

**Fission products and nuclear fuel behaviour under
severe accident conditions Speciation of fission
products in the Verdon 3 and -4 samples**

F. Audubert, C. Le Gall, L. Fayette, P. Bienvenu, I. Zacharie-Aubrun, K.
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DE LA RECHERCHE À L'INDUSTRIE



FISSION PRODUCTS AND NUCLEAR FUEL BEHAVIOUR

UNDER SEVERE ACCIDENT CONDITIONS:

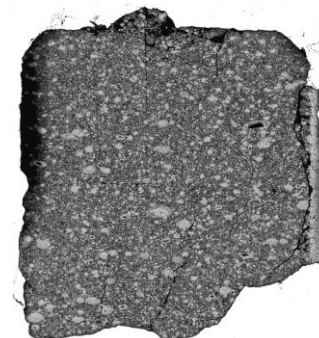
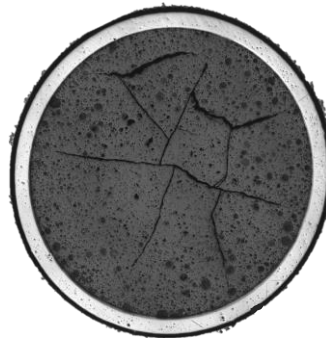
SPECIATION OF FISSION PRODUCTS

IN THE VERDON 3 AND -4 SAMPLES

NUMAT 2018 | October 19th – 23th, 2018

CEA Cadarache | DEN | DEC | SA3E | LAMIR

F. Audubert, C. Le Gall, L. Fayette, P. Bienvenu,
I. Zacharie-Aubrun, K. Hanifi, Y. Pontillon



CONTEXT

Phenomenology of a PWR severe accident

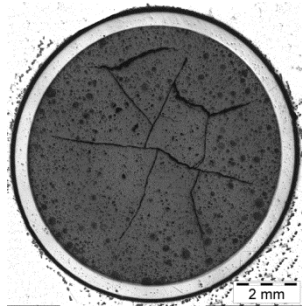
Initial state

Temperature ramp
(400-1100°C)

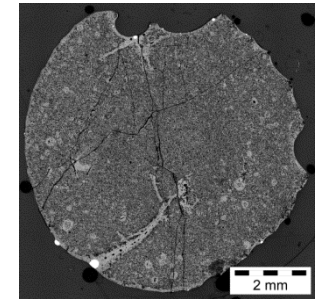
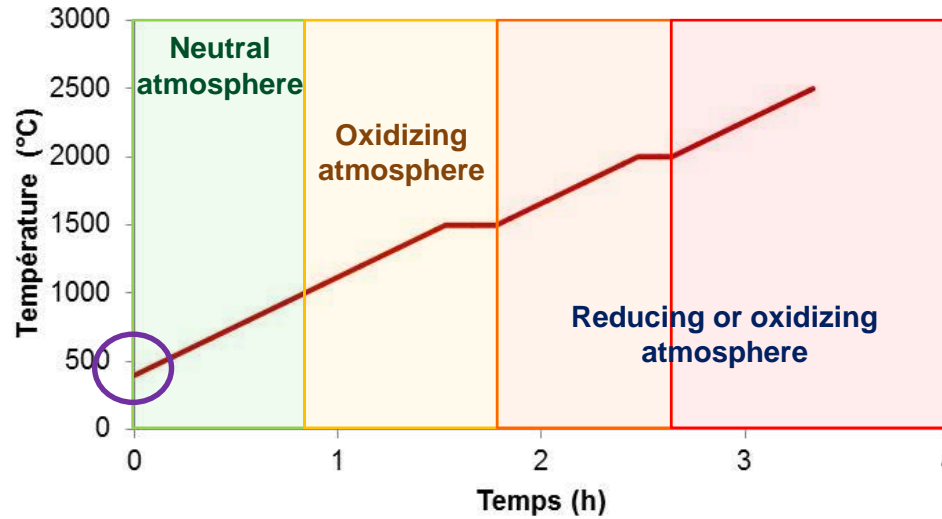
Oxidation plateau
(1100-1500°C)

Temperature ramp
(1500-2000°C)

High temp. plateau
(≥ 2300°C)

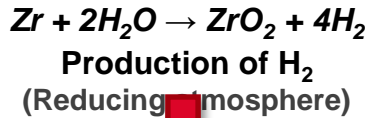


T_0
MOX fuel irradiated
 t 56 GWd.t_{ML}⁻¹

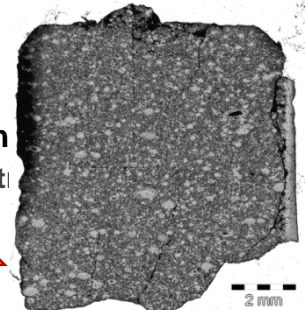


O 2300
Thermal treatment up to 2300°C under oxidizing atm.

