GEN IV International Forum

INTRODUCTION TO NUCLEAR REACTOR DESIGN

Dr Claude Renault
CEA/INSTN, France

November 22, 2016

Meet the presenter

Claude Renault has been working at CEA (*The French Alternative Energies and Atomic Energy Commission*) for more than 30 years in R&D and E&T. He is senior expert at CEA and professor.

In 2010, he joined the INSTN (*The National Institute for Nuclear Science and Technology*) where he is currently International Project Leader. His expertise and teaching experience mainly cover thermal-hydraulics, design and operation of nuclear reactors, including the different families of reactors in particular the concepts of 4th generation.

Claude Renault came to CEA in 1984 in the development team of CATHARE, the reference CEA-EDF-AREVA-IRSN computer code for the simulation of accidental transients in Pressurized Water Reactors (PWR). He was subsequently responsible, at national and international level, for several R&D projects in the areas of severe accidents (ASTEC) and nuclear fuel behavior (PLEIADES).

Between 2001 and 2009, he was heavily involved in R&D programs devoted to future nuclear reactors. He intervened at the Directorate of Nuclear Energy (CEA/DEN) in the definition and monitoring of research programs on the different concepts of 4th generation reactors. He chaired the Steering Committee of the Molten Salt Reactor in Generation IV.

Email: claude.renault@cea.fr

Introduction to nuclear reactor design

Subtitle: From neutrons to Gen IV reactors

Outline

From fission to electricity: a pioneering history

Basic principles and mechanisms

Chain reaction and criticality

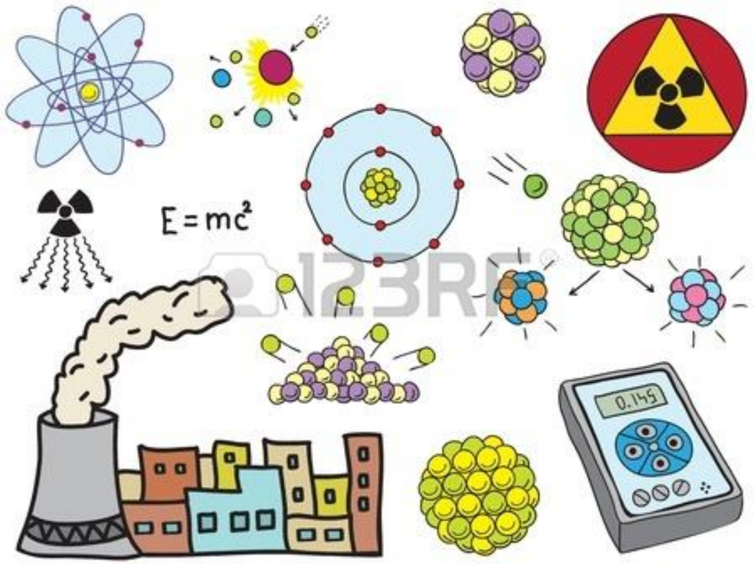
Conversion and breeding

Nuclear reactors today

Why is a new generation of nuclear reactors needed?

Reopening the scope for reactor design

The systems selected in Gen IV



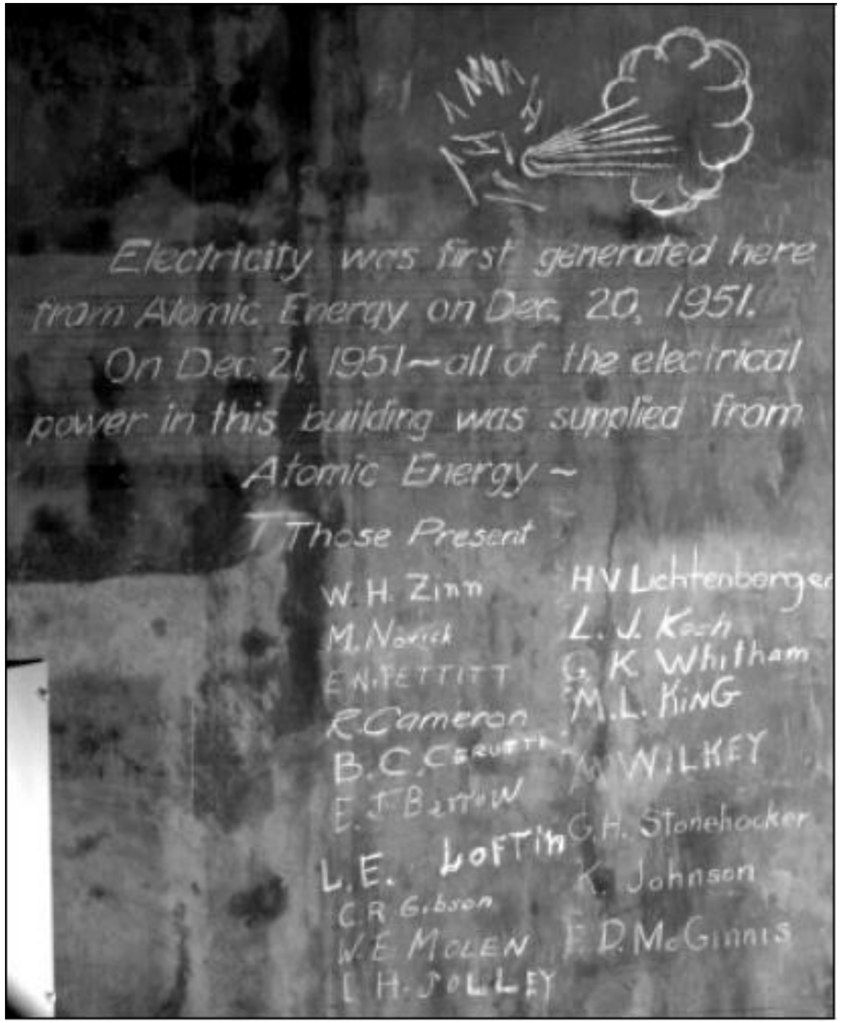
From fission to electricity

CP1, the first nuclear "pile"

Enrico Fermi led a group of scientists in initiating the first *self-sustaining nuclear chain reaction (Chicago, December 2, 1942)*

From fission to electricity

1951: the first nuclear electricity production and the first « fast neutron » reactor



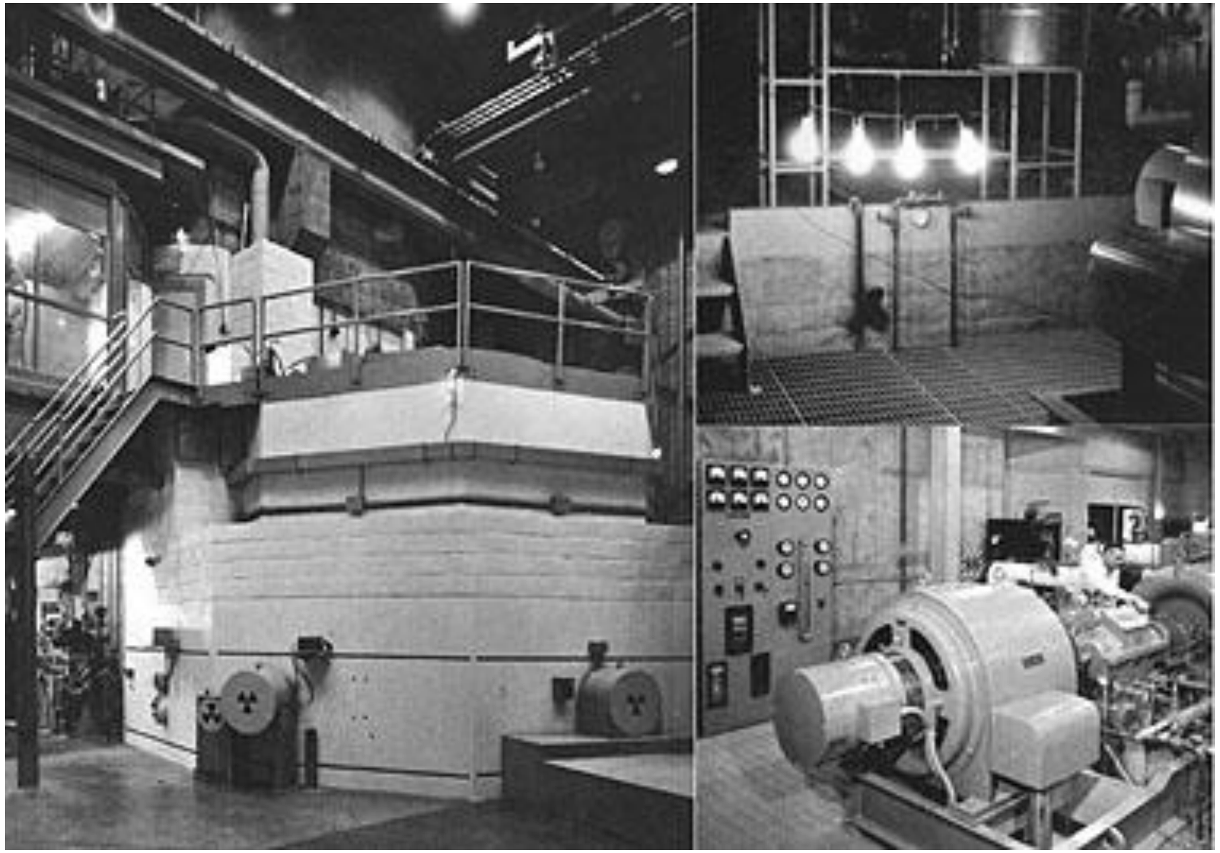
Electricity was first generated here
from Atomic Energy on Dec. 20, 1951.
On Dec. 21, 1951—all of the electrical
power in this building was supplied from
Atomic Energy ~

Those Present

W. H. Zinn
M. Novick
E. N. PETTITT
R. Cameron
B. C. CERUTTI
E. J. Barrow
L. E. LOFTIN
C. R. Gibson
W. E. MOLEN
L. H. JOLLEY

H. V. Lichtenberger
L. J. Koch
G. K. Whitham
M. L. KING
W. WILKEY
G. H. Stonehocker
K. Johnson
F. D. McGinnis

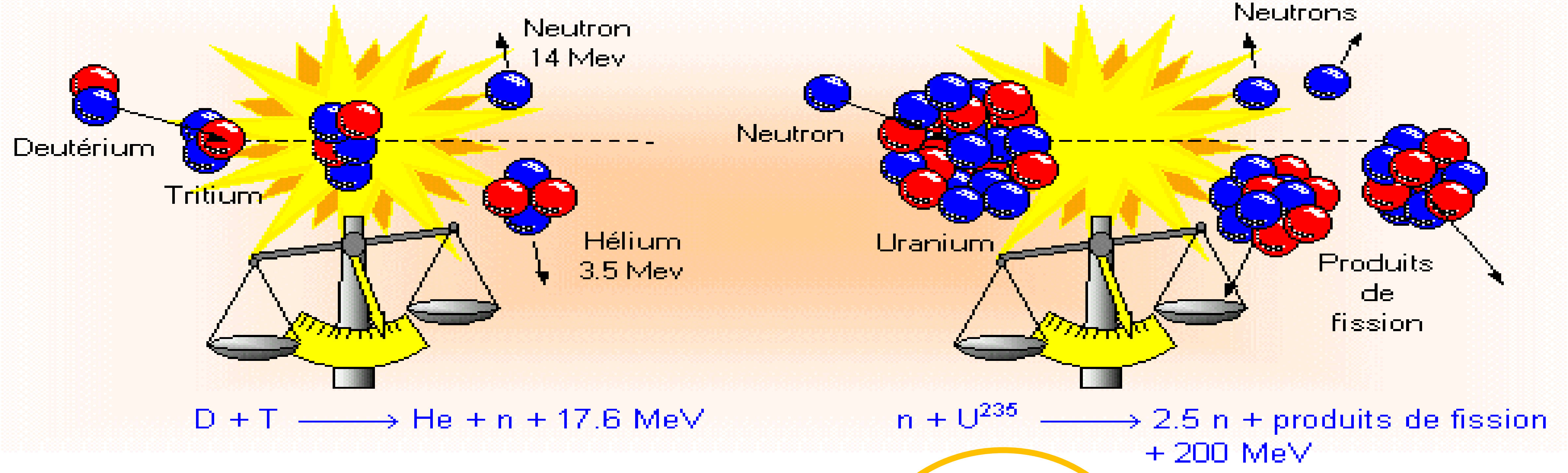
EBR-1 (USA, Idaho)



« EBR 1 lits Arco »

Fission, fusion, fossil fuel burning?

