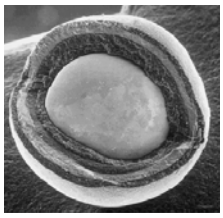
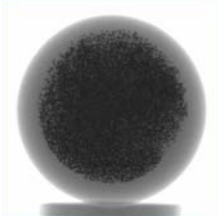
Reactor Physics and Design Aspects of High Temperature Reactors

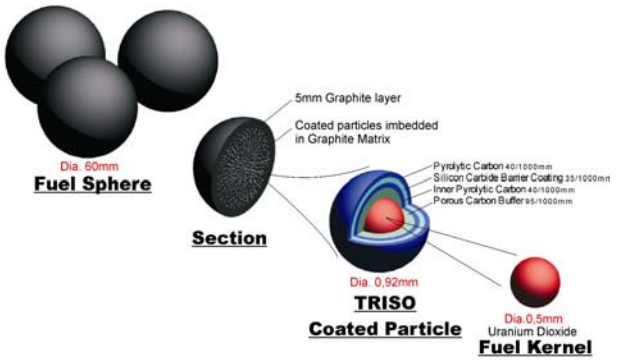
Jan Leen Kloosterman
Delft University of Technology

J.L.Kloosterman@tudelft.nl
www.JanLeenKloosterman.nl

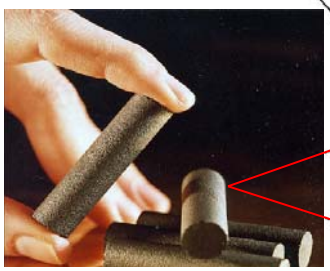
Pebble-bed fuel

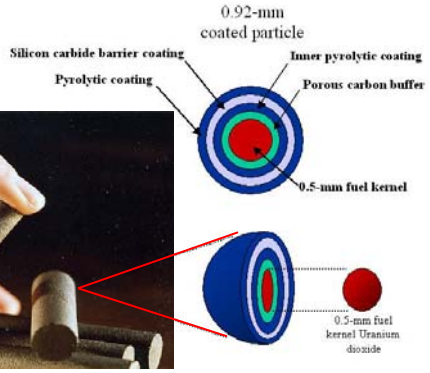






Prismatic fuel

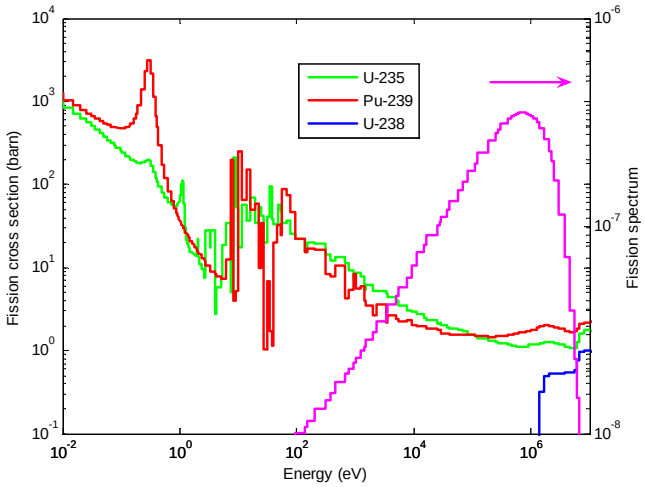




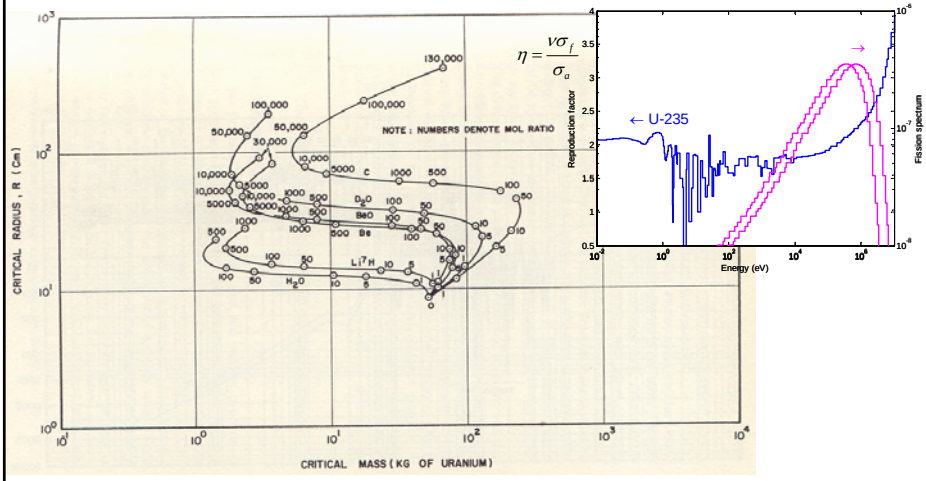
Differences between LWR and HTR

	LWR	HTR
Fuel	UO_2 pin	UO_2 sphere
Moderator	Water	Graphite
Coolant	Water	Helium
Temperature (°C)	300	900
Enrichment (%)	5	10
Burnup (MWd/kgU)	60	120
Specific power (kW/kgU)	40	80
Power density (kW/l)	100	6

Moderation of neutrons



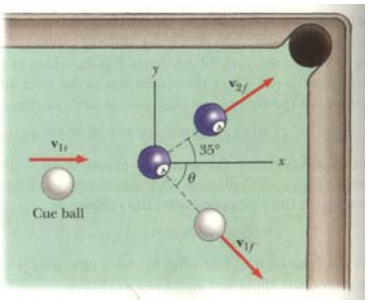
Moderation of neutrons



Ferziger&Zweifel, Theory of neutron slowing down in nuclear reactors, 1966

Energy transfer in collisions

- Elastic scattering most important
- Conservation of energy and momentum
- Large energy transfer in collisions at light nuclei