Production of steam
(Oxidizing atmosphere)



Failure of the cladding
(Oxidizing atmosphere)



R 2500
Thermal treatment up to 2500°C under reducing atmosphere

Normal operating conditions

Heat-up of Fuel rods

Cladding oxidation

Further heat-up Of the rods



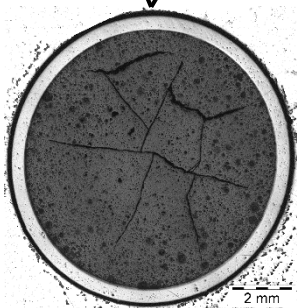
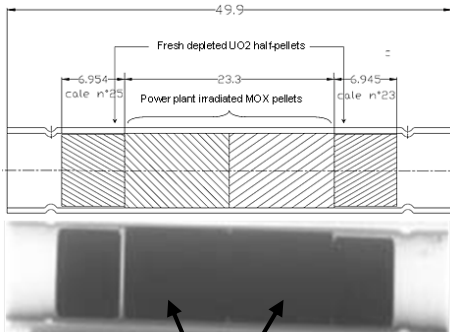
Behavior of MOX fuel and FP in SA conditions?

THE VERDON-3 AND 4 SAMPLES

Characteristics

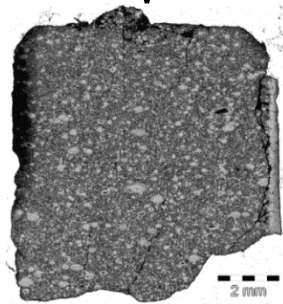
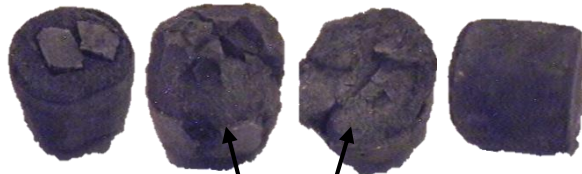
Father rod,
56 GWd.t_{HM}⁻¹

2 PWR MOX fuel pellets + M5 cladding
+
2 unirradiated half pellets (depleted UO₂)
reirradiated in OSIRIS



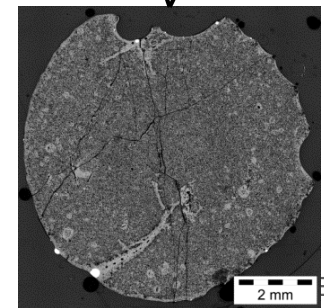
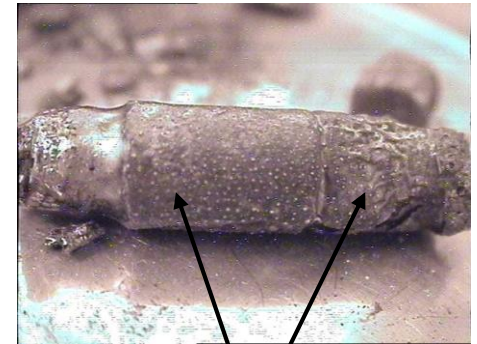
VERDON-3,
2300°C, H₂O

2 irradiated pellets, scarce visible
pieces of cladding
+
2 unirradiated half pellets (depleted UO₂)



VERDON-4,
2530°C, H₂

2 irradiated pellets + molten Zr
cladding
+
2 unirradiated half pellets (depleted UO₂)



