Materials for nuclear energy

Outline

- Some concepts of nuclear physics
- Working principle and structure of a pressurized water nuclear power plant
- Metallic materials for nuclear energy
- Ageing of fuel assemblies
- Possible future developments

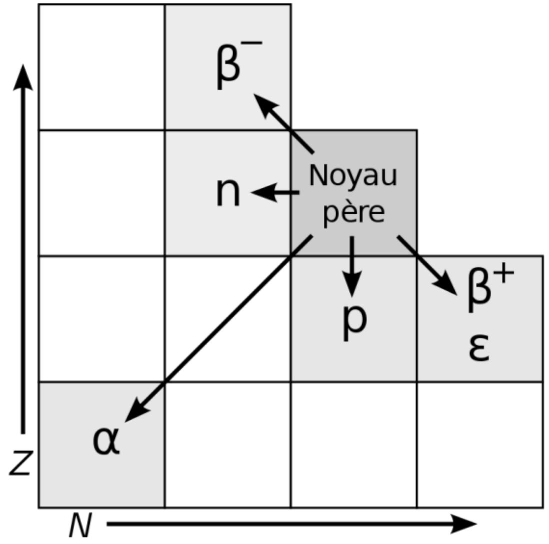
Some concepts of nuclear physics

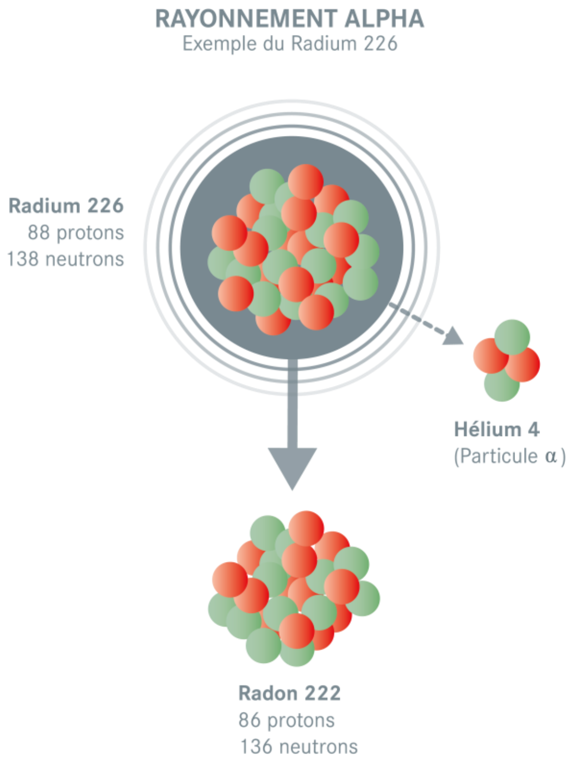
Radioactivity

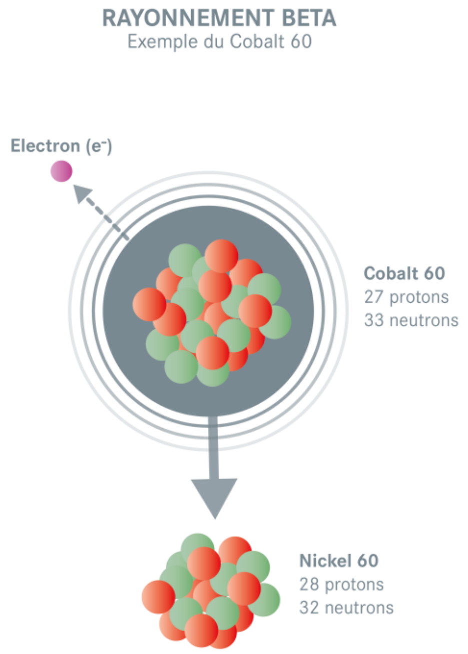
Radioactivity: Physics phenomenon leading tunstable atomic radii (called radionucleides or radio isotopes) to transform into other atoms (desintegration) while emitting paticles of matter (electrons, helium nuclei, neutrons, …) and NRJ (photons, kinetic)

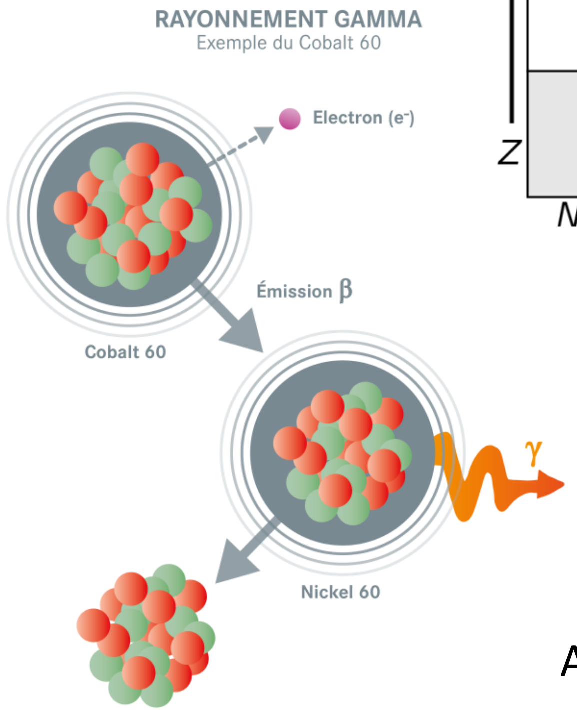
Desintégrations and radiations

Different desintegration modes (wikipedia)









ANDRA

Too many protons and neutrons

⇒ Emission of Helium 4 (α)

Travels few cm in air

Stopped by a sheath of paper

Too large difference in protons and neutrons numbers

⇒ Proton -> neutron + e^- capture (β^+)

or Neutron -> proton + e^- emission (β^-)

Travels few m in air

Stopped by an aluminum sheath

The atom has too much NRJ

⇒ Emission of a photon of high energy (γ)

Can travel several 100 m in air

Stopped by a large thickness of lead, concrete, …

Radioactivity

https://laradioactivite.com/le-phenomene/lavalleedestabilite

Fission

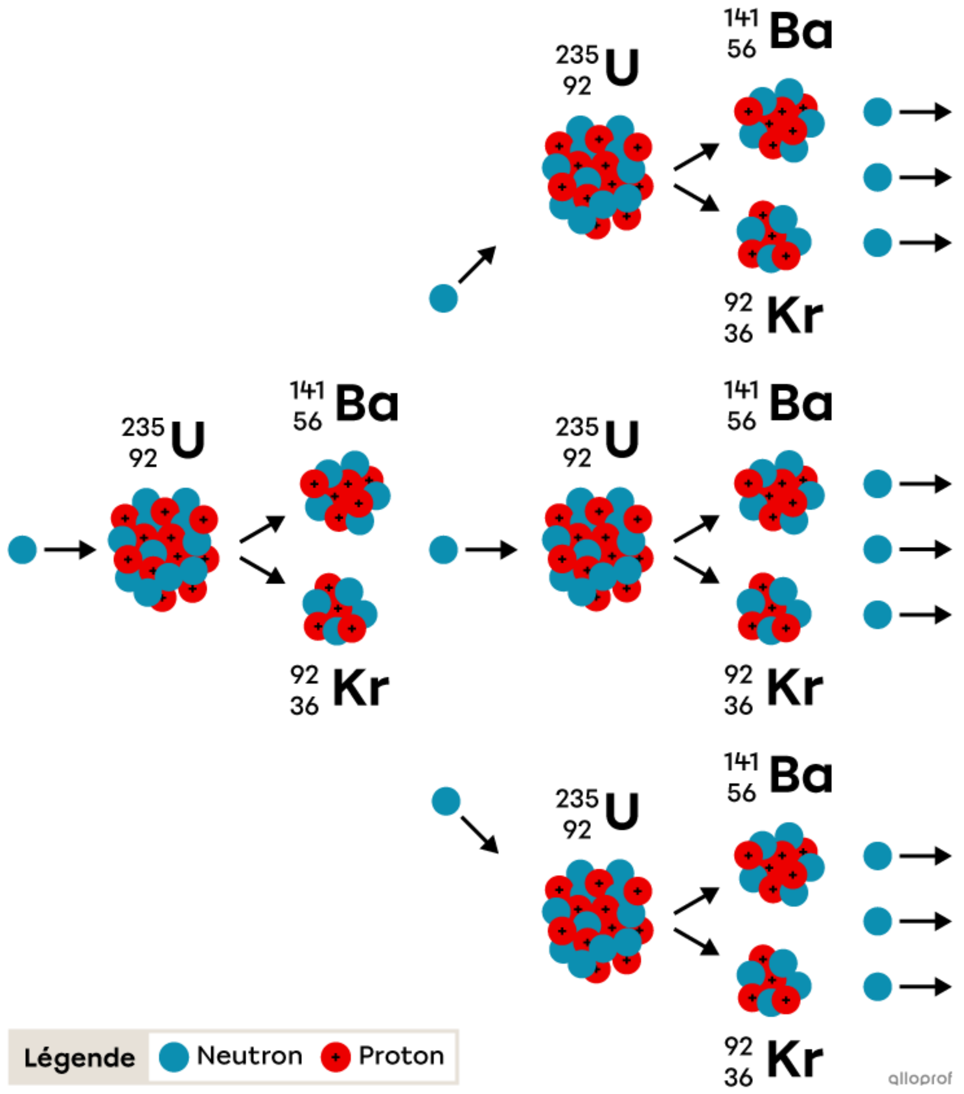
Spontaneous fission: some very heavy isotopes have too much NRJ and their nucleaus breaks apart into at least two lighter nuclei without the need of external NRJ.

Nuclear fission: this fission reaction requires the input of external energy to the nucleus in the form of neutrons or other particles. **Used in nuclear power plants**

Spontaneous and nuclear fission reactions produce neutrons and can induce self-sustained reaction (also called chain reaction) if a critical mass of the radioactive element is available.

Criticity and chain reaction

The desintegration of a fissile nucleus is accompanied by emission of neutrons, ionizing radiations and large heat emission (**harvested and transformed in nuclear power plant**).



Criticity

1st raaction between 1 radioactive atom and 1 neutron
=> Lighter nuclei + several neutrons

On average, only 1 of the emitted neutrons produces a new fission reaction
=> The reaction is self-sustained and stable

Chain reaction

1st raaction between 1 radioactive atom and 1 neutron
=> Lighter nuclei + several neutrons

On average, more than 1 of the emitted neutrons produce new fission reaction
=> The reaction runs away

Nuclear fission reaction

Main nuclear fission reactions used

$$({}^{235}_{92}U \text{ or } {}^{239}_{94}Pu) + {}^{1}_{0}n \rightarrow PF_1^* + PF_2^* + x\,{}^{1}_{0}n$$

170 MeV

2 MeV

200 MeV d'NRJ emitted

$PF_1^*\ et\ PF_2^*$: Excited fission products
x : average number of neutrons emitted
2,46 for ^{235}U and 2,88 for ^{239}Pu

- Kinetic energy transferred to PF and thermally dissipated

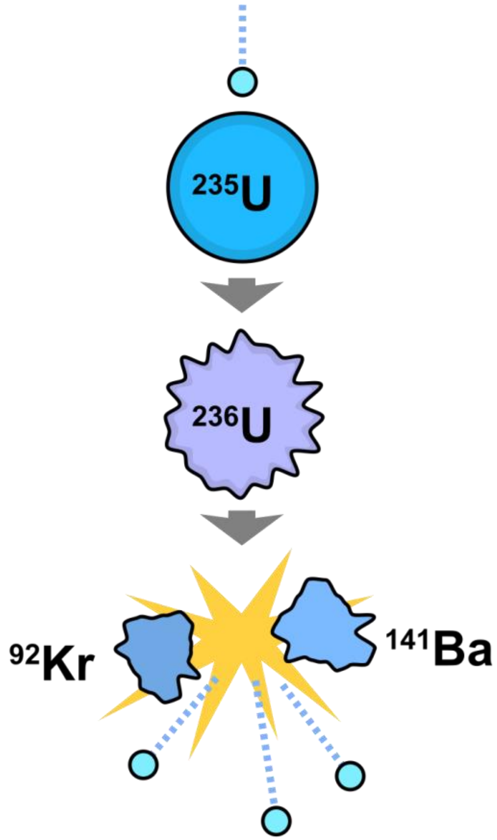
(e.g. the temperature of earth mantle or increase in temperature of nuclear fuel in a nuclear power plant)

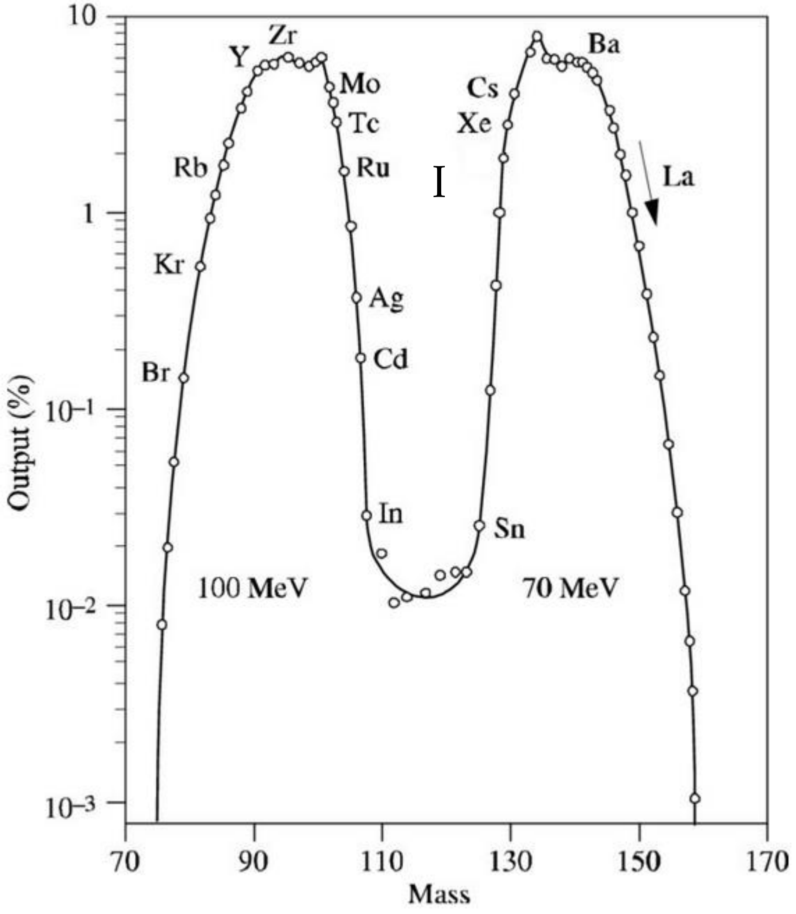
- Kinetic energy transferred to neutrons => eventual new fission reaction

(self-sustained reaction)

Distribution of fission products

Exemple of uranium 235





C. Lemaignan, J.C. Niepce, In Ceramic Materials (2007), Wiley

The result of a fission reaction is unknown a priori. A large number of combinations is possible
Statstically, the reactions produce a large number of fission products => wastes

Uranium

Tableau 1 : Les isotopes de l'uranium

Isotope	Pourcentage de l'uranium naturel (en masse)		Pourcentage de l'uranium naturel (en radioactivité)	Demi-vie
Uranium 238 (U-238)	99,284	Fertile	47,9	4,46 milliards d'années
Uranium 235 (U-235)	0,711	Fissile	2,3	704 millions d'années
Uranium 234 (U-234)	0,0055	Fissile	49,8	245 000 ans

Current reactors (2^{nd} generation REP or REB) work essentially with Unrainum enriched with 3 to 5% ^{235}U

Fissile vs fertile isotopes

^{235}**U** is a **fissile** isotope of uranium :
Its **desintégration is directe following the interaction of a neutron**, for instance

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

It is the main reaction in use in current REB and REP reactors

^{238}**U** is a **fertile** isotope of uranium :
Its **desintégration is indirect through the formation of ^{239}Pu (fissile)**

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U \Rightarrow ^{239}_{92}U + \beta^{-} \rightarrow ^{239}_{93}Np + e^{-} \Rightarrow ^{239}_{93}Np + \beta^{-} \rightarrow ^{239}_{94}Pu + e^{-}$$

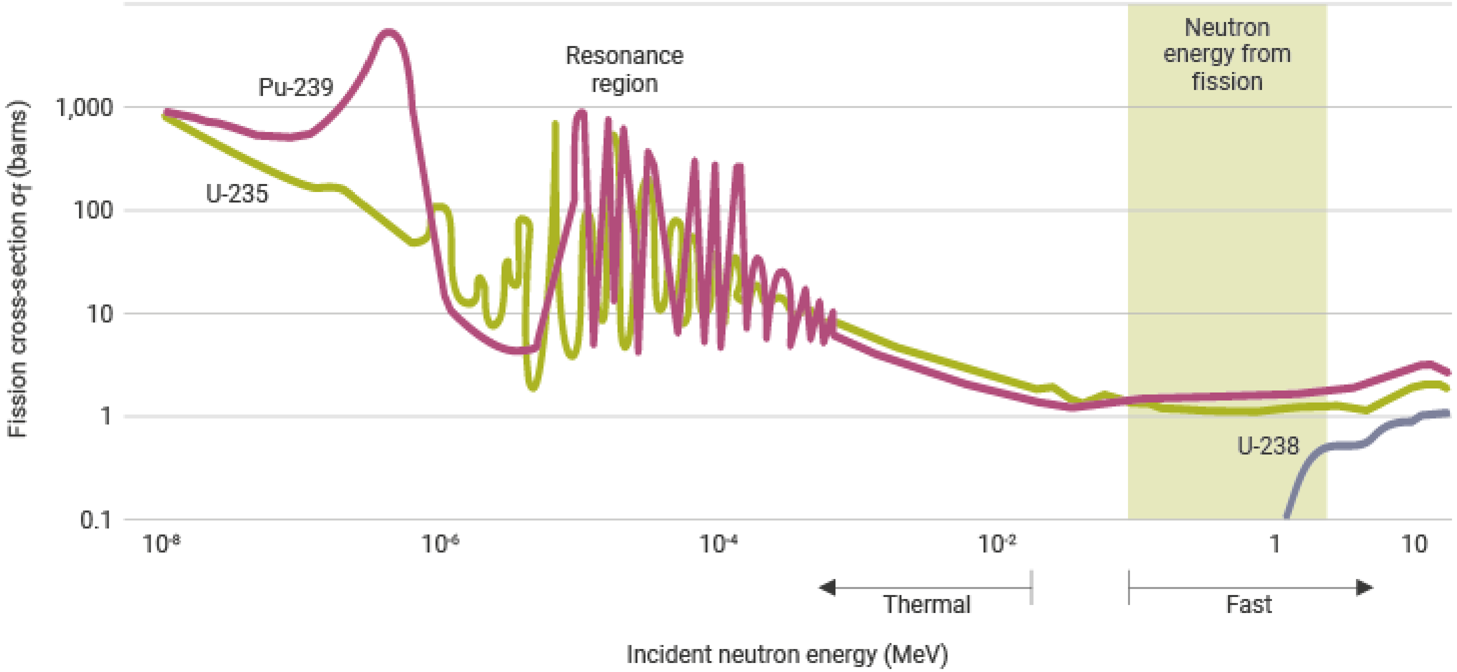
$$^{239}_{94}Pu + ^{1}_{0}n \rightarrow ^{134}_{54}Xe + ^{103}_{40}Zr + 3^{1}_{0}n$$

In current reactors **plutonium 239 is formed from uranium 238** : part of it experience fission reaction (~1/3 of the thermal NRJ produced in french nuclear power plants), the remaining (~2/3 is part of nuclear wastes)

Fission cross section and neutron NRJ

Thermal neutrons
Thermal neutrons reactors
(2nd and 3rd generations)

Fast neutrons
Fast nentrons reactors
(some projets for 4th generation)



Note that both scales are logarithmic.
Source: NEA, Plutonium fuel – an assessment (1989); Taube, Plutonium – a general survey (1974)
1 barn = 10^{-28} m², 1 MeV = 1.6 x 10^{-13} J

Fissile nuclei
The fission reaction can occur for all neutron NRJ values
^{235}U, ^{233}U, ^{239}Pu, ^{241}Pu

Fertile nuclei
The fission reaction requires fast neutrons
^{232}Th, ^{238}U, ^{240}Pu

- For the fission of ^{235}U and ^{239}Pu : It is needed to slow down the neutrons (2 MeV => 0,025 eV) to increase the fission cross section (see log scale in the figure) => **Use of a moderator (water)**
- Fission of ^{238}U requires fast neutrons (MOX fuel and future generators)

Radiations observed in nuclear power plants

<u>Nuclear installations are subject to various fluxes:</u>

- **Photons emitted from γ decay**

Strong penetration, concerns all installations

- **Electrons**

From β- desintagrations or induced by γ photons

- **Neutrons from fission reactions**

In the core of reactors

- **α particles**
- **Heavy and energetic ions (fission products)**

Types of reactions induced by radiations

Types of reactions with important impact on materials properties

$N_1(p_1, p_2)\,N_2$

N_1 impacted nucleus
p_1 incident particle
N_2 impacting nucleus
p_2 emitted particle

- N_1 (n,α) N_2 reactions

Induce internal doping in Hélium

- N_1 (n,γ) N_2 correspond to the capture of a neutron

Useful to control the nuclear reaction

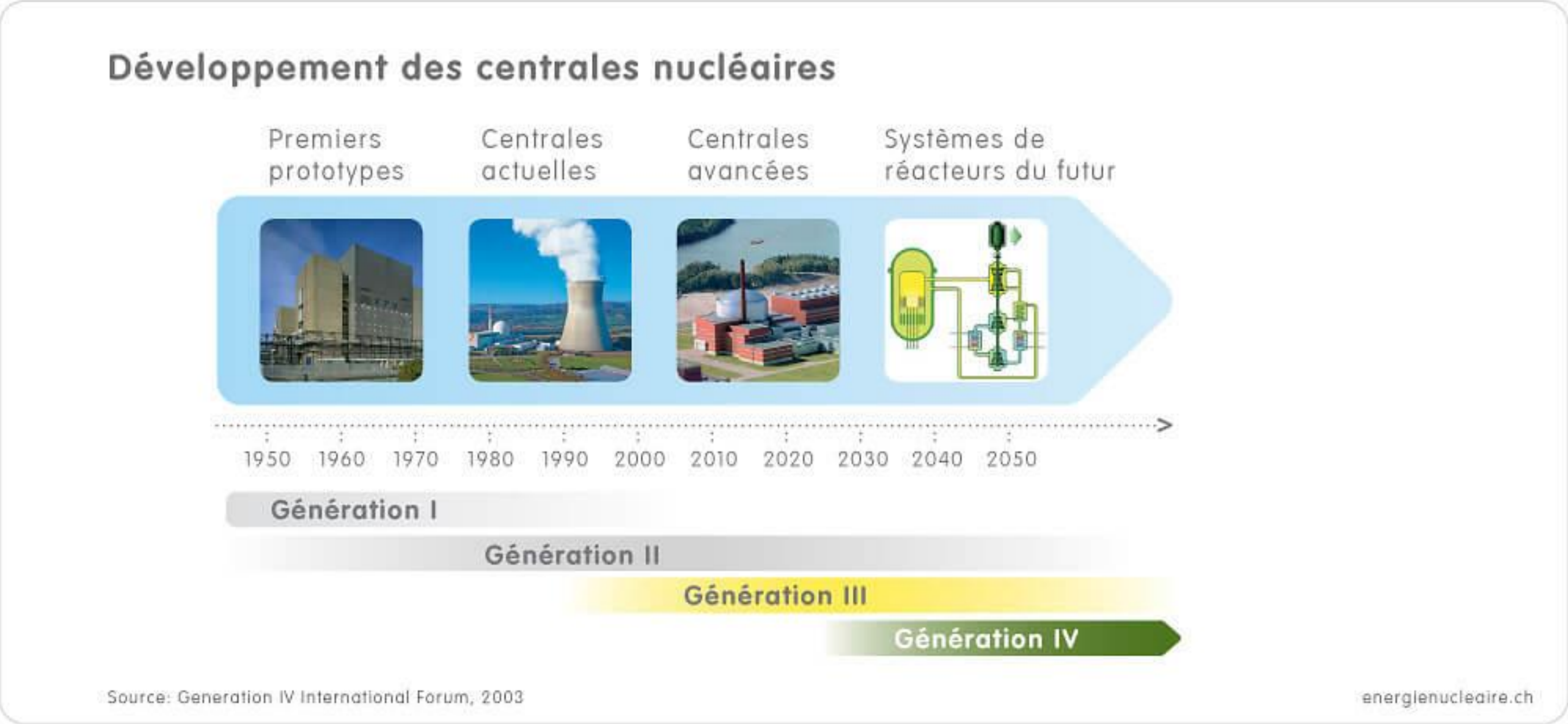
- N_1 (n,f) N_2 reactions correspond to fission reactions