- Hydrogen same mass as a neutron* $\Rightarrow$ largest E-transfer

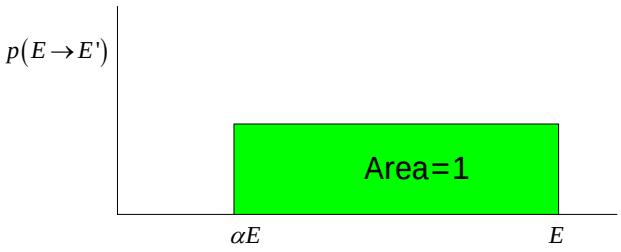


$$A = \frac{M}{m} = \frac{\text{mass nucleus}}{\text{mass neutron}} \qquad \alpha = \left(\frac{A-1}{A+1}\right)^2$$

*a neutron is 0.1% heavier. Think over the consequences.

Energy transfer in collisions

$$p(E \rightarrow E') = \begin{cases} \dfrac{1}{(1-\alpha)E} & \text{for } \alpha E < E' < E \\ 0 & \text{elsewhere} \end{cases}$$



Energy transfer in collisions

Average energy:

$$\overline{E'} = \int_{\alpha E}^{E} E' \, p\left(E \to E'\right) dE' = \frac{1}{2} E\left(1+\alpha\right)$$

Average energy loss:

Proportional to *E*

$$\overline{\Delta E} = E - \overline{E'} = \frac{1}{2} E\left(1-\alpha\right)$$

Lethargy

Transform Energy to a new variable that changes linearly in each collision $\Rightarrow$ Lethargy

$$u = \log\left(\frac{E_H}{E}\right)$$

Average lethargy increase per collision:

$$\xi = \int_{\alpha E_H}^{E_H} \log\left(\frac{E_H}{E}\right) \cdot \frac{1}{\left(1-\alpha\right) E_H} dE$$