POST-TEST CHARACTERIZATIONS

Method



Qualitative analyses

**Optical microscopy, SEM,
SIMS, X-ray maps**

Microstructure evolution

Fuel-cladding interaction

**FP distribution and
associations**



Quantitative analyses

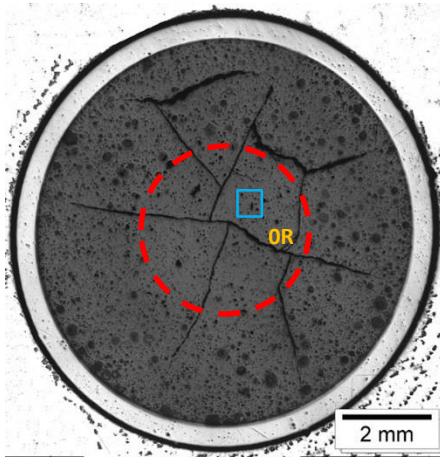
EPMA

**Phases chemical
composition**

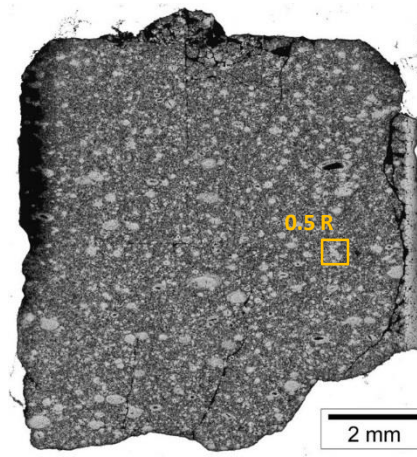
MICROSTRUCTURE EVOLUTION

Father rod, VERDON-3 and VERDON-4 samples

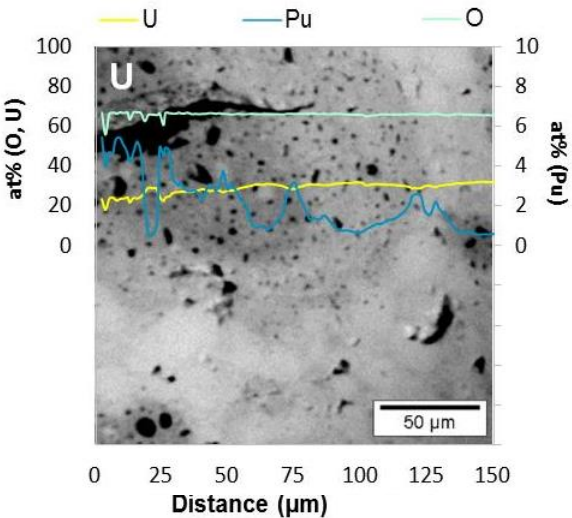
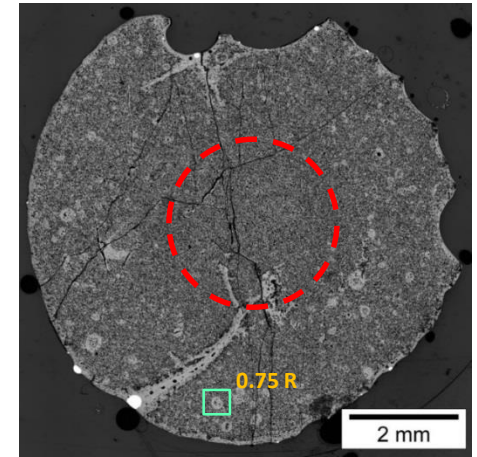
Father rod *,
56 GWd.t_{HM}⁻¹



