Materials Issues in Present and future fission reactors

Yves Brechet
Haut Commissaire à l’Energie Atomique

Yves.brechet@cea.fr

Focus on

materials issues

since materials are what makes any

industrial design turn

into a reality

or into a dream, or into a nightmare

Present, Future and beyond…

Present

Two major issues

- Ageing of nuclear plants
  - Life limiting componant

  =>Pressure Vessel

  - Avaliability limiting componants

  =>Internals, piping

  - Fuel consumption limiting componant

  => Fuel cladding

- Decommissionning
  - Planned decommissioning

  =>Manipulation

  =>Waste Processing

  - Accidental decommissioning

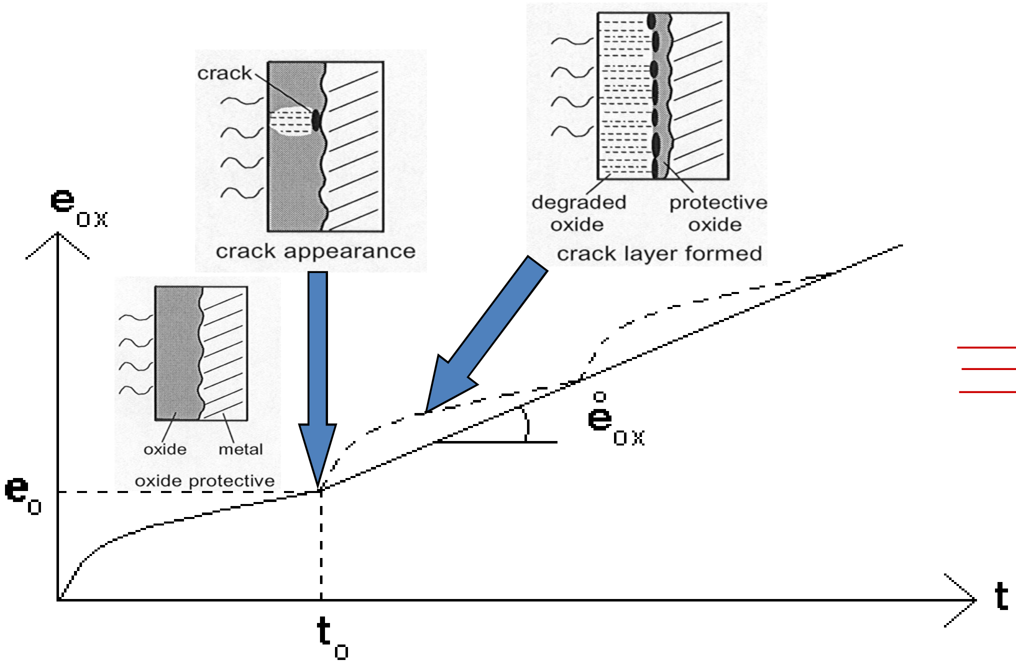
  =>Non standard Robotics

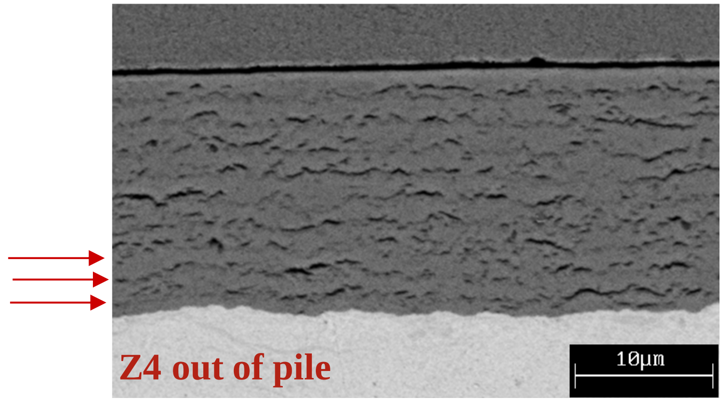
  =>Soil depullution

Consumables: Fuel Cladding

Oxydation of Zr alloys

Objective: Understanding the relationship between corrosion kinetics and material properties.





- Corrosion kinetics is periodic, cycles being separated by several transitions.
- Kinetic transitions are well correlated to a periodic cracking of oxide scales.
- Large compressive stresses due to variation of volume during oxidation.

Corrosion characteristics observed whatever the conditions.

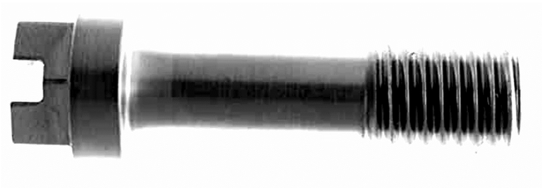
Missing link

- Coupling between internal stresses induced by oxydation and plastic relaxation in the metallic sublayer

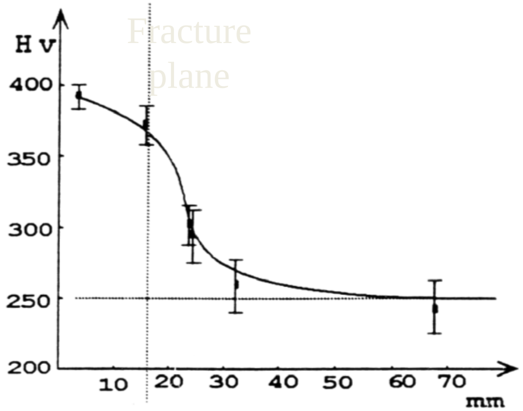
- Influence of irradiation on this process

