Design Criteria for the HTR Core

Jan Leen Kloosterman, Physics of Nuclear Reactors, TU-Delft
20-11-2008

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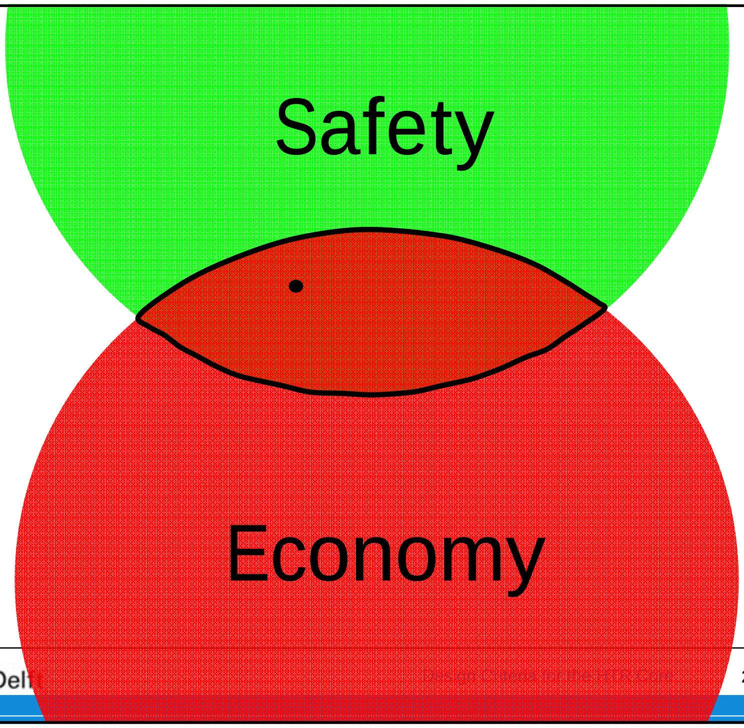


What is Nuclear Safety?

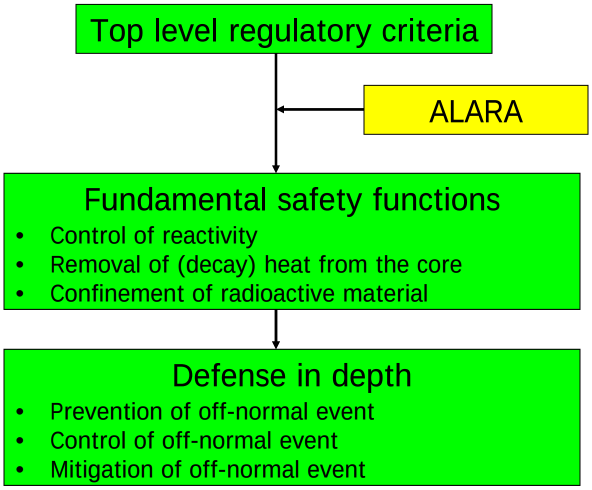
Target: no health hazard to the public or personnel

Subtargets:

- No one near the boundary should take shelter or be evacuated
- No need for moving mechanical components to ensure this target
- Exposure to plant personnel significantly lower than current international values

Koster *etal*, Nucl. Eng. Des. 222(2003) 231

Safety design philosophy



Top level regulatory criteria

ALARA

Fundamental safety functions

- Control of reactivity
- Removal of (decay) heat from the core
- Confinement of radioactive material

Defense in depth

- Prevention of off-normal event
- Control of off-normal event
- Mitigation of off-normal event

Safety classification in defense of depth

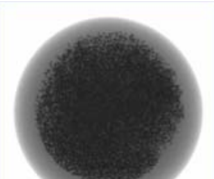
Prevention systems

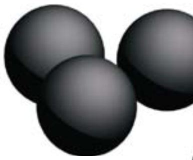
1. Systems that can cause damage to the core if not working properly (inwp)
2. Systems that can cause fission product release inwp
3. Systems that can trigger off-normal events inwp

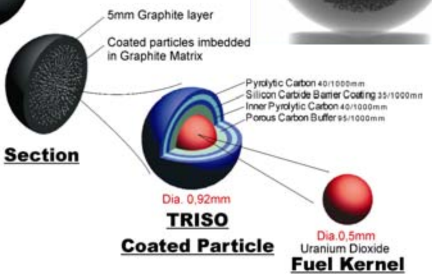
Mitigation systems

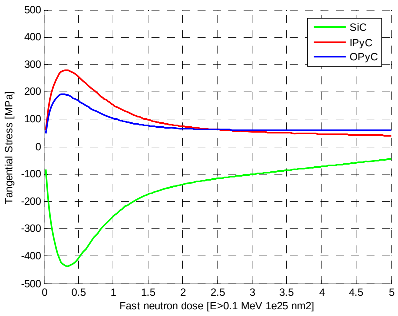
1. Systems to stop the reactor rapidly and remove residual heat
2. Systems to reduce radiation exposure to the public
3. Countermeasures and systems in off-normal states

Fission product containment



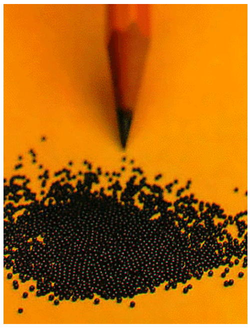






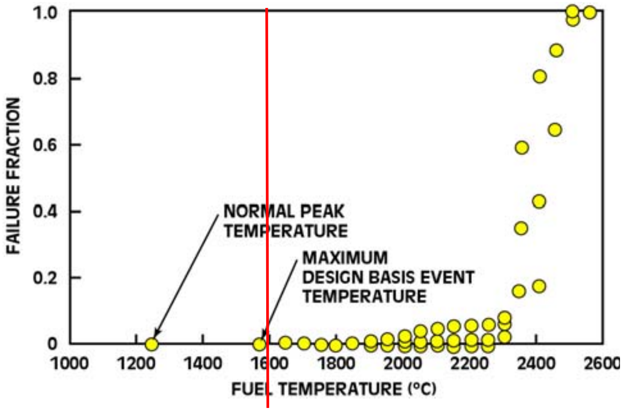
Fission product containment

HTR



LWR

Fission product containment



Considered to be a safe lower temperature limit

Decay heat production

1) Fission products decay

β^- production $(\approx 8\ \text{MeV/fission})$, γ-rays $(\approx 7\ \text{MeV/fission})$

2) Actinide decay

U-239 (23.5 min) and Np-239 (2.35 days)

Much more important for irradiated MOX fuel

3) Delayed neutron induced fission

Comparable to fission products decay; time span?