Produce neutrons and new nuclei (fission products)

Fission products strongly modify the chemistry of the nuclear fuel

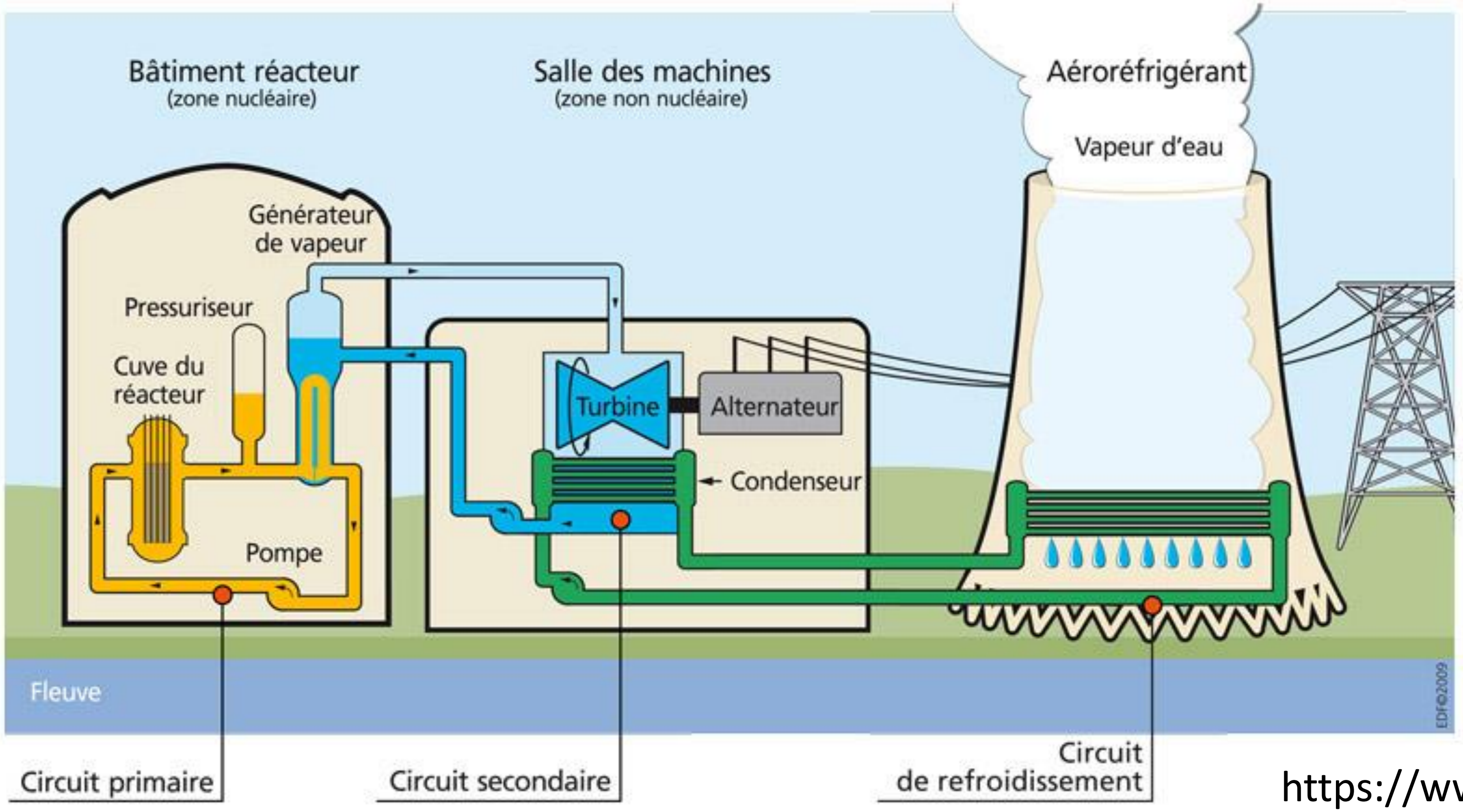
Working principle and structure of a nuclear power plant

Generations of nuclear reactors



Working principle of 2nd generation nuclear power plants

Pressurized water reactors (REP)
Water is fed into the reactor at ~295°C and exits at~325°C (~155 bar, 15,5 MPa), efficiency ~33%

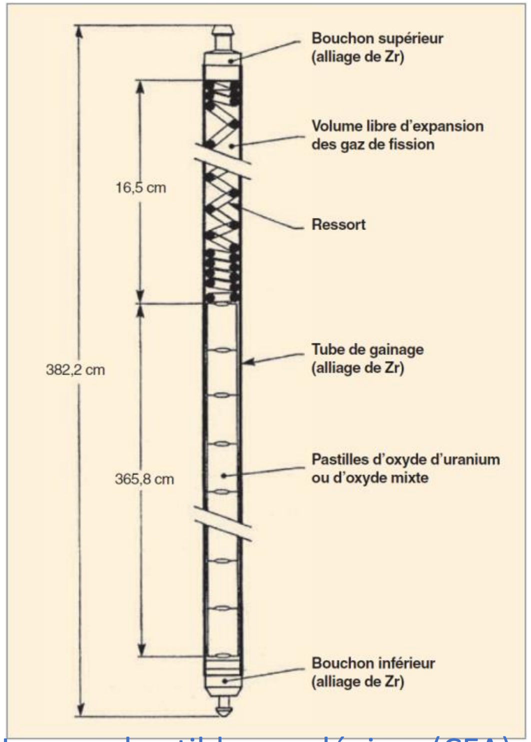


https://www.irsn.fr/

Internal elements and reactor tank are submitted to temperature, pressure and radiations

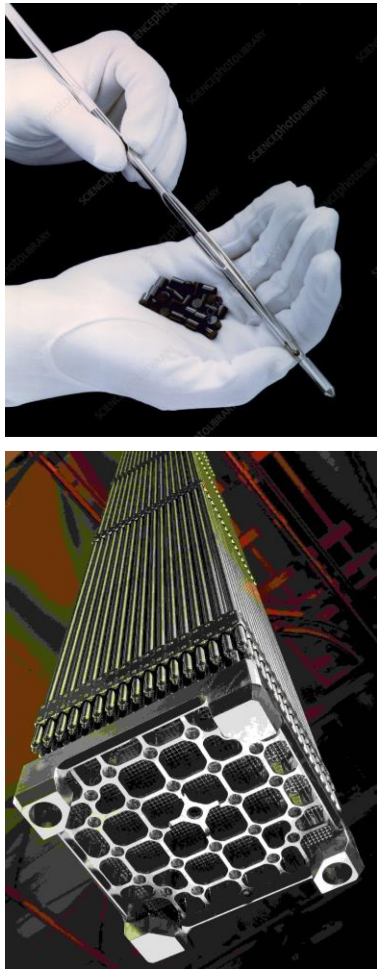
Working principle of 2nd generation nuclear power plants

Fuel rod
(25 bar He)

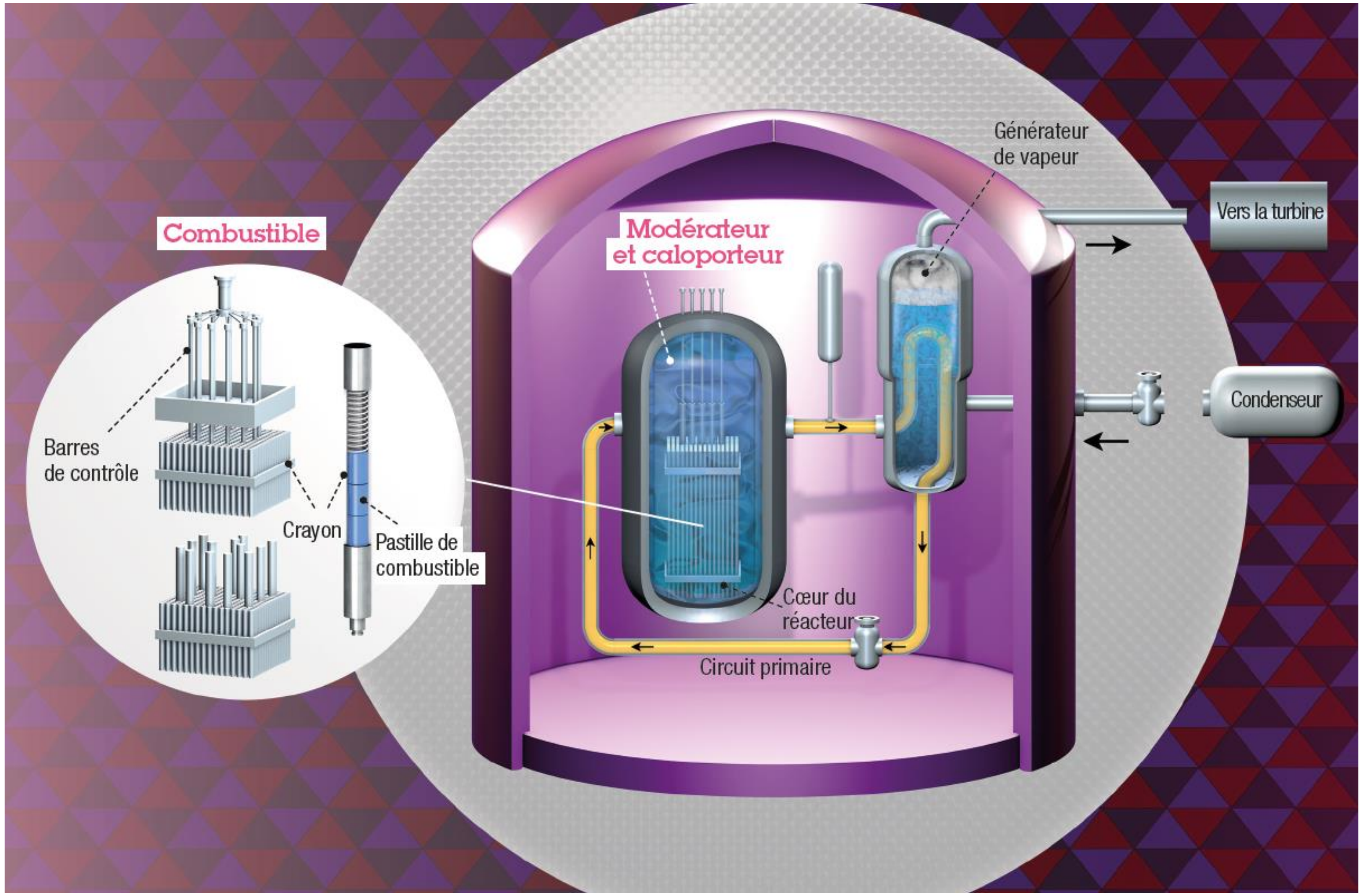


Les combustibles nucléaires (CEA)

Pressurized water reactor (~325°C, ~155 bar)



Assembly →



Filières et générations de réacteurs nucléaires (CEA)

Fuel = Uranium oxide UO_2 pellets or mixed oxide (MOX : UO_2 + PuO_2) pellets in a zirconium alloy rod (nuclear fuel sheath)
Control bars = neutron absorbers (e.g. : alloys containing B, Ag, In, Cd …)

Metallic materials for nuclear energy

Metallic materials for nuclear energy

Challenges

- Need to master materials that are little known
- Need to master new phnomena

=> Develop a materials science specific to nuclear energy

Chellenges

The nuclear fuel sheath and the reactor tank are safety barriers whose the operator have to demonstrate the suitability for service

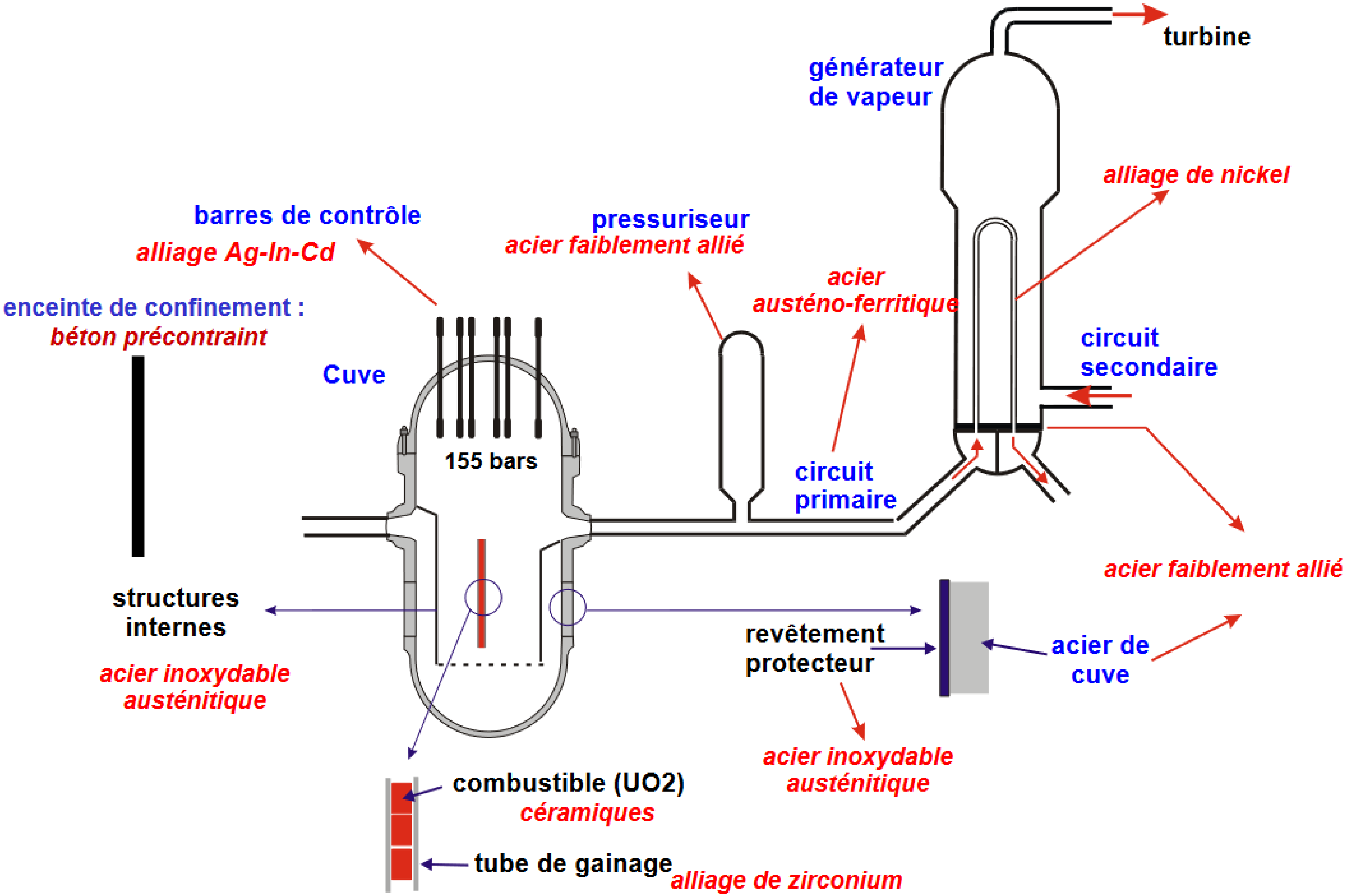
- Propose new materials for nuclear fuel sheath and increase the combustion rate(considerable economical challenge)
- The reactor tank cannot be replaced. The degradation of tank material properties determine the reactor end of use

The remplacement of consumables materials (e.g. heat exchanger pipes) affects the availability of the reactor

Metallic materials for nuclear energy

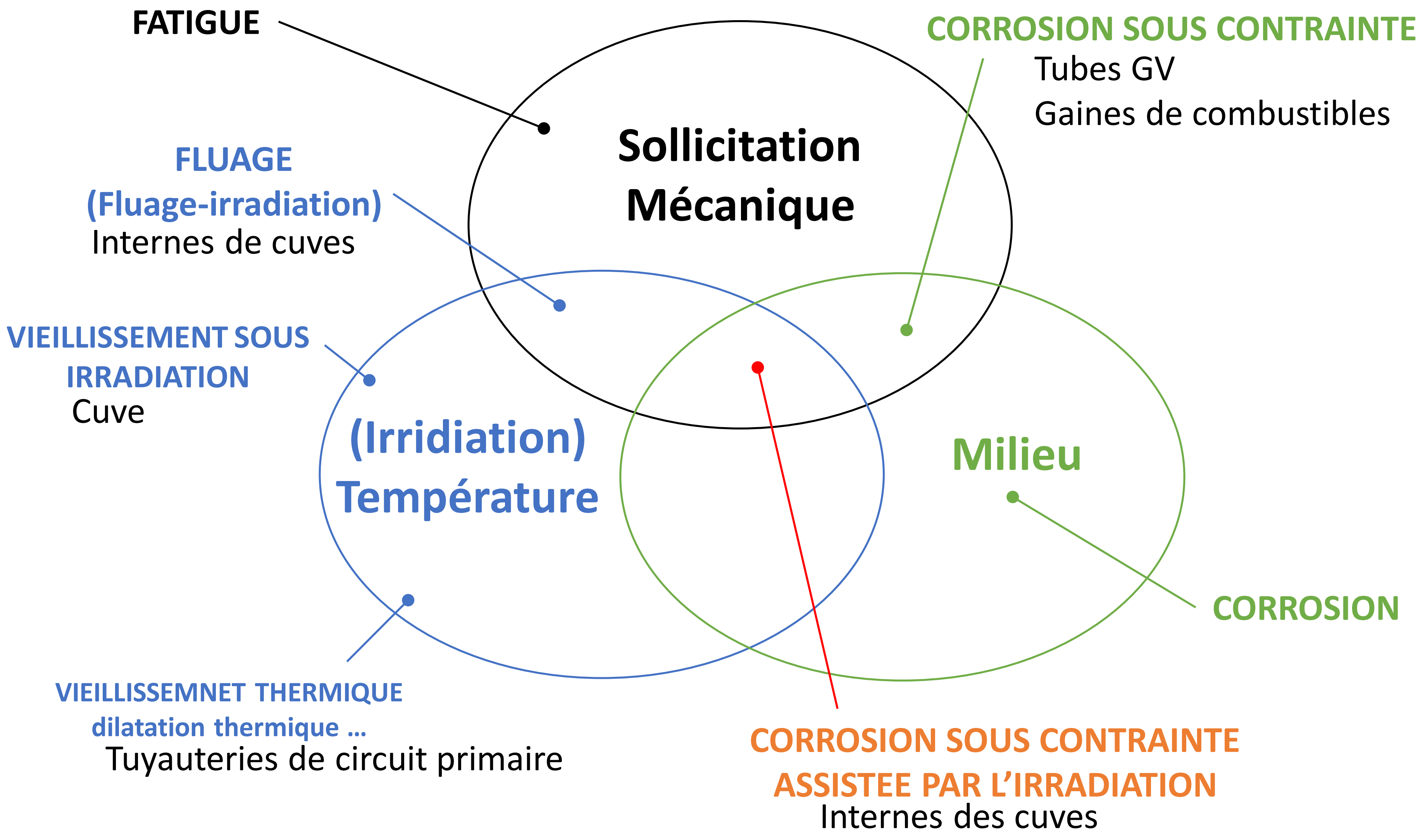
Overview

- aciers faiblement alliés
- aciers inoxydables
- alliages base nickel
- alliages de zirconium
- alliages divers (Ag-In-Cd)
- céramique (UO_2-PuO_2)
- matériaux cimentaires



Source "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste

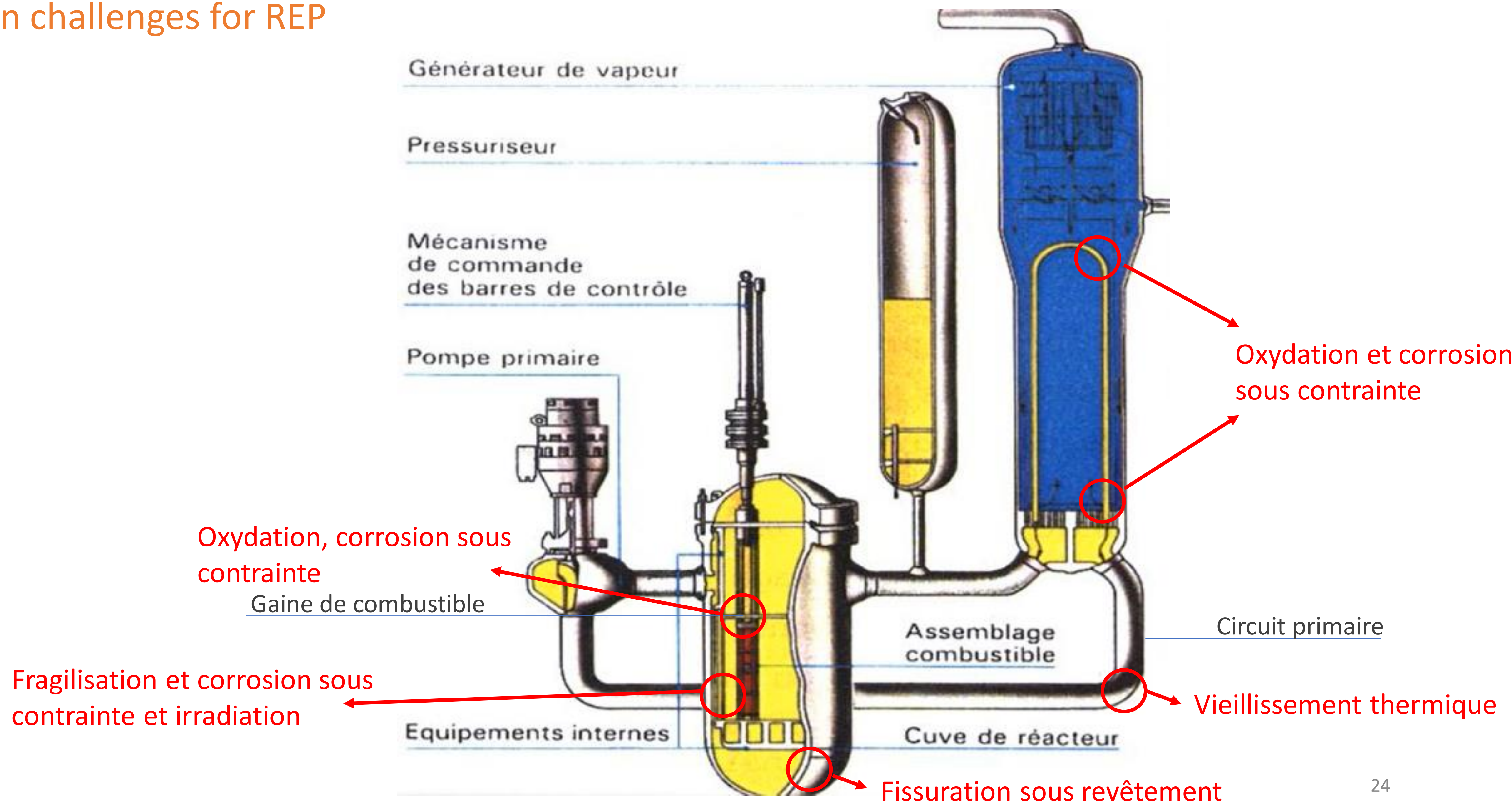
Metallic materials for nuclear energy
Sollicitations



