ESFR-SMART Spring School
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MOX fuel safety and performances

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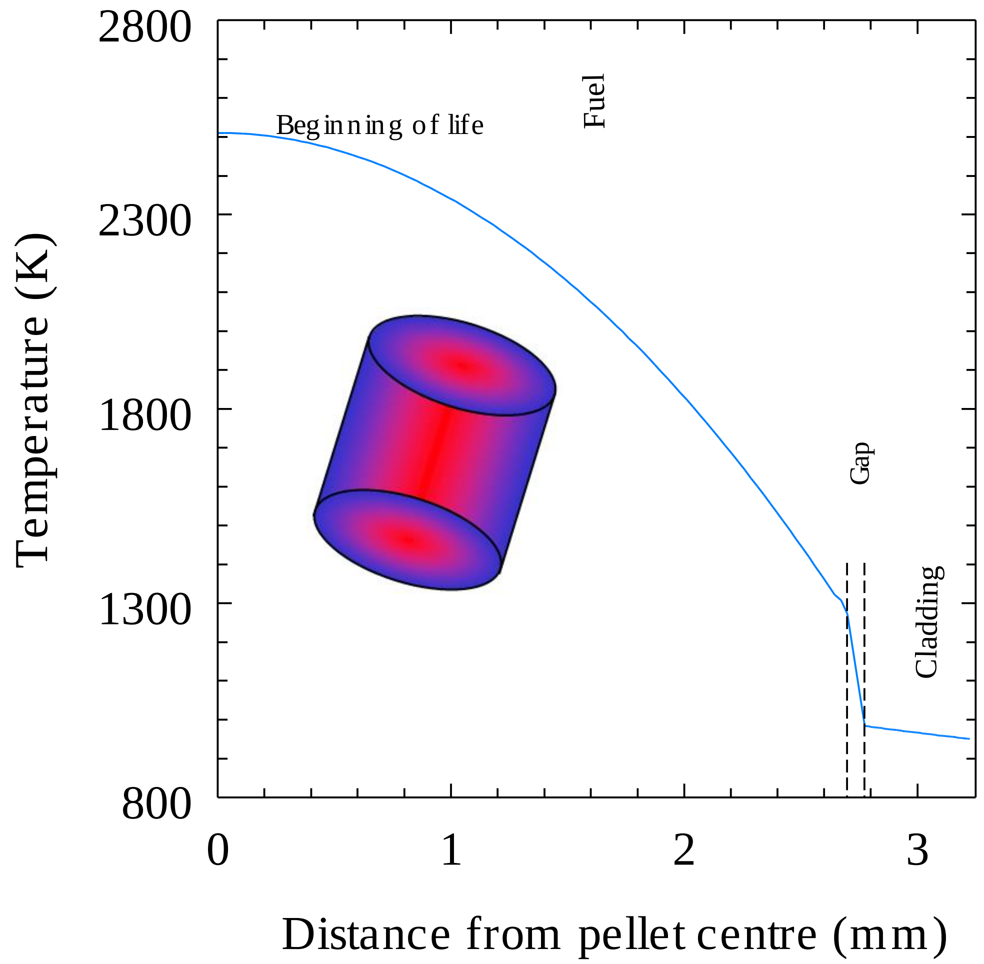
Motivations for using MOX fuel

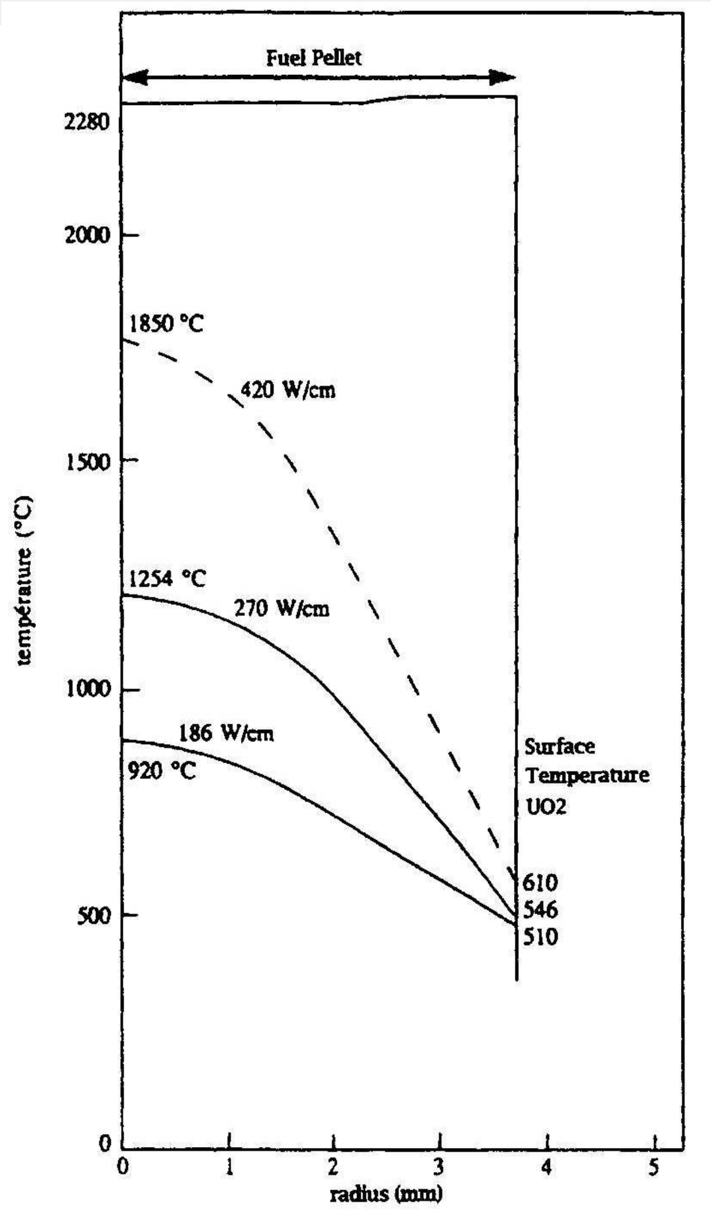
- Oxide fuels have higher melting points and lower thermal expansion than metallic fuels, carbides and nitrides, but have a lower thermal conductivity

- **MOX fuel demonstrated a good behaviour** up to ***very high burn-ups*** (15 at.%), during the ***fuel cycle***, drawbacks are *a high fission gas release*, ***low density of fissile atoms*** and the ***compatibility with sodium***.

- *Metallic fuels, carbide or nitrides* have a higher conductivity (lower irradiation temperature), but higher **swelling** and still large FGR.

Temperature gradient in a fuel pellet, FBR vs. LWR





- The target burn-up for FBR MOX fuels is about 15 at. %, which is considerably higher than for LWR fuels and will result in the formation of a large amount of fission products:

- forming a solid solution with the matrix (Y, La, Ce, Pr, Nd, Pm, Sm, Eu)
- oxide precipitates (Ba, Zr, Sr, Cs), appear as “grey phases”
- metallic precipitates (Mo, Ru, Tc, Rh, Pd),
- volatile (Cs, Te, I) which migrate to the pellet periphery
- gaseous (Xe, Kr).