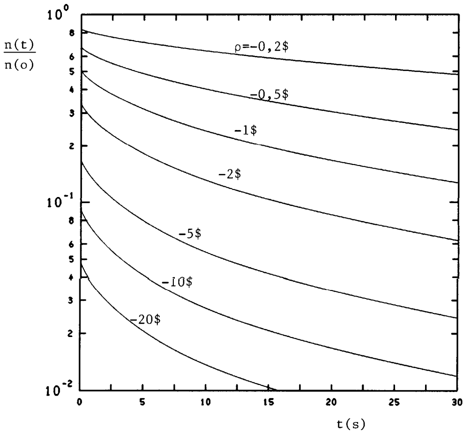
4) Spontaneous fission

Much more a shielding problem than decay heat

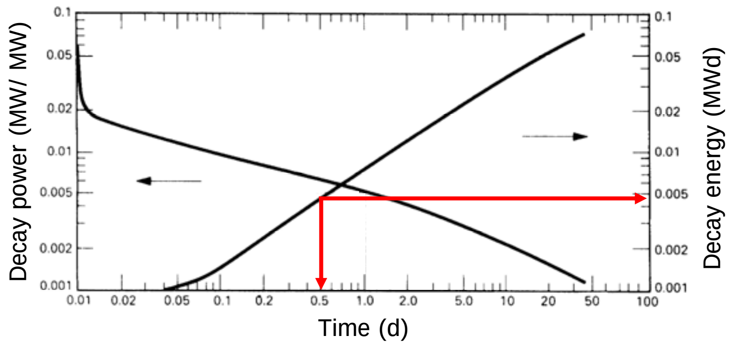
5) Activation of structural materials (only few % of FP decay heat)

Decay heat production

$$P(t) \approx P_0\left[\left(\frac{\beta}{\beta-\rho_0}\right)\exp(-\lambda t)-\left(\frac{\rho_0}{\beta-\rho_0}\right)\exp\left(\frac{\rho_0-\beta}{\Lambda}t\right)\right]$$



Decay heat production



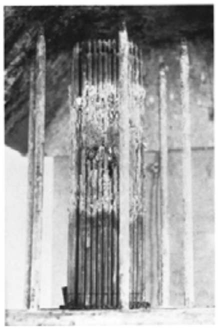
Source: ORNL

Decay heat production

Produced heat after 0.5 day amounts:

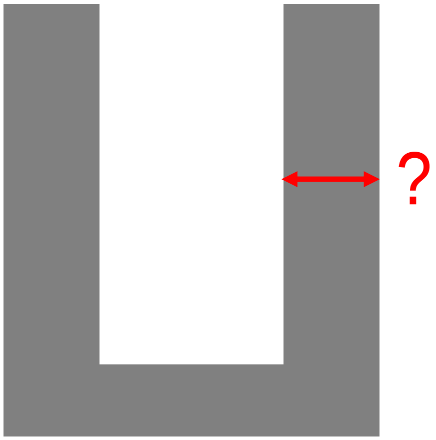
$$0.0047\ \text{MWd} \approx 400\ \text{MWs} = 400\ \text{fps}$$

Heat reservoir in BWR	Energy (fps)
Fuel from operating temp to $100^{o}C$	9
Coolant from $286^{o}C$ to $100^{o}C$	112
Reactor vessel and internals	43

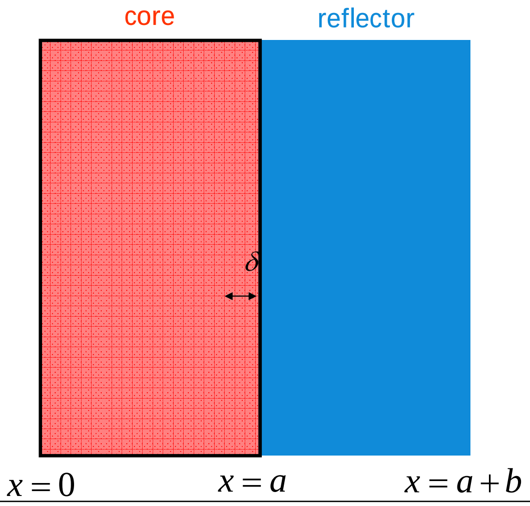


$\left(\begin{array}{l}\text{Pershagen, Light Water Reactor Safety, 1989} \\ \text{J.L.Kloosterman, FJOH summerschool, 2000}\end{array}\right)$

Pebble-bed reactor core design



Reflector savings

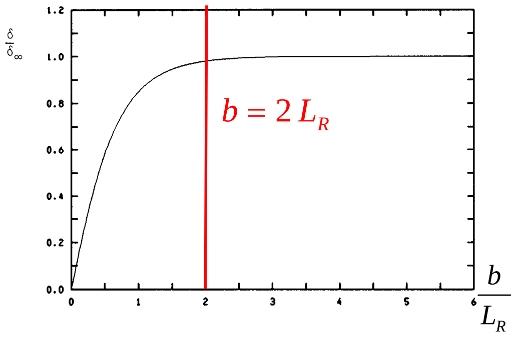


Reflector savings

$$\delta = a(\text{bare}) - a(\text{refl}) = \frac{1}{B_{mC}} \tan^{-1}\left(\frac{D_C B_{mC}}{D_R} L_R \tanh \frac{b}{L_R} \right)$$

Thick reflector $\left(b \gg L_R \right)$

$$\delta \to \delta_\infty = \frac{D_C}{D_R} L_R$$



Reflector savings

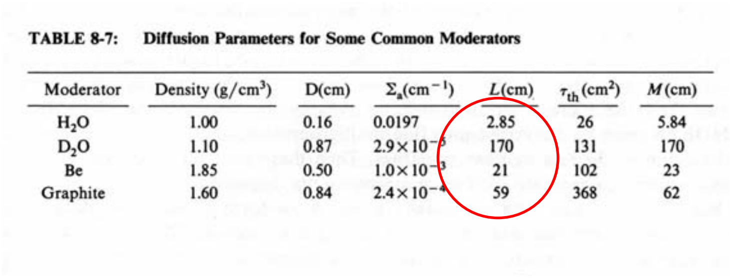
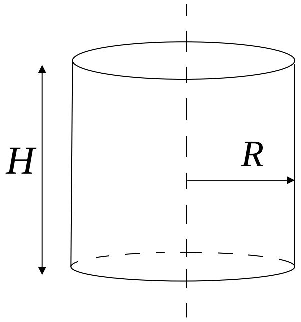


