Progress in fuels for fast reactors

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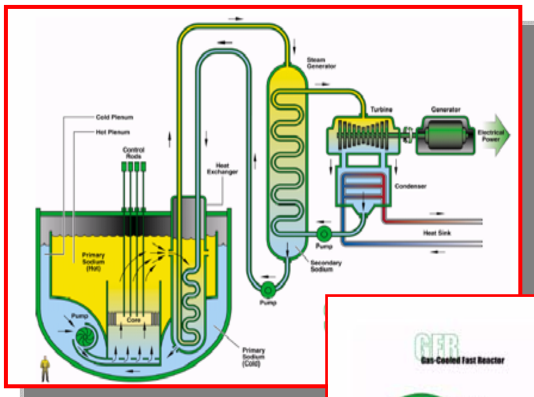
Nuclear strategy for future reactors

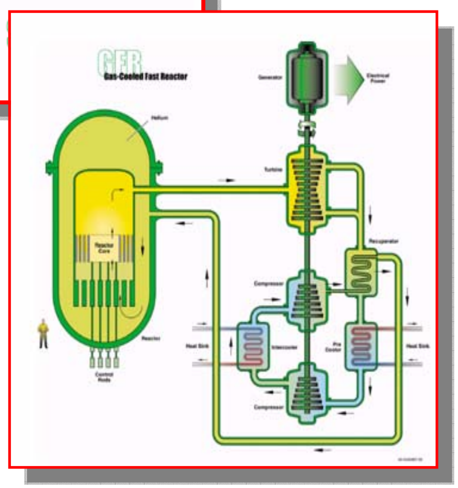
President Chirac decision beginning of 2006

and

French waste law, june 28th 2006 :

GENIIV prototype reactor in service in 2020





1. Sodium fast reactor is the favorite candidate : background with innovation
2. Gas fast reactor is an alternative : experimental reactor ETDR to be decided in 2012
3. Both open to international partnership
4. Wide R&D programs to adress key points
5. Technological choices in 2012
6. Industrial development around 2040

Goals of future system reactors

CLOSED CYCLE

- Flexible and efficient use of natural ressources
- Significant reduction of long life radioactive elements in ultimate waste
- Proliferation resistant technologies and processes

REACTOR OPTIMISATION

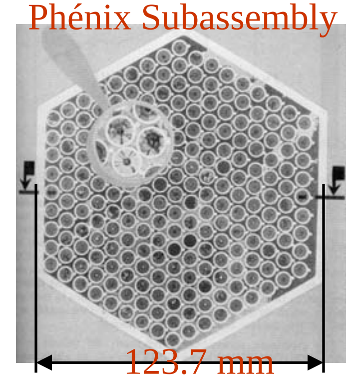
- Enhanced economic competitiveness
- Still enhanced safety and reliability

Standard oxide SFR fuel element has been largely experienced

Fuel : (U,Pu)O_2

- Advantages
  - High melting point > 2 700 °C for 20% Pu
  - Excellent stability under irradiation
- Disadvantages
  - Poor thermal conductivity : 2.9 $W.m^{-1}.K^{-1}$
  - Chemical reactivity with sodium

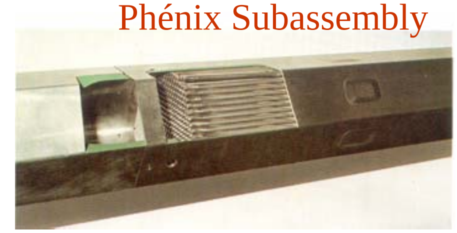
Cross-section of Phénix Subassembly



Cladding : swelling is a limitation for high burn up of SFR fuels

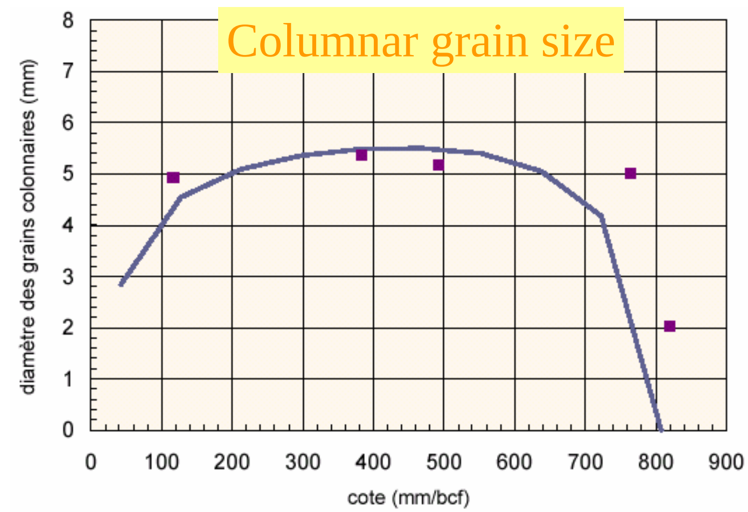
- Austenitic Steels seem limited to 130 dpa
- Oxide Dispersion ferritic Steels (EM10) could combine the swelling resistance of ferritic steels and thus allow to reach more than 160 dpa