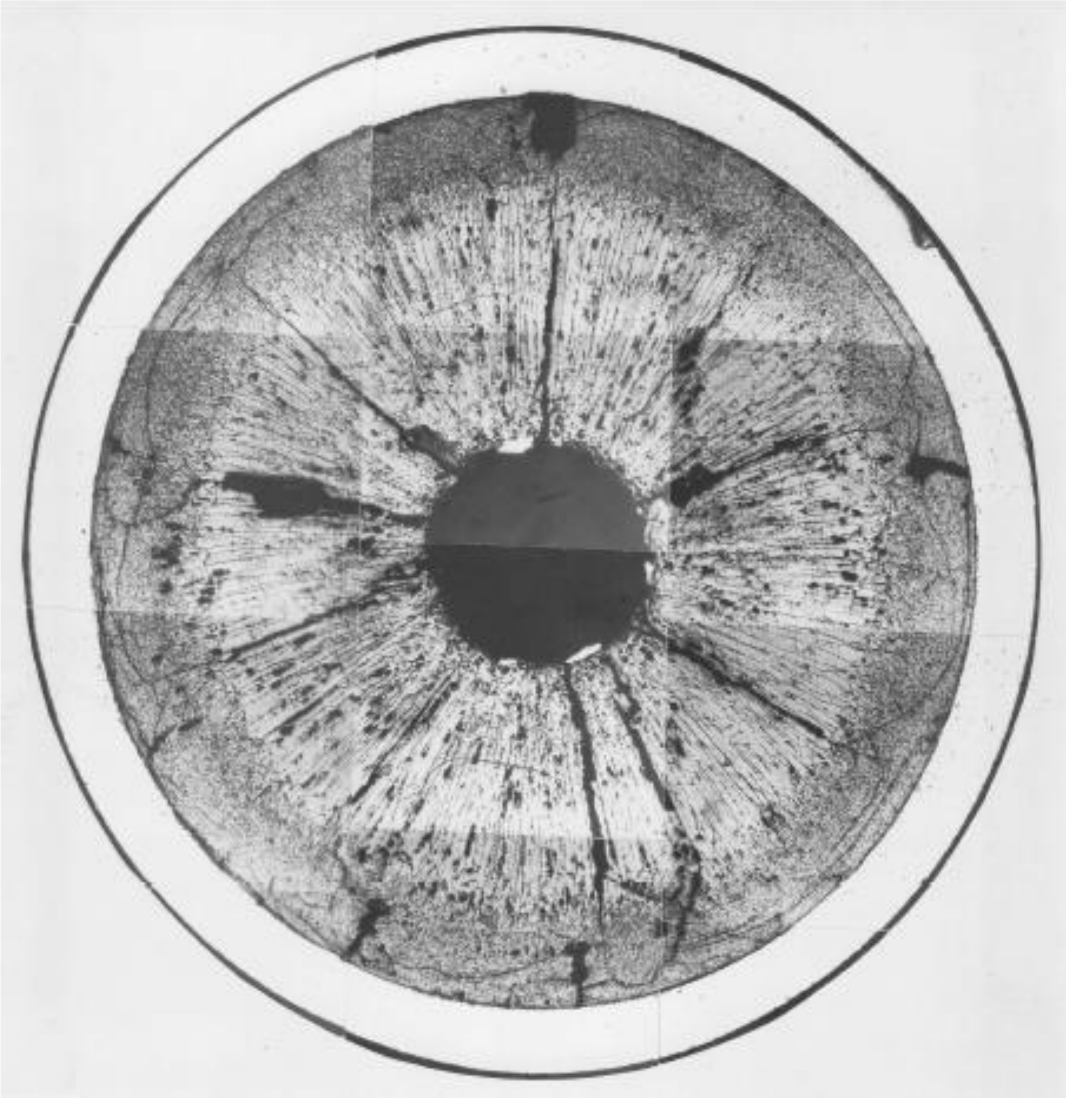
Irradiation behavior different from LWR due to the high temperatures.

Outline

- Fuel restructuring
- Redistribution of Pu, Oxygen
- Fission gas release
- The JOG
- Impact of redistribution on properties

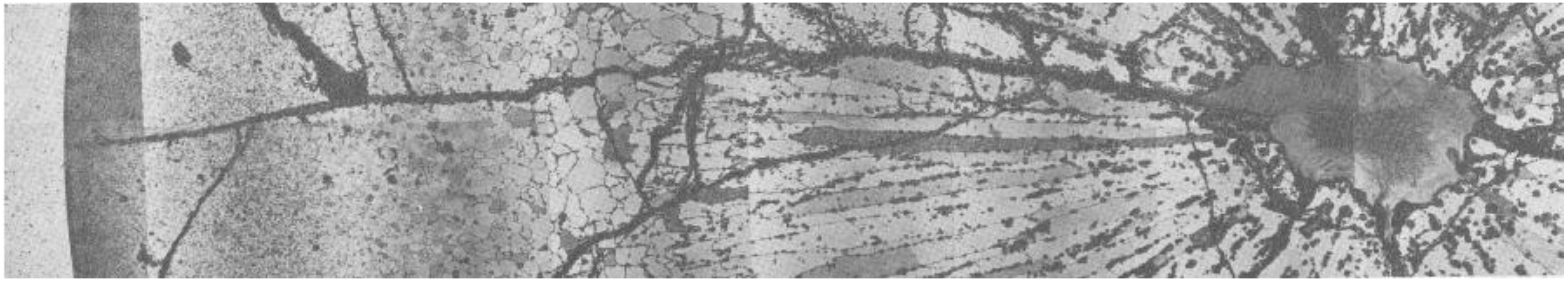
Restructuring

The initial microstructure (grains size, porosity) is strongly modified during irradiation as a result of restructuring.



Restructuring

- **FBR, T** >2000° C : extensive restructuring



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4 regions:

Grains: as fabricated/RIM → equiaxed → columnar → central hole

T<1200° C

dense

transport of the as fabricated porosity

Pellet cracking, Grain growth, Columnar grains and central hole (initial or forms within minutes)