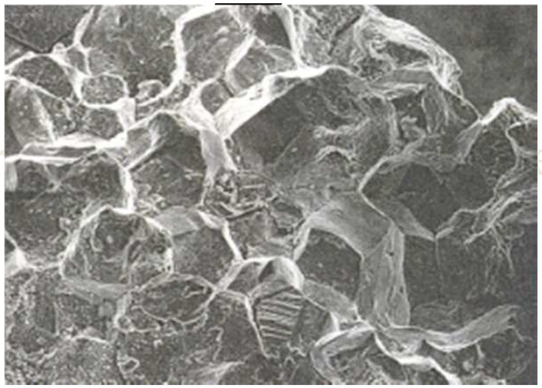
Repleacable: Internals

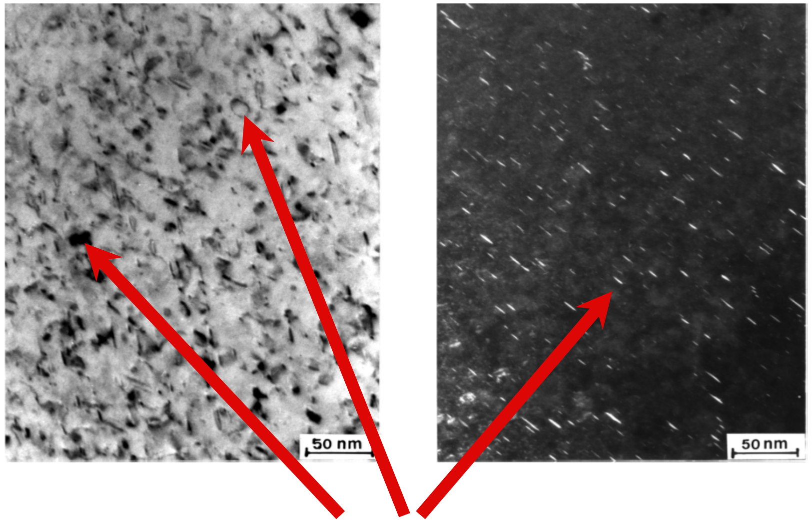
Fracture of internal screws in PWR



10 dpa **2 dpa**







Frank dislocation loops

$\rho \approx 2\ 10^{22}\ m^{-3}$ $\phi \approx 12$ nm

Vanishing of the initial dislocation network

Modelling techniques

- Cluster evolution: Cluster Dynamics methods:

  a chemical reation type of model to predict the evolution under irradiation of a distrribution of clusters of point defects

- Hardening and work hardening: Analytical methods

  Classical approach of physical metallurgy : collective pinning and internal variables modelling via KME approach

- Dislocation cluster interaction and cluster destruction : Molecular dynamics

- Clear band formation : Discrete Dislocation Dynamics coupled with defect cluster destruction

=> Modelling methods coming both from the Nuclear Materials tradition, but also from classical materials physical metallurgy

The Missing links…

- **Localisation bands** : what stress concentration ?

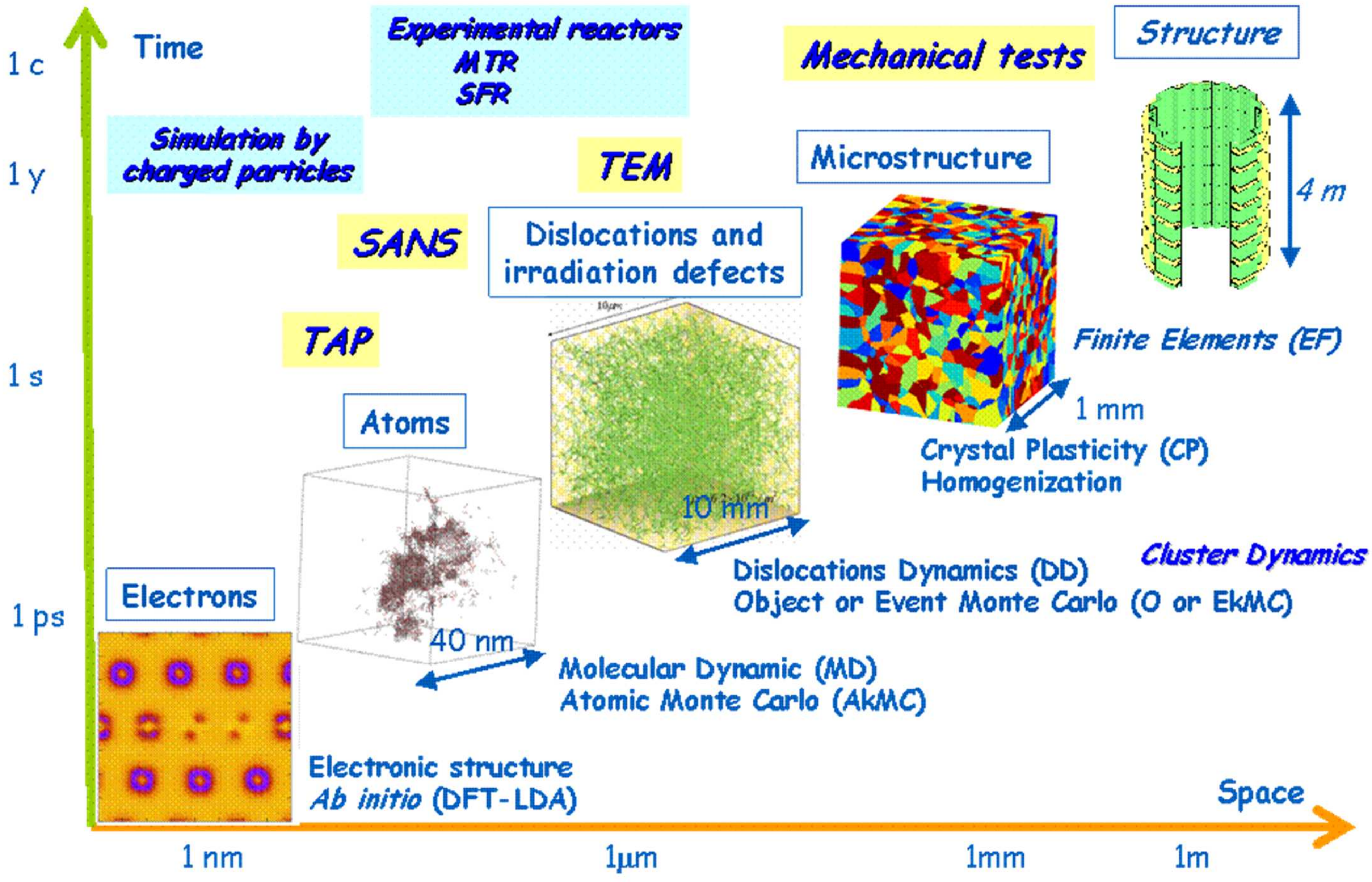
- **Fracture of the passive layer** via the localised bands

  Healing of the passive layer and competing phenomena: IASCC

- **Reduced ductility and reduced toughness**:
  - what is the relative importance of hardening effect and depression of strain hardening?