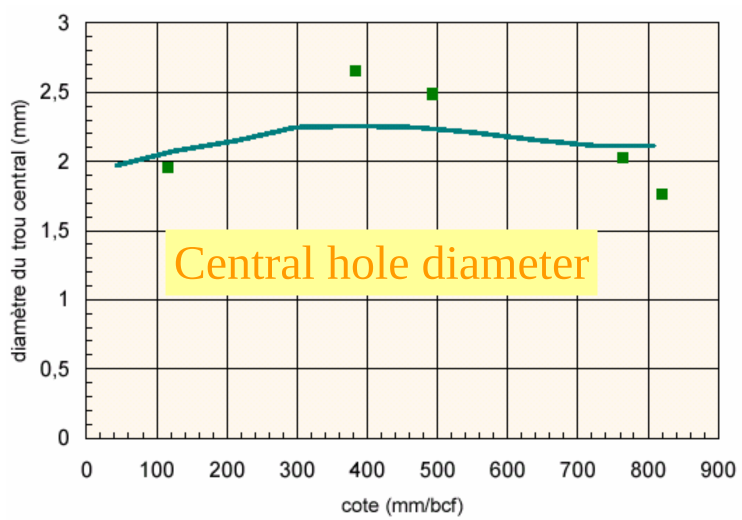
Phénix Subassembly

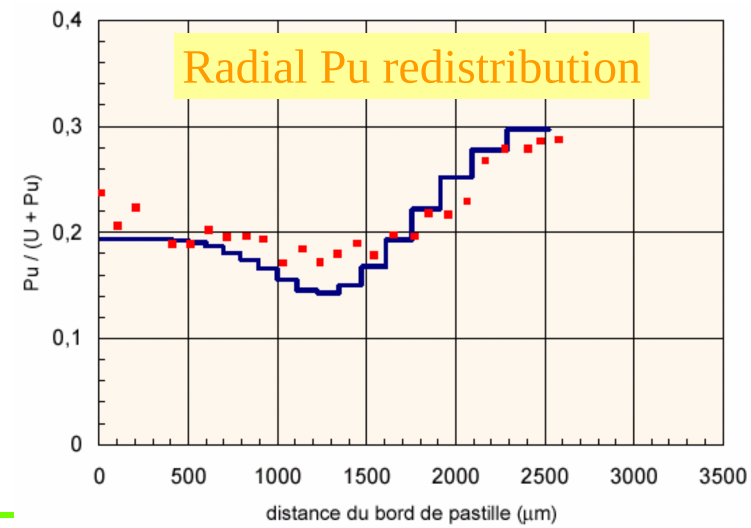


… and well simulated by calculation

- Example : SANTENAY 1
  (BU = 9 at% ; LHR ≈ 550 W/cm)







MA SFR oxide fuel : SUPERFACT 1 experiment

- Demonstration of the MA (Am and Np) transmutation feasibility (Collaboration between ITU and CEA)

- 1986 to 1988 : Irradiation in Phénix Reactor

- Fuels
  - 2 Am Pins : Solid solution $(U_{0,74},Pu_{0,24},\mathbf{Am_{0,02}})O_2$
  - 2 Np Pins : Solid solution $(U_{0,74},Pu_{0,24},\mathbf{Np_{0,02}})O_2$

- Linear power
  - BOL : 380 W/cm (std : 430 W/cm)
  - EOL : 325 W/cm (std : 370 W/cm)

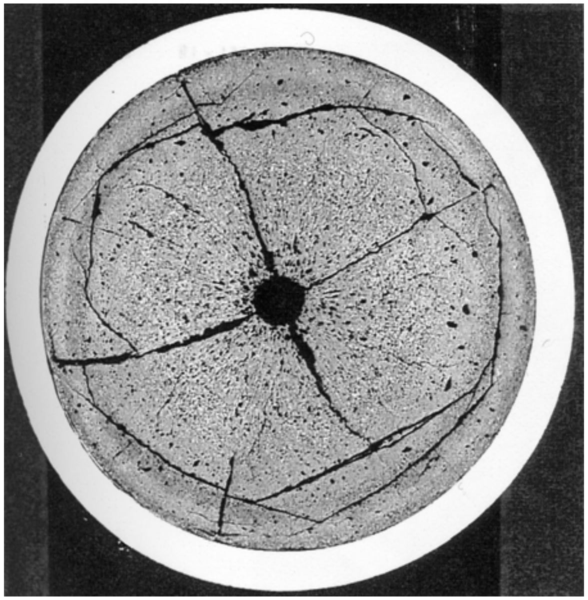
SUPERFACT 1 : Results

⇨ Transmutation ratio at the reactor middle plane are ≈ 30 % for ^{237}Np and ≈ 28 % for ^{241}Am

- Same fuel microstructure evolution than standard fuels ones

- U, Pu, Am and Np radial distributions are very flat → No actinides redistribution

⇨ **For low Linear Power, no real influence of the low MA amount up to a BU equal to 6,7 at%, except for the He release of the Am fuel (4 times greater than standard pins ones)**



MA fuel manufacturing Process

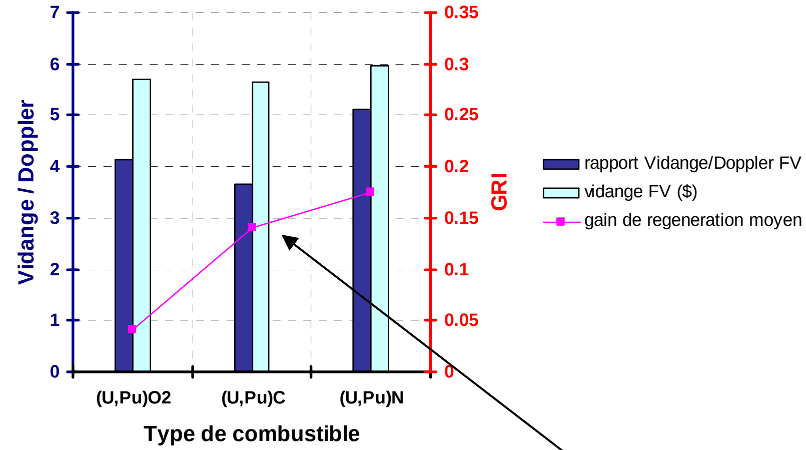
- Powder Metallurgy Process will be very difficult (and expensive) for MA Fuels
  - Contamination by fine powders
  - High number of steps for pellets and pins manufacturing
- New process :
  - limited powder handling and no separation of MA
    - ✓Coprecipitation of powders + Powder Metallurgy
    - ✓Low Pressure Injection of a plastic paste containing coprecipitated powders
  - or avoid powder handling and simplify pin fabrication
  - ✓Sol-gel process and spherepac process

