INL/MIS-21-62418-Revision-0

High Temperature Gas-cooled Reactors: Core Design

April 2021

Changing the World's Energy Future

Gerhard Strydom

Idaho National Laboratory

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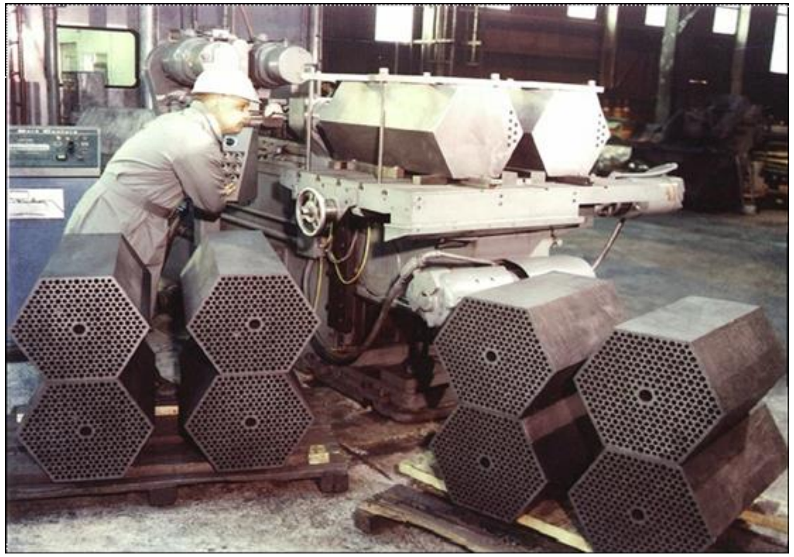
High Temperature Gas-cooled Reactors: Core Design

CNSC Seminar

Idaho National Laboratory

Outline

- General Attributes of Modular Prismatic and Pebble Bed HTGRs
  - Common features and physics
  - Neutronics
  - Thermal-Fluidics
- Plant Systems and Power Conversion
  - Instrumentation and Control
- Normal Operation and Power Maneuvers

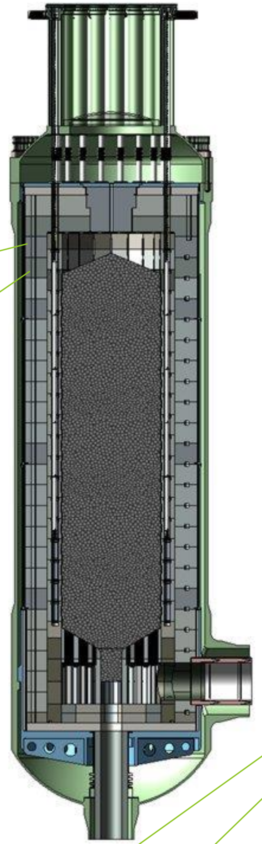


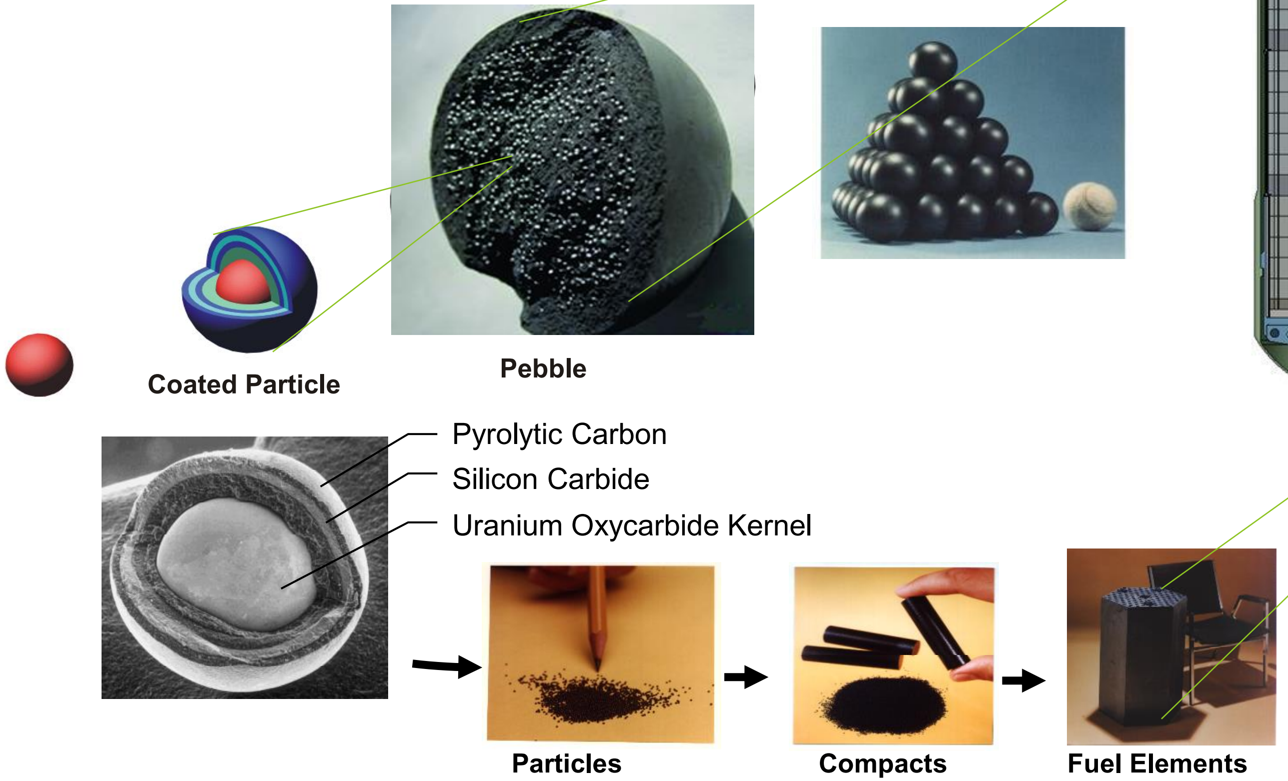
Gun drilling long holes in Ft. St. Vrain fuel elements
Today - drilled with numerically controlled machines

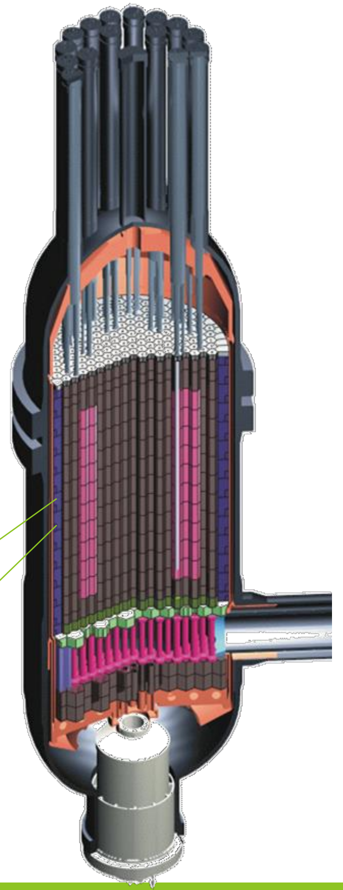
Image: Vollman, R. Prismatic HTGR Core Design Description, Module 5A -HTGR Technology Course for the Nuclear Regulatory Commission, 2010.

Modular HTGR(s) from the bottom up

- UO_2 or UCO (ceramic) kernels
- Tristructural isotropic (inner pyrolytic carbon (PC), SiC, outer PC)
- Pressed into semi-graphitic matrix and shaped into either ‘compacts’ or pebbles
- Cylindrical or annular cores (with central graphite reflector)

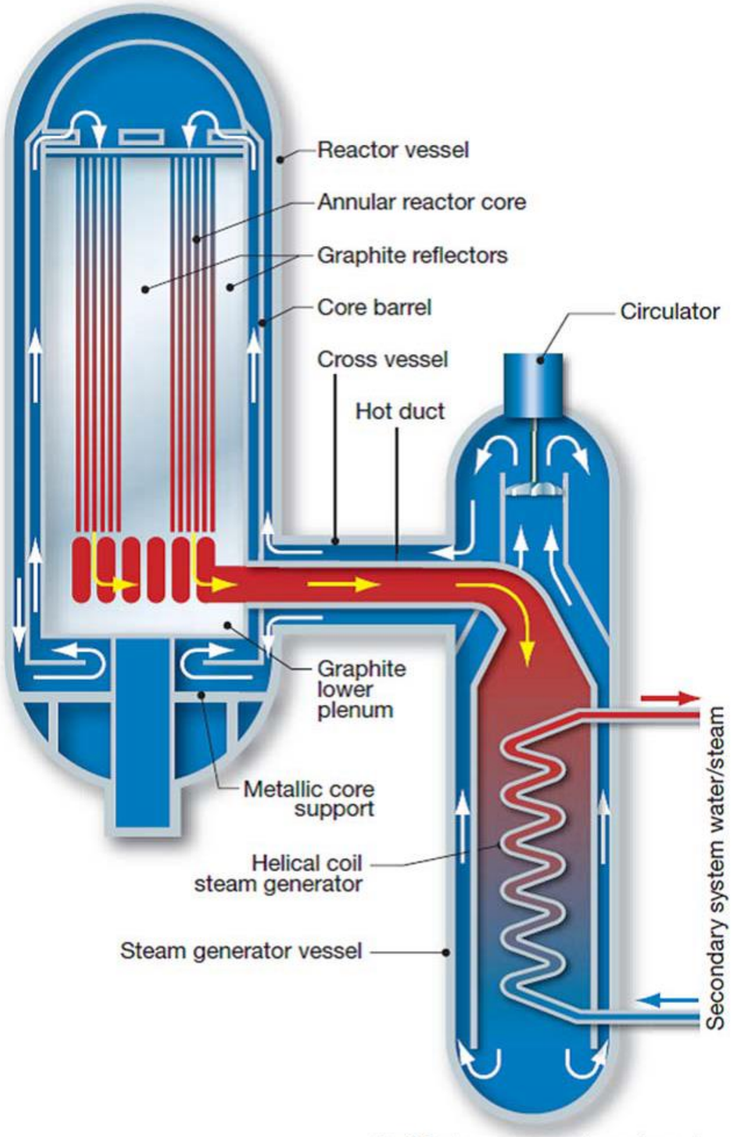






Main Attributes of Modular HTGRs

- Graphite-moderated and reflected
- Cooled (usually) by helium (~7 MPa). Molten salt (Kairos Power) under development and nitrogen has been proposed
- Large axial temperature gradient (>400^{o}C) across the core compared to 30^{o}C for an LWR
- Uninsulated reactor vessel
- Large aspect ratio (tall, thin active core regions): heat escapes radially via conduction and radiation if forced cooling is lost. This attribute also limits the power density (~400 MWt for PBRs; ~600MWt for prismatic reactors)
- Slow temperature response during accidents (combination of high graphite heat capacity and low power density)



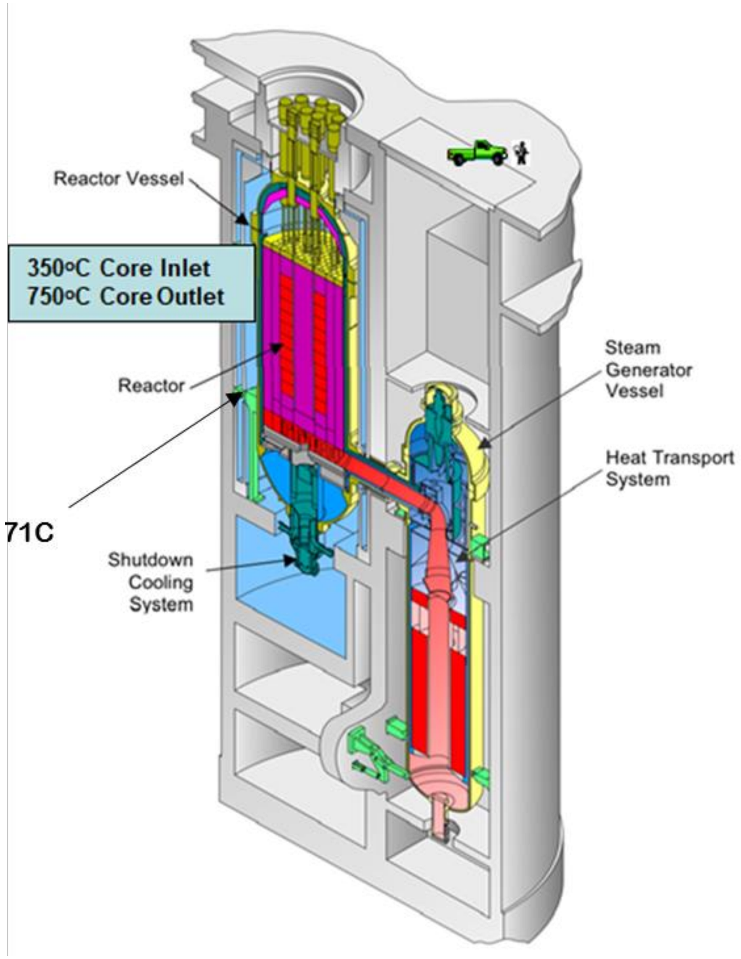
(1 of 2 steam generators shown)