- **Irradiation creep : still not understood**
  - Possibility of an irradiation induced instability of the dislocation lattice ???

Non repleacable: pressure vessel



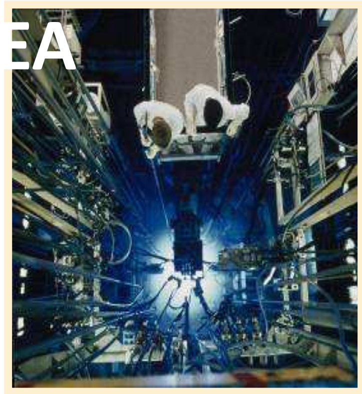
Time
1 c
1 y
1 s
1 ps
Experimental reactors
MTR
SFR
Mechanical tests
Structure
Simulation by charged particles
TEM
Microstructure
SANS
Dislocations and irradiation defects
4 m
TAP
Finite Elements (EF)
1 mm
Atoms
Crystal Plasticity (CP)
Homogenization
10 mm
Cluster Dynamics
Dislocations Dynamics (DD)
Object or Event Monte Carlo (O or EkMC)
Electrons
40 nm
Molecular Dynamic (MD)
Atomic Monte Carlo (AkMC)
Electronic structure
Ab initio (DFT-LDA)
Space
1 nm
1µm
1mm
1m

Missing links

- Good description of irradiation induced hardening
- A phenomenological description of temperature shift in ductile brittle transition due irradiation induced hardening
- Only empirical understanding of the « chemical aspect » of irradiation damage
- No fundamental understanding of toughness evolution

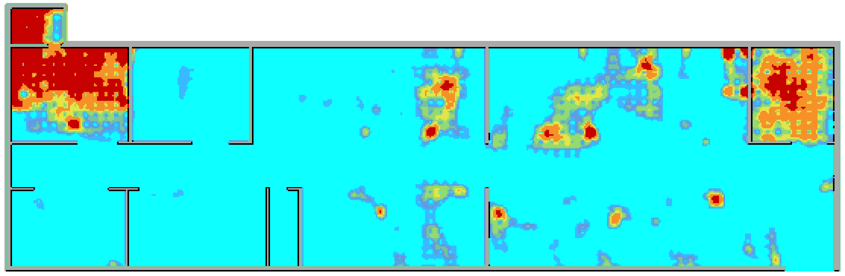
DECOMMISSIONNING

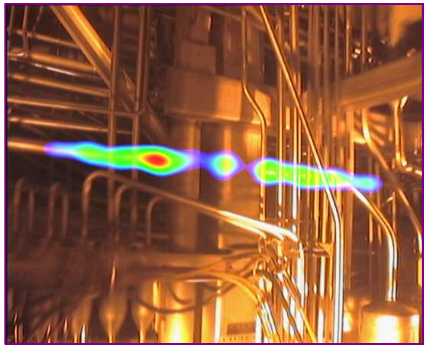
- **A wide variety of installations:**
  - Power plants : pools, reactors
  - Accelerators, irradiation devices,
  - Laboratories, workshops, fuel manufacturing plants
  - Waste management plants
- **No serie « standards »**
- **R&D equipments,**
  - Modifications during operation life
  - Variety of wastes,…
- **Used fuel treatment plants:**
  - highly contaminated plants
- **Historical Sites**



Evaluation of the initial state and of its evolution

- **Developpements :**
  - **gamma measure** (contamination of concrete,
  - **Alpha Camera :** Pu
  - **LIBS :** in situ measure of contamination
  - **Geostatistical approach to sampling**





Robotics

- **Developpements :**
  - **Teleoperated arm,**
  - **Laser cutting for thick plates**
  - **3D simulation and virtual reality**

Decontamination

- **Developpements :**
  - **Laser surface decontamination (ASPILASER)**
  - **Foams, Gels**
  - **Soil decontamination**

Additional difficulties after an accident

- **Evaluation of the initial state and of its evolution**

  =>Much higher levels of contamination, in a non closed space

- **Robotics**

  =>Motion in highly disturbed environment

  =>Insect Bio-inspiration?

