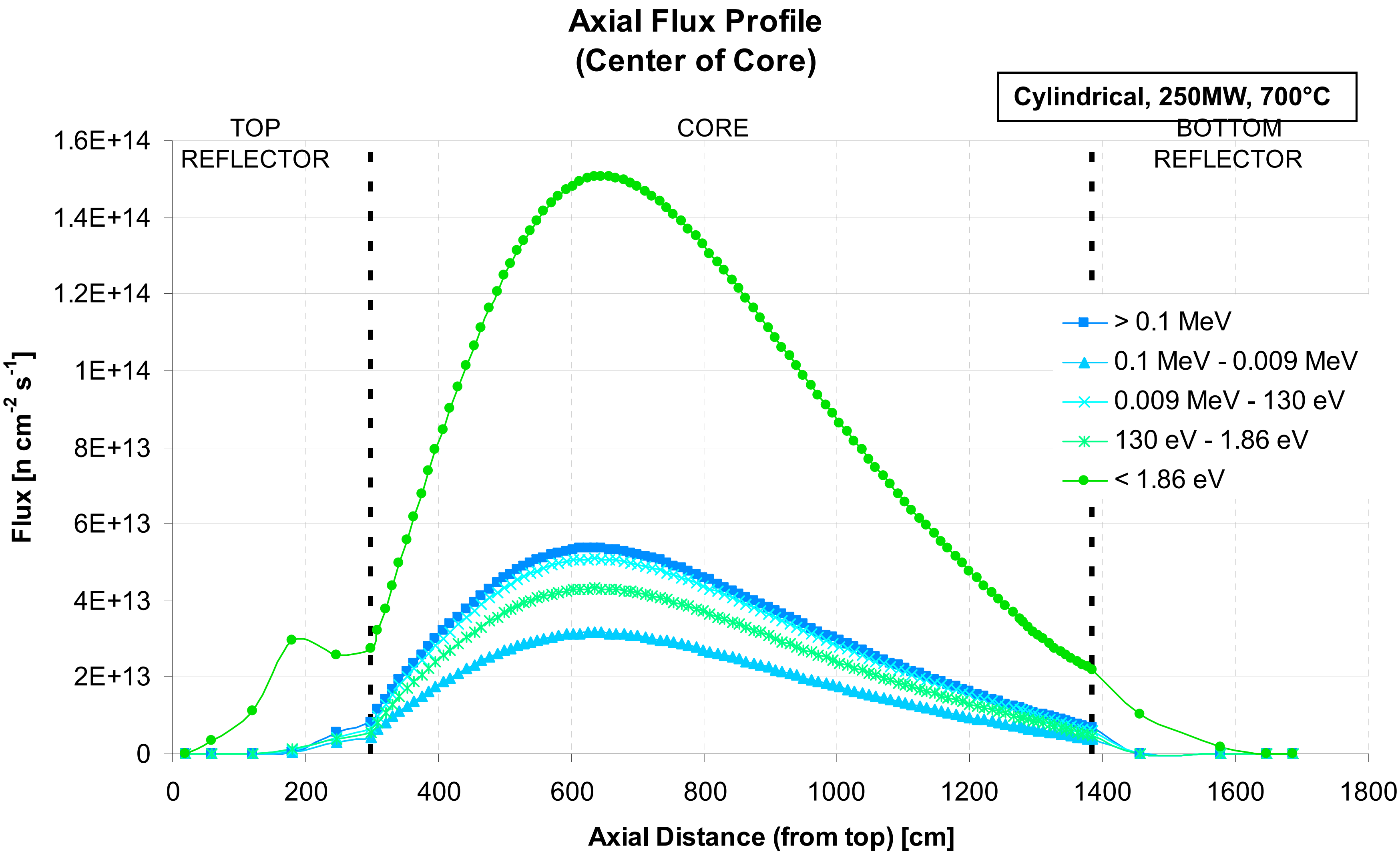