HTGR vs LWR vs CANDU in a Nutshell

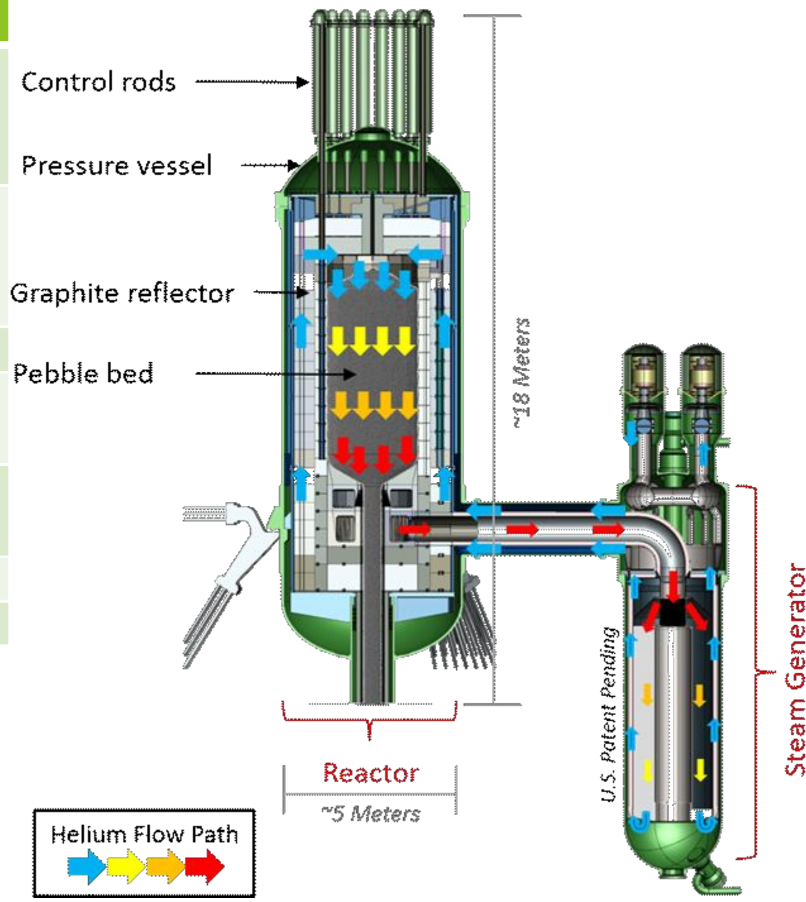
Item	HTGR	LWR	CANDU
Moderator	Graphite	Water	Heavy Water
Coolant	Helium	Water	Heavy Water
Average coolant exit temperature	700-950°C	~310°C	~310°C
Structural material	Graphite	Steel	Steel
Fuel clad	SiC and PyC	Zircaloy	Zircaloy
Fuel	UO_2, UCO	UO_2	UO_2
Fuel damage time at temperature	Tested at 1800°C for >150 hours (AGR program)	1260°C, minutes?	>1700°C, minutes?
Power density, W/cm^3	4 to 6.5	60-100	~10
Linear heat rate, kW/ft	57	6	~11-12

Shenoy, A.. (General Atomics) History and Evolution of HTGRs, HTGR Technology Course for the Nuclear Regulatory Commission, 2010.

Common Primary Loop Features – Prismatic and Pebble Bed HTGRs



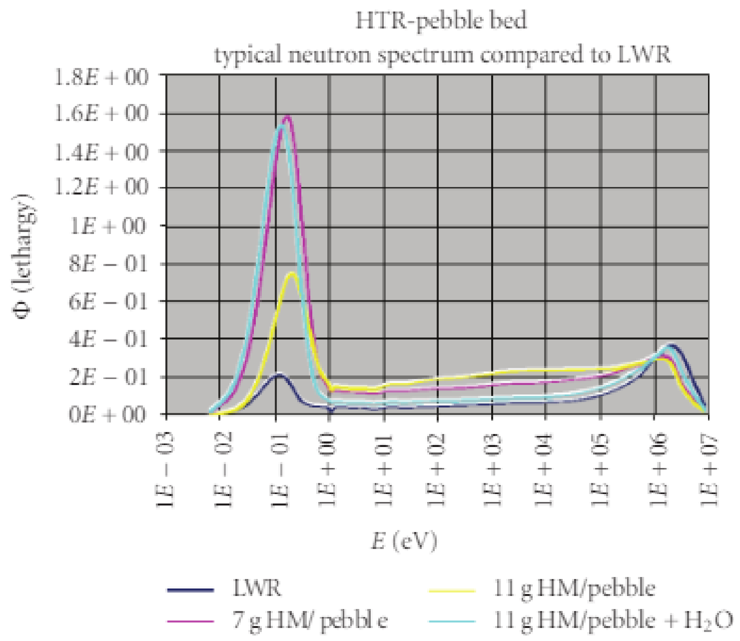
Parameter	PMR	PBR
Fuel	TRISO (<20% LEU) in compacts and blocks	TRISO (<20% LEU) in pebbles
Core Geometry	102 columns,10 fuel blocks per column	~300,000 pebbles in a cylindrical bed
Reactor Power	625 MWt	200 MWt
Reactor Outlet Temperature	750°C	750°C
Reactor Inlet Temperature	350°C	260°C
Primary	Helium at 6 MPa	
Secondary (x2)	Steam @ 16.7 MPa, 566°C	



Framatome 625 MWt Prismatic SC-HTGR: *framatome.com*
Xe-100 200 MWt Pebble Bed HTGR *(x-energy.com)*

Basic HTGR physics

	LWR (H2O)	HTGR (Graphite)
Average Thermal Energy (eV)	0.17	0.22
Enrichment %	3-5	8-16
Moderating Ratio $(\xi\Sigma_s/\Sigma_a)$	62	216
# scatters to thermal	~18	~114
Mean free path (cm)	~0.5	3.9
Migration Length (cm)	57	6



- So much graphite…
  - Criticality benchmark evaluations (Bess, 2014) frequently overpredicted k_{eff} by several hundred pcm until new measurements dropped C-12 σ_scattering by ~0.3 mb. (under-prediction resulted)
  - Relatively large uncertainties in neutronic calculations (e.g., XS input uncertainties lead to ~600 pcm keff uncertainty (1 std.dev))
  - Fortunately, safety parameters (e.g., rod worth, power peaking) are largely insensitive (e.g., <1.5% variation in local block power) to these XS uncertainties (Strydom, 2018)
- Large temperature and burnup variation along *z*
  - Need to discretize the core along axial dimension.
  - Must couple (at least loosely) to thermal-fluidics.
- Large mean free path (mfp): neutronic coupling between blocks or pebble bed 'zones' – single assembly lattice calculations do not capture leakage effects.

Temperature Coefficients	Unit	Under Operating Conditions
Fuel (Doppler coefficient of mainly ^{238}U)	Δρ/°C	- 4.4 x10^{-5}
Moderator	Δρ/°C	- 1.0 x10^{-5}
Reflector regions (all together)	Δρ/°C	+ 1.8 x10^{-5}
Total	**Δρ/°C**	**- 3.6 x10^{-5}**

John D. Bess, Leland M. Montierth, Oliver Köberl and Luka Snoj (2014) Benchmark Evaluation of HTR-PROTEUS Pebble Bed Experimental Program, Nuclear Science and Engineering, 178:3, 387-400,DOI: 10.13182/NSE14-13

G. Strydom, P. Rouxelin (2018). IAEA CRP on HTGR UAM: Propagation of Phase I cross section uncertainties to Phase II neutronics steady state using SCALE/SAMPLER and PHISICS/RELAP5-3D. Proc. of HTR2018, Warsaw, Poland.

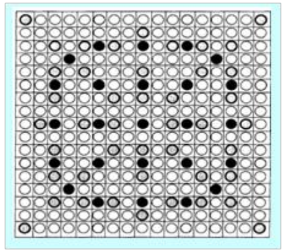
Relative Fuel and Core Size (mean free path)

Assembly | **Core**

mean free path

LWR

1 cm



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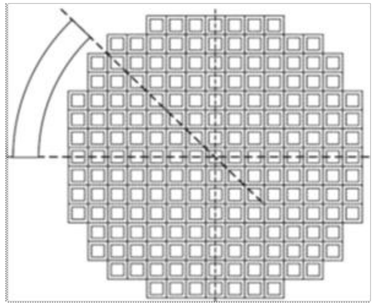
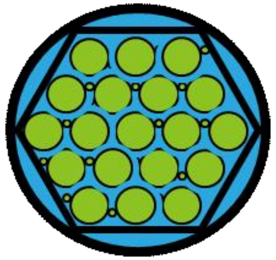


~300

Weak coupling, strong local resolution

SFR

5-8 cm



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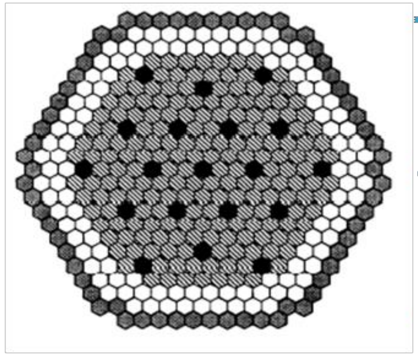

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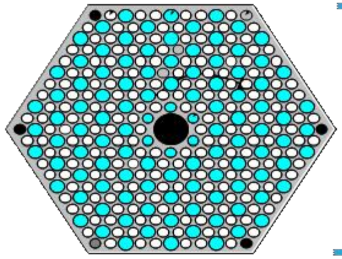
Strong coupling, weak local resolution

HTGR

3-4 cm



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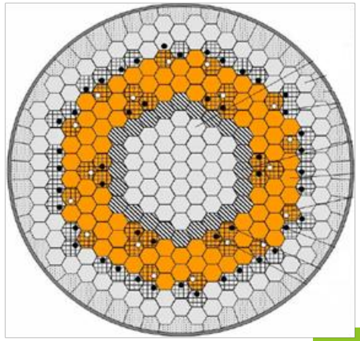
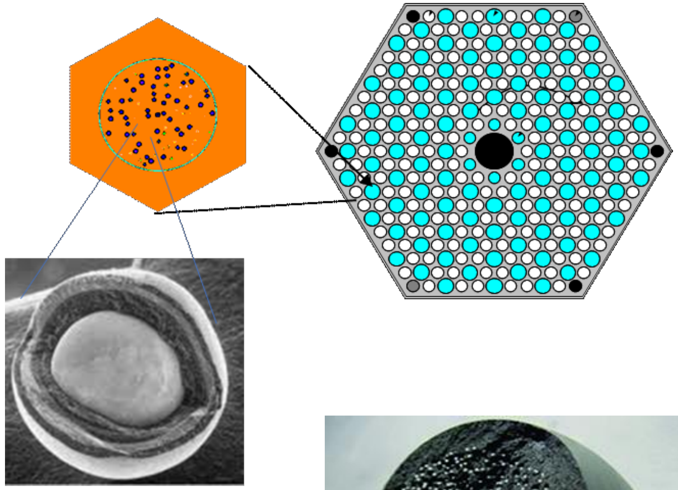


~30

Moderate coupling, Moderate local resolution

Cross-Generation Considerations

- 3 or 4 levels of heterogeneity
- More scattering in the resonance region
- Long migration area – stronger coupling between regions of the core
- Reflectors and control rods not located in the core
- Uncertainties in nuclear data (1 sigma~ 0.5%)
- Good agreement can be obtained by using:
  - More energy groups (8-26)
  - A supercell method for capturing leakage and generating cross sections for the control rod regions in the reflector
  - 'SuperHomogenization' or discontinuity factors for harmonizing transport and diffusion reactor rates
  - Proper discretization in the axial dimension