Adapté de "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste

Metallic materials for nuclear energy

Main challenges for REP

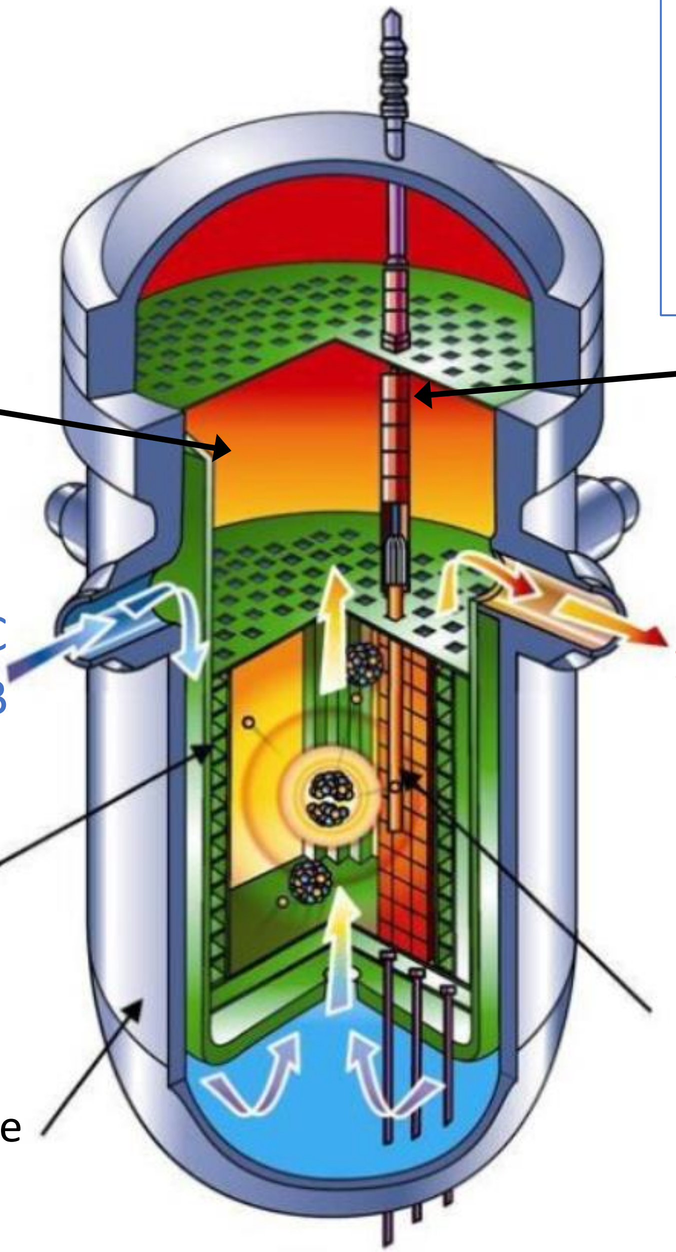


Materials for core and tank

Overview

Irradiation de la cuve ~ 2 10^{22} n $m^{-2}an^{-1}$
Irradiation des internes de cœur ~ 1,25 10^{25} n $m^{-2}an^{-1}$
Densité atomique surfacique~10^{19} at.m^{-2}

➡ Les conséquences de l'irradiation se quantifient en "déplacements par atome" (dpa)



Internes supérieurs

Alliages de nickel
Conditions : ~320°C, qq 0,1 dpa
Durée de vie : 40 => 60 ans

Barres de commandes (control bars)

Acier austénitique
Conditions : ~320°C, ~10 dpa
Durée de vie : qq années

155 bars, 293°C
Eau, H_2, LiOH, B

155 bars, 328°C

Internes de cœur

Acier austénitique
Conditions : 300-380°C, 30-120 dpa
Durée de vie : 40 => 60 ans

Gaine d'assemblage de combustible (Nuclear fuel sheath)

Alliages de Zr
Conditions : 320-400°C, 90 Mpa, 5 dpa
Durée de vie : 5-6 ans

Cuve (Tank)

Acier bainitique revêtu en face interne
Conditions : ~290°C, 15 Mpa, 0,1 dpa
Durée de vie : 40 => 60 ans

Adapté de "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste et Thèse P. Lapouge

Reactor tank – Materials, fabrication, challenges

Composant - Fonction - Remplaçable	Alliages	Composition chimique État métallurgique	Conditions de service (nominales)
Cuve - Barrière de sûreté - Non remplaçable	Acier faiblement allié	- Fe-Mn-Ni (Cu-P) Bainitique revenu	- 150 bars - 290 °C - 0,2 dpa (à 60 ans)

2nd confinment barrier (1st is the sheath, 3rd is the containment building)
Heigth ~13 m, width ~4 m, thickness~200 mm, wigth ~330 tons

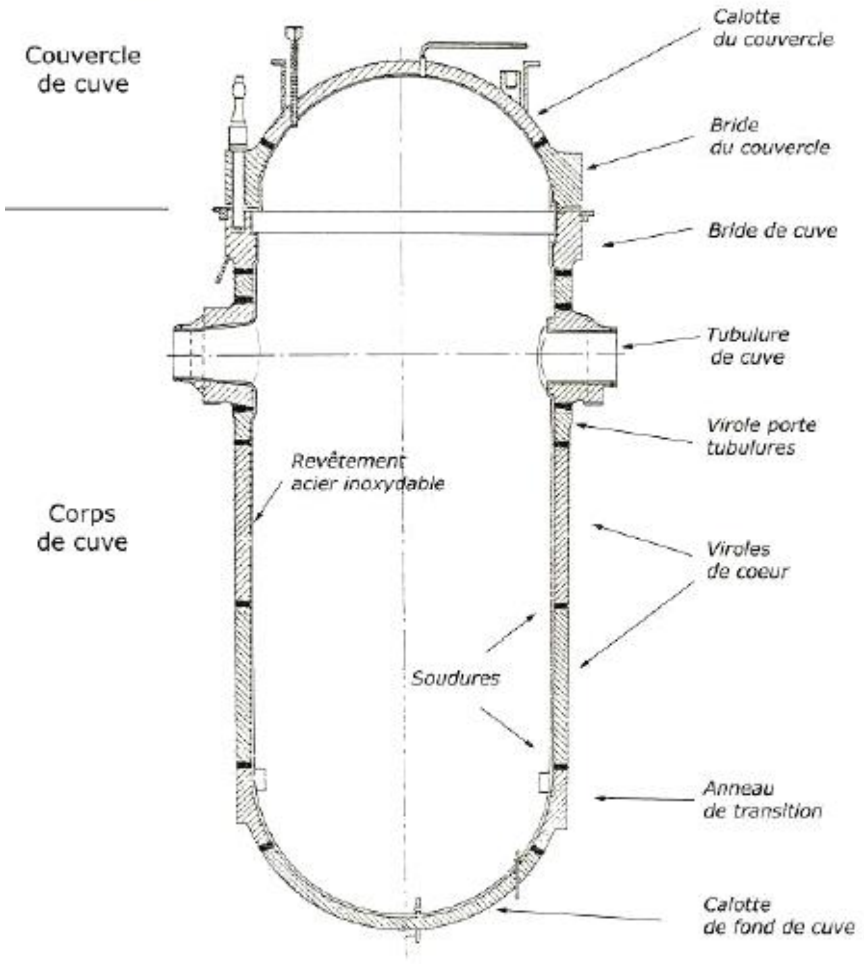
Material :

16 MND5 low alloyed steel

Eléments d'addition (w%)						Impuretés (w%)	
Mo	Mn	Ni	Cr	Si	C	P	Cu
0,5	1,4	0,6	0,15	0,3	0,15	0,008	0,08

- Good thermal conductivity
- Very good weldability
- Good resistance to radiations
- Low cost
- But poor resistance to corrosion

Selection criteria



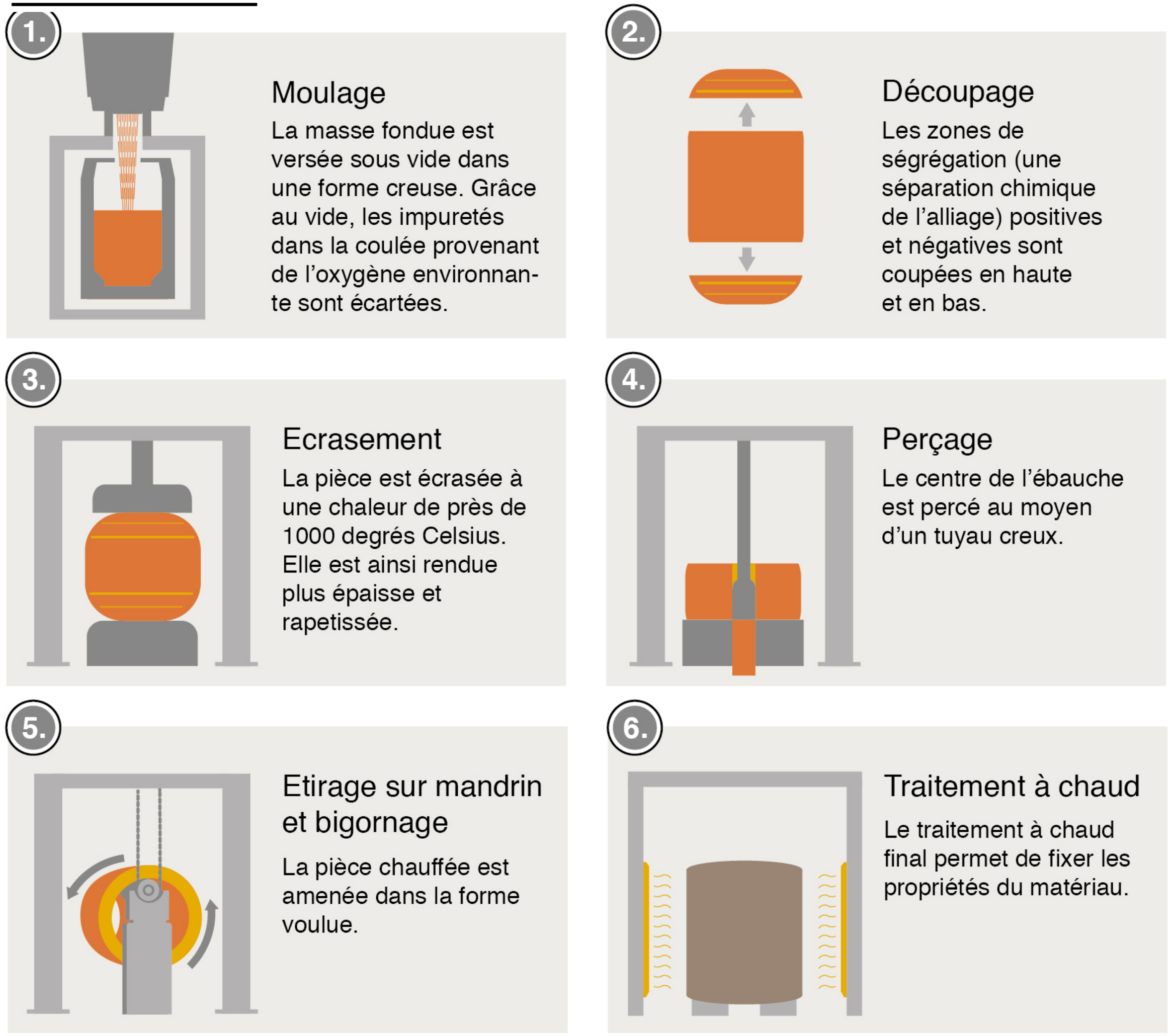
Cuve de réacteur 1300 MWe

Source IRSN

Reactor tank – Materials, fabrication, challenges

VIROLE DE LA CUVE DE PRESSION DU RÉACTEUR

Fabrication



Graphique: KEYSTONE, source: IFSN

Origin of segregations
https://www.youtube.com/watch?v=eH3YX4L7uKo&t=60s

Thermal treatment:

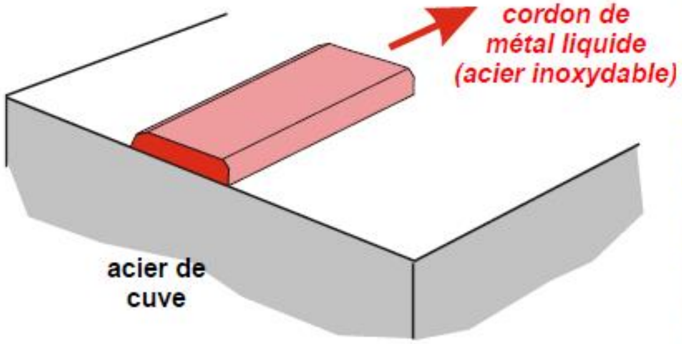
- Quenching followed by annealing (650°C)
- ➢ ferrito-perlitic microstructure
- Reheating in 200-350°C range to
- ➢ Relaxation des contraintes

Reactor tank – Materials, fabrication, challenges

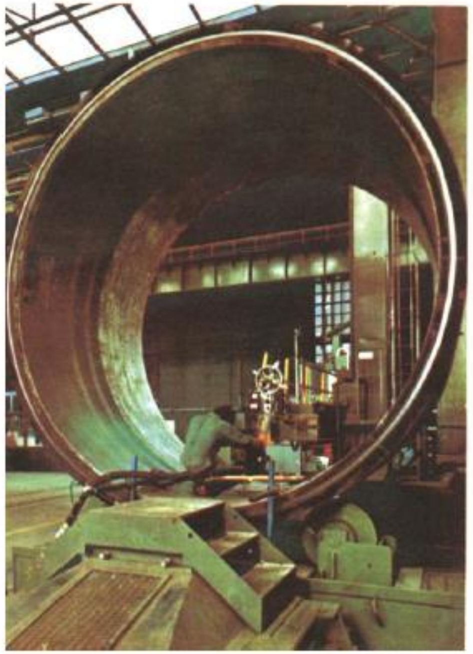
○ Poor resistance to corrosion

⇨ Coating of the inner wall by stainless steel layers

Coating of the 1st layer



Dépôt du revêtement par bandes successives par fusion à partir d'un ruban métallique



Revêtement de la surface interne d 'une virole en acier inoxydable (« beurrage »)

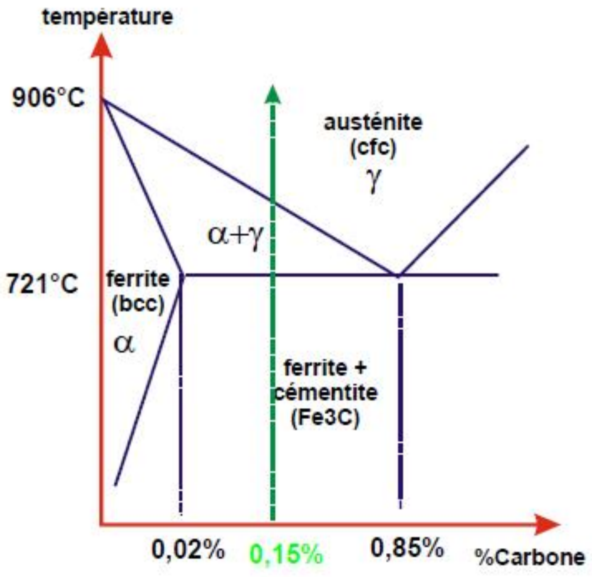
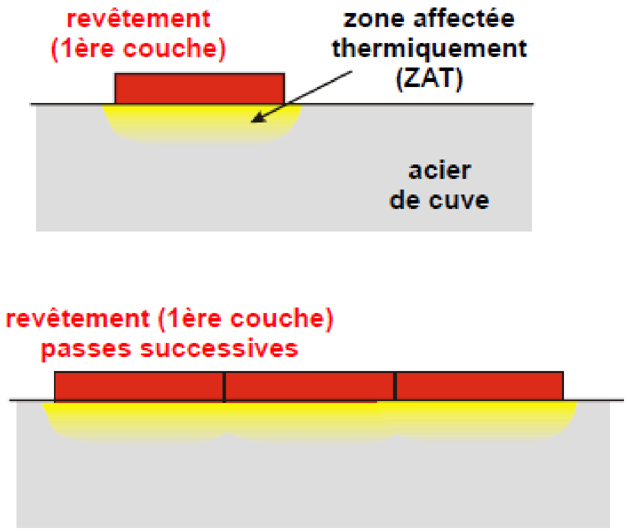


Diagramme de phases des aciers Fe-C

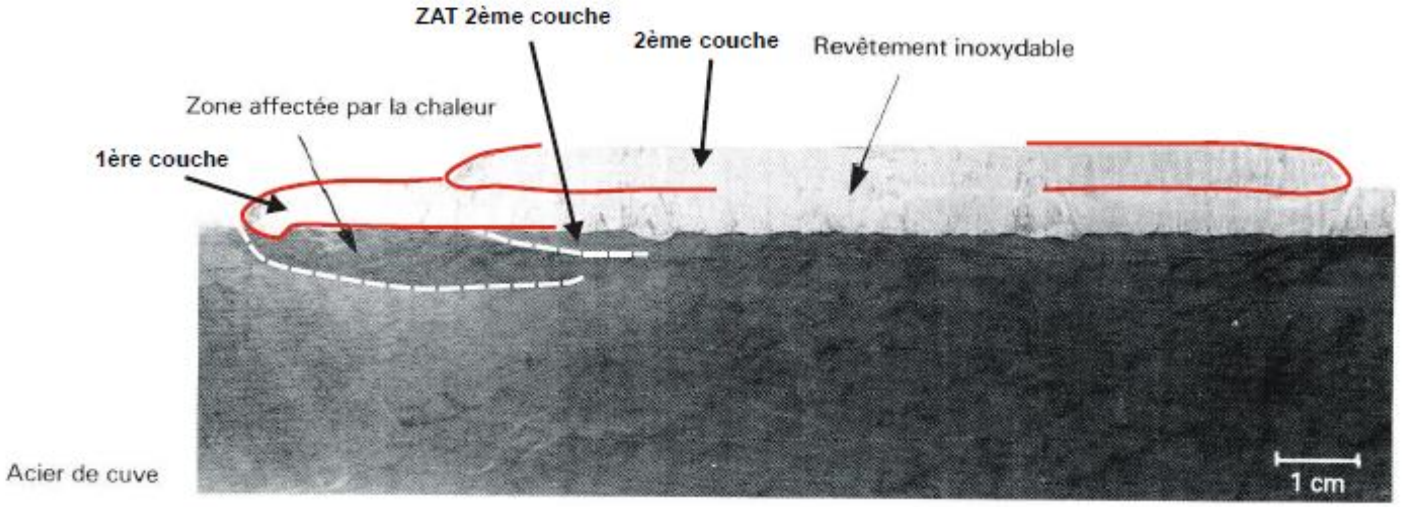


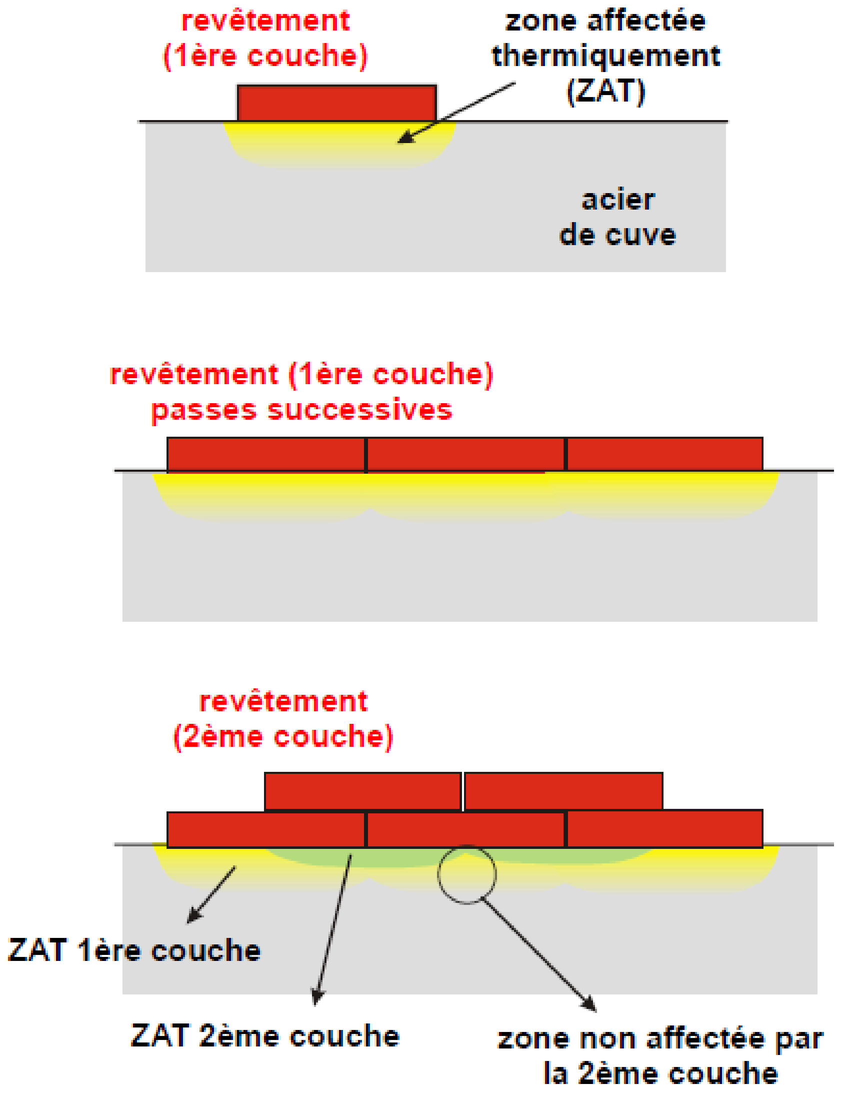
<u>During coating, the increase in base alloy temperature</u> is high enough to induce the ferrite => austenite transformation and grain growthin the thermally-affected zone (ZAT)

During cooling, the reverse transformation occurs (austenite => ferrite) with remaining large grains and strong segregations

Source "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste et Thèse P. Lapouge