$$= 1 + \frac{\alpha}{\left(1-\alpha\right)} \log\left(\alpha\right)$$

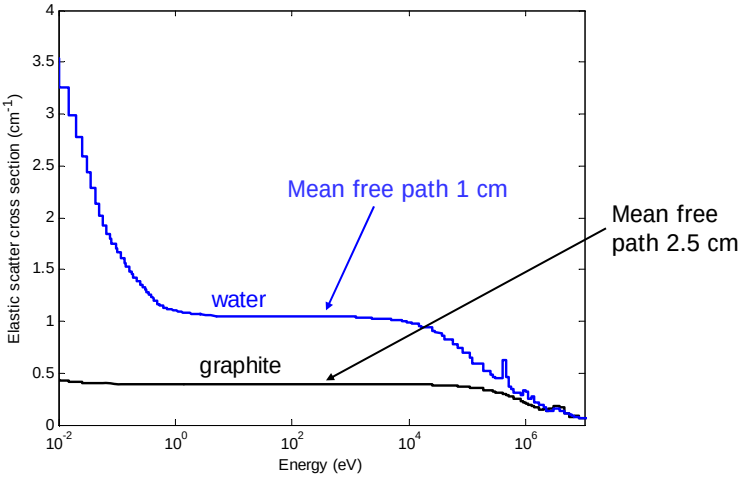
Number of collisions

Number of collisions to slow down a neutron from E_H =1 Mev to E_L =1 eV in various media:

$$n = \frac{\log\left(E_H / E_L\right)}{\xi}$$

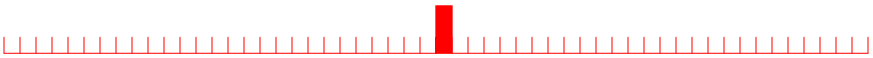
Element	A	α	ξ	n
H	1	0	1.000	14
D	2	0.111	0.725	19
Be	9	0.640	0.207	67
C	12	0.716	0.158	88
U	238	0.983	0.00838	1649

Elastic scatter cross section



Space-dependent slowing down

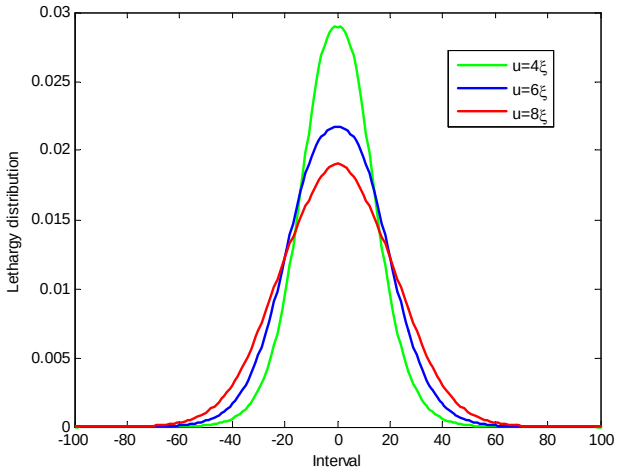
- Moderating power $\equiv \xi\Sigma_s$
- Energy transfer to the moderator per unit path length
  = lethargy gain by the neutron: $du = \xi\Sigma_s dx$



Monte Carlo game:

- Start particles at isotropic plane source
- Follow the particles from interval to interval
- In each interval, certain probability to scatter
- When scattering, particles can reverse direction
- When scattering, particles gain ξ lethargy

Space-dependent slowing down



Space-dependent slowing down

Fermi-age model

Age-diffusion equation

Continuous slowing down model

Takes the form of time-dependent diffusion eq. without absorption

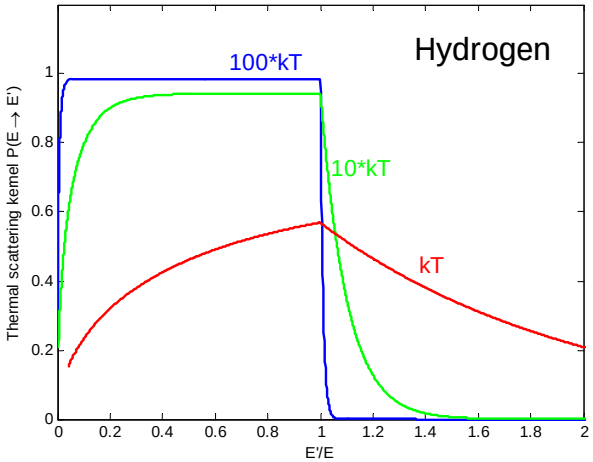
$$\nabla^2 q(\mathbf{r},\tau) = \frac{\partial q(\mathbf{r},\tau)}{\partial \tau}$$

