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Calculations
Verification
Analysis

https://www.iaea.org/NuclearPower/Downloadable/Meetings/2012/2012-10-22-10-26-WS-NPTD/Day-2/8.Reitsma.pdf

Pebble-bed Reactor Core Neutronics Design and Fuel Cycle

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IAEA Course on High temperature Gas Cooled
Reactor Technology

Oct 22-26, 2012

Two areas to be covered

- Core Neutronics
- Fuel Cycle

For the most part these two are closely coupled…

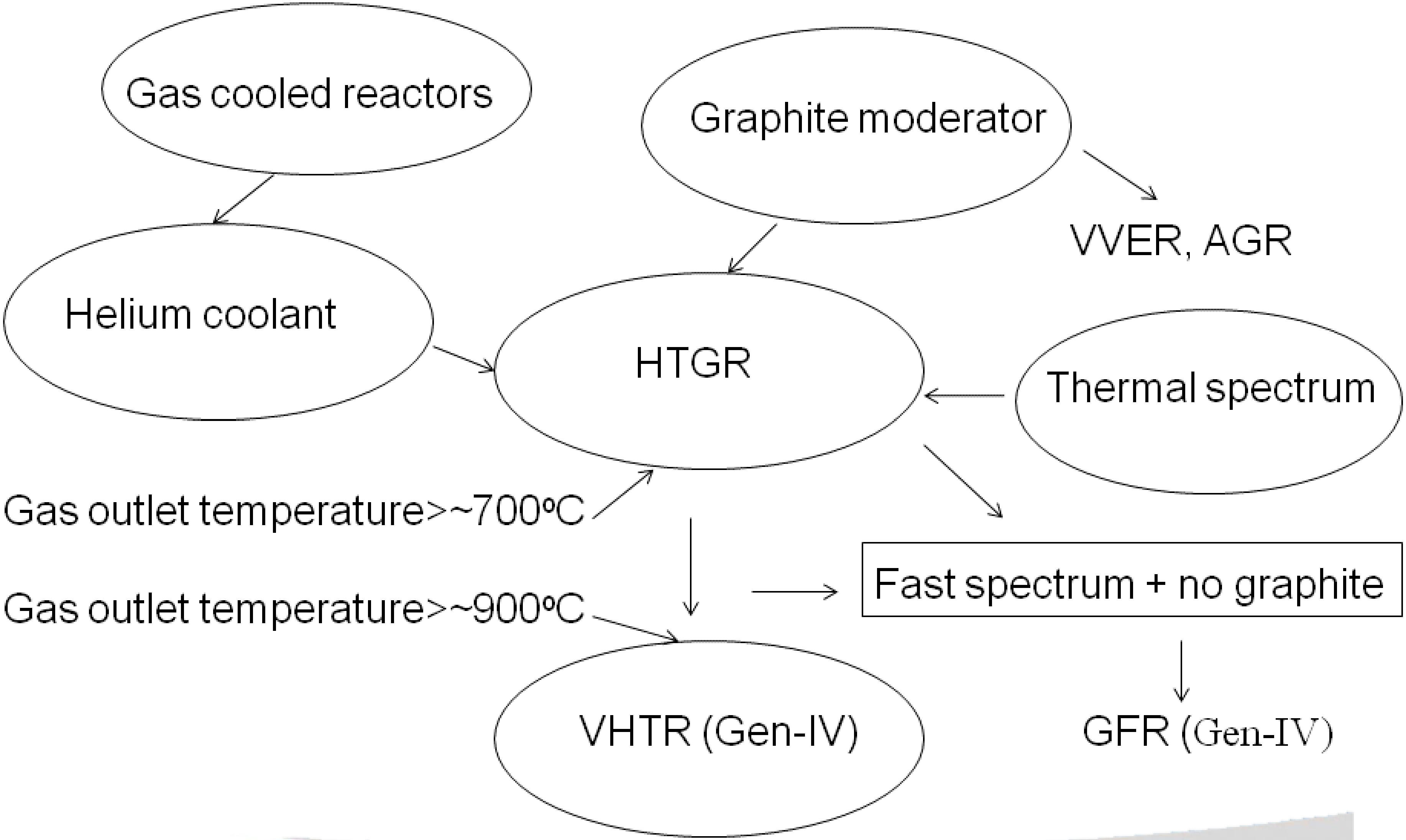
  - Power distribution
  - Decay heat values
  - Accident condition temperatures
  - Temperature feedback coefficients

… but will look at fuel cycles without expressing any opinion of its neutronics, thermal and safety performance.

Core neutronics contents

- Pebble bed reactors
  - Family heritage
  - Some characteristics
  - Why pebble bed reactors ?
- Core neutronics focus areas
  - Unique features of graphite moderated pebble bed reactors
  - Why is multi-physics / multi-scale needed
- Concluding remarks

HTGR Family Tree



Gas cooled reactors

Graphite moderator

VVER, AGR

Helium coolant

HTGR

Thermal spectrum

Gas outlet temperature>~700ºC

Gas outlet temperature>~900ºC

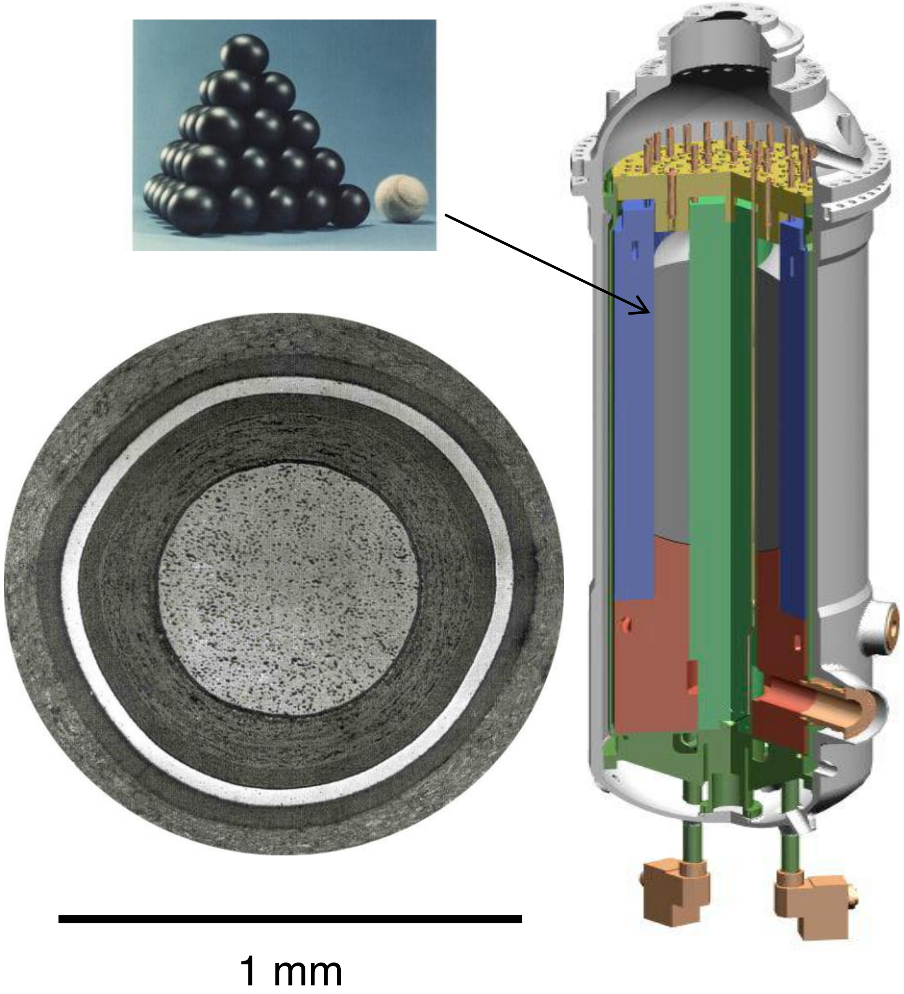
Fast spectrum + no graphite

VHTR (Gen-IV)

GFR (Gen-IV)

Pebble type HTGRs

Pebble Bed Reactor (PBR)



- Spherical graphite fuel element with coated particles
- Possibility of continuous fuel loading / shuffling
- Fuel loaded in cavity to form a pebble bed

HTR-Module principle

DIMENSIONS AND POWER ARE FIXED BY INHERENT PROPERTIES

[can not be chosen as usually]

Diameter: 'given' by shutdown from outside

D ~ 300 cm

Power density: 'given' by maximum fuel temperature [T = 1600 ^{o}C]

Q ~ 20 MW/m

Core height: 'given' by blower [dp~ 1.5 bar, Xenon]

H ~ 10 m

This yields a maximum power per Modul of:

P_{max} **= 200 – 280** MW_{th}

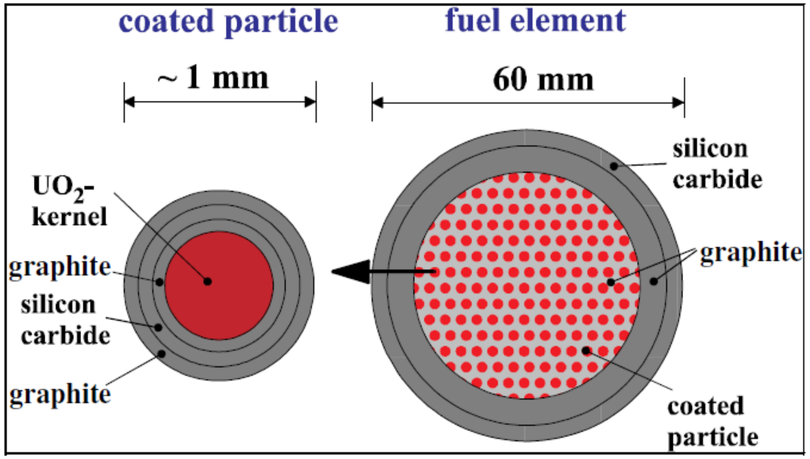
Prof Lohnert, Nov 10,2009

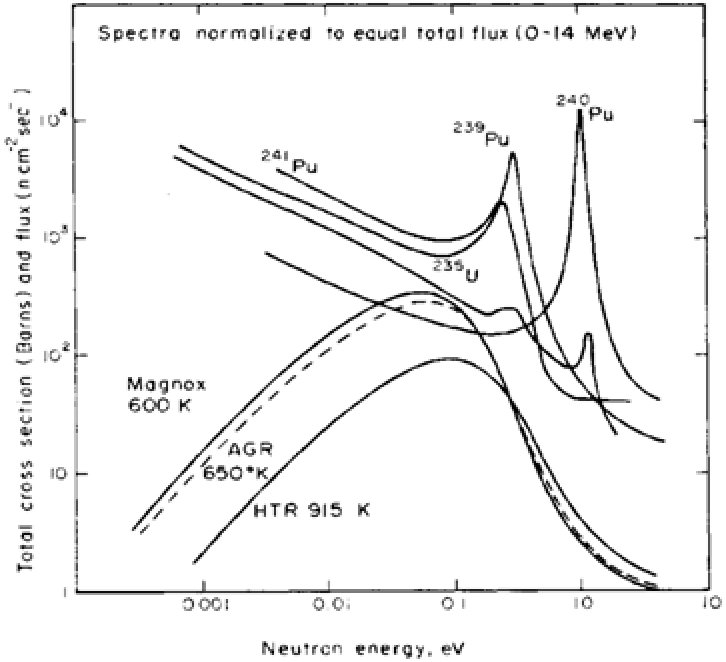
Why High-temperature Gas-cooled Reactors? Modular…

- Significantly improved safety
- Higher efficiency than conventional nuclear plants
- Attractive economics (to be proven in future…)
- Market is growing for smaller reactors
- Smaller reactors lend themselves to distributed generation (advantages relate to grid stability and transmission costs)
- Extended scope of application due to higher temperature availability; supply of process steam for petro-chemical industry and future hydrogen production
- Pebble Bed reactors offers enhanced non proliferation characteristics.
- The use of Th-232 in a HTR (specifically an on-load fuelling Pebble Bed Reactor) with U-233 recycle could significantly reduce reliance on uranium resources