TABLE 8-7: Diffusion Parameters for Some Common Moderators

Moderator	Density (g/cm^3)	D(cm)	$\Sigma_a(cm^{-1})$	L(cm)	$\tau_{th}(cm^2)$	M(cm)
H_2O	1.00	0.16	0.0197	2.85	26	5.84
D_2O	1.10	0.87	2.9×10^{-5}	170	131	170
Be	1.85	0.50	1.0×10^{-3}	21	102	23
Graphite	1.60	0.84	2.4×10^{-4}	59	368	62

Duderstadt and Hamilton, Nuclear Reactor Analysis, 1976

Low leakage core design



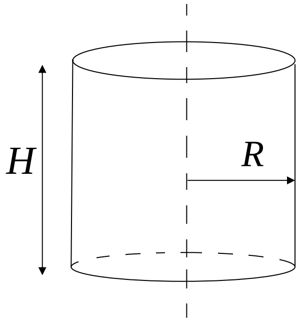
$$
\begin{aligned}
P_{NL} &= P_{FNL} \cdot P_{TNL} \\
&= \frac{1}{1+B_g^2\tau} \cdot \frac{1}{1+B_g^2 L^2} \\
&\approx \frac{1}{1+B_g^2 M^2}
\end{aligned}
$$

τ is a measure for the rms distance travelled until the neutron reaches the thermal energy range

L^2 is a measure for the rms distance a thermal neutron travels until is is absorbed

M^2 is migration area

Low leakage core design



$$\boxed{H = 1.85\,R}$$

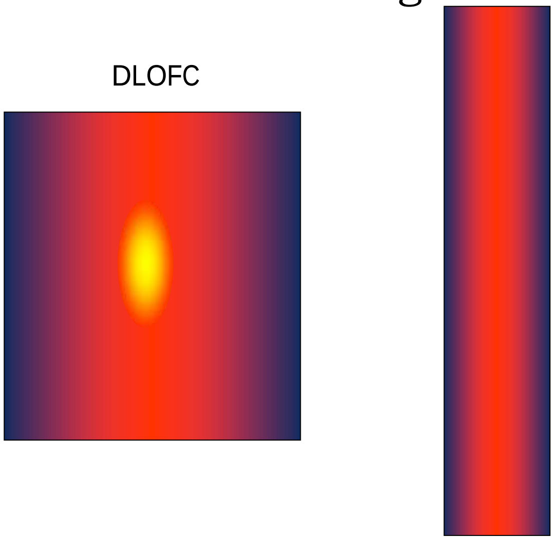
$$\nabla^2\phi + B_g^2\phi = 0$$

$$\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial \phi}{\partial r} + \frac{\partial^2 \phi}{\partial z^2} + B_g^2 \phi = 0$$

$$\phi(r,z) = \Re(r) \cdot Z(z)$$

$$\boxed{\begin{aligned} \phi(r,z) &= A\, J_0\left(\frac{\nu_0 r}{\tilde{R}}\right) \cos\left(\frac{\pi z}{\tilde{H}}\right) \\ B_g^2 &= \left(\frac{\nu_0}{\tilde{R}}\right)^2 + \left(\frac{\pi}{\tilde{H}}\right)^2 \end{aligned}}$$

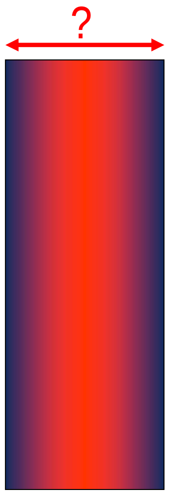
Reactor core design

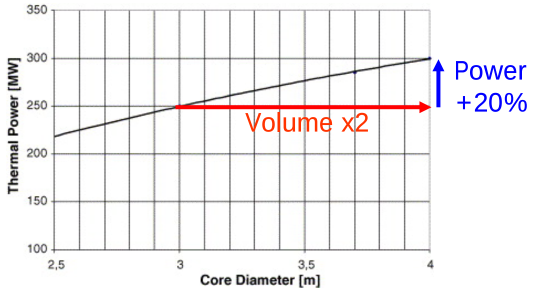


Passive decay heat removal calls for long tall reactor cores

Reactor core design

Reactor core design



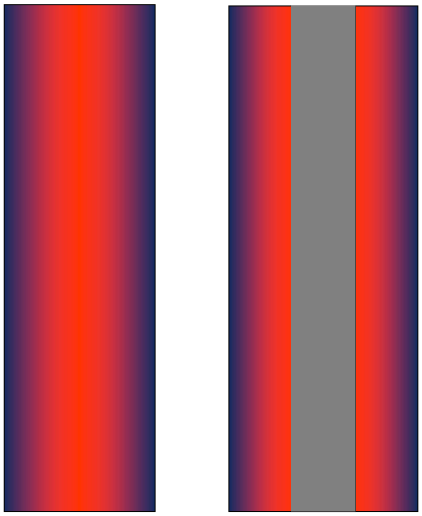


Ben Said etal, Nucl Eng Des, 236(2006) 648

Core diameter limited by

- shutdown capability
- RPV diameter
- decay heat removal

Reactor core design



Passive decay heat removal calls for long tall reactor cores

Or

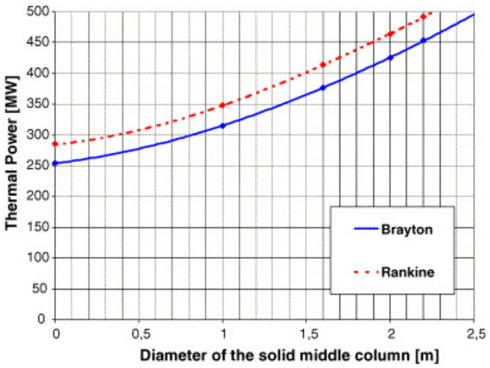
Cores with a fuel-free central column

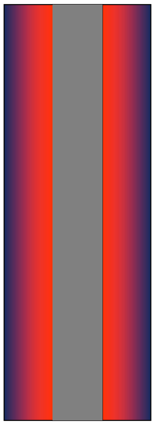
Reactor core design

Design				
Core height [m]	11		11	
Inner core diameter [m]	-		2	
Outer core diameter [m]	3		3.7	
RPV outer diameter [m]	5.7		6.4	
Variant	*Brayton*	*Rankine*	*Brayton*	*Rankine*
Inlet temperature [°C]	500	250	500	250
Outlet temperature [°C]	900	750	900	750
Thermal power [MW]	**220**	**250**	**425**	**464**
Mean power density [MW/m^3]	2.83	3.21	5.07	5.54
Helium mass flow rate [Kg/s]	105.9	96.24	204.5	178.6
Pressure drop over the core [bar]	1.27	0.84	3.55	2.18