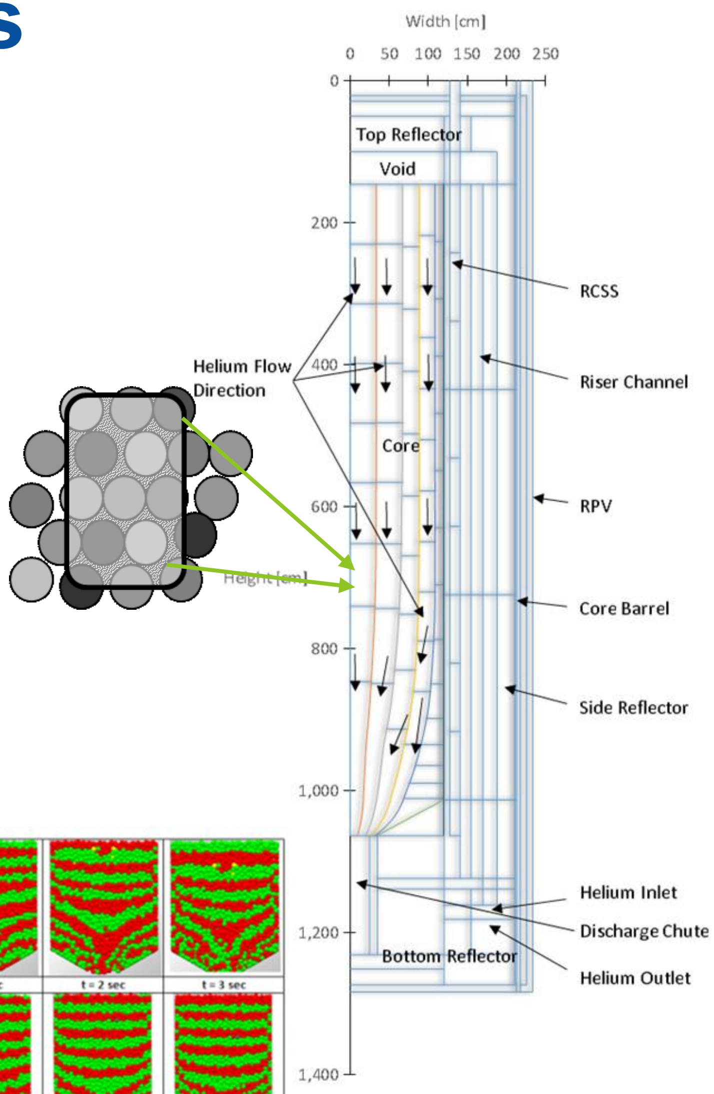


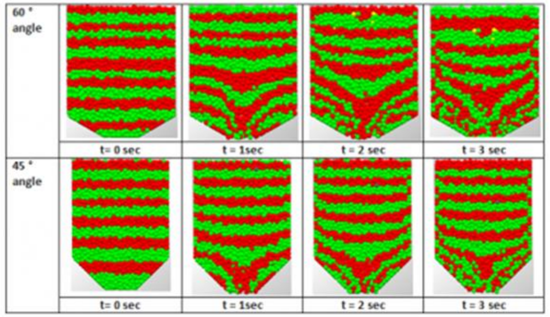
H. Gougar, A. Ougouag, W. Yoon, Multiscale Analysis of Pebble Bed Reactors, Proceedings of 5th International Topical Meeting on High Temperature Reactor Technology, (HTR 2010), Prague, 2010.

Laboure, V., Ortensi, J., Hummel, A., HTTR 3-D Cross-Section Generation with Serpent and MAMMOTH, INL/EXT-18-51317, September 2018.

Pebble Bed Core Physics Considerations

- Lack of 'natural' assemblies; cross sections are computed for somewhat arbitrarily chosen 'spectral zones' to account for variations in temperature and nuclide composition
- Fuel movement and reshuffling
  - Loaded from the top (unless it's cooled with molten salt)
  - Pebbles roughly follow axial "flowlines"; radial motion toward a discharge chute. Burnup is solved along these.
  - Partially burnt pebbles sent back to the top (requires online burnup measurement)
  - If the power and fuel pebble design are kept constant, eventually the core reaches an equilibrium burnup profile
  - Online (continuous) fueling allows for a very low excess reactivity
  - Pebble flow is subjected to drag forces along reflector walls (variable residence time); leads to non-uniform flow patterns.
  - Cylindrical or annular cores, multiple pebble types, and different loading patterns are possible (cylindrical vessels with a single pebble type are the most common)
  - First core is started with lower-enriched pebbles on top of graphite-only bed
  - Analysis of the 'running-in' period (which can be a few years) poses a challenging optimization problem.

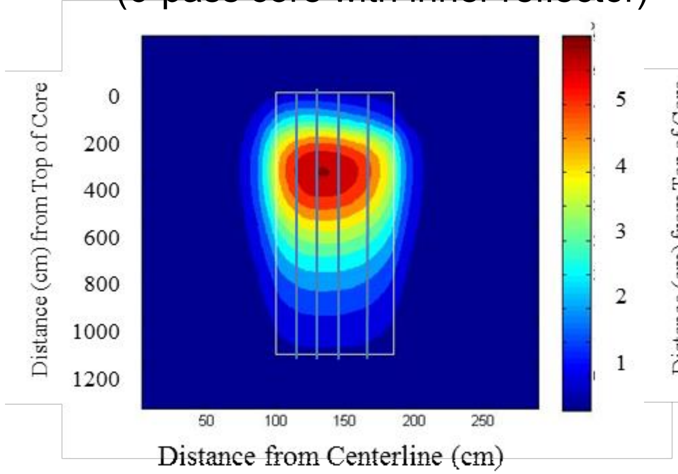


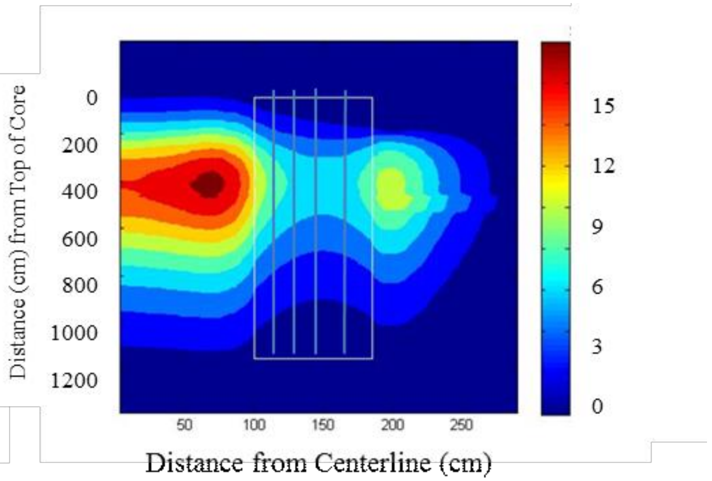


A.M. Ougouag, H.D. Gougar, R.S. Sen, "Identification of Spectral Zone Boundaries in Pebble Bed Reactors," Proceedings of 9th International Topical Meeting on High Temperature Reactor Technology, (HTR 2018), Warsaw, 2018.

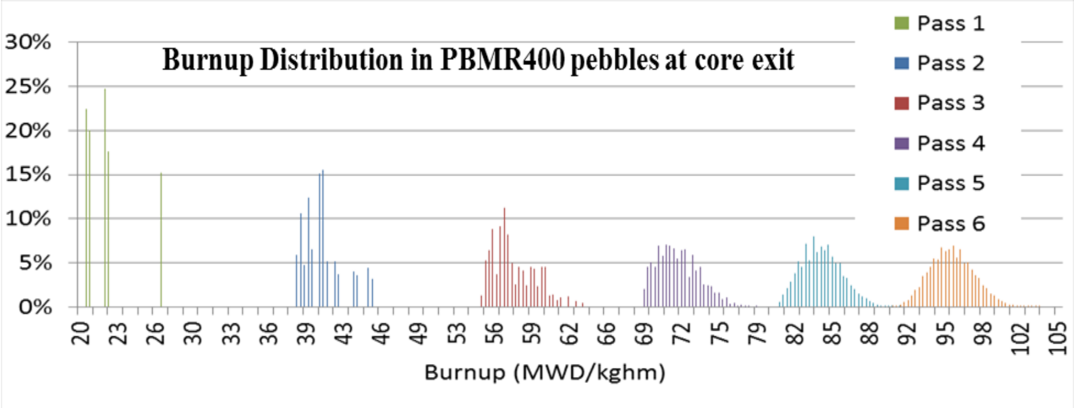
Pebble Bed HTGR Core Physics Data

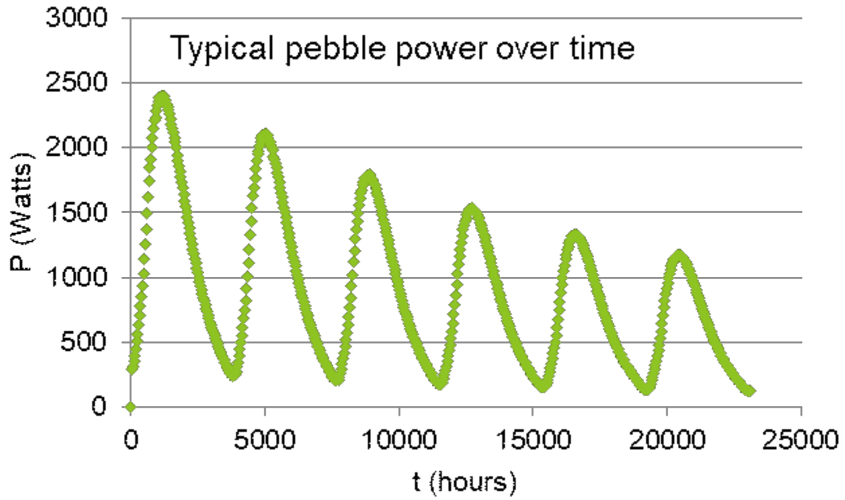
Fast and thermal flux profiles in the PBMR-400 equilibrium core (6-pass core with inner reflector)

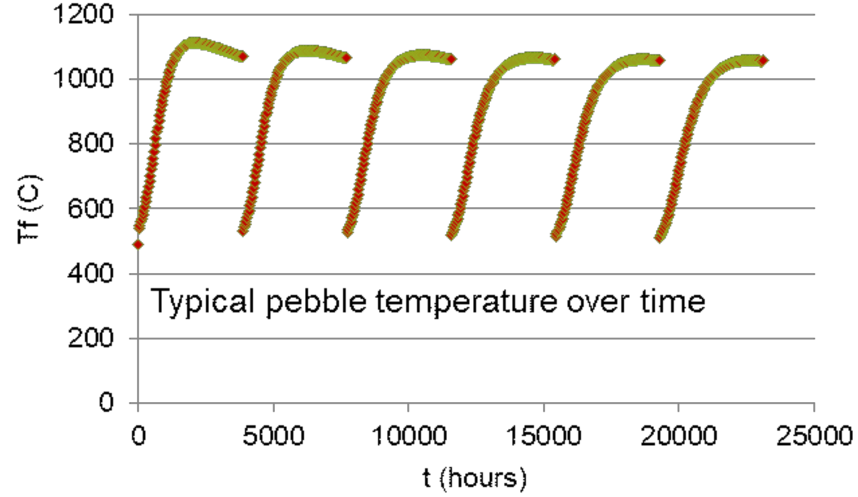




Spectral variations leads to a burnup distribution in pebbles leaving the core



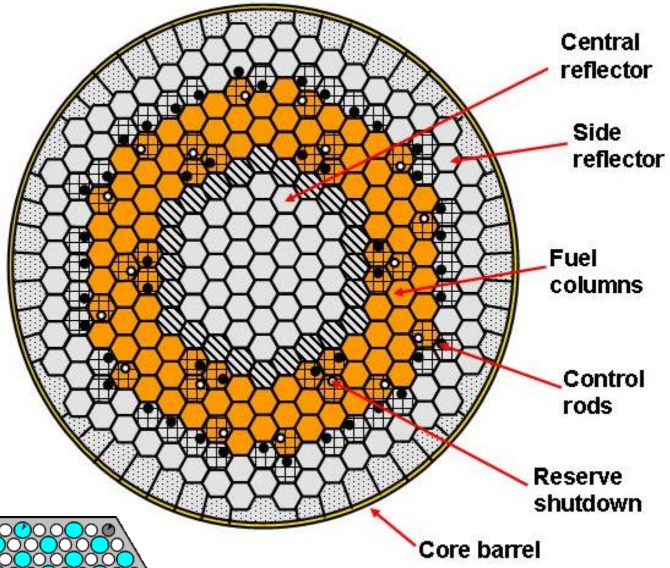


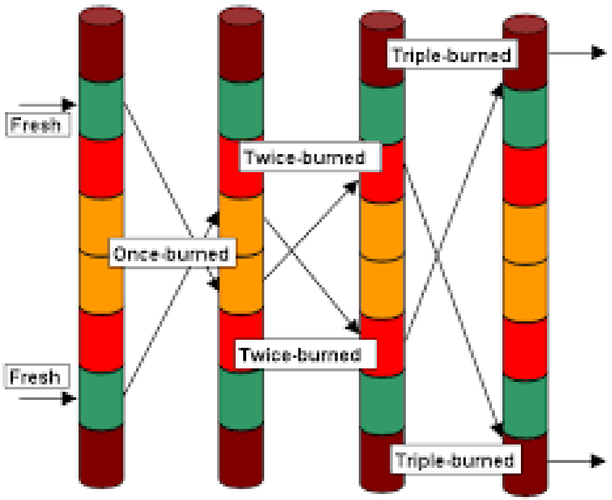


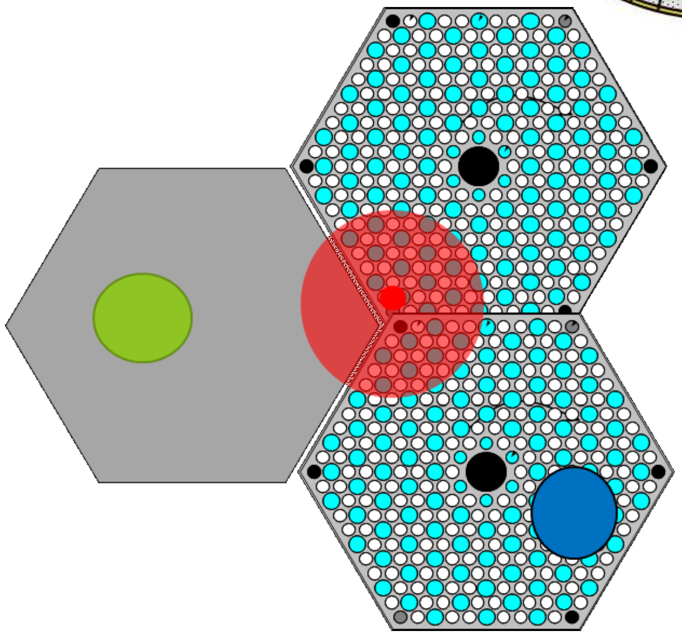
Gougar, H.D., Ougouag, A. M., Terry, W. K., and Ivanov, K. I., "Automated Design and Optimization of Pebble Bed Reactor Cores, Nuclear Science and Engineering, Oct. 2008.

