MOX FUEL FOR ADVANCED REACTORS

Nathalie Chauvin
CEA, France
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Meet the Presenter

**Nathalie Chauvin** is working at CEA Cadarache IRESNE in the fuel Studies Department International Expert on fuels for fast reactors. She worked for a long time on the minor Actinides transmutation program, participating to the optimization of the fuel design, the irradiation experiments and the synthesis reports. Then she was project manager for the development of very innovative fuels for the Gas cooled Fast Reactor with oxide/carbide fuels, refractory cladding including ceramic composites one for pin or plate type fuel element. She is now in charge of international cooperations devoted to fast reactor fuels development as 1) Chair of the Working Party on the Fuel Cycle at OECD/Nuclear Science Committee; 2) Chair of the Expert Group on Innovative Fuel at OECD/NSC/WPFC; 3) GIF French representative in the GFR system – Fuels & material; 4) Project manager of PUMMA (Plutonium Management for More Agility at EURATOM); 5) Leader of fuel properties workpackage in the project ESFR-SMART; 6) French representative in the CRP on Fuels and Materials for Fast Reactors at the IAEA. She is also participating in several activities in different scientific committees of international conferences (IEMPT, FR GLOBAL), and she is the CEA counterpart in several bilateral collaborations with other international scientific organizations devoted to MOX fuel.

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# Nuclear Materials for Gen IV Reactors

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Gen II/III LWR</th>
<th>SCWR</th>
<th>SFR</th>
<th>LFR</th>
<th>ADS</th>
<th>GFR</th>
<th>VHTR</th>
<th>MSR</th>
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<tbody>
<tr>
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<td>UO$_2$, MOX Th-MOX</td>
<td>UO$_2$, MOX Th-MOX</td>
<td>UP$_{uO_2}$</td>
<td>UP$_{uZr}$</td>
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<td>UP$_{uO_2}$</td>
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<td>Pb</td>
<td>Pb or Pb/Bi</td>
<td>He</td>
<td>He</td>
<td>NaF-NaBF$_4$</td>
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</table>
Operating Conditions in Fast Reactors

- High linear heat rate: 400 to 500 W/cm max
- High fuel temperature 600 to 2400°C for (U,Pu)O₂
  ~1000°C for (U,Pu)Zr
- High burnup 130 GWD/t or 15 at %
- Residence time >800 days or >130 dpa

Criteria for Choice of Fuel Materials

- **Material properties**
  - High density of fissile atoms
  - High thermal conductivity and high melting point + high thermal stability
    - High margin to melt
    - No phase transition, no dissociation,
  - High mechanical stability
    - Isotropic expansion, radiation resistant
  - Acceptable chemical compatibility with cladding and coolant: no strong reaction

- **Performances for evaluation**
  - High burn-up and flexibility towards operation conditions
  - Behaviour during transients & accidents
  - Fuel Cycle:
    - Flexibility towards fuel cycle options (Pu and Minor Actinides management)
    - Cost of fabrication and reprocessing
CONTENT

- **Main features of mixed oxide fuel for advanced reactors**
  - Characteristics of the material
  - Fuel properties
  - Comparison of (U,Pu)O₂ properties under irradiation with the others fuels
  - Fuel element design with (U,Pu)O₂

- **Fuel behaviour under irradiation**
  - Main features of fuel behaviour
  - Evolution of fuel microstructure and composition
  - Thermo-mechanical behaviour
  - Behaviour during accident

- **Fuel element performances, design and qualification**
  - Fuel element performances
  - Improvement in the design and qualification of MOX pins
  - Qualification of fuel performance codes

- **Synthesis & Conclusion**
PART 1: Main Features of Mixed Oxide Fuel for Advanced Reactors

Cadarache facilities:
LEFCA
LECA
Structure of mixed oxides $(U_{1-y}Pu_y)O_{2\pm x}$

Face Centred Cubic (fcc) : fluorite type

- U - Pu substitutions : from 0% to 100% (theoretical)

- Non stoichiometry in actinide oxides
  - $x < 0$ : O vacancies or An interstitials (or mixture)
  - $x > 0$ : O interstitials or An vacancies (or mixture)