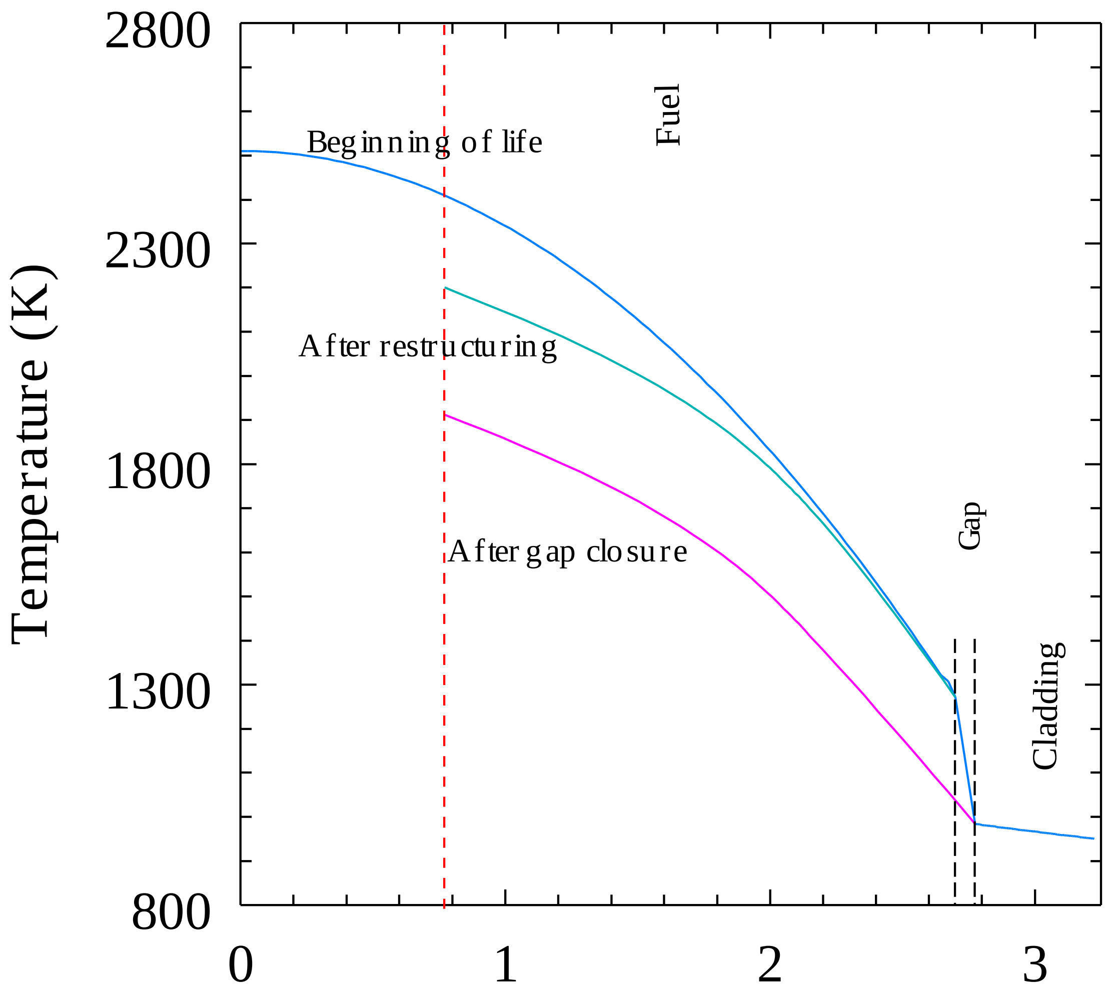
-**LWR, T** <1200° C **:**

RIM **structure (HBS,** grains subdivision) at high burn-up at pellet periphery and in the Pu rich-agglomerates of heterogeneous MOX

Restructuring

- Central hole limits the maximum temperature reached and avoids melting at beginning of life

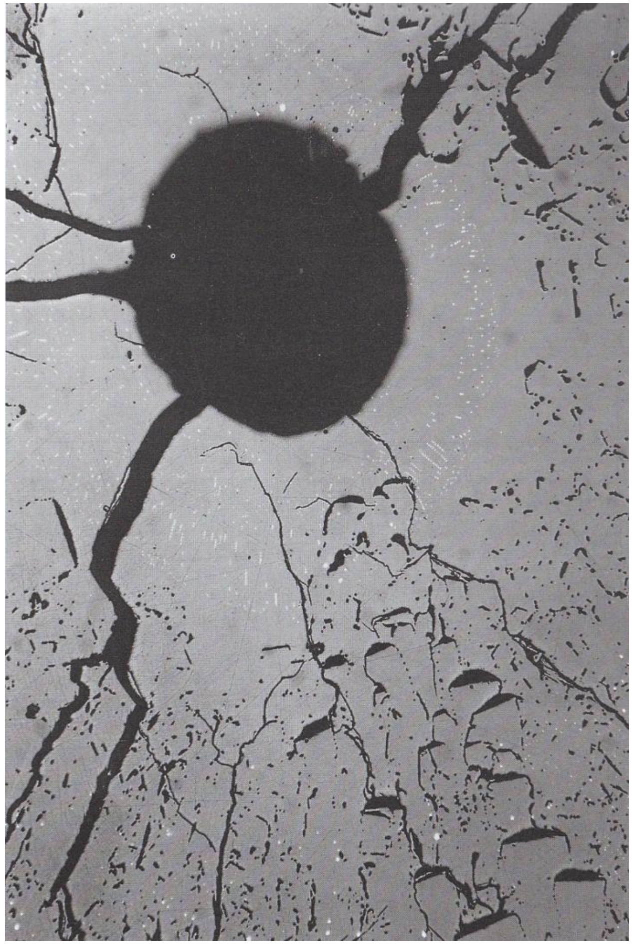
- Central temperature decreases after to gap closure

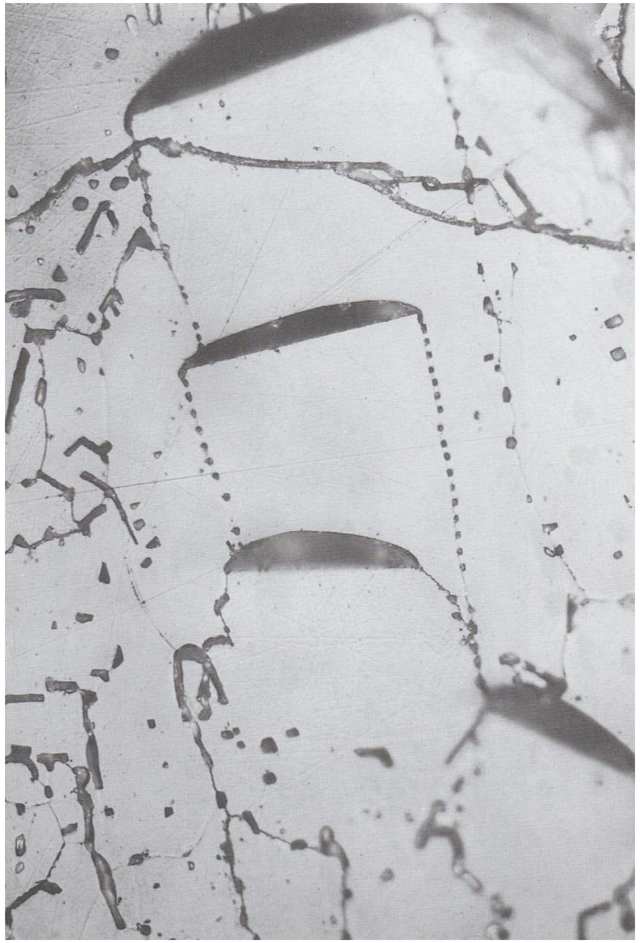


Restructuring

Lenticular pores form under steep temperature gradients in fast reactor $(U,Pu)O_2$ fuel

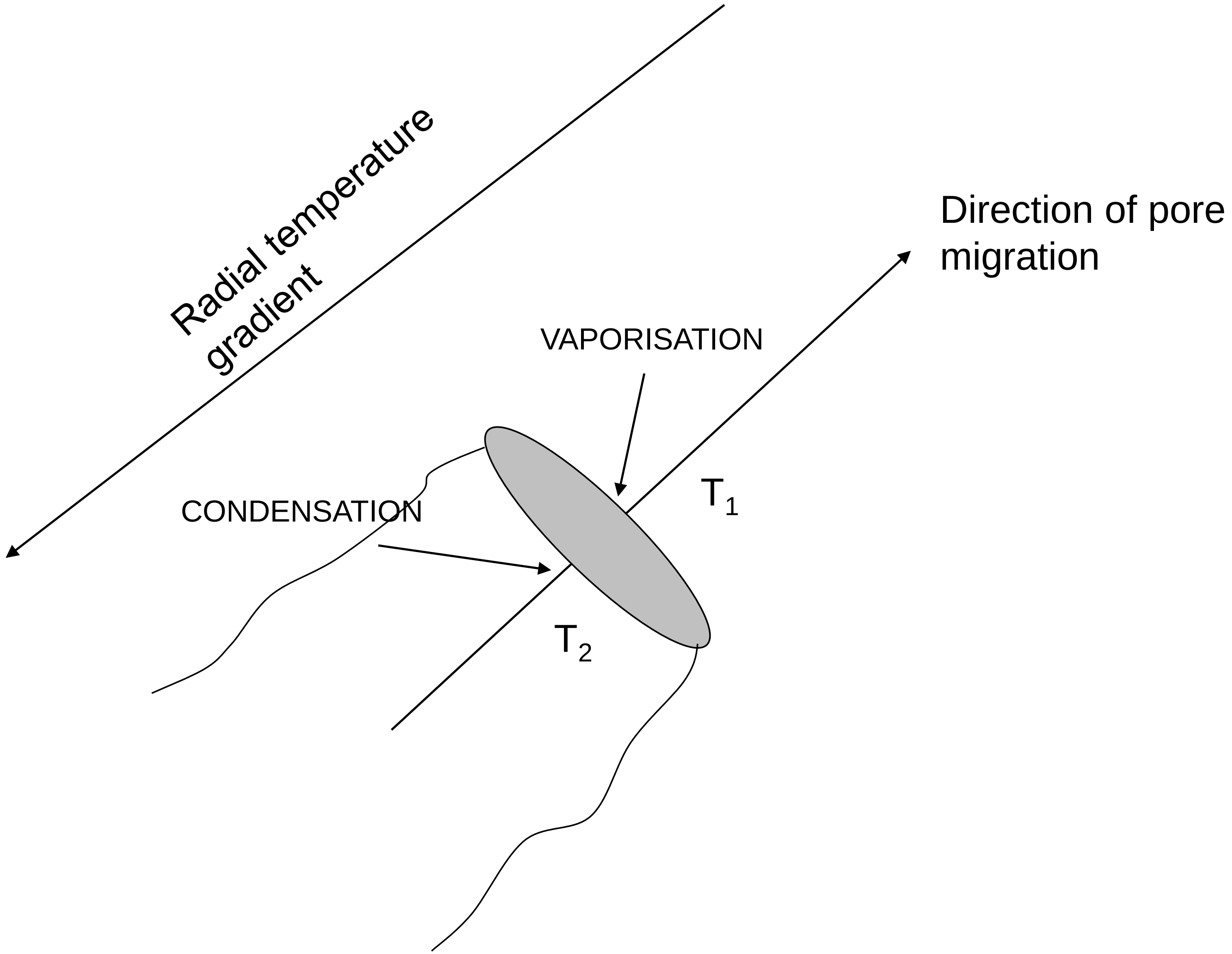
Pores and cracks move towards central void via evaporation/condensation mechanism