where $q(\mathbf{r},u) = \xi \Sigma_s(u)\phi(\mathbf{r},u)$ (slowing down density) and $\tau(u)$ is the Fermi age:

$$\tau = \frac{1}{6}\langle r^2 \rangle$$

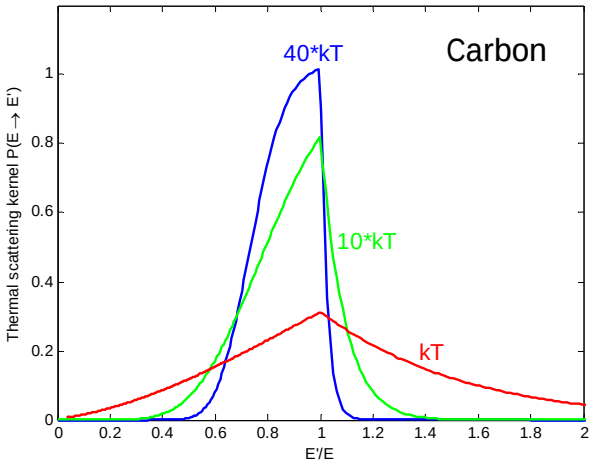
τ is proportional to the mean squared distance a source neutron travels until it reaches τ

Thermal scattering kernel



Lamarsh, Introduction to Nuclear Reactor Theory, 1966

Thermal scattering kernel



Massimo, Physics of High Temperature Reactors, 1976

Thermal neutron spectrum

$$M(E) = \frac{2\pi n_0}{(\pi kT)^{3/2}} \sqrt{E} \exp\left(\frac{-E}{kT}\right)$$

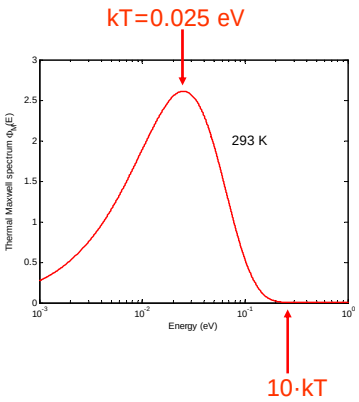
Average neutron energy:

$$\overline{E} = \int_0^\infty E\, M(E)\, dE = \frac{3}{2} kT$$

$$\phi_M(E) = \frac{2\pi n_0}{(\pi kT)^{3/2}} \left(\frac{2}{m}\right)^{1/2} E \exp\left(\frac{-E}{kT}\right)$$

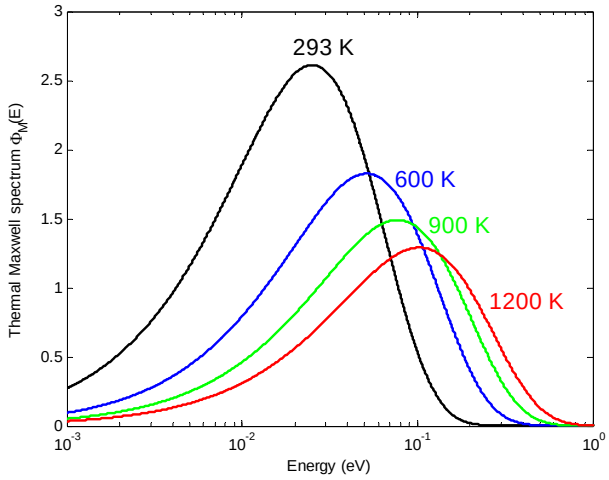
Most probable energy:

$$\frac{\partial \phi_M(E)}{\partial E} = 0 \Rightarrow E_T = kT$$

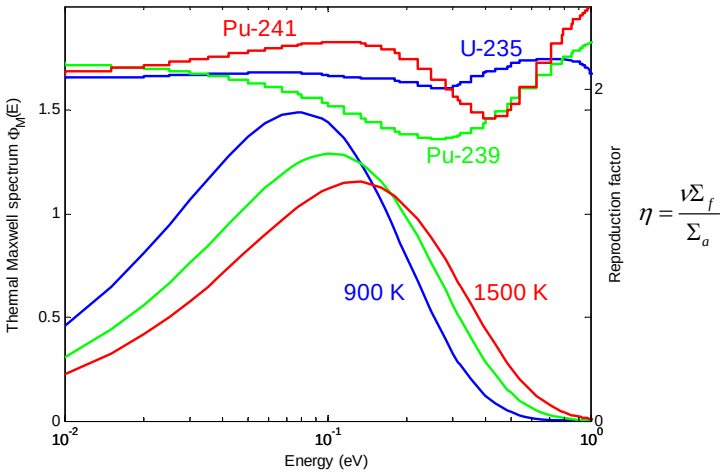


Corresponding velocity: $v = \sqrt{\frac{2kT}{m}}$ (2200 m/s for T=293 K)

Thermal neutron spectrum



Moderator temperature effect



$$\eta = \frac{\nu\Sigma_f}{\Sigma_a}$$

Moderator temperature effect

	T_{PEBBLE}	T_{REFLEC}	k	$\alpha\,(\mathrm{pcm/K})$
	1100	1100	1.32553	
Pebble	1400	1100	1.30006	-4.9
Reflec	1100	1400	1.33318	1.4

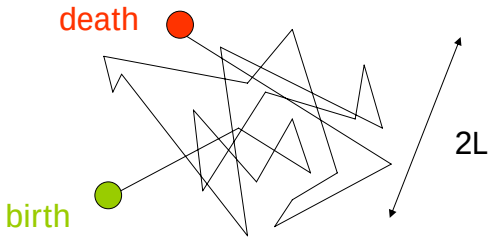
Space-dependent slowing down

Recall from diffusion theory (assumed to be known)

L is diffusion length

$$L^2 = \frac{1}{6}\langle r^2 \rangle$$

L^2 is mean squared distance a thermal neutron travels until absorption



Space-dependent slowing down

Fermi age $\tau = \frac{1}{6}\langle r^2 \rangle$ Diffusion length $L^2 = \frac{1}{6}\langle r^2 \rangle$

Migration area $\boxed{M^2 = \tau + L^2}$

Migration length M is $1/\sqrt{6}$ of the rms distance a neutron travels between birth as a fission neutron and absorption in thermal range

TABLE 8-7: Diffusion Parameters for Some Common Moderators

Moderator	Density (g/cm^3)	D(cm)	Σ_a(cm^{-1})	L(cm)	τ_{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&Hamilton, Nuclear Reactor Analysis, 1976

Safety design philosophy

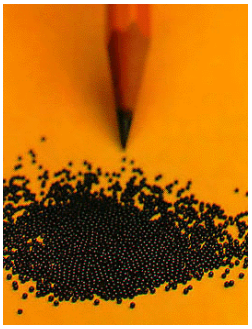
Fundamental safety functions
- Control of reactivity
- Removal of (decay) heat from the core
- Confinement of radioactive material

↓

Defense in depth
- Prevention of off-normal event
- Control of off-normal event
- Mitigation of off-normal event