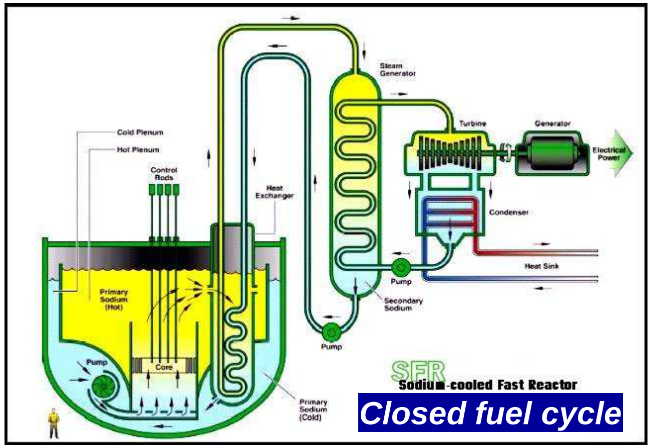
- **Decontamination**

  =>Phytoremediation

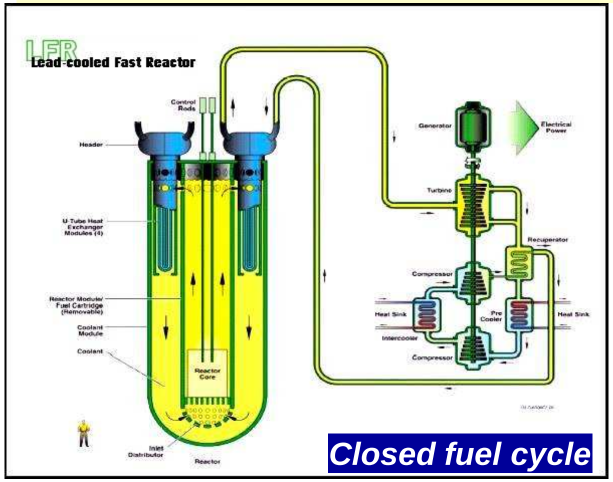
  =>Possible role of GMO

Future:
Gen IV reactors

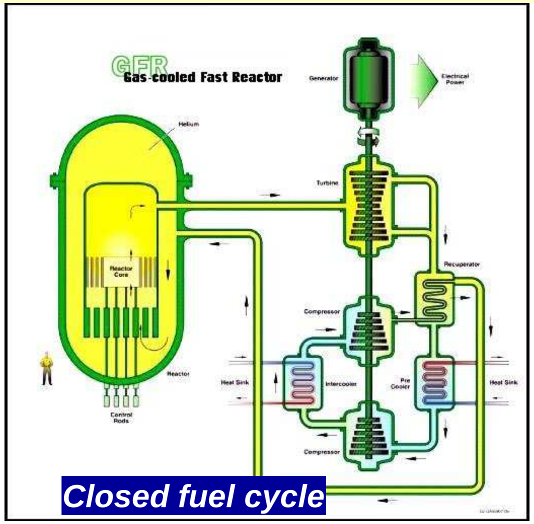
GIF Selection of six Nuclear Systems



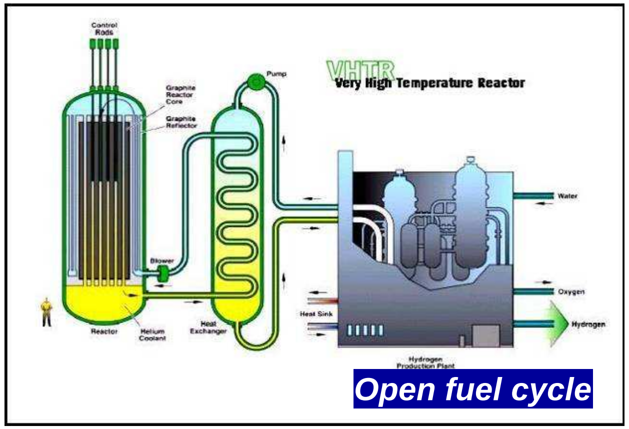
Sodium Fast Reactor



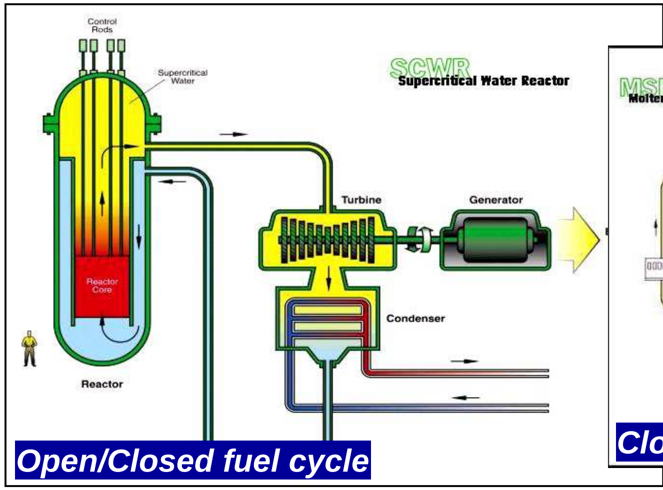
Lead Fast Reactor



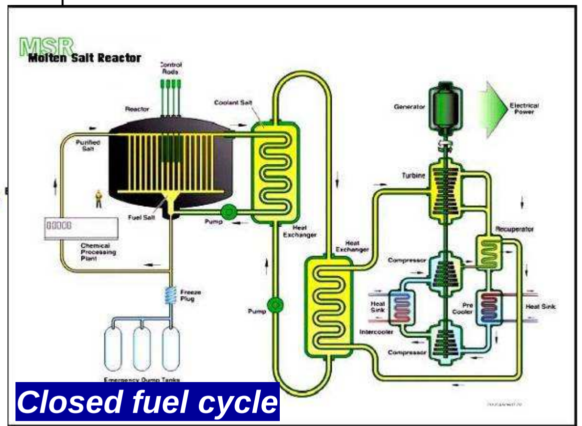
Gas Fast Reactor



Very High Temperature Reactor



Super Critical Water Reactor



Molten Salt Reactor

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

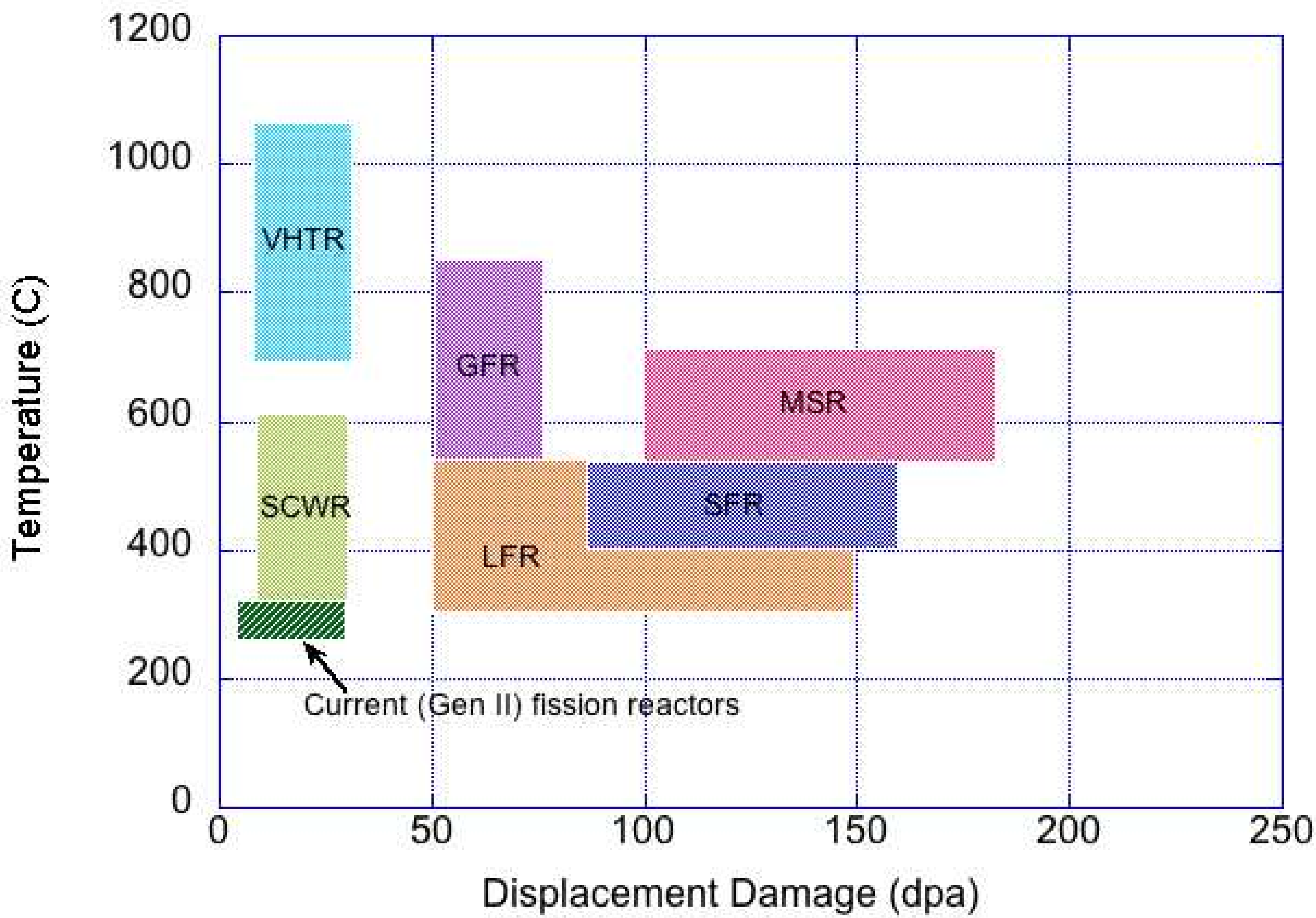
The new demands on materials are essentially due to the heat extractor fluid and to the increased operating temperature and irradiation required

Materials Environment Comparaison with classical PWR

	Fission (Gen. I/II) PWR…	Fission (Gen. IV)	Fusion (Demo)	NASA space reactor
temperature max	<300˚C	500-1000˚C	550-1000˚C	~1000˚C
Irradiation dose max	~50 dpa	~30-200 dpa	~150 dpa	~10 dpa
transmutation concentration He	~0.1 appm	~3-10 appm	~1500 appm (~10000 appm pour SiC)	~1 appm
