Experimental Results from the OECD Halden Reactor Project

Lecture 9.2

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The Training in Basic Radiation Materials Science and its Application to Radiation Effects Studies and Development of Advanced Radiation-Resistant Materials

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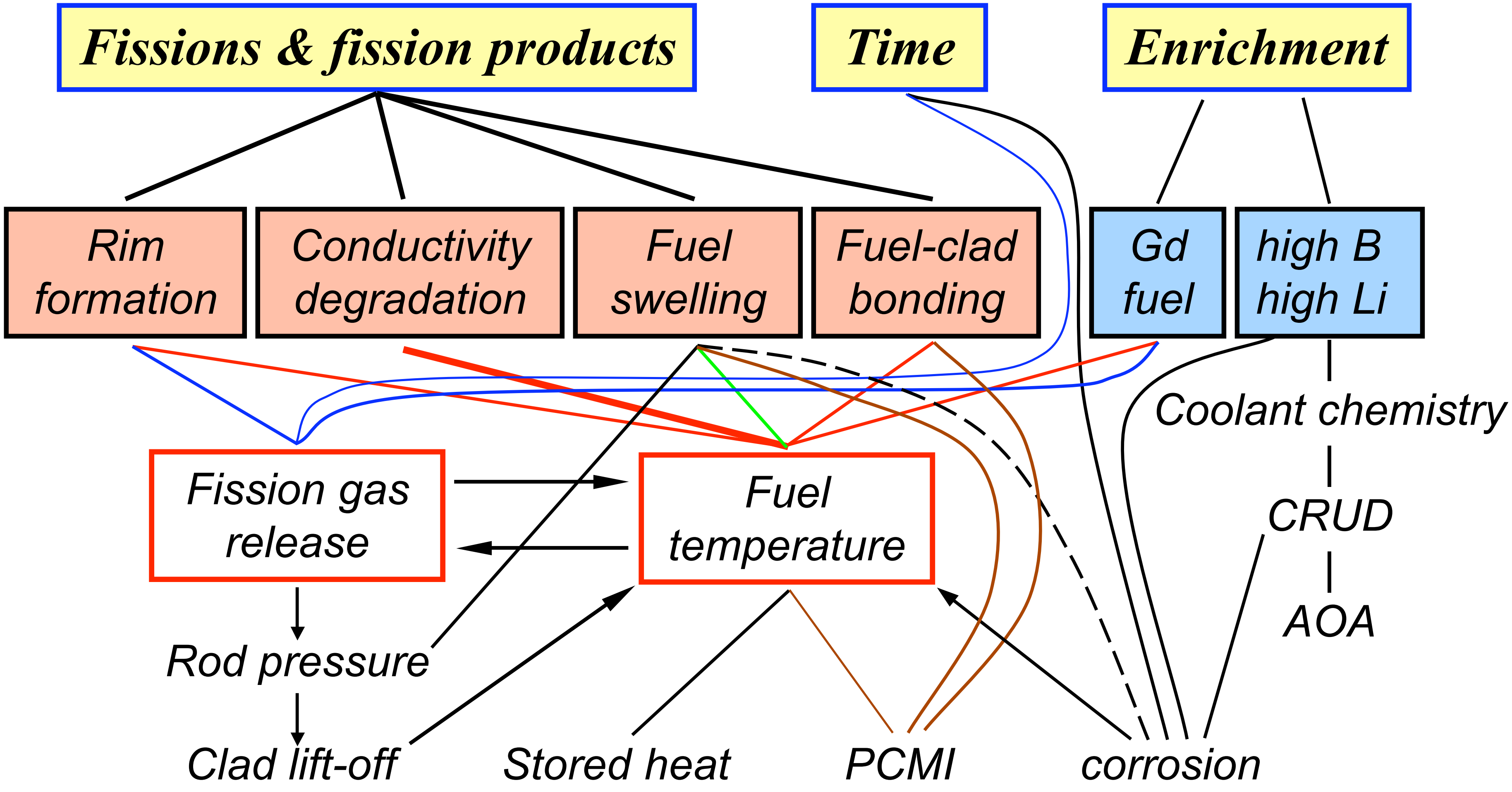
Overview

- Issues to be addressed and their interaction
- Phenomena influencing temperatures
- Fission gas release
- Dimensional changes and pellet-clad interaction
- Typical results of fuels testing

Experiments must address and untangle complex interactions – if possible ...