General neutronics focus areas

- Fuel and core geometry require double heterogeneous treatment
- There is no direct coolant reactivity feedback; just moderator(-), fuel (-), and reflector (+)
- Burnup is (much) higher than in LWRs; uncertainties in cross sections exist
- Thermal upscattering into low-E resonance range (Pu)
- Heterogeneity at the core/reflector interface
- Control rods located in the reflector
- Coupling between pebbles – spectrum is not determined by the local fuel composition





Some unique features

- *Mean free paths*
- *Neutron spectrum*
- *Temperature coefficients of reactivity*
- *Reflector effects*
- *Spectrum zone concept / in-line or imbedded calculations*
- Pebbles / fuel spheres
  - Randomly packed spheres
  - *Multi-cycle / multi-pass*
  - Variations in packing, physics and heat removal
  - *Pebble flow lines and residence times*
  - Burnup treatment / book keeping…..
  - Burnup measurement

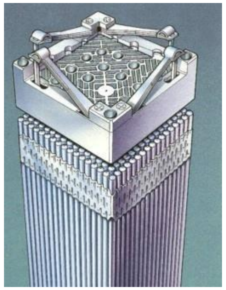
Neutronic Resolution and Coupling

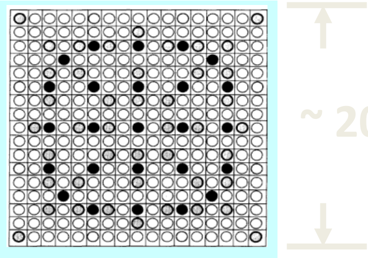
Assembly

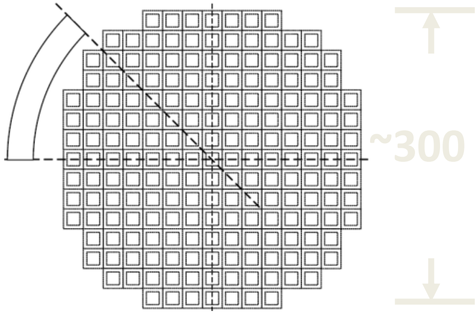
Core

LWR

1 cm

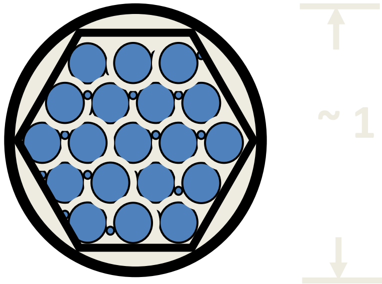


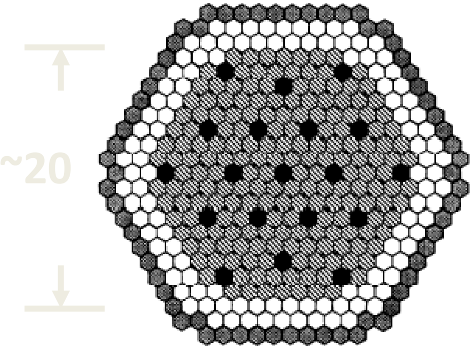




SFR

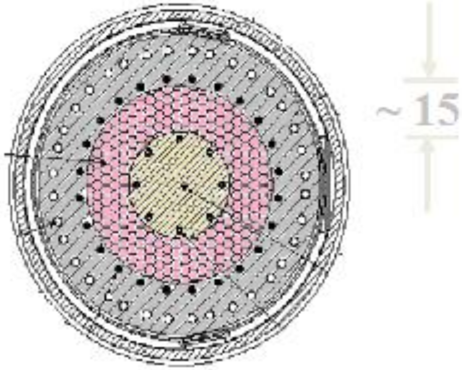
5-8 cm



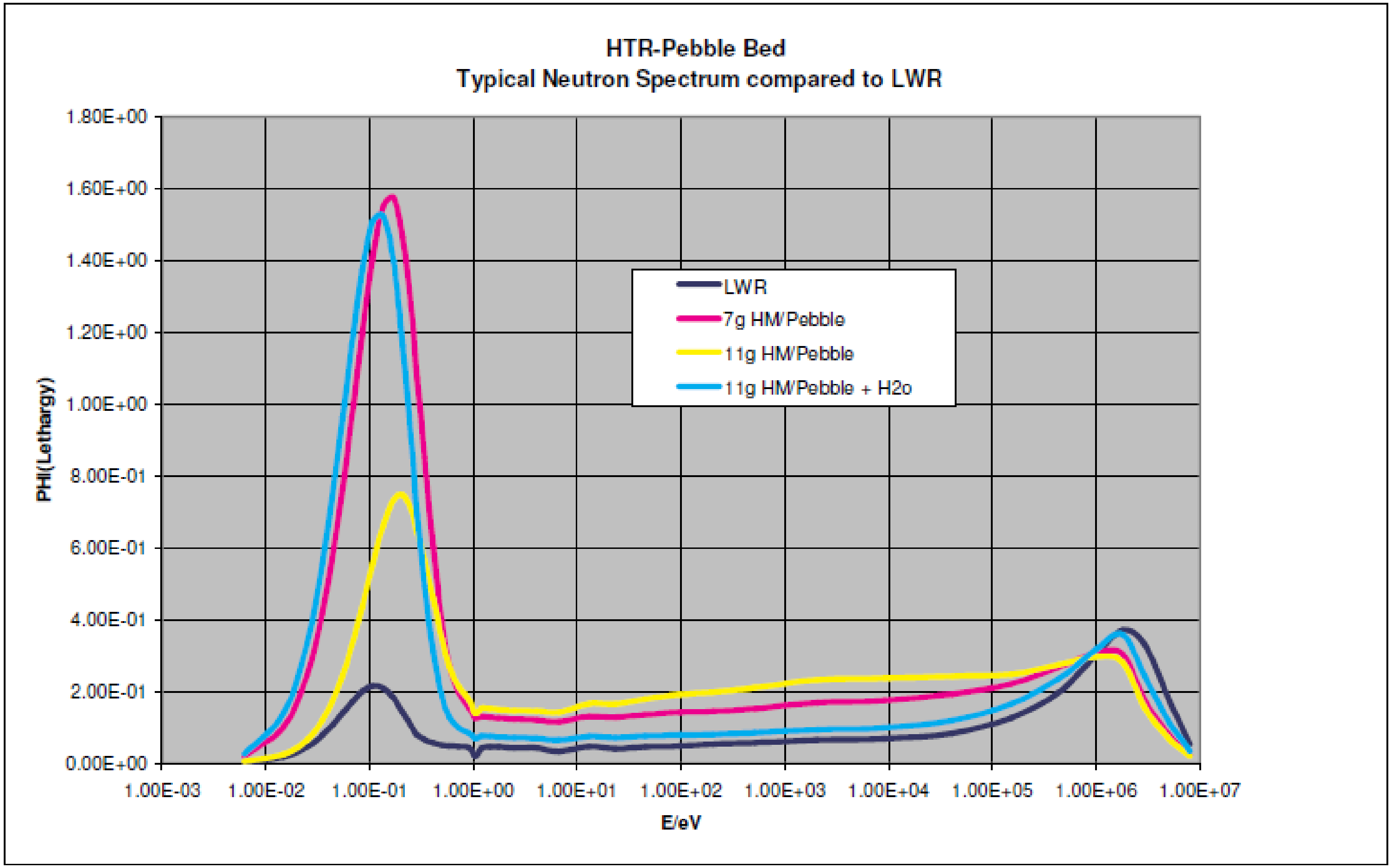


HTR

3-4 cm



HTGR Neutron Spectrum



Pebble-Bed Typical Neutron Spectrum compared to LWR

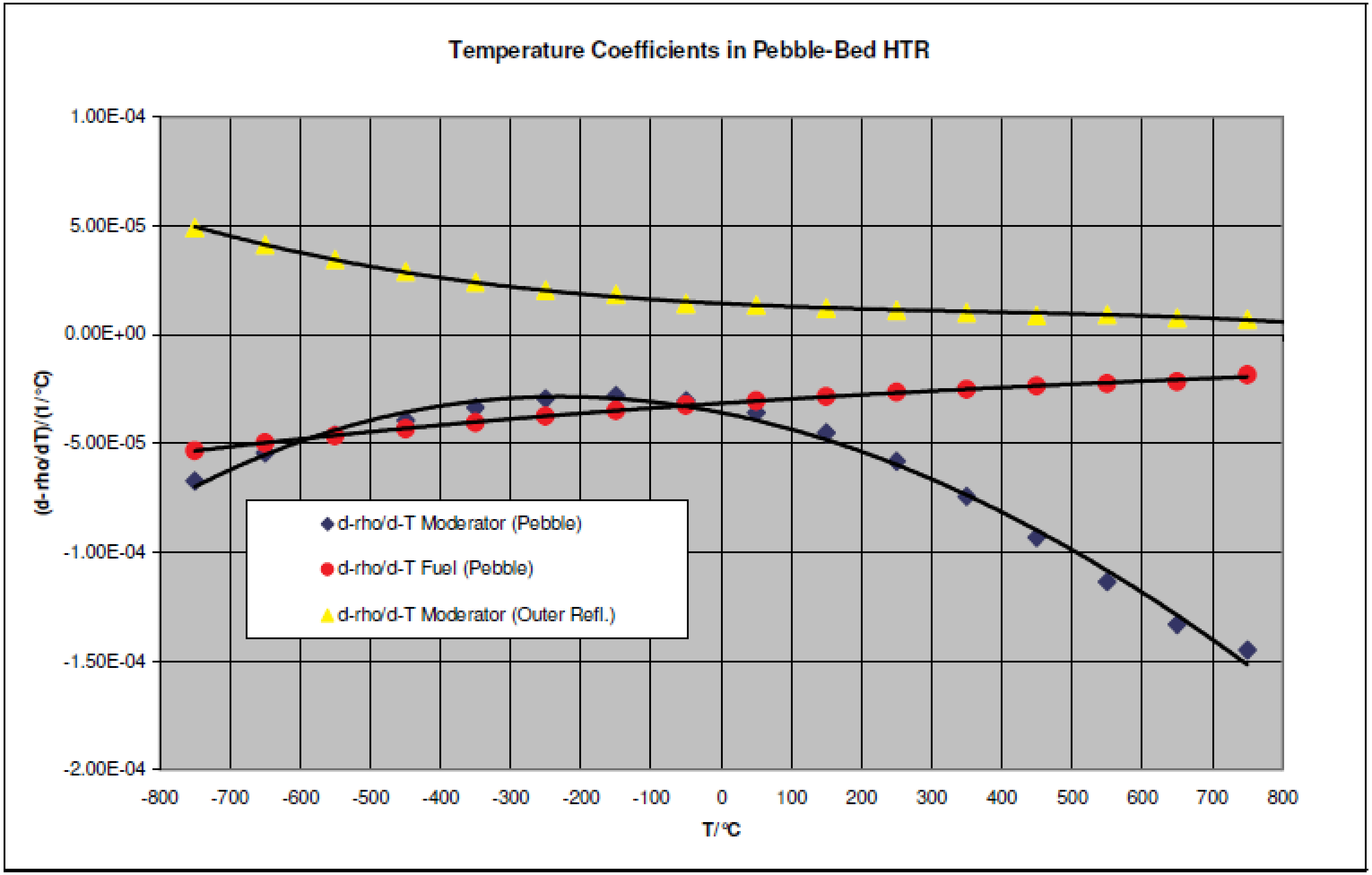
Neutron Spectrum

- Neutron Spectrum is characterised by
  - high flux in slowing-down energy region due to graphite moderating properties
  - high thermal flux peak (at higher temperature than LWR caused by “high-temperature” moderator)
  - reactivity sensitivity to water ingress because of general under-moderation
- Flux distribution in fuel element characterised by
  - almost flat in coated particle (except resonance region)
  - almost flat in fuel pebble (caused by low heavy metal content)