Lattice parameter depends on $x$ and $y$
MOX fuel: microstructure & fabrication

- Microstructure: grain size, density, porosity shape and size
- Microstructure depends on fabrication process

Powder metallurgy
Pore former process
JAEA

Powder metallurgy
COCA process
CEA

SOLGEL process
JRC - Karlsruhe

AIEA – TECDOC n°1689 “Design, manufacturing and irradiation behavior of fast reactor fuel”.
Mixed oxides \((U_{1-y}Pu_y)O_{2\pm x}\)

- O/M < 1.98 and T<1100K and Pu>18% with possible phases : \((U, Pu)O_2\), \((U, Pu)O_{2\pm x}\), \((U, Pu)_2O_3\),
- \(1.98 < O/M < 2.0\) or T>1100K : fcc solid solution

MOX properties: NEEDS FOR FUEL PERFORMANCE CODES

<table>
<thead>
<tr>
<th>(U-Pu)O₂ properties / models of interest</th>
<th>Temperature (293 – boiling)</th>
<th>Pu/M ratio (15 – 35%)</th>
<th>O/M ratio (1.94 – 2.00)</th>
<th>Fract. porosity (0 – 40%)</th>
<th>Grain size (4 – 30 μm)</th>
<th>Stress (1 – 100 MPa)</th>
<th>Burn up (0-125 GWD/t)</th>
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New measurements expected
## Comparison of fuel properties during irradiation

<table>
<thead>
<tr>
<th>Properties</th>
<th>(U0.8Pu0.2)O2</th>
<th>(U0.8 Pu0.2)C</th>
<th>(U0.8Pu0.2)N</th>
<th>U-19Pu-10Zr</th>
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</thead>
<tbody>
<tr>
<td>Theoretical density, g·cc</td>
<td>11.04</td>
<td>13.58</td>
<td>14.32</td>
<td>15.73</td>
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<tr>
<td>Melting point, K</td>
<td>3083</td>
<td>2750</td>
<td>3070</td>
<td>1400</td>
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<tr>
<td>Thermal conductivity, (\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}) at 1000–2000 K</td>
<td>2.6–2.4</td>
<td>18.8–21.2</td>
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<td>NaCl</td>
<td>NaCl</td>
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</tr>
<tr>
<td>Breeding ratio</td>
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<td>1.2–1.25</td>
<td>1.2–1.25</td>
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<td>Moderate</td>
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<td>Handling</td>
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<td>Pyrophoric</td>
<td>Inert</td>
<td>Inert</td>
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<tr>
<td>Compatibility: clad</td>
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<td>Carburisation</td>
<td>Good</td>
<td>Eutectics</td>
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<tr>
<td>Compatibility: coolant</td>
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<tr>
<td>Dissolution and reprocessing</td>
<td>Good</td>
<td>Demonstrated</td>
<td>Risk of C14</td>
<td>Amenable for pyro reprocessing</td>
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<tr>
<td>Fabrication/irradiation experience</td>
<td>Large and good</td>
<td>Limited</td>
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### Metal Fuel Properties

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<tr>
<td>Breeding ratio</td>
<td>2–1.25</td>
<td>1.35–1.4</td>
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</table>

**Key Properties**

- Low melting temperature
- High thermal conductivity
- High swelling: large gap + metal bond
- Eutectic with clad

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**Legend**

- **Blue Box**: Values for (U0.8Pu0.2)O2
- **Red Box**: Values for (U0.8 Pu0.2)C
- **Green Box**: Values for (U0.8Pu0.2)N
- **Orange Box**: Values for U-19Pu-10Zr
# Carbide fuel

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<tr>
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- High melting temperature + high thermal conductivity:
- High margin to melt
- Moderate thermal creep
- High swelling (to be managed with Na bond or low thermal level or reduced Burn Up)
- Fabrication complex, costly
Nitride fuel

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</table>

- High melting temperature
- High margin to melt but possible dissociation at 1800K
- High thermal creep (low mechanical interaction with clad)
- Moderate swelling
Oxide fuel