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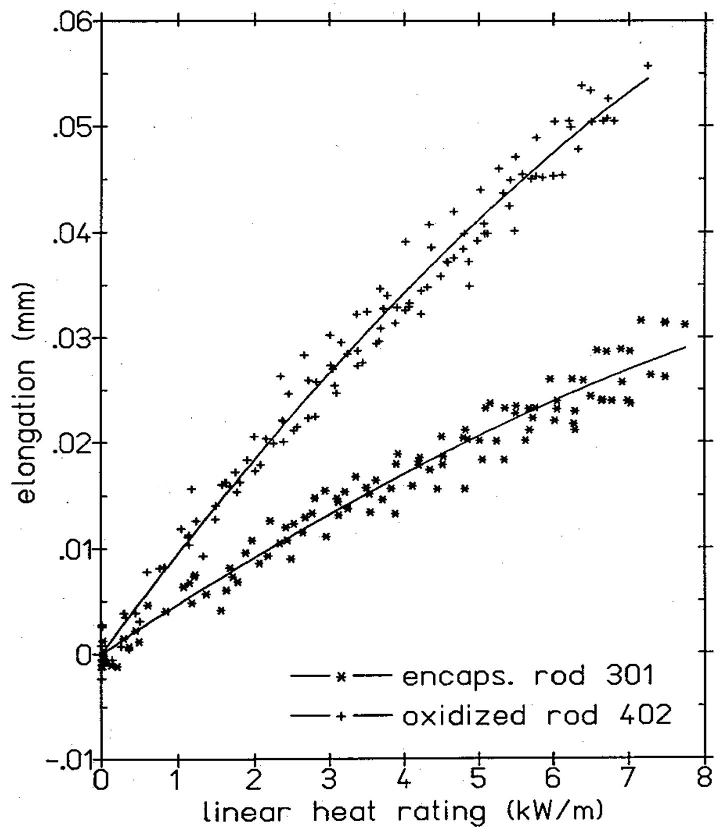
(Fuel) temperature overview

- Cladding temperature
- Gap size determination
- Gap conductance
  - Gap width
  - Surface roughness
  - Eccentricity
  - Gas composition
- Pellet
  - Densification and swelling
  - Thermal conductivity (degradation)

Cladding temperature

Measurement of the cladding temperature is normally not within the scope of the HRP experimental programme. However, if PCMI can be eliminated, details of cladding elongation behaviour can be used to qualify

- Coolant-clad heat transfer coefficient (Jens-Lottes not satisfactory for low power)
- Zry-oxide conductivity



