Design, development and qualification of advanced fuels for an industrial ADS prototype

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OUTLINE:

- **Objectives & Background**
- **Addressed topics**
- **Some results:**
  - Core configuration and performances
  - Thermomechanical behaviour of the pins
  - FUTURIX-FTA, HELIOS, BODEX tests
  - Thermo-chemical compatibility tests
- **Conclusion**

Objectives & background for fuel developments

- **Objectives:**

→ Ranking of fuel concepts according to in-pile behaviour, out-of-pile properties, predicted behaviour in normal operating conditions and safety performance.

→ Recommendations for the most promising fuel.

- **Background:**
  - Emphasis in Europe on oxide-based fuels → **reference fuels**

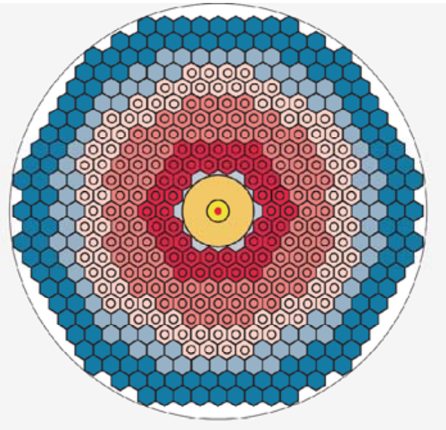
    CERCER (Pu, MA)O_2 + MgO and CERMET (Pu, MA)O_2 + ^{92}Mo

    - First development in the frame of the FP5 - FUTURE program: best candidates according to performance, safety and fabricability criteria, synthesis of oxide compounds, out-of-pile characterisation.
    - Strong synergy with transmutation target programs
    - Large industrial experience on oxide fuel fabrication for critical reactors
  - Nitride-based fuels: (Pu,MA,Zr)N → **backup solution**
    - Development in the frame of the FP5 - CONFIRM program: (Am,Zr)N synthesis, irradiation of (Pu,Zr)N pellets in HFR, out-of-pile measurements
    - Development by JAEA

Topics addressed within the project

- **TRU-fuel design and performance assessment:**
  - Neutronic design of CERCER and CERMET cores
  - Neutronic and thermo-mechanical behaviour from BOL to EOL
- **Safety Analysis:** transients conditions (ULOF, UTOP, …) and accidents
- **In-pile experiments:**
  - PIE on an irradiated CONFIRM pin: (Pu,Zr)N fuel
  - FUTURIX-FTA test in PHENIX
  - HELIOS test in HFR
  - BODEX test in HFR and Post Irradiation Examinations
- **Out of pile experiments:**
  - Thermal and mechanical properties of CERMET, CERCER fuels
  - Chemical compatibility : fuels/clad, fuels/coolant, TRU compounds/Inert Matrices
  - Oxygen potential measurements
  - Phase diagrams : Pu-Am-O, Pu-Am-Zr-O

^{92}Mo-CERMET core configuration and performances



Parameter		Zones	
	Inner	Medium	Outer
Assembly number	42	90	80
Wrapper inner width (mm)		178	
Pin number/assembly		169	
Clad outer diameter (mm)		9.52	
Fuel pellet diameter (mm)		8.00	
Fuel/ clad gap (mm)		0.160	
Fuel/matrix ratio	35/65	43/57	50/50
Pu/MA ratio		45/54	
Av. fuel power density ($W.cm^{-3}$)	270	262	211
Peak pellet linear power ($W.cm^{-1}$)	190	172	154

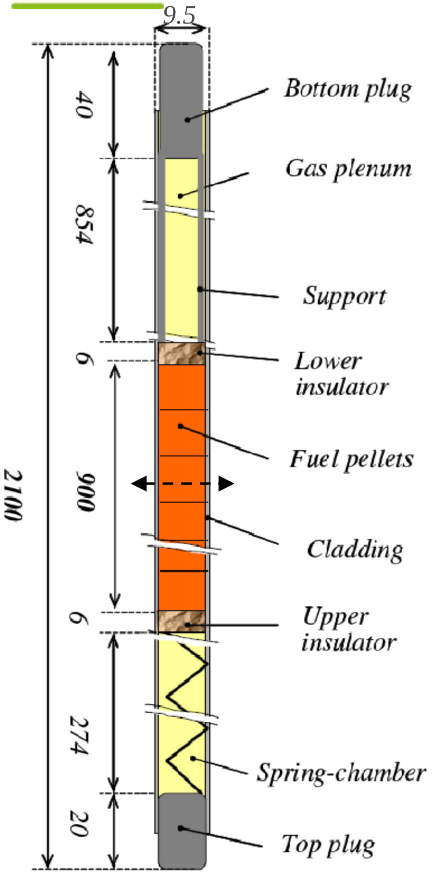
EFIT design specifications:
- *400MWth*
- *proton beam: 800MeV - 20mA*
- *Pb target: 11MW - Φ782mm*
- *k_{eff} ~0.97*
- *fuel vector*
- *inlet-outlet Pb T°: 400-480°C*
- *clad and wrapper: T91*
- *efficiency: ~42kg MA/TWh_{th}*