<table>
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- High melting temperature
- Low thermal conductivity
- High margin to melt
- High thermal creep (low mechanical interaction with clad)
- Low swelling: pin design easier
Melting temperature of (U,Pu)O$_2$

- Existence of a minimum around 60-70% Pu content to be confirmed
- Disparity of measurements above 60% of Pu (200 K deviation for PuO$_2$)
- O / M impact to be evaluated
  - CALPHAD evaluation under estimates solidus.
  - The existing law for melting temperature should be revised following all these and other recent results.
- Needs for additional measurements:
  - high Pu content
  - Effect of O/M
  - Pu% for the lowest $T_{\text{melting}}$ (safety analysis)

$T_m = 3040$ K for 24%Pu
Thermal conductivity of (U,Pu)O₂

- Strong effect of temperature, O/M, Pu content, density, irradiation:
  - Discrepancy between the laws of \( \lambda \)
  - Main source of uncertainty on the fuel temperature

- Intensive European experimental programme:
### Potential fuel designs

<table>
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<th>Fuel form</th>
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<td>Particle</td>
</tr>
<tr>
<td>Nitride</td>
<td>Composite</td>
<td>Liquid</td>
</tr>
<tr>
<td>Carbide</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluoride (salt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e.g. (U,Pu)O₂</td>
<td>e.g. Mo+UO₂</td>
<td>Sintered pellets</td>
</tr>
</tbody>
</table>

- e.g. \( \text{UO}_2 \)
- Sphere pack
## Potential fuel elements (1/2)

<table>
<thead>
<tr>
<th>Fuel elements</th>
<th>Standard pin</th>
<th>Standard pin with metal slug</th>
<th>Pin with innovative clad: composite SiC-SiC&lt;sub&gt;fiber&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With oxide pellets</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Fuel elements

#### Standard pin
- With oxide pellets

#### Standard pin with metal slug

#### Pin with innovative clad: composite SiC-SiC<sub>fiber</sub>
## Potential fuel elements (2/2)

<table>
<thead>
<tr>
<th>Fuel elements</th>
<th>Coated particles</th>
<th>Plate fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard pin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With vipac fuel or</td>
<td></td>
<td></td>
</tr>
<tr>
<td>spherepac fuel</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Two ceramic plates close a honeycomb structure containing cylindrical fuel pellets
PART 2 : Fuel Behaviour Under Irradiation
Fuel behaviour : real life

(Complete) view of how phenomena interact
Complex system with coupled effects

- Safety evaluation
  - Margin to clad failure
  - Margin to fuel melt

Ref. Manning et al., MMSNF conference
MOX behaviour: microstructure & composition evolution (1/2)

Thermal expansion
Gap reduction
Cracking

Oxygen migration by vapour diffusion in cracks and thermodiffusion
Lenticular pores migration
Actinide radial migration
Pore migration
Central hole formation
Cracks healing

Gap closure
MOX behaviour: microstructure & composition evolution (2/2)

- Atomic diffusion (thermal and athermal) of O, U and Pu (bulk diffusion)
- Grain boundary and surface diffusion
- Vaporisation condensation (pore diffusion)
Chemical state of fission products in irradiated oxide fuel

- Each fission creates 2 FPs:
  - Chemical state of the fuel depends strongly on the oxygen chemical potential of \((U_{1-y}Pu_y)O_{2-x}\) that increases during irradiation. Fission is oxidizing.
  - Modification of physical and chemical properties of the irradiated fuel (FP in solution, oxides precipitates, metallic precipitates).
  - Formation of:
    - JOG (oxide/clad joint): \(Cs_2MoO_4\) + others compounds
    - FCCI (Fuel Clad Chemical Interaction) or corrosion: \(Te, I, Cs\) reacts with clad (Fe, Ni, Cr): \(Cs_2CrO_4, FeTe_{0.9}, NiTe_{0.6}\)
MOX behaviour: effects of the irradiation

Clad and fuel evolution

Clad swelling

FUEL-CLAD CHEMICAL INTERACTION (FCCI or corrosion) Cs, Te, I
FISSION PRODUCTS JOINT (JOG) Pd, Mo, Te, Cs, I, O + Rb, Cd, Sn, ...
FUEL GASEOUS SWELLING & GAS RELEASE Xe, Kr
FUEL SOLID SWELLING Sr, Zr, La, Ce, Nd
FUEL PROPERTIES EVOLUTION all FP + fuel damage