⇨ **Two innovative manufacturing processes must be investigated**

Alternative for SFR fuel

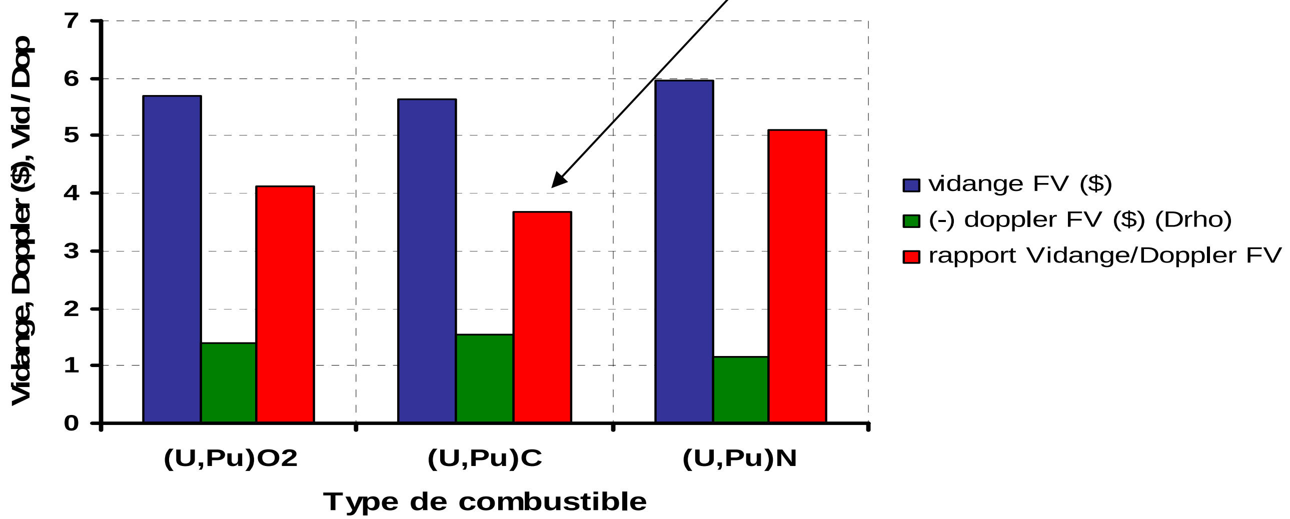
High density fuels (carbides, nitrides) will be assessed as they may help designing cores with enhanced intrinsic neutronics characteristics

(void worth, doppler coefficient)



Dependance on the fuel material is weak for safety parameters, but significant on the breeding ratio

(U,Pu)C looks a good compromise for lower void/Doppler ratio and higher breeding ratio



International collaborations for irradiation tests of SFR Fuels

- Phénix shut down is planned in 2009
- BOR60 could be stopped in 2010

⇨JOYO could be the last experimental SFR

⇨A collaboration framework between DOE, CEA and JAEA is currently in discussion in order to define a common program, particularly on SFR fuels

MA SFR fuels : conclusions

- Large experience accumulated on standard SFR oxide fuel
- SFR oxide fuel behaviour is modelled with a good accuracy even for high burn up and high linear power
- Good results on Superfact experiment has been obtained on MA oxide Fuels

- **MAIN GOALS for MA SFR fuel :**
  - **manufacturing process for MA fuels**
  - **behaviour under irradiation**
  - **optimisation of ODS up to 160 dpa**
  - **enhanced burnup**
  - **Still enhanced safety**
  - **modelling**
- **In addition assess dense fuels (carbide, nitride) as alternative candidates**
  - **Optimisation of MA incorporation**
  - **Enhanced safety**

The fuel element is identified as one of the major feasibility issue of the GFR

- **high heavy atom density** (typically fuel/structure/gas : 50/10/40 vol%),
  - high volumic ratio **fissile phase / inert materials in the fuel element (between 50 / 50 and 70 / 30)**
  - **dense fissile phase like** carbide or nitride**,**
- fissile phase composition: **18-20% Pu + 78-80% U + 2% M.A.** (Minor Actinides: Am, Np, Cm),
- Fuel temperature of about **1000-1200°C** in normal condition, **~1600°C** in case of a depressurization with fission products **confinement**