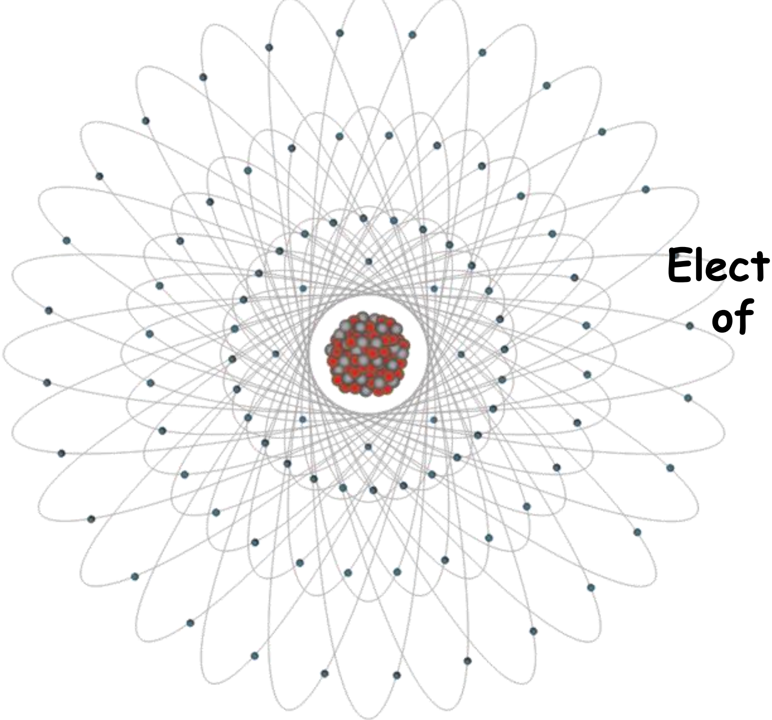
The potential of nuclear energy is fantastic!



Combustion of 1 ton of fossil oil:	**0.5 MWd**	**(42 GJ)**
Total fission of 1 g of ^{235}U:	**1 MWd**	**(83 GJ)**
Total fusion of 1 g of fuel (D,T):	**4 MWd**	**(330 GJ)**

Fission requires “nuclear fuel”

The only resource that can directly be used for nuclear energy production is natural uranium



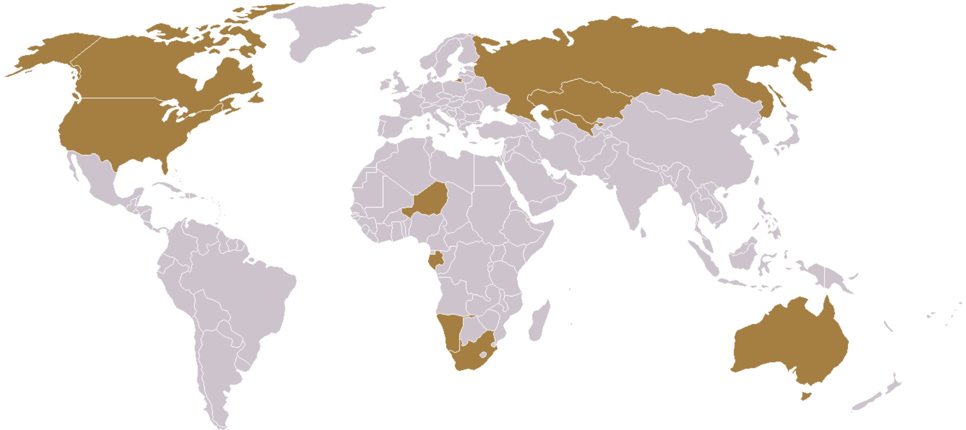
Electronic structure of Uranium 235

Natural uranium: 99.3% ^{238}U, 0.7% ^{235}U

Natural uranium is made of 2 “isotopes”

protons neutrons

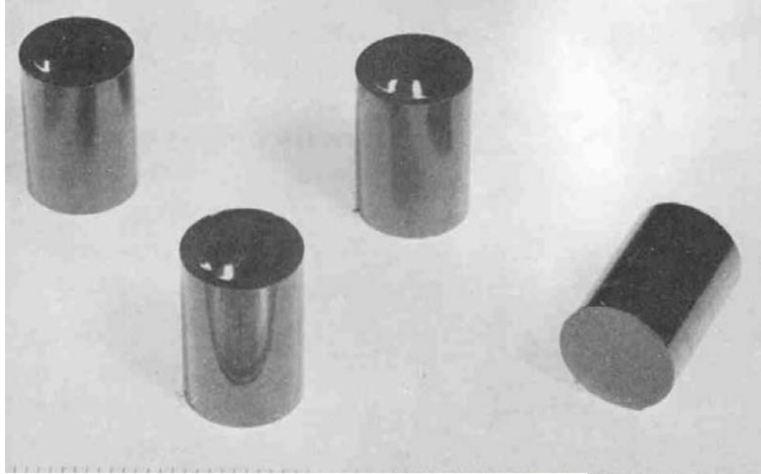
isotope	A	Z	A-Z
^{238}U (U8)	238	92	146
^{235}U (U5)	235	92	143



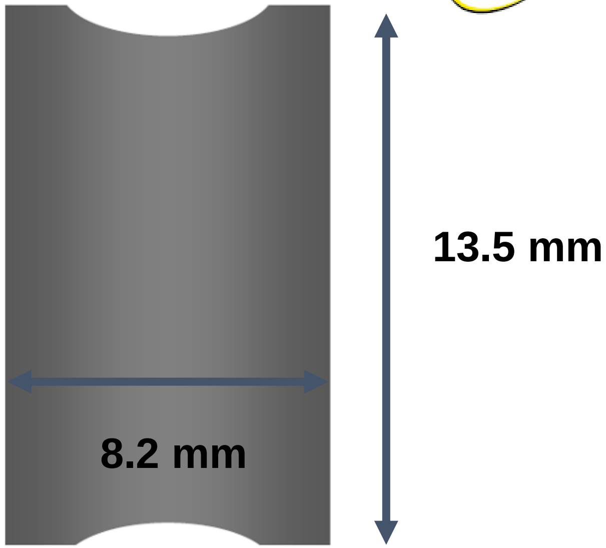
Uranium production in the world

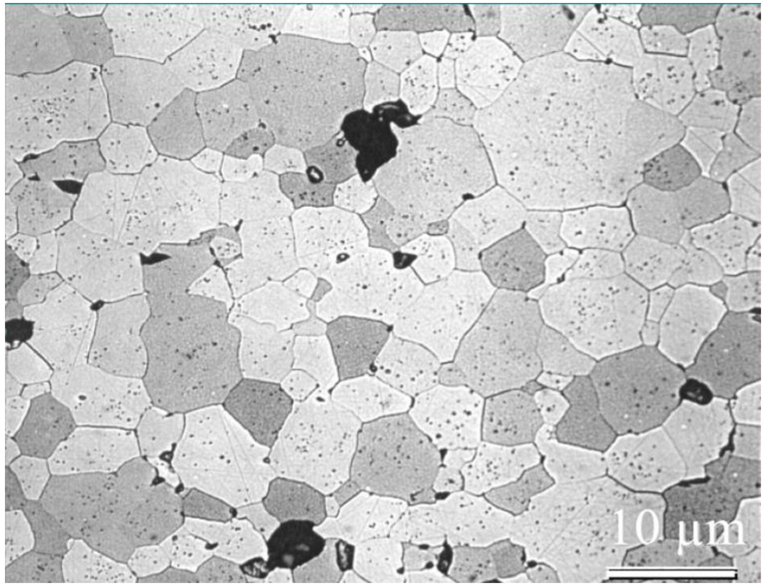
The nuclear fuel of PWRs

PWRs' nuclear fuel is "enriched" (3-4% ^{235}U)

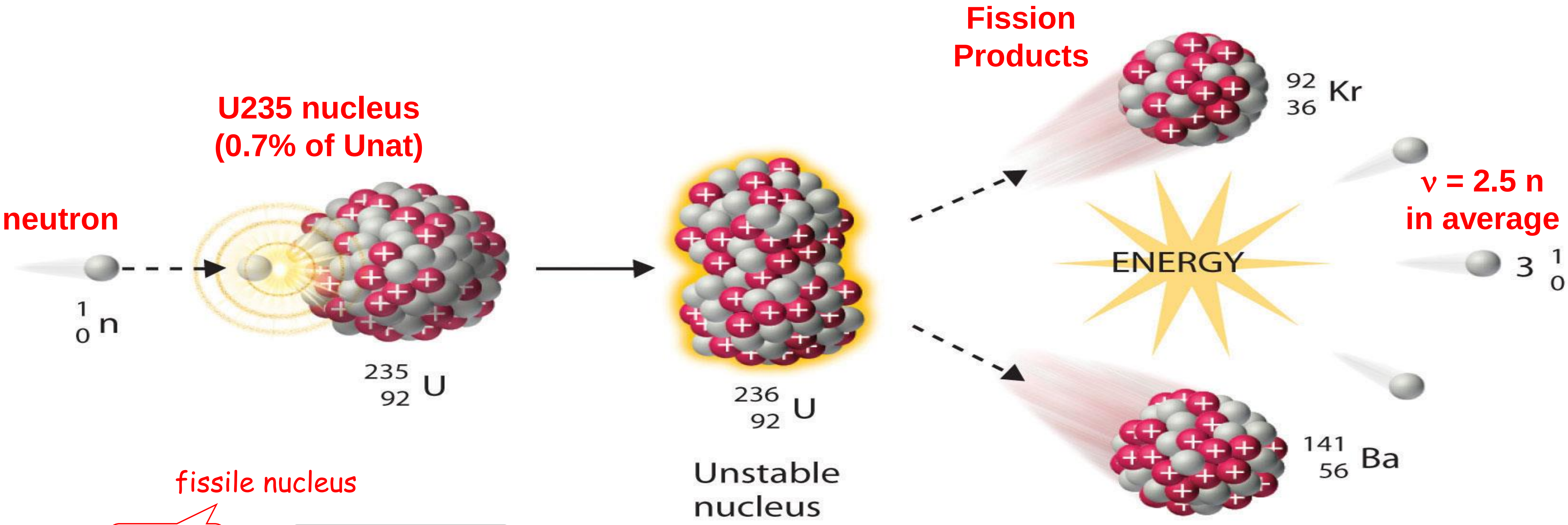


UOx pellet
(uranium oxide, UO_2)





The fission reaction on U235 nucleus



fissile nucleus

$$n + \boxed{^{235}U} \rightarrow \boxed{^{A1}X_1 + {}^{A2}X_2} + \nu\, n + \gamma$$

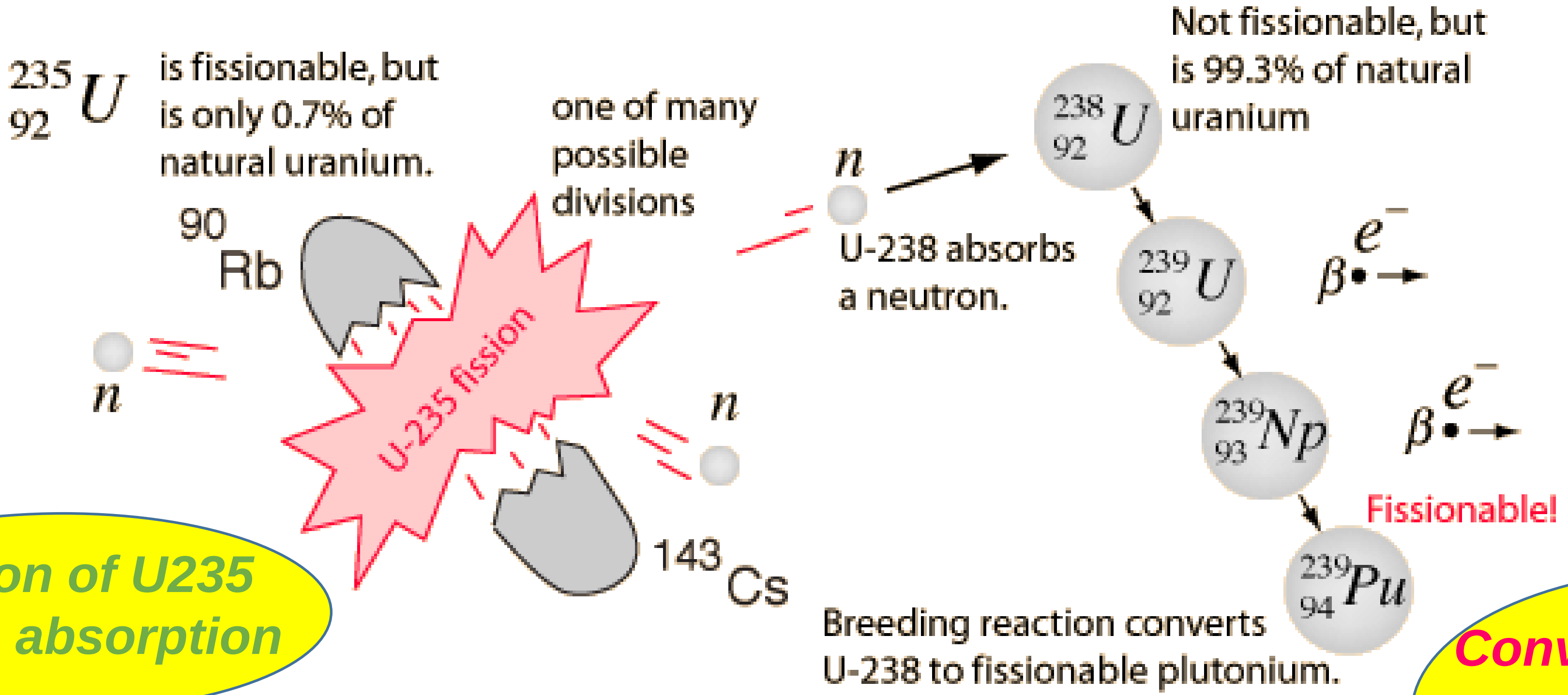
fission products

U235 is a "fissionable" material (isotope capable of undergoing nuclear fission after capturing a neutron)