Heat extracting fluids	H_2O (REP: pression 155 bars)	He, H_2O, Pb-Bi, Na	He, Pb-Li, Li	Li, Na, or He-Xe

No requirement on pressure

New reactors : Gen IV et Fusion
Comparison with classical PWR



Driving forces

Fast neutrons

- Toward a better management of transuranic fissile nuclides (especially Pu isotopes) generated by PWR technology
- Toward a better use of potentially fissile nucleides material resources

Efficient electric power generation

- Toward more efficient generation of electricity : increase the temperature of the thermodynamic cycle

Gen IV Project: The French decision

An international project

Increasing demands:

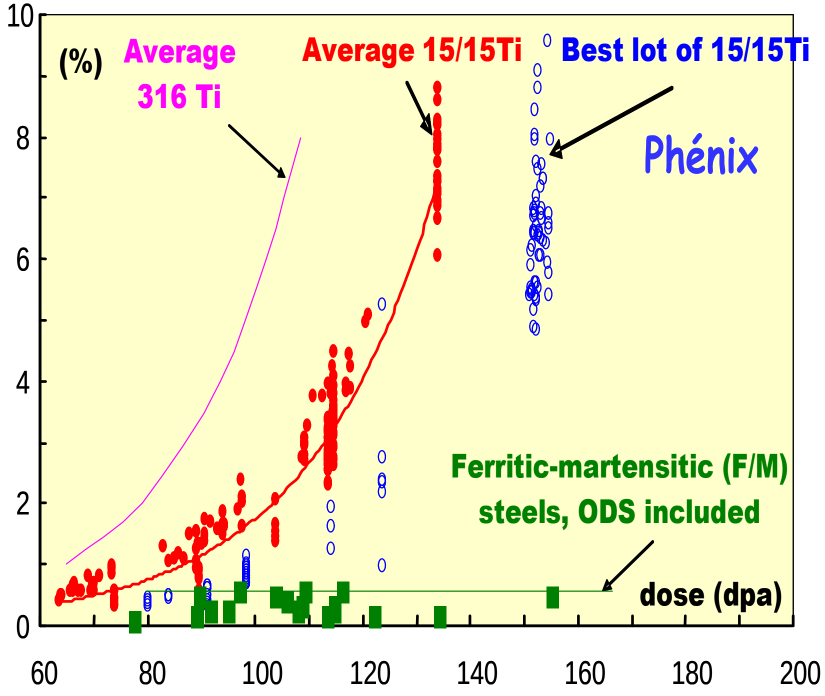
- Durability
- Safery
- Economy
- Non proliferation

Independance with respect to fuel esources
Management of theBack end of the cycle

Six concepts

- Gas Cooled Fast Reactor GFR
- Lead Cooled Fast Reactor LFR
- Sodium Cooled Fast Reactor SFR
- Molten Salt Reactor MSR
- Supercritical Water Reactor SCWR
- Very High Temperature Reactor VHTR