Restructuring

Vaporisation condensation (pore diffusion)



Redistribution

Redistribution of :

- plutonium : enrichment in the central area
- oxygen : migrates towards the low temperature region of the pellet
- minor actinides (if MA recycling): Am migrates to the center
- fission products ($\rightarrow$ JOG)

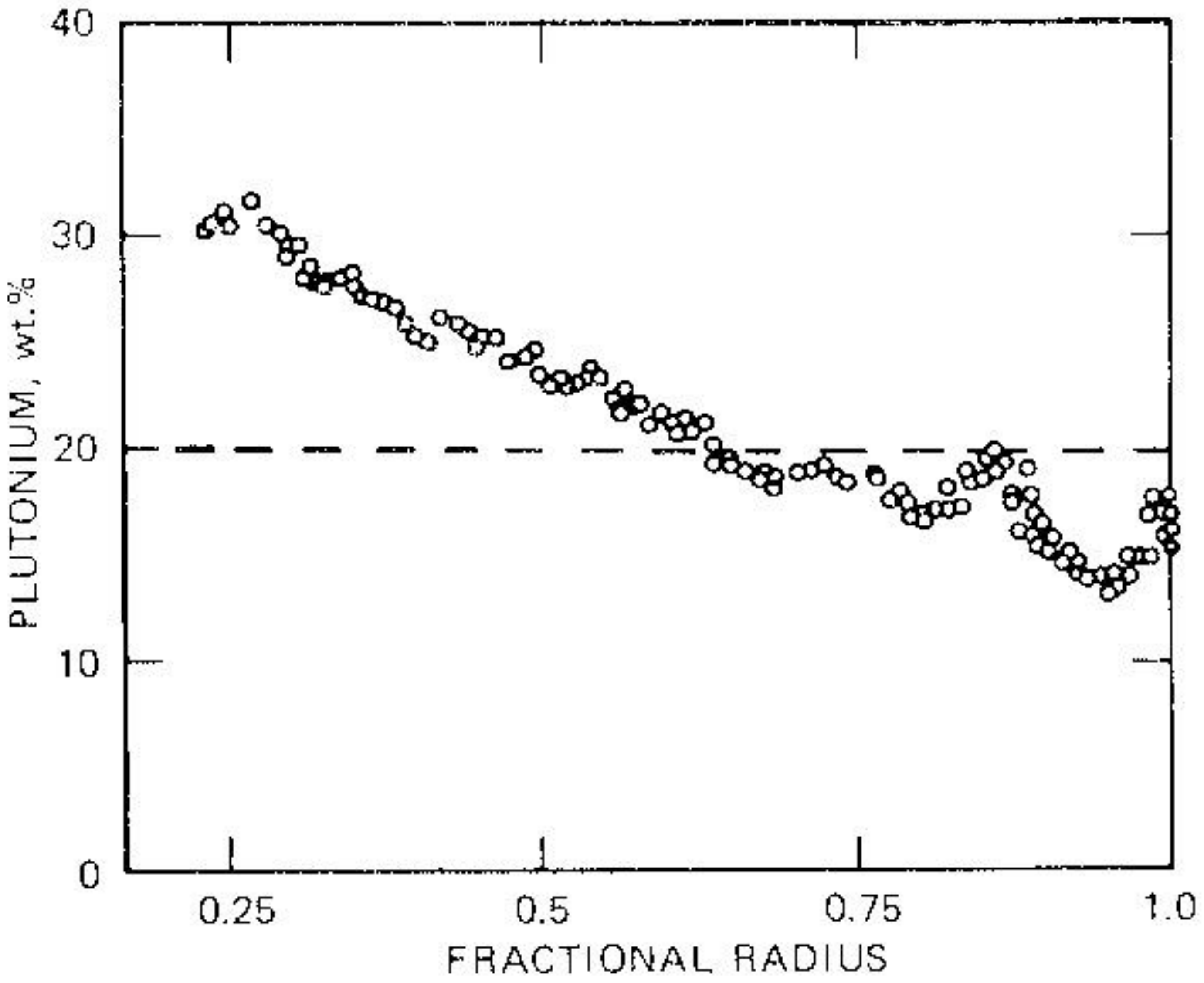
Possible mechanisms:

- Atomic diffusion (thermal and athermal): bulk diffusion
- Grain boundary and surface diffusion
- Vaporisation condensation (pore diffusion)

Redistribution of Pu

Pu redistribution in FBR fuel after a burnup of 5% at 660 W/cm:

enrichment in the center

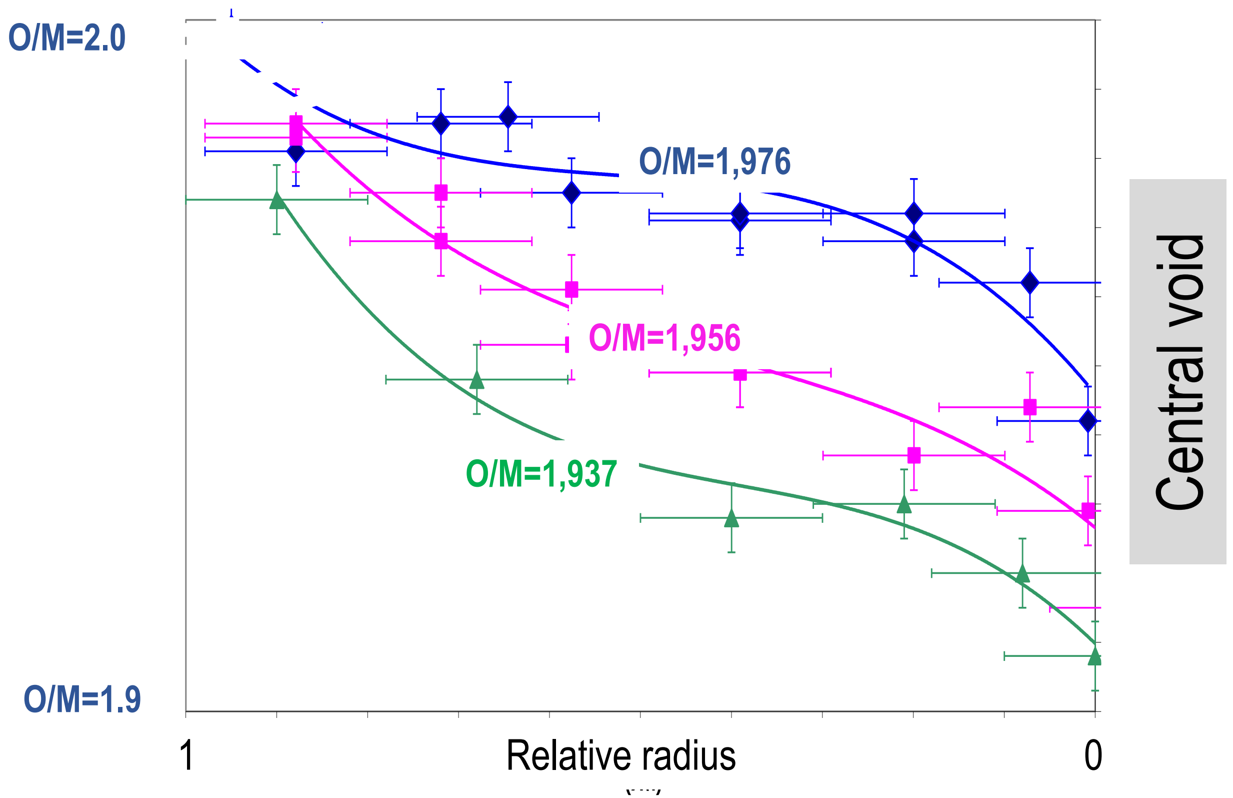


Ref.: Olander

Redistribution of Oxygen

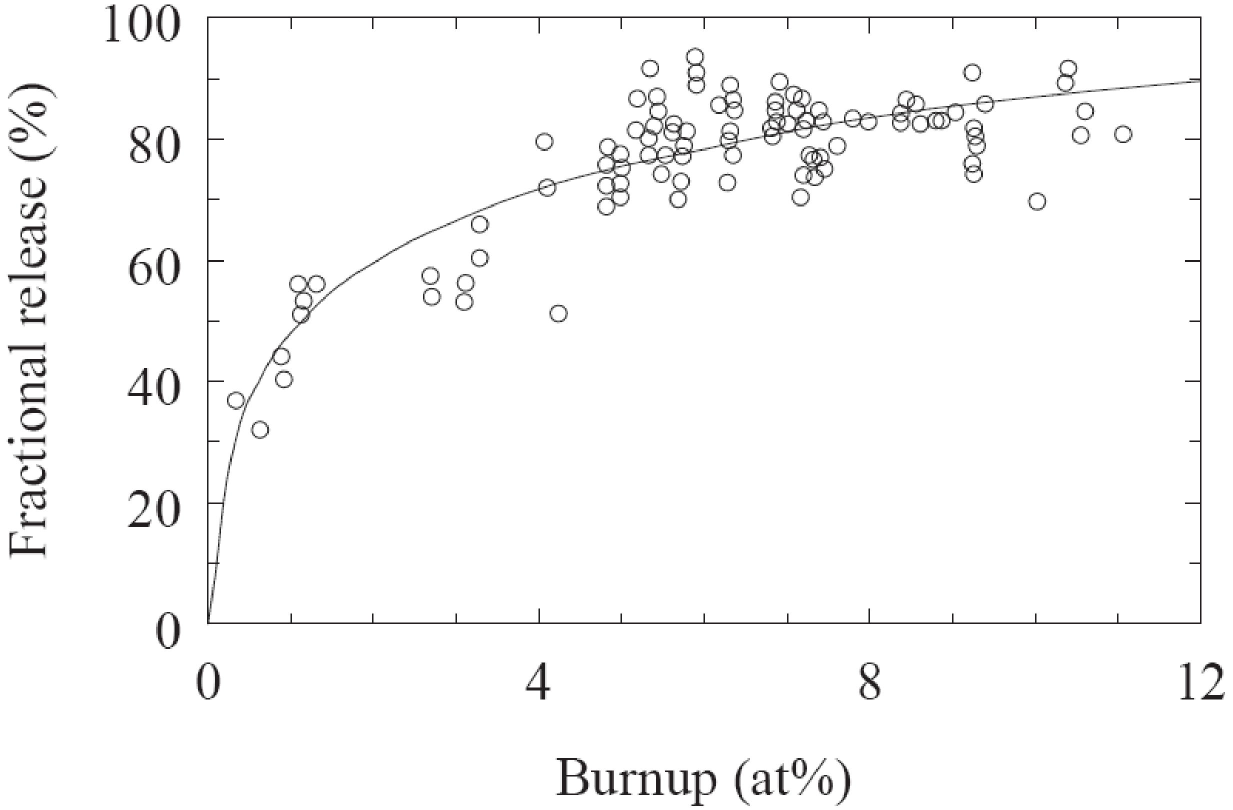
Fresh fuel is fabricated hypostoichiometric.

During irradiation, oxygen is rapidly redistributed radially



Fission Gas release

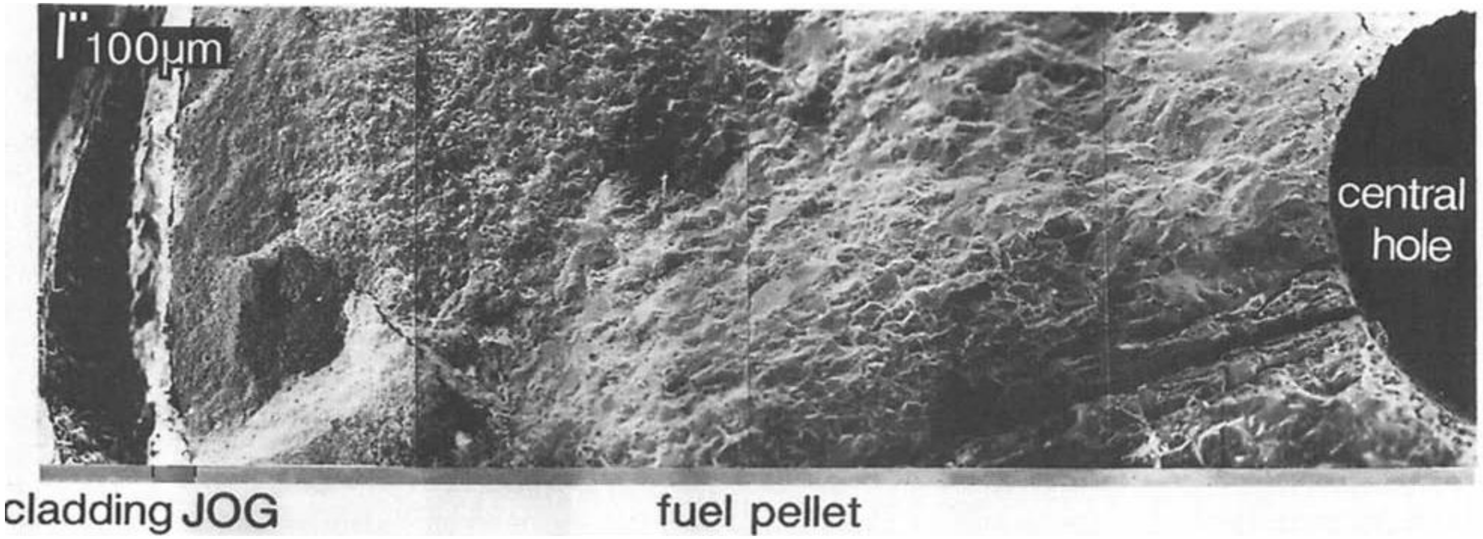
- High fission gas release (FGR) already at low burn-up: fuel pin must have sufficient free volume
- Large grains are favourable to fission gas retention, but the diffusion coefficients are very high (high T)
- Fission gas is mainly located at the pellet periphery, almost no gas remains close to center
- In typical PWR fuel, FGR is below 2% at the burn-up of 50 GWd/t