Coating of 2nd layer





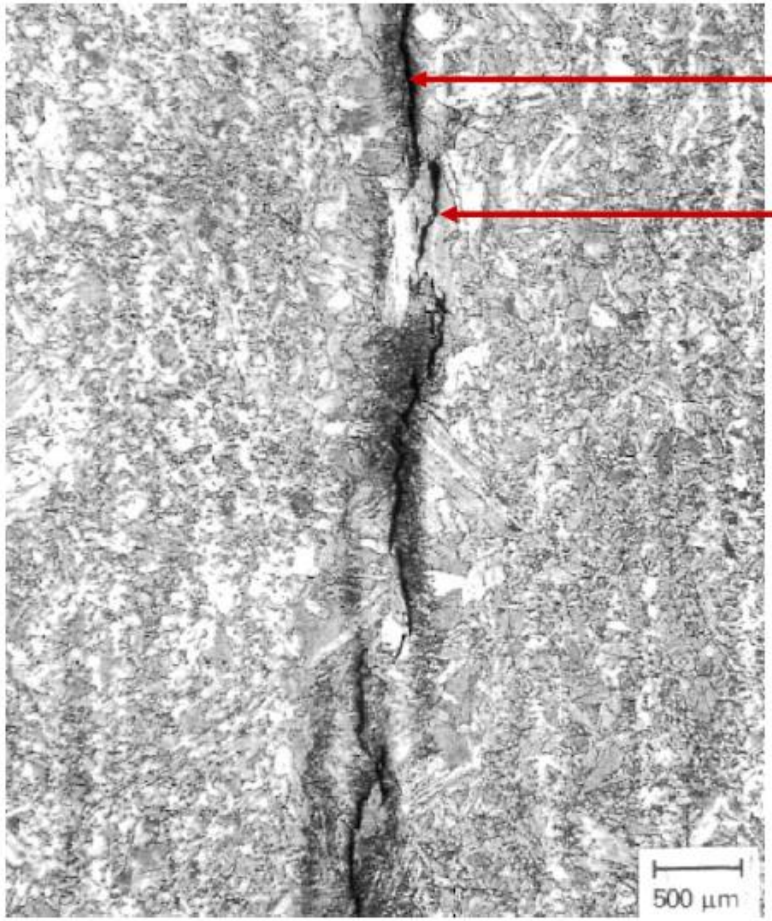
Lower temerature of the base alloy :

- No long time in the austenitic phase, grains are refined and segregations are reduced in the ZAT of the 2nd coating layer
- Nevertheless, a non-regenerated zone remains and induces a risk of crack initiation

Source "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste et Thèse P. Lapouge

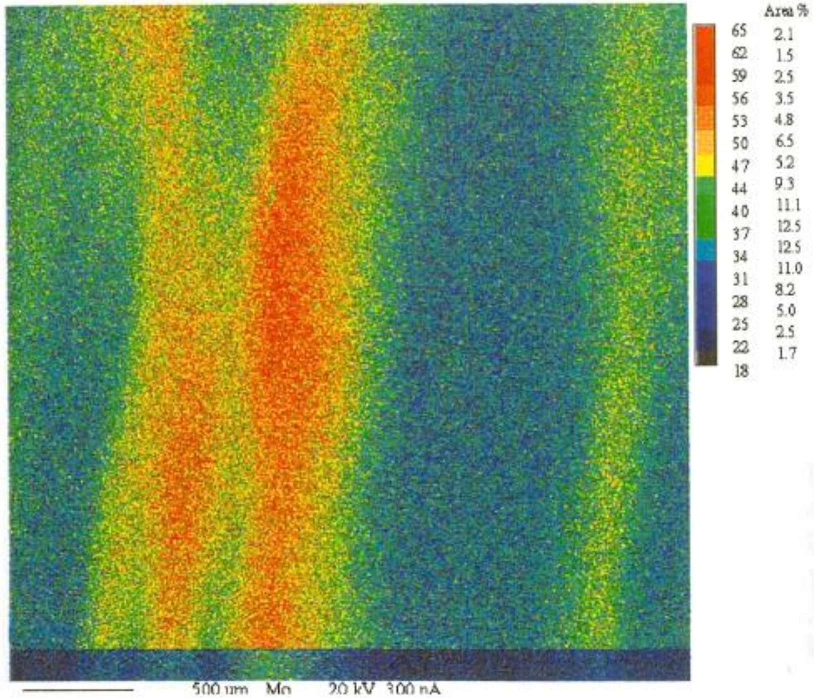
Reactor tank – Materials, fabrication, challenges

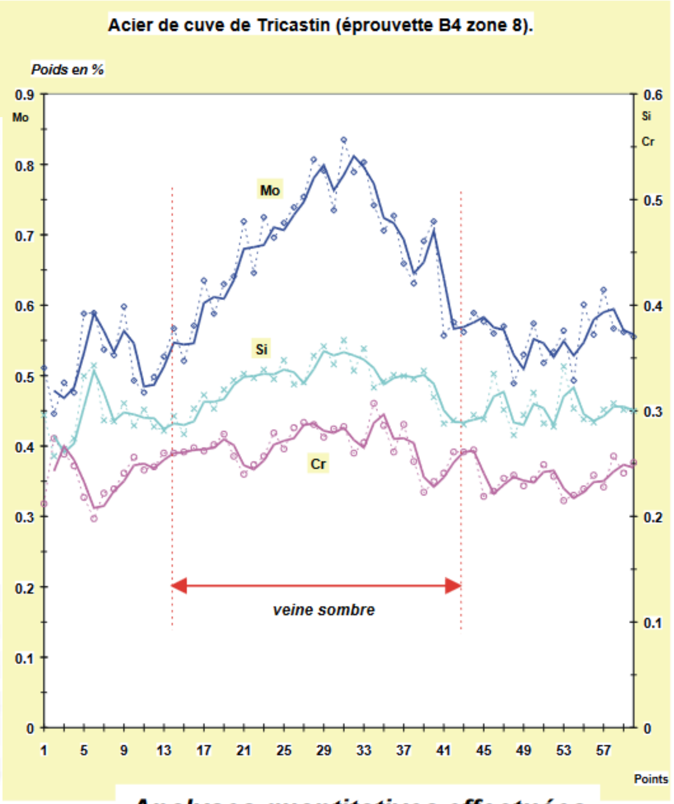
Crack under stainless steel coating layers



Veine sombre (« ghost lines »)

fissure





Analyses quantitatives effectuées par microanalyse X par sonde électronique, en traversée d 'une veine sombre

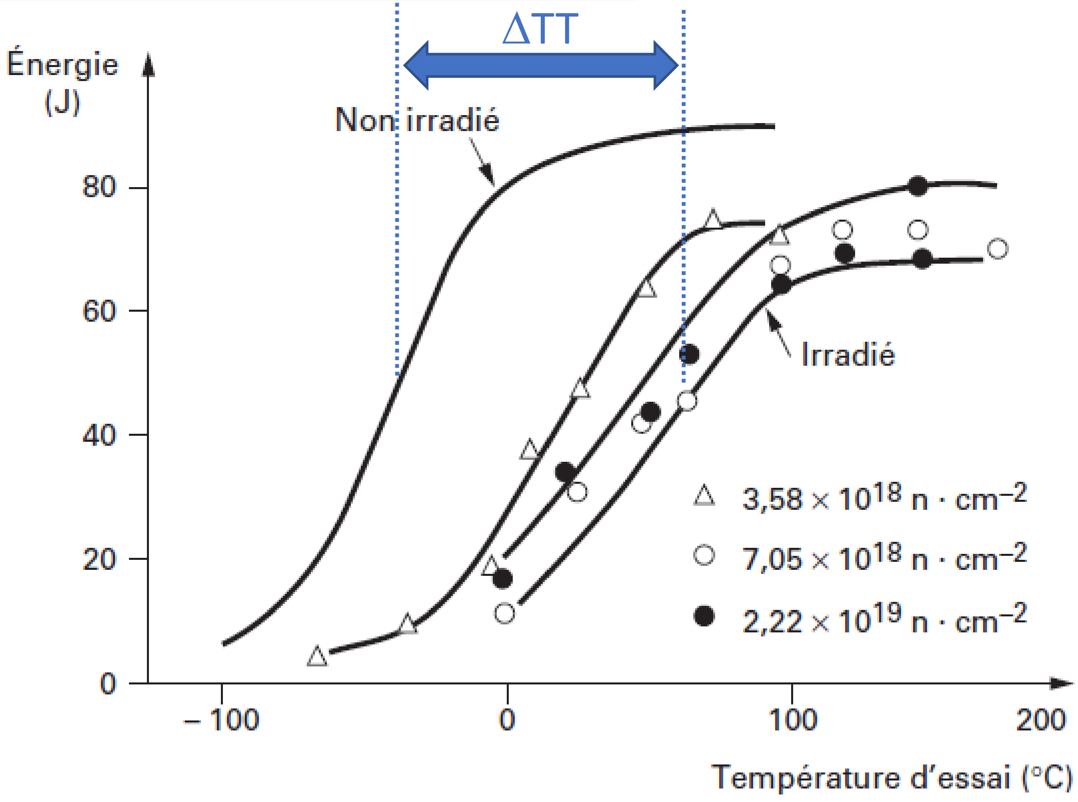
Ghost lines are (too) enriched in alloying elements and can be enbrittled => Cracks are observed when these zones coincide with non regenerated zones

It is needed to optimize the coating strategy in order to minimize segregation and ease regeneration

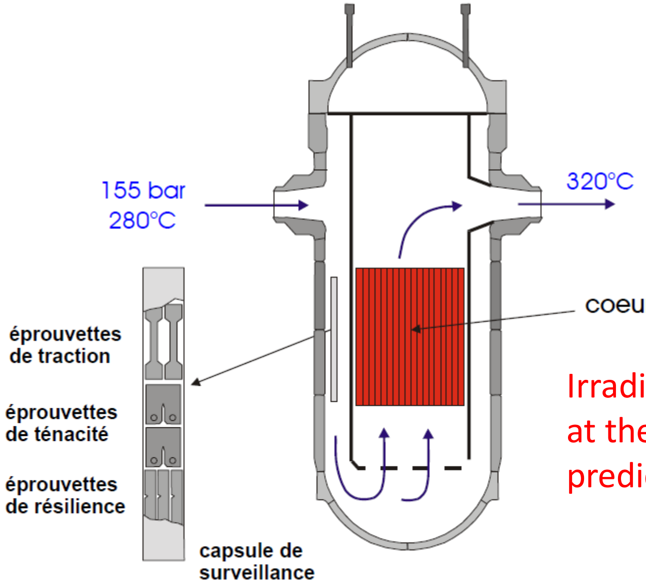
Source "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste et Thèse P. Lapouge

Reactor tank – Materials, fabrication, challenges

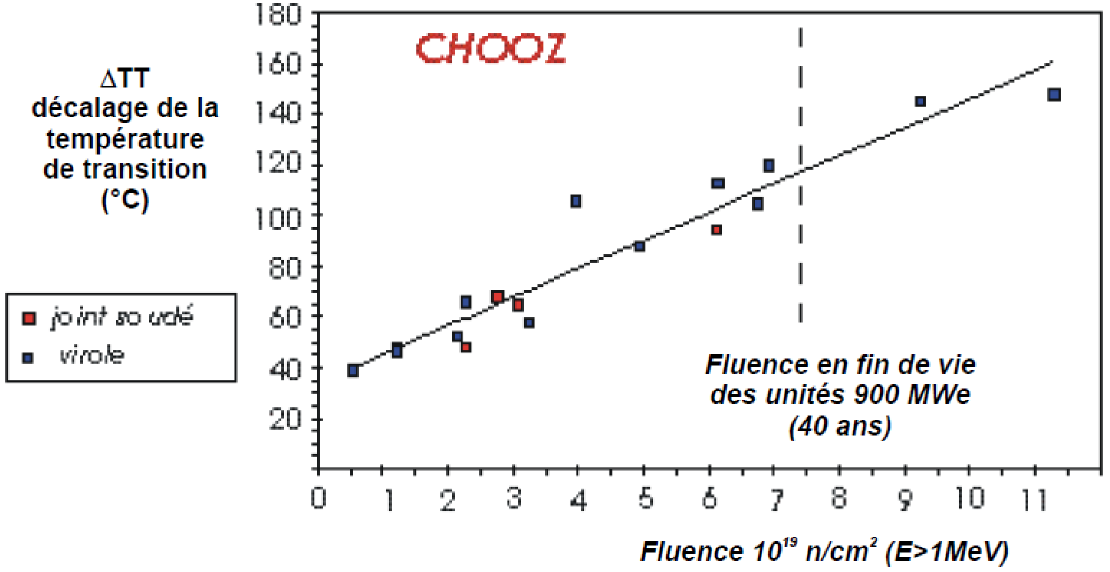
Enbrittlement under irradiation



Source « Matériaux pour le nucléaire" Technique de l'Ingénieur, dossier N1280 V1



Irradiation 3x larger than at the tank wall (allow to predict the tank behavior)



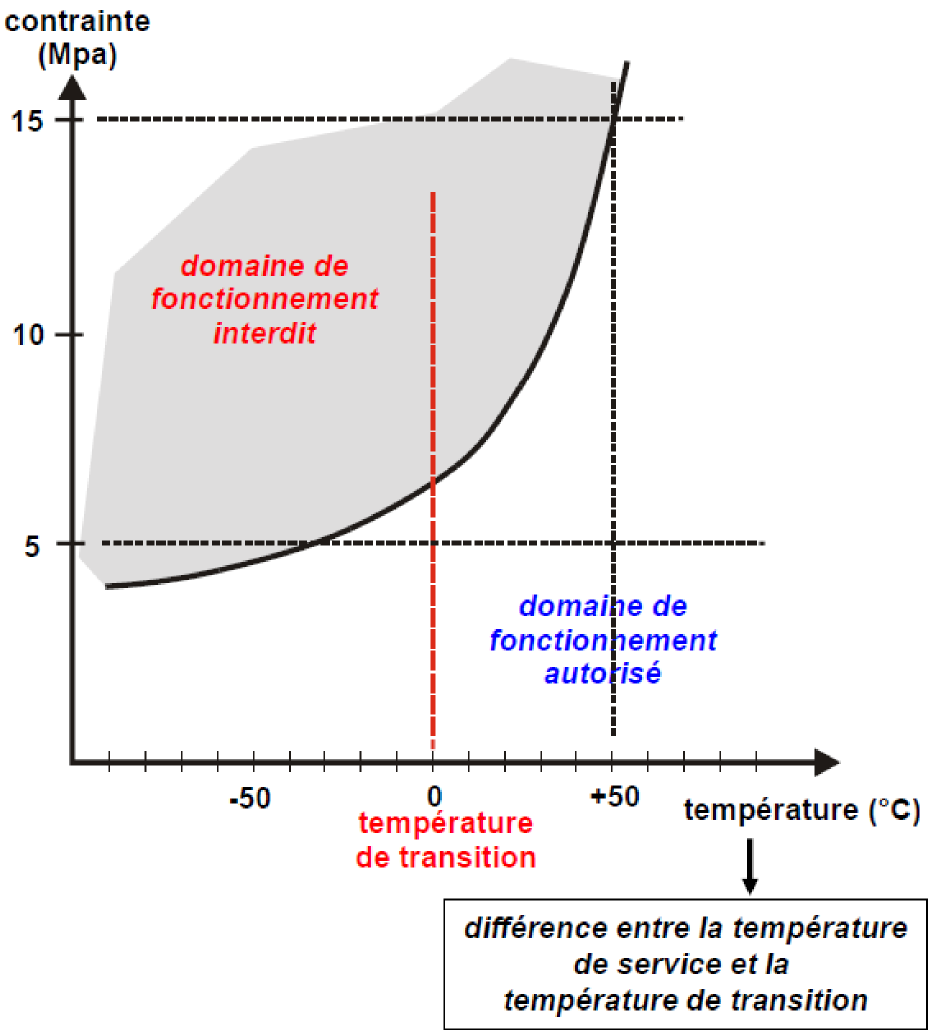
Programme de surveillance de la centrale de Chooz après 17 ans d'irradiation

Source "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste et Thèse P. Lapouge

- The ductile/Brittle transition is shifted to higher temperatures
- The height of the resilience plateau decreases

Reactor tank – Materials, fabrication, challenges

Enbrittlement under irradiation



155 bars = 15 Mpa

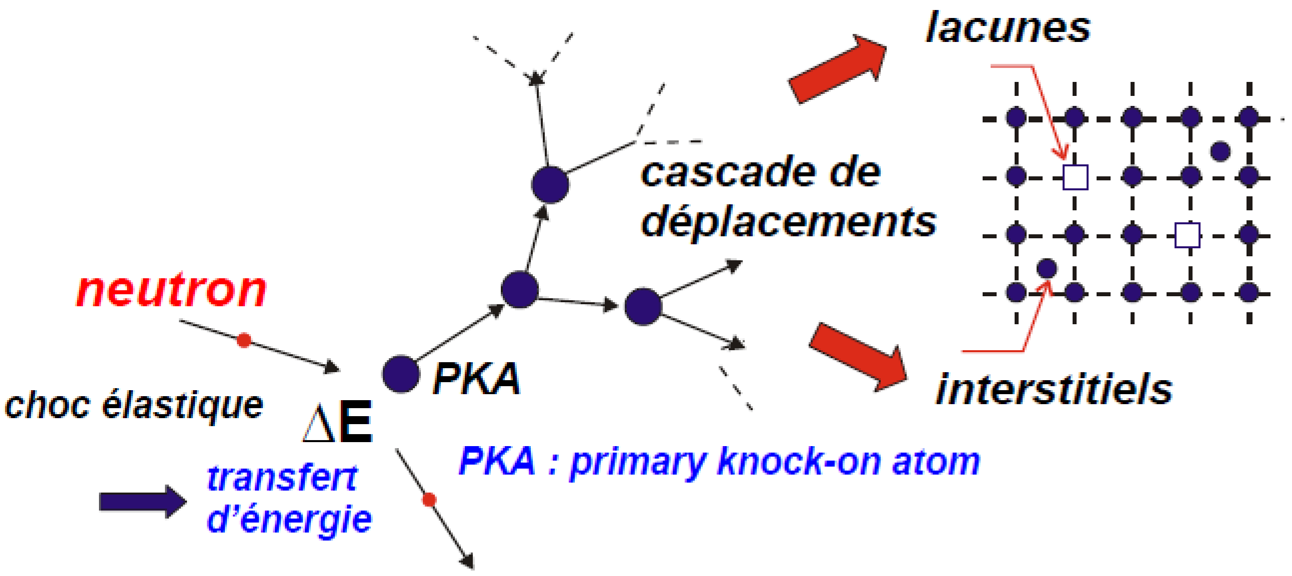
The tank temperature (286°C) most be at least 50°C above the transition temperature

- Suitable during ~40 years for 900 MW reactors
- Suitable during ~75-80 years for 1300 MW reactors
- EPR tank has been conceived to withstand >80 years

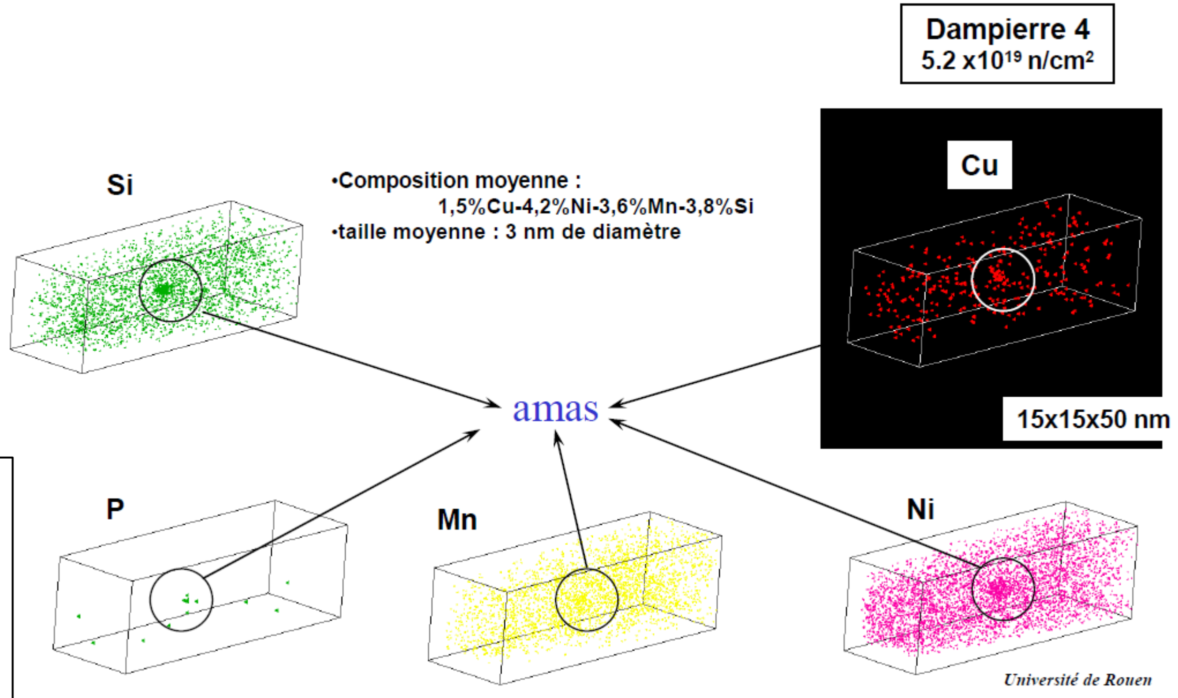
Source "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste et Thèse P. Lapouge

Reactor tank – Materials, fabrication, challenges

Origin of the shift in Ductile/Brittle transition

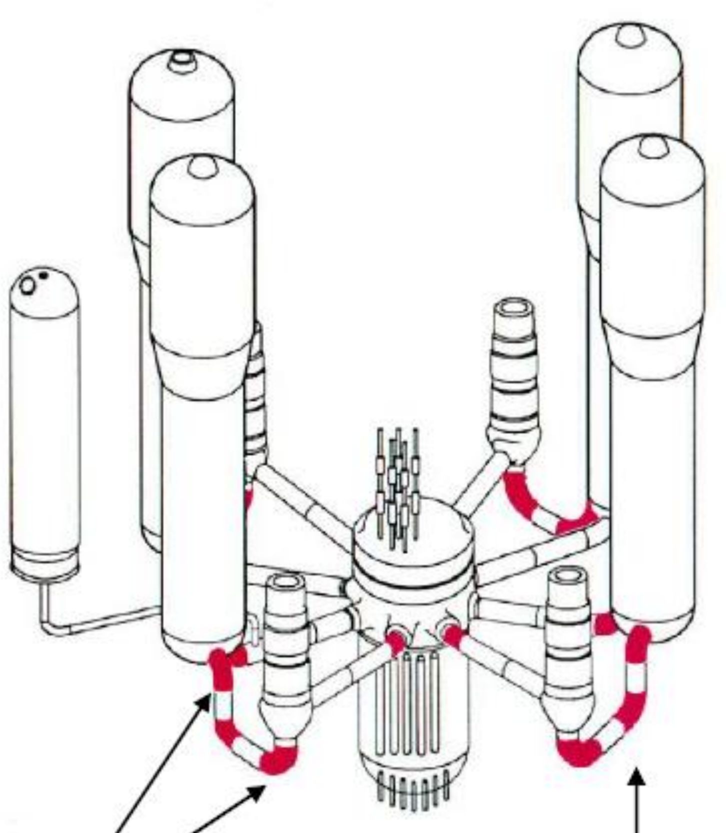


- Some brittle aggregates form
- The copper content favors their formation
- It is needed to monitor the reactors in place, modify the geometry and alloys composition (less copper or alloys less subject to embrittlement) for new reactors



Source "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste et Thèse P. Lapouge

Primary circuit – Casted products



Aciers Z3CND20-10M ou Z3CN19-10M
20% Cr - 10% Ni - 2,5% Mo - 1% Si – 0,003% C

Austeno-ferritic stainless steel, Very good castability, better resistance to corrosion and good mechanical properties thanks to the presence of ferrite

Source "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste et Thèse P. Lapouge