Fission on U235 and capture on U238

***Nuclear fuel is a mixture of U5 and U8,
two main mechanisms are competing***

[source hyperphysics.phy-astr.gsu.edu]



Fission of U235 after n absorption

Conversion due to n capture on U238 (Pu239 production)

U238 isotope is a "fertile" material (not fissionable by thermal neutrons but which can be converted into fissile isotope)

The primary challenges of nuclear reactor design

"Pampering" both neutrons and fissile nuclei

When a neutron is absorbed by a U235 nucleus, 1 neutron disappears and 1 fissile nucleus disappears (fission or capture)

2 main challenges:

- **To sustain a chain reaction of fission (feasibility ➔ criticality)**

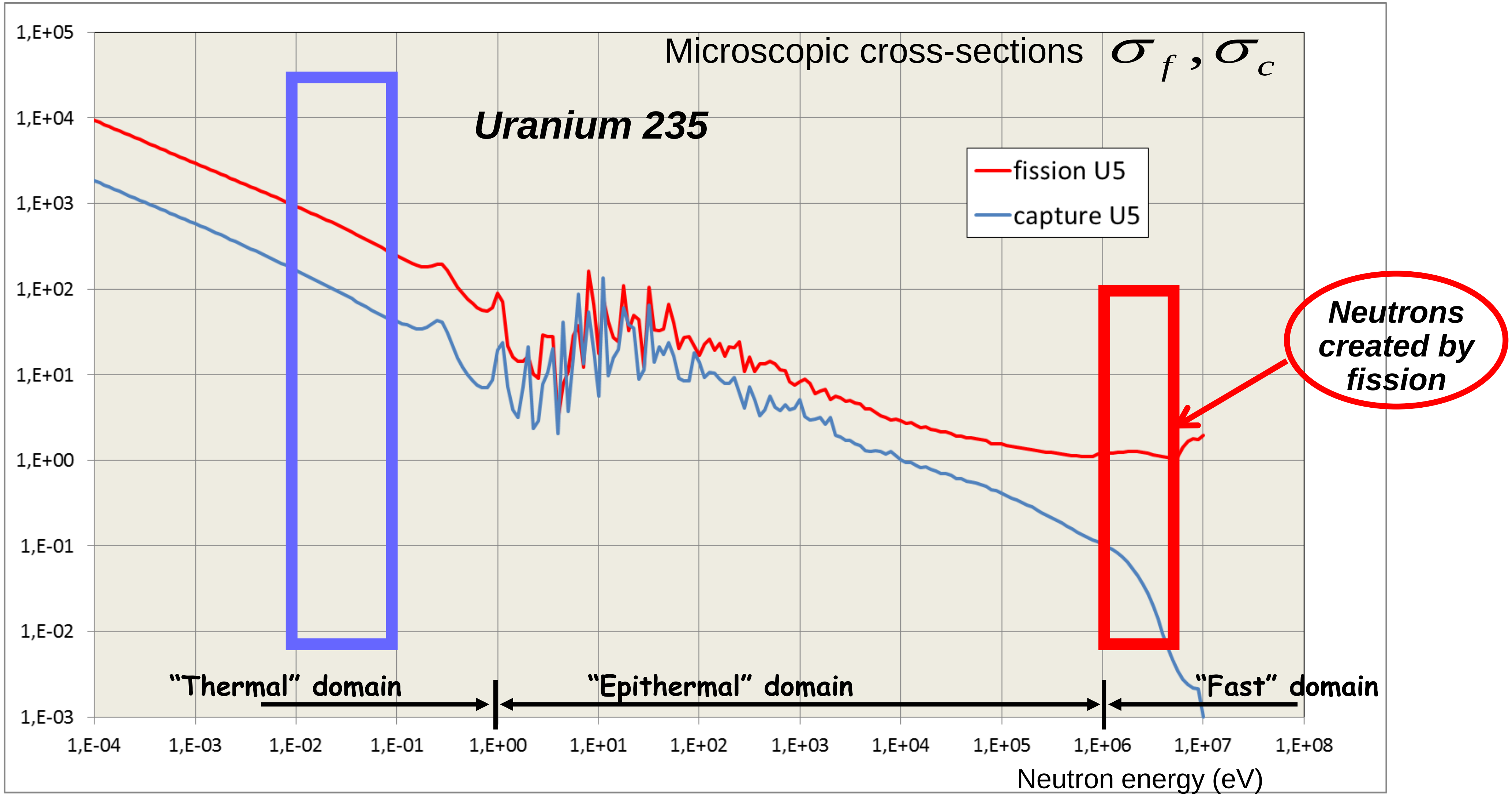
  ➔ neutron balance

- **To optimize fuel exhaustion in the fuel (fuel utilization↗)**

  ➔ fissile material balance

The probability of fission, "fast" or "thermal"?

The probability for a fission to occur is dependent on neutron energy (velocity)



The fission probability is much larger for "thermal" neutrons

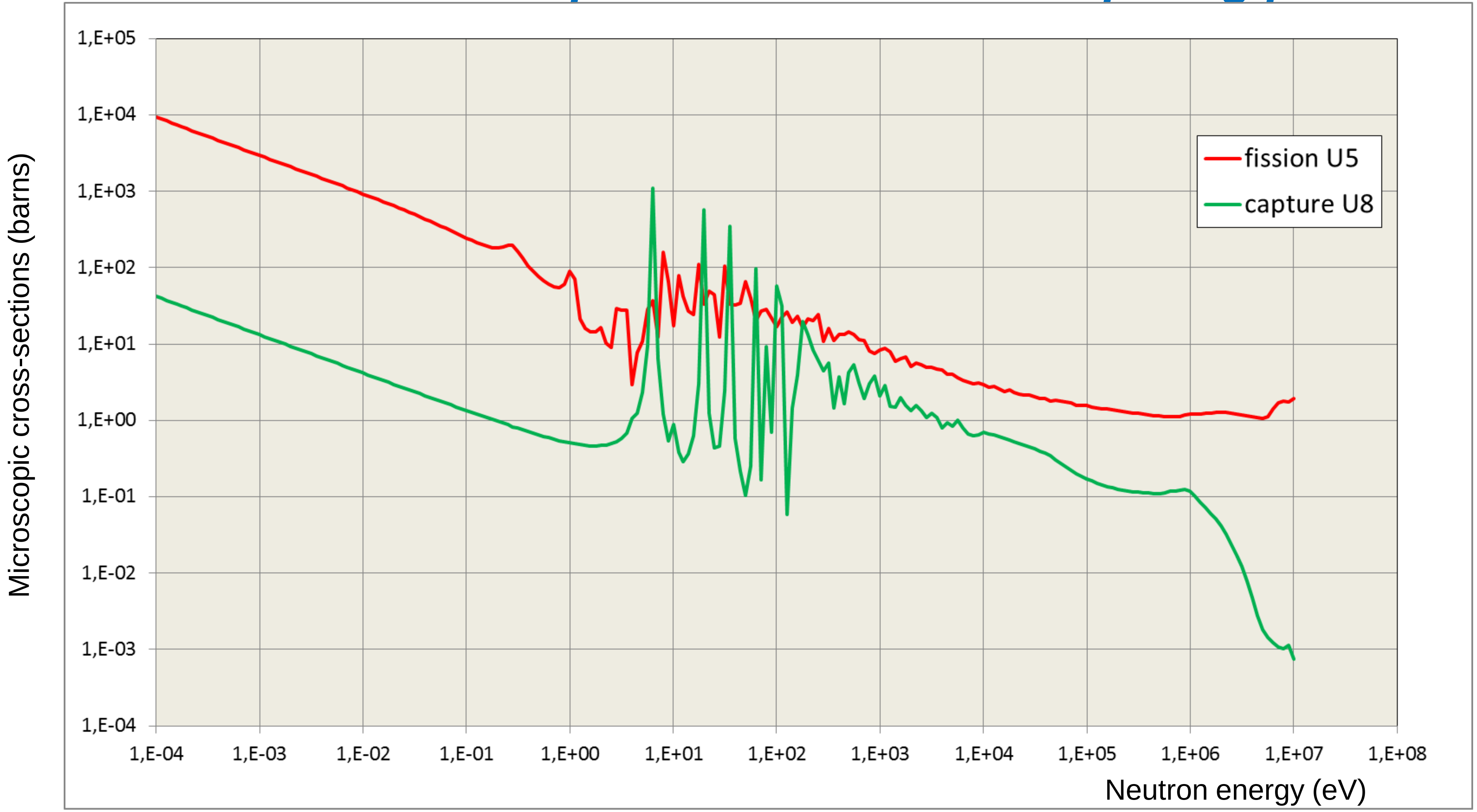
Is a sustained chain reaction possible?

Fission on U235 and neutron absorption on U238 are competing phenomena

Natural U !

0.7% ^{235}U

99.3% ^{238}U



With Unat, the feasibility (chain reaction) is tricky (only 0.7% of fissile U235) but can be improved by increasing the fissile fraction (fuel "enrichment").

What is the condition for self-sustained reaction?

The potential for self-sustained reaction is measured by the "multiplication factor" k

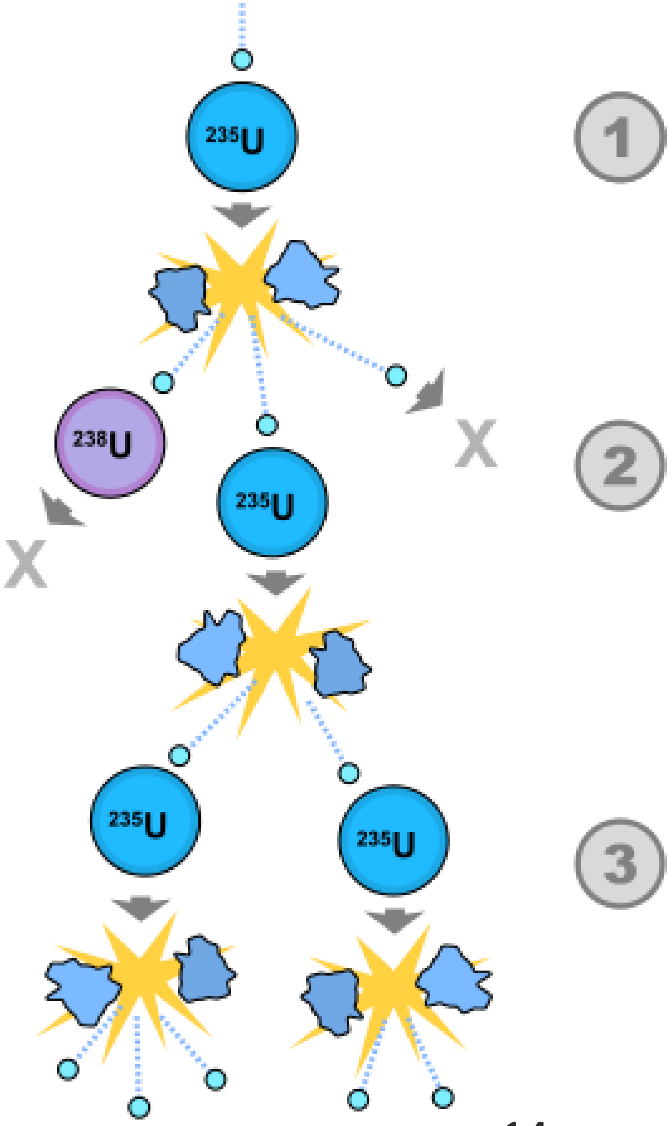
$$k = \frac{neutron\ production}{neutron\ absorption + leakage}$$

The mechanisms affecting *k* are:

- fission of fissile isotopes (U235) in the fuel
- neutron captures on fuel (U238, U235), coolant, moderator, structures, FPs
- neutron leakage out of the core

$$k = \frac{\bar{\nu} FR}{AR + LR} = \frac{\bar{\nu} FR}{AR_{fuel} + AR_{other} + LR}$$

The condition for a self-sustained reaction is k > 1
k=1 is the criticality equation



What is the condition for self-sustained reaction?