Ben Said etal, Nucl Eng Des, 236(2006) 648

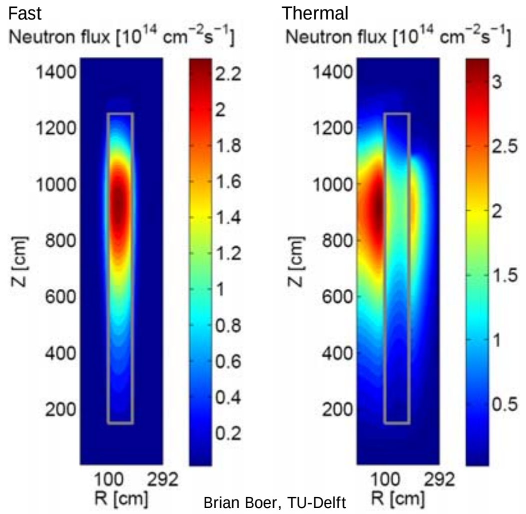
Reactor core design



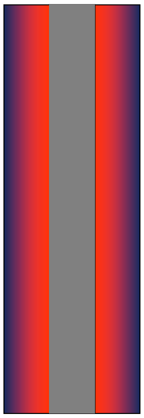


Ben Said etal, Nucl Eng Des, 236(2006) 648

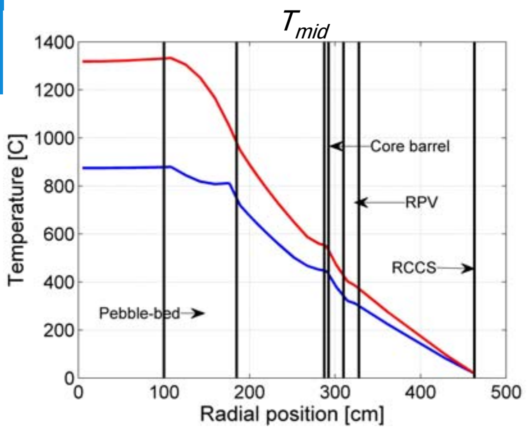
Neutron flux profile

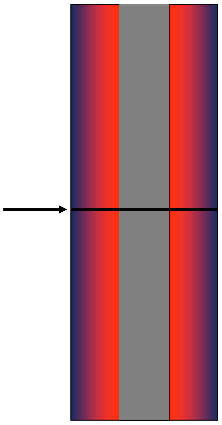


Brian Boer, TU-Delft



Reactor core design





PBMR results DLOFC

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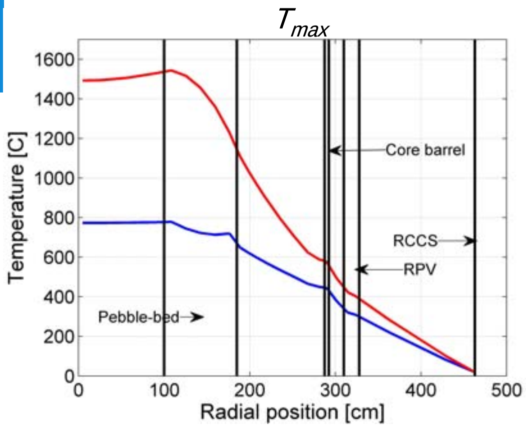
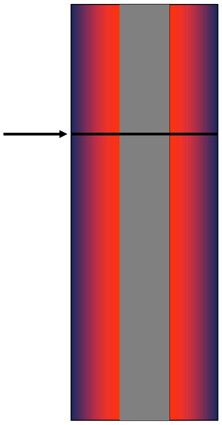
Reactor core design

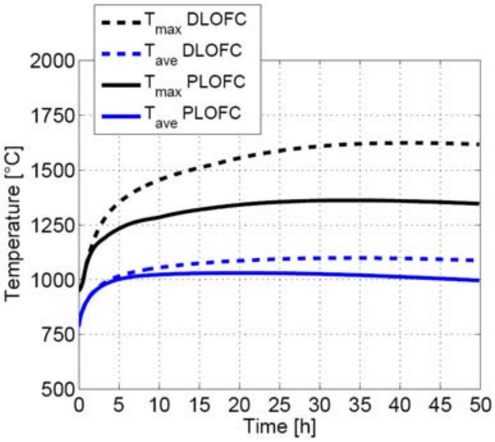




PBMR results DLOFC

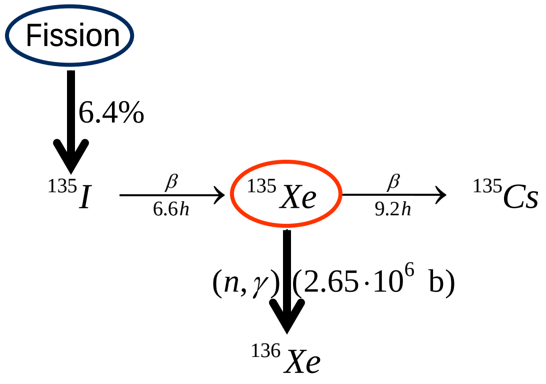
Brian Boer, TU-Delft

Pressurized and Depressurized LOFC



Brian Boer, TU-Delft

Maximum core height



Fission

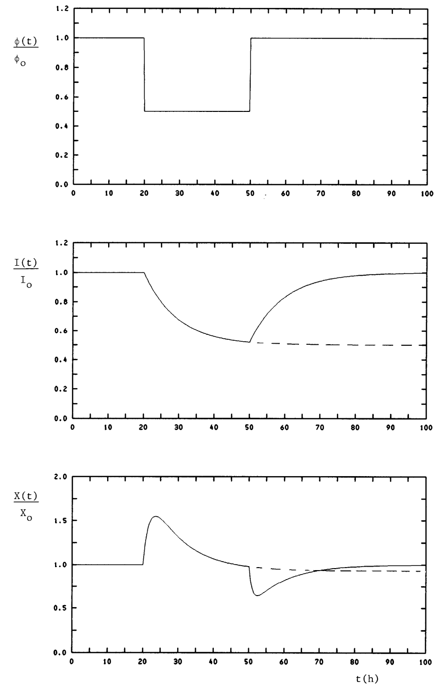
6.4%

$$^{135}I \xrightarrow[6.6h]{\beta} {}^{135}Xe \xrightarrow[9.2h]{\beta} {}^{135}Cs$$