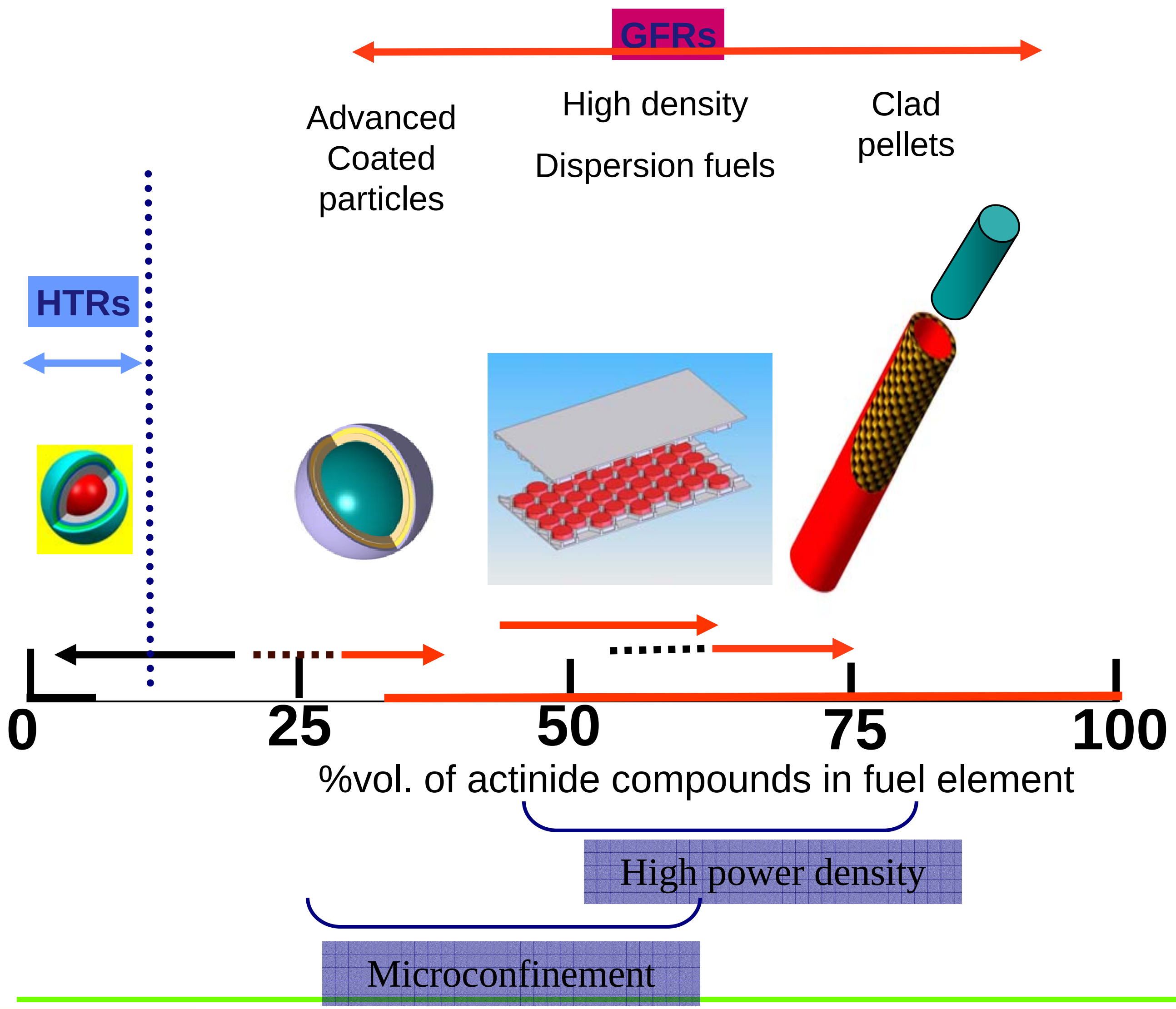
Main fuel requirements for GFR design

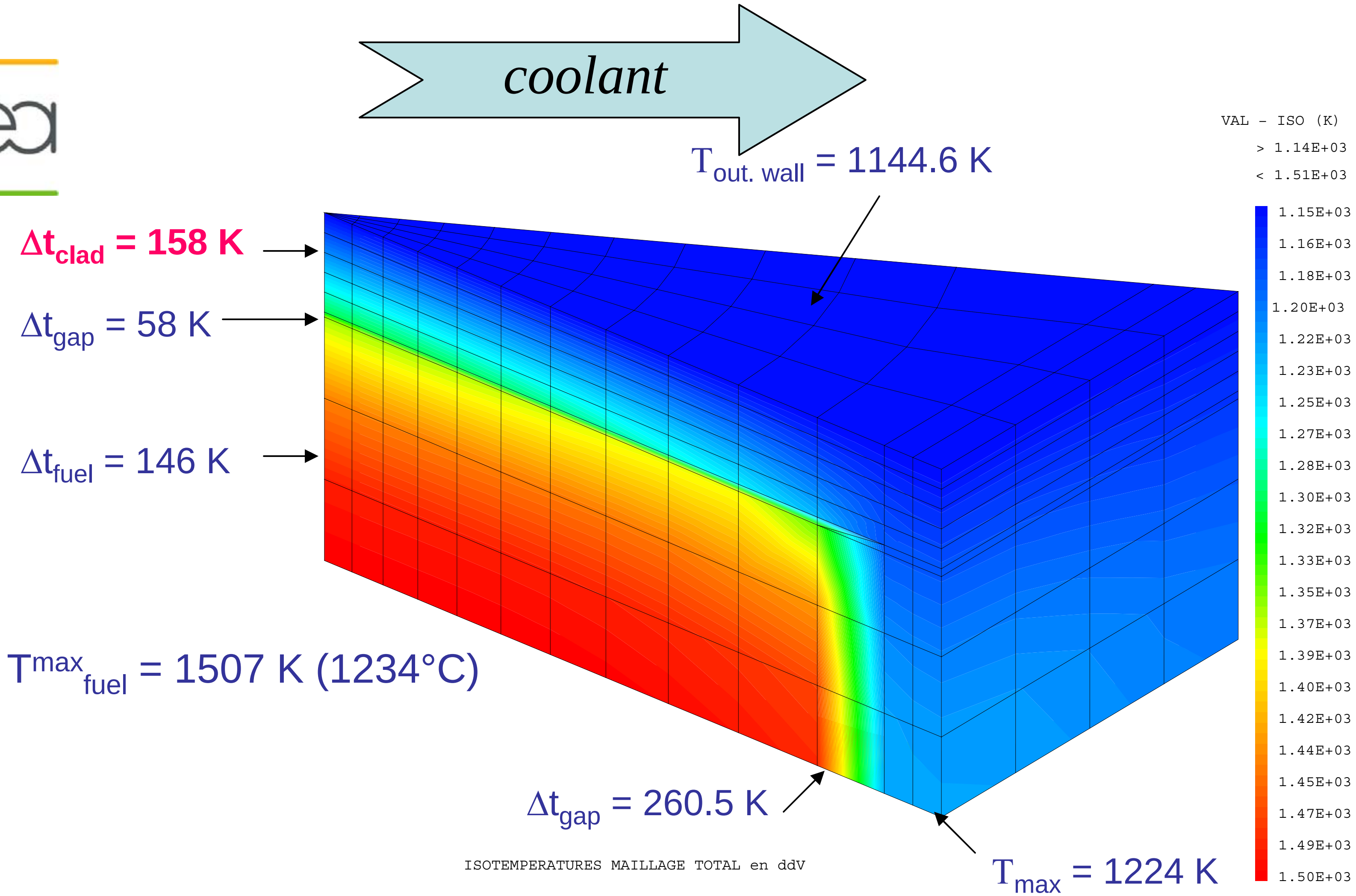
- **High helium temperatures (outlet 850°C)**
- **Low thermal properties of heliumi induces high temperature for cladding**
- **but « cold » fuel element is needed**
  - Extended life time (gaseous FP release)
  - Safety in case of depressurization : the low is the temperature , the safe is the reactor
- **And FP confinement**