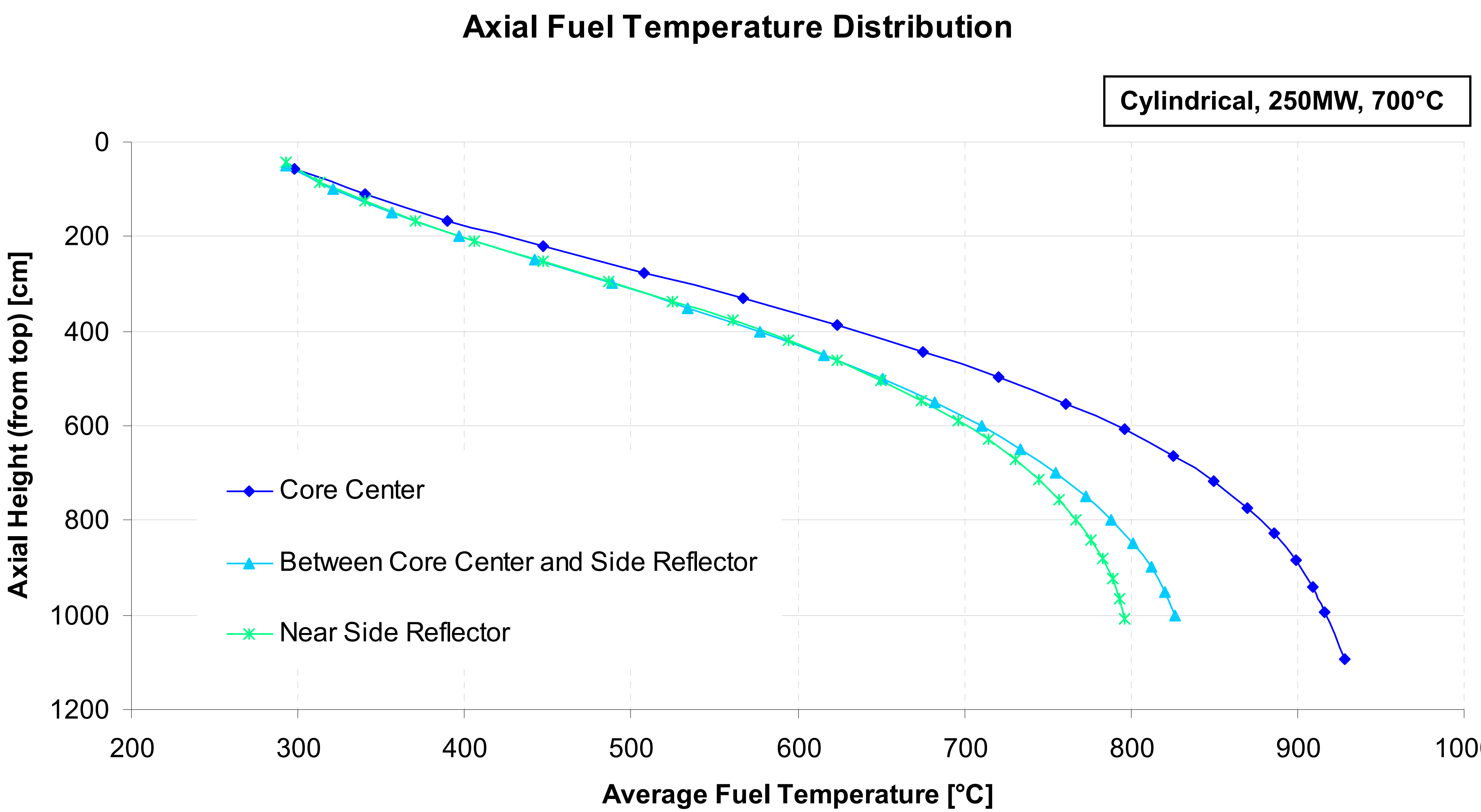
Neutron Flux Distribution (Axial)