Modular HTGR Temperature Coefficients

- Except for control rod motion, the only significant reactivity effect in modular HTGRs is that caused by changes in core temperature
  - Helium is essentially transparent to thermal neutrons
  - Core dimensional changes are negligible
- Reactivity decreases as core temperature increases
  - Ensures the passive safety of the system
  - Large prompt negative Doppler effect from the fuel
  - Core moderator effect is slightly slower and negative
  - Reflector effect is slower small and can be slightly positive
- Great reactor stability. Reactivity coefficients
  - Fuel, immediate $(\sim -2x10^{-5}\ \Delta k/k/^{o}C)$
  - Moderator, delayed sec - minutes $(\sim -16x10^{-5}\ \Delta k/k/^{o}C)$
  - Reflector, very delayed > minutes $(\sim 8x10^{-5}\ \Delta k/k/^{o}C)$

Modular HTGR Temperature Coefficients

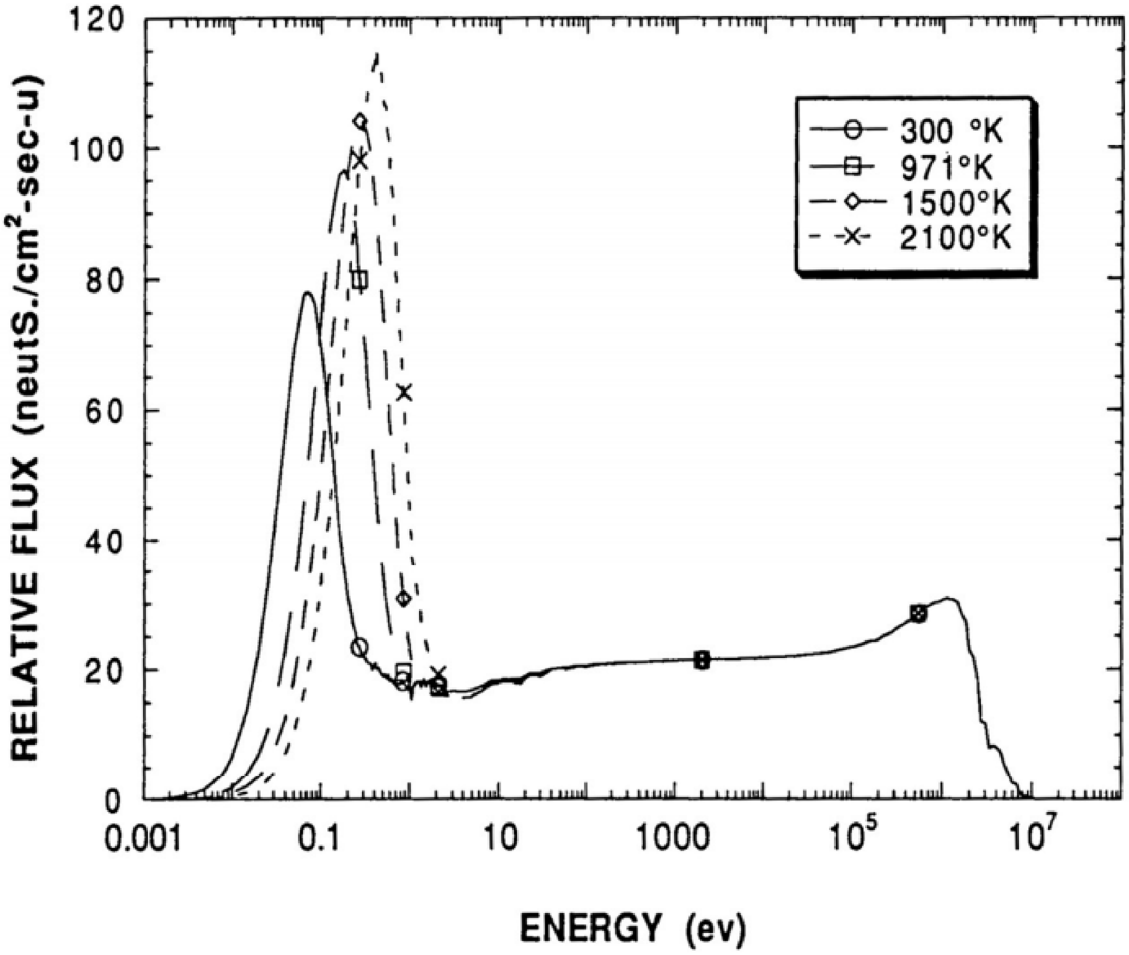


– Iso-deltic temperature coefficients of reactivity

Modular HTGR Temperature Coefficients

- HTR Temperature feedback is characterised by
  - instantaneously and fast acting fuel feedback due to Doppler effect and low heat capacity in CP kernel
  - stabilising moderator feedback due to spectral shift
  - non-stabilising, but very time-delayed acting reflector feedback
- Temperature dependence of feedback caused by
  - reduction of Doppler effect at elevated temperatures
  - complex interaction of moderator temperature with isotopic mixture in core
  - interaction of neutron importance with temperature distribution in core

Modular HTGR Temperature Coefficients

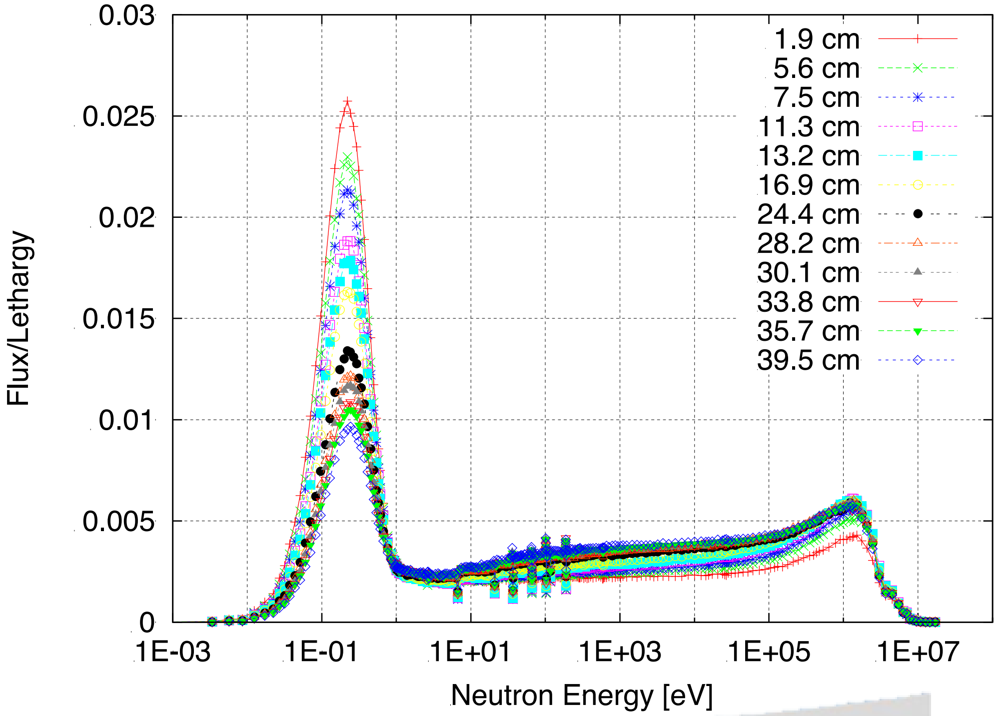


As core temperature increases, the flux spectrum moves into the U-238 and Pu-240 resonance absorption cross section range.

Fuel / Reflector Interface (1/2)

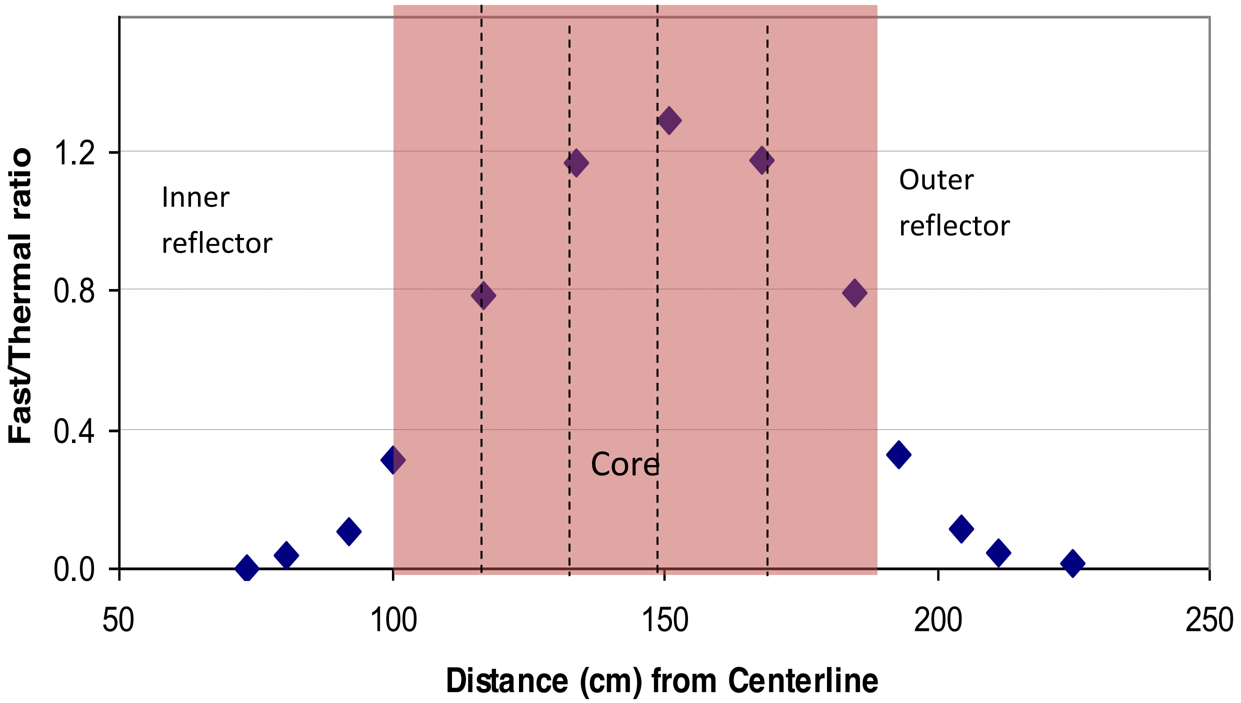
- Large # of neutrons slow down in the reflectors and return to the active core bypassing resonance region
- Reflectors have large effect on the power shape within the first 36 cm of active core -> affect local peaking and fuel burnup

- Need better spectrum to generate cross sections
- Traditional approaches for whole core calculations
  - In-line spectrum correction
  - Use large # of coarse groups



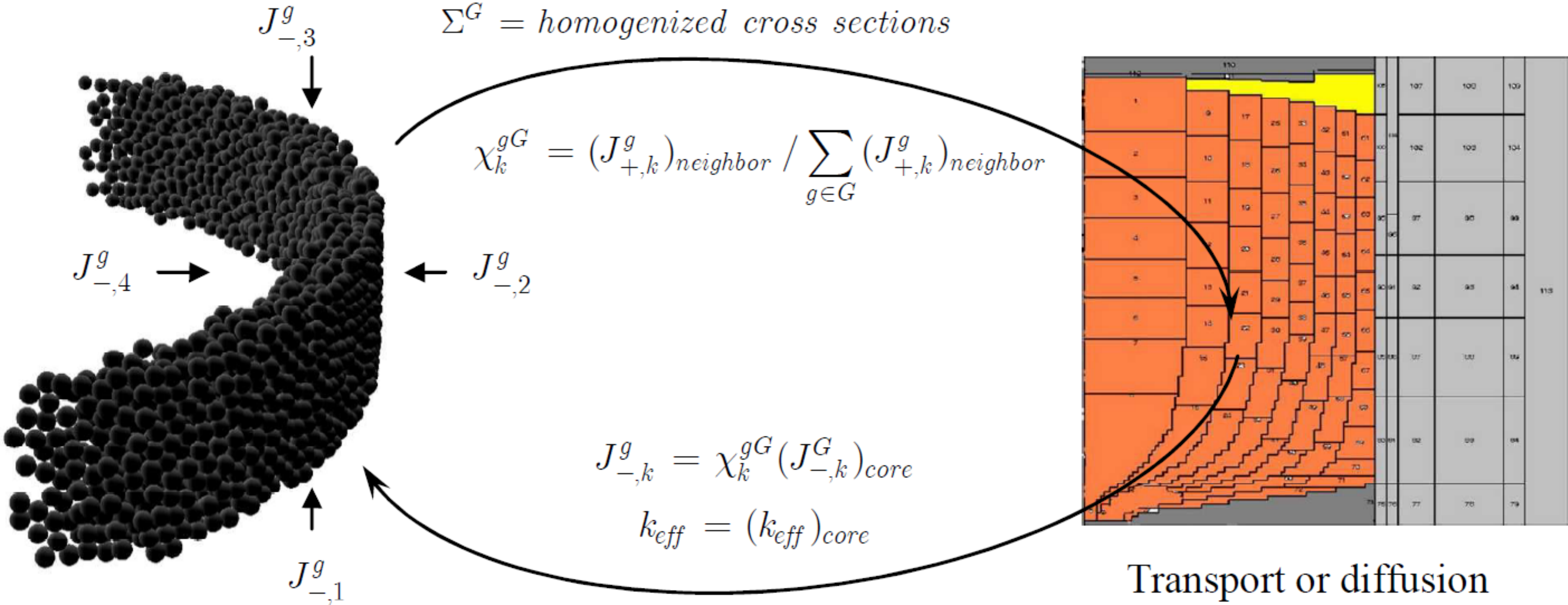
Fuel / Reflector Interface (2/2)