Innovative fuel cladding



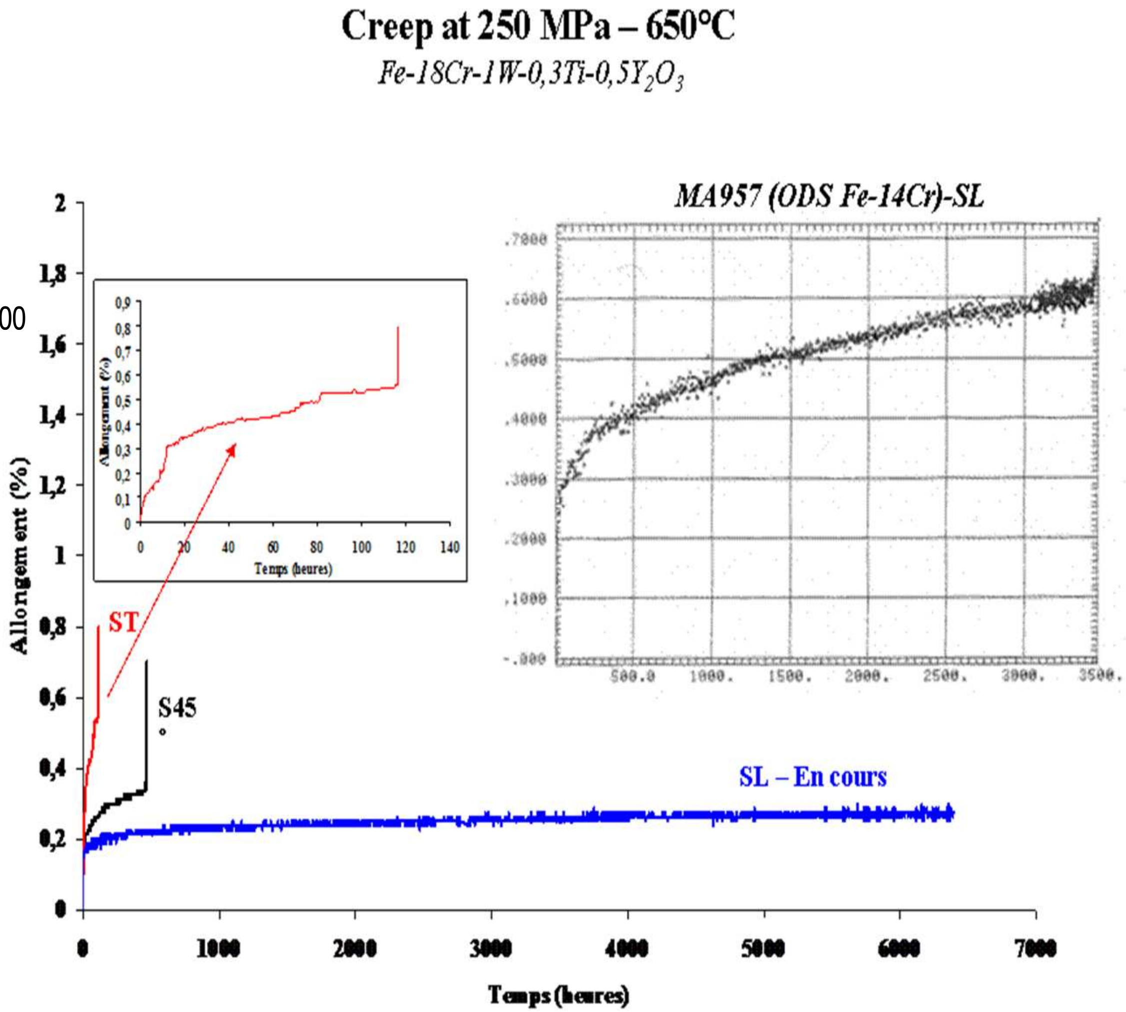
ODS steels for fuel cladding with a good Creep resistance and swelling resistance

Damage and onset of Tertiary creep in reinforced alloys

Irradiation creep?

Role of interfaces?

Anisotropy and reX ?



Coolant in Fast breeders

Heat exchange : a major issue
Coolant : a central actor

- Conflicting requirements: confine radioactivity and transmit heat
- Importance of exchange surfaces : maximize surface to minimize thermal gradients
- Requirements for thermodynamic efficiency : increase temperature, increase pressure
- Avoid phase transformation in the fluid!!!

Constraints on the coolant fluid

Thermal constraints

- Transport Heat : **Heat capacity** ρCp
- Remain **single phase** : Tf, Te, **pressure**
- Being pumped: **density, viscosity**

Neutronic constraints : thermal neutrons vs fast neutrons depending on the neutrons/atoms interaction : **Capture/fission**;

chemical nature/atomic density

Issues with the coolant fluid (1)

- Possible radio-activation of the coolant
  - **Chemical nature** + impurities
- Interaction fluid /**materials**
  - Corrosion
- Interaction fluid /structure
  - **Pressure** => creep, plasticity, fracture
  - Vibrations =>**fatigue**
- Interaction fluid /**surfaces**
  - Boundary layers (hydrodynamics, chemistry)
  - **Exchange layers** (heat transfer, phase transformation)

Issues with the coolant fluid (2)

- Fluid **etancheity** (pumps, valves…)
- Control (non destructive testing)
- maintenance (reparation, replacement of components…)

- Loading / unloading the fuel while cooling
- Interaction with
  - air, with the secondary circuit
  - the whole cold source
  - thermodynamic work

Fluid coolants: a comparison?