Diametral deformation at 75GWd/t [%]

Elevation from pin bottom (mm)
MOX behaviour: effects of the irradiation

Clad and fuel evolution

CLAD SWELLING
neutrons

FUEL-CLAD CHEMICAL INTERACTION (FCCI or corrosion) Cs, Te, I

FISSION PRODUCTS JOINT (JOG) Pd, Mo, Te, Cs, I, O + Rb, Cd, Sn, ...

FUEL GASEOUS SWELLING & GAS RELEASE Xe, Kr

FUEL SOLID SWELLING Sr, Zr, La, Ce, Nd

FUEL PROPERTIES EVOLUTION all FP + fuel damage

Corrosion thickness: until 200 µm

CEA-LECA
MOX behaviour: effects of the irradiation

Clad and fuel evolution

**CLAD SWELLING**

neutrons

**FUEL-CLAD CHEMICAL INTERACTION (FCCI or corrosion)**

Cs, Te, I

**FISSION PRODUCTS JOINT (JOG)**

Pd, Mo, Te, Cs, I, O + Rb, Cd, Sn, ...

**FUEL GASEOUS SWELLING & GAS RELEASE**

Xe, Kr

**FUEL SOLID SWELLING**

Sr, Zr, La, Ce, Nd

**FUEL PROPERTIES EVOLUTION**

all FP + fuel damage

JOG thickness: until 160 µm
MOX behaviour: effects of the irradiation

Clad and fuel evolution

CLAD SWELLING

neutrons

FUEL-CLAD CHEMICAL INTERACTION (FCCI or corrosion) Cs, Te, I
FISSION PRODUCTS JOINT (JOG) Nd, Mo, Te, Cs, I, O + Rb, Cd, Sn, ...
FUEL GASEOUS SWELLING & GAS RELEASE Xe, Kr
FUEL SOLID SWELLING Sr, Zr, La, Ce, Nd
FUEL PROPERTIES EVOLUTION all FP + fuel damage

Retention FG (cm²/g) vs. Pellet radius (mm)

EPMA EBSD TEM MEB-FIB

Noirot et al, Nuc. Eng. Tech., 50, 2018
MOX behaviour : effects of the irradiation

Clad and fuel evolution

CLAD SWELLING, neutrons
FUEL-CLAD CHEMICAL INTERACTION (FCCI or corrosion): Cs, Te, I
FISSION PRODUCTS JOINT (JOG): Pd, Mo, Te, Cs, I, O + Rb, Cd, Sn, ...
FUEL GASEOUS SWELLING & GAS RELEASE: Xe, Kr
FUEL SOLID SWELLING: Sr, Zr, La, Ce, Nd
FUEL PROPERTIES EVOLUTION: all FP + fuel damage

\[ \Delta V/V \sim 0.6 \% / \text{at\%} \]

\[ y = 0.064x - 0.779 \]
MOX behaviour: effects of the irradiation

Clad and fuel evolution

**Clad Swelling**
- Neutrons

**Fuel-Clad Chemical Interaction (FCCI or corrosion)**
- Cs, Te, I

**Fission Products Joint (JOG)**
- Pd, Mo, Te, Cs, I, O + Rb, Cd, Sn, ...

**Fuel Gaseous Swelling & Gas Release**
- Xe, Kr

**Fuel Solid Swelling**
- Sr, Zr, Ce, Nd

**Fuel Properties Evolution**
- All FP + fuel damage

---

**Fig. 3.5** - Defect complexes in UO₂: 🟡, cation interstitials; ☓, normal oxygen; 🟠, type 1 interstitial oxygen; 🟠, type 1 interstitial oxygen; ☑, vacancy in normal oxygen site; ➤, interstitial at center of cube formed by eight normal oxygen sites.