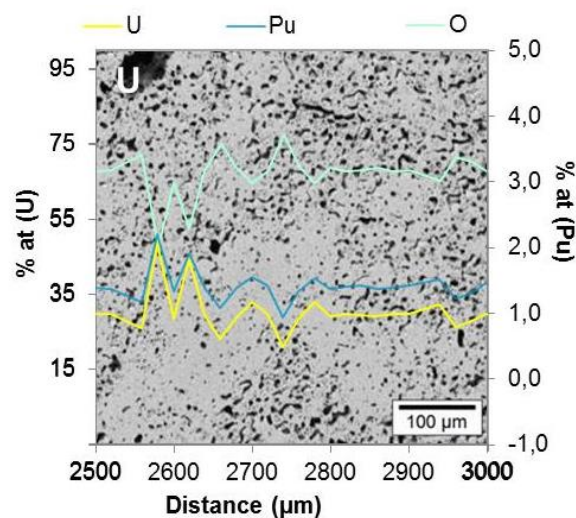
VERDON-3,
2300°C, H₂O



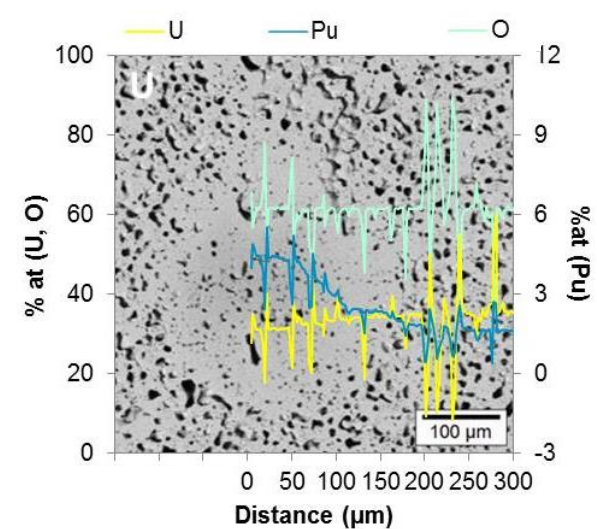
VERDON-4,
2530°C, H₂



Pu agglomerates (5 at% Pu)

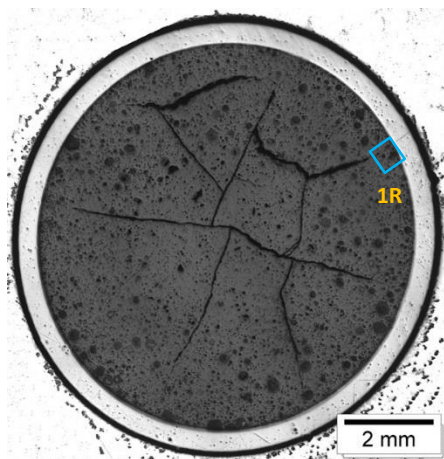


Pu agglomerates (1.8 at% Pu)

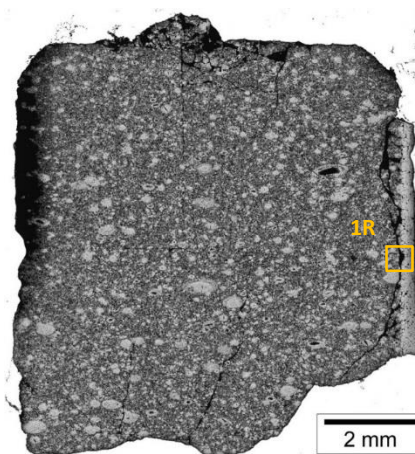


Father rod, VERDON-3 and VERDON-4 samples

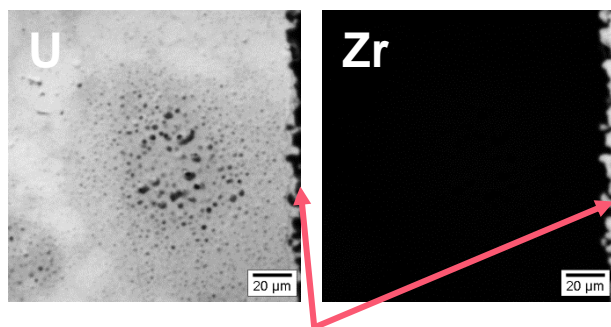
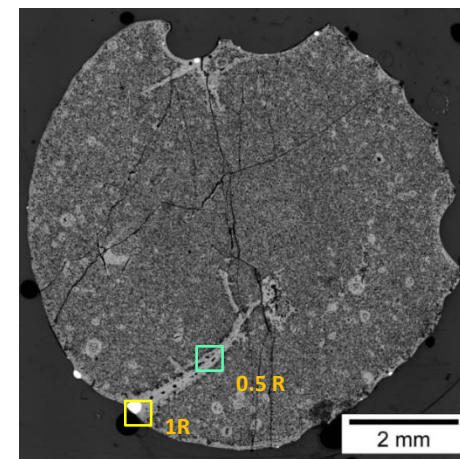
Father rod *,
56 GWd.t_{HM}⁻¹