	Sodium	Lead	Molten Salt	Helium
Better use of fuel resources (U, Pu, Th…)	+++			
Better efficiency of heat conversion (higher T)				+++
Better interaction fluid structure (corrosion)	++	--	---	+++
Easier operation condition and maintenance	--	--		

Scientific issues to be adressed

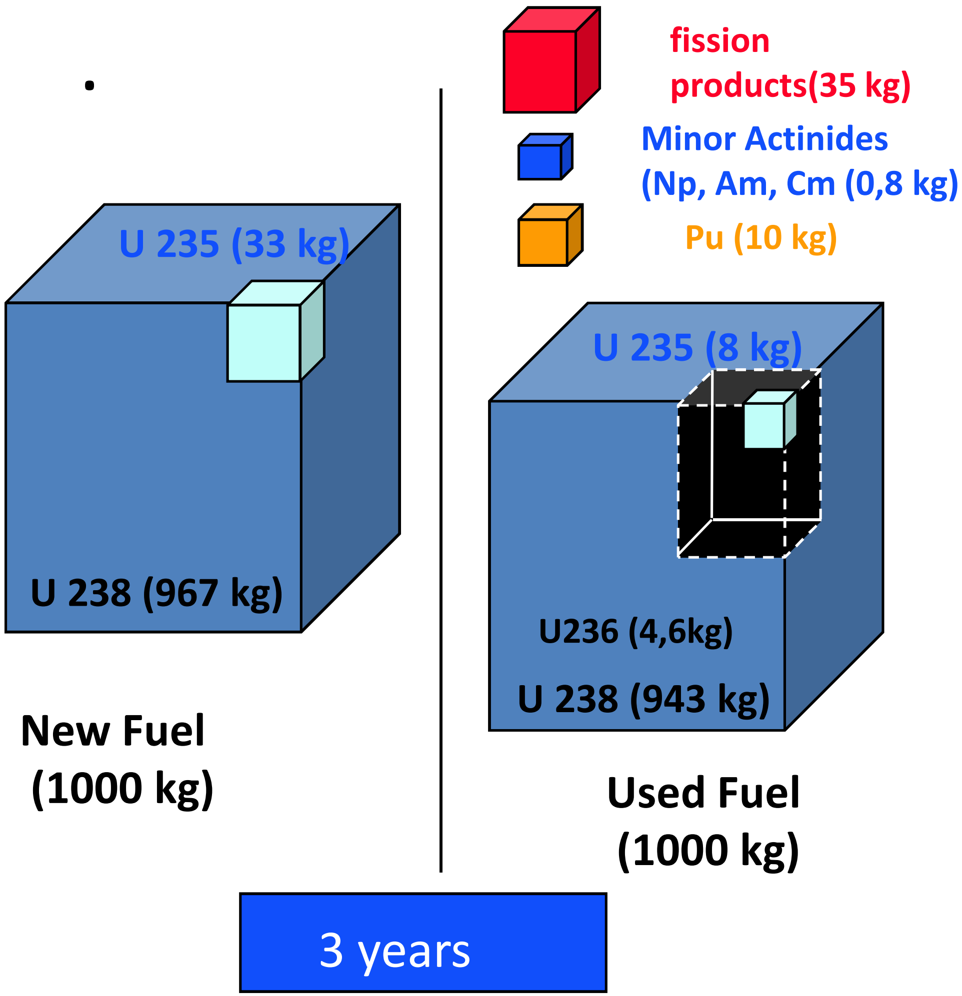
- Liquid metal interaction with the structures: possible conditions of grooving, of GB embrittlement
- Interation fluid / surface / fluid transport to understand the conditions and kinetics of phase transformation
- Thermohydraulics and turbulence in confined geometries. What is the physical foundation of the phenomenological rules?
- Interaction between the structural materials and a chemically agressive environment: what is the influence of the metallurgical structure?

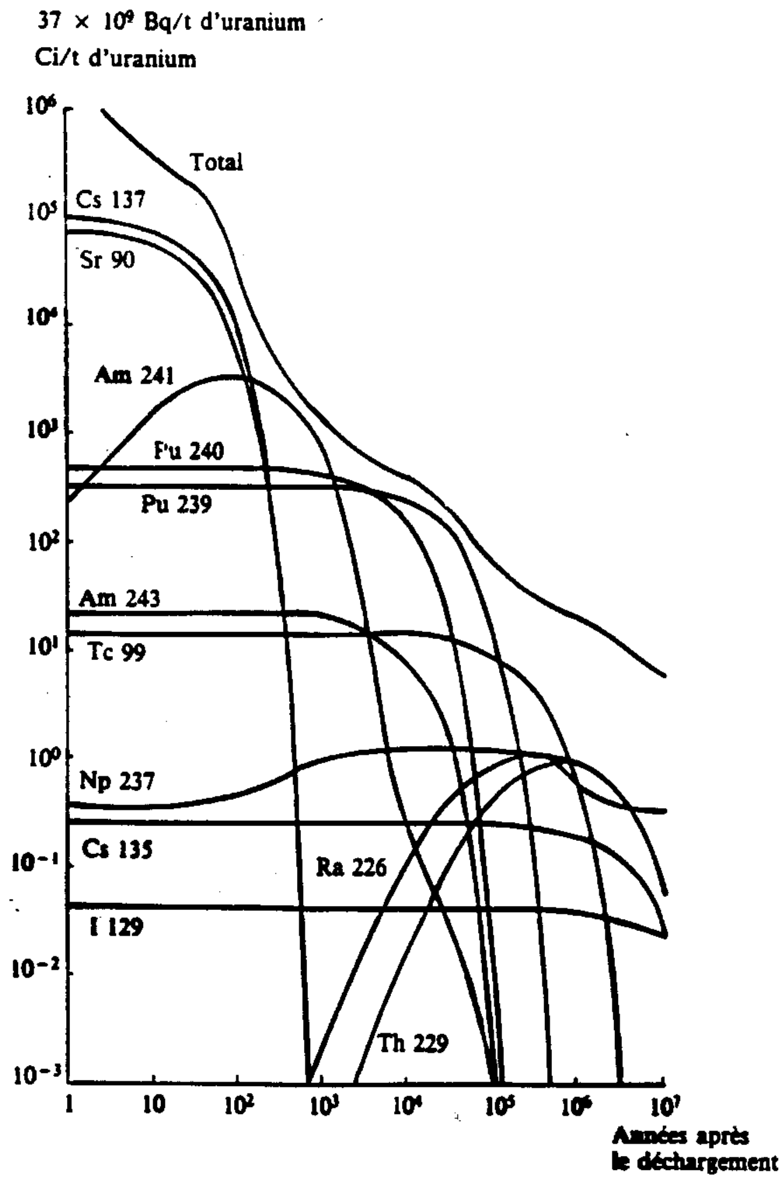
Technical issues to be addressed

- Size/power of the « energy production system » as function of the coolant
- Fluid of the converting system (gaz or vapour)and thermodynamic cycle: pro’s and con’s
- Etancheity of pumping devices and alternative to mechanical pumps
- Chemistry of the fluid and chemistry control, globally, locally and in leaking situations
- Materials and materials implementations (especially welding)
- Non destructive testing during operation and maintenance
- Cleaning of the componants, cleaning of the coolant fluid
- Confinement? Protection agains radioactive leaks and cooling: what are the alternatives?
- Availability of the industrial tool to make things
- Availability of people. Training?