Fast to Thermal Flux Ratio vs. radius in PBMR 400



The steep curve indicates significant changes in neutron spectrum from one region to the next – this is a challenge for existing reactor physics tools

Spectrum zones / imbedded calculations



$$\Sigma^G = homogenized\ cross\ sections$$

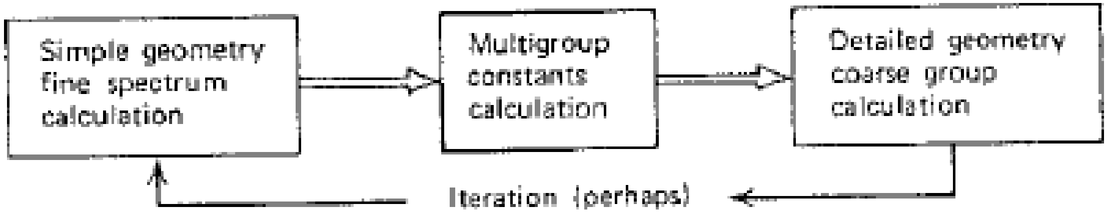
$$\chi_k^{gG} = (J^g_{+,k})_{neighbor} / \sum_{g\in G} (J^g_{+,k})_{neighbor}$$

$$J^g_{-,k} = \chi_k^{gG} (J^G_{-,k})_{core}$$

$$k_{eff} = (k_{eff})_{core}$$

Spectrum zone CP calculation

Transport or diffusion core calculation



Simple geometry fine spectrum calculation

Multigroup constants calculation

Detailed geometry coarse group calculation

Iteration (perhaps)

Spectrum zones / Imbedded calculations boundary conditions

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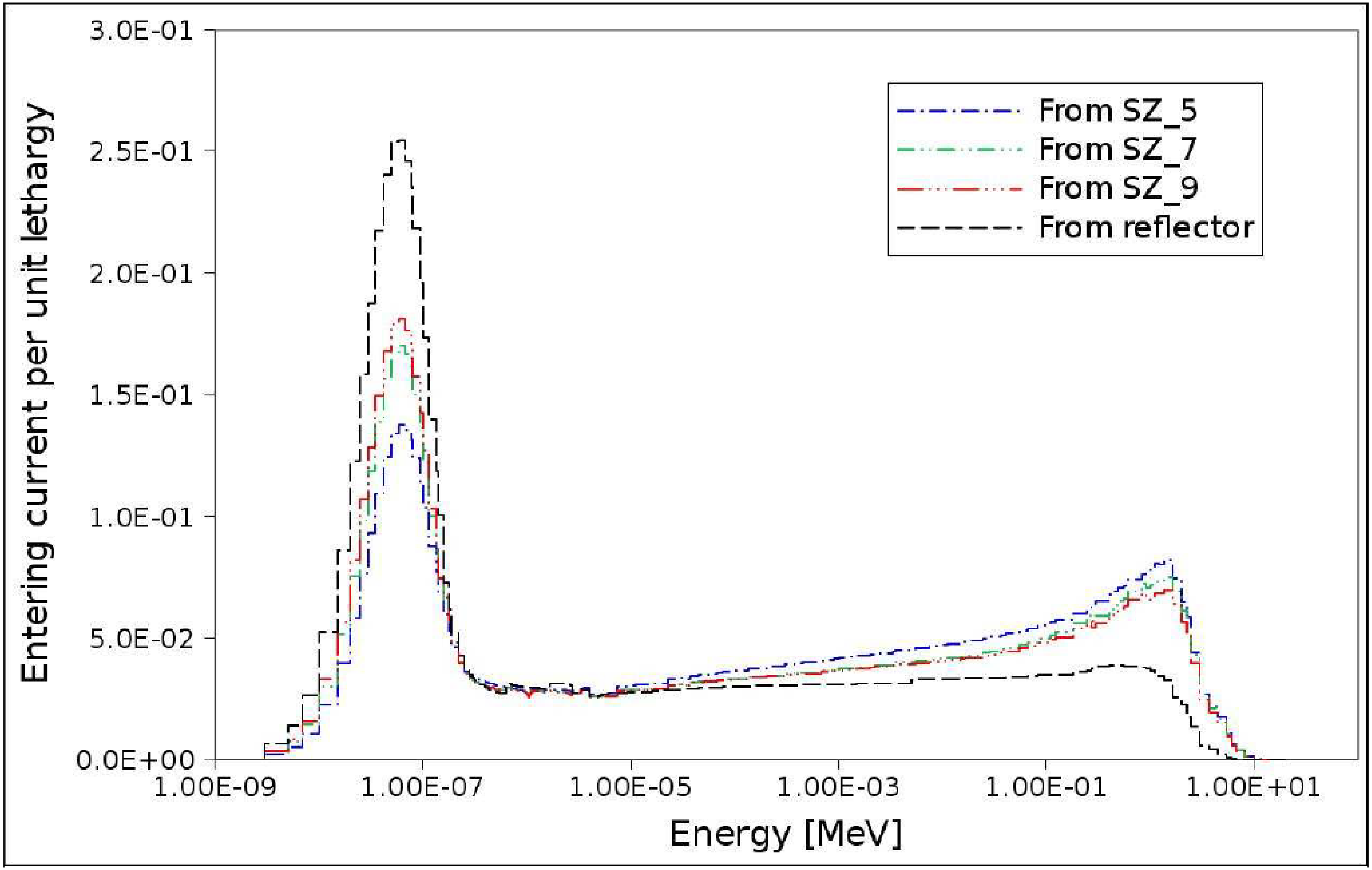
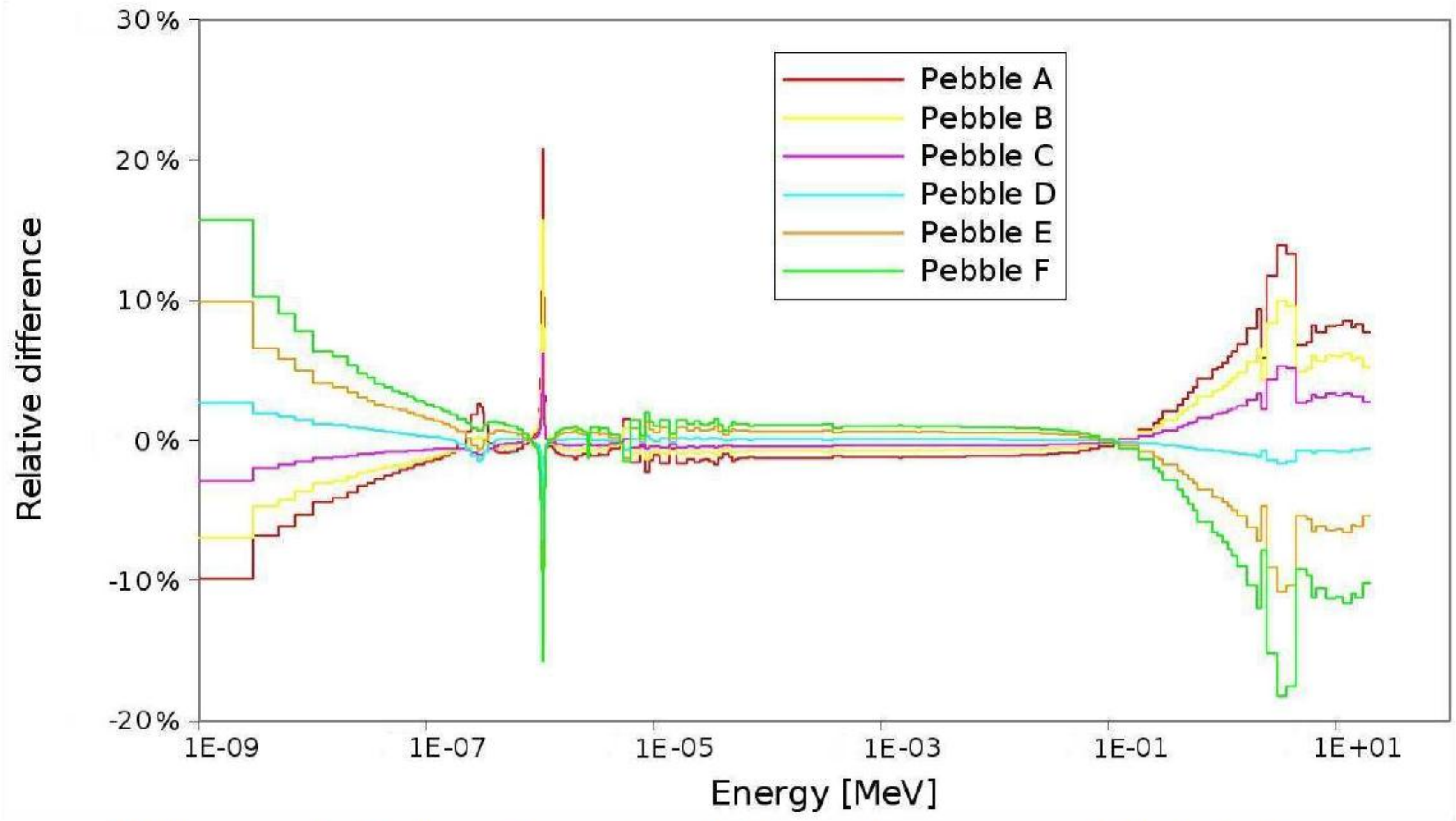
Calculations Verification Analysis