The JOG

The Joint Oxyde-Gaine, JOG:

- For burn-ups above about 5 to 7 at.%, some fission products are released and compounds accumulate as a solid medium in the gap.
- Forms in the hotter regions of the fuel pin, thickness increasing with burn-up up to 150 to 300 μm



Tourasse et al. (1992), J. Nucl. Mater.188:49

The JOG

- Evolution of the gap:

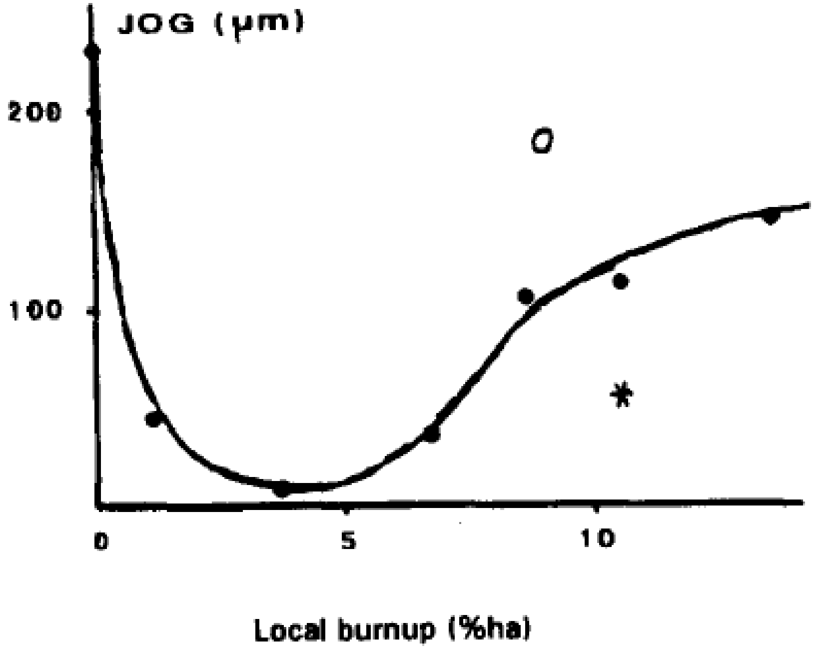
1 - below about 5 at.%, gaseous and decreasing

2 – about 5 to 10 at.%: increasing rapidly, it is filled with JOG

3 – above 10 at.%: slower increase

- JOG contains neither U nor Pu. It is an oxde phase mainly with Mo and Cs, but Ba, Pa, Cd, I, Te are also present. Mo has left the noble metal precipitates.

- Pellet–cladding mechanical interaction (PCMI) does not take place during the first years of irradiation, and then remains moderated, even less with annular pellets



Tourasse et al. (1992), J. Nucl. Mater.188:49

The JOG

- No JOG in the lower part of the fissile column, where T is lower

- The exact composition of the JOG is not known, it varies axially and azimutally in the pin, depending on local temperatures, oxygen potential...

  > fuel properties like conductivity are expected to vary accordingly!

- The thermal conductivity of the JOG (Cs_2MoO_4, …) is 5 to 10 times lower compared to the fuel matrix

- JOG formation induces a decrease of the matrix swelling.

Tourasse et al. (1992), J. Nucl. Mater.188:49

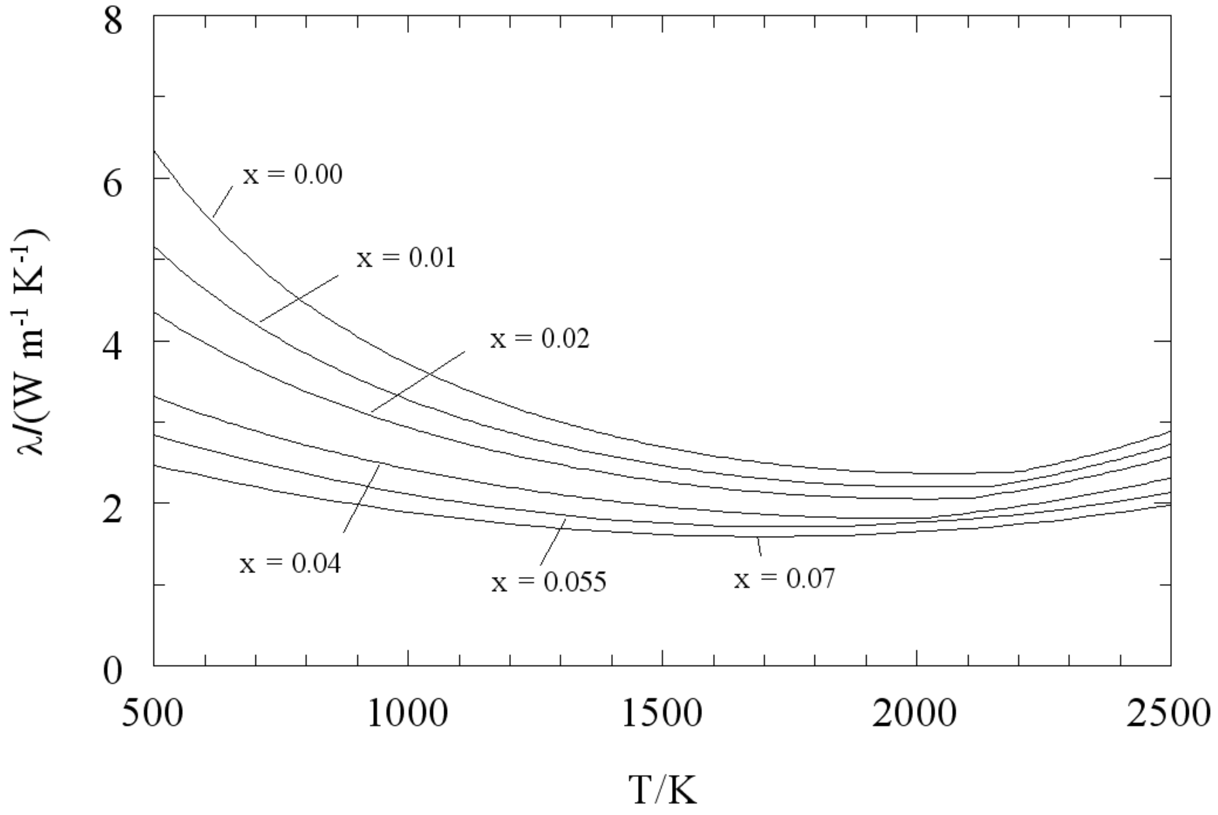
Impact of redistribution of properties

- Pu, O redistribution have an impact on the fuel properties: melting point, thermal conductivity which will depend on radial position.