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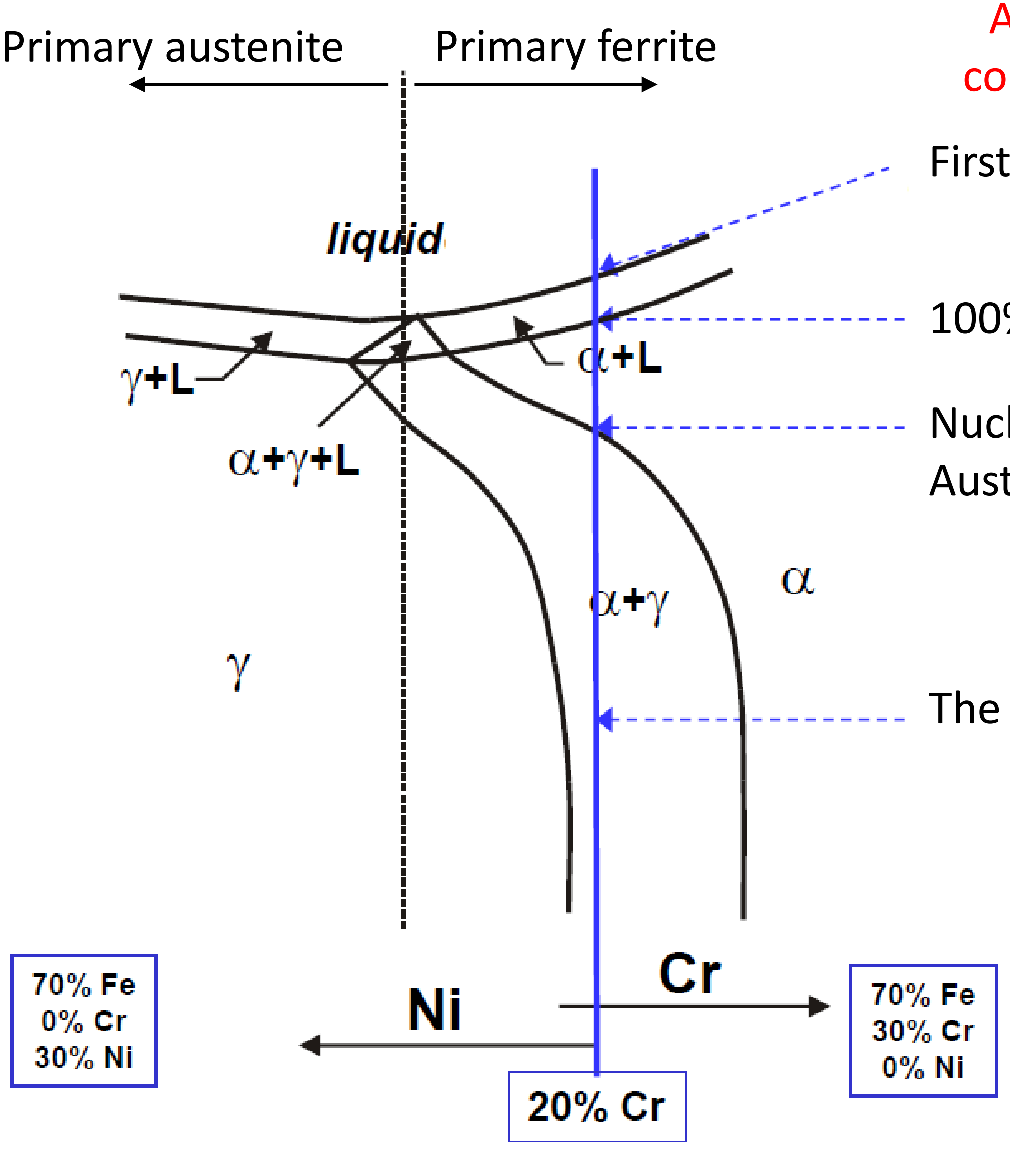
20% Cr - 10% Ni - 2,5% Mo - 1% Si – 0,003% C

Austeno-ferritic stainless steel, Very good castability, better resistance to corrosion and good mechanical properties thanks to the presence of ferrite



First germs of ferrite in liquid

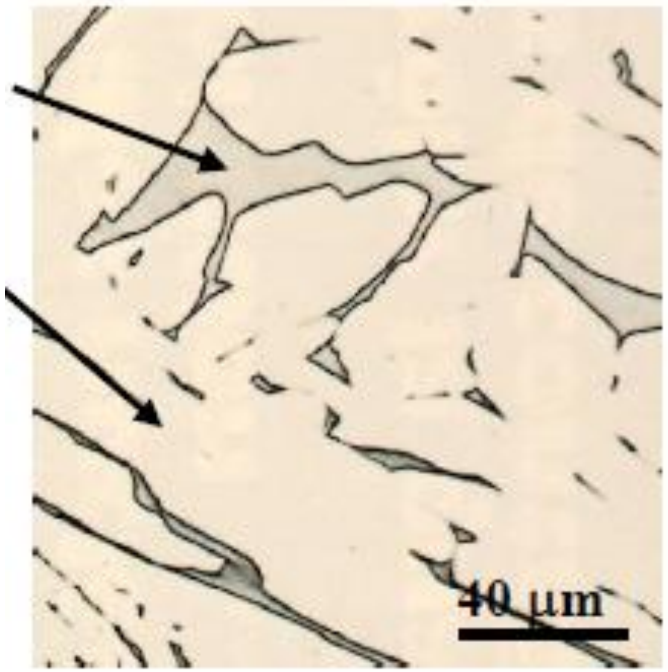
100% Ferrite

Nucleation, then growth of Austenite

The alloy is quenched

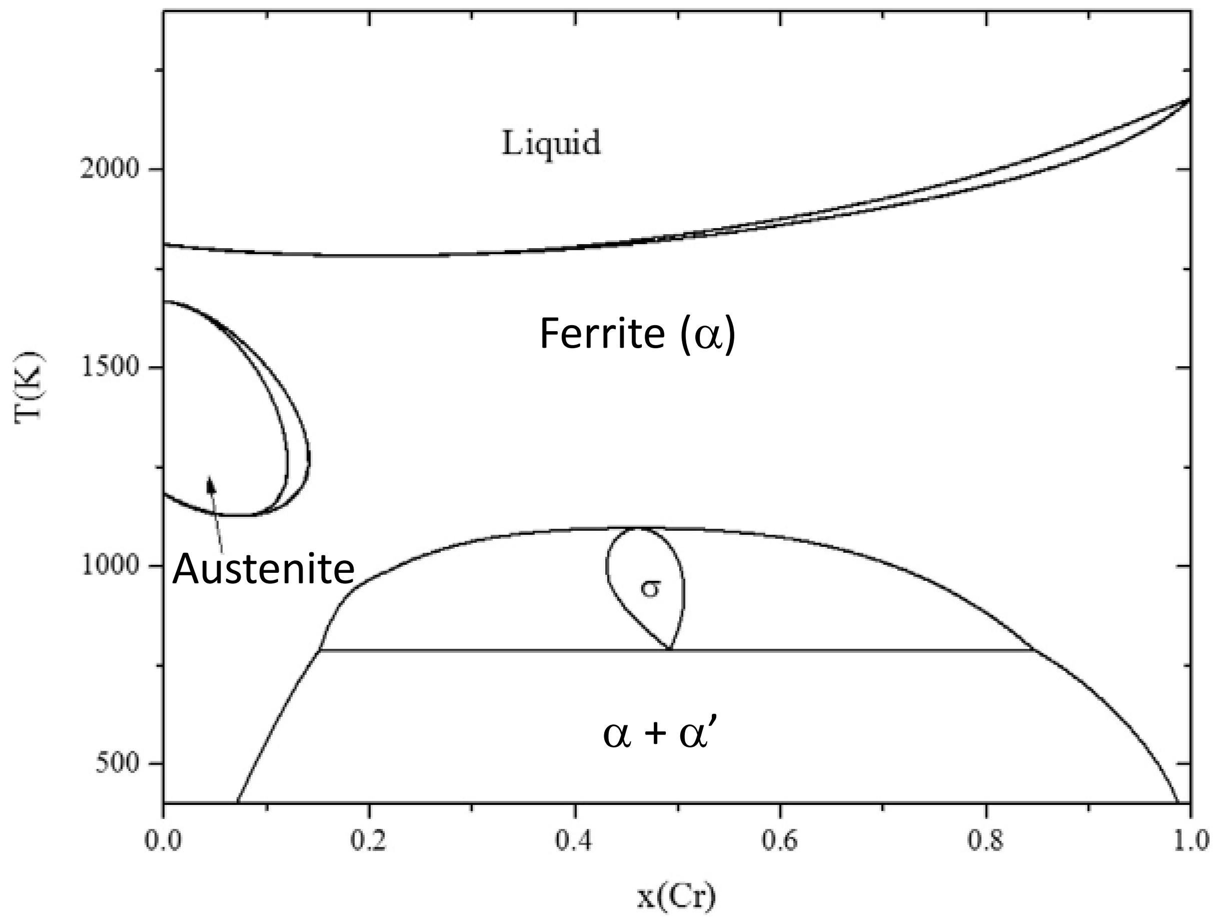
5-25% Ferrite

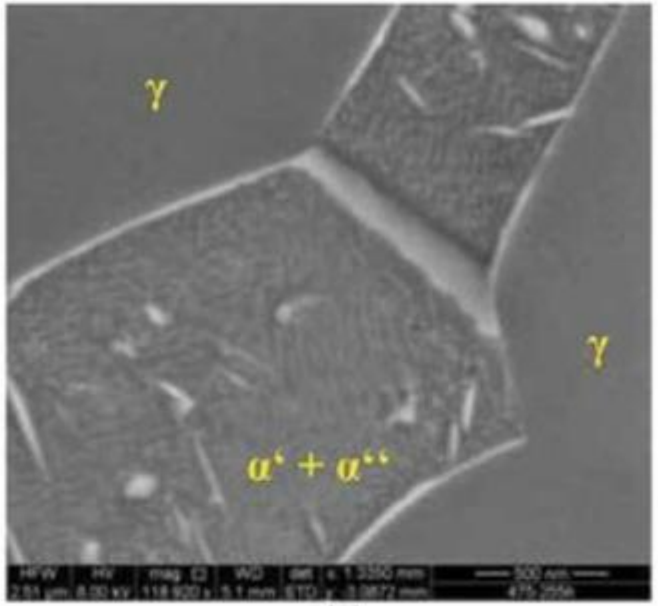
Austenite



Source "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste et Thèse P. Lapouge

Primary circuit – Casted products



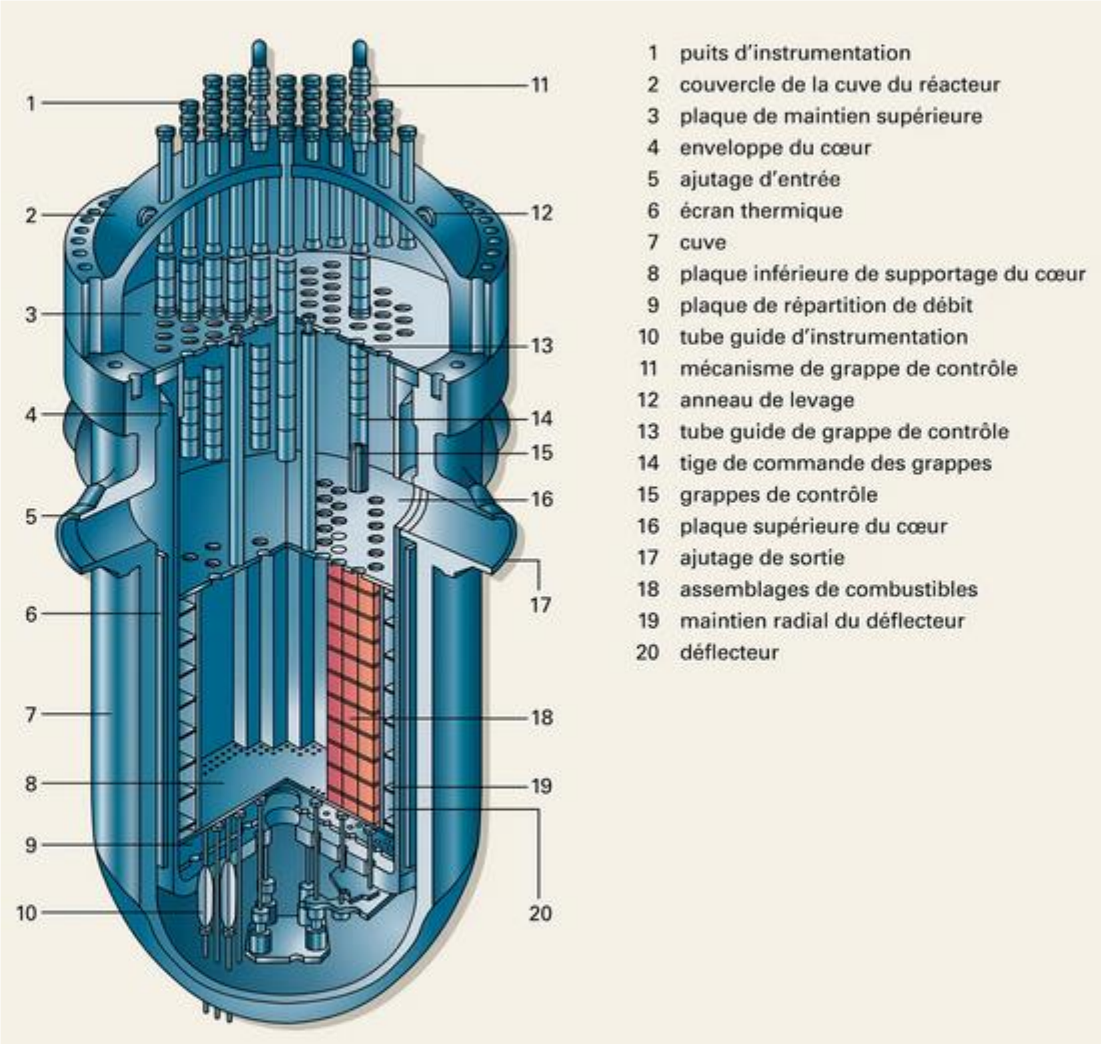


Source C. örnek et al. presented at EuroCorr 2013 conference

<u>Spinodal decomposition of ferrite is observed with time due to service temperature (~300°C) :</u>

- Formation of Fe-rich and Cr-rich phases
- Increase of hardness and embrittlment
- Monitor existing reactors
- New reactors with modify composition (less ferrite) or use of austenitic forged alloys

Internal components



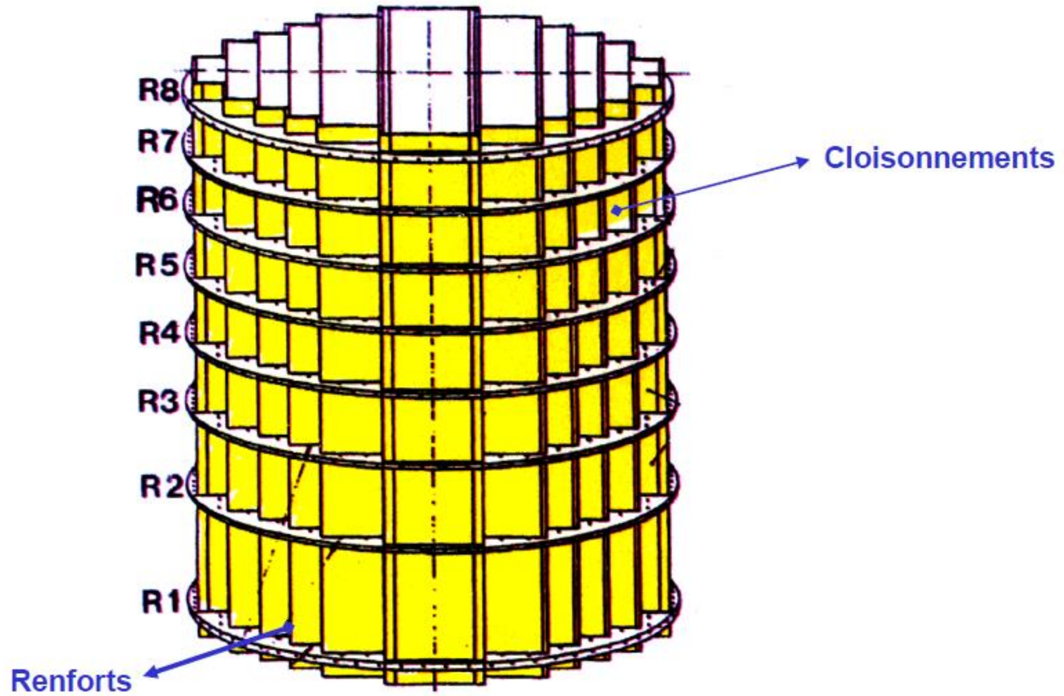
Roles of lower internal structures:

- Hold the core
- Maintain the alignment between fuel assemblies, control bars and instruments
- Guide the heat transfer fluid
- Protect the tank against irradiation
- Maintain sufficient rigidity in order to ensure alignment

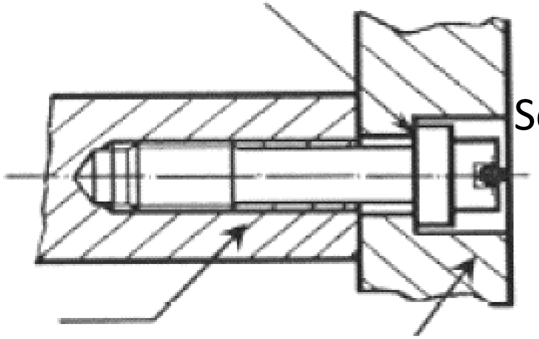
Roles of upper internal structures:

- Maintain the alignment between assemblies and control bars
- Immobilize the fuel assemblies

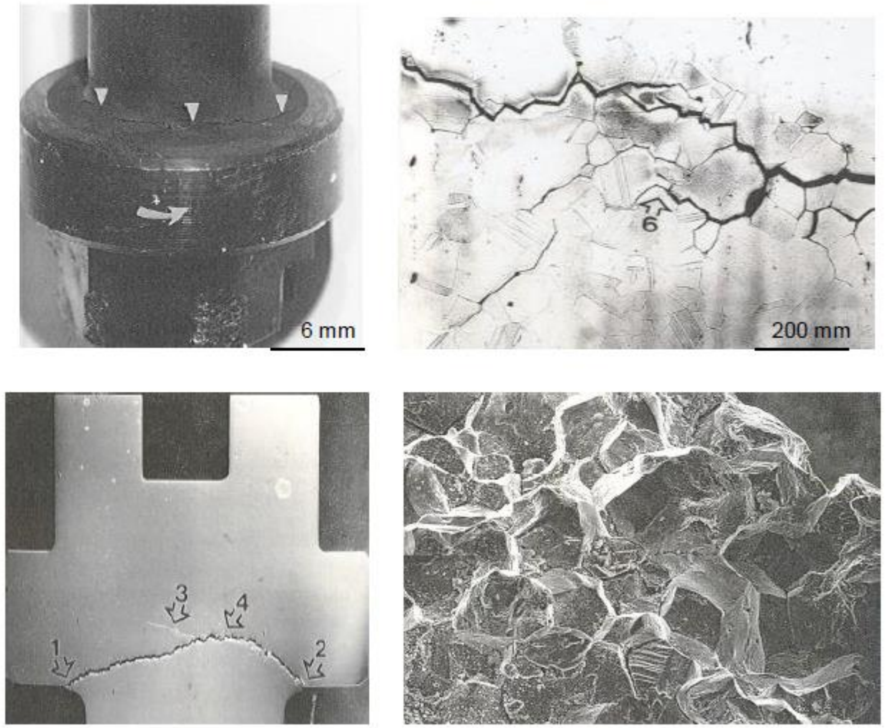
Internal components



Walls and reinforcements are made of austenitic stainless steel (18% Cr, 10% Ni)

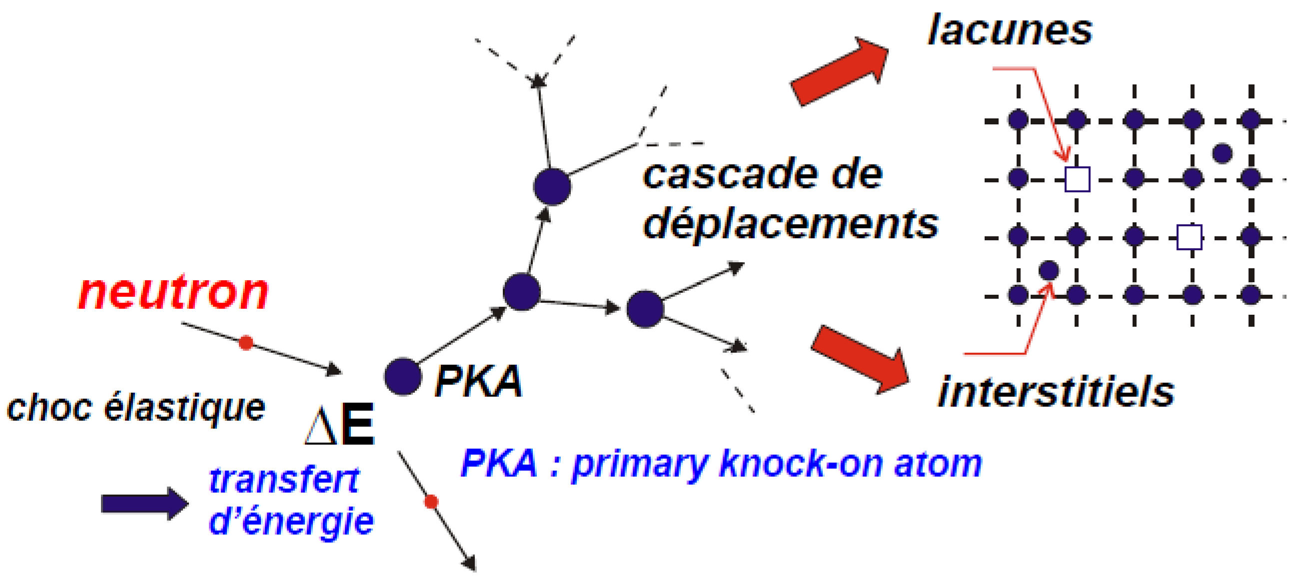


Screws are made of austenitic stainless steel (17% Cr, 11% Ni, 2.5% Mo)

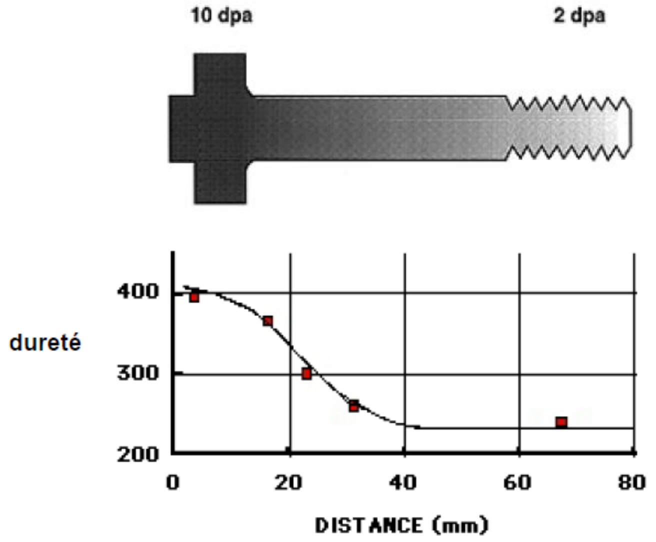


Cracks appear on screws by irradiation-assisted corrosion under stress

Internal components



- Disclocation loops form (increase the hardness



- Grain boundary segregation

- Formation of cavities (along with Helium bubbles)

Source "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste et Thèse P. Lapouge