Temperature Distribution for Equilibrium Core



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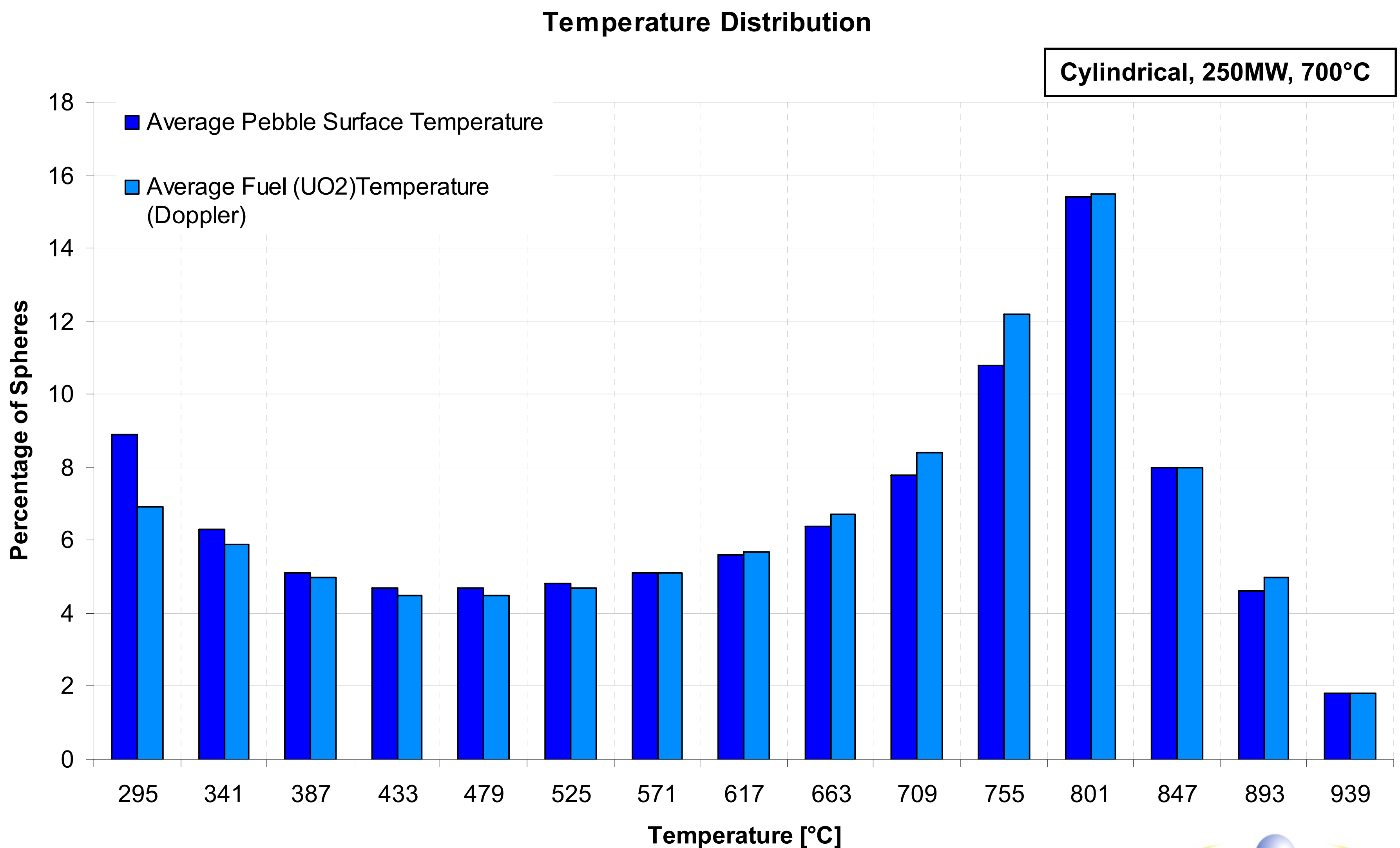
Fuel Temperature Distribution



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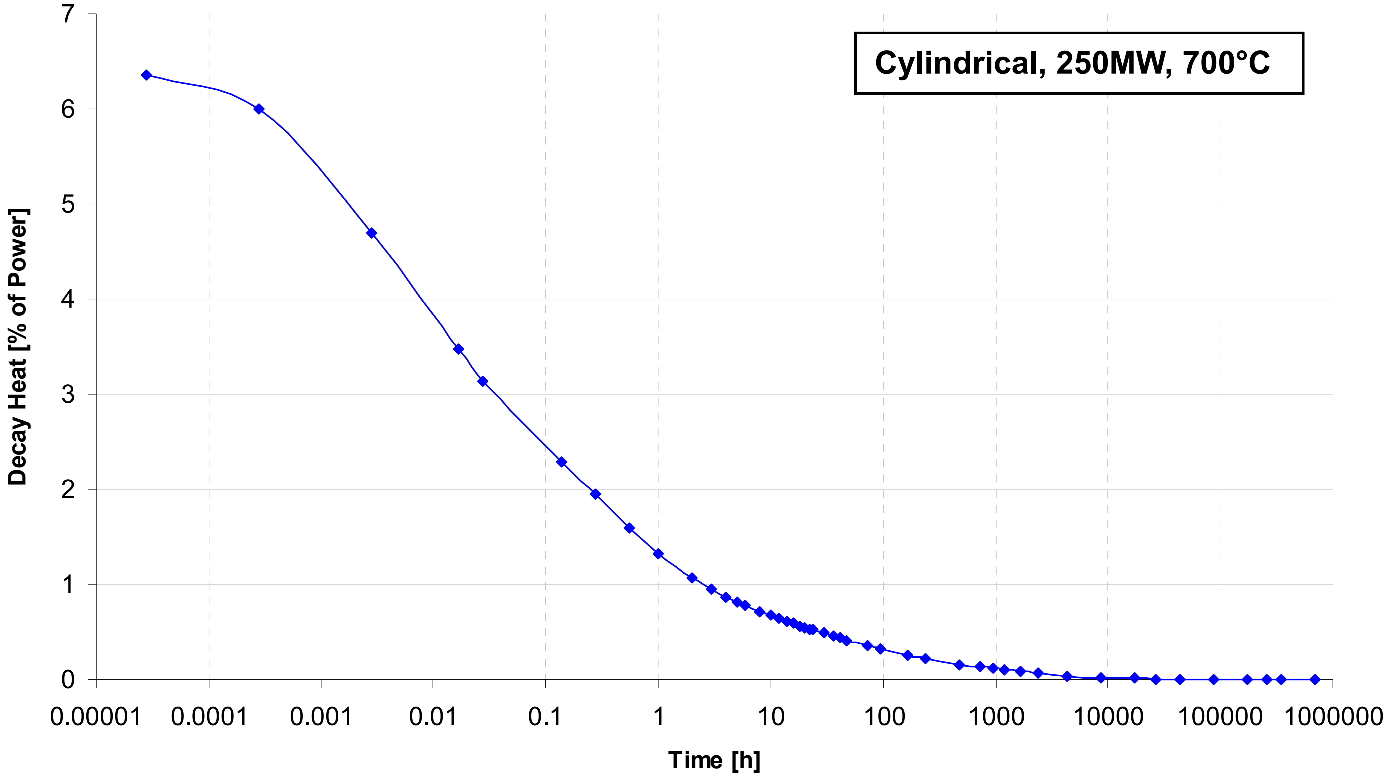
Burnup