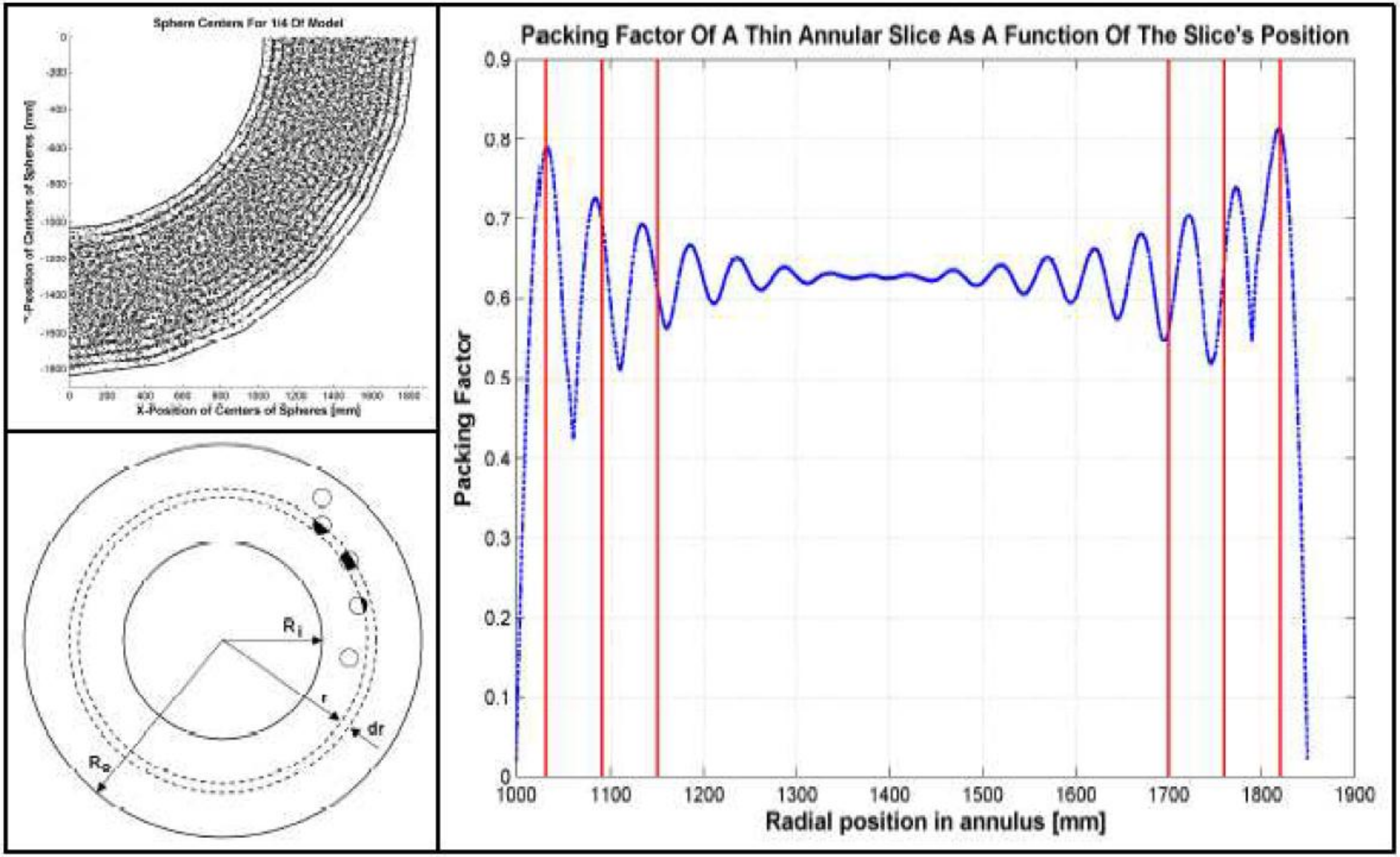
Spectra of currents entering SZ 8

Spectrum zones / multi-pass spectra



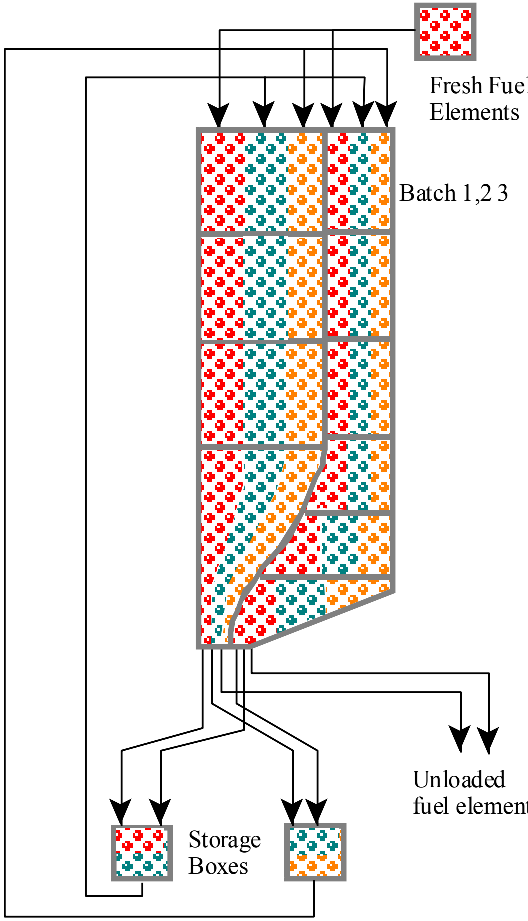
Differences in the kernels spectra relative to the average pebble in SZ 5

Packing / packing fraction



Pebble Beds Multi-pass

- The pebble bed reactor technology's fuel handling system makes provision for on-line refueling by allowing fuel sphere circulation.
- It is limited to certain design constrains such as the requirements of the Burnup Measuring System (BUMS).
- The technology has a safety advantage as it allows for very small excess reactivity bounded by the control rods which limits reactivity-induced power transients.
- A balance should be obtained between:
  - operational requirements (fuel handling system design, burn-up measurement times and accuracies, dust generation and so on)
  - and an optimized core design with a flatter power profile and lower peaking factors.

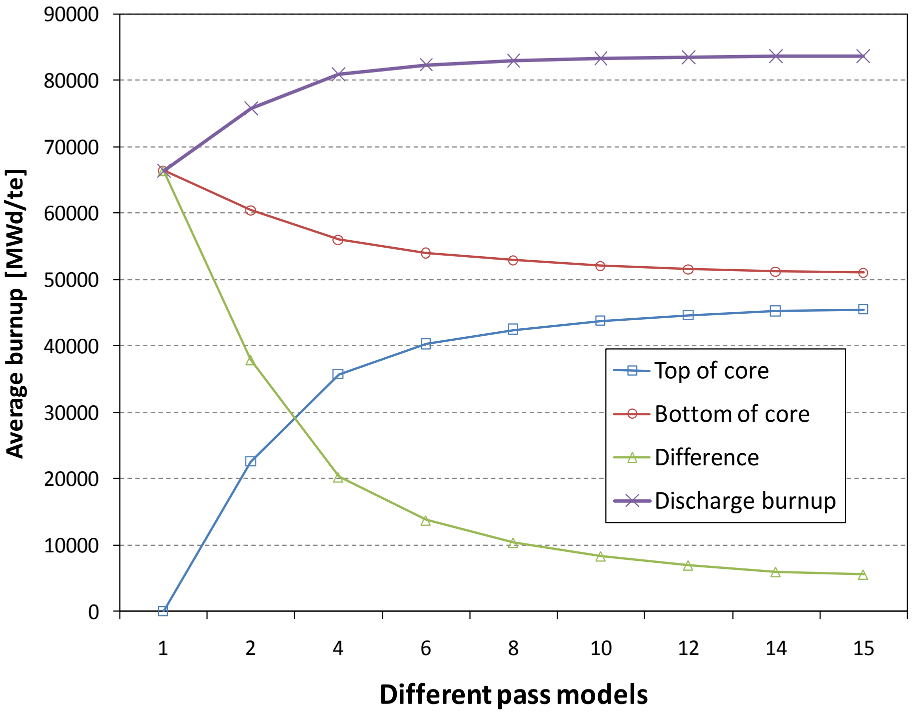


Multi-pass: Burnup

- Fuel utilization increases with increased passes
  - 20% lower burnup for a OTTO compared to a 15-pass cycle
  - smoothes out to only 1.6% difference for the 6-pass cycle
- The burnup difference between the top and bottom of the core is an indication of the possible power peaking

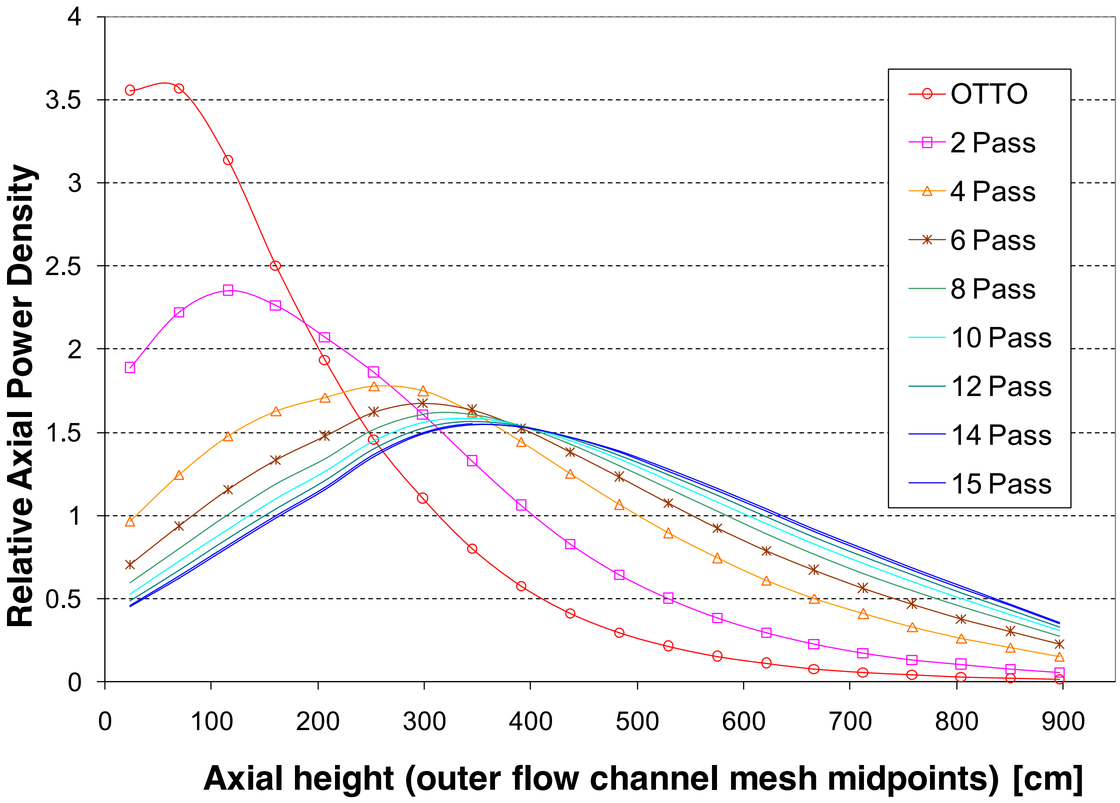
- The neutron leakage decreases as the fuel pass circulations increased
  - Difference of 3.5% between the 15-pass case and OTTO cycle (16.9%).

- The requirement specification of the fuel handling and burnup measuring system is directly influenced by the multi-pass models.
- Decay and Measuring time is required for accurately measuring Cs-137 gamma peaks.



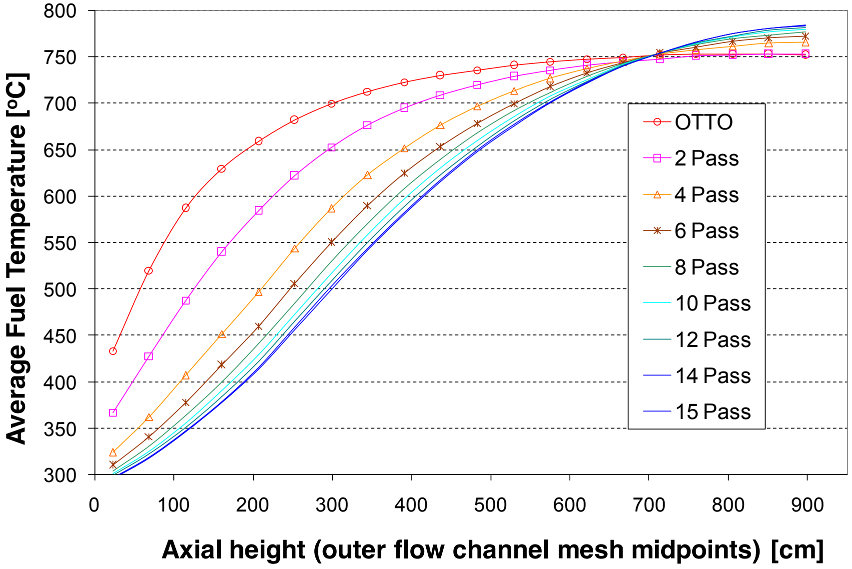
Multi-pass: **Power profile results**

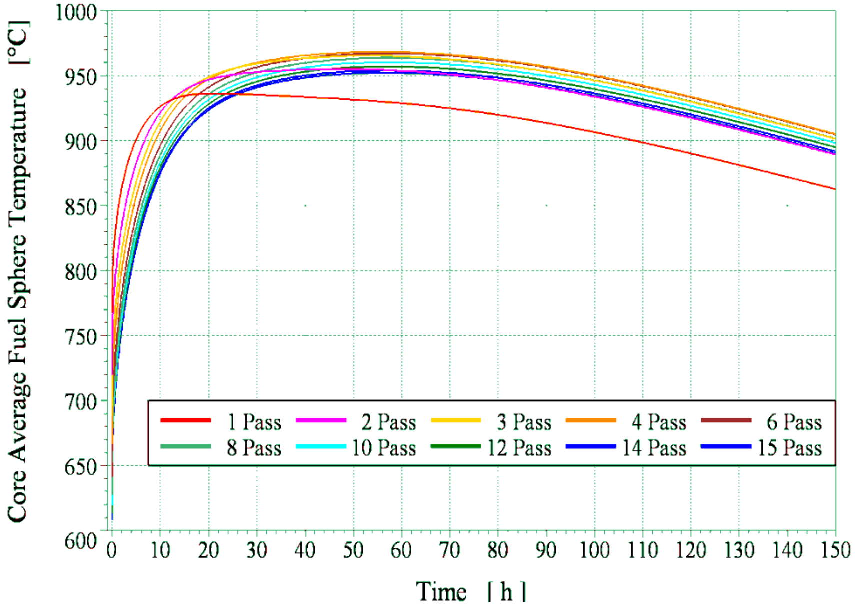
- For an optimal core design it is required to achieve a flattened power distribution over the core.
- Fresher fuel mixture causes peaking at the top of the core (in the low pass numbers)