Ageing of fuel assemblies

Nuclear fuel

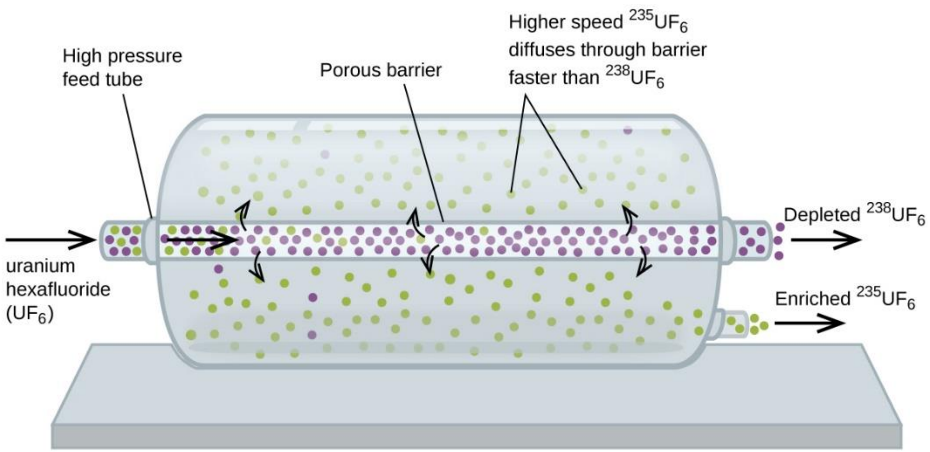
Raw material: Yellow cake
$Na_2U_2O_7$ (formerly) of yellow color or **U_3O_8** of greenish-blackish color

After several chemical reactions
U_3O_8 => **UF_6 (Uranium hexafluoride, gazeous)**

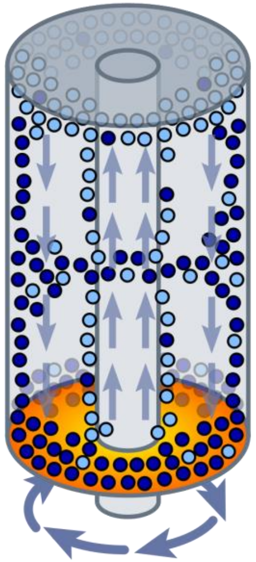
Enrichment (from UF_6) at Georges BESSE II factory (Tricastin)

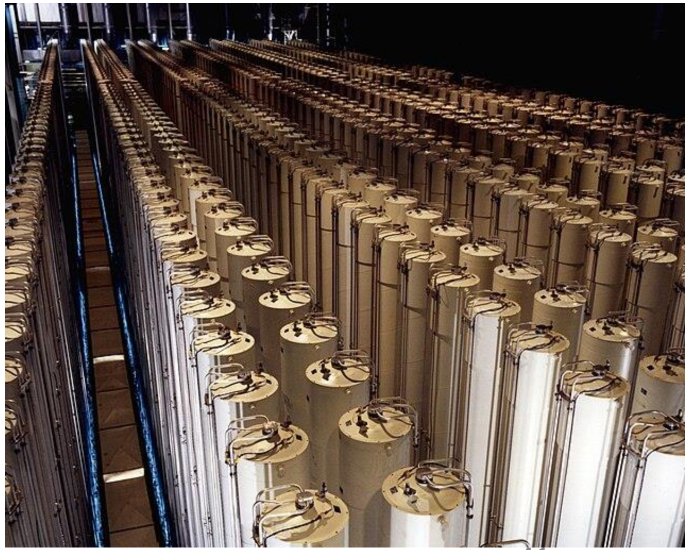
The different methods are based on the difference of mass between ^{235}U and ^{238}U

Gazeous diffusion



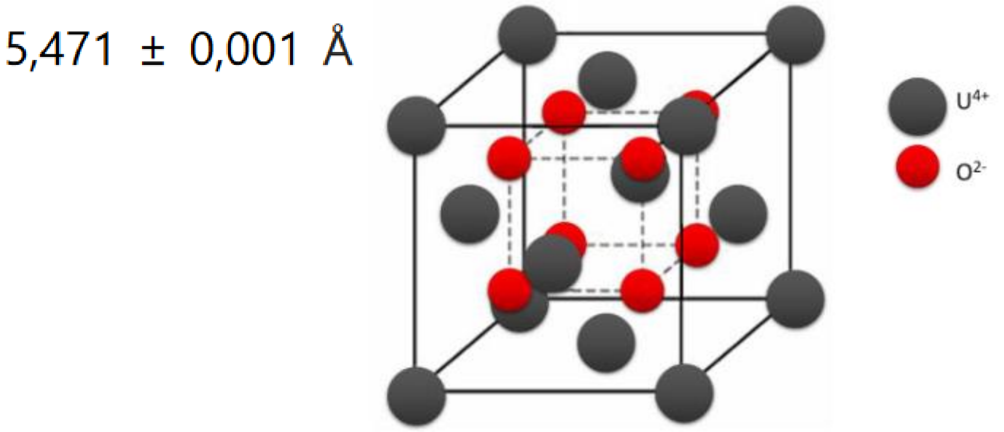
Ultracentrifugation





Wikimedia commons

Nuclear fuel

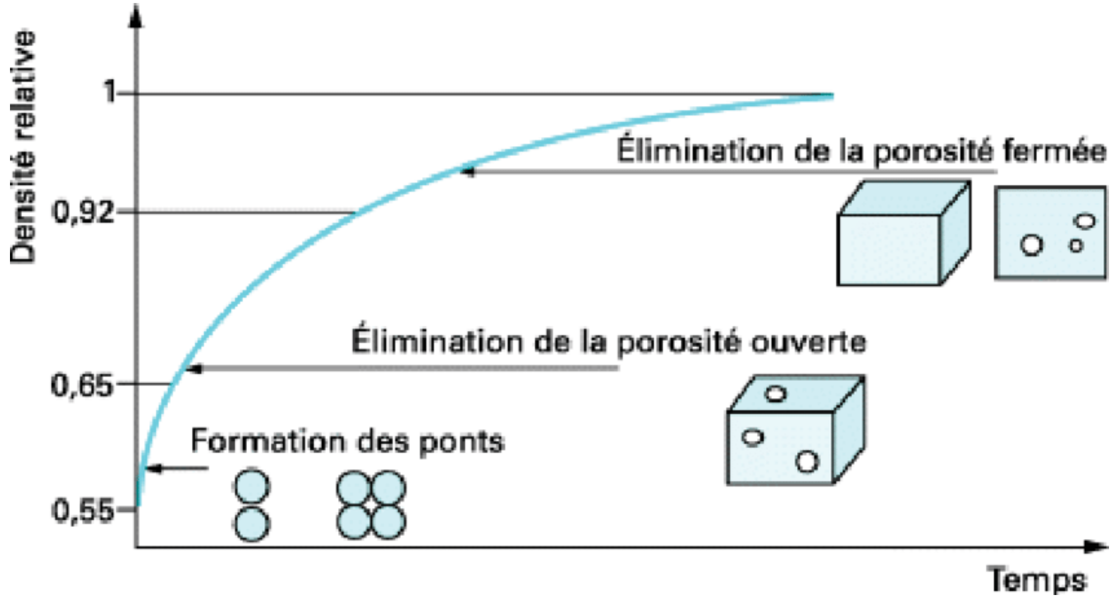


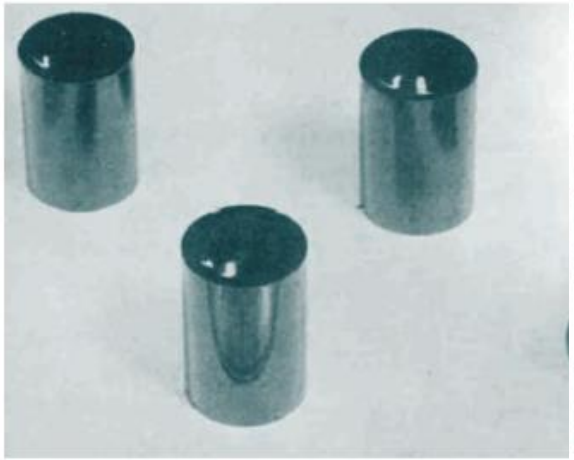
Conversion into UO_2

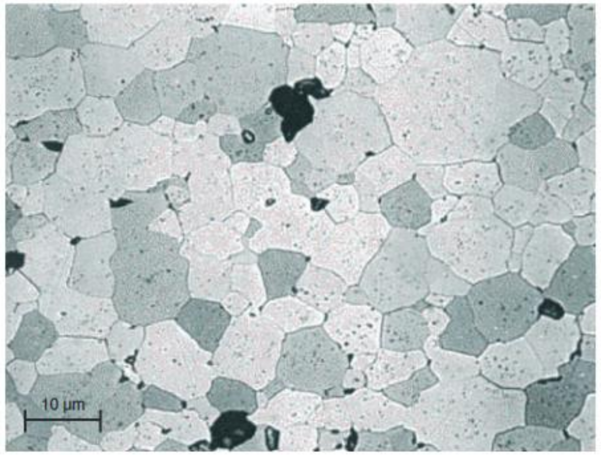
Hydrolysis : $UF_6 + 2\ H_2O \rightarrow UO_2F_2 + 4\ HF$
Reduction : $UO_2F_2 + H_2 \rightarrow UO_2 + 2\ HF$

Sintering

Sintering at 1700°C for 4h of a $UO_2 + U_3O_8$ (porogen) mixture under reducing atmosphere (H_2)
95% density is targetted in order to compensate for the densification during operation







Les combustibles nucléaires (CEA)

Irradiation rate and composition when removed from reactor

For 1T fuel

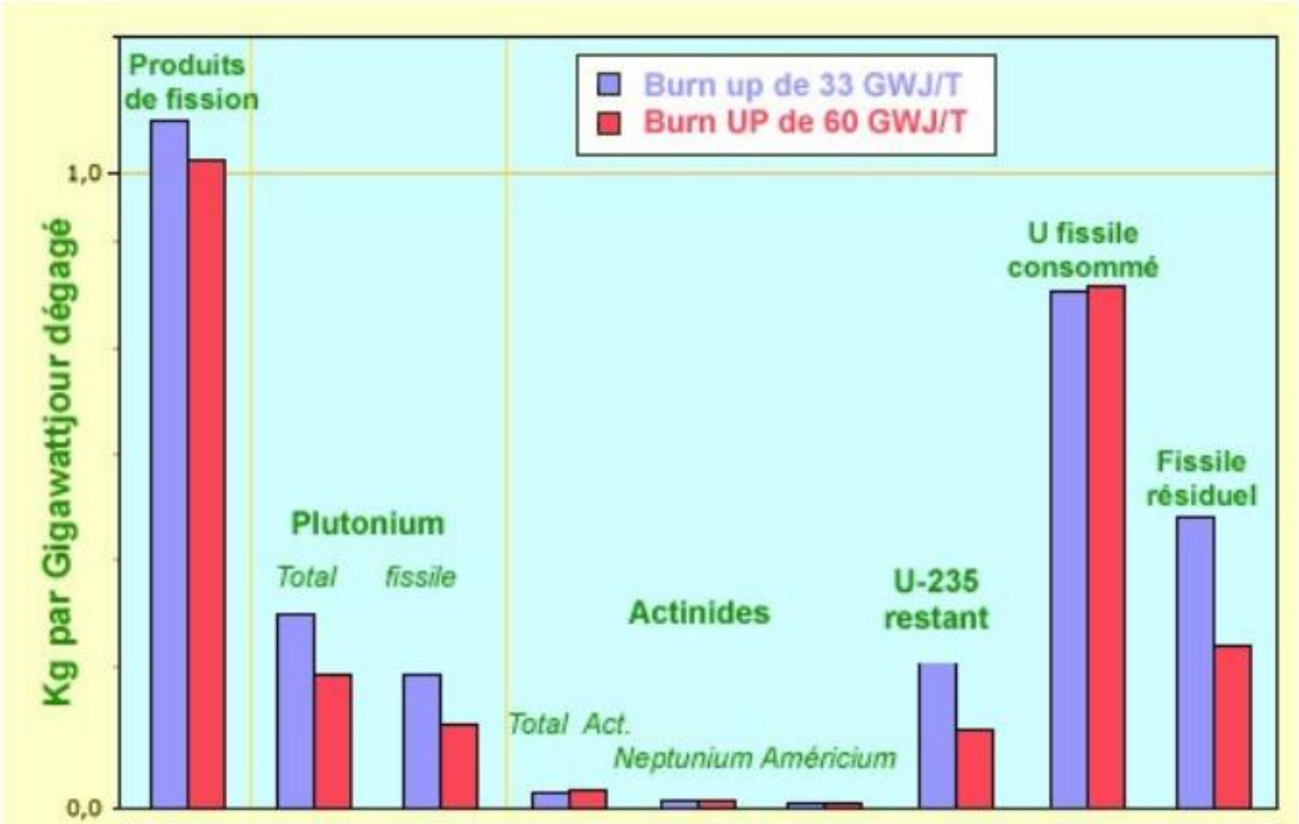
GWJ/T
Gigawatt*day of NRJ per fuel ton

Burn-up	33 GWJ/T (+82% →)	60 GWJ/T
Enrichissement	35 kg 3,5 % U-235 (+41% →)	49,5 kg 4,95 % U-235
Uranium U-238 U-235 U-236	952,8 kg 940,4 8,2 4,6	923,5 kg 908,7 7,6 7,2
Plutonium Pu fissile	10,1 kg 7,0	12,8 kg 8,0
Produits de fission	35,8 kg	61,3 kg
Actinides mineurs Netptunium-237 Américium-241 Américium-243 Curium-244	0,8 kg 0,5 0,2 0,1 0,03	1,6 kg 0,9 0,3 0,1 0,1

Influence du burn-up sur la composition du combustible
Comparaison de la composition en sortie de réacteurs de deux combustibles enrichis à 3,5 et 4,95 % en uranium-235 après qu'ils aient fourni une énergie de 33 et 60 GWJ, par tonne de combustible (UO2) initial.

Fuel enrichment allows to increase the total amount of energy provided by a ton of fuel

Irradiation rate and composition when removed from reactor

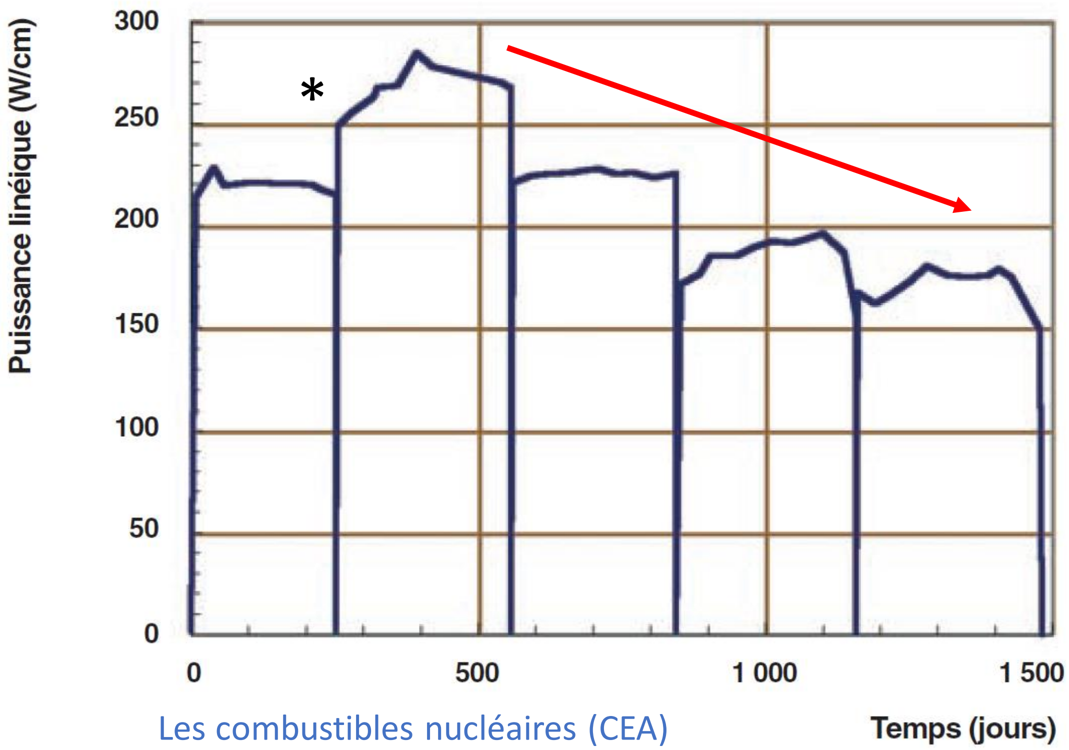


Kg	1,08	0,306	0,212	0,024	0,015	0,009	0,248	0,81	0,46
	1,02	0,213	0,133	0,027	0,015	0,010	0,127	0,82	0,26

It is interesting to increase the amount in 235U in order to increase the irradiation rate and decrease the amount of wastes to be reprocessed

Evolution of fuel rods under irradiation

Fuel rods work typically at linear power values in the 150-250 W/cm



Les combustibles nucléaires (CEA)

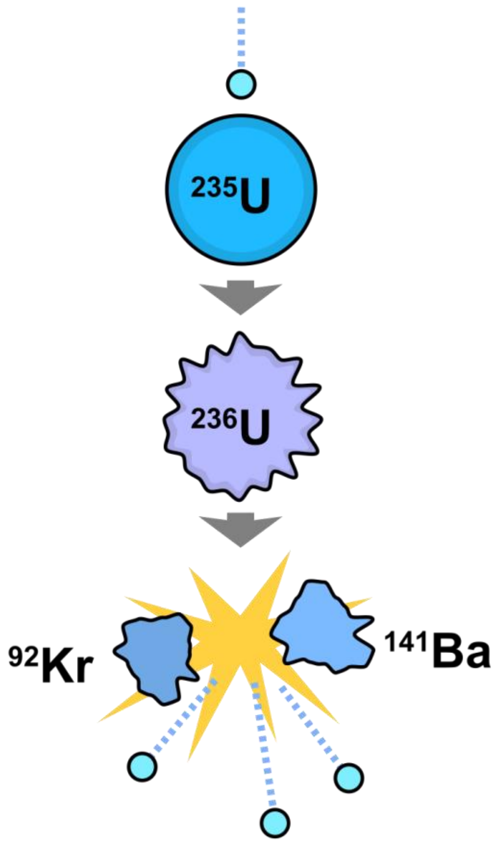
* Fuel Assembly was moved towards the reactor core between cycles 1 and 2

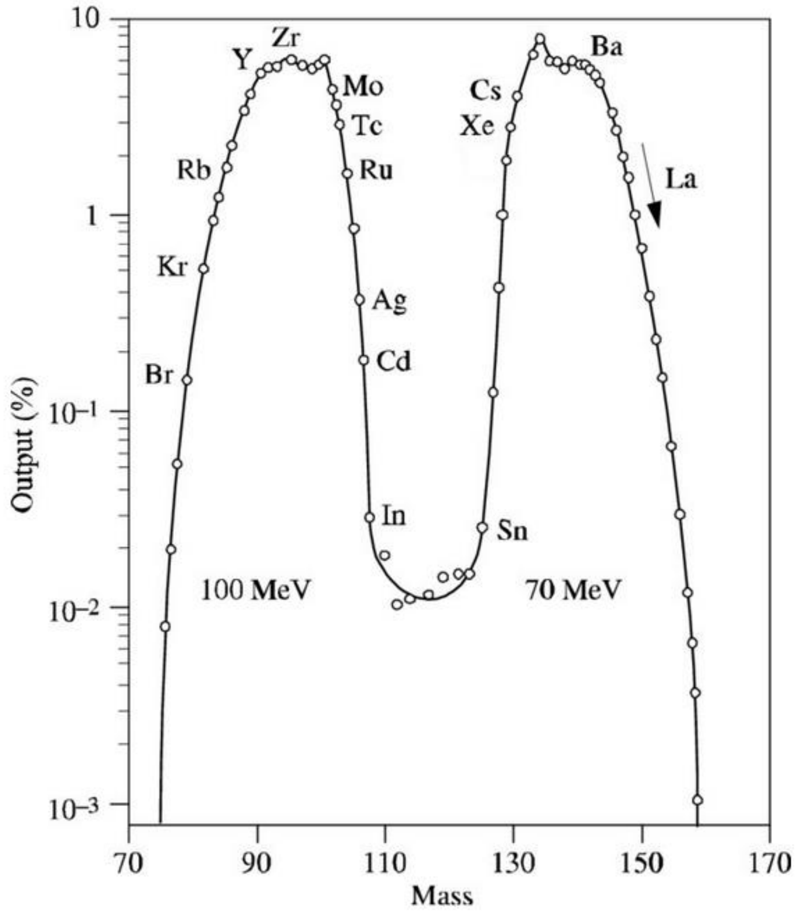
The produced linear power progressively decreases due to the consumption of fissile fuel

There is strong economical interest for longer cycles of the nuclear fuel ((currently 3-4 cycles of 12-18 months, i.e. 3 to 5 years)

Nuclear fuel is the only component of a reactor whose parformance can be improved thanks to innovation between refills

Evolution of fuel rods under irradiation





C. Lemaignan, J.C. Niepce, In Ceramic Materials (2007), Wiley

- Each reaction produces 1 heavy of ~65 MeV and 1 light of ~90 MeV fission products (PF)
- PF progressively loose their kinetic energy and finally implant in the fuel solid
- Most abundant are Mo, Zr, Ba, Cs and Xe

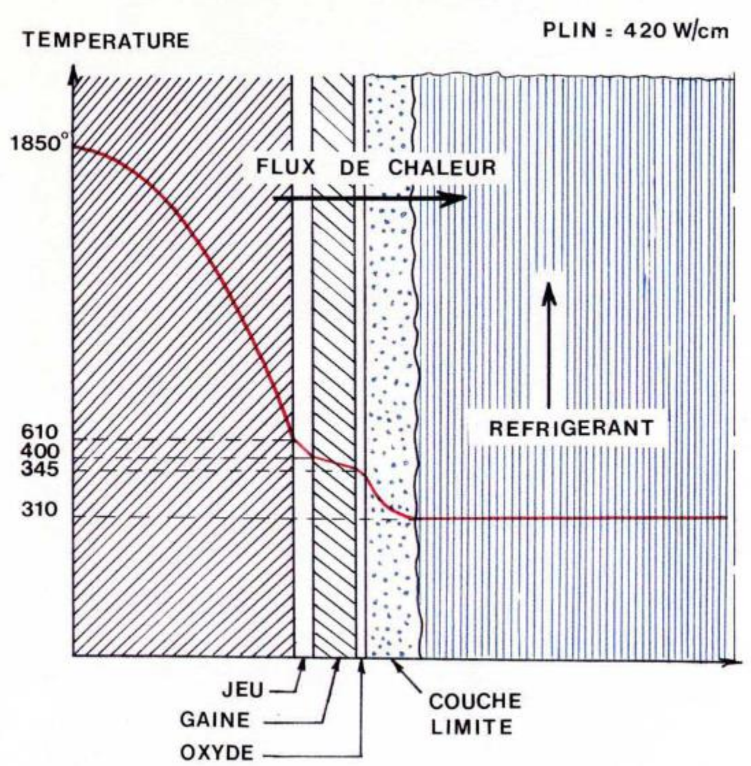
They are present in the solid in form of solid solution, solid precipitates or gazeous precipitates

- Due to their excess of neutrons and energy, PF experience themselves several $\beta^-$and α desintegrations to form stable nucleides and emit γ radiations

⇒ Fuel properties (thermal conductivity, composition, density, volume) are significantly modified by the fission reactions