Elongation of cladding with and without outer oxide layer

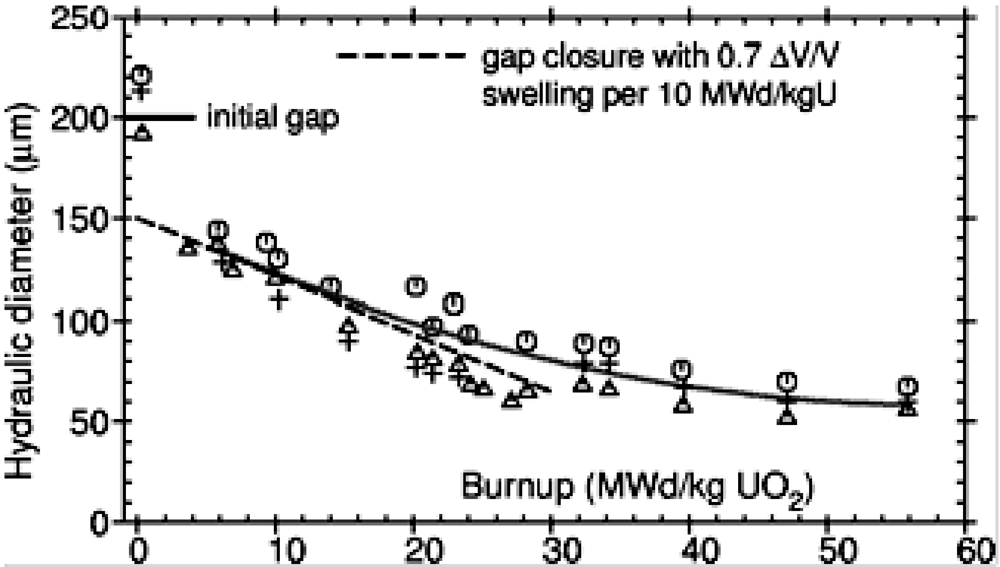
Gap size, relocation, gap conductance

- The determination of (effective) gap size and gap conductance has been the subject of many HRP separate effects experiments which include:
  - Determination of gap size by different techniques
  - Systematic variation of gap conductance model parameters such as gap size, surface roughness and fill gas composition
- The comprehensive set of experiments provide an extensive basis for gap conductance model verification.

Gap size determination

- The size of the gap between fuel pellet and cladding can be assessed by different direct and indirect techniques:
  - Clad squeezing (mechanical in-core device)
  - Hydraulic diameter measurements
  - Evaluation of onset of pellet-clad mechanical interaction
  - Gas exchange and effect on fuel temperature

Hydraulic diameter measurements



Change of hydraulic diameter (free fuel column volume)

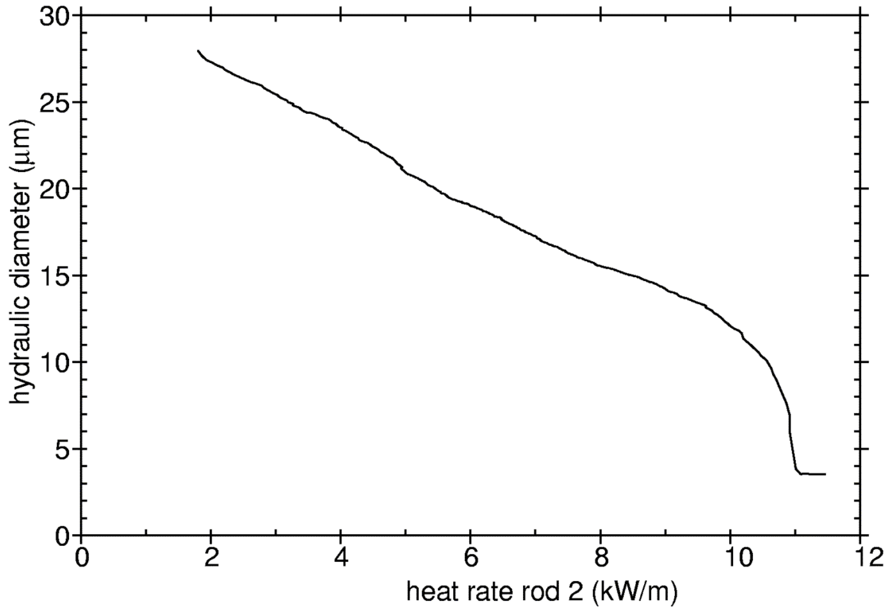
The hydraulic diameter reflects the free volume in the fuel column. Normal changes are:

- initial pellet cracking and fragment relocation
- solid fission product fuel swelling
- development of a minimal HD as fuel and cladding accommodate to each other