- **Fuel spheres are circulated through the core continuously and each sphere is measured for burnup as it comes out of the core**
- **Fuel spheres that have not yet reached target burn-up, or more specifically the burnup limit setpoint, can be reloaded and recycled continuously during normal reactor operation.**
- **Fuel spheres with higher burn-up as the setpoint are discharged from the refueling line, and replaced with a fresh fuel sphere. In practice some fuel may pass through the reactor less than the average number of passes while others may pass more times before reaching the setpoint burnup value.**
- **The Burnup Measurement System discriminates between spent and used fuel spheres by analyzing the gamma energy spectrum to determine the inventory of specific nuclides (specifically Cs-137).**

Decay Heat

- German standard DIN is used to evaluate decay heat
- The standard provide the methodology to calculate the heat power generated by the decay of the fission products (valid for all kinds of thermal reactors) and rules concerning the additional sources of decay heat (activation) in the fuel of pebble-bed high temperature reactors



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PBMR Nuclear Codes

- **Analysis Codes**
  - **VSOP99/5:** HTR core neutronics code including cell calculations, 2D and 3D reactor physics simulation, depletion and 2D quasi-static thermal-hydraulic
  - **T-REX:** 1-D transport solution used to model control rods for VSOP99/5
  - **TINTE:** HTR transient analysis tool based on 2-D spatial kinetics
  - **GETTER:** Metallic (long lived) fission product release calculation software for normal and accident conditions.
  - **NOBLEG:** Steady state gaseous (short lived) fission product release calculation software
  - **SCALE5:** Used for the calculation of the fuel source term and fuel depletion
  - **DAMD:** Calculation of radioactive source terms on the surfaces and in the coolant due to the plate-out of condensable atomic fission products released from the fuel in the core. The code also calculates the deposition of dust and the amount of dust circulating in the coolant.
  - **MCNP5:** Monte Carlo code for neutron, photon and electron transport and the calculation of criticality
  - **FISPACT:** Code for the calculation of neutron induced activation source terms

Summary

- The nuclear design of a pebble bed reactor is simple and straightforward
- The on-line refueling provides significant flexibility to the core designer to choose a fuel cycle whilst reducing uncertainty in the core calculations
- The core designer has well proven and validated nuclear design codes at his disposal to calculate the core behavior and characteristics

Suggested Reading

- PBMR Nuclear Design and Safety Analysis: An Overview, Stoker, C.C., PHYSOR 2006, Vancouver, BC, Canada, September 10-14.
- Plutonium Disposition in the PBMR-400 HTGR, E. Mulder, PHYSOR 2004, April 2004
- The Pebble Bed Modular Reactor Layout and Neutronics Design of the Equilibrium Cycle, Reitsma, F., Proceedings of PHYSOR2004 Meeting, Chicago, USA, April 25-29, 2004.
- An Overview of the FZJ-Tools for HTR Core Design and Reactor Dynamics, the Past, Present and Future, Reitsma, F., Rütten, H. J. and Scherer, W., Mathematics and Computation, Supercomputing, Reactor Physics and Nuclear and Biological Applications, Palais des Papes, Avignon, France, September 12-15, 2006
- Comparison of VSOP and MCNP Results of PBMR Equilibrium Core Model, Sen, S., Albornoz, F., and Reitsma, F., Proceedings of the 3rd International Topical Meeting on High Temperature Reactor Technology, Johannesburg, Gauteng, South Africa, 2006
- The Re-evaluation of the AVR Melt-Wire Experiment Using Modern Methods with Specific Focus on Bounding the Bypass Flow Effects, Viljoen, C. F., et al Proceedings of the 4th International Topical Meeting on High Temperature Reactor Technology, HTR-2008, Washington DC, USA, 2008