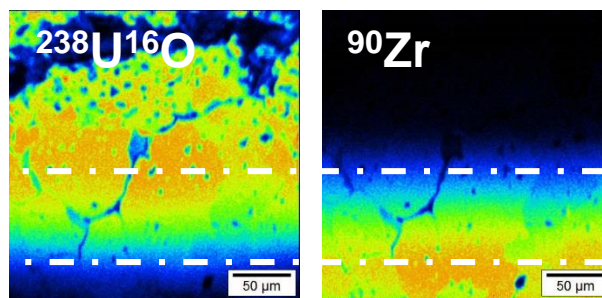
VERDON-3,
2300°C, H₂O



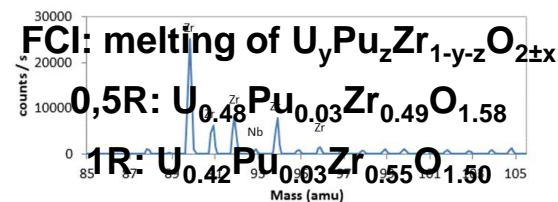
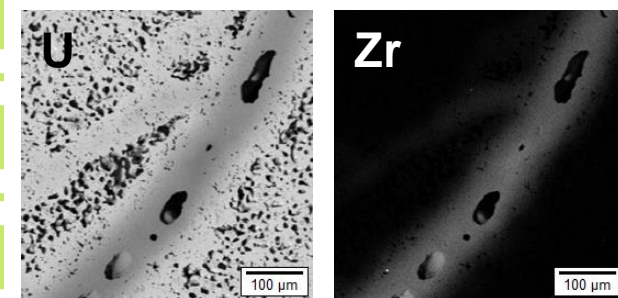
VERDON-4,
2530°C, H₂



FCI on 5 µm at the
periphery of the fuel



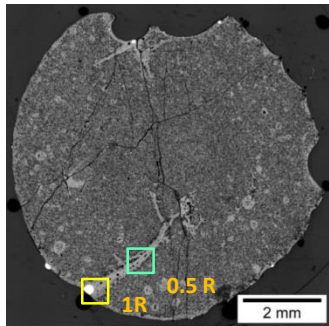
FCI on 70 µm at the
periphery of the fuel
(U_yZr_{1-y}O_{2±x} 0 ≤ y ≤ 1)



VERDON-1 and VERDON-4 samples

VERDON-4,
MOX, 56 GWd.t_{HM}⁻¹
2530°C, H₂

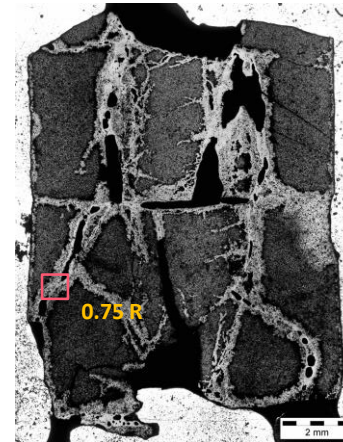
VERDON-1 *,
UO₂, 72 GWd.t_{HM}⁻¹
2600°C, H₂O/H₂ = 0.9



FCI: melting of U_yPu_zZr_{1-y-z}O_{2±x}

0,5R: U_{0.48}Pu_{0.03}Zr_{0.49}O_{1.58}

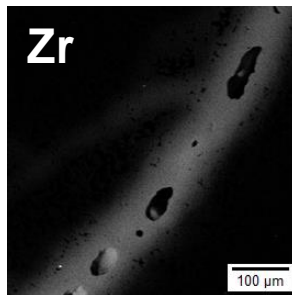
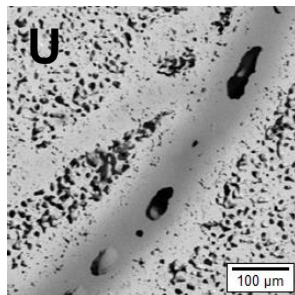
1R: U_{0.42}Pu_{0.03}Zr_{0.55}O_{1.50}



FCI: melting of U_yZr_{1-y}O_{2±x}

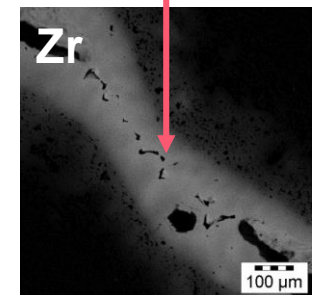
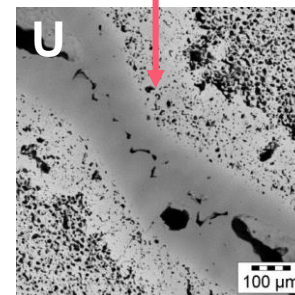
Similar compositions in
both cases