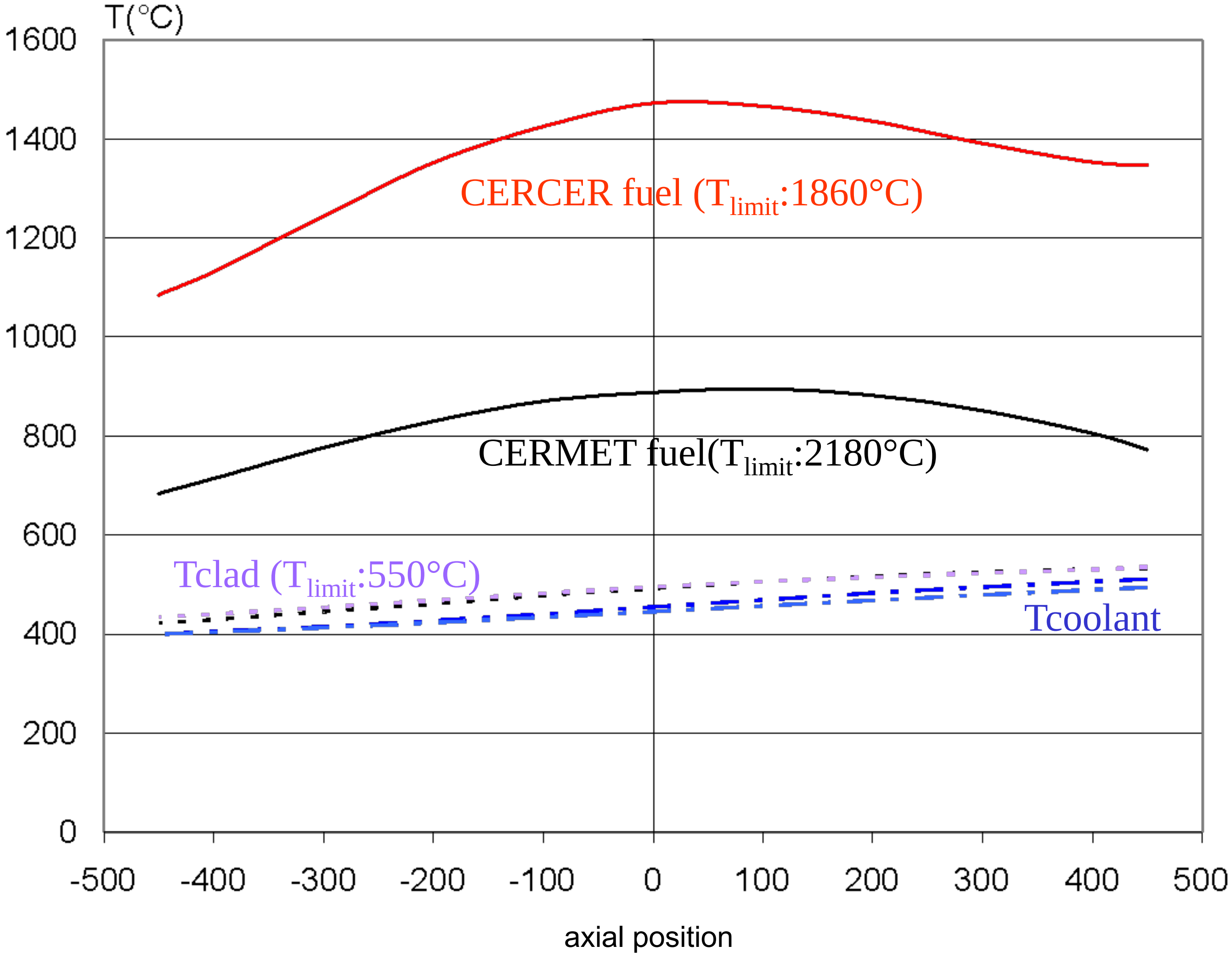
k_{eff}	k_{source}	Void worth	Beta eff.	Doppler Contant
0.97336	0.93337	7335 pcm	192 pcm	-68 pcm