$$(n,\gamma)\ (2.65\cdot 10^{6}\ \text{b})$$

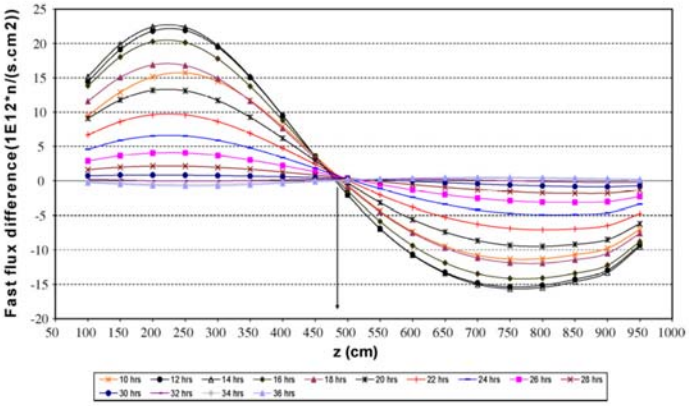
$$^{136}Xe$$

$\Phi \uparrow \ \Rightarrow \ [Xe]\downarrow \ \Rightarrow \ \rho \uparrow \ \Rightarrow \ \Phi \uparrow$ Positive feedback !



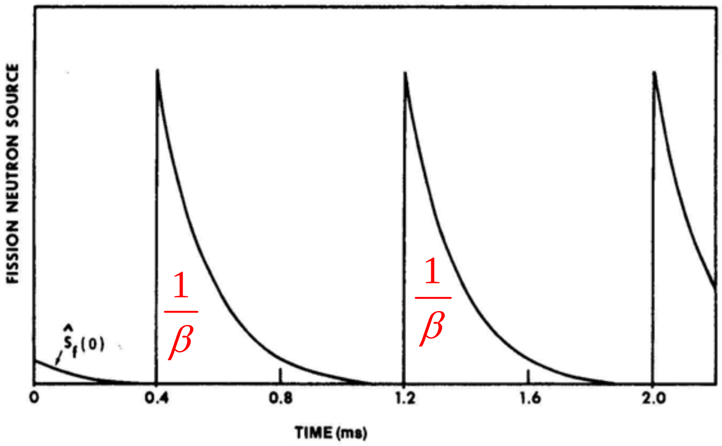
Xenon oscillations

Xenon oscillations



Strydom, Nucl Eng Des, 238(2008) 2960

Maximum core height



Ott and Neuholt, Introductory Dynamics of Nuclear Reactors

Maximum core height

Migration area: $M^2 = L^2 + \tau = \frac{1}{6} \left\langle \ell^2 \right\rangle$

$(L$ diffusion length, τ Fermi age$)$

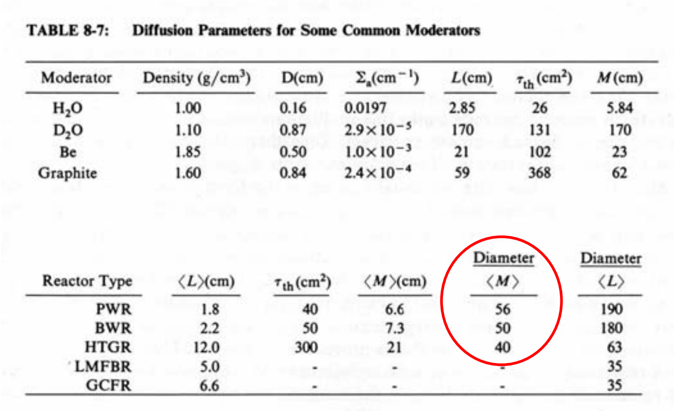
Squared prompt fission chain length: $L_{PFC}^2 = \frac{1}{\beta}\left\langle \ell^2 \right\rangle = \frac{1}{\beta} 6M^2$

Prompt fission chain length: $L_{PFC} = \sqrt{\frac{6}{\beta}\left\langle \ell^2 \right\rangle} \approx 30\,M$

Any core larger than 30M is loosely coupled

and therefore sensitive to Xenon oscillations

Maximum reactor core height



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Graphite	1.60	0.84	2.4×10^{-4}	59	368	62

Reactor Type	$\langle L\rangle$(cm)	$\tau_{th}(\mathrm{cm}^2)$	$\langle M\rangle$(cm)	Diameter $\langle M\rangle$	Diameter $\langle L\rangle$
PWR	1.8	40	6.6	56	190
BWR	2.2	50	7.3	50	180
HTGR	12.0	300	21	40	63
LMFBR	5.0	-	-	-	35
GCFR	6.6	-	-	-	35

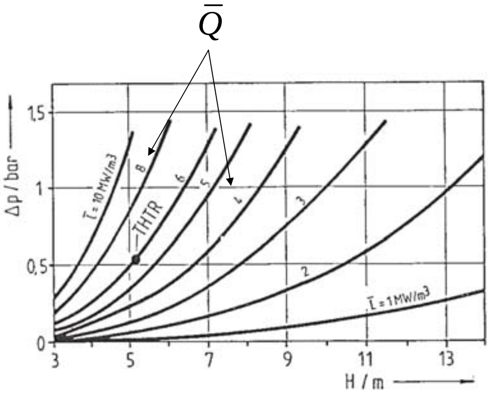
Duderstadt and Hamilton, Nuclear Reactor Analysis, 1976

Maximum reactor core height

Pressure drop: $\Delta p \sim \dfrac{\bar{Q}^2 H^3}{\rho \Delta T^2}$

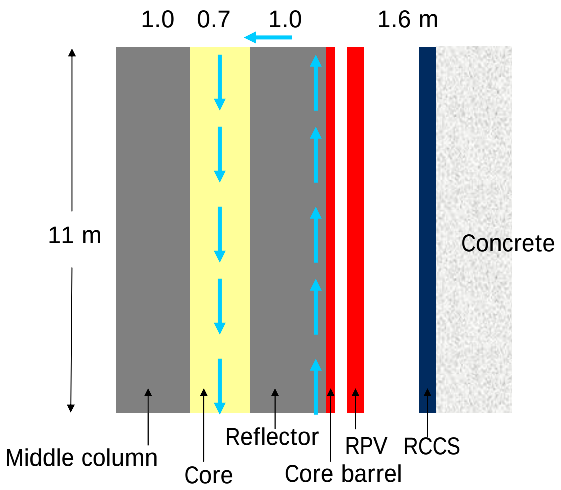
Pumping power: $P_P = \dfrac{\Delta p}{\rho}\dot{m}$