Same phenomena in the
case of UO₂ and MOX fuels



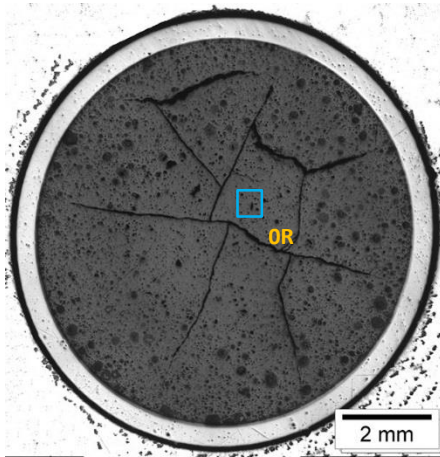
U_{0.77}Zr_{0.23}O_{1.85}

U_{0.48}Zr_{0.52}O_{1.70}

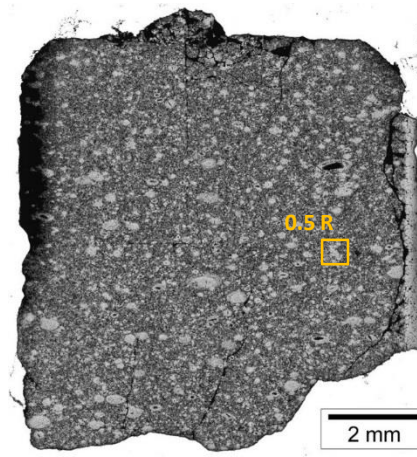


Metallic precipitates

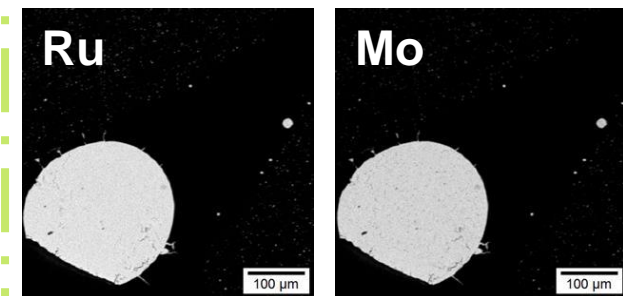
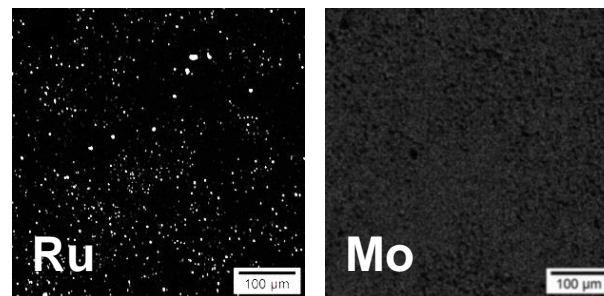
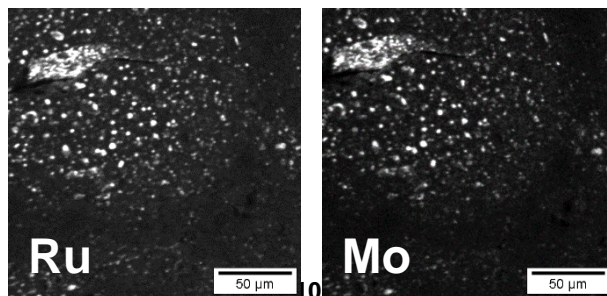
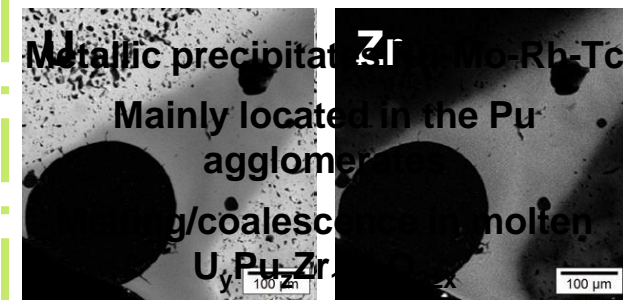
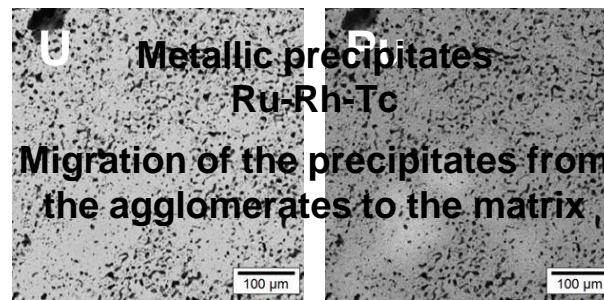
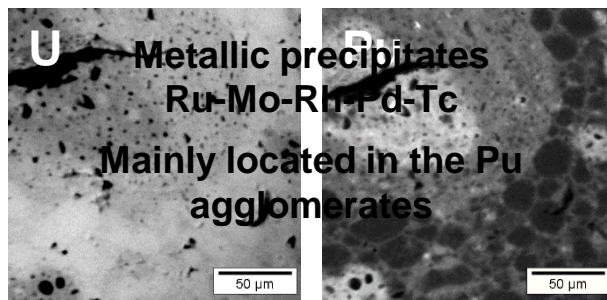
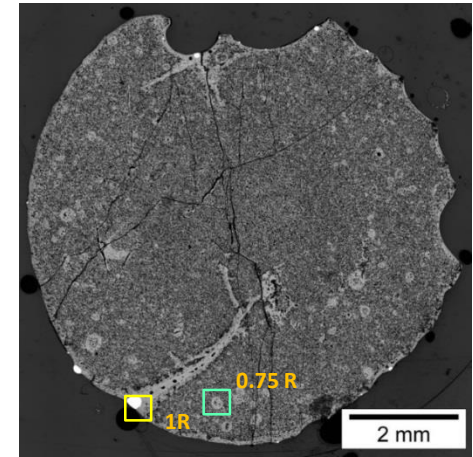
Father rod *,
56 GWd.t_{HM}⁻¹