Multi-pass: **Temperature effects**

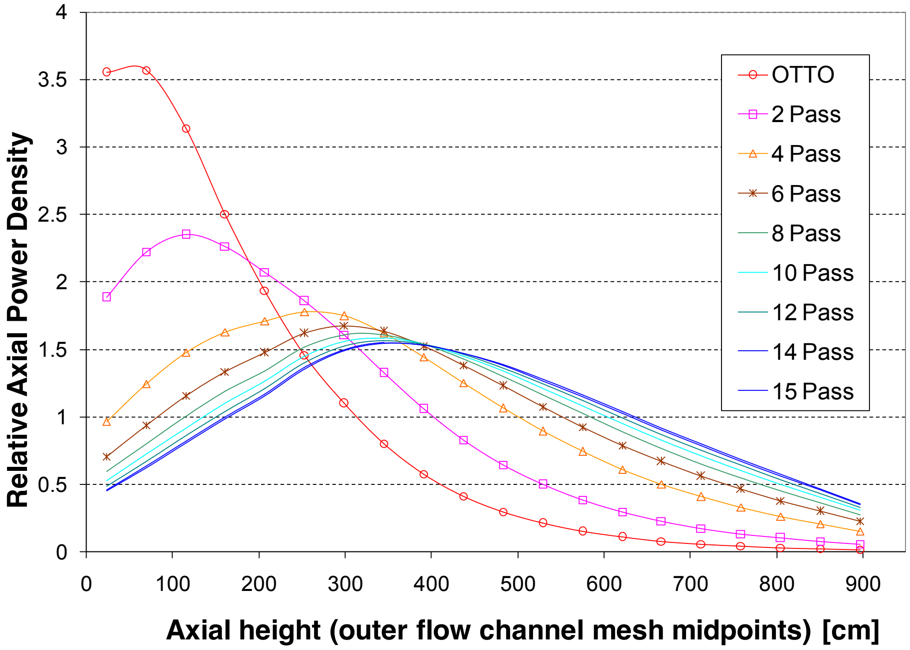
- Normal operating temperatures
  - Lower average as passes increases
  - Peak fuel temperature values increase slightly as power peak shifts down
- Average fuel temperatures in DLOFC remain far below 1600°C for accident conditions.

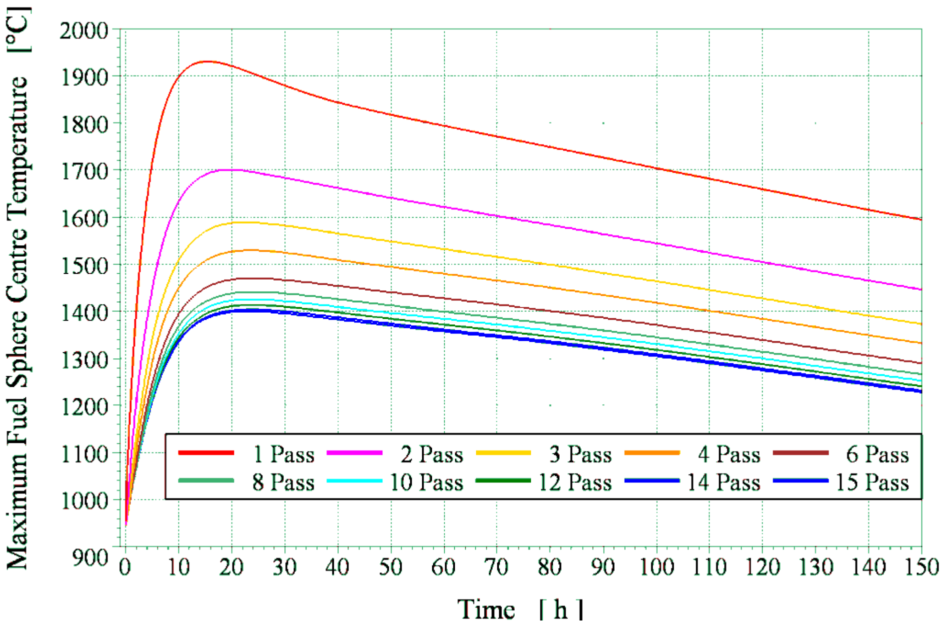




Multi-pass: **Temperature effects**

- For DLOFC conditions the OTTO-pass case and the two-pass case goes above specified conditions and temperatures over and at 1900°C and 1700°C are achieved respectively.
- “follows” the power peaking values



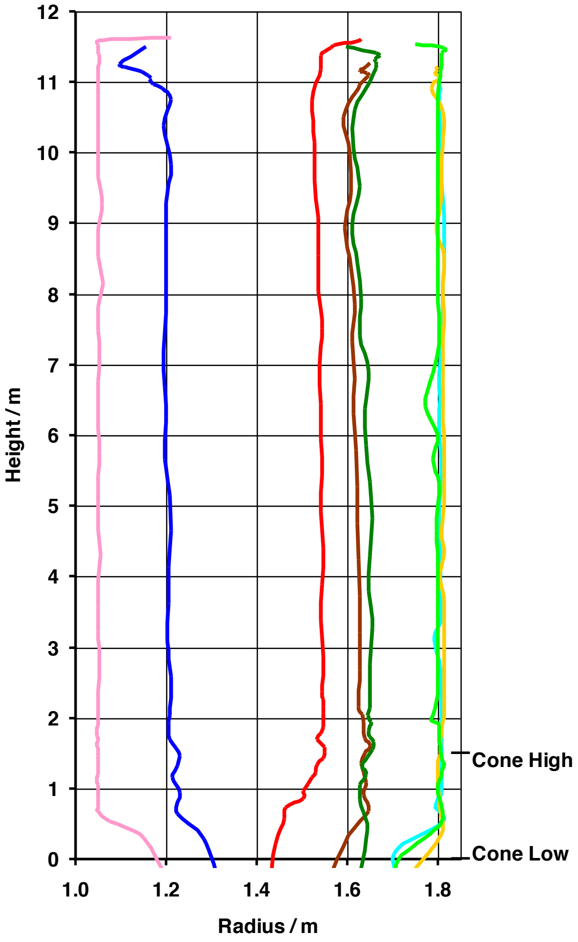


Pebble Flow Characteristics

- Pebble flow characteristics (at temperature and in helium environment) well quantified in German experimental and reactor program (cylindrical cores)

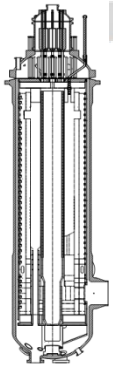
- Simulations (PFC^{3D})
  - Distinct Element Modeling for Micromechanical Analysis of geomaterials and particulate systems in two and three dimensions

– INL
  - PEBBLES code
  - “Methods for Modeling the Packing of Fuel Elements in Pebble Bed reactors” A M Ougouag et al, M&C2005
  - “Pebble Bed Reactor Dust Production Model”, Joshua J. Cogliati, Abderrafi M. Ougouag, HTR2008.



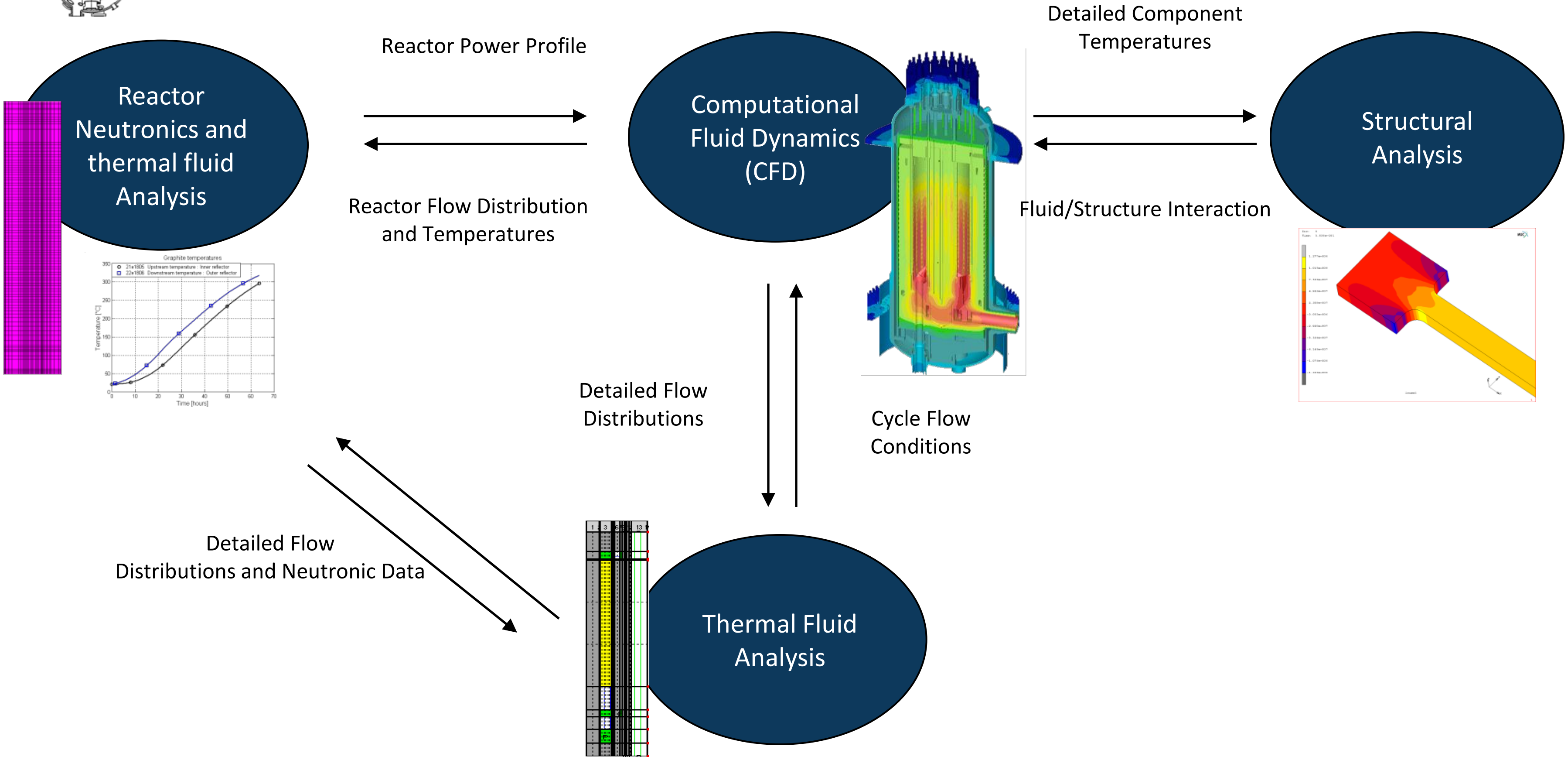
Higher enrichment needs…

- Enrichment > than needed for LWR
  - – Typically >5% compared to <5% for LWR’s
  - – HTGR’s fuel homogeneity
    - lower lumping effects
    - Limited geometrical self-shielding of resonances absorbers
    - Resonance escape probability smaller