- **Plates design with ceramic cladding and dispersed fuel is the reference for GFR fuels**

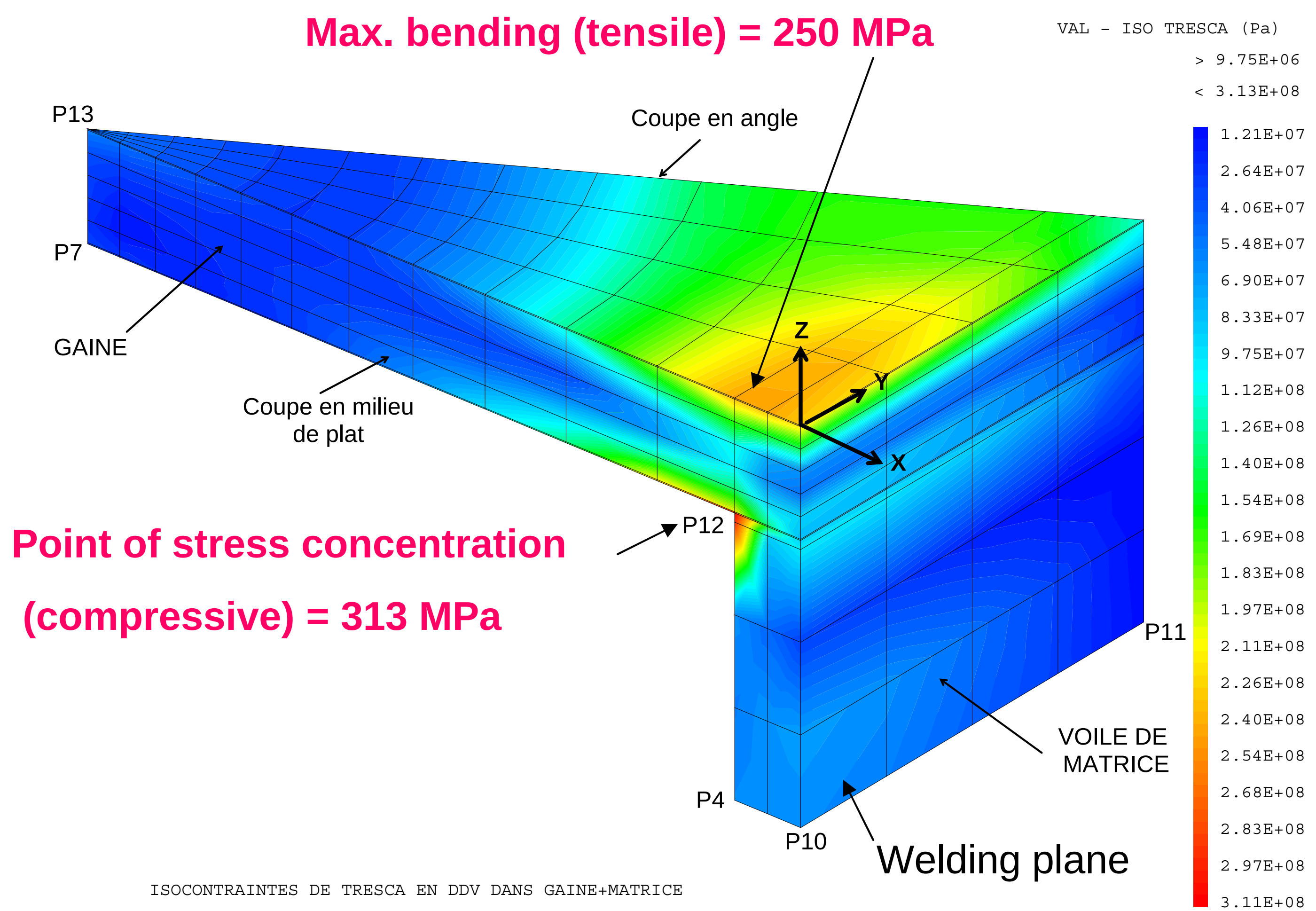
- **Pin design is the alternative**

GFR fuel designs





R/D key point : improve thermal conductivity of the clad

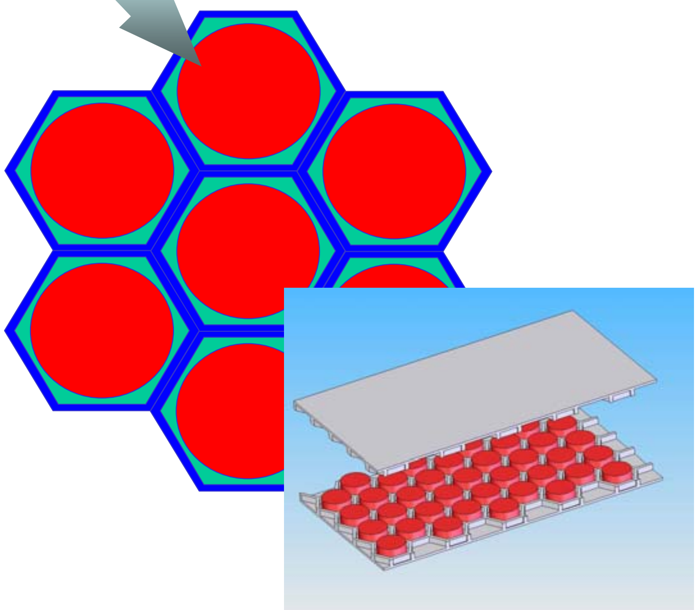


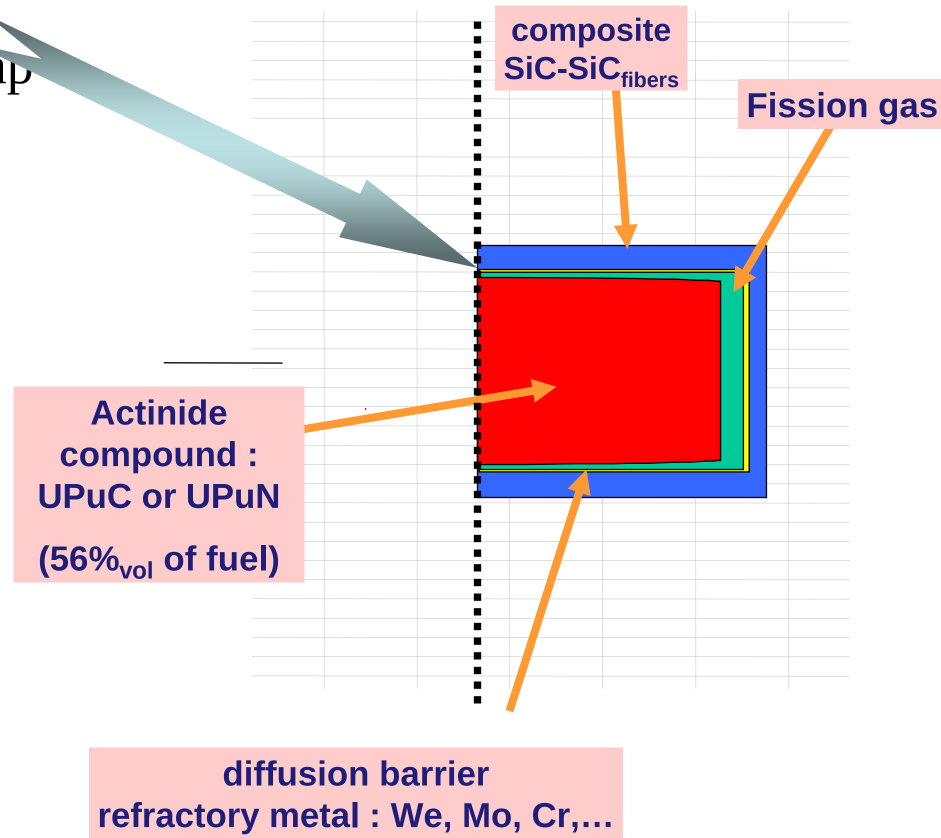
R/D key point : understanding of mechanical properties of the clad

Plates with pellets : first design

Axial gap : closed at BOL to have homogeneous thermal behaviour

Radial gap: closed at EOL to trap gaseous fission products





CEA Patent

Plate design : predicted behaviour under irradiation

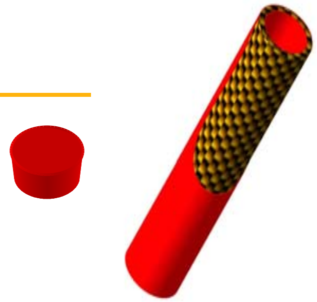
- Thermomechanical: *« designed for »*
  - Low temperature with axial gap closing at BOL (heat transfer) and radial gap closing at EOL (swelling, FGR)
    → Nominal : Max Temp. 1350°C, depressurization : T~1650°C
  - Low level primary stresses, gap sized for 70 bars of int. pressure at EOL.
  - A reasonable level of secondary stresses: compressive stress (~30 MPa), 1 point under tensile stress (175MPa)
- Thermochemical : suspected eutectic (1600-2000°C) between IM/FC : barrier needed
- Tightness:
  - FP and helium tightness
- Effect of minor actinides :
  - Free volume for He (IM vol. reduced)