The multiplication factor k can be rewritten as:

$$k=\frac{\bar{\nu}\,\dfrac{FR}{AR_{fuel}}}{1+\dfrac{AR_{other}+LR}{AR_{fuel}}}=\frac{\bar{\nu}\,\dfrac{\Sigma_f}{\Sigma_a}}{1+\dfrac{AR_{other}+LR}{AR_{fuel}}}$$

fuel-related effects

other effects

$\eta=\bar{\nu}\dfrac{\Sigma_f}{\Sigma_a}$ ***is the "reproduction factor"***

$\Sigma=N\sigma$ *(N isotope concentration, at/cm^3)*

For uranium (mixture U235-U238):

$$\eta(U)=\nu_{235}\frac{\Sigma_f^{235}}{\Sigma_a^{235}+\Sigma_a^{238}}$$

or

$$\eta(U)=\frac{\nu_5\dfrac{\sigma_f^5}{\sigma_a^5}}{1+\dfrac{1-e}{e}\dfrac{\sigma_a^8}{\sigma_a^5}}$$

fissile isotope

fissile fraction e

***k* is a function:**

- **the nature of the fissile isotope (U235)**
- **fuel composition ("enrichment", etc.)**
- **and the core geometry (neutron leakage)**

What is the condition for self-sustained reaction?

A necessary condition for criticality is that the reproduction factor η is significantly larger than 1

$$k = \frac{\bar{\nu}\dfrac{\Sigma_f}{\Sigma_a}}{1 + \dfrac{AR_{other} + LR}{AR_{fuel}}}$$

Reproduction factor η for uranium fuel (fissile fraction e):

Fissile fraction e	0.71 % (U nat)	3 %	10 %	15 %	100 %
For fast neutrons	0.10	0.35	0.85	1.07	1.88
For « thermal » neutrons	1.33	1.84	2.00	2.02	2.07

The chain reaction is not possible with natural uranium <u>and</u> fast neutrons.

Therefore 2 solutions:

- **to <u>slow down neutrons</u> (criticality possible whatever the fissile content, Unat possible for strict neutron economy)**

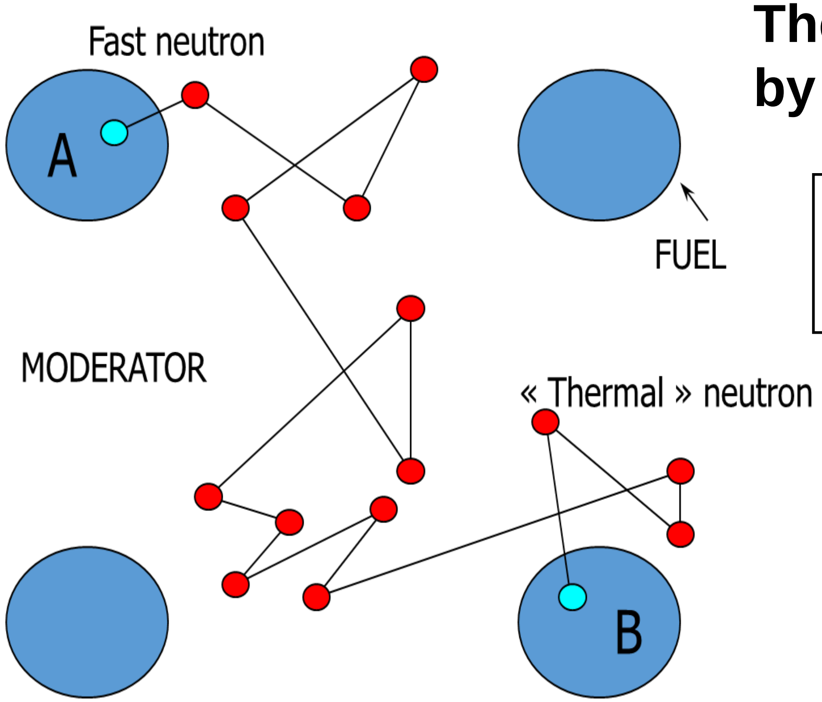
  ➔ ***Thermal Neutrons Reactors, TNR* (PWR, BWR, CANDU,…)**

- **to use fast neutrons and subsequently increase the fissile fraction in the fuel**

  ➔ ***Fast Neutrons Reactors, FNR***

How to slow down neutrons? A moderator

A neutron moderator is a medium that reduces the velocity of fast neutrons



The variation of neutron kinetic energy by collisions is characterized by the parameter ξ (*average logarithmic energy decrement*)

$$\boxed{\xi = 1 + \frac{\alpha}{1-\alpha} Ln\alpha}$$

$$\boxed{\alpha = \frac{(A-1)^2}{(A+1)^2}}$$

➔ **low mass number A**

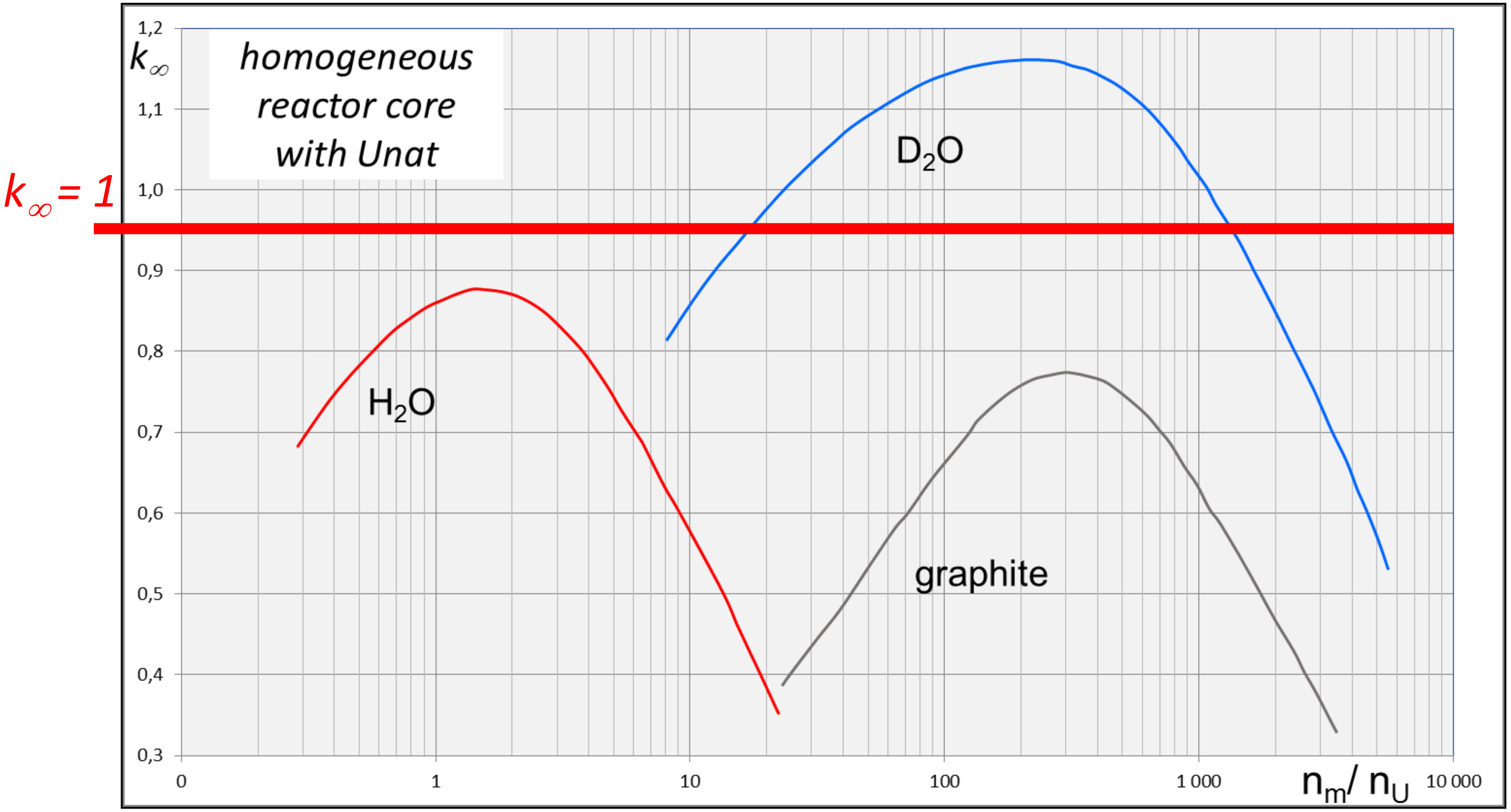
Other factors are high scattering probability (Σ_s) and low neutron absorption (Σ_a)

« Moderating efficiency »

moderator	ξ	n_{co}	Σ_s (cm^{-1})	Σ_a (cm^{-1})	$\xi\Sigma_s/\Sigma_a$
light water (H_2O)	0.96	19	3.48	0.02	152
heavy water (D_2O)	0.48	38	0.35	$4.1\ 10^{-5}$	4155
graphite (C)	0.16	115	0.40	$2.7\ 10^{-4}$	231

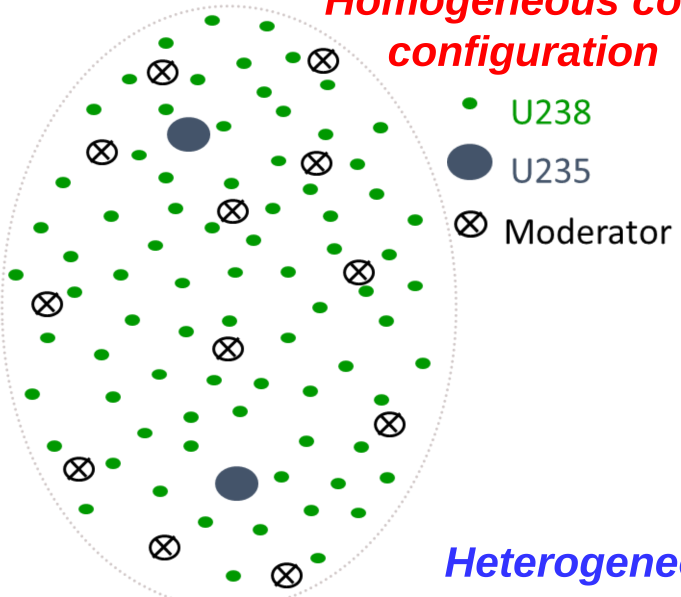
How to slow down neutrons? A moderator

What quantity of moderator and which core configuration?

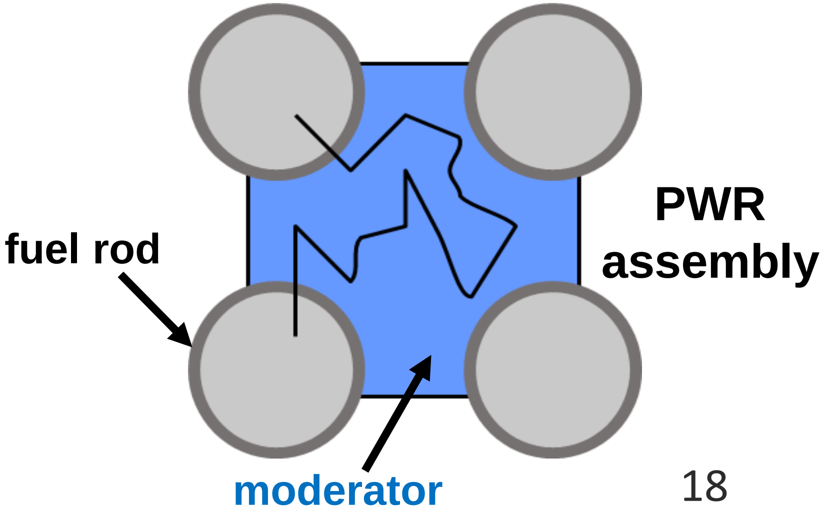


For example, solution of uranyl nitrate ($UO_2(NO_3)_2$)
(water soluble uranium salt)

Homogeneous core configuration



Heterogeneous core configuration



Conversion and breeding

Neutron capture on U238 produces Pu239 (conversion)

$$n + {}^{238}U \rightarrow {}^{239}U \xrightarrow[23\text{ min}]{} {}^{239}Np + e^- \xrightarrow[2.3\text{ days}]{} {}^{239}Pu + e^-$$

The conversion efficiency can be measured using the "breeding ratio"

$$BR = \frac{P_f}{C_f} = \frac{fissile\ production}{fissile\ consumption}$$

(fissile mass balance)

If $BR > 1$ ***The reactor produces more fissionable fuel than it consumes.***
It is called a « breeder reactor »

A necessary (but not sufficient) condition for breeding is: $\eta > 2$ ***with*** $\eta = \nu \frac{\sigma_f}{\sigma_a}$

isotope	U235		Pu239	
spectrum	thermal	fast	thermal	fast
σ_f (barn)	582	1.81	743	1.76
σ_c (barn)	101	0.52	270	0.46
ν	2.42	2.43	2.87	2.94
$\eta=\nu\sigma_f/\sigma_a$	2.07	1.88	2.11	2.33

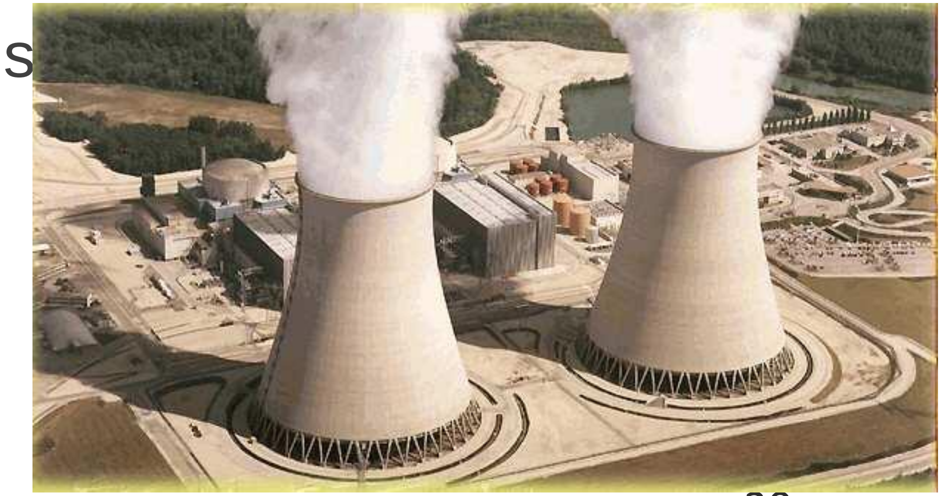
For PWRs, $BR \approx 0.5 - 0.6$

For FNRs, $BR \approx 0.8 - 1.2$

What are the “ingredients” of a nuclear reactor?