Analysis Requirements

(A typical picture needed)



Reactor Neutronics and thermal fluid Analysis

Reactor Power Profile

Reactor Flow Distribution and Temperatures

Computational Fluid Dynamics (CFD)

Detailed Component Temperatures

Fluid/Structure Interaction

Structural Analysis

Detailed Flow Distributions

Cycle Flow Conditions

Detailed Flow Distributions and Neutronic Data

Thermal Fluid Analysis

Summary of features

- Graphite is the moderator and structure, not metal and water
  - high temperature solid moderator
  - hard thermal spectrum
  - fixed burnable poison possible
  - large physical dimensions
  - low power density
- Helium is the coolant not water
  - Coolant is transparent to thermal neutrons
  - Coolant has no phase change
- Fuel is carbide-clad, small ceramic, particles not metal clad UO_2
  - PyC/SiC carbide clad is primary fission product release barrier
  - Fuel operates at high temperatures with wide margin to failure
  - Double heterogeneity in physics modelling in fuel
- Heat removal path through core structures
  - Modular requires metallic vessel
  - For increased power (and lower maximum fuel temperature in DLOFC) - have to go to annular core

FUEL CYCLES

Contents

- Background
- Capabilities of HTRs with respect to the fuel cycle
  - physical reasons of the adaptability of HTRs to different fuel cycles
  - possible fuel cycles for HTRs
- Review of different fuel cycles
  - LEU
  - MOX
  - Plutonium
  - Thorium
  - Mixed
- Why look at thorium (again)
- Material inventories
  - Consumption of natural uranium
  - Consumption and production of plutonium
- Conclusion

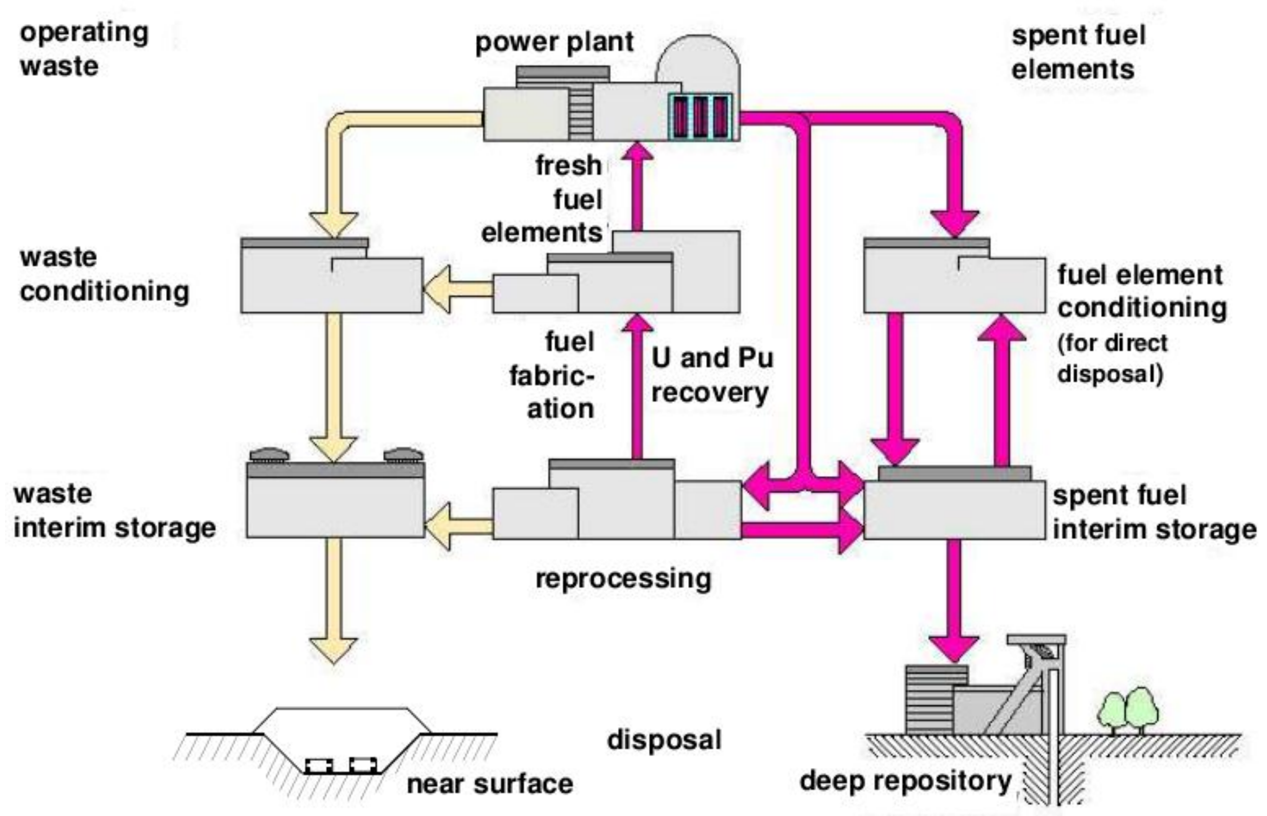
Background

- The selection of a fuel cycle do not only influence:
  - Economics (Feedstock, enrichment, neutron economy)
  - Core neutronics (spectrum, burnup, power peaking, safety characteristics / kinetics, conversion ratio)
  - Core thermal fluid behaviour (Fuel Temperatures, DLOFC temperatures)
  - Fuel performance (kernel behaviour, FP release, source term)

  But also

  - Fuel manufacturing (kernel type, shielding)
  - Reprocessing facilities (U, Pu, Thorium/U^{233})
  - Waste storage and final disposal (source term, form)

Nuclear waste management : Operating wastes and spent fuel elements



Why HTRs?

Why HTRs are so flexible with regard to fuel cycle ?

- ALMOST PERFECT UNCOUPLING BETWEEN :
  - Parameters that determine COOLING GEOMETRY
  - Parameters that characterize NEUTRONIC OPTIMIZATION

PLUS

- SOLID MODERATOR :
  - No void effect (no limit of Pu content)
  - Very low density effect on temperature coefficient
- And other features :
  - very good neutron economy,
  - low parasitic captures (C-12, structures),
  - possibility to achieve very high burnups.

Physical reasons for Flexibility

Technical parameters which may be adjusted (degree of freedom)	Physical characteristics which are influenced by technical parameters	Neutronic conditions which are influenced by physical characteristics
Packing fraction of particles Size of kernels Relative proportion of various kinds of particles (if any)	Average density of heavy nuclides in the fuel pebbles Distribution of heavy nuclides inside the fuel pebbles / between different pebbles Fertile / fissile "mixtures"	Moderation ratio, thus neutron spectrum Self shielding effect, thus resonance absorption

Range of choices for mixtures of fertile and fissile materials

		Fissile Material				
		LEU	20% enriched	HEU	U-233	Pu
Fertile Material	Th-232	Possible, *Not optimum	Possible, *Not optimum	The ideal starting fuel for Thorium cycle	Thorium cycle with U^{232} recycling	Pu-Th cycle
	U238 (natural or depleted)	Not applicable (by definition)			Not studied?	"MOX"
	No fertile material added	LEU cycle	May need BPs	Not studied?	Not studied?	"Plutonium only" cycle

* Preferably not to mix thorium and plutonium cycles

LEU cycle

- Enrichment from ~5% - 15%
  - Required because of fuel homogeneity
- Typically the reference cycle for most projects today (HTR-PM, Japan, NGNP, PBMR, EU)

- Main advantage:
  - Well known fuel and fuel cycle
  - Good in-situ use of plutonium
  - High burnup can be achieved
- Main drawback
  - Requirement of >5% enrichment
  - Once through cycle only

MOX cycle

- Currently used at an industrial scale in LWR ’s (oxide form) but with several constraints on the MOX loading allowed in current designs.
- May be used in HTRs (in other forms such as carbides) with much more flexibility.
- Needs more detailed studied
  - Good potential to use LWR pass 1 Plutonium in pebble bed reactors

“Pu only” cycles

- Early studies on plutonium fuel but more recent interest for two purposes
  - « control » plutonium build up,
  - « burn » weapon grade plutonium coming from the dismantling of nuclear weapons.
- Main issues
  - Needs extended R&D on fuel design and performances, fuel qualification and fuel fabrication.
  - Difficulties may arise from neutronic point of view (temperature coefficient, kinetic behaviour, residual heat,…)

Thorium cycle: HEU

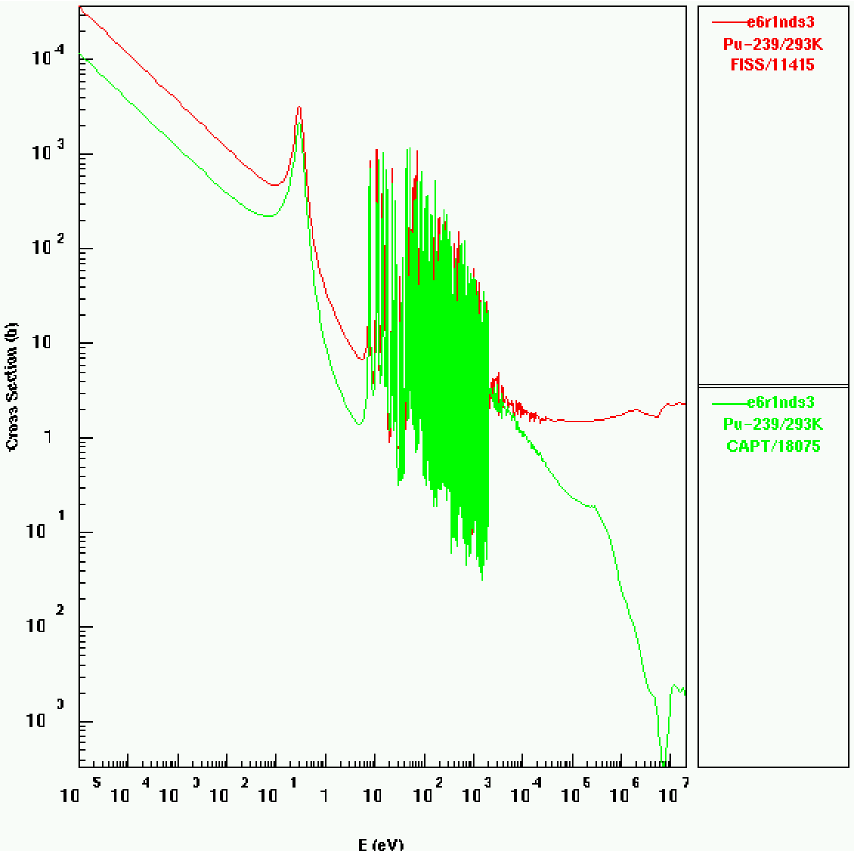
- Was the reference cycle for the former HTR projects in the 70 ’s and all prototypes which have been operated in the past :
  - AVR and THTR in Germany, Peach Bottom and FSV in USA.
- Main advantages:
  - Reduction of uranium consumption : high conversion ratio or near breeder concepts, U-233 recycling.
  - Dramatic reduction of long-lived minor actinides amounts.
- Main issues:
  - Recycling technologies : high radiation level of U-233 daughter products (Tl-208, Bi-212) and U-232 decay
  - PROLIFERATION CONCERNS.