Prismatic HTGR Phisics Considerations

- Compacts in blocks with engineered coolant channels – more heterogeneous than PBRs.
- Burnable poison compacts/pins in corners of blocks are used to flatten the power and hold down reactivity over the cycle.
- Shutdown rods are inserted into the fuel blocks. Holes become streaming pathways during normal operation when these rods are out.
- Fuel reshuffling can be 3D, but generally not, due to uneven swelling of blocks. Axial shuffling generally preferred.







Cetnar, J. et al, Assessment of Pu and MA utilisation in deep burn Prismatic HTR by Monte Carlo Method – MCB, Project PUMA, AGH-University of Science and Technology, Krakow, Poland, 2013

Outline

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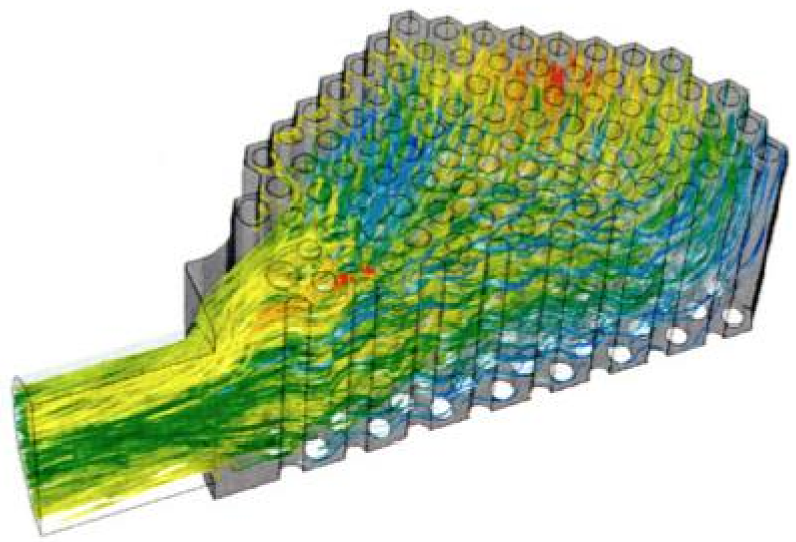
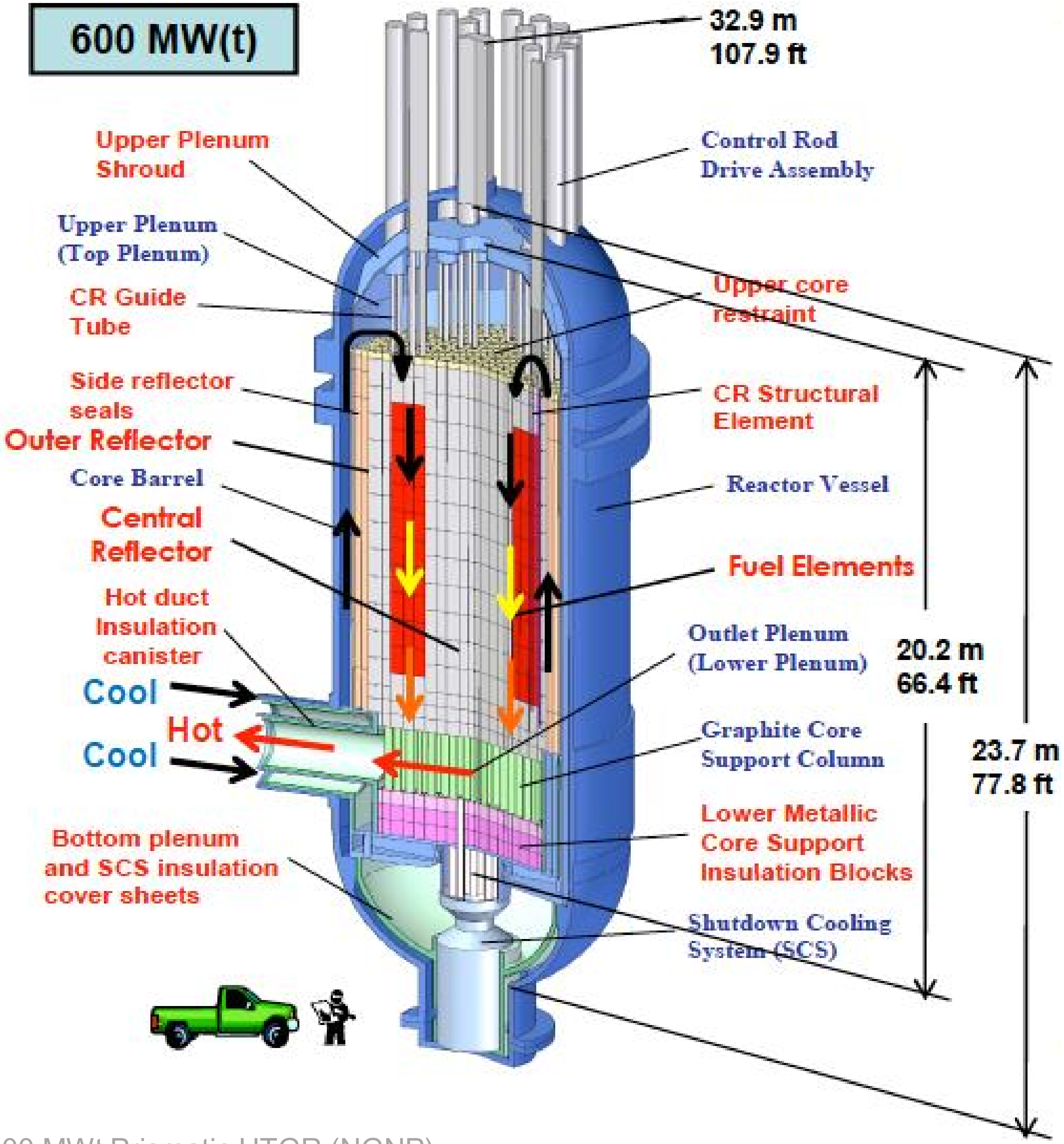
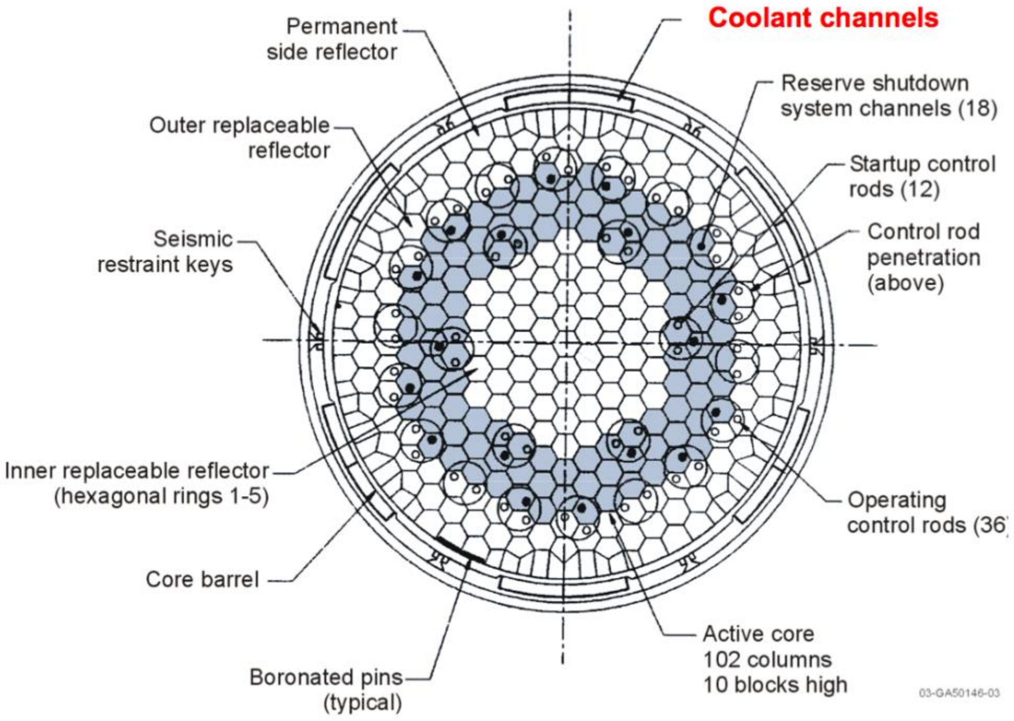
Coolant flow in Lower Plenum



 Petti, D. et al (2019). Current Status of VHTR Technology Development.

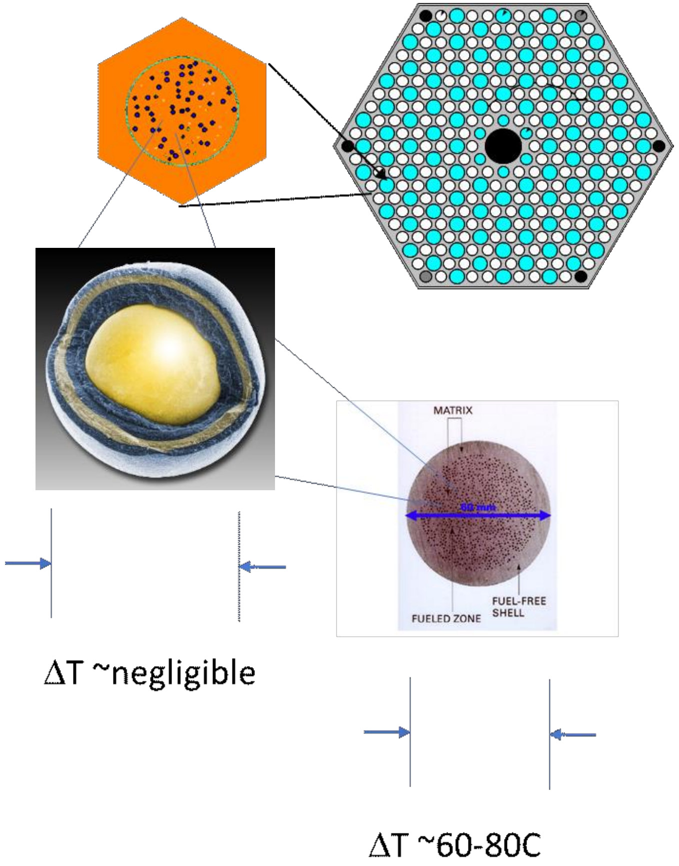
Helium Flow Path





Thermal-Fluids and Local Heat Deposition

- Downward flow in core
  - Inlet coolant directed upward along the inside of the RPV to keep it and the Control Rod structures cool
  - Flow reverses during LOFC
  - Complex mixing structure at core outlet to prevent thermal ‘hot-striping’ and stress on downstream components
- Graphite’s role
  - Thermal transients are relatively slow due to large heat capacity
  - Heat transfer via conduction/radiation after a loss of force flow
  - HTGRs can assume “*no coolant*” for safety case transients
- Helium is neutronically transparent and chemically inert