	Initial mass (kg)	Variation (3 year cycle + 3 year cooling)
MA	3610	-461 kg
Pu	3055	-9 kg
Total	6665	-43 kg/TWh_{th}

Thermo-mechanical behaviour at BOL

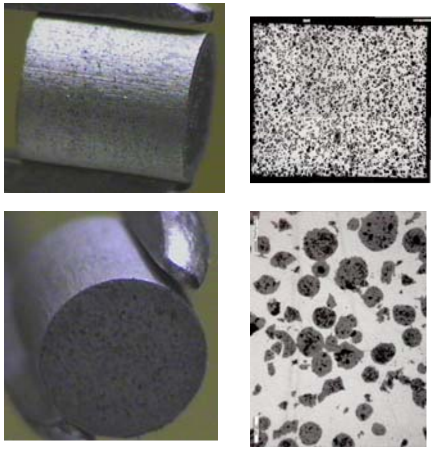
- fuel, clad and coolant temperatures for the hottest pin in the inner zone - 24 hours after start :





FUTURIX-FTA test in PHENIX

- In-pile behaviour comparison of 3 fuel types: oxide, nitride, metallic
- Collaboration DOE-JAEA-ITU-CEA
- CERMET and CERCER studies under EUROTRANS project



Fuel composition	Max. linear power (W/cm)	T° max. estimated (°C)
$Pu_{0,80}Am_{0,20}O_{2-x}$ + 86 vol%Mo	140	1590
$Pu_{0,23}Am_{0,24}Zr_{0,53}O_{2-x}$ + 60 vol%Mo	130	1510
$Pu_{0,5}Am_{0,5}O_{2-x}$ + 80 vol%MgO	100	1420
$Pu_{0,8}Am_{0,2}O_{2-x}$ +75 vol%MgO	80	1260

CERCER and CERMET fuels in pile since may 2007 for ~240 EFPD
- CERCER : 5th ring. Flux : 4,4x10^{15} n.cm^{-2}.s^{-1}
-CERMET: 1st ring. Flux: 3,2x10^{15} n.cm^{-2}.s^{-1}

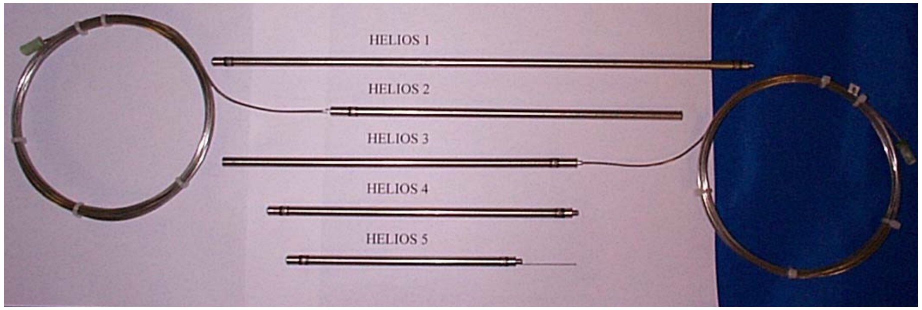
Sept. 08: 153 EFPD achieved

HELIOS test in HFR

- Influence of microstructure and temperature on gas release and fuel swelling.

Fuel composition	T° max. estimated (°C) (Ne+He in gap)
$Am_2Zr_2O_7$ + 80 vol%MgO	800
$Zr_{0,80}Y_{0,13}Am_{0,07}O_{2-x}$	720
$Pu_{0,04}Am_{0,07}Zr_{0,76}Y_{0,13}O_{2-x}$	1470
$Am_{0,22}Zr_{0,67}Y_{0,11}O_{2-x}$ + 71 vol%Mo	750
$Pu_{0,80}Am_{0,20}O_{2-x}$ + 84 vol%Mo	1240