Beyond ….

The High activity long life nuclear waste





The french solution : deep geological storage

- **Fission Products**:
  - Glass
  - Additional Protection by stainless steel

Engineering solutions (Glass) to prevent diffusion of fission product during 500 years

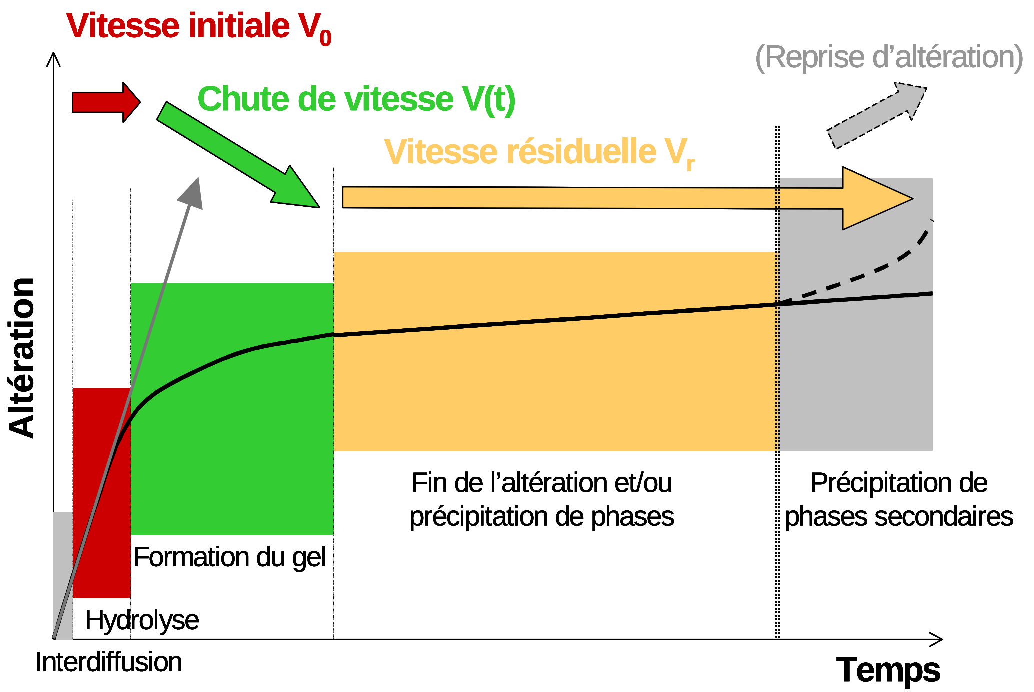
- **Actinides**
  - Plutonium: reprocessed inside the cycle
  - Minor Actinides (Am, Cm, Np)

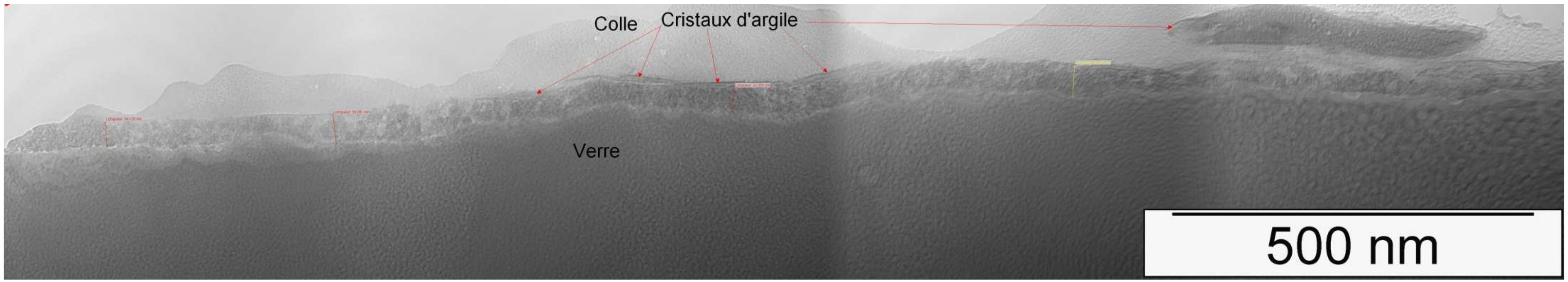
  ⇒ Transmutation?

  ⇒ Deep geological storage

Geological storage (argilite) to trap actinides for a few 100 000 years

Materials issues : glasses





Missing links…

- Basic understanding on Transport in disordered systems and transport under irradiation

- Mechanical stability of the « protective gel » on the time scale of the storage , and influence of irradiation on this rheology

Conclusions

Some fundamental questions on the role of modelling

What research to be done?

- Qualification of materials
  - Be as close as possible to operating conditions
  - Be as close as possible to the materials to be used in power plats
- Understanding Mechanisms
  - Model materials in relation with multiscale modelling
  - Critical experiments

Role of simulation?

- Changing length scales
  - Damage at the atomistic level, consequences at the macroscopic level
  - Required for alloy design
- Changing time scales
  - Test carried out on much shorter timescales than operating time scales
  - Required for Life management and safety

Caveat

- Multiscale modelling platform should not hide the missing fundamental blocks
- Understanding the missing blocks requires studies on model materials
- Basic phenomena not understood in classical physical metallurgy are unlikely to be better understood with the extra complexity of irradiation

- Only if we admit that we can hope to go beyong qualification toward real materials development, in a realistic manner , combining experiments and modelling