GFR pin : thermal behaviour and gap closing

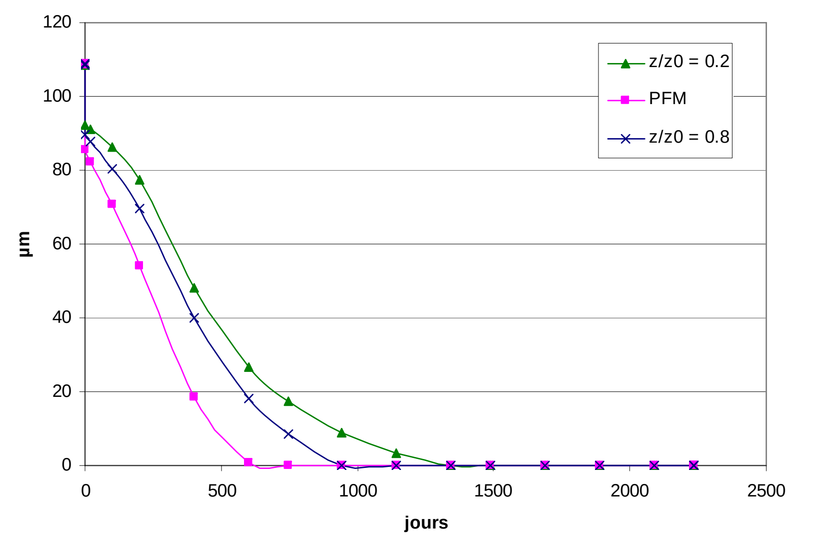
Pellet : UPuAmC, UPuAmN **Φ = 5,92 mm**

Clad: SiC-SiC$_{fibers}$ **Φ_{ext}/Φ_{int} = 8.15 /6.15 mm**

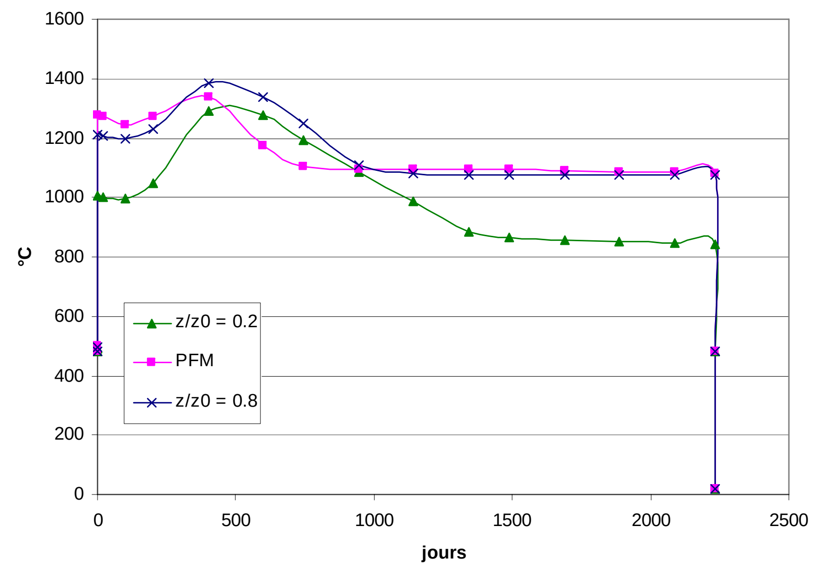
$e_{cladding}$ = 1 mm



Radial Gap pellet/cladding



Fuel temperature (max °C)



gap closing : too fast

Pellet Cladding Mechanical Interaction

1/ High temp. → FG release and swelling activated

2/ gap pollution → temp. ↗

3/ Then pellet swelling → gap closing

4/ temp. Stabilised after pellet/cladding interaction

Pin concept : predicted behaviour under irradiation

- Thermomechanical:
  - Temp. Max of FC : 1400°C with a possible decrease of 100-200°C with closed porosity (FGR<10%), internal pressure and gap size optimisation
    → **increase gap conductance**
  - Cladding stress < 50MPa **before** pellet/cladding mechanical interaction, **after** >200MPa in tensile stress
    → **Burn up limited (8-9at%)**
- Thermochemical : suspected eutectic (1600-2000°C) between IM/FC : *liner needed*
- Tightness: *liner needed*
- Effect of MA :
  - Free volume for released He outside the core (pin plenum)→ no effect on power density but effect on core size

R&D on ceramic materials ($SiC-SiC_{fiber}$ …)

- **$SiC-SiC_{fiber}$ … : Fiber, interphase, matrix optimisation**
  - Thermal properties,Toughtness
  - Tightness, Thermal creep, Swelling
  - Strain capacity,
- **Liner, coatings**
- **Interaction between materials (Helium, materials, FPs …)**
- **Damage under irradiation**
  - Osiris and Phenix are testing many materials
  - Experiments with proton or ion
  - Implanted materials
  - …
- **Modelling**

Main neutron irradiations on GFR R&D

FUTURIX MI : inert material intended to GFR in Phenix (EOL 2009)

CARBIDES – NITRIDES – REFRACTORY METALS

- Representative of operating conditions
- High temperature : 900 – 1000°C
- Fast neutron fluence : closed to 10^{27} n m^{-2}
- Dose $_{max.}$ 42 dpa $_{SiC}$