$\left(\text{In practice } \Delta p < 0.02\, p\right)$

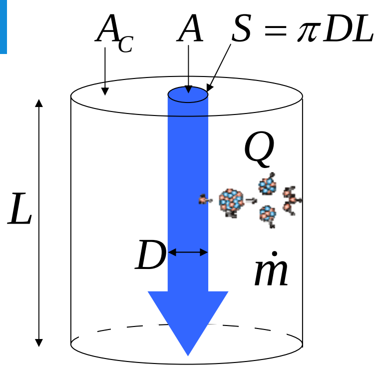


Kugeler and Schulten, Hochtemperatur Reaktortechnik, 1989

Reactor core layout



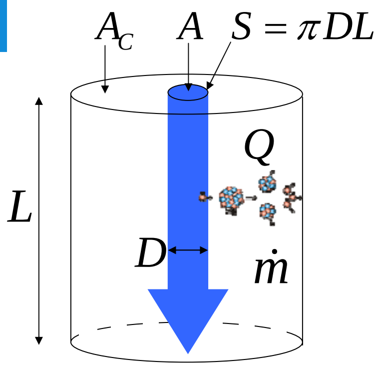
Gas coolant choice



Mass flow	$\dot{m} = \rho V A$
Power	$Q = \dot{m}\, C_P \left(T_{out} - T_{in}\right)$ $= h\, S\, \Delta t$
Pressure drop	$\Delta p = \frac{1}{2} \rho V^2 \left(\frac{4 f L}{D}\right)$
Pumping power	$P_P = \frac{\Delta p}{\rho} \dot{m}$
Gas law	$P = \frac{\rho R T}{M}$

Melese and Katz, Thermal and Flow Design of Helium-cooled Reactors, ANS, 1984

Gas coolant choice



$$\frac{Q}{A_C} \propto \sqrt{\frac{c_P^3}{M}}$$

$$\begin{pmatrix} c_P & = \text{molar heat capacity} \\ M & = \text{molar mass} \end{pmatrix}$$

Melese and Katz, Thermal and Flow Design of Helium-cooled Reactors, ANS, 1984

Gas coolant choice

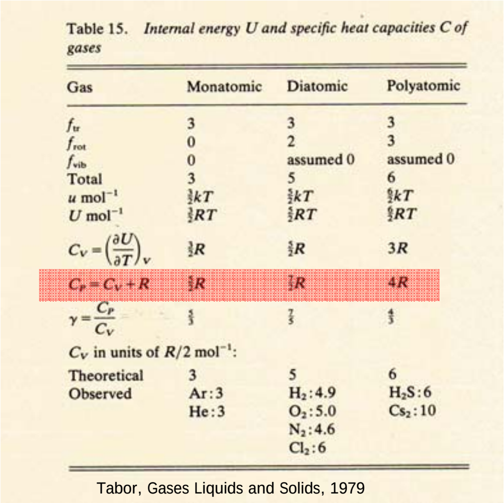


Table 15. *Internal energy U and specific heat capacities C of gases*

Gas	Monatomic	Diatomic	Polyatomic
f_{tr}	3	3	3
f_{rot}	0	2	3
f_{vib}	0	assumed 0	assumed 0
Total	3	5	6
u mol^{-1}	$\frac{3}{2}kT$	$\frac{5}{2}kT$	$\frac{6}{2}kT$
U mol^{-1}	$\frac{3}{2}RT$	$\frac{5}{2}RT$	$\frac{6}{2}RT$
$C_V = \left(\frac{\partial U}{\partial T}\right)_V$	$\frac{3}{2}R$	$\frac{5}{2}R$	$3R$
$C_P = C_V + R$	$\frac{5}{2}R$	$\frac{7}{2}R$	$4R$
$\gamma = \frac{C_P}{C_V}$	$\frac{5}{3}$	$\frac{7}{5}$	$\frac{4}{3}$
C_V in units of $R/2$ mol^{-1}:			
Theoretical	3	5	6
Observed	Ar:3 He:3	H_2:4.9 O_2:5.0 N_2:4.6 Cl_2:6	H_2S:6 Cs_2:10

Tabor, Gases Liquids and Solids, 1979

Gas coolant choice

Gas	Power for fixed frontal area (Q/A_c)	Heat transfer area for fixed flow area	Pressure for a given system pressure
Helium	1.00	1.00	1.00
CO_2	1.22	1.32	2.52
H_2	2.41	1.09	1.42
Steam	1.18	1.60	1.96
Air	0.70	1.24	1.53

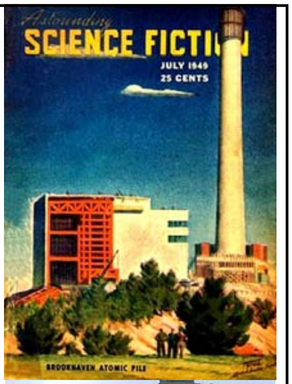
Melese and Katz, Thermal and Flow Design of Helium-cooled Reactors, ANS, 1984