Hydraulic diameter measurements

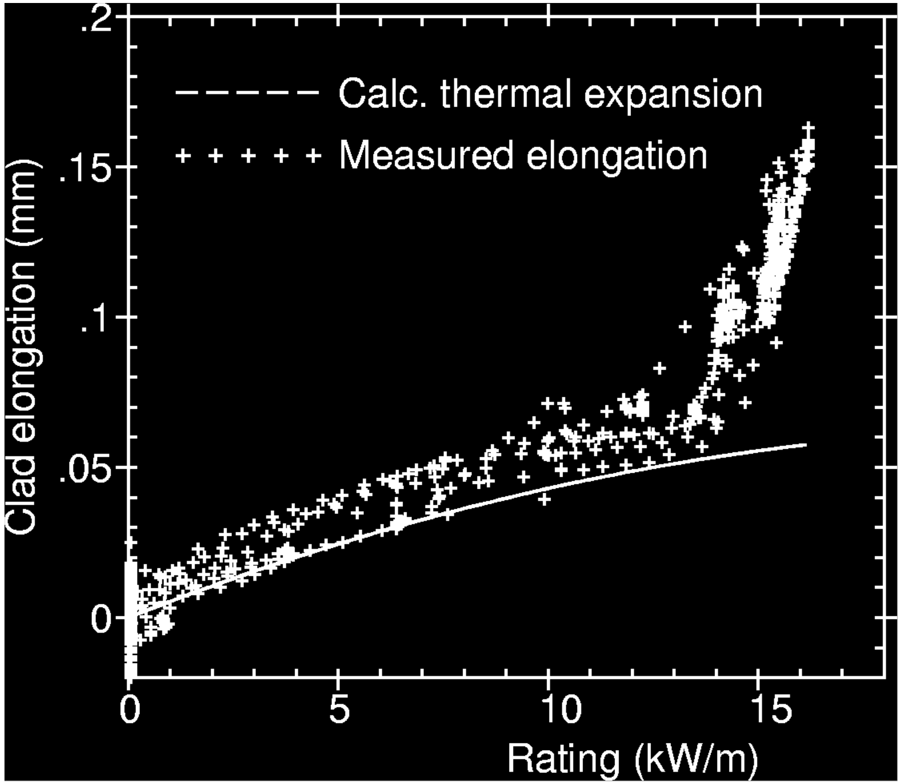
- At zero power, high burnup fuel typically has a “gap” size reflecting thermal contraction from the accommodation power level
- When the accommodation power level is approached, the hydraulic diameter decreases at a higher rate, similar to the onset of PCMI
- Regular measurements in a number of HBWR experiments connected to the gas flow system

High burnup fuel example



The hydraulic diameter measurements show a linear decrease of ”gap” size with increasing power

Gap size - onset of PCMI



Cladding elongation of ex-PWR fuel (57 MWd/kgU) during several start-up / shut-down sequences

Pellet-clad mechanical interaction undergoes various phases. When the cracked fuel has accommodated to the cladding, the onset of appreciable PCMI indicates gap closure. The high burnup fuel example illustrates:

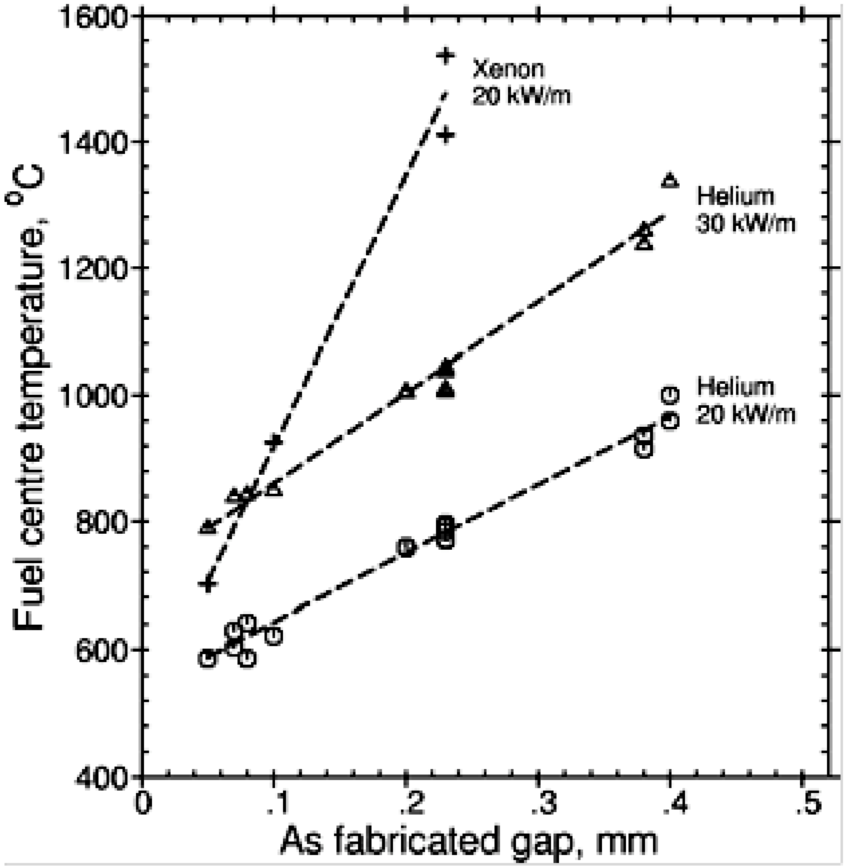
- cladding elongation deviates little from free thermal expansion
- onset of interaction occurs at previously reached maximum power (14-16 kW/m)