VERDON-3,
2300°C, H₂O

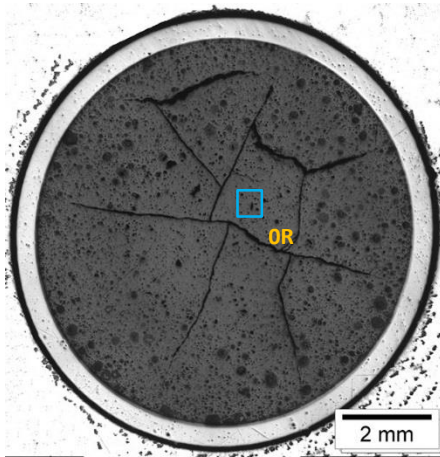


VERDON-4,
2530°C, H₂

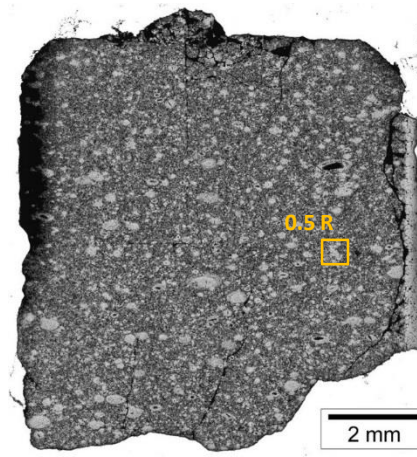


Dissolved FP

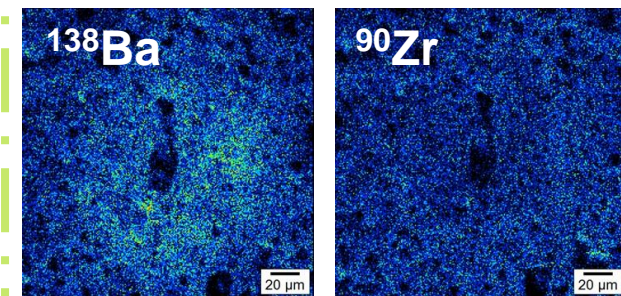
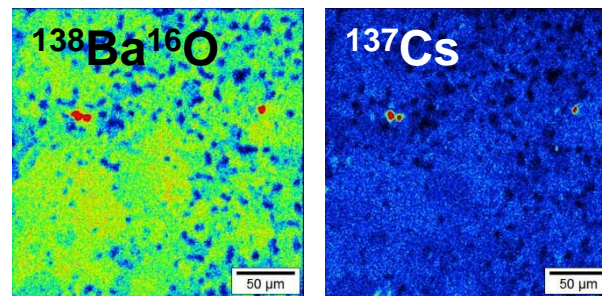
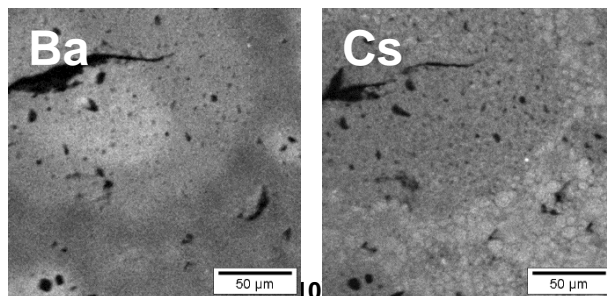
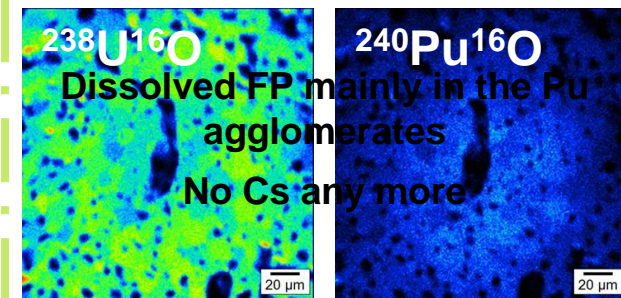
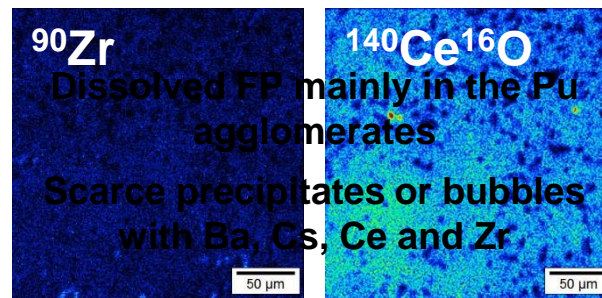
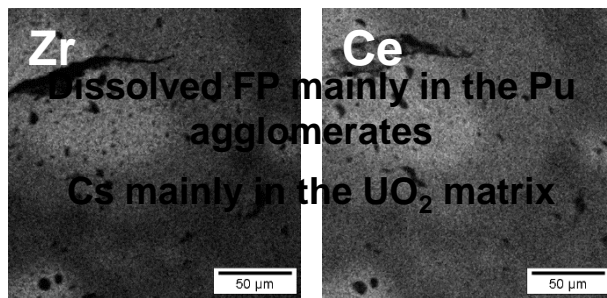
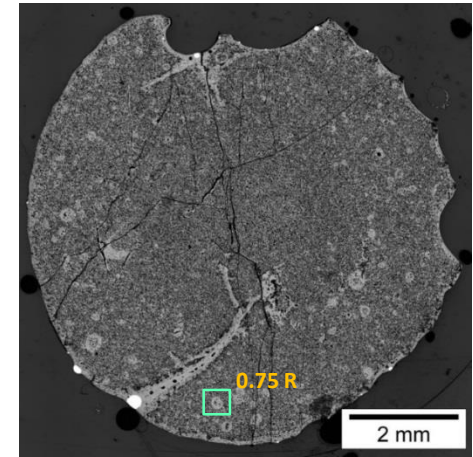
Father rod,
56 GWd.t_{HM}⁻¹



VERDON-3,
2300°C, H₂O



VERDON-4,
2530°C, H₂



CONCLUSIONS

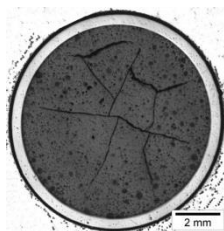
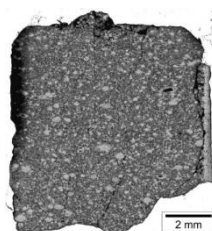
Behavior of MOX fuel and
FP in SA conditions?



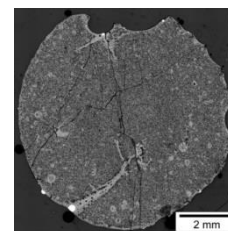
Post-test qualitative and
quantitative analyses

Father rod,
MOX, 56 GWd.t_{HM}⁻¹

VERDON-3,
2300°C, H₂O



VERDON-4,
2530°C, H₂



Oxidizing atmosphere:

FCI but no fuel melting (T effect)

Enhanced diffusion (Pu, FP...)

Mo and Cs total release *

Reducing atmosphere:

Melting of $U_yPu_zZr_{1-y-z}O_{2\pm x}$
(dissolution of (U, Pu)O₂ by ZrO₂)

Melting and coalescence of
metallic precipitates

Chemical state of dissolved FP (Cs, Mo, Ba, Zr...)?



CEA / DEN / DEC / SA3E / LCPC:

S. Reboul, I. Roure, T. Blay,
I. Félines, J. Noirot, V. Basini

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