Locally, conductivity depends on:

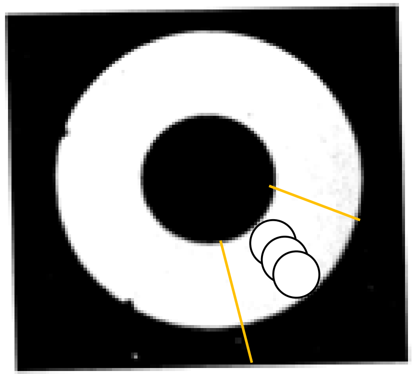
- Temperature
- Burn-up
- FP content
- O/M
- Pu content
- Microstructure

⇒ Modelling is required, more challanging that in LWR

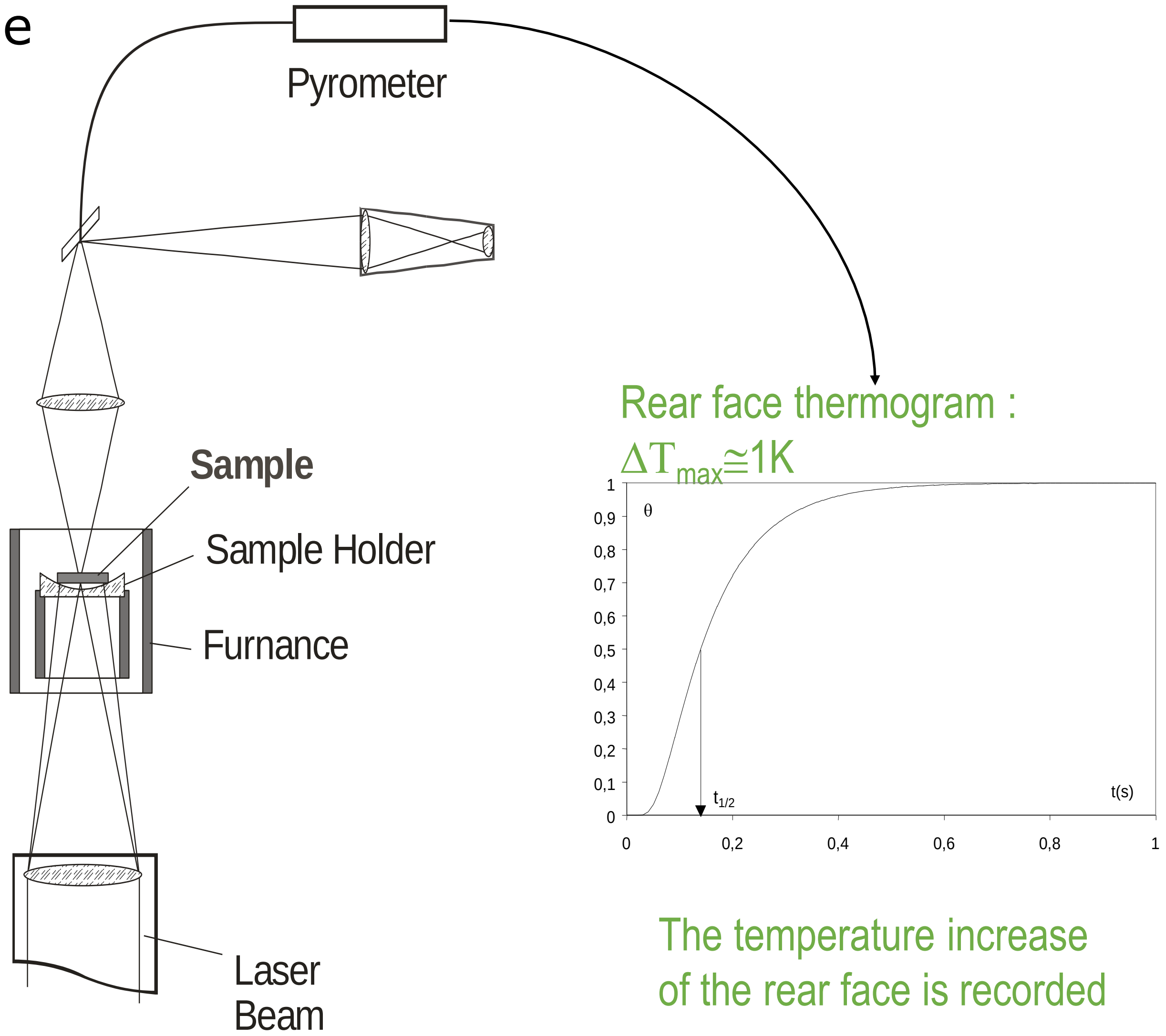


Thermal diffusivity

Local measurement of the thermal diffusivity

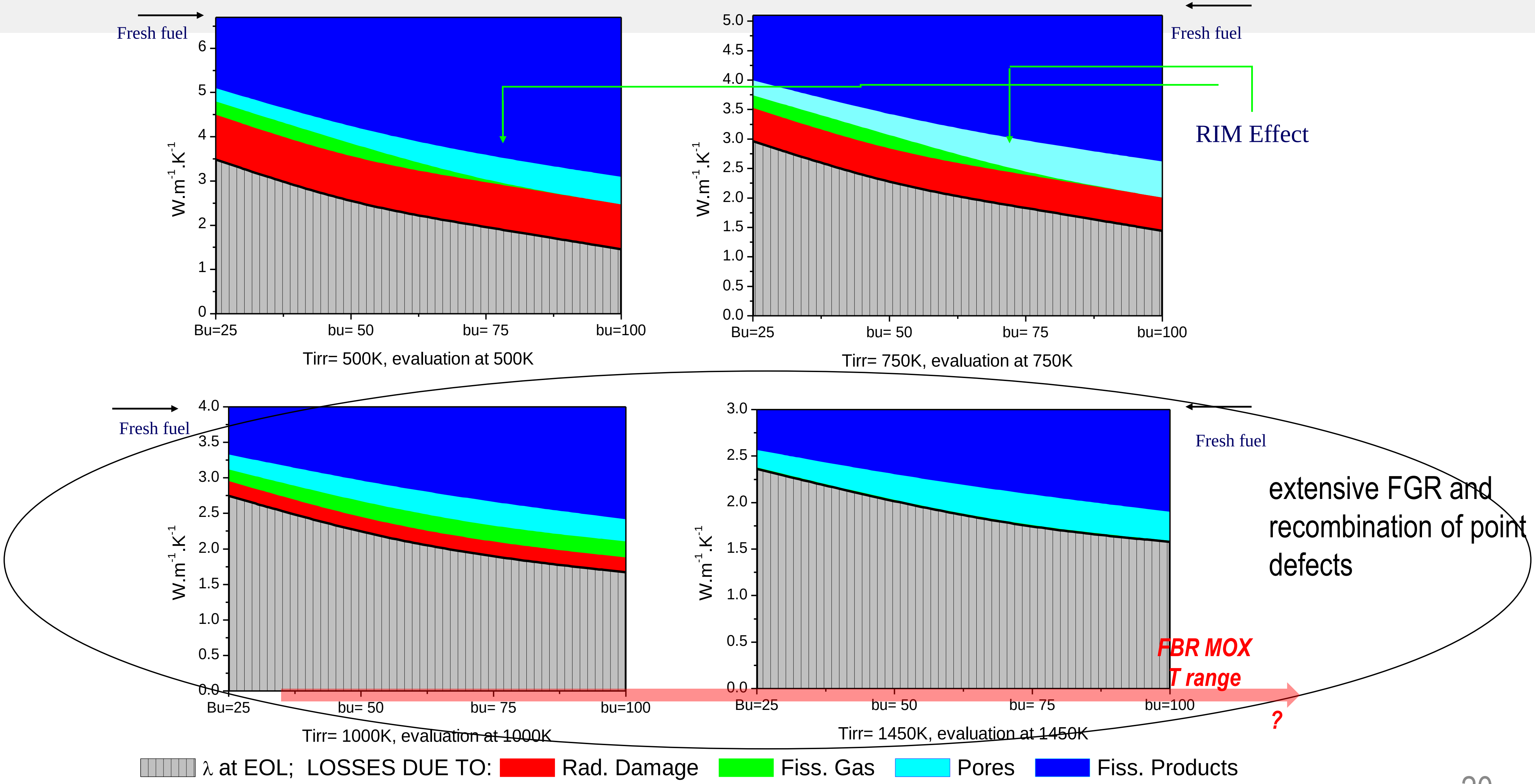


A heat pulse is produced by the laser on the front face

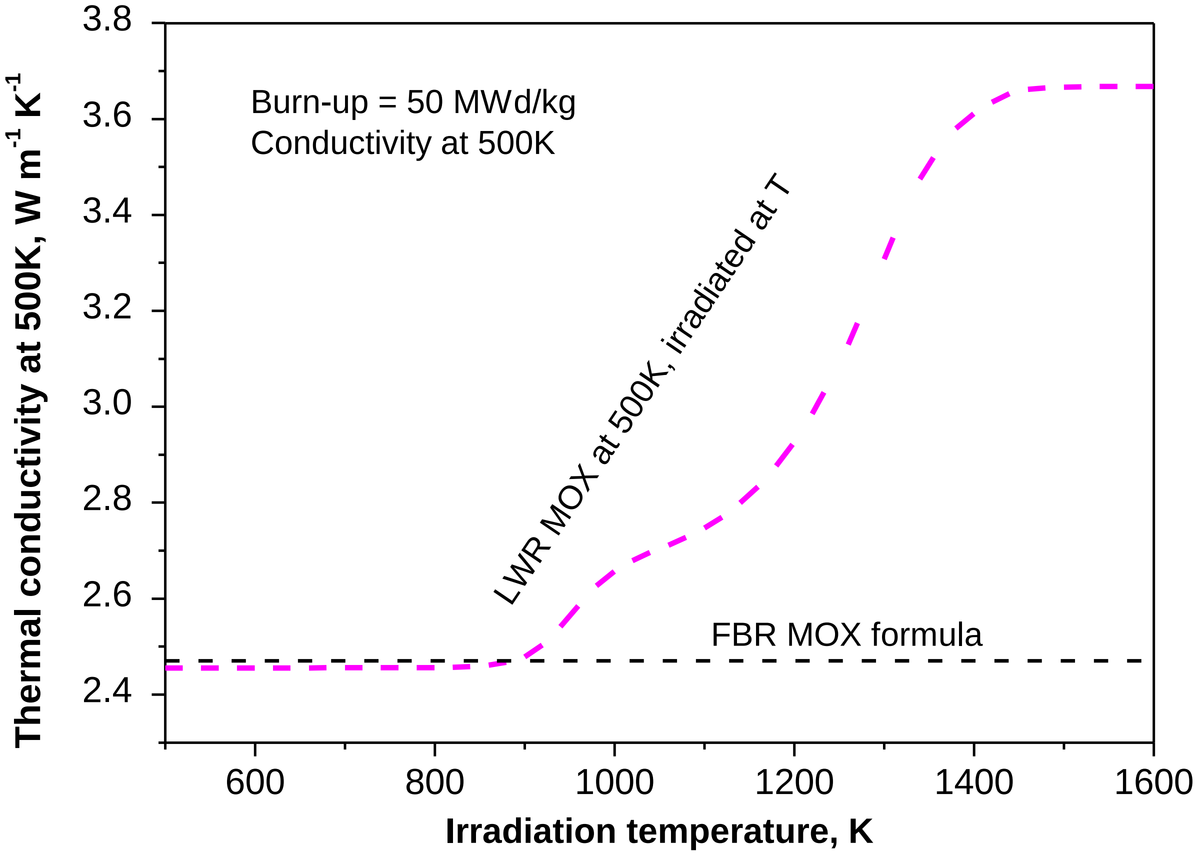


The temperature increase of the rear face is recorded

Contributions to the thermal conductivity decrease in irradiated $(U,Pu)O_2$

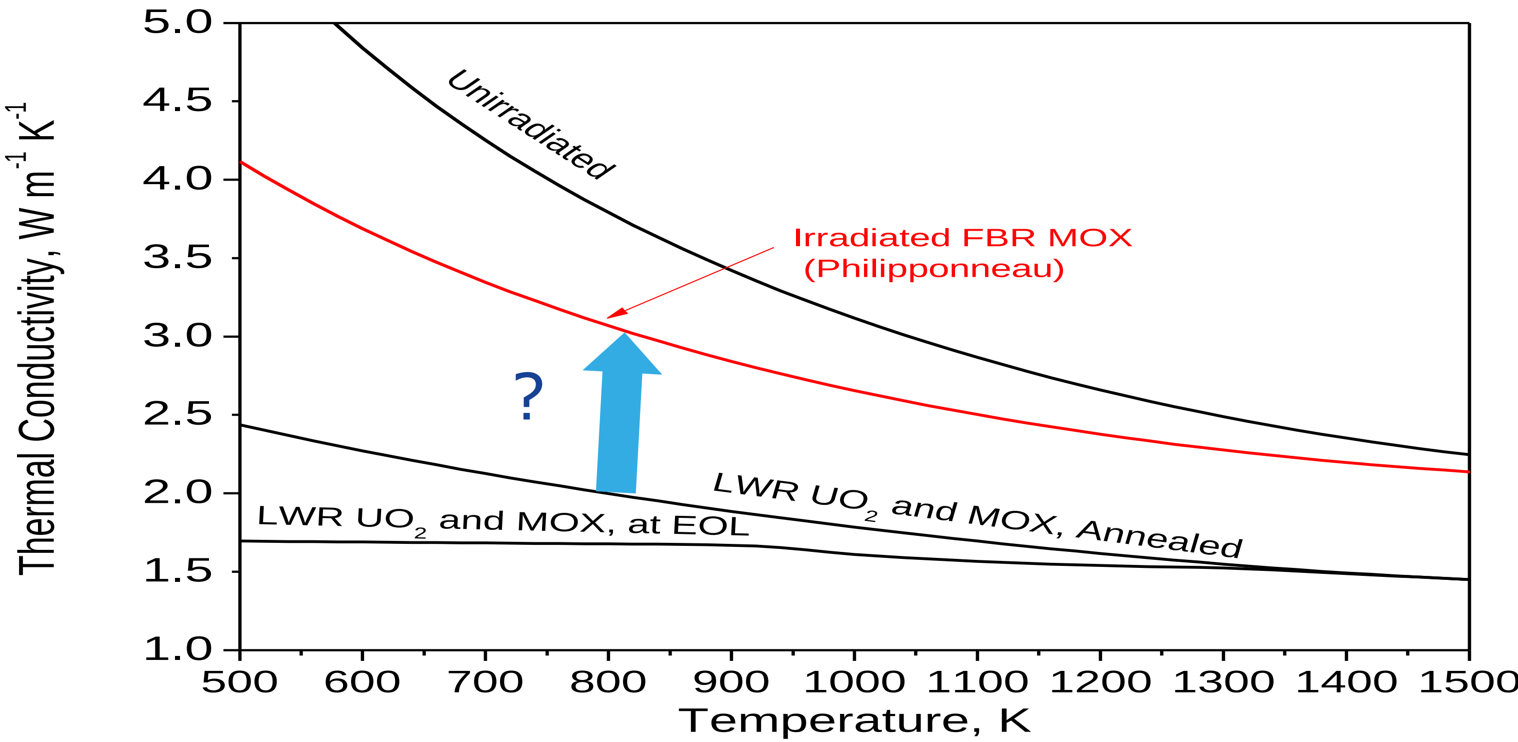


Stoichiometric irradiated LWR and FBR MOX fuels: annealing effects are known in LWR MOX: conductivity at 500K is much higher if the fuel was irradiated at higher T



Degradation of the thermal conductivity during irradiation

- Measured high thermal conductivity values can not be explained by LWR fuel formulas by suppressing the contribution of radiation damage and fission gas.
- Agreement if FP effect reduced by 75%



- The FP movement out of the fuel pellet and the presence of the JOG are proposed as main parameters

- Oxide fuel shows extensive restructuring due to the high operating temperatures and the steep temperature gradient
- FR oxide fuel has a high fission gas release as a result of which the radiation induced swelling is limited
- Radial and axial redistribution of volatile fission products takes place
- A broad knowledge base for the properties of $(U,Pu)O_2$ is available but still uncertainties exist, e.g. melting temperature and thermal conductivity

Thank you!