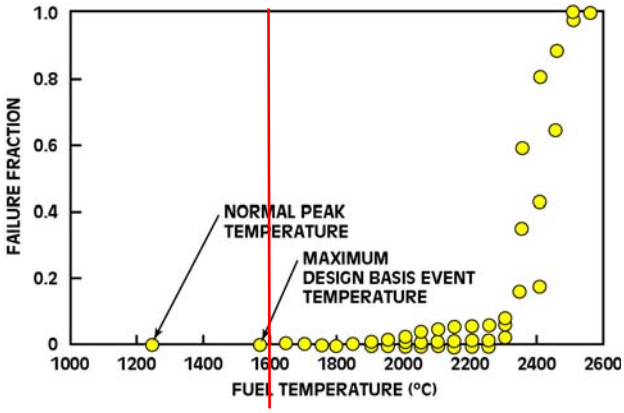
Fission product containment

HTR



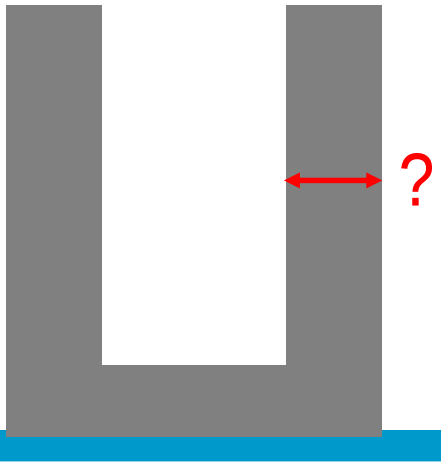
LWR

Fission product containment

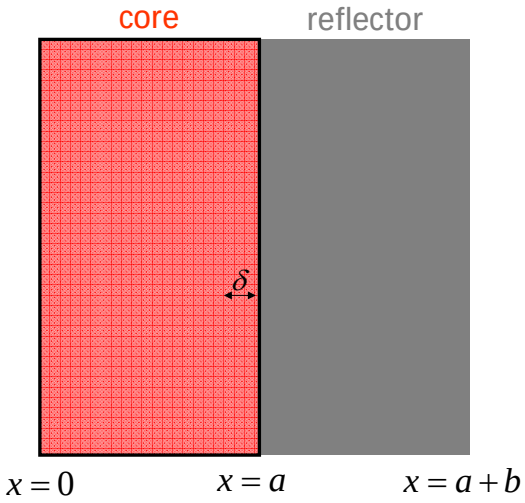


Considered to be a safe lower temperature limit

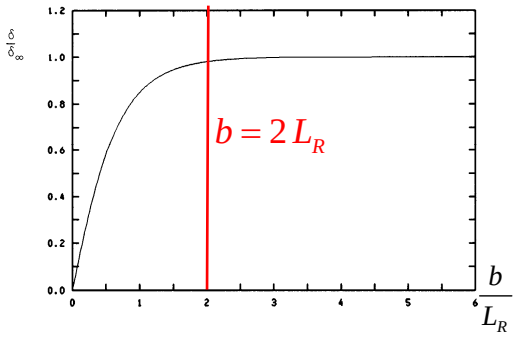
Pebble-bed reactor core design



Reflector savings



Reflector savings



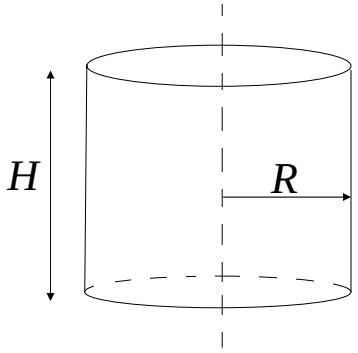
Reflector savings

TABLE 8-7: Diffusion Parameters for Some Common Moderators

Moderator	Density (g/cm^3)	D(cm)	Σ_a(cm^{-1})	L(cm)	τ_{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



$$P_{NL} = P_{FNL} \cdot P_{TNL}$$

$$= \frac{1}{1+B_g^2\tau} \cdot \frac{1}{1+B_g^2 L^2}$$

$$\approx \frac{1}{1+B_g^2 M^2}$$

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

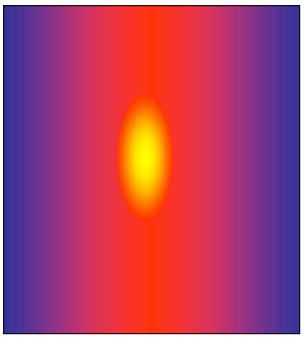
L^2 is a measure for the rms distance a thermal neutron travels until is is absorbed