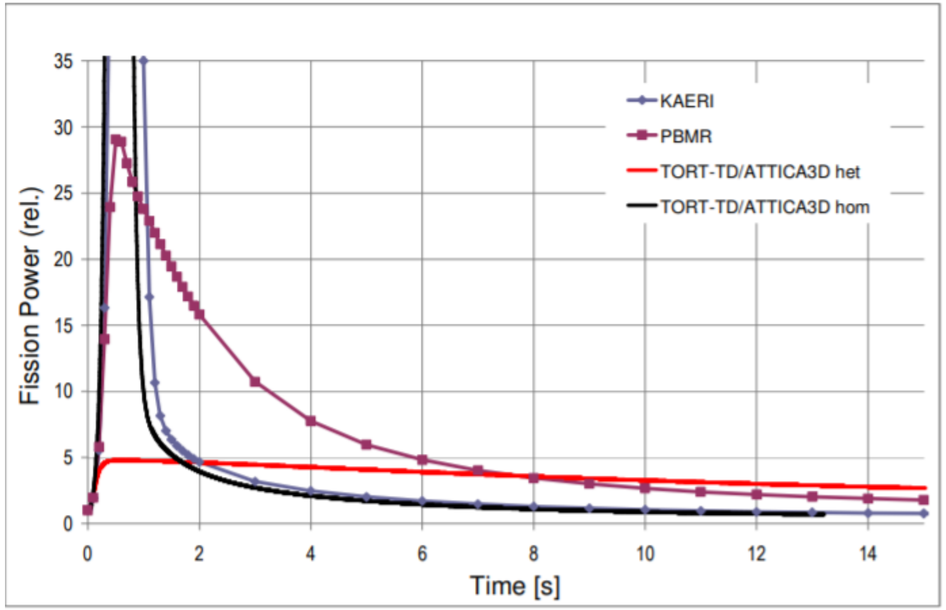


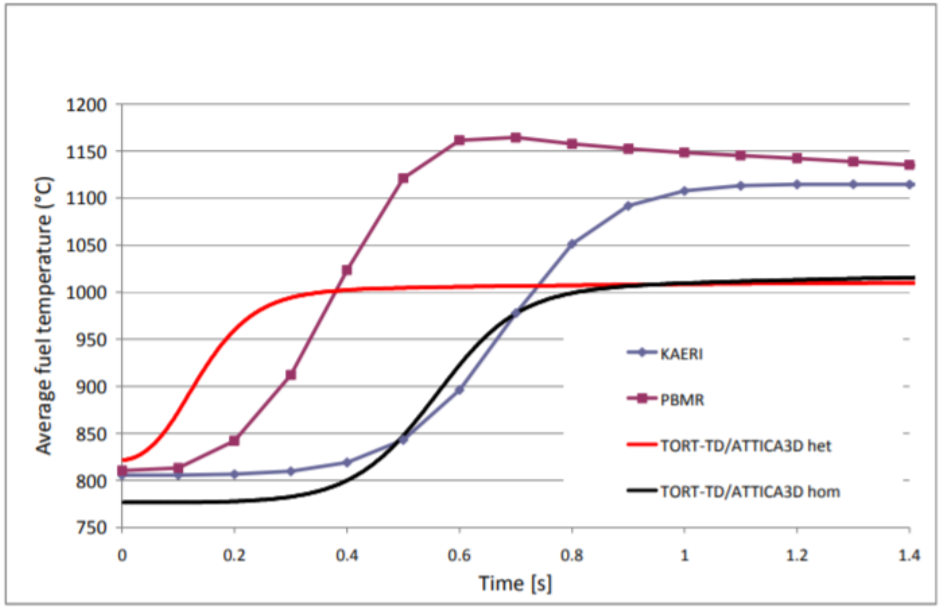
- Kernels are small, but still larger than the recoil distance of fission products ⇒ most of the fission heat is deposited in the kernel, but…
- This heat dissipates easily into the surrounding matrix, so for all but the most extreme reactivity spikes, the particles are largely in thermal equilibrium with the surrounding matrix, even during transients
- This allows one to define the ‘fuel temperature’ as the compact or fueled region of the pebble

Melese and Katz, “Thermal and Flow Design of Helium-Cooled Reactors”, American Nuclear Society, ISBN 0-89448-027-8, 1984.

Explicit Particle Heat Deposition Models for RIAs

- Some codes have been developed with a ‘subgrid’ model of heat deposition only in the kernel; and transient heat conduction out of the particles and into the matrix.
- Results show very different fuel temperature and power trajectories between ‘smeared’ and explicit models for large (and in some cases unphysical) reactivity insertion accident (RIA) transients
- The smeared fuel models are generally much more conservative – kernel-limited heat deposition leads to faster Doppler turnaround





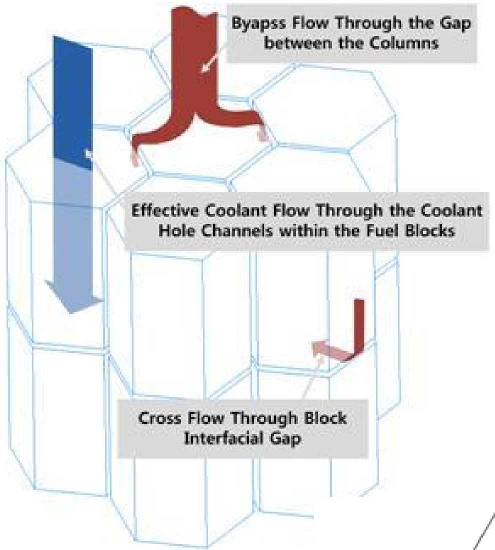
Power and temperature excursion during Total Rod Ejection (0.1 cm) – this scenario is precluded by design

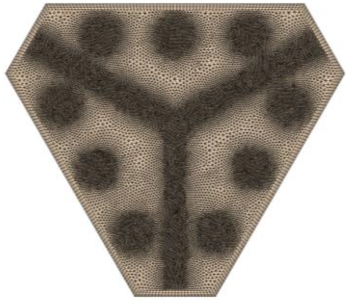
Lapins, Janis and Seubert, A and Buck, Michael and Bader, Jo and Laurien, E. (2011). Tort-td/AtticA3D: A Coupled Neutron Transport and Thermal Hydraulics Code System for 3-D Transient Analysis of Gas Cooled High Temperature Reactors. 10.13140/2.1.3526.3369.

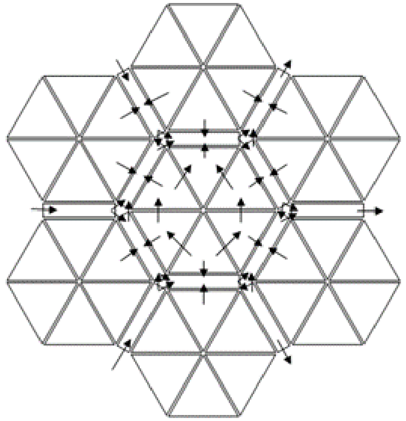
Ortensi,J., Boer, B, and Ougouag, A,. Thermo-mechanical Analysis of Coated Particle Fuel Experience a Fast Control Rod Ejection, Proceedings of the 5th International Topical Meeting on High temperature Reactor Technology (HTR2010), Prague, October 2010.

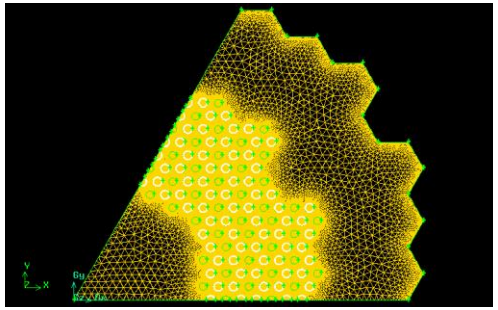
Core Thermal-Fluids: Prismatic

- To first order, heat transfer during power operation can be captured with 1-D pipe flow models and 2-D heat conduction
- Slow (days/weeks/months) dimensional changes in graphite as function of fluence and temperature lead to alternate coolant pathways (bypass flow) – significantly altering the temperature profile in the core and reflector. Bypass flows can be modeled as extra channels in network codes.
- Little momentum upon loss of pumping power, coolant quickly slows (re-laminarization) and is then driven by buoyancy. If there are significant bypass gaps, radiation across the gaps becomes a dominant heat transfer mechanism
- Transient analysis are still performed with simple homogenized block (or subblock) models (e.g., AGREE code).
- Coarse mesh CFD methods may be an adequate compromise (cf. NEAMS tools, e.g., PRONGHORN) for long-running transients (typical LOFC event is 60-100 hours).





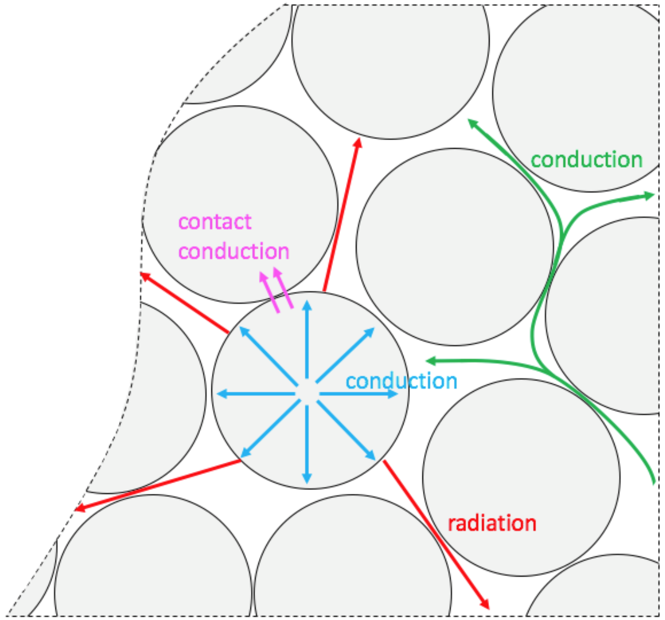


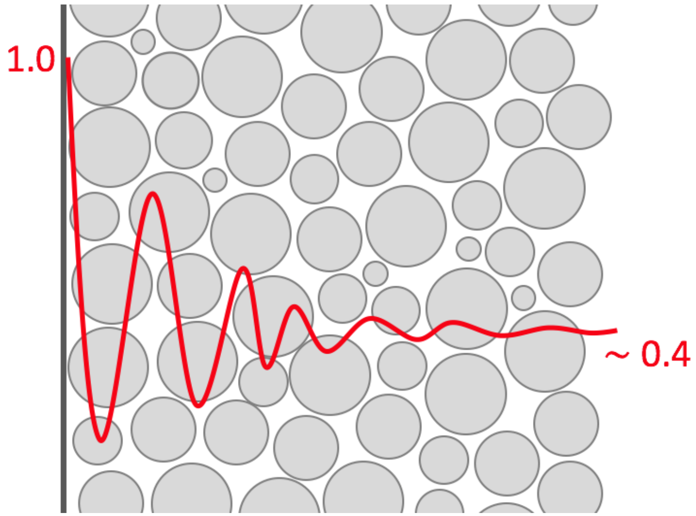


Seker, V.. (2007). Multiphysics methods development for high temperature gas reactor analysis. ETD Collection for Purdue University.
Richard W. Johnson, Hiroyuki Sato, and Richard R. Schultz. CFD Analysis of Core Bypass Phenomena. United States: N. p., 2009. Web. doi:10.2172/974775.

Core Thermal-Fluids: Pebble Bed

- Combined correlations have been developed to capture heat transfer in pebble bed core via conduction, convection and radiation.
- Variable porosity near the wall leads to significant flow changes at bed/reflector interface
- Radiation and conduction dominate under LOFC conditions
- CFD models of local geometries have been executed and avoid many of these empirical assumptions, but *full core* CFD models are still very expensive.