D.R. Olander (1976)

Thermal behaviour of fuel element

• Objectives:
  • Predict the temperature of clad and fuel with an evaluation of margin to melt

• Thermal profile in the pin

Axial

Radial

Factors affecting the temperature profile

• Thermal conductivity degradation
• Fuel swelling
• Fuel restructuring
• Pellet-cladding interaction
Mechanical behaviour of fuel element (1/2)

**Objectives:**
- Predict dimensional changes: clad strain (5-10% of max. strain), gap closure
- Predict the risk of clad failure during nominal conditions or power increases

**Mechanical phenomenons**
- **Fuel:** swelling, creep, mechanical properties evolution, cracking due to very high thermal gradient (5000K/cm) → differential expansion leading to fracturing of the pellets, relocation of the fragments
- **Clad:** swelling at high dose, creep (causing damage), embrittlement, loss of properties during irradiation
Mechanical behaviour of fuel element (2/2)

✓ Fuel / cladding mechanical interaction (FCMI)
In fast oxide fuels, this benign effect of FCMI during steady-state operation is a consequence of the following points:

- Low swelling rate (~0.6%/at%) of oxide as compared to carbide or metal fuels
- High fuel temperature that allows high creep rates. Even in the outer part of pellets, thermal creep and irradiation creep in oxide fuels relieve the FCMI stresses induced by fuel swelling.
- JOG formation that acts as an elastic joint (composition Cs, Mo, O, mainly Cs$_2$MoO$_4$)
- Design of fuel element in order to avoid FCMI through low smear density and with plenum to avoid primary stresses (pressure due to fission gas release)

✓ Fuel / cladding chemical interaction (FCCI)

- Reduce clad thickness and thereby limiting fuel burn-up
- FCCI may be evaluated with fission products diffusion, thermodynamics of fuel/clad interface
MOX behaviour during accidents

- Unexpected Control Rod Withdrawal Accident (CRWA): slow/limited power transient (SA prevention domain: demo of pin integrity)
- Unprotected Transients: transient of power or loss of flow (UTOP/UOLF): fast/very large power transient (SA mitigation domain: demo of fuel ejection phenomena)
- Total Instantaneous assembly inlet Blockage (TIB): (SA mitigation domain: study of heat transfer and propagation phenomena)

Associated R&D aimed at:

- Data acquisition from separate effect or integral tests (e.g. single rod in CABRI reactor or with fuel bundle in SCARABEE: from 19 to 37 pins). Feedback exists (CABRI, TREAT, …) but still low and expensive, so a large panel of scenarii and uncertainties still exist.
- Development of simulation codes validated on tests with complex interactions between a lot of phenomena.

<table>
<thead>
<tr>
<th>Programme</th>
<th>Objectives/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971-1974</td>
<td>SCARABEE 1st phase Na ebulition, fuel melt; 16 single-pin tests, 8 bundle tests (7 pins)</td>
</tr>
<tr>
<td>1976-1986</td>
<td>CABRI-1 CDA primary phase, 32 tests, full pellets, 316 stainless steel, burnup: 0-1-2, 8-4-8 at%</td>
</tr>
<tr>
<td>1983-1990</td>
<td>SCARABEE-N TIB/APL (10 tests), CDA (3 tests), fuel bundle tests (19 and 37 pins)</td>
</tr>
<tr>
<td>1986-1994</td>
<td>CABRI-2 CDA (9 tests) and CRWA (3 tests) Industrial fuel, full/annular pellets; 15-15 Ti clads</td>
</tr>
<tr>
<td>1992-1997</td>
<td>CABRI FAST Annular pellets, CDA (5 tests), CRWA (2 tests)</td>
</tr>
<tr>
<td>1996-2001</td>
<td>CABRI RAFT CDA transition phase (5 tests), fuel ejection during CRWA (2 tests)</td>
</tr>
</tbody>
</table>

Fuel partly melt during (CABRI – E5 test)
SFR MOX driver fuel: main features of the irradiation behaviour

- Microstructure, composition and properties evolution
  - Microstructure evolution early during the irradiation
  - Species transport (actinides and O migration) and oxygen potential evolution
  - Fuel gaseous and solid swelling, coupled with creep
  - Fuel properties evolution depending on: composition, density, microstructure, temperature, burn-up
  - Clad properties: creep, swelling at high burn-up/temperature, embrittlement, loss of mechanical properties under irradiation