The ingredients of a fission reactor:

- **Fuel** material that contains "enough" fissile isotopes (*U235*, *U238*, *Pu239*...) or even fertile isotopes
- **A heat transfer medium**, **coolant** (liquid, gas) able to extract the heat energy generated in fission fuel
- **A moderator,** material able to slowdown fast neutrons
- **Absorbents,** materials for capturing neutrons (control of the chain reaction)



Nuclear reactors today

General characteristics of nuclear reactors in operation

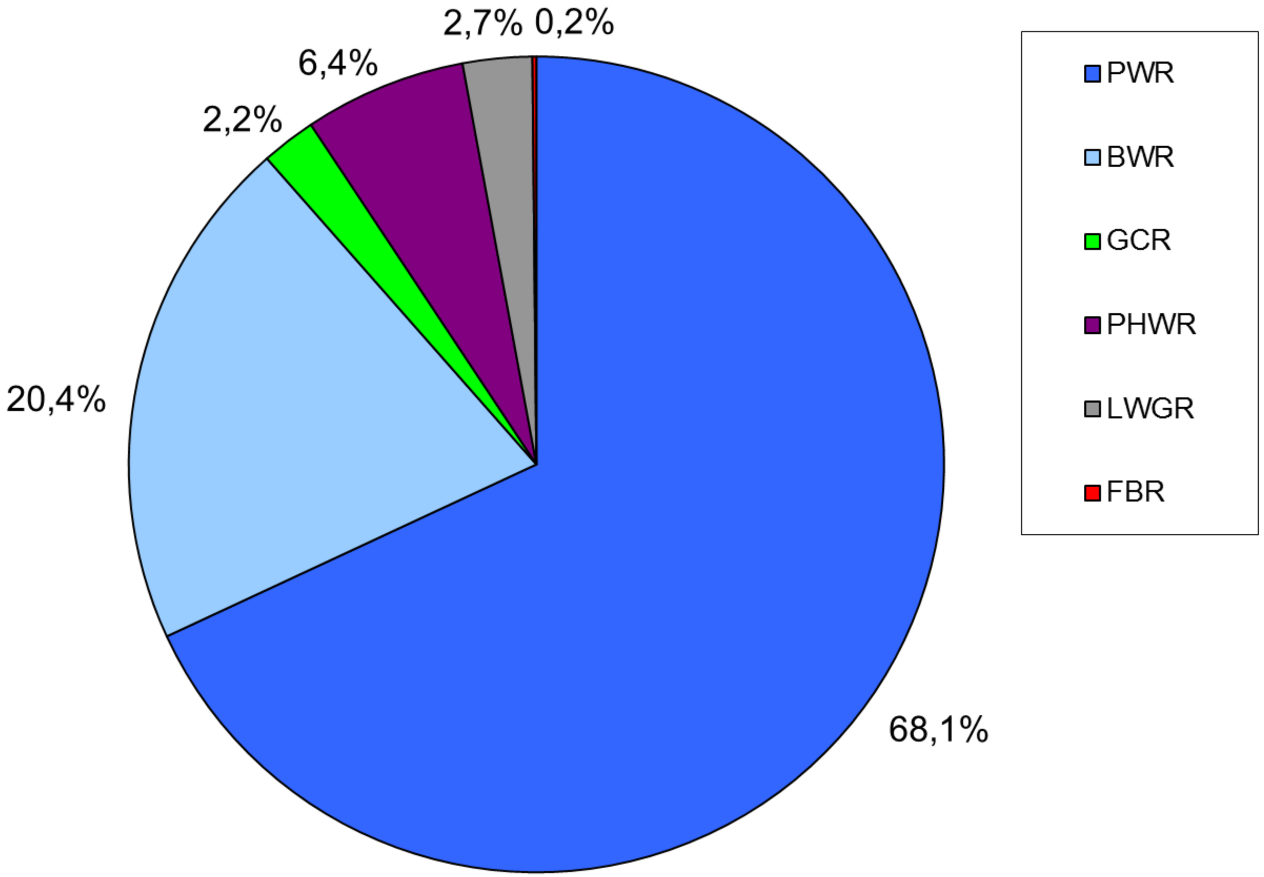
Reactor type	Fuel type	Moderator	Coolant	Core power density (MW/m³)	Pressure (bar)	Temperature (°C)	Efficiency (%)
UNGG	**Unat**	C	CO_2	1	41	400	30
Magnox							
PHWR		D_2O	D_2O	12	130	300	30
LWGR	**U 1-2%**	C	H_2O	2	70	284	31
AGR		C	CO_2	3	40	645	40
BWR	**U 3-5%**	H_2O	H_2O	50	72	288	37
PWR				100	155	330	35
FBR (FNR)	**Pu 20-30%**	-	Na	500	1	550	40

Nuclear reactors today

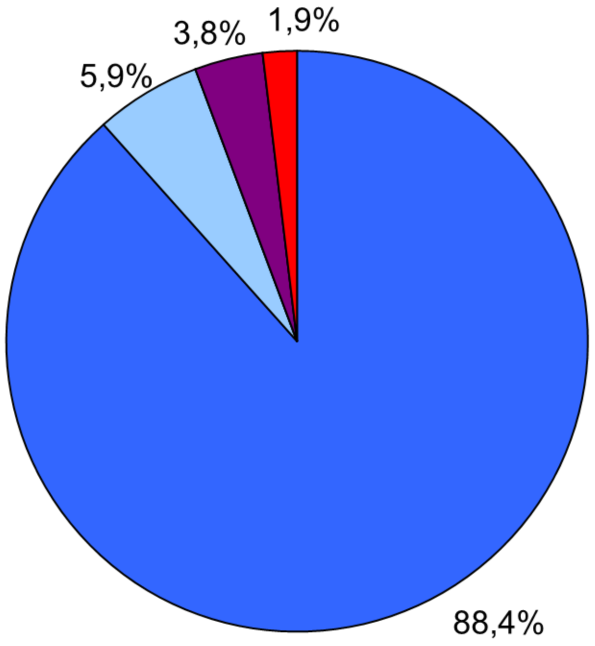
And the winner is…

Nuclear power plants worldwide (operated end 2013)

Total installed power: 372 GWe



Under construction: 66 GWe



PWR + BWR → 88.5%

Total electricity production = 2359 TWhe (10.7%)

Why is a new generation of nuclear reactors needed?

Why should we do better than the 3rd generation?...

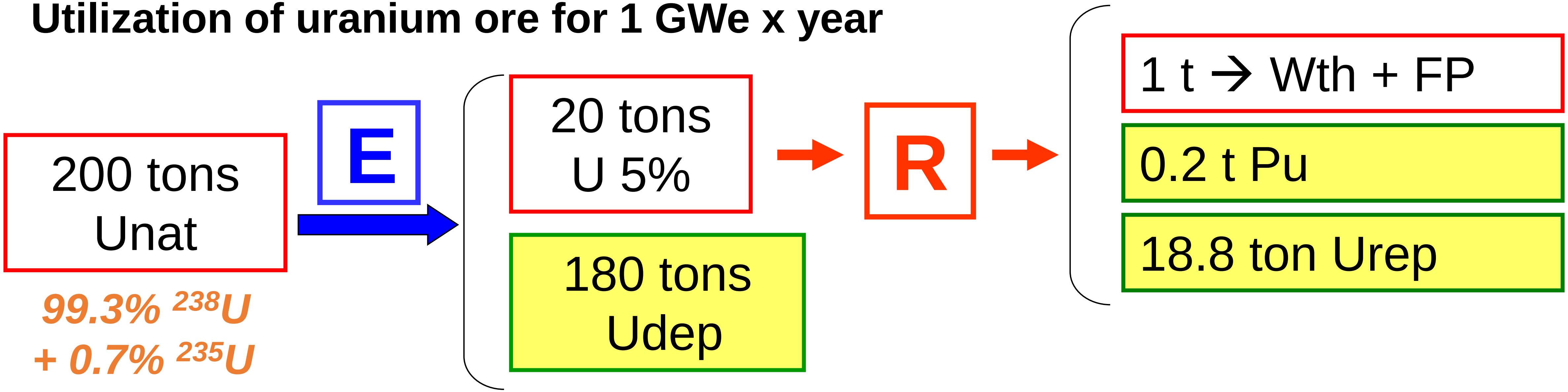
- The large scale development of 3rd generation reactors challenges uranium resources: identified conventional resources (at a cost < 130 $ /kg) represent 160 years of today’s consumption (only about 0.5% of natural uranium is used)
- The management of nuclear wastes will have to be further improved
- Having in mind a perspective of fossil fuel shortage, nuclear technology should get prepared to answer other needs than electricity supply: hydrogen, process heat, desalination,…
- Larger spreading of nuclear power needs proliferation resistance

→ New types of nuclear reactors must be designed in order to ensure energy supply in a context of sustainable development

Why is a new generation of nuclear reactors needed?

Open cycle in LWRs

Utilization of uranium ore for 1 GWe x year



200 tons Unat

99.3% ^{238}U + 0.7% ^{235}U

E

20 tons U 5%

180 tons Udep

R

1 t → Wth + FP

0.2 t Pu

18.8 ton Urep

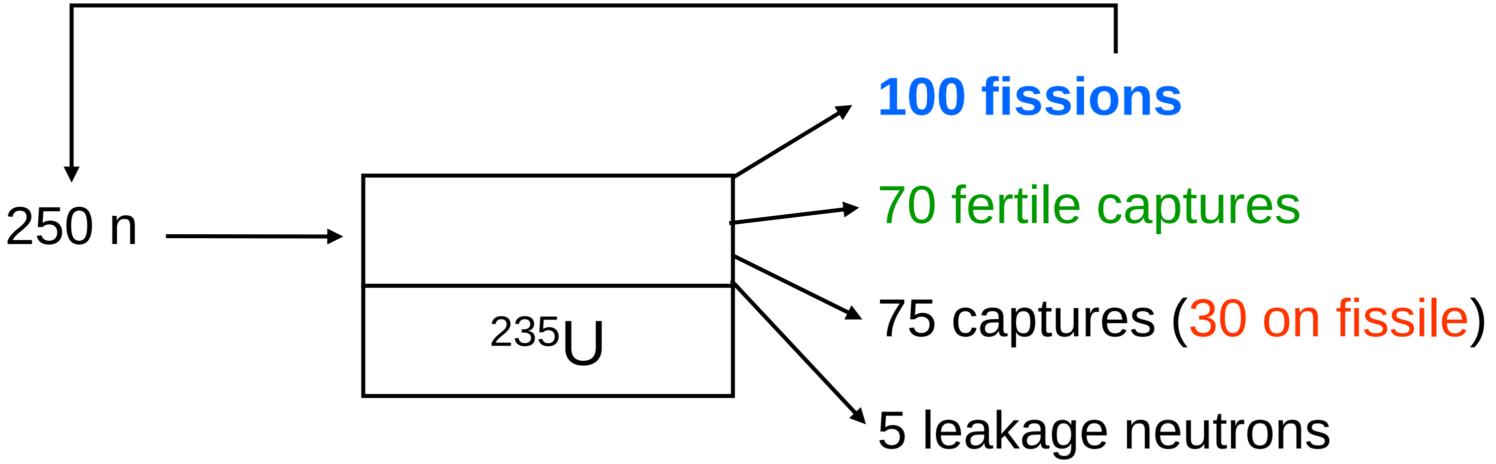
In PWRs, about 5% of the initial uranium set in reactor (enriched U) is consumed for electricity production (fuel technological limits)