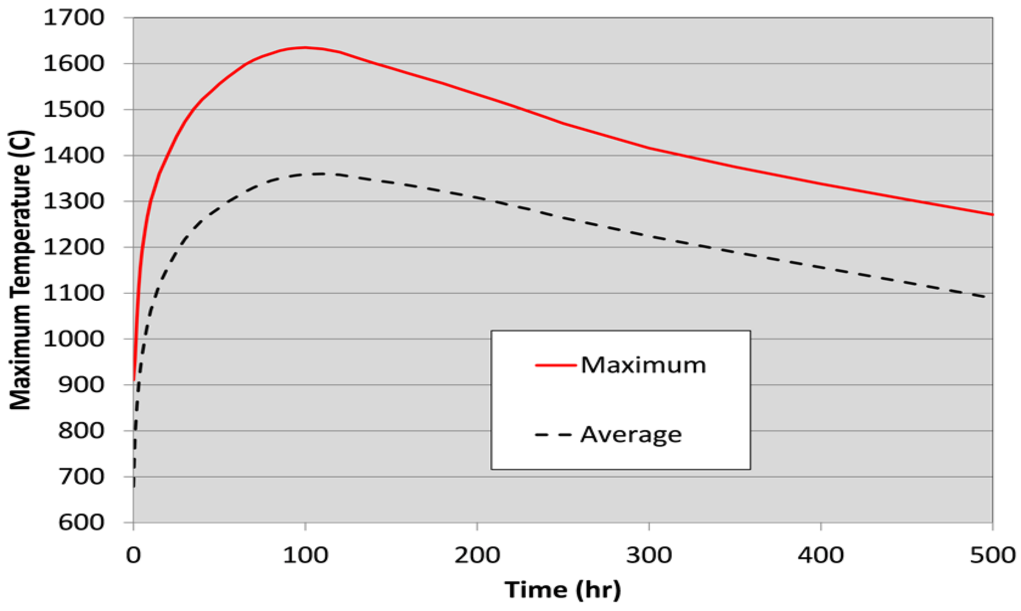
R. Stainsby , 2009. Investigation of local Heat Transfer Phenomena in a Pebble Bed HTGR Core. AMEC NSS Limited, NR001/RP/002 R01. https://www.nrc.gov/docs/ML0909/ML090900017.pdf

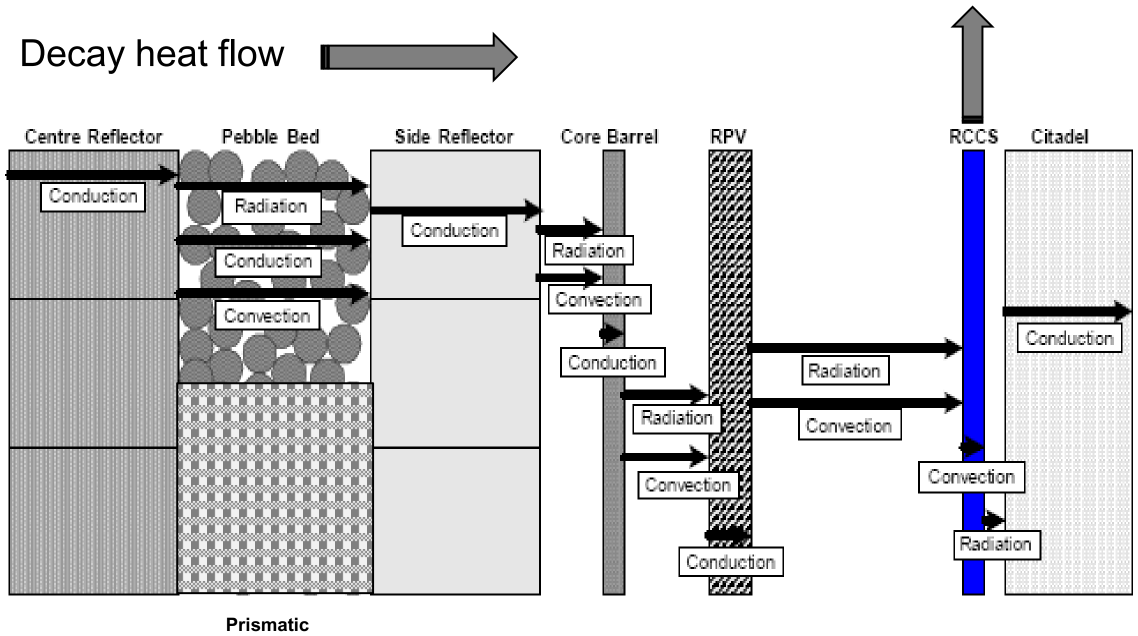
J. J. Janse van Rensburg, M. Kleingeld, 2010. A CFD method to evaluate the integrated influence of leakage and bypass flows on the PBMR Reactor Unit. Nuclear Engineering and Design 240(11):3841-3850.

HJ Vermaak, 2019. CFD analysis of thermal dispersion in a structured pebble bed. M. Eng Thesis, North-West University.

Inherent Safety: LOFC transient

No operator intervention required: heat transfer via combination of inherent physics (Doppler shutdown, radiation heat transfer, graphite heat capacity) and design choices (low power density, tall & slender core, TRISO fuel) keeps peak fuel temperatures below 1600-1800C.





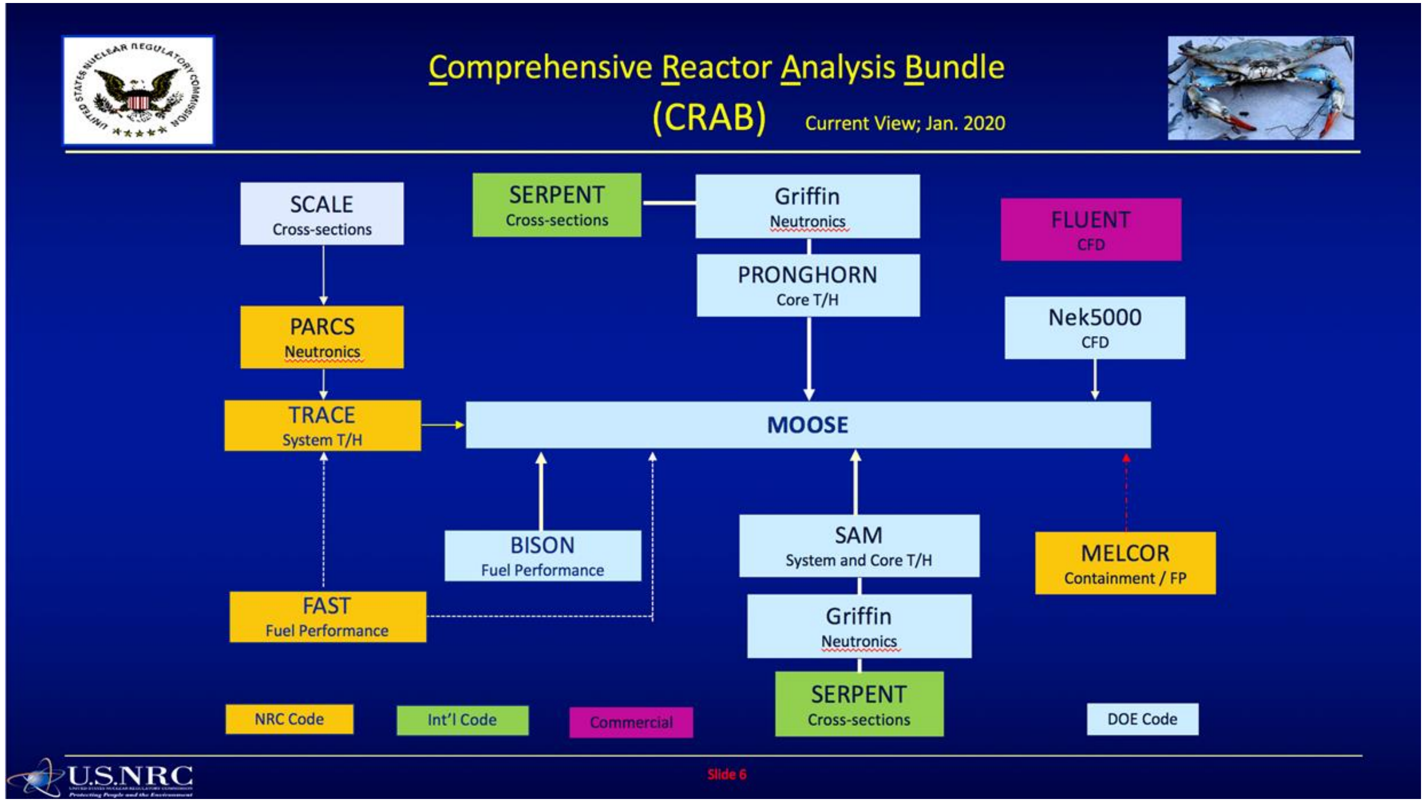
1800C – No appreciable UCO particle failures observed in AGR heating test below 1800C, although accelerated diffusion of certain FP (Sr, Cs, Eu) is observed.
Only a small fraction of the core experiences these high temperatures.

Core temperatures during a DLOFC
AREVA Technical Document 12-9251926-001, Summary Report-SC-HTGRE Demonstration Reactor

Comparison of Response to Accidents

Accident	HTGR	CANDU
Control Rod Withdrawal - prompt feedback	Small, negative	Small, negative
Control Rod withdrawal - long term feedback	Power increase, terminated and shutdown by strong temperature feedback. Damped low-power (<1%) oscillations after xenon decay and core cooldown (for ATWS).	Slow power increase terminated by shutdown or control systems
(Depressurized) loss of coolant	Rapid decrease of power by temperature feedback. Core can be completely “uncovered” by coolant for days.	Fast rise in power requiring shutdown systems. Core requires continued cooling for a significant time.
Cold H_2O injection	Increase in power (then shut-down by temperature feedback). Graphite oxidation might occur depending on steam temperature and inventory. (H_2O is limited by design)	Drop in power - H_2O acts as neutron absorber

US DOE NEAMS HTGR Code Development



- US DOE invested significantly in development of high-fidelity new-generation codes for analysis of non-LWRs in recent years through NEAMS program.
- Industry input to NEAMS program has resulted in a focus on demonstration of NEAMS tools for gas reactors, e.g., Griffin, Pronghorn, BISON.
- Also developed high-resolution capability of resolved pebbles (Nek5000, MOOSE, BISON, OpenMC).

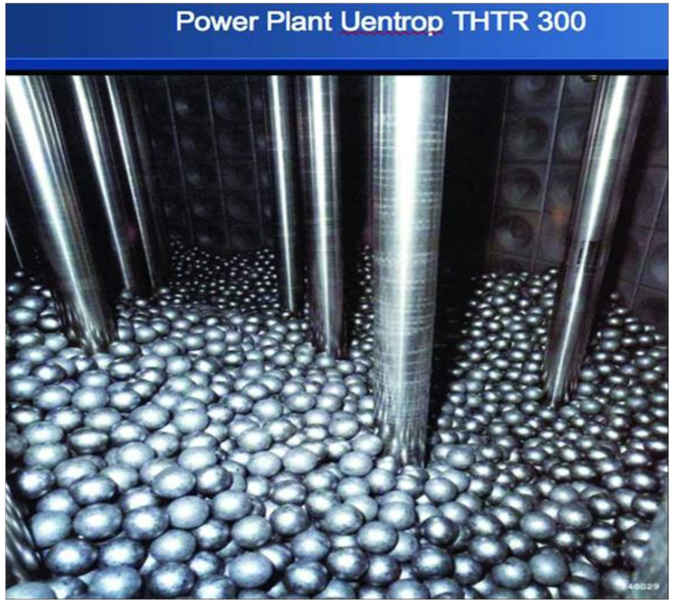
NRC, 2020. NRC Non-Light Water Reactor (Non-LWR) Vision and Strategy, Volume 1 – Computer Code Suite for Non-LWR Plant Systems Analysis. https://www.nrc.gov/docs/ML2003/ML20030A176.pdf

This slide content credit: Chris Stanek (LANL), NEAMS Director. Also see https://inl.gov/neams/ for more detail.

Outline

- General Attributes of Modular Prismatic and Pebble Bed HTGRs
  - Common features and physics
  - Neutronics
  - Thermal-Fluidics
- Plant Systems and Power Conversion
  - Instrumentation and Control
- Normal Operation and Power Maneuvers

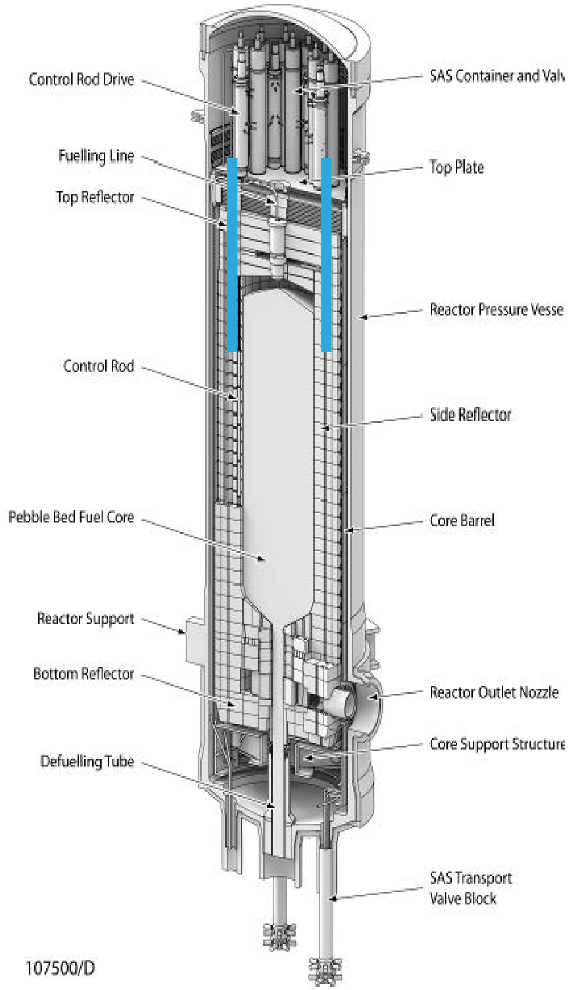
THTR featured a Shutdown CR system in which the rods were forced into the pebble bed. It was designed to be used only intermittently but unintended scrams were frequent. Broken pebbles were a result.