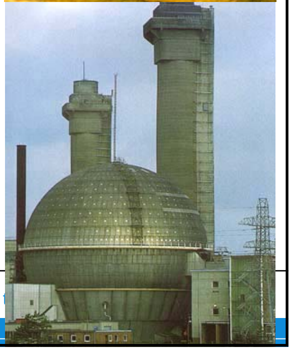
History of gas-cooled reactors

Early Gas-Cooled Reactors

X-10 reactor in Oak Ridge, 1943

3.5 MW, air-cooled

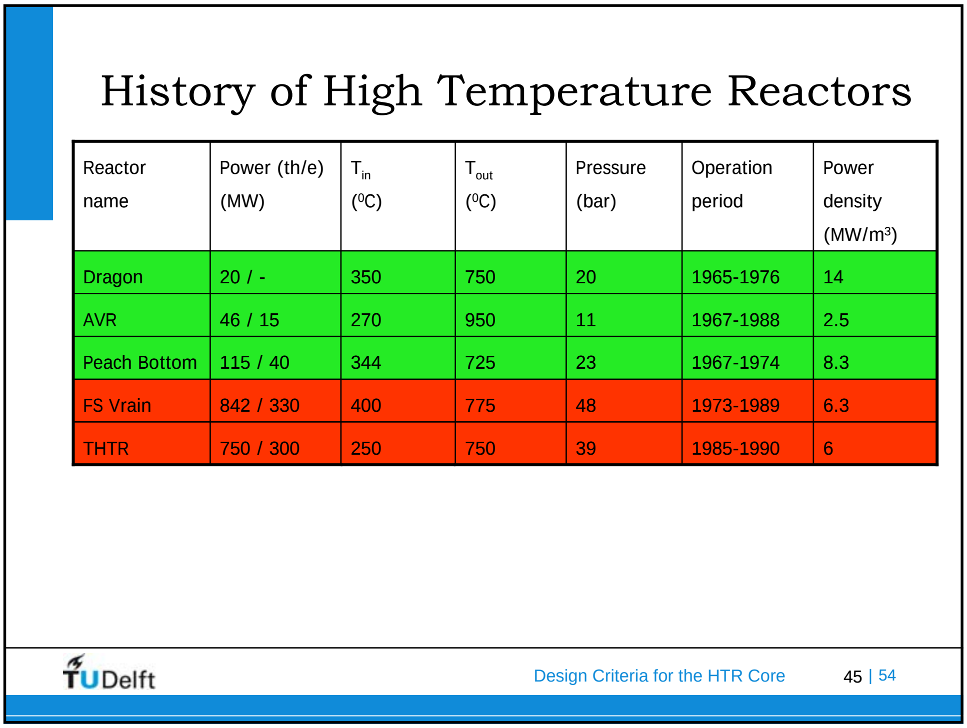




- 2 MW reactor in Saclay, 1951, N_2 cooled (later CO_2)
- Calder Hall reactors, 1953, CO_2 cooled
- 166 MWe reactor in Tokai, 1966, CO_2 cooled
- Magnox and AGRs in the UK, CO_2 cooled

History of High Temperature Reactors

Reactor name	Power (th/e) (MW)	T_{in} (^{0}C)	T_{out} (^{0}C)	Pressure (bar)	Operation period	Power density (MW/m^3)
Dragon	20 / -	350	750	20	1965-1976	14
AVR	46 / 15	270	950	11	1967-1988	2.5
Peach Bottom	115 / 40	344	725	23	1967-1974	8.3



History of High Temperature Reactors

Reactor name	Power (th/e) (MW)	T_{in} (^0C)	T_{out} (^0C)	Pressure (bar)	Operation period	Power density (MW/m^3)
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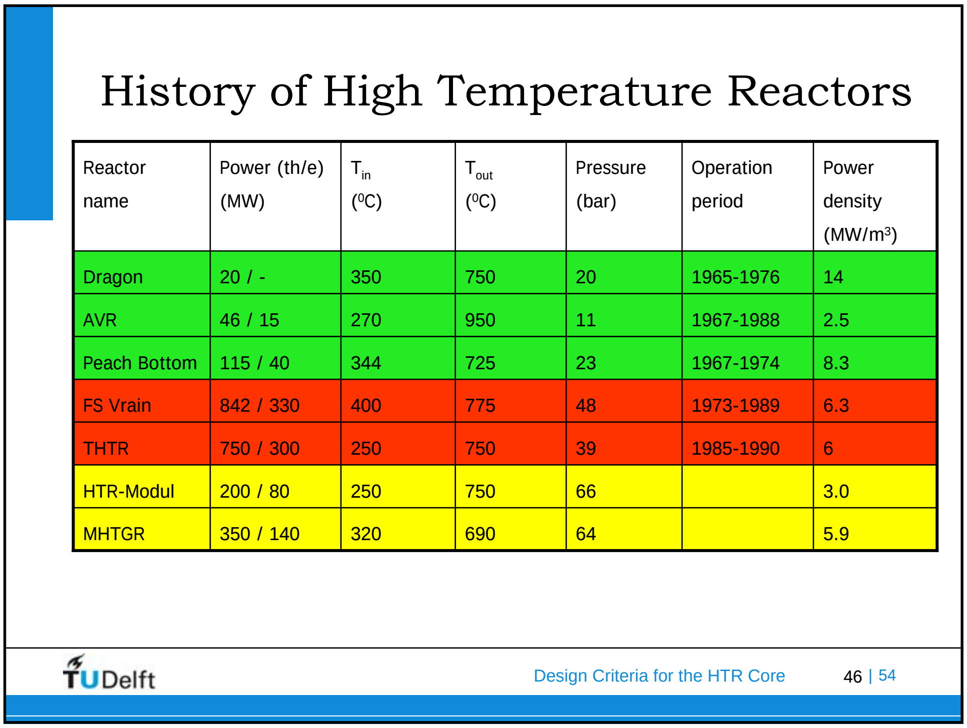
AVR	46 / 15	270	950	11	1967-1988	2.5
Peach Bottom	115 / 40	344	725	23	1967-1974	8.3
FS Vrain	842 / 330	400	775	48	1973-1989	6.3
THTR	750 / 300	250	750	39	1985-1990	6



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MHTGR	350 / 140	320	690	64		5.9

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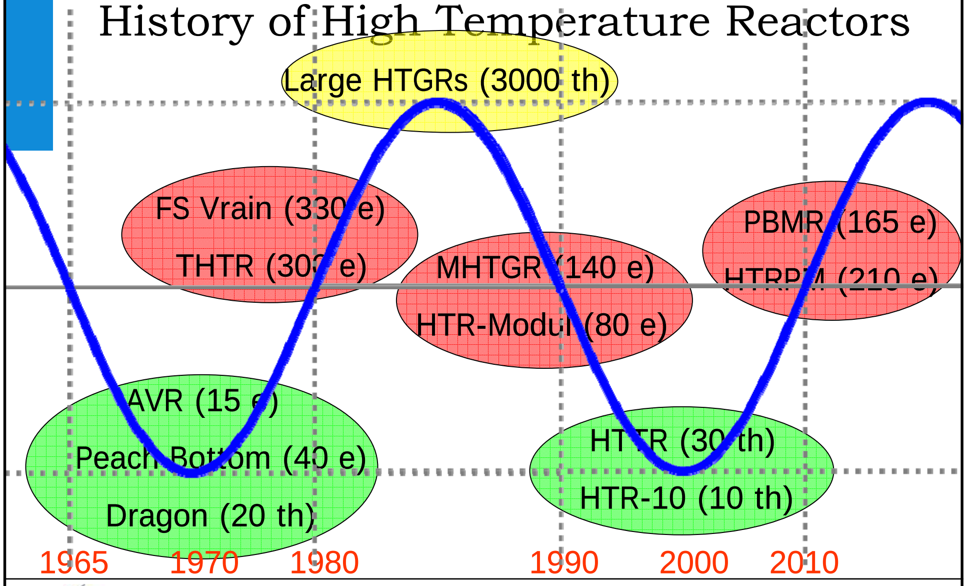
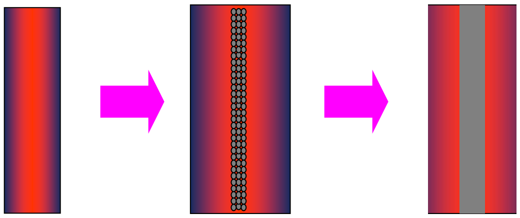
MHTGR	350 / 140	320	690	64		5.9
HTTR	30 / -	395	950	40	1998-	2.5
HTR-10	10 / -	250	700	30	2000-	2