- Thermomechanical and thermochemical behaviour
  - Fission gas release: effect of all parameters (T, Burn-up, fuel microstructure,...)
  - Fuel to clad gap closure and Heat transfer in the fuel-clad gap
  - JOG formation and axial transfert
  - Pellet cracking and re-location of the fragments
  - FCMI: threshold of over-power or over-temperature during transients
  - Burn up linked phenomena: FCCI (clad corrosion), JOG composition
PART 3 : Fuel Element Performances, Design and Qualification
Performances of MOX Pins in SFR

- **Long experience:**
  - Started in BR-5 in 1957 in Russia, Rapsodie in 1967 in France, SEFOR in USA,
  - Then EBR-II and FFTF in the USA, BR-10, BOR-60, BN-350, BN-600 and BN-800 in Russia, the prototype fast reactor (PFR) in the UK, Phenix and Superphenix in France, KNK and SNR-300 in Germany, JOYO and Monju in Japan, FBTR in India and Experimental Fast Reactor (CEFR) in China.

- **Performances in recent SFR:**
  - more than 20 at% (200 GWd.t\(^{-1}\))
  - 155 dpa
  - 550 W/cm max

- **Fast reactor in operation:**
  - BOR60, BN600, BN800 : UO\(_x\) and MOX, pellet or vi-pack
  - JOYO : MOX, pellet
  - FBTR : carbide and MOX experimental pins and \textit{PFBR} : MOX, pellet
  - CEFR : UOX, pellet

<table>
<thead>
<tr>
<th>Standard MOX fuel</th>
<th>Experimental fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No. of pins irradiated</strong></td>
<td><strong>Burnup reached MWd(\text{t}^{-1})</strong></td>
</tr>
<tr>
<td>265000</td>
<td>135000</td>
</tr>
<tr>
<td>64000</td>
<td>130000</td>
</tr>
<tr>
<td>50000</td>
<td>100000</td>
</tr>
<tr>
<td>13000</td>
<td>135000</td>
</tr>
<tr>
<td>1800</td>
<td>100000</td>
</tr>
<tr>
<td>1500</td>
<td>100000</td>
</tr>
</tbody>
</table>
Improvements in the Fuel Element Design

- Improvements on the geometry:
  - Annular pellet (for safety improvement: BOL & transients)
  - Large pin diameter
  - Axially heterogeneous pin (safety improvement)

- Large range of composition:
  - Uranium: natural, depleted, reprocessed
  - Plutonium: 15 to 45%, several grades (ex spent LWR-MOX)
  - Minor actinides: transmutation with different ways \((U, Pu, Am)O_{2-x}, (U, Am)O_{2-x}, (MA, O)_{2-x} + inert\) matrix

- Specifications:
  - Mastered by several processes
  - Adapted to industrial fabrication
  - Responding to safety issues
Fuel Element Qualification

- **Objectives:**
  - Licensing: authorisation of safety authorities for fuel loading in NPP

- **Requirements:**
  - Regulatory guidance:
    - higher level safety objectives,
    - qualification of computational tools,
    - uncertainties consistent with Safety Margins
  - Regulatory criteria/limits:
    - maintaining cladding integrity, coolable geometry, and limiting radiological consequences
    - fuel failure and degradation mechanisms are identified & controlled
Fuel Element Qualification

- An essential part of fuel qualification is to define a test envelope to cover expected operating, transient, and accident conditions to assess fuel performance and validate fuel performance codes.