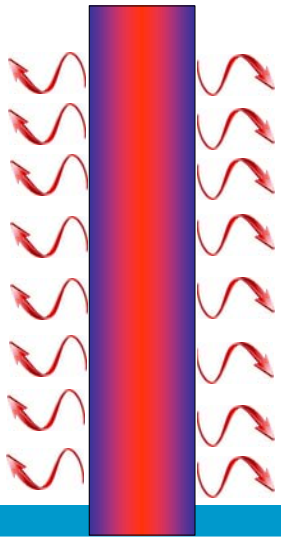
M^2 is migration area

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

Reactor core design

DLOFC

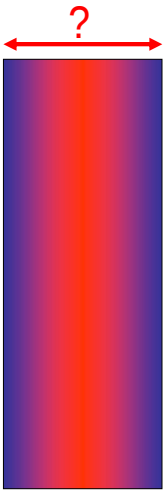


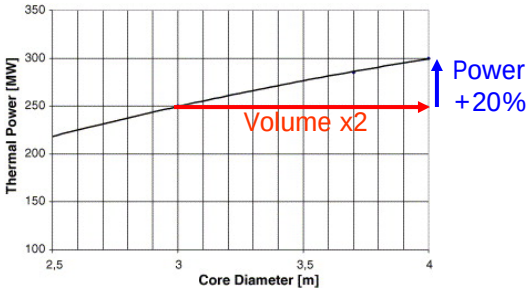


Passive decay heat removal needs long tall reactor cores

Reactor core design

Reactor core design



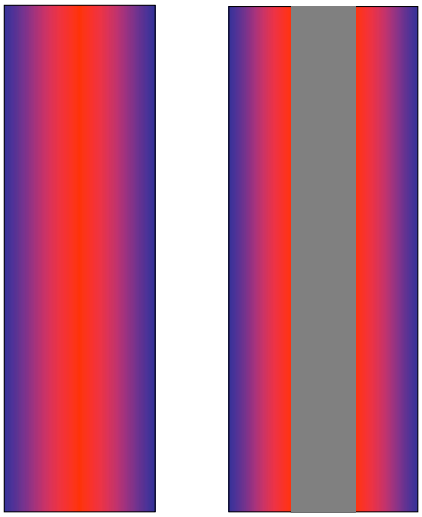


Ben Said etal, Nucl Eng Des, 236(2006) 648

Core diameter limited by

- shutdown capability
- RPV diameter
- decay heat removal

Reactor core design

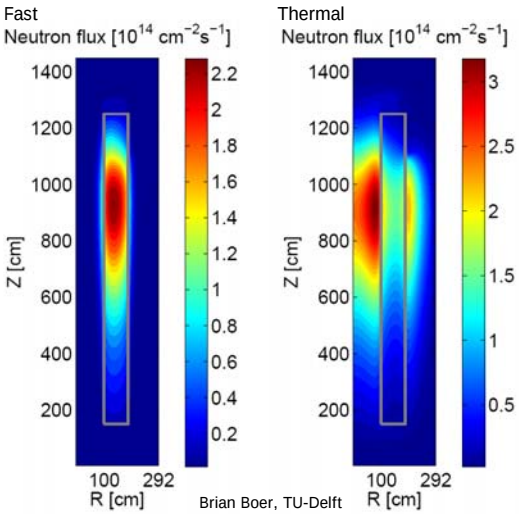


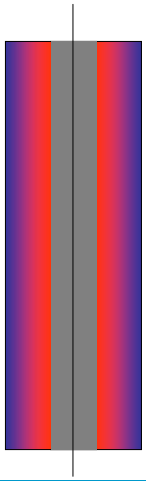
Passive decay heat removal needs long tall reactor cores