History of High Temperature Reactors



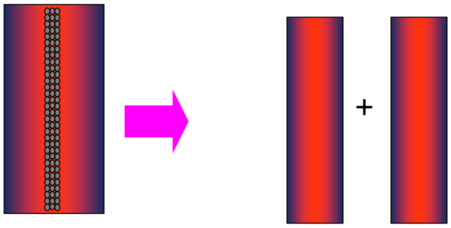
Current developments

PBMR



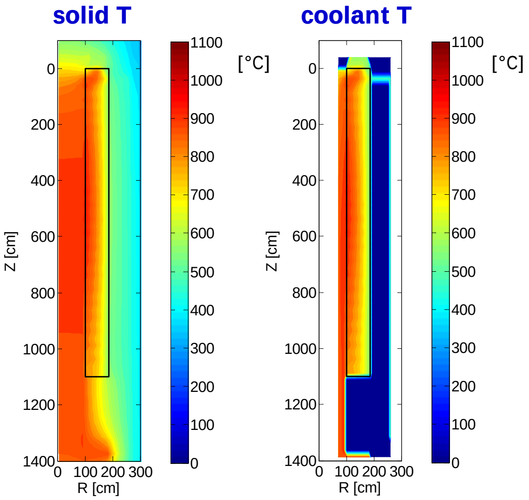
Koster *etal*, Nucl. Eng. Des. 222(2003) 231

HTR-PM



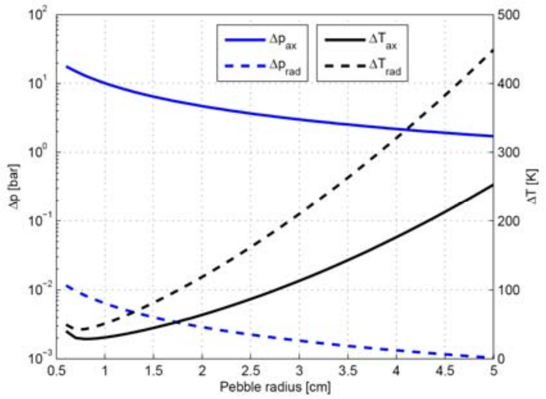
Zhengy and Shi, HTR2008, Washington

Future developments: Radial cooling



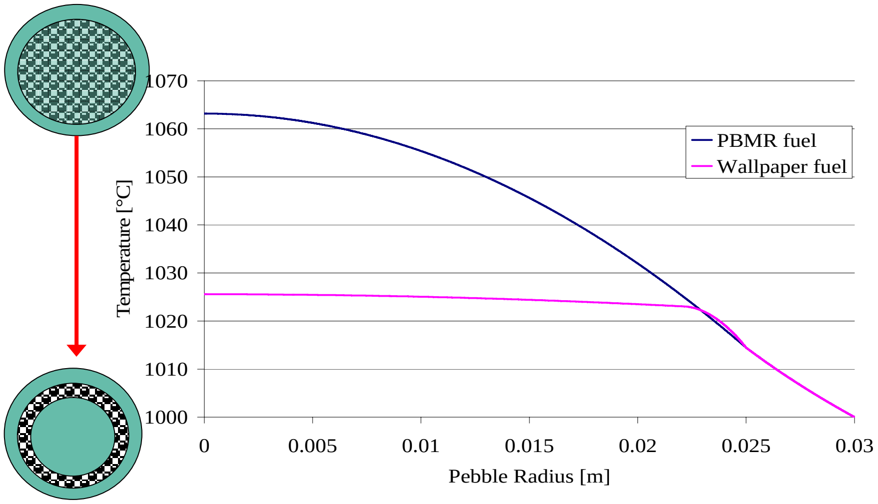
Boer *etal*, HTR2008, Washington

Future developments: Radial cooling



Boer *etal*, HTR2008, Washington

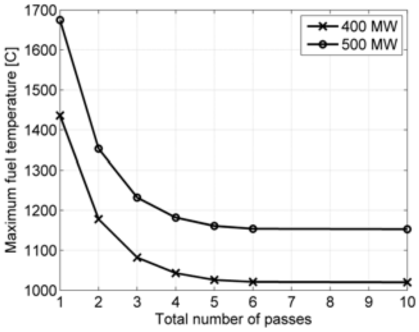
Future developments: Wall paper fuel



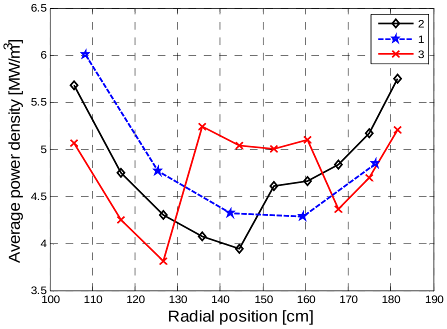
Marmier *etal*, HTR2008, Washington

Future developments: Optimization

Effect of recycling

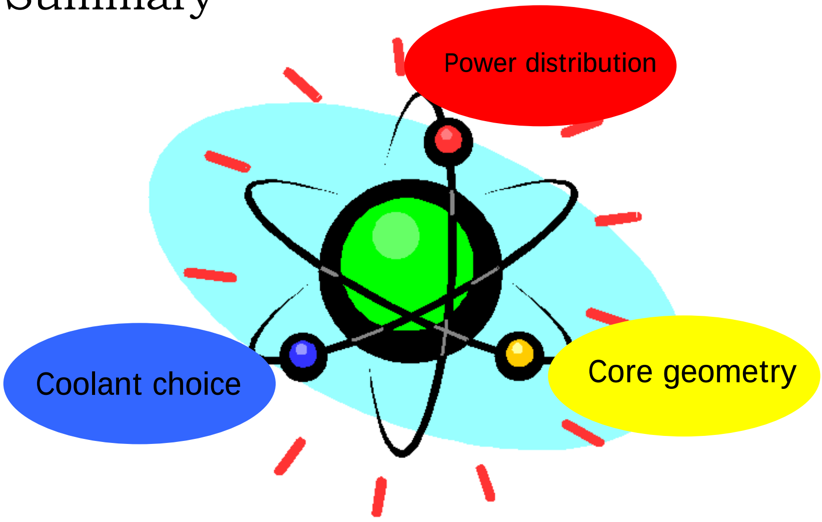


Effect of fuel zoning



Brian Boer, TU-Delft

Summary



Power distribution

Coolant choice

Core geometry