This represents only 0.5-0.6% of the initial natural uranium

Breeder reactors (FNRs) need only 1 ton U238 (Udep & Urep) that is converted into plutonium and burned in situ *(regeneration → breeding of fissile fuel)*

Why Fast Neutron Reactors? The breeding issue

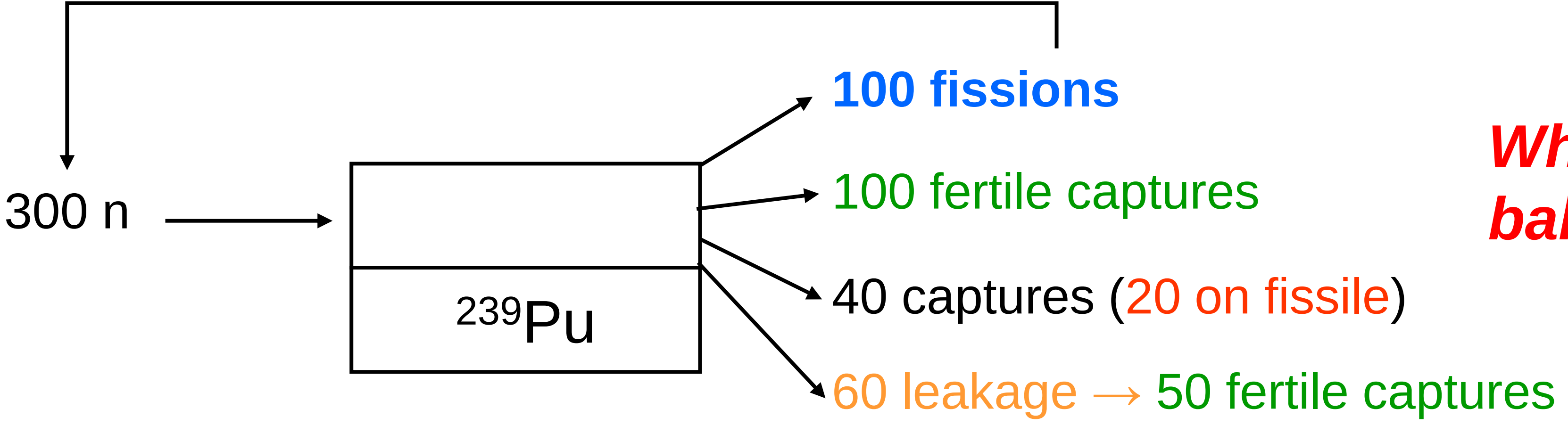
Simplified neutron balance in PWR: BR = 70/(100+30) ≈ 0.55



Simplified neutron balance in FNR:

BR internal = 100/(100+20) ≈ 0.85

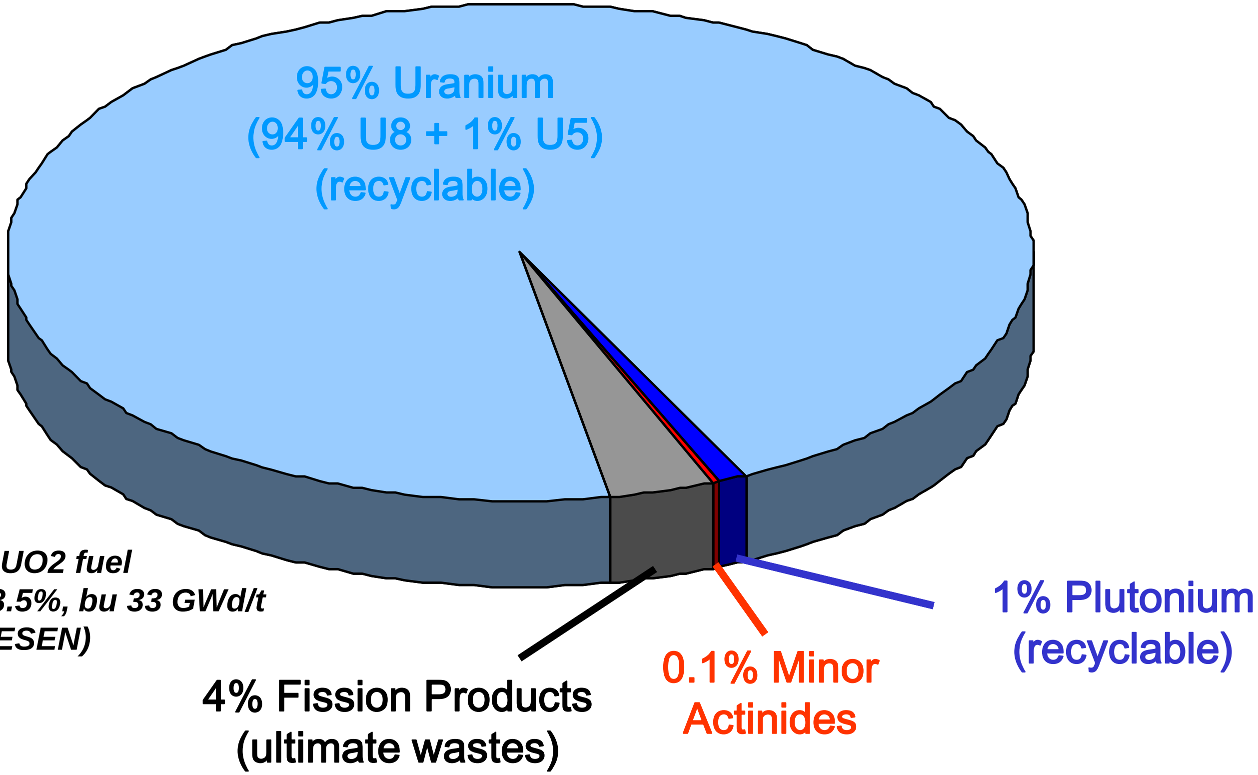
BR total = (100+50)/(100+20) ≈ 1.25



Why is the FNR neutron balance better for breeding?

Why Fast Neutron Reactors?
The waste management issue

Composition of spent fuel from PWRs



PWR 900, UO2 fuel
enriched 3.5%, bu 33 GWd/t
(source CESEN)

What strategy for nuclear waste management?

open cycle

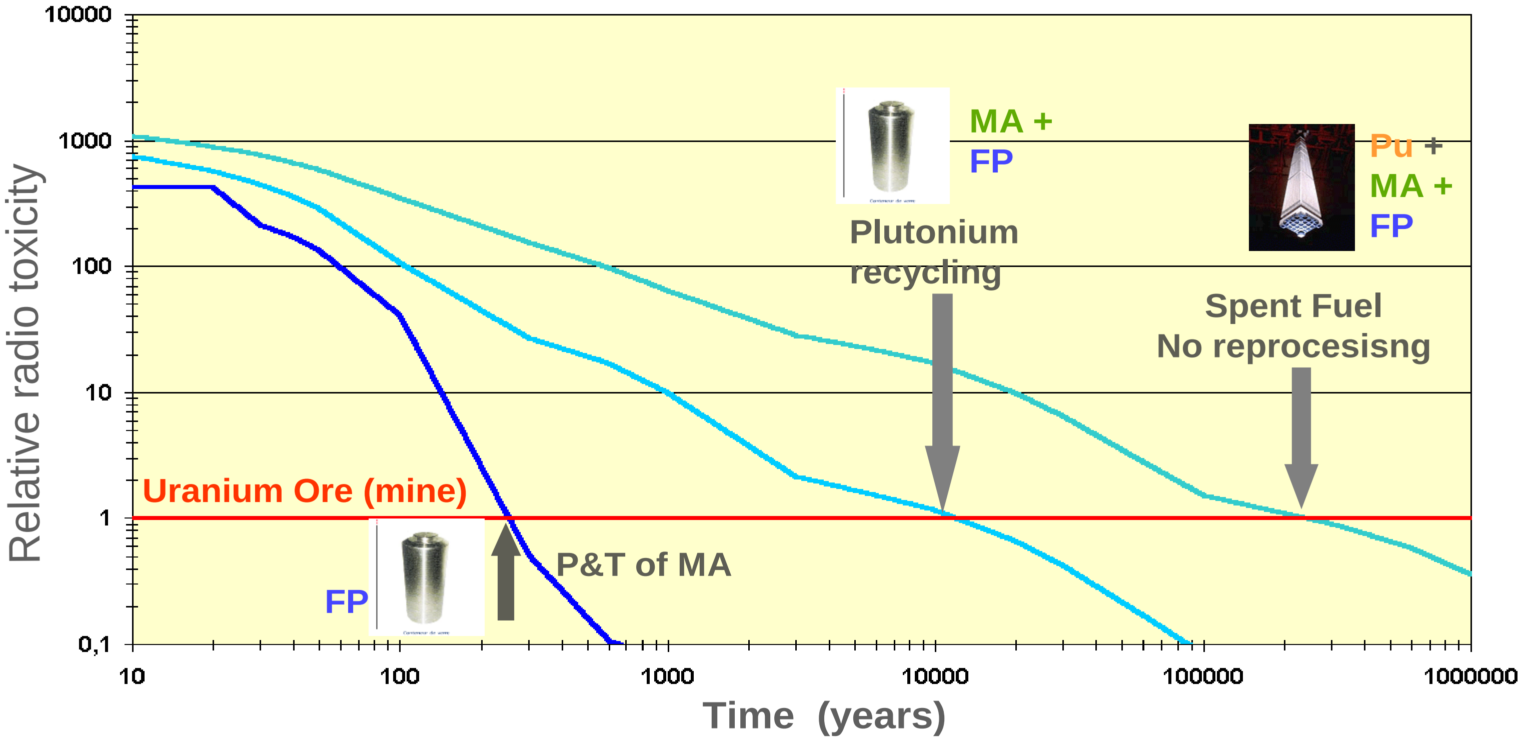
sorting of radioactive waste

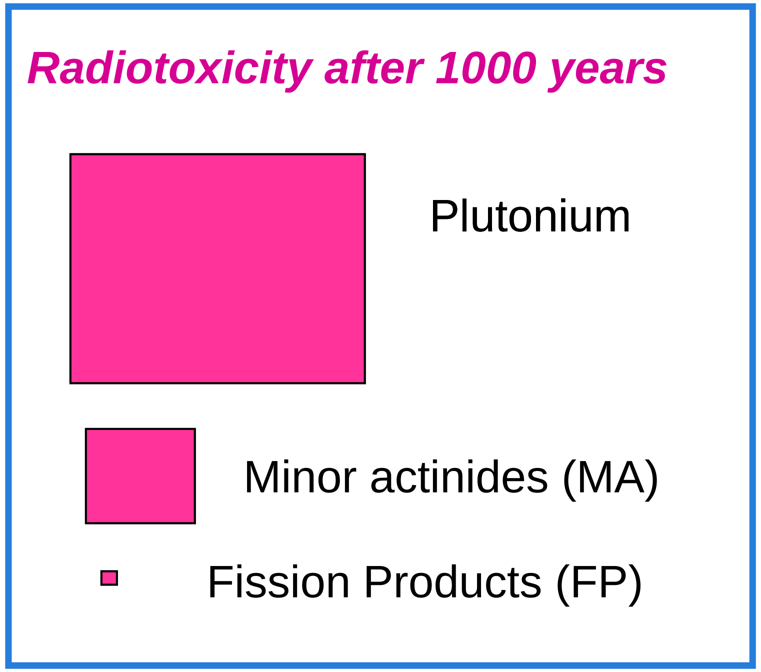
96% of the content of spent nuclear fuel is recyclable

Only 4% should be considered as nuclear wastes (FPs + MAs)

Why Fast Neutron Reactors?
The waste management issue

- Plutonium is the major contributor to the long term radiotoxicity of spent fuel → ***Plutonium recycling***
- After plutonium, MA (Am, Cm, Np) have the major impact to the long term radiotoxicity → ***MA transmutation***




Radiotoxicity after 1000 years

The ratio fission/capture is favourable to MA fission with fast neutrons

Reopening the scope: potential options and combinations

Coolant

Water: H_2O D_2O

Gas: CO_2 He

Liquid metal: Na Pb, Pb-Bi

Molten salts, organic liquids... FLiBe, FLiNa,…

Moderator

H_2O D_2O C (graphite) none

Fuel

Fissile: ^{235}U ^{239}Pu ^{233}U

Fertile: ^{238}U ^{232}Th

U^{235}:

U natural : 0,7 %
U LEnr : 1-5 to 2 %
U Enr : 3 to 5 %
U MEnr : 10 to 20 %

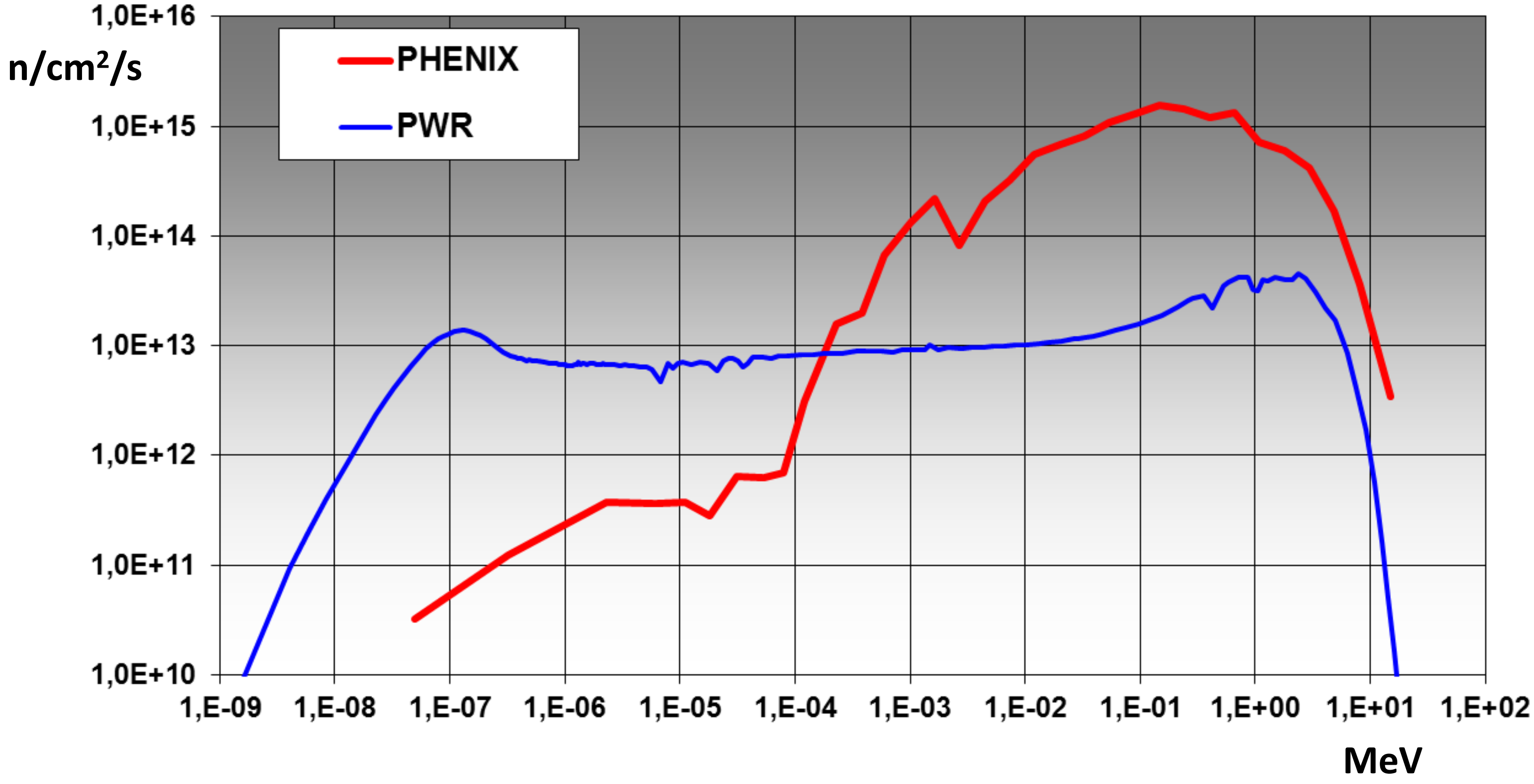
Other design options to choose?

- energy conversion system,
- fuel compound, structural materials,
- fuel cycle technologies

Multiple combinations are possible…

Reopening the scope:
potential options and combinations

Fast spectrum, thermal spectrum?

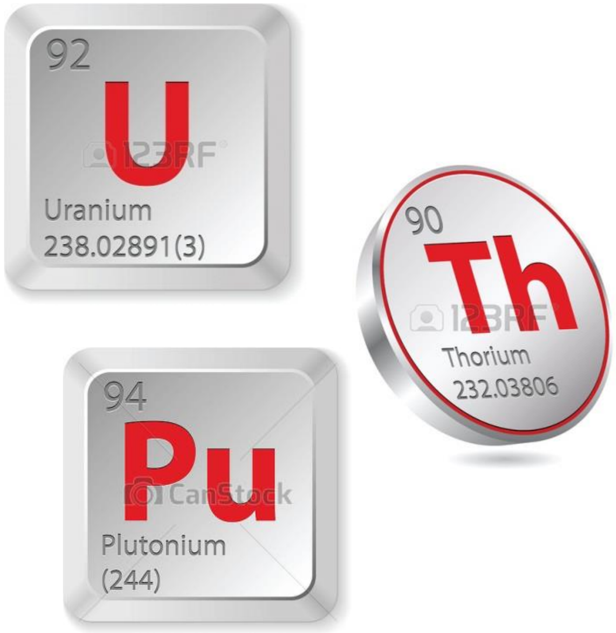


The choice should be guided by criticality, breeding, transmutation

Reopening the scope:
potential options and combinations

Potential isotopes for criticality and breeding

isotope	U235		Pu239		U233	
spectrum	thermal	fast	thermal	fast	thermal	fast
σ_f (barn)	582	1.81	743	1.76	531	2.79
σ_c (barn)	101	0.52	270	0.46	46	0.33
ν	2.42	2.43	2.87	2.94	2.49	2.53
$\eta=\nu\sigma_f/\sigma_a$	2.07	1.88	2.11	2.33	2.29	2.27



A necessary condition for breeding (BR > 1) is $\eta > 2$

U235 is not well fitted for breeding ➔ Pu239 with fast neutrons

U233 is another attractive option (Th/U3 fuel cycle)

Reopening the scope: potential options and combinations

The choice of the fuel

Pu/(U+Pu)=0.2	Carbide (U,Pu)C	Nitride (U,Pu)N	Oxide $(U,Pu)O_2$	Metal (U,Pu)Zr
Heavy atoms density (g/cm^3)	12.9	13.5	9.7	14
Melting temperature (°C)	2420	2780	2750	1080
Thermal conductivity (W/m/K)	16.5	14.3	2.9	14

What is your choice?

Reopening the scope: potential options and combinations

The choice of the coolant is a complicated issue

Main requirements	
Neutronics	« Transparency » (low neutron capture σ_a, low activation) *For FNR, low moderation effect*
Thermal-hydraulics	Heat capacity C_p ↗, thermal conductivity λ ↗, viscosity μ ↘ Phase change: melting t° ↘, boiling t° ↗
Other	Chemically inert (air, water) and non corrosive (structural materials) Stability (t°, irradiation) Optical transparency Cheap!

The potential coolant families:

- ***Water, excellent coolant (and moderator!)***
- ***Gases (helium, CO_2), opening the door to high t°***
- ***Liquid metals (Na, Pb, Hg…)***
- ***Molten salts***

Good thermal-hydraulics properties

Merit factor	He	CO_2	water	Na	Pb	*FLiBe*
Pumping	3.10^{-5}	5.10^{-5}	1	0.02	0.004	0.3
Heat transfer	1.0	0.7	1	24	9	0.4

Liquid metals?

Properties at 0.1 MPa and 500°C	**Pb**	**EPB** **44.5%Pb-55.5%Bi**	**Na**
Melting t° (°C)	327	123	98
Boiling t° (°C)	1745	1670	881
Specific mass (kg/m^3)	10470	10050	833
Conductivity (W/m/K)	15	14	66

GIF and a new generation of nuclear systems

Nuclear is a CO_2-free option for sustainable energy

New requirements for sustainable nuclear energy

Search innovative solutions for:

Waste minimisation

Natural resources conservation

Proliferation resistance

***Perform continuous progress on*:**

Competitiveness

Safety and reliability

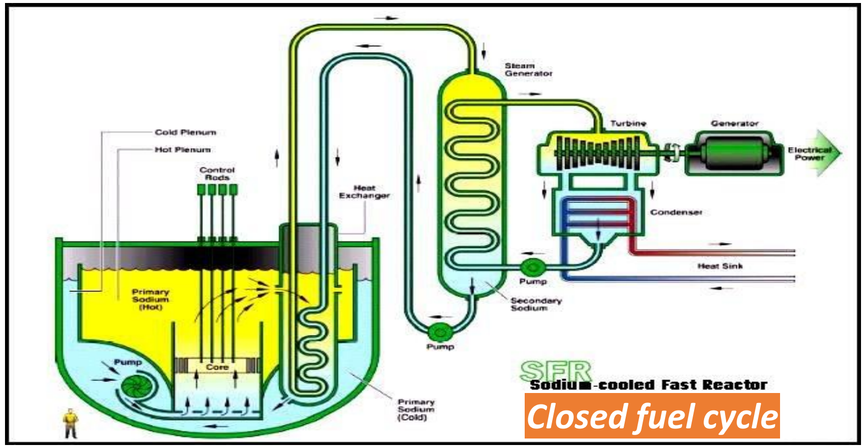
Develop the potential for new applications:

hydrogen, syn-fuels, desalinated water, process heat

➔ ***Systems marketable from 2040 onwards***

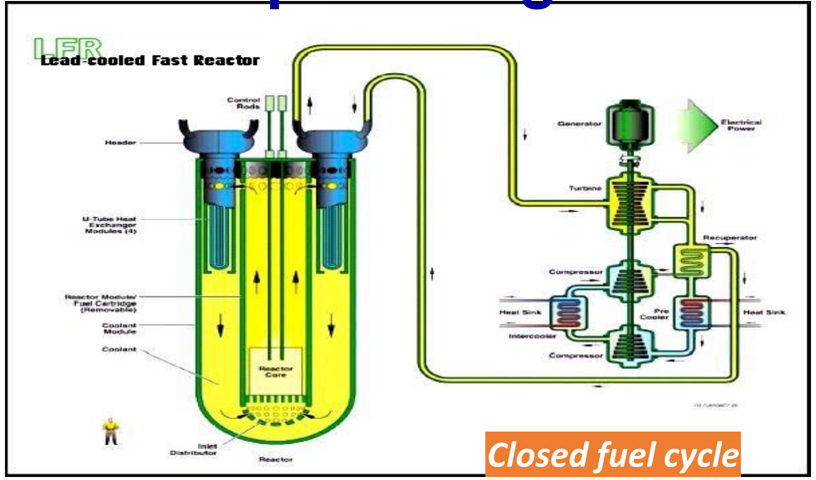
GIF and a new generation of nuclear systems

Top-ranking and outsiders ?