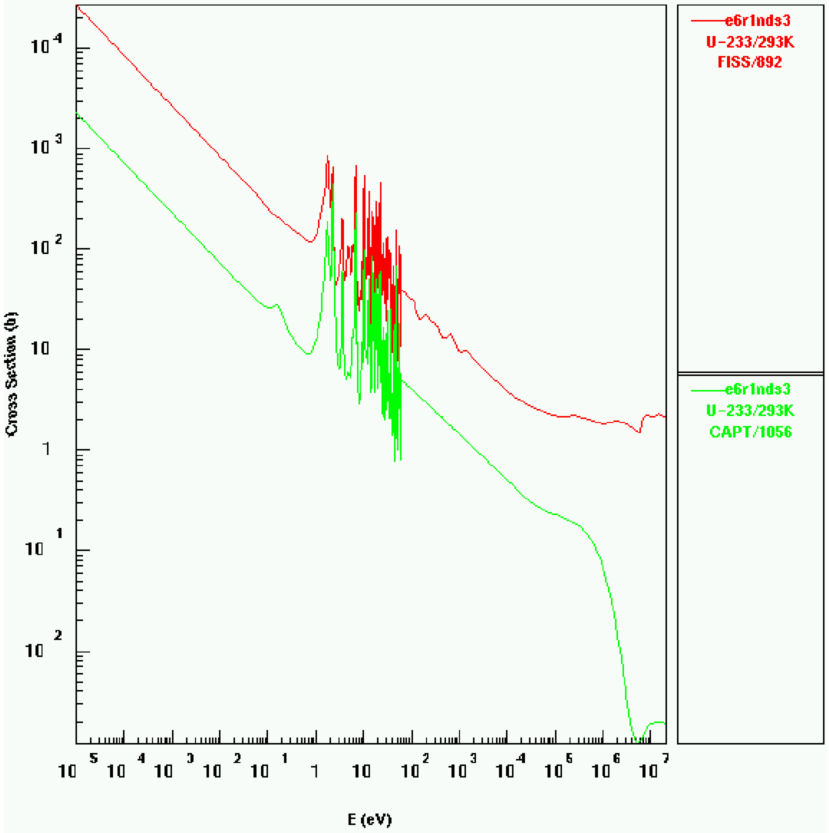
Thorium-Plutonium cycles

- Studies were conducted a the very early stage of HTR development:
  - DRAGON project (begining of 60 s).
  - General Atomic : joint program with Edison Electric Institute (test element in Peach Bottom).

- May have attractive features with regard to core management
  - possible cycles in which the entire core is replaced at each reload for prismatic type reactors -> better power distribution (can help to increase temperatures and power density); or periodic reload of pebble bed reactors.
  - Smooth change in reactivity (Pu-240 -> Pu 241) then less control devices (burnable poisons, …).
  - Maintain some of the advantages of the plutonium cycle but with better neutronics performance

U/Pu *vs* Th/U: neutron balance





-U/Pu: σ_f/σ_c = 70/30 for thermal,
and 90/10 for fast energies;

- In thermal range Pu-240 is produced;
- Pu-241 is fissile but likely to absorb neutrons rather than fission -> Actinides

-Th/U: σ_f/σ_c = 90/10 over total energy range;

- An average 1.1 neutrons required for fission;
- 2.5 Neutrons produced on average

Why Th is so attractive

$$\mathrm{n} + {}^{232}_{90}\mathrm{Th} \rightarrow {}^{233}_{90}\mathrm{Th} \xrightarrow{\beta^-} {}^{233}_{91}\mathrm{Pa} \xrightarrow{\beta^-} {}^{233}_{92}\mathrm{U}$$

1. When a neutron interacts with a fissile atom it fissions or is captured and transmuted
2. When U-233 captures a neutron it fissions or become U-234
3. In the HTR neutron spectrum the probability to fission is:
   - 88% for U-233
   - 76% for U-235
   - 41% for Pu-239
   - 59% for Pu-241

Rationale for going Thorium

- Uranium resources are finite
- Current utilization for all nuclear reactors is around 66,500 tons/a
- Leaves us with around 65 – 70 years' supply based on "proven reserves" of 4.7 mtons, i.e. uncertain long term of security of supply
- 2005: fuel costs contribute about 26 % of the average electricity production cost of 1.72 USc/kWh for operating NPPs, *versus* about 78 % of the 2.21 USc/kWh for coal fired plants
- The bulk of this nuclear fuel cost of 0.45 USc/kWh was contributed to uranium enrichment and other aspects of fuel manufacturing, while only about 0.1 US¢/kWh would be contributed by the cost of natural uranium at a price of 10 US$/lb. This would increase to about 1 US¢/kWh at a price of 100 US$/lb

Rationale for going Th

- After TMI and Chernobyl two decades of stagnation followed
- U mining activities also stagnated due to prices suppression below $18/lb
- The Nuclear Renaissance caused U prices to skyrocket to $100/lb
- The economic crises caused sharp decline to $40/lb
- There is, however, 3-4 times more Th in the earth's crust than U
- In thermal reactors the energy content is 8 times higher of Th than U
- Depending on reactor type (thermal, epithermal, or fast) the efficiency may vary from 60 – 200%. In HTRs assume 100%
- Based on the proven reserves of uranium one may conclude 70 years' supply to be increased to 2240 years and by switching to HTRs to 4500 years

Challenges when going for Th

- Experimental plants operating on Th-232/U-233 have not yet demonstrated the expected commercial gain over a well-proven U/Pu cycle
- Due to the relatively small impact of the fuel cost on the production cost no true incentive was found as yet
- Licensing risk of a novel fuel cycle has been a strong deterrent
- People have been indoctrinated to go for “off-the-shelf,” large-scale, grid-supply solutions
- The disruptive nature of new technology deprive reactor vendors of their vested interests
- Fast reactor technology promises an increase in the conversion ratio dramatically to better utilize the 99.3% U-238 content of natural uranium
- Conversion Ratio = Fissionable material produced / Fissionable material destroyed
  - In a fast reactor the U/Pu cycle outperforms a Th/U-233 cycle
  - In a thermal reactor a Th/U-233 cycle outperforms U/Pu cycle

Natural uranium consumption:

LEU cycle:

- Comparison between HTRs and PWR’s:
  - Large size HTRs enable savings of 15 to 20 % in natural uranium consumption.
  - **BUT this gain barely corresponds to direct benefit of the increase of** electrical efficiency of HTRs compared to PWRs (~ + 20 %)
  - For small modular reactors: Saving in U_{Nat} is less than the increase in electrical efficiency
  - Intrinsically HRT cores consume a little bit more U_{Nat} than PWRs

Natural uranium consumption:

MOX:

- Probably comparable performances as the one of PWRs that is :
  - 10 to 15 % savings with once-cycling of Pu,
  - 15 to 30 % savings with indefinite recycling.
- Better optimization is probably achievable with HTGR's

Pu only (Reactor grade):

- Need to consider « symbiotic » reactor fleet, for example composed of 85 % of PWRs and 15 % of HTRs :
  - Pu production of PWRs : 25 kg / TWhe,
  - Pu loading of HTRs : 140 kg / TWhe
  - Pu net consumption of HTRs : 100 kg / TWhe (40 kg / TWhe are unloaded and are waste)
- 15 % of saving in U_{nat} (~ MOX)
- But much less Pu in wastes (per TWhe : 25 kg for a fleet of only PWRs and 40 x 0,15 = 6 kg for a PWR + HTR fleet).

Natural uranium consumption:

Thorium + Pu (Reactor grade)

- Need of scenario studies involving a « symbiotic » reactor fleet with Pu and U-233 recycling.
- U_{nat} savings from both recycling of Pu and U-233 would be added, leading to significant gains.

Consumption and production of plutonium (and U-233)

- LEU
  - HTRs produce less plutonium
  - Higher efficiency
  - Higher in-situ utilization
  - Pu is more degraded
- MOX
  - Same conclusion as the one for U_{Nat} consumption (similar results for HTRs and PWRs but greater flexibility of HTRs)

Consumption and production of plutonium (and U-233)

- Pu-only
  - Net consumption : 94 kg / TWhe (for an HTR with 47 % efficiency)
  - May be compared to :
    - PWRs 100 % MOX : 65 kg / TWhe,
  - HTRs are very efficient plutonium burners, and perform at least as well as most advanced concepts of Pu recycling in PWRs (multi-recycling).

Consumption and production of plutonium (and U-233)

Thorium Cycles

- HEU
  - Very few Pu production,
  - U-233 production : 180 kg / GWe-Yr (burnup 91 GWd/t),
  - « Symbiotic » scenarios may enhanced production and reuse of U-233
- Th-Pu
  - Plutonium consumption is not very different than the one of « Pu-only » cycle
  - This cycle allows production of significant amounts of U-233 which can be recycled.

Thorium in a Pebble Bed Fuel Cycle

Preferred fuel cycle

Cycle		Th/U93%		Th/U-233		Th/U20%		LEU	
Enrichment of feed fuel	w%	8.04		6.54		10.76		10.82	
Fuel residence time	Years	3.8		3.8		3.8		3.8	
Target burn-up	MWd/Kg$_{HM}$	77.2		77		77.5		77.4	
Conversion ratio		0.462		0.557		0.519		0.487	
U_3O_8 requirement	Kg/GWd$_{th}$	278		-		359		357	
Separative work	SWU/GWd$_{th}$	243		-		284		263	
Loading ® unloading:		**Load**	**Unload**	**Load**	**Unload**	**Load**	**Unload**	**Load**	**Unload**
Fissile: U-233	Kg/GWd$_{th}$	0	0.23	0.85	0.31	0	0.14	0	0
U-235	Kg/GWd$_{th}$	1.06	0.16	0	0.02	1.39	0.5	1.4	0.52
Pu-239 + Pu-241	Kg/GWd$_{th}$	0	0	0	0	0	0.11	0	0.17
Fertile: Th-232	Kg/GWd$_{th}$	11.79	11.24	12.07	11.46	5.9	5.65	0	
U-238	Kg/GWd$_{th}$	0.07	0.06	0	0	5.62	5.25	11.51	10.95
Pu-240	Kg/GWd$_{th}$	0	0	0	0	0	0.03	0	0.05
Additionally Pu-242	Kg/GWd$_{th}$	0	0	0	0	0	0.01	0	0.02
Fractional neutron absorption :									
Fissile: U-233	%	12.2		43.7		3.7		-	
U-235	%	35.8		0.9		34.4		33.3	
Pu-239 + Pu-241	%	-		-		12.9		18.5	
Fertile: Th-232	%	21.8		23.7		9.4		-	
U-238	%	0.4		-		14		20.9	
Pu-240	%	0.1		-		3.1		4.5	
Additionally Pu-242	%	-		-		0.1		0.1	
In-situ utilization of bred nuclides:									
U-233	%	57		78.8		40.2		-	
Pu-239 + Pu241	%	-		-		75.6		73.4	

Conclusions - I

- CONSIDERABLE ADAPTABILITY OF HTRs TO DIFFERENT FUEL CYCLES
- This is an asset which may prove highly useful in the future because
  - Scarcity of uranium may become a concern in few decades,
  - reprocessing / recycling technologies may improve significantly in the future,
  - Sound plutonium management may become a major requirement in the coming decades.

Conclusions - II

- With regard to material balance :
  - HTRs consume less natural Uranium than LWR ’s (thanks to their higher efficiency),
  - HTRs prove to be excellent consumers of plutonium,
  - HTRs using thorium in a close cycle (recycling of U-233) offer considerable potential for savings in natural Uranium (factor 2 or 3 or even more).

- The LEU cycle has emerged as the option of choice for the first stage of development of HTRs.

Conclusions - III

- Some amount of work still need to be done on different fuel cycles for modular HTRs
    - (not to speak of technological development on fabrication, reprocessing, recycling).
    - In core fuel management for LEU (fraction of core replaced at each refueling, cycle length, refueling scheme, Feed/breed in same or separate fuel / kernels…),
    - Parametric studies for Pu-cores (MOX, « Pu-only »),
    - Core neutronic characteristics (kinetic, reactivity coefficients,…),
    - Transition phases between different cycles,
    - Scenario studies for closed cycles (Pu, U-233 management).

- Source material:
  - HTGR Technology Course for the Nuclear Regulatory Commission, May 24 – 27, 2010
  - HTR/ECS 2002 High temperature Reactor School, 2002
  - MUA 784: Reactor Physics, F Reitsma, Mechanical Engineering Post-Graduate: Nuclear Theme, University of Pretoria, 2012
  - Advanced Reactor Concepts Workshop, PHYSOR 2012
  - Thorium and uranium fuel cycle symbiosis in a Pebble Bed High Temperature Reactor, Eben Mulder et.al., HTR2010-022
  - Deep Burn Strategy for Pure Reactor-Grade Plutonium in Pebble Bed High Temperature Gas-Cooled Reactors, Eben Mulder et.al., HTR2008-58082
  - Steenkampskraal Thorium Limited (STL) presentations on the TH-100 reactor design, South Africa