TRL 9 for Phenix type pins (Phenix, SNR300, Joyo) & same geometry with central hole (EBR2, PFR, BN800), SPX type
TRL 6-7 for others concepts
QUALIFICATION OF MOX FUEL FOR GENIV SYSTEMS
Fuel performance code qualification: ex. platform PLEIADES with GERMINAL for fast reactor

- Material evolution
- Thermal analysis
- Mechanical calculations
- Physico-chemistry analysis
- Thermochemistry

Material damage & properties
Fuel temperature distribution
Mechanical fields
Fission gas Location/Migration/Release
Fission product speciation
Thermo-migration Source term

VER Dislocation Dynamics
Cluster dynamics
Empirical Potential MD
First Principles DFT

Physico-chemistry analysis
Fission gas Location/Migration/Release

MARGARET/CARACAS

Fission gas inventory before transient as calculated by ALCYONE code

C. Valot, Annual NSC meeting, 2019. Linking modeling/simulation and experiments for Fuel R&D at CEA
Portelette et al., J. Nuc. Mat., 510, 2018
Bourasseau et al., J. Nuc. Mat., 517, 2019
Synthesis & Conclusion
Oxide fuels

- Demonstrated a good stability and behaviour under irradiation up to very high burn-ups (20 at.%), limitation is due to clad and wrapper deformation.
- High creep rate (high temperature) and optimised pin design (smear density) to avoid FCMI
- Low thermal conductivity compensated by high melting point
- Compared to metal fuel, lower fuel swelling under irradiation
- Na reaction to be managed as well as clad corrosion at high burn-up
- Compatibility with stainless steel cladding
- Large feed back of safety tests
- Fuel Performance Codes: numerous and qualified on a set of reliable exp. tests
- Manufacturing and reprocessing processes similar to the Light Water Reactors (LWR) fuel industrial processes, taking advantage of LWR experience and existing facilities
- Fuel cycle: well known fabrication process and large experience on reprocessing
- Scenario: flexible towards Pu management (% and grade), Uranium use and high capabilities for Minor Actinides transmutation
Perspectives for R&D on MOX Pins

- **Fuel material:**
  - Properties measurements and recommandation for uncertainties reduction
  - Different fuel compositions for an enhanced flexibility towards fuel cycle options

- **Clad material:**
  - Development of several candidates for high neutron doses (>150dpa) with low swelling and FCCI resistance

- **Fuel element:**
  - Improvement design:
    - Annular pellets (enhance thermal behaviour and transient consequences)
    - Large pin diameter (reducing Na volume and structural materials)
  - Assessment of pin behaviour during incidental and accidental scenarios
  - Modelling – Simulation: thermochemical, thermomechanical, 3D, multiscale approaches
SOURCES

- **Bibliography**
  - Dedicated reports or TECDOC from IAEA and Sate Of the Art Reports from OECD/NEA
  - Publications mainly from *Journal of Nuclear Materials, Nuclear Engineering and Design* and *Nuclear Technology*

- **Courses/school**: FJOH, ISNE, ENEN

- **Conferences**: FR09, 13, 17, GLOBAL 1993 →2019, IEMPT, NUMAT, ATALANTE

- **Current International activities on oxide and others fuels for advanced reactors**:
  - OECD: expert group on innovative fuel elements (NSC/WPFC/EGIF)
  - AIEA : CRP fuels and materials for fast reactors
  - GIF : Advanced fuel project management board in the SFR, GFR and VHTR systems
  - EUROPEAN PROJECTS : ESFR-SMART, INSPYRE, PUMMA

- **International data bases**:
  - [http://therpro.hanyang.ac.kr/search/search_map.jsp](http://therpro.hanyang.ac.kr/search/search_map.jsp)
Prototypes & industrial SFRs

108 years. Reactors of operating experience
Total electricity generation > 150 TWh
Upcoming Webinars

25 February 2021  Overview of Waste Treatment Plant, Hanford Site  Dr. David Peeler, PNNL, USA

25 March 2021  Introducing new Plant Systems Design (PSD) Code  Dr. Prinja Nawal, Jacobs, UK

22 April 2021  Experience of HTTR licensing for Japan's New Nuclear Regulation  Mr. Etsuo ISHITSUKA, JAEA, Japan
Attention Junior Researchers
Get Ready to

“Pitch your Gen IV Research”

- Are you a current PhD student or did you complete your PhD after January 1, 2019?
- Was your PhD research related to Generation IV Advanced Nuclear Energy systems?
- Can you explain your research in three minutes?

If you answered yes to those questions, you may be interested in the Virtual Pitch your Gen IV Research Competition

https://www.gen-4.org/gif/pitch-your-generation-iv-research