Gap conductance

- Gap conductance models usually contain a number of parameters that are accessible to experimental set-ups. HRP separate effects experiments include:
  - Systematic variation of gap size (50 – 400 mm)
  - Variation of surface roughness of fuel and cladding
  - Assessment of effect of eccentric pellet location
  - Different initial fill gases (He, Ar, Xe) and their mixtures
  - Variation of gap gas composition in-pile
- The associated data are indispensable for the verification of correct modelling of basic phenomena in fuel-clad gap heat transfer

Variation of gap size

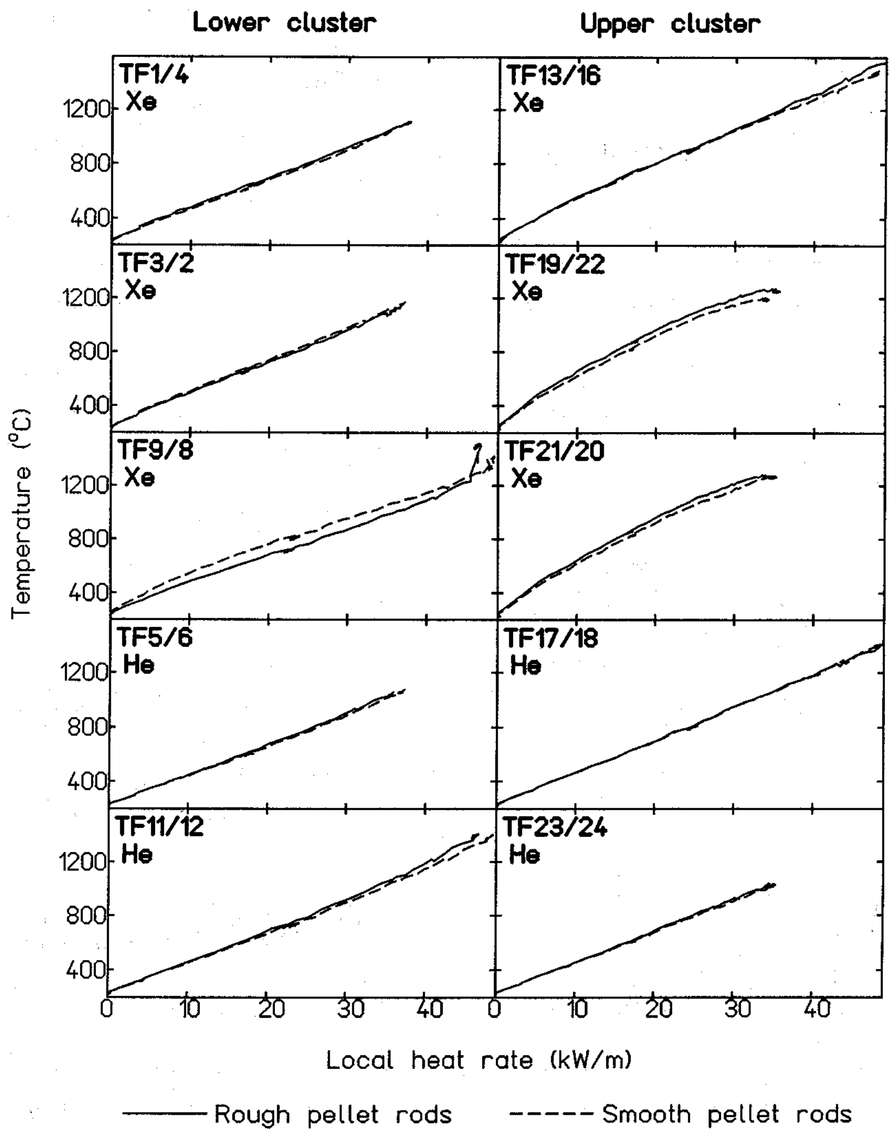
The gap between fuel and cladding is a design parameter and in addition changes with exposure. Numerous HRP experiments provide an extensive data base for assessing the basic influence of gap size on gap conductance. The general trend is summarised in the graph on the right for Helium and Xenon