Or

Cores with a fuel-free central column

Neutron flux profile





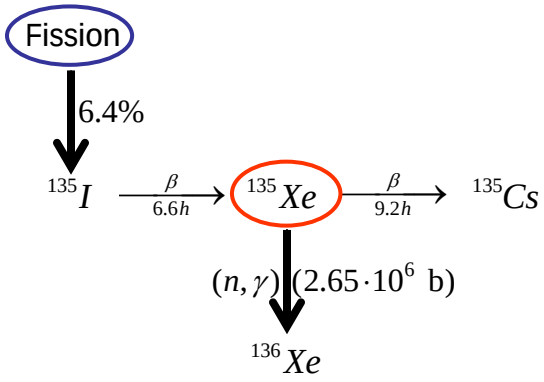
Brian Boer, TU-Delft

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

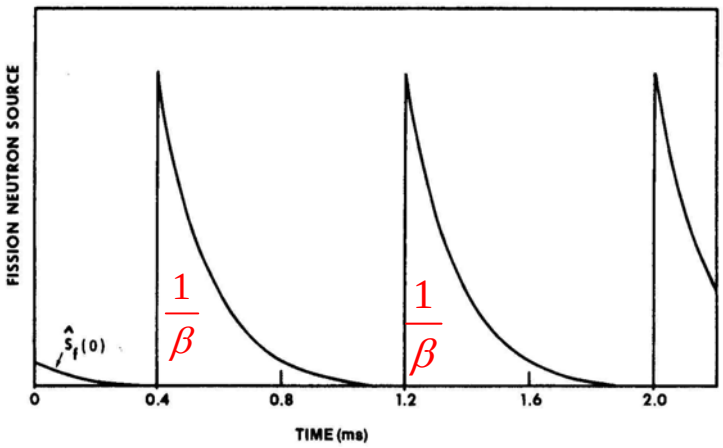
Maximum core height



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

Xenon oscillations

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

Any core larger than 30M is loosely coupled

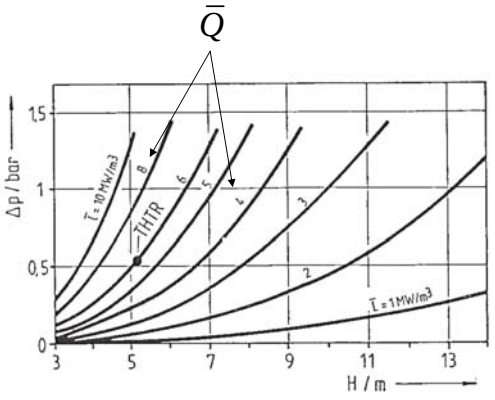
and therefore sensitive to Xenon oscillations

Maximum core height

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

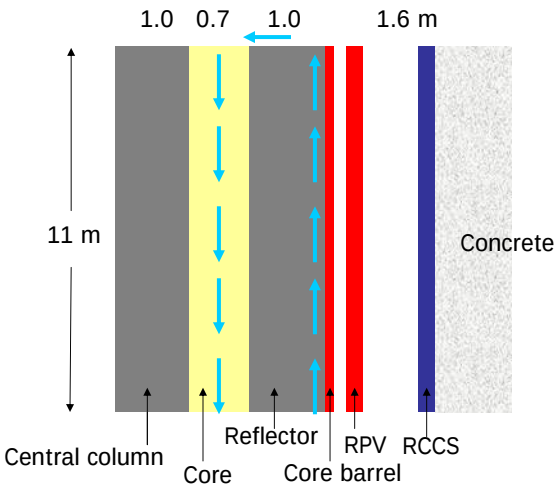
Pumping power: $P_P = \frac{\Delta p}{\rho}\dot{m}$

(In practice $\Delta p < 0.02\,p$)

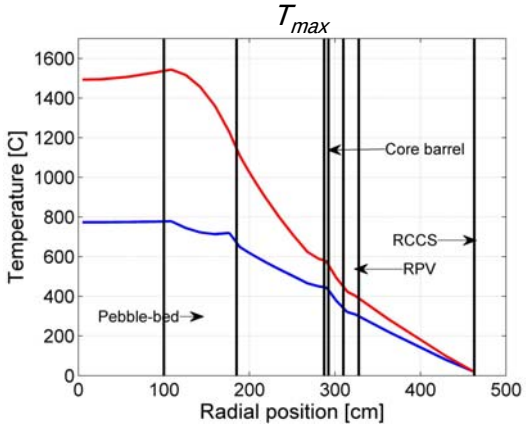


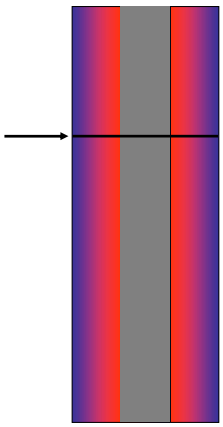
Kugeler and Schulten, Hochtemperatur Reaktortechnik, 1989

Reactor core layout



Temperatures during DLOFC





PBMR results DLOFC, Brian Boer, TU-Delft