FUTURIX CONCEPT : UPuN, UPuC/TiN,SiC in Phenix (EOL 2009)

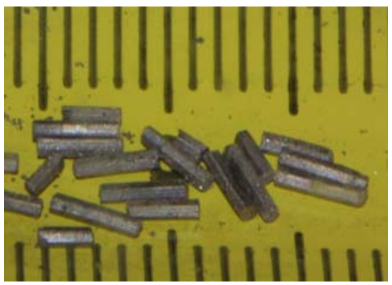
- Power density: 40 à 100 MW/m3 of core
- Max. temperature : 700 - 1200 °C
- Burn-up : 5 to 10 at. %
- Dose $_{max.}$ 42 dpa $_{SiC}$

GFR-REA in OSIRIS reactor : Material irradiations (EOL 2006 and 2008)

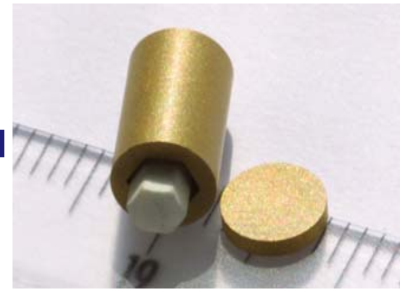
- Neutron damages on liners materials(W, W-Re, Mo, Mo-Re, V, Cr, Nb, Ti) and ceramic weldings (BRASIC, SPS, …)
- Composite ceramics under irradiation testing (creep test such as BSR),
- Welding of composites or liners testing
- Around 500°C up to 2 dpa

IRRDEMO : Demonstration on pre-selected materials and designs (EOL 2012)

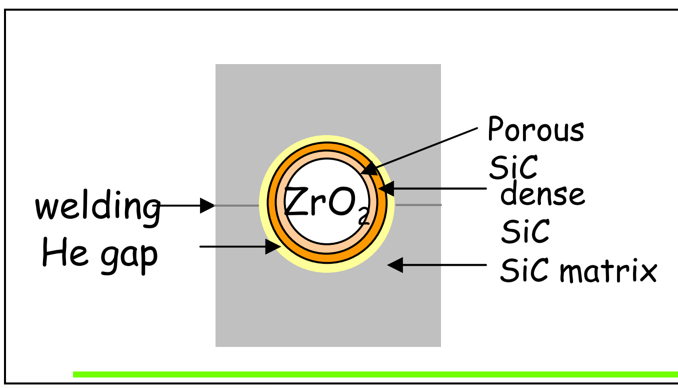
Experimental pellets

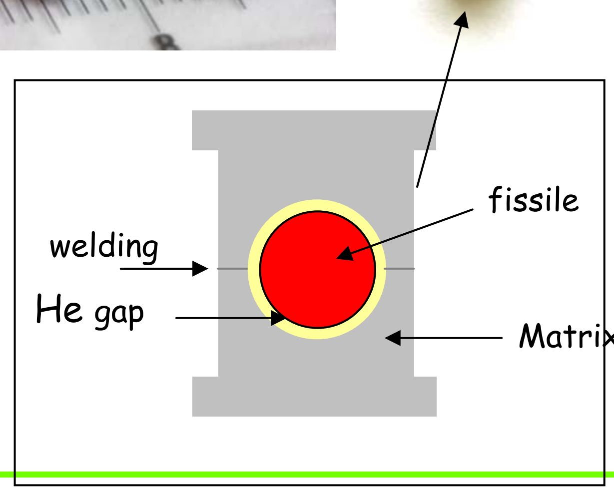


UPuN / TiN



UPuC / SiC





Objective : to study irradiation creep of fibers

MECASIC device under ion beam (JANNUS project)

Traction ,Creep, Dilatation
Electrical conductivity
from : 20 to 1600°C

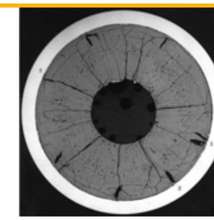
CEDRIC device under neutron irradiation (Osiris)

On line elongation measurements
600°C to 1000°C
Strained situation : 200MPa

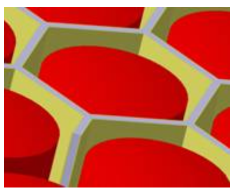
International collaborations for GFR Fuels

GENIV: PMB GFR fuel	USA, Japan, France	GFR fuel
INERI-GFR fuel	CEA-DOE (INL, ANL, ORNL, LANL)	GFR fuel : design, fabrication, behaviour ATR irradiation
irradiation FUTURIX-MI in Phénix	DOE	inert materials high temp. & fast fluence
Europe : GCFR-STREP WP2	ITU, HFR, NRG, CEA	GFR fuel: design, fabrication, behaviour
Kyoto university	Pr Koyama	R&D composite: SiC-SiCf

Orientations for fuel element in future reactor systems



- SFR fuel element design
  Reference: pin type fuel
  - with MA in UPuO2 and ODS cladding
  - Main issue on MA fuel manufacturing and ODS optimisation
  - Assessment of dense fuels
  - Still enhanced safety



- GFR fuel element design
  Reference: plate type fuel, option: pin type fuel
  - MA in UPC / UPuN with inert matrix-cladding
  - Main issue on MA fuel manufacturing ceramic material c P barrier ….

- Both fuel element development with an irradiation program.
  - First step : material and design selection (Phénix, Osiris, Joyo …)
  - Second step : technological choices (2012)
  - SFR prototype : 2020
  - GFR experimental reactor (ETDR) and GFR prototype to be decided in 2012
  - Industrial reactors : around 2040