Daoud, H., Serries, F., & Schollmeyer, H. (1989). Operating experience with the THTR core control rods. Germany: INFORUM Verl. (available through IAEA INIS)

Reactivity Control

- Typical: Two independent rod banks
- Articulated rods suspended from drives by chains to be lowered into the radial reflector
- Bypass flow cools the rods
- May be partially inserted during power operation to provide Xenon restart/load follow capability
- Power load following is achieved with helium flow control
- Prismatic – Shutdown rods inserted into fuel blocks
- Pebble bed – Small absorber spheres have been proposed for past designs as cold shutdown mechanism.



Both AVR and HTR-10 were shut down without rods – circulators are stopped to allow core heat up and Doppler shutdown. *No operator intervention* in 24 hours following blower trips.

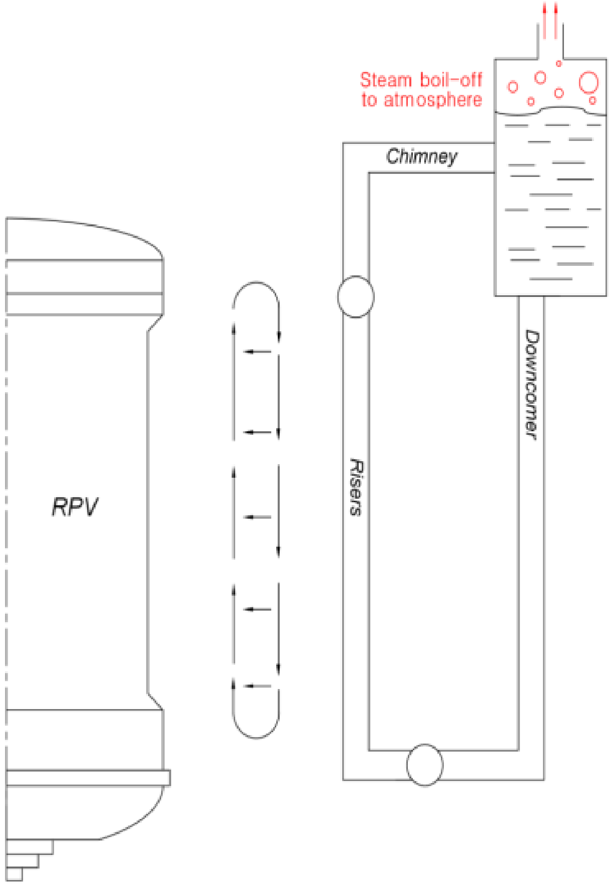
Helium Conditioning System

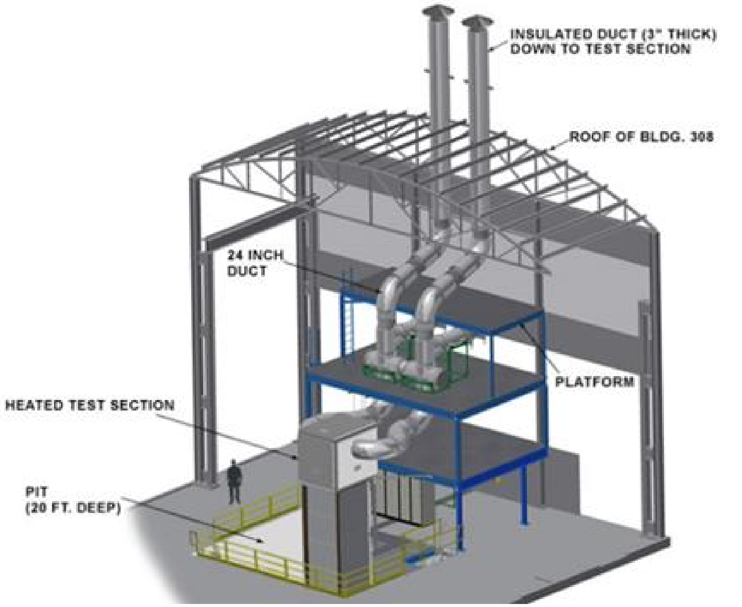
- Removes chemical and radionuclide impurities from helium coolant (H_2O, CO, CO_2, H_2, N_2, O_2, H_2S, CH_4, and higher molecular weight hydrocarbons)
- Pressurizes, depressurizes, and controls the primary helium coolant inventory in conjunction with Helium Transfer and Storage System (HT&SS)
- Purifies helium pumped to storage
- Removes H_2O from primary circuit following water ingress event

Hanson, D. (General Atomics) – Module 10c - Helium Inventory and Purification, HTGR Technology Course for the Nuclear Regulatory Commission, 2010.

Reactor Cavity Cooling System

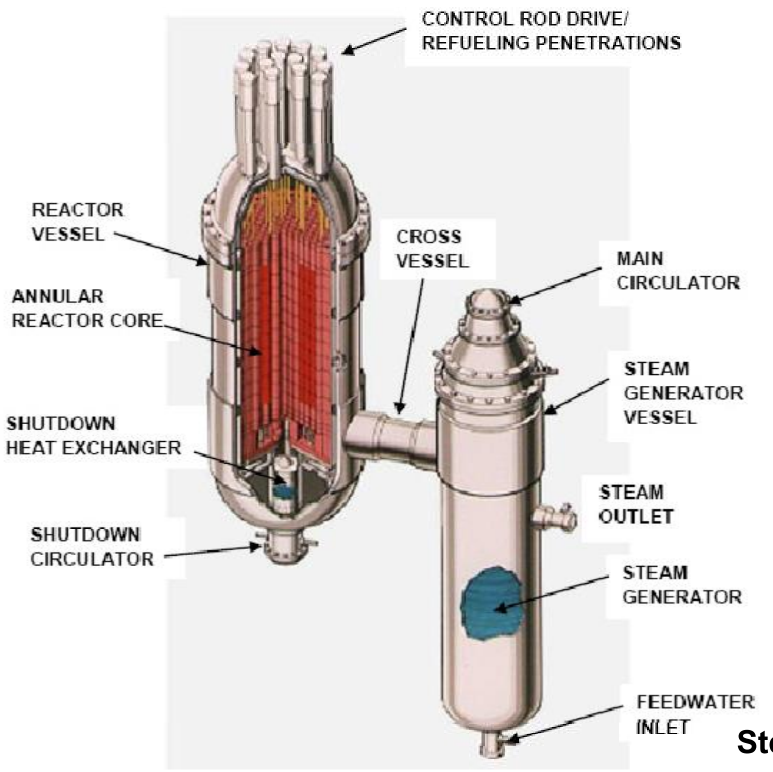
- Primary function is vessel and reactor building (investment) protection during Loss of Forced Cooling (LOFC) transients
- Active and passive heat removal modes via absorption of thermal radiation emitted from uninsulated reactor pressure vessel
- Ultimately rejects heat to the atmosphere
- Air-cooled, water-cooled, or hybrid configurations in series of pipes/panels surrounding vessel



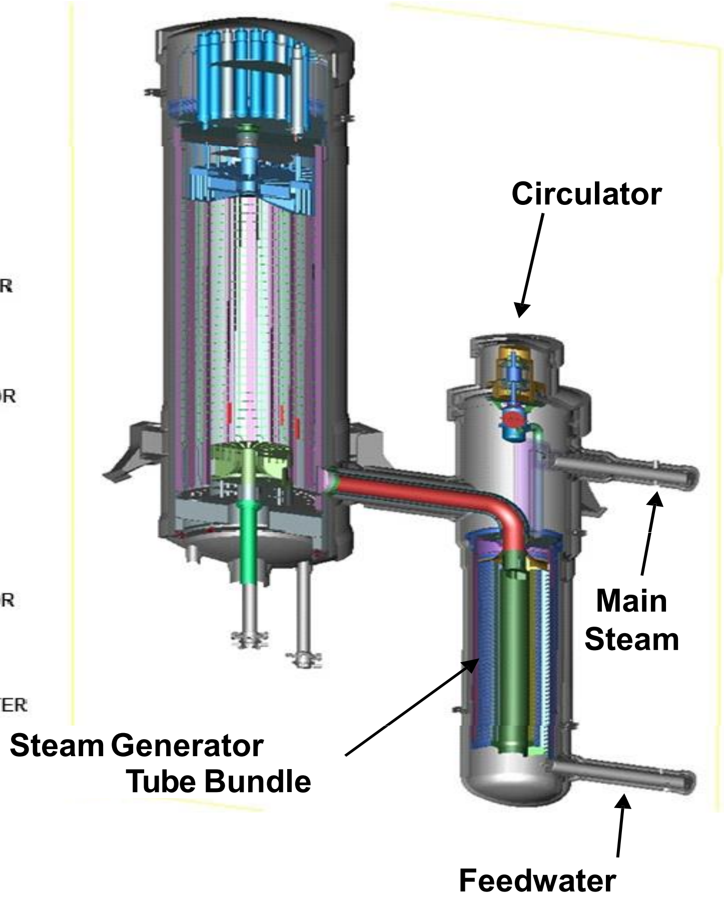


Lisowski, D.D. et al, Experimental Observations of Natural Circulation Flow in the NSTF, Nuclear Engineering and Design 306, (2016) 124-132.
Image: https://www.anl.gov/nse/natural-convection-shutdown-heat-removal-test-facility

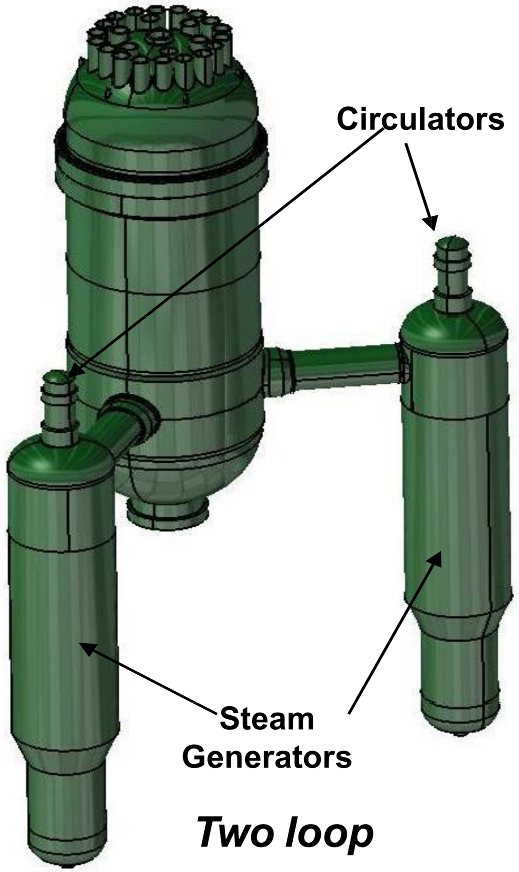
Power Conversion



Single Loop (MHTGR)



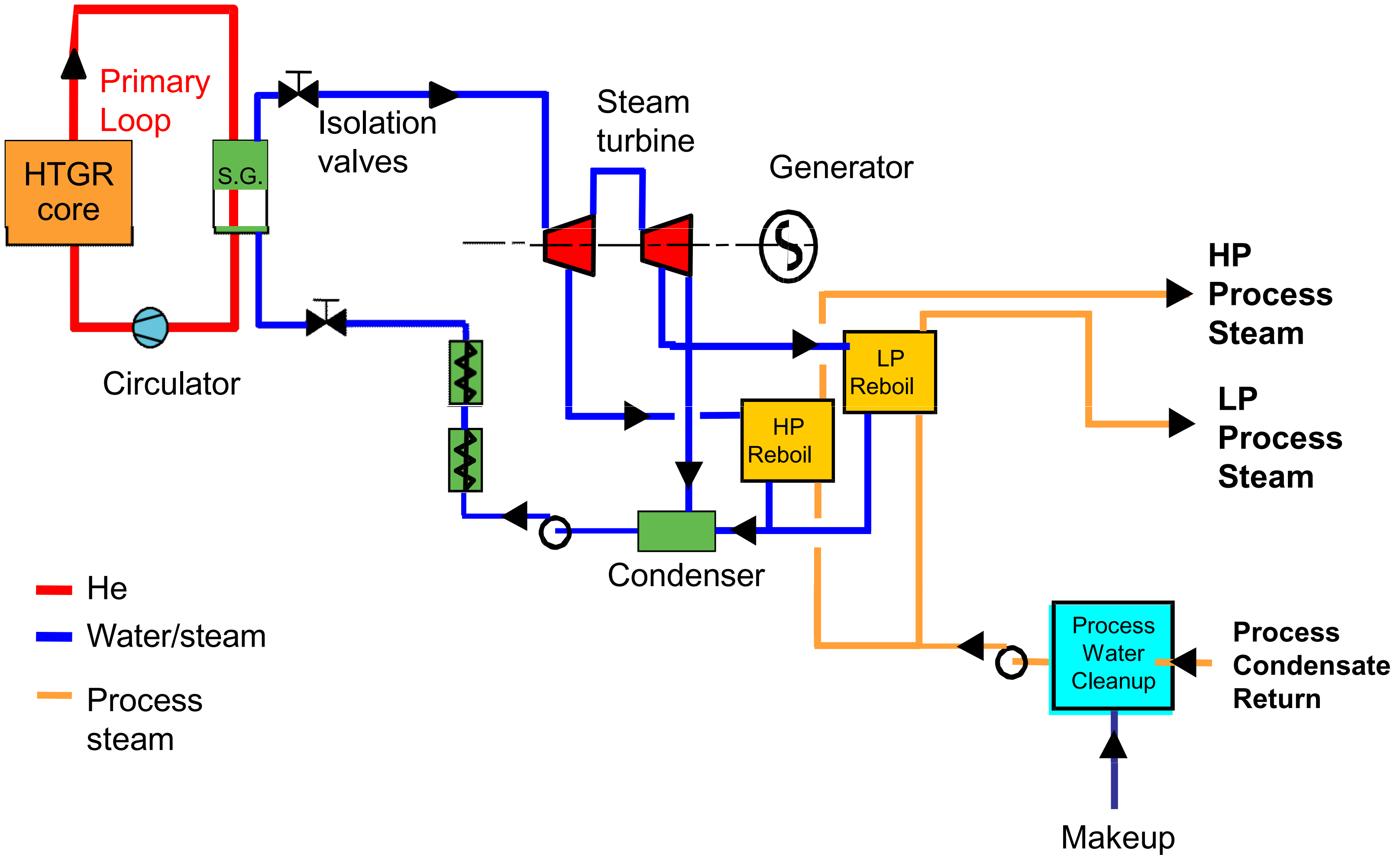
Single Loop (PBMR-CG)



Two loop (Framatome)

Lommers, L. (Framatome) – Module 10b - Steam Cycle Power Conversion System, HTGR Technology Course for the Nuclear Regulatory Commission, 2010.