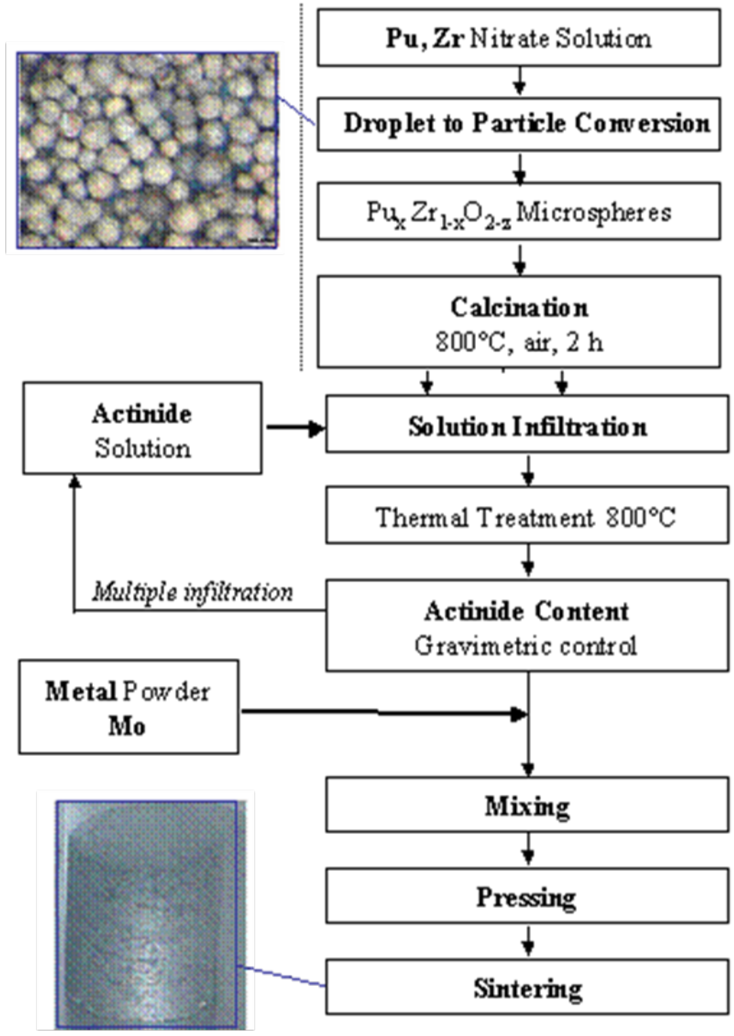
0.7g Am/cm^3



⇒ Beginning of the irradiation expected by Nov. 08 for 200 EFPD

CERCER and CERMET fabrication processes

ITU flowsheet / CERMET:



Pu, Zr Nitrate Solution

Droplet to Particle Conversion

$Pu_xZr_{1-x}O_{2-z}$ Microspheres

Calcination
800°C, air, 2 h

Actinide Solution

Solution Infiltration

Thermal Treatment 800°C

Multiple infiltration

Actinide Content
Gravimetric control

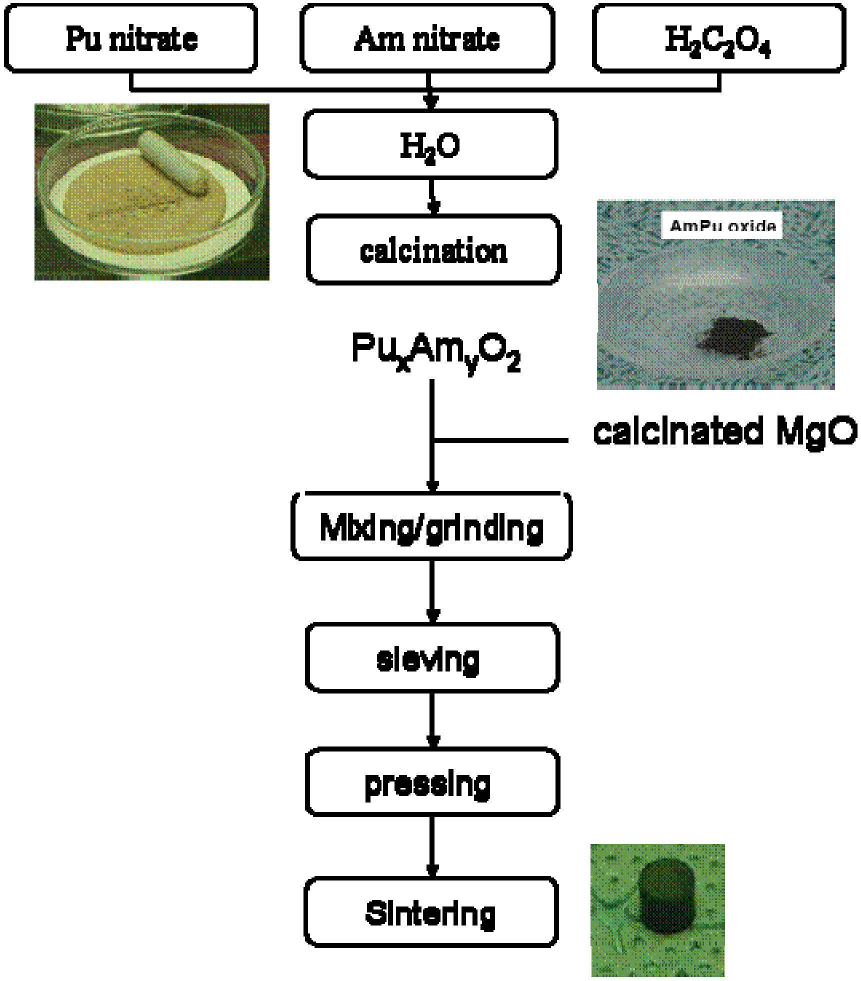
Metal Powder
Mo

Mixing

Pressing

Sintering

CEA flowsheet / CERCER:



Pu nitrate

Am nitrate

$H_2C_2O_4$

H_2O

calcination

$Pu_xAm_yO_2$

calcinated MgO

Mixing/grinding

sieving

pressing

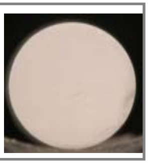
Sintering

BODEX test in HFR

- Study of helium build-up and release mechanism study on inert matrices
  - ^{10}B surrogate of ^{241}Am to simulate He production: $^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}\alpha$
  - Advantages : no Am handling & short irradiation time (~1-2 months)

✓ 3 matrices : Mo, MgO, ZrO_2	✓ 2 T° : 800-1200°C	✓1.5 mmole B /cm^3

✓ 3 boron compounds :

Mo_2B / Mo	ZrB_2 / ZrO_2	$Mg_3B_2O_6$ / MgO
60-70MPa *1600°C / 5h / Ar* *D: 97%* 	*600MPa* *1600°C / 5h / Ar* *D: 92%* 	*800MPa* *1300°C / 5h / Ar* *D: 78%* 

✓ 2x3 capsules : 3 pellets doped with ^{10}B + 1 pellet doped with ^{11}B + 1 undoped pellet

^{10}B	^{10}B	^{10}B	^{11}B	^{0}B

→ Irradiation achieved – PIE on-going

TRU-oxides/Inert Matrices compatibility tests

- Experimental grid:
  - powder blend
  - 1800K or 1300K - 2x24 h
  - Air/Ar/Ar-H_2 5%,
  - XRD analysis:

Atm	PuO_2+MgO	AmO_2+MgO	PuO_2+Mo	AmO_2+Mo
Air	MgO PuO_2	AmO_2 MgO		
Ar		Am_2O_3 h & c AmO_{2-x} c MgO Other peaks	PuO_2 Mo	Mo Am-Mo-O m?
Ar/H_2 5%	PuO_2 MgO	Am_2O_3 h & c MgO	PuO_{2-x} c Mo	Am_2O_3 h Mo

[Belin&al., ARWIF 2008]

no reaction between PuO_2 and Inert Matrices

minor interactions between AmO_2 and Inert Matrices

Conclusion

- Major results:
  - Reference designs of ^{92}Mo-CERMET and MgO-CERCER Cores :
    - MA/(Pu+MA)~54% - MgO and Mo content ≥ 50%
    - transmutation efficiency (1st cycle): 42 kg MA/TWhth - ΔPu~0
    - safety under analysis
  - CERCER and CERMET fabrication (20%Am) demonstrated at lab. scale
  - Thermal properties of CERCER, CERMET fuels and $(Pu,MA)O_2$ phases: accurate and reliable data available
  - In-pile fuel behaviour investigation on-going
  - Fuel thermomechanical behaviour modeling under development

- Additional information:
  - Fernandez-Carretero et al. (Oct.8 – 9:00): fuel fabrication
  - Maschek et al. (Oct. 9 – 14:15): Core design and safety analysis
  - Chen et al. (Poster - section IV): Safety studies on the EFIT with CERMET fuel