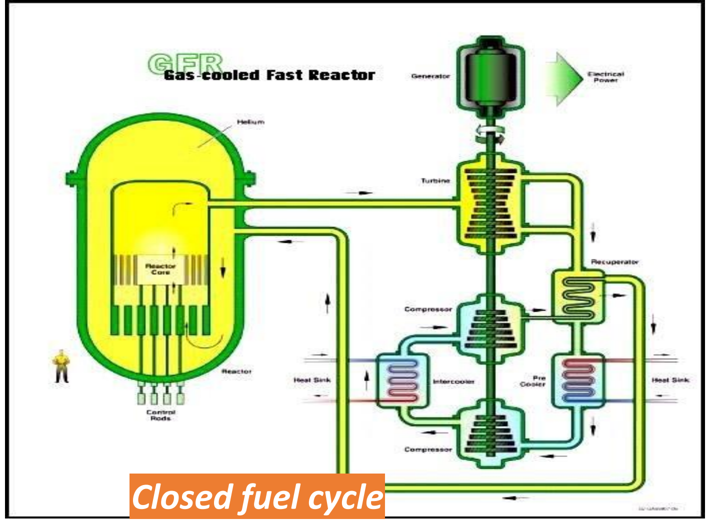
Closed fuel cycle

Sodium Fast Reactor



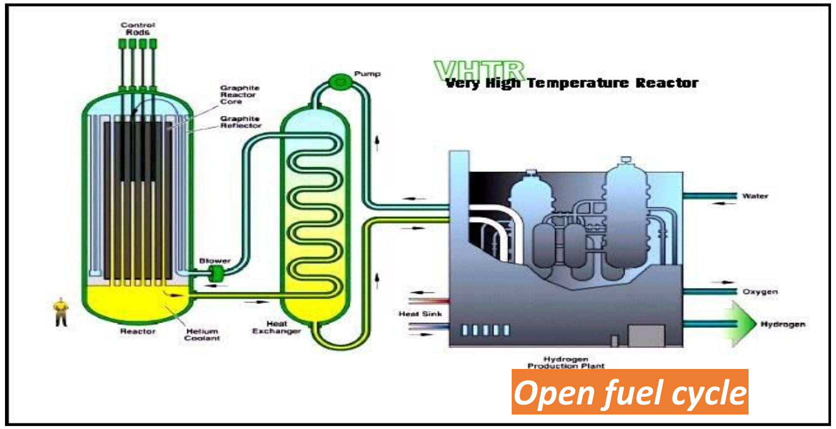
Closed fuel cycle

Lead Fast Reactor



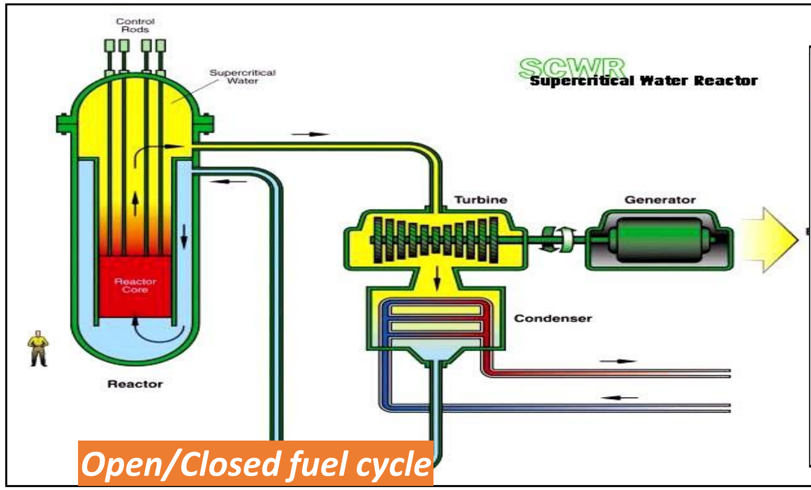
Closed fuel cycle

Gas Fast Reactor



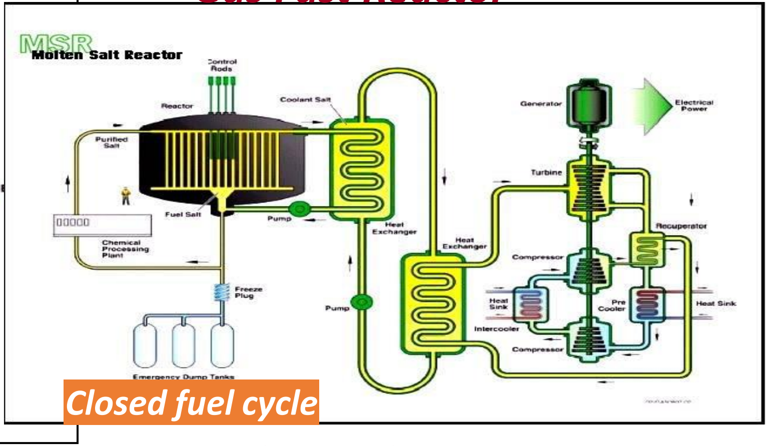
Open fuel cycle

Very High Temperature Reactor



Open/Closed fuel cycle

Super Critical Water Reactor

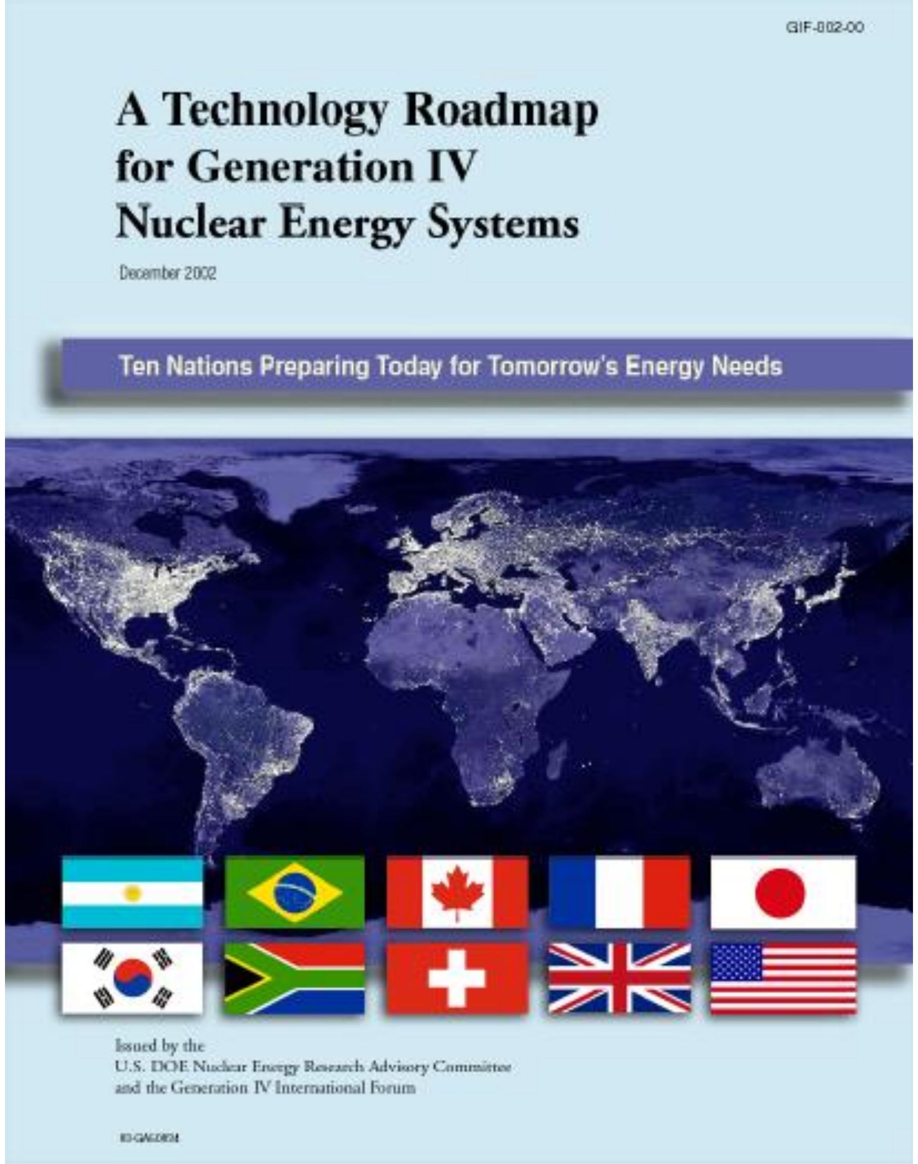


Closed fuel cycle

Molten Salt Reactor

The recognition of the major potential of fast neutron systems with closed fuel cycle for breeding (fissile regeneration) and waste minimization (minor actinide burning)

GIF and a new generation of nuclear systems



GIF-002-00

A Technology Roadmap for Generation IV Nuclear Energy Systems

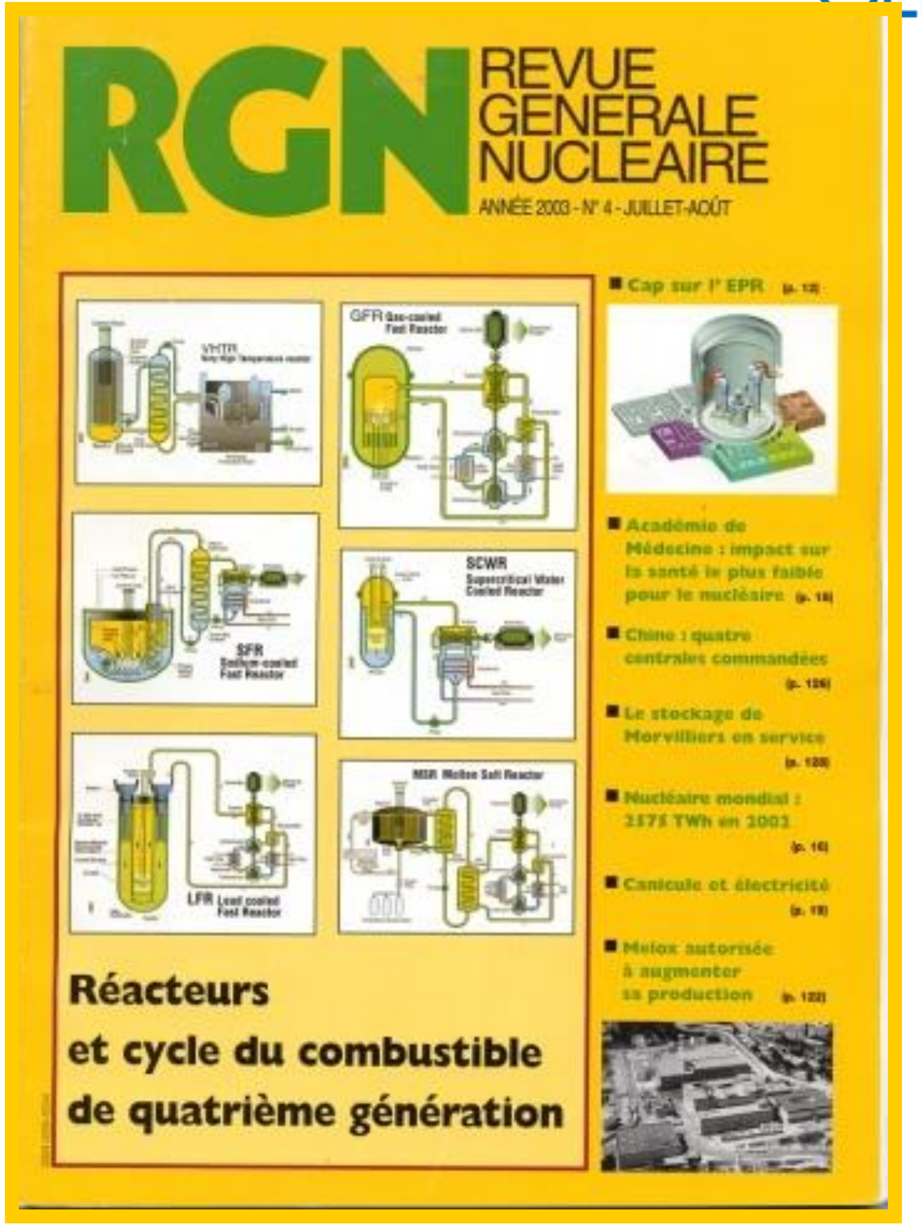
December 2002

Ten Nations Preparing Today for Tomorrow's Energy Needs

Issued by the
U.S. DOE Nuclear Energy Research Advisory Committee
and the Generation IV International Forum

03-GA50034

(GIF-002-OO, Dec 2002)



RGN REVUE GENERALE NUCLEAIRE

ANNÉE 2003 - N° 4 - JUILLET-AOÛT

Réacteurs et cycle du combustible de quatrième génération

- Cap sur l' EPR (p. 12)
- Académie de Médecine : impact sur la santé le plus faible pour le nucléaire (p. 18)
- Chine : quatre centrales commandées (p. 126)
- Le stockage de Morvilliers en service (p. 120)
- Nucléaire mondial : 2575 TWh en 2002 (p. 16)
- Canicule et électricité (p. 19)
- Melox autorisée à augmenter sa production (p. 122)

(RGN, Juily-August 2003)

The nuclear systems selected in Generation IV

GEN IV International Forum℠

General characteristics of Gen IV systems

	SFR	LFR	GFR	VHTR	SCWR	MSR	***PWR***
Neutron spectrum (T/F)	F	F	F	T	T/F?	T/F	*T*
Moderator	[redacted]	[redacted]	[redacted]	graphite	H_2O (or D_2O)	graphite (or none)	H_2O
Coolant	Na	Pb (or Pb-Bi)	He	He	H_2O	molten salt	H_2O
Fuel type	MOX (pins)	nitride (pins)	carbide	carbide (particles)	UOX, MOX	liquid fuel (U, Pu, Th)	*UOX,* *MOX*
Core outlet t° (°C)	550	500	850	> 900	550	700	*330*
Primary pressure (MPa)	0.1	0.3-0.4	7	5-8	25	0.1-0.2	*15.5*
Core power density (MW/m^3)	240	140	100	4-6	100	20-300	*100*

The values given in the table are fairly indicative!

The design of Gen IV systems is ongoing (R&D development work)

Summary and conclusions

- ***GIF is stimulating the innovative design of new nuclear systems taking into account the criteria for long term development of nuclear energy (in particular safety, competitiveness, sustainability, PRPP).***
- ***The fundamentals for nuclear reactor design, Gen IV or not, are criticality (feasibility) and breeding (nuclear fuel utilization).***
- ***FNRs offer strong opportunities for sustainability (fast neutrons). They are best fitted for breeding and transmutation.***
- ***Breeding can be achieved in TNRs but feasibility constraints are strong.***
- ***The webinar was strongly focused on sustainability issues (best use of Unat resources and minimization of HLW nuclear waste). Other important issues were not addressed (safety, competitiveness, PRPP,…).***

You want to know more about Gen IV systems?

Stay on the line with the GIF ETTF webinars series…

UPCOMING WEBINARS

15 December 2016	**Sodium Cooled Fast Reactors**	**Dr. Robert Hill, ANL**
25 January 2017	**Very High Temperature Reactors**	**Mr. Carl Sink, DOE**
22 February 2017	**Gas Cooled Fast Reactors**	**Dr. Alfredo Vasile, CEA**