Steam and Process Heat



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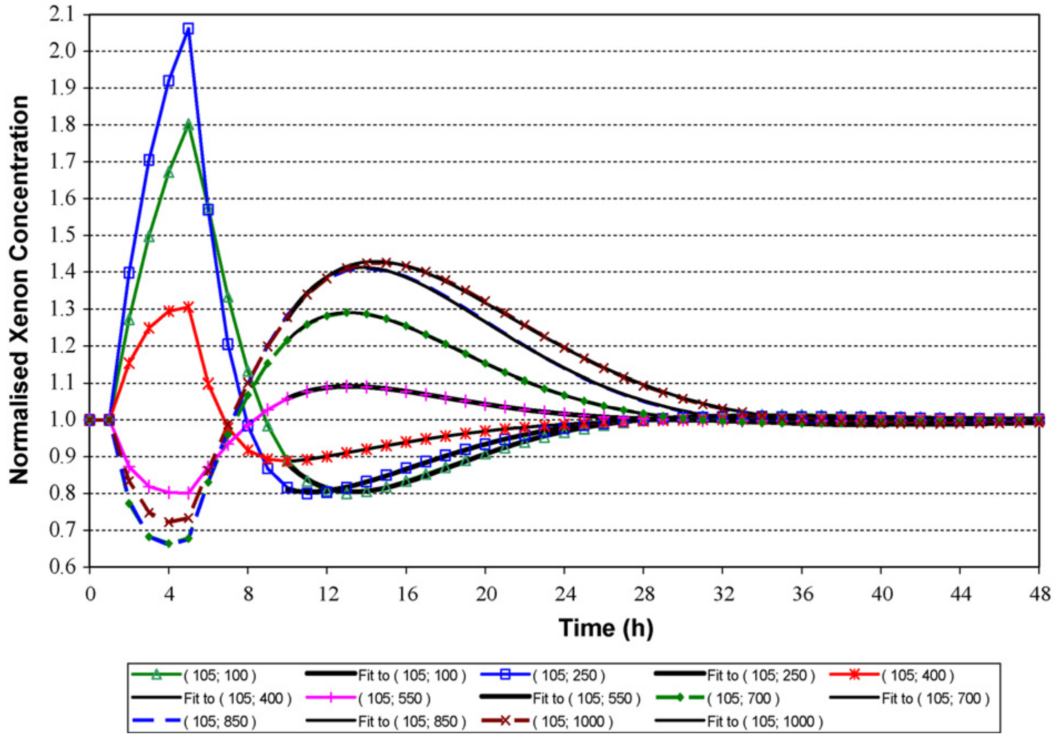
Power Operation/Load Follow

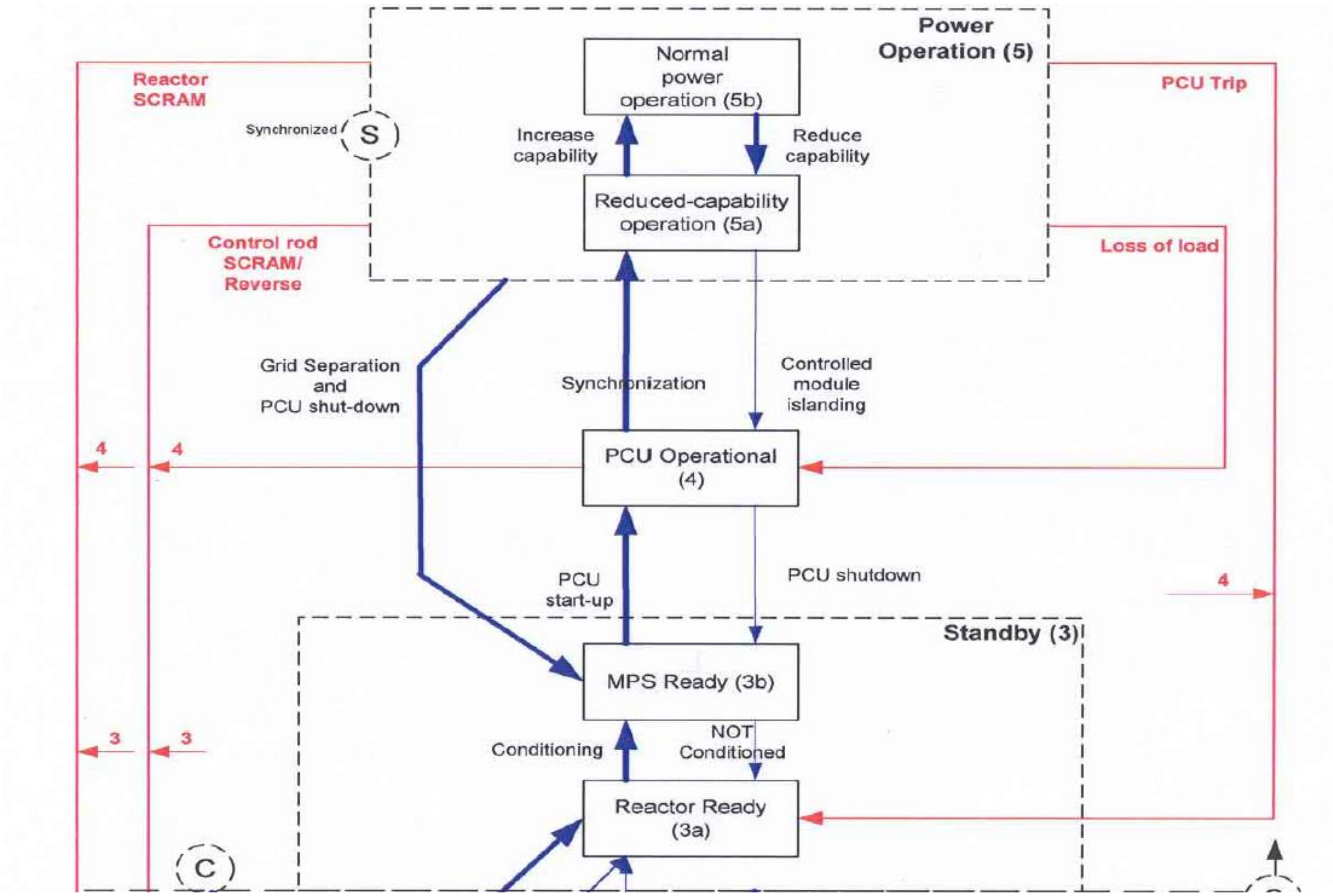
- Various maintenance, shutdown, standby and operational states are usually defined (PBMR example shown in next slide)
- Flexible load-follow capability via helium mass flow rate control allows 100-40-100 e.g., power maneuvering to follow demand.
- Load follow range mostly limited by excess fuel (+) and control rod (-) reactivity available to counter xenon swings
- No xenon spatial instability possible in HTGRs due to long neutron mean-free path. The Xenon oscillations are strongly damped, no need for spatial detection and control.

100-50-100% Load Follow Trajectory



Strydom, G. 2008. Xenon-induced axial power oscillations in the 400 MW PBMR. Nuclear Engineering and Design 238 pp. 2960–2975.

Operating Modes and States (PBMR example)



- Power Operation (Mode 5)
  - 100% MCR Load
  - 40% MCR load
- PCU Operational (Controlled Island Operation (Mode 4)
- Standby (Mode 3)
  - Main Power System ready
  - Reactor ready
- Shutdown (Mode 2)
  - Partial (control rods inserted only)
  - Intermediate (control rods and shutdown rods inserted)
  - Full (all rods and small absorber spheres inserted)
- Fueled Maintenance (Mode 1)
  - Helium Pressure Boundary closed
  - Open Power Conversion Unit
- Defueled Maintenance (Mode 0)

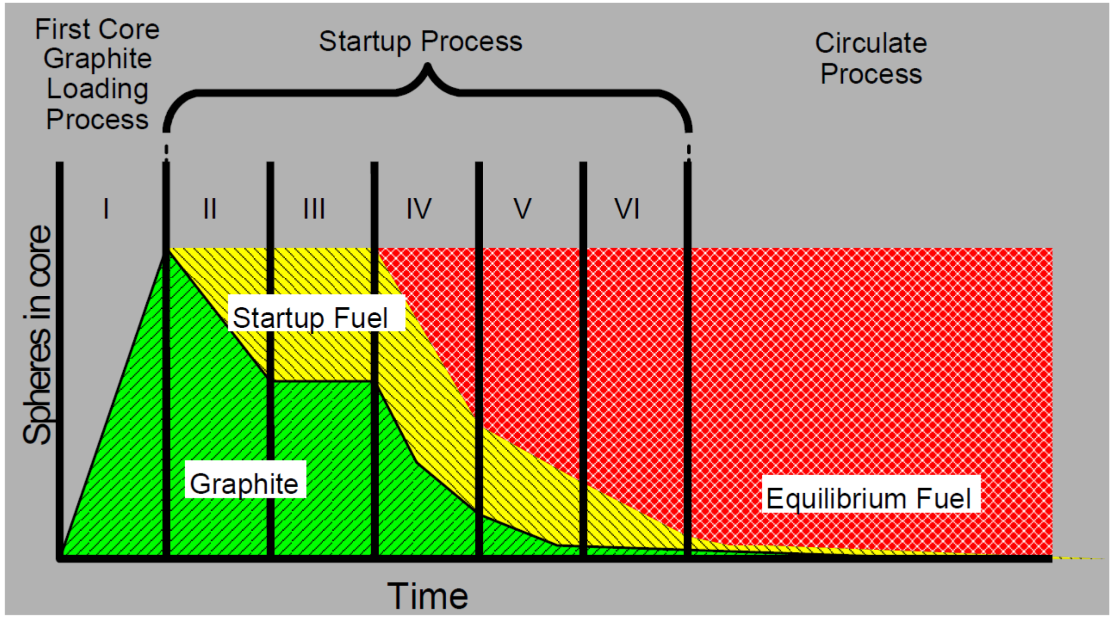
H. W. Chi. 2006. PBMR Plant Operations and Plant Operations and Maintenance Overview. https://www.nrc.gov/docs/ML0607/ML060790549.pdf

Pebble Bed HTGR Start-up Strategy

- Core is filled initially with graphite pebbles. Start-up fuel loaded until initial criticality is reached.
- Core internal structures heated by circulators/blowers up to 300- 400^{o}C.
- Power gradually increased to full power.
- Considerations during start-up and running-in period:
  - Power per pebble limits
  - Maximum fuel temperatures
  - Shutdown margins
  - Pebble circulation rates (not a safety concern, more of a design issue)
- Most of the accidents have lower consequences since the burnup of the fuel is not high enough.

Transition from Startup to Equilibrium Core

- Core “running-in” phase is an optimization problem with multiple constraints:
  - peak fuel temperature typically <1200^{o}C,
  - maximum power typically <5 kW/sphere,
  - minimize fuel costs - limit fuel types to two enrichments,
  - minimize time-to-full-power (revenue $ vs. time).
- Example – “revenue $ vs. time” (above) leads to discharging low-enriched start-up fuel out of the core as quickly as possible, but fuel (and fuel $) is wasted.



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Idaho National Laboratory