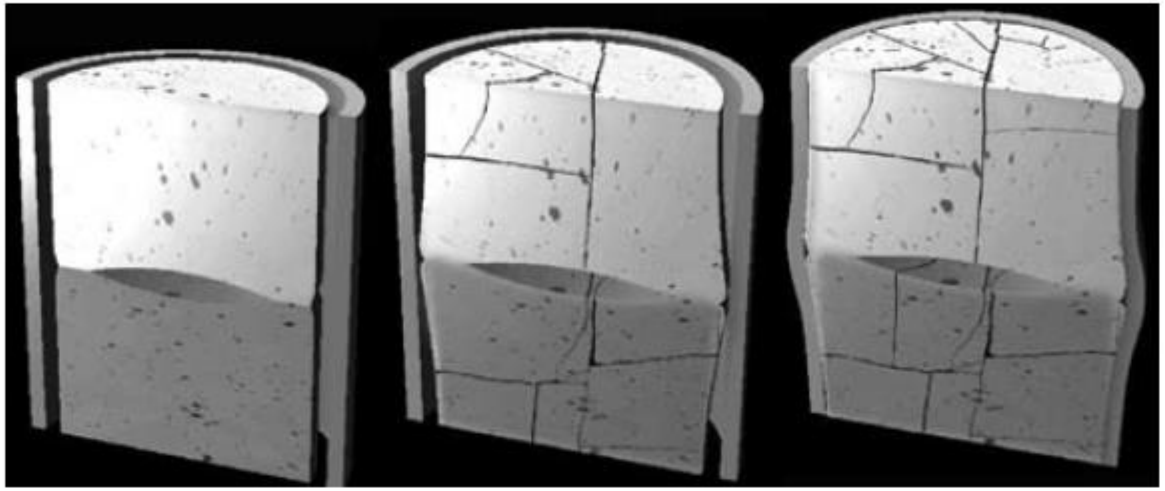
Evolution of fuel rods under irradiation

Damages at the fuel pellets and at the cladding (metallic tube) under service is due to several effects:



Thèse J.B MINNE, U Bourgogne, 2013

Thermomecanichal behavior



Les combustibles nucléaires (CEA)

- ○ UO_2 is a poor thermal conductor. In normal operating conditions, temperature is close to 1400°C and 400-500°C at pellet axis and periphery, respectively
- ○ Pellet and cladding experience different thermal dilatations

⇒ Thermomechanical stresses and friction induce cracks in the pellet, hourglassing (mise en diabolo) of the pellet leading to stress and deformation of the cladding

Evolution of fuel rods under irradiation

Damages at the fuel pellets and at the cladding (metallic tube) under service is due to several effects:

Influence of fission products on the pellet volume

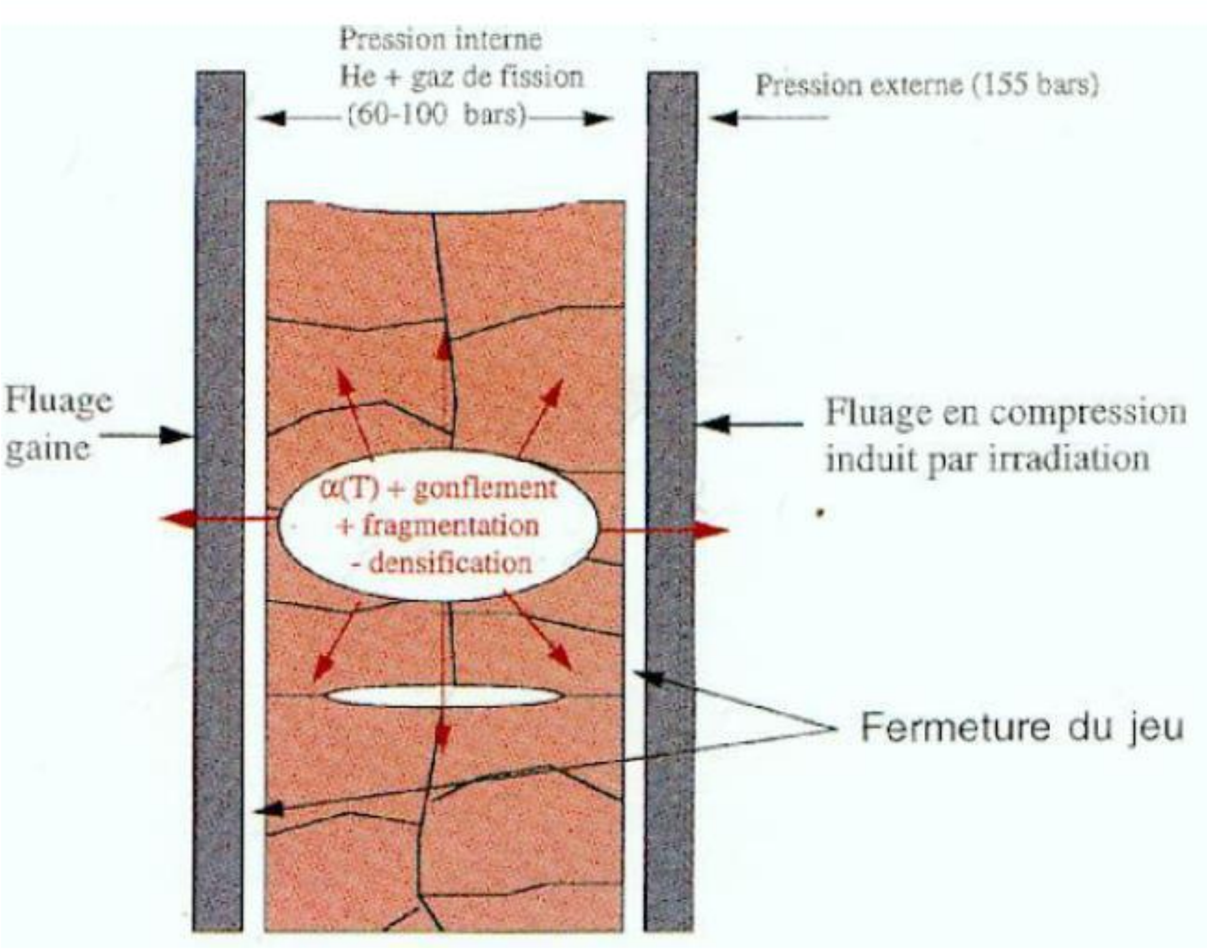
- Along their trajectories, fission products disperse the cavities into vacancies that evacuate thanks to grain boudaries => Contraction
- Fission products increase the number of atoms => Dilatation

⇒ At low irradiations contraction dominates while dilatation dominates at larger irradiations, the threshold is around 15 GWJ/tU

Evolution of fuel rods under irradiation

Damages at the fuel pellets and at the cladding (metallic tube) under service is due to several effects:

Effect of pressure

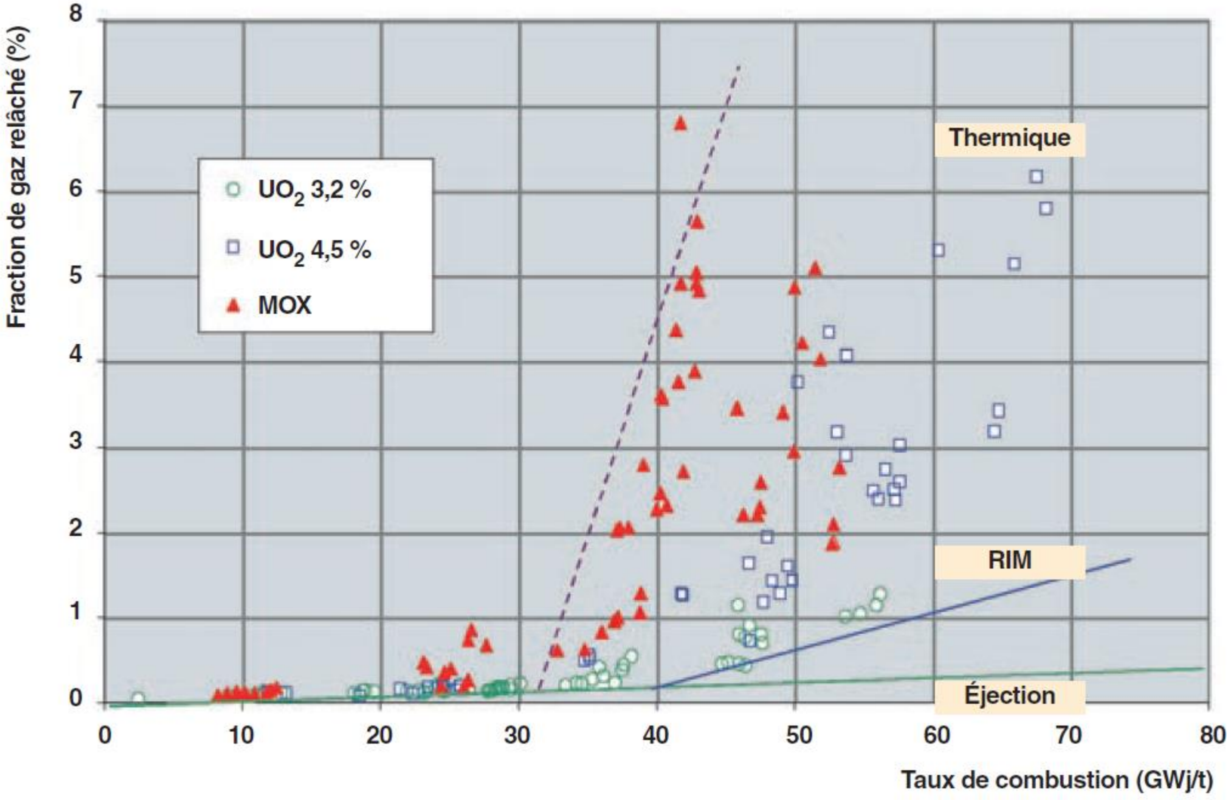


- There is competition between internal gas pressure (Helium + gazeous fission products) and external water pressure
- This combines with changes in pellet shape (previous slides)

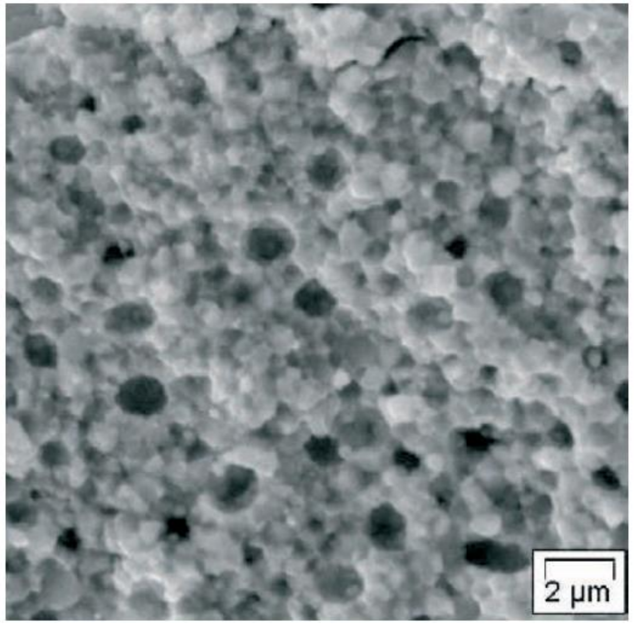
=> Creep deformation and pressing of the cladding against the pellet (occurs around 25 GWJ/tU)

Evolution of fuel rods under irradiation

Damages at the fuel pellets and at the cladding (metallic tube) under service is due to several effects:



Microstructure in the areas of high irradiation rates



Les combustibles nucléaires (CEA)

- Kinetic energy of fission products induce the ejection of atoms and athermal diffusion

⇒ The pellet periphery restructures (RIM effect)

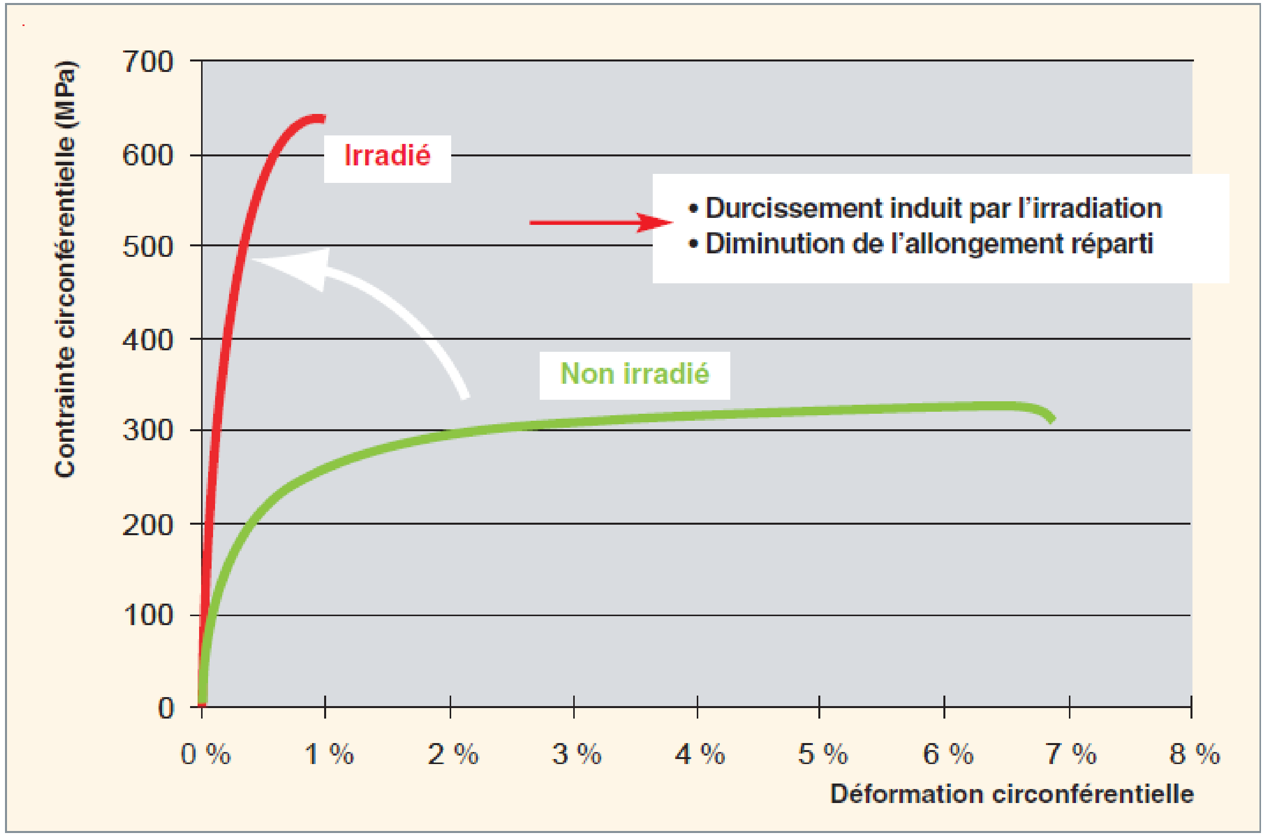
- With temperature, fission products diffuse into free volumes

⇒ Increase of the internal pressure

Evolution of fuel rods under irradiation

Damages at the fuel pellets and at the cladding (metallic tube) under service is due to several effects:

Effect of irradiation on cladding mechannical properties



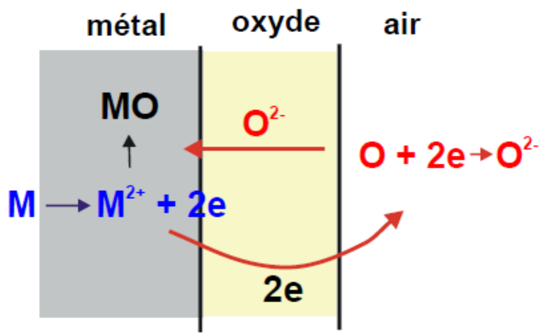
Les combustibles nucléaires (CEA)

- The ductility of Zr alloy degrades upon irradiation

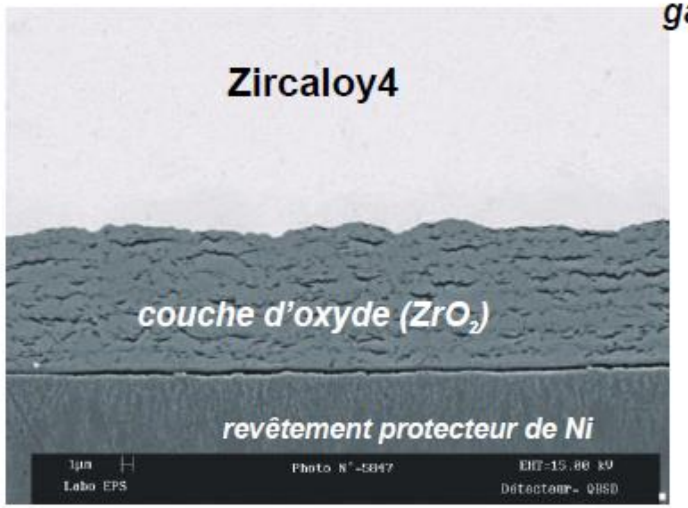
$\Rightarrow$ The cladding is more prone to failure during its deformation

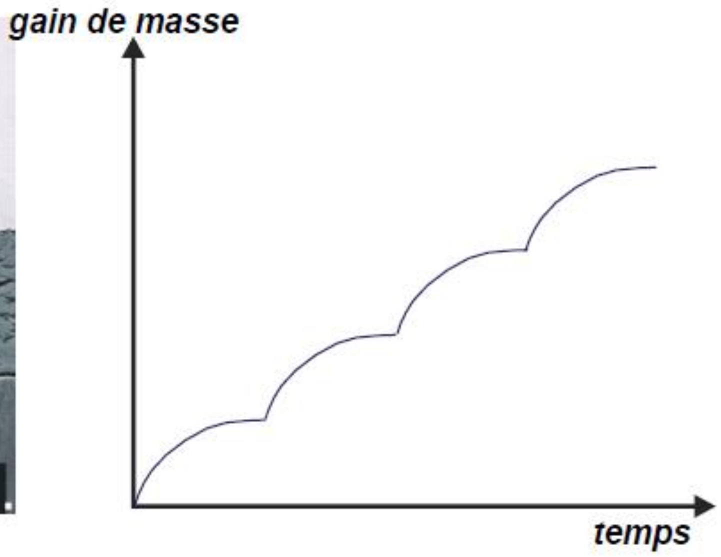
Evolution of fuel rods under irradiation

Oxidation of the metal cladding



Source "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste et Thèse P. Lapouge





- Oxidation of zirconium devlops at the metal/oxide interface by diffusion of oxygen through the oxide layer
- This diffusion slows down as the oxide layer increases (parabolic shape)
- As zirconia reaches a certain thickness, cracks appear letting the oxygen to penetrate

⇒ sequential growth of the oxide layer

⇒ Risk of rupture as the proportion of metal decreases

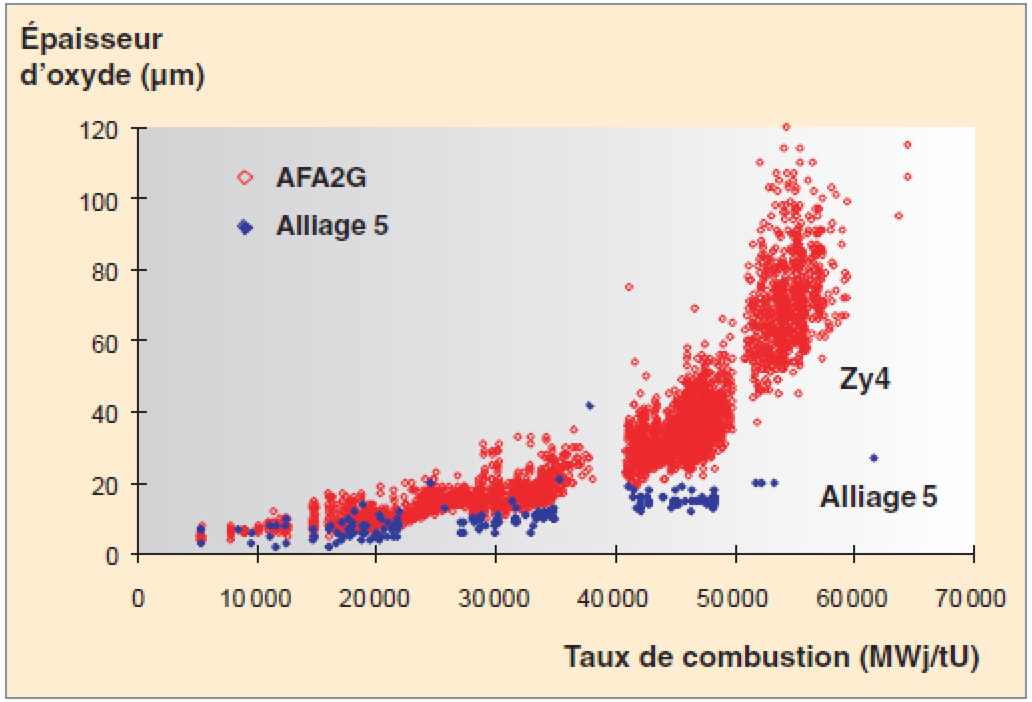
Evolution of fuel rods under irradiation

Oxidation of the metal cladding

Composition (en % poids) des principaux alliages de zirconium utilisés dans les réacteurs à eau légère

Nom de l'alliage			
Composant de l'alliage	Zircaloy-2	Zircaloy-4	Zr 1-Nb, ou M5®
Sn	1.2-1.7	1.2-1.7	
Fe	0.07-0.2	0.18-0.24	
Cr	0.05-0.15	0.07-0.13	
Ni	0.03-0.08		
Nb			1
O	1 100 à1 400 ppm		

Les combustibles nucléaires (CEA)



- New alloys with better resistance to corrosion are developped

⇒ Longer stay or higher service temperature in reactor are possible

Possible future developments

Possible future developments

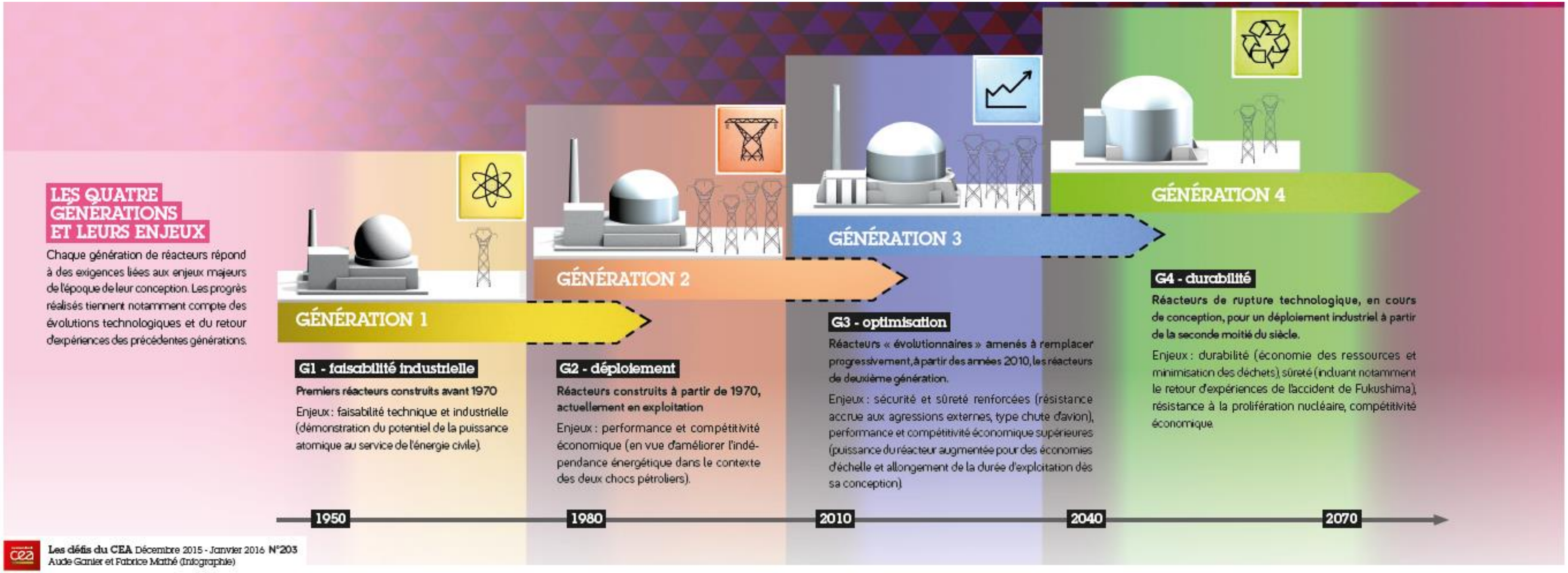
Irradiation rates are not limited by the fuel energetic capacities but by materials damages

R&D approaches are conducted in order to e.g.:

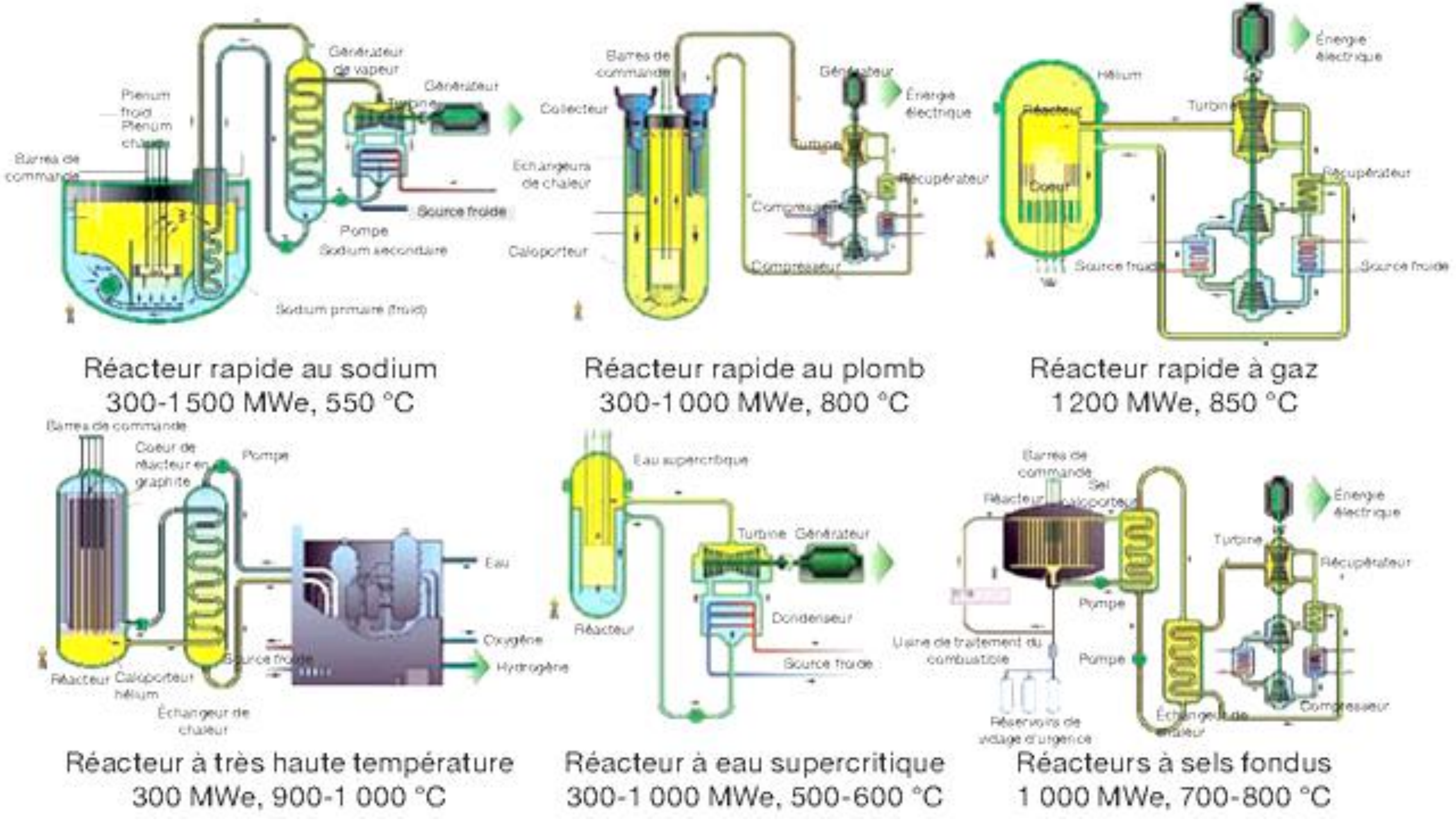
- Improve the behavior of cladding in temperature
- Improve the thermal conductivity of the fuel material to facilitate its cooling (for instance replace oxides by nitrides or carbides)
- Develop new concepts of reactors (fast neutrons, …)

Combustible	**(UPu)C**	**(UPu)N**	**UO_2**
Température de fusion (°C)	2325	2720	2847
Masse volumique d'atomes lourds ($g.cm^{-3}$)	12.9	13.5	10.97
Conductivité thermique à 1000°C ($W.m^{-1}.K^{-1}$)	19.6	19.8	3.2

Possible future developments

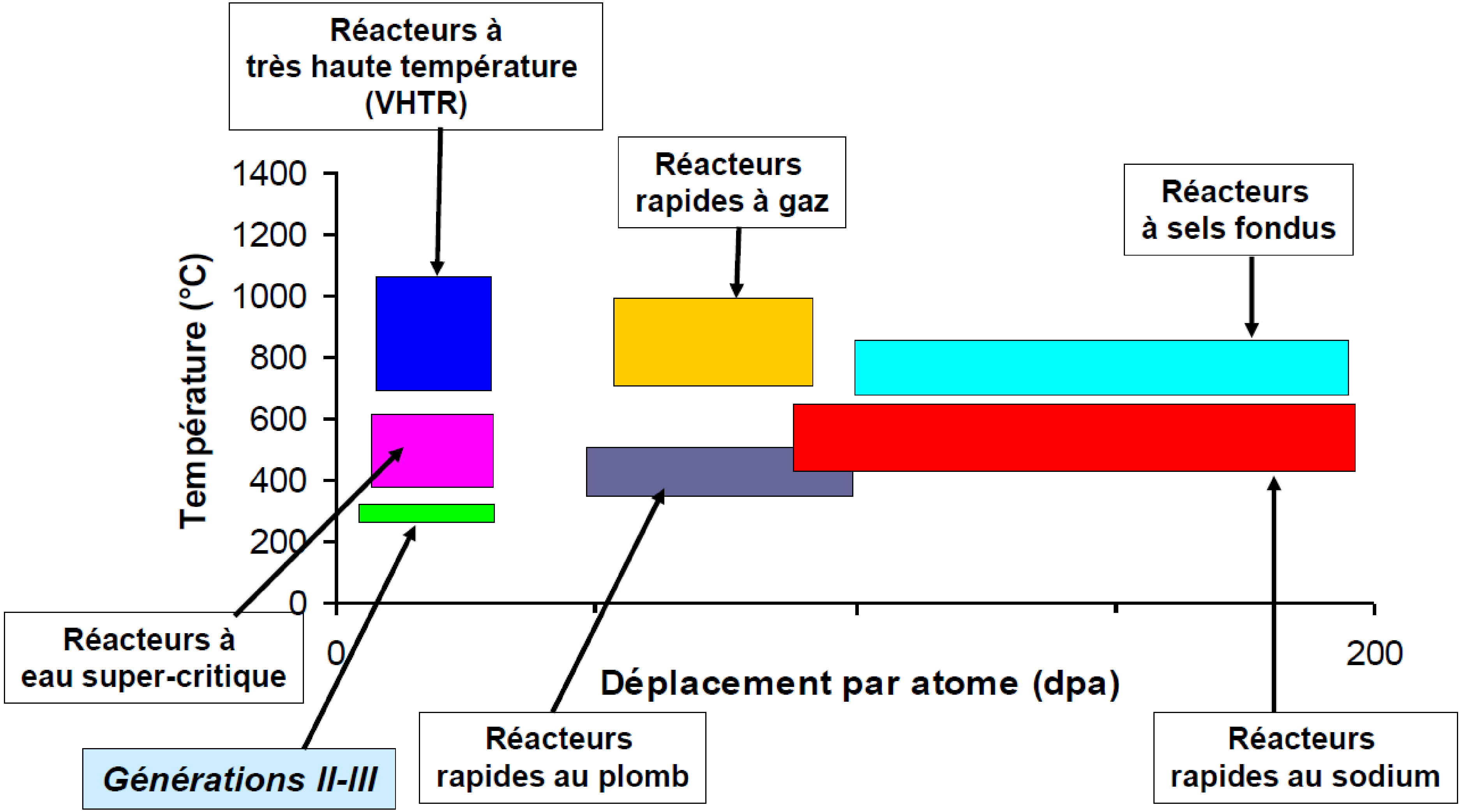


Possible future developments (6 technical solutions selected by Forum Génération IV)



http://books.openedition.org/editionscnrs/docannexe/image/10994/img-1.jpg

Expected sollicitations in generation IV reactors



Source "Les matériaux du nucléaire endommagement et évolution" EDF, J. Ruste et Thèse P. Lapouge

⇒ Temperature and/or irradiation rates will be higher

⇒ Challenges for the development of new materials

Interest of fast neutrons reactors

Sections efficaces (exprimées en barns*) des radionucléides à transmuter									
Isotope	Réacteur à neutrons lents (REP-UOX)			Réacteur à neutrons épithermiques* (REP - MOX)			Réacteurs à neutrons rapides (RNR)		
	σf	σc	α = σc / σf	σf	σc	α = σc / σf	σf	σc	α = σc / σf
Np 237	0,52	33	63	0,6	18	30	0,32	1,7	5,3
Am 241	1,1	110	100	0,8	35,6	44,5	0,27	2,0	7,4
Am 243	0,44	49	111	0,5	31,7	63,4	0,21	1,8	8,6
Cm 244	1,0	16	16	1	13,1	13,1	0,42	0,6	1,4
Cm 245	116	17	0,15	33,9	5,4	0,2	5,1	0,9	0,18
Tc 99	-	9	-	-	-	-	-	0,5	-

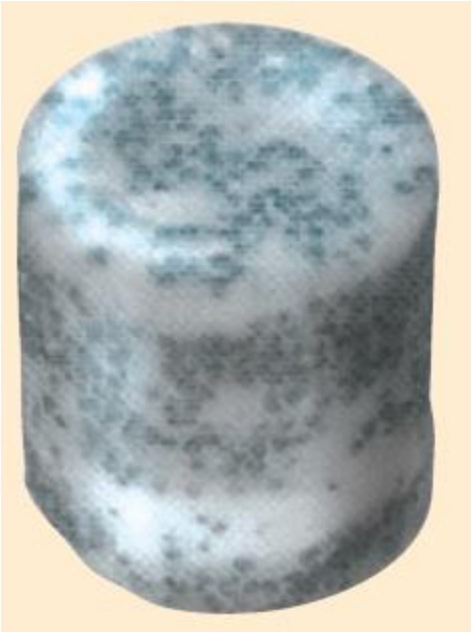
Les combustibles nucléaires (CEA)

2nd and 3rd generations reactors produce minor actinides as wastes because the fission cross section σ_f of these actinides is lower than the capture (the element is transformed into another one by neutron capture) cross section σ_c. They cannot be transformed into stable elements by fission.

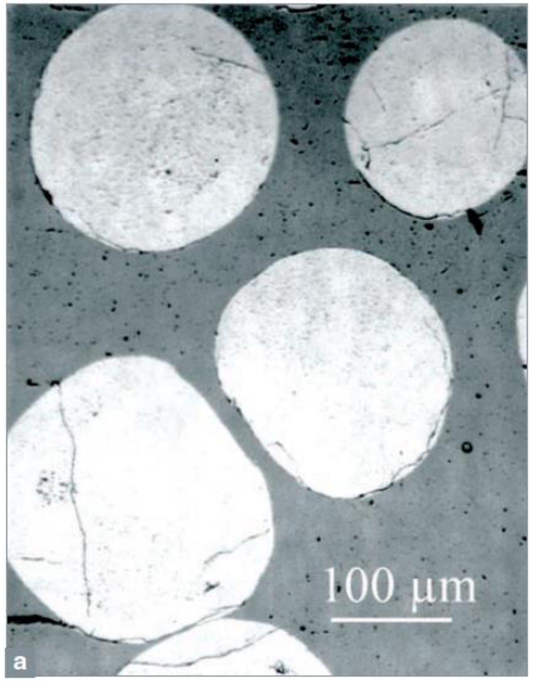
⇒ Fast neutrons reactors solve this problem by providing more favorable conditions for fission of these waste radionucleides

New types of fuel forms

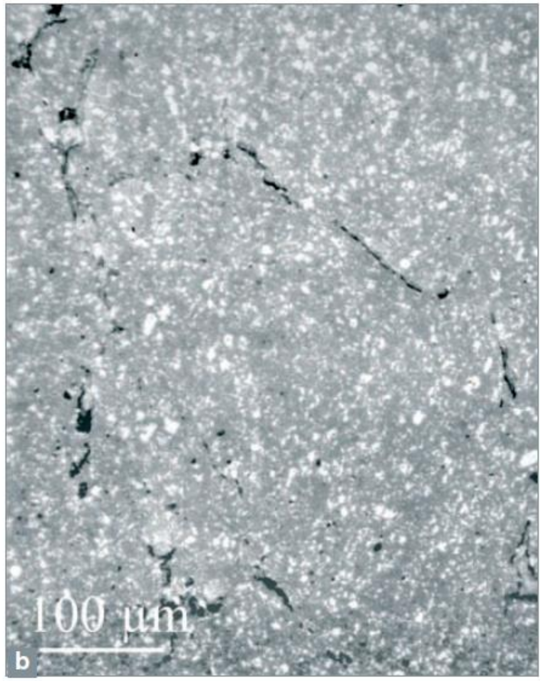
Composite fuels
Minor actinides in neutral matrix



Macro-dispersed



Nano-dispersed



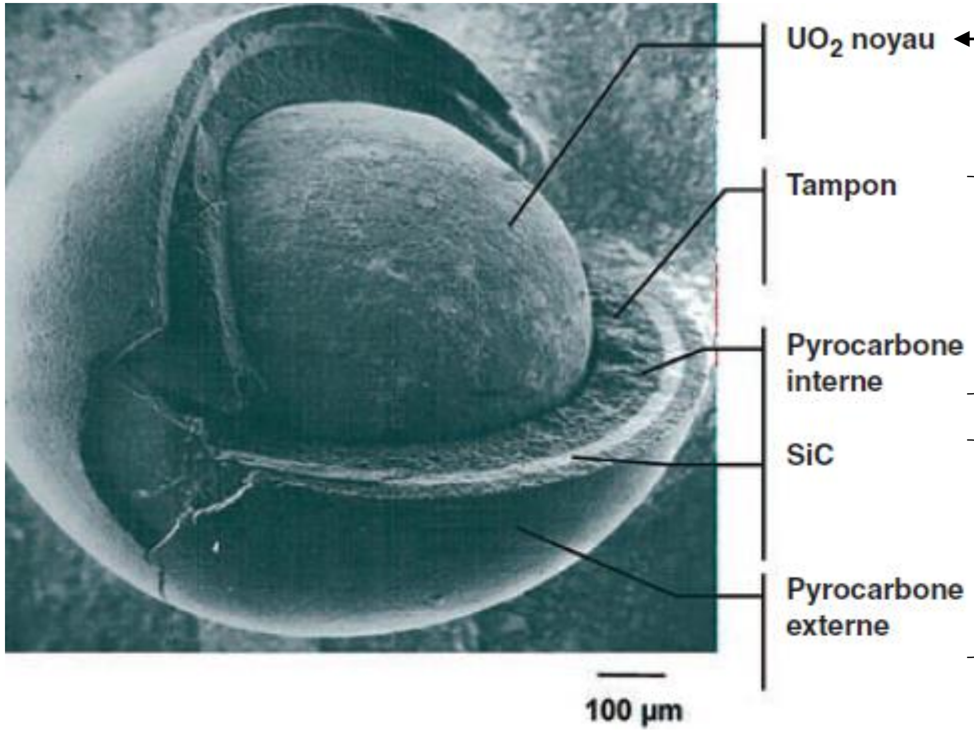
Les combustibles nucléaires (CEA)

⇒ Suitable for fast neutrons reactors
⇒ Allow to accomodate irradiation damages by localizing it

New types of fuel forms

Particulate fuels

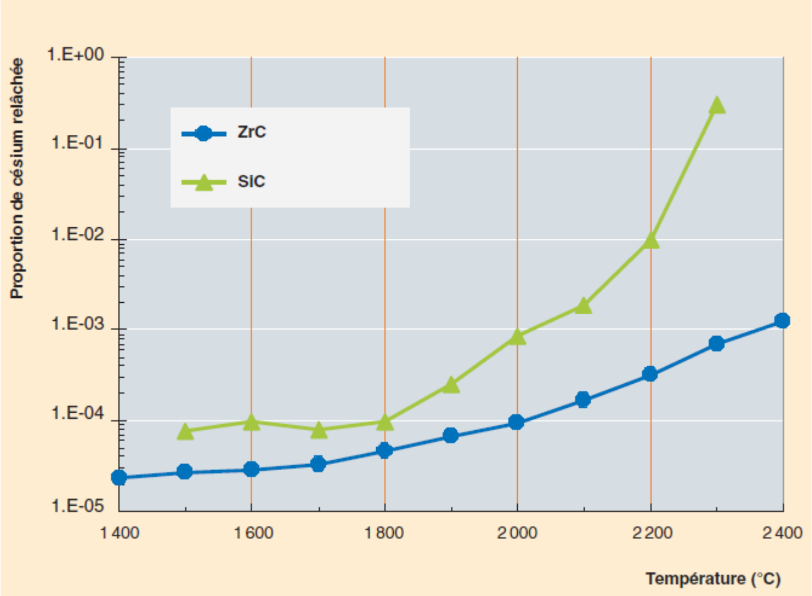
TRISO: **TR**istructural **ISO**tropic particulate fuel



Fuel

Porous, allows to accomodate fission products

Dense, contain the fuel



Les combustibles nucléaires (CEA)

⇒ Initialy developped for high temperature gas-cooled reactor, it is now seen as versatile for various types of reactors and for incident and accident-tolerant fuels after Fukushima accident

⇒ Each particle self-confines the fuel

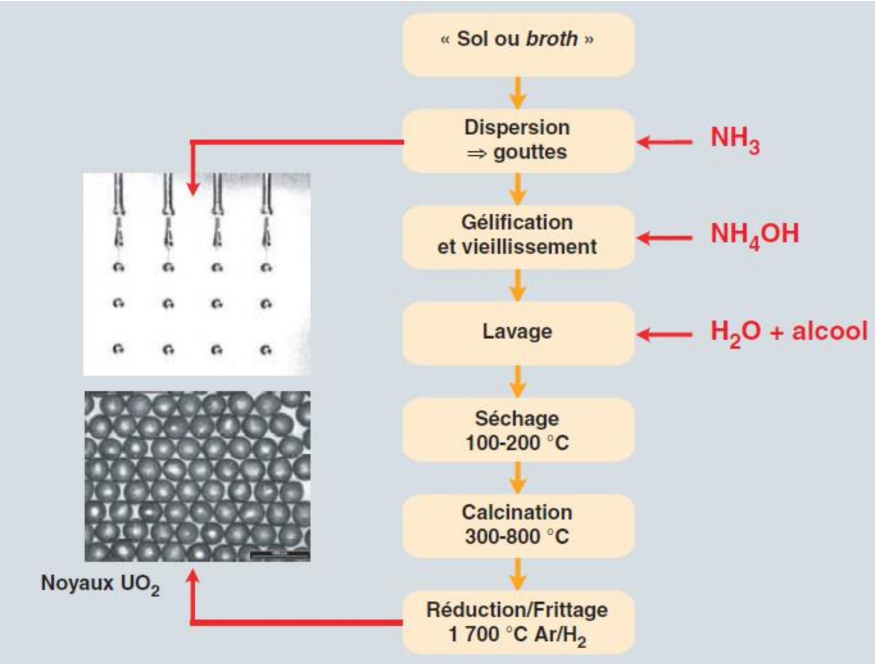
⇒ Reputed to be very safe, can withstand ~1800°C without substantial damage

⇒ The particles can be packed together into various shaped

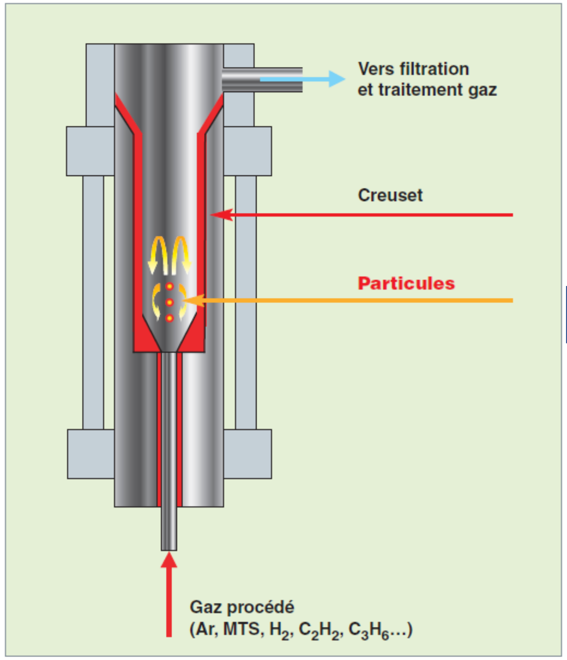
New types of fuel forms

Particulate fuels fabrication

Sol-Gel fabrication of the core

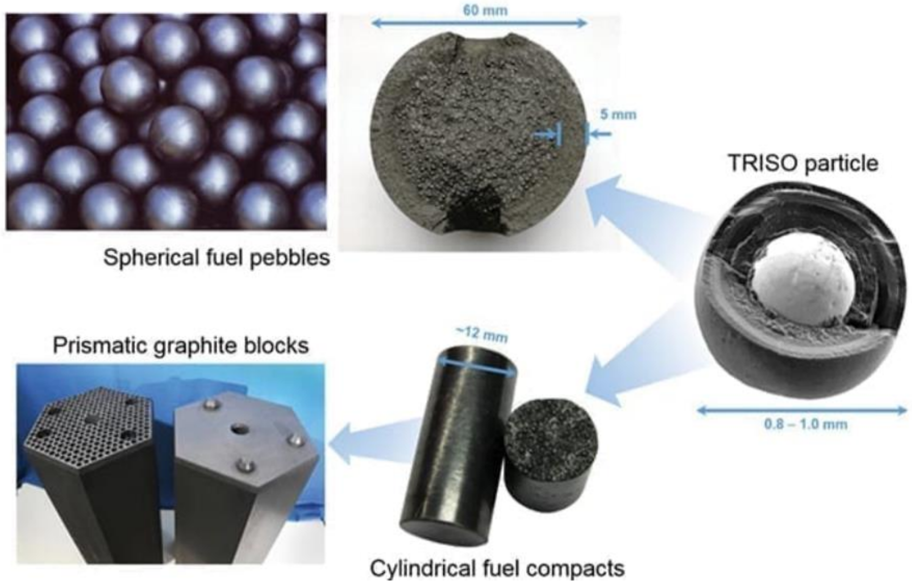


CVD coating of the core



Les combustibles nucléaires (CEA)

Compaction to form a variety of shapes, e.g.



Source: https://www.powermag.com/the-allure-of-triso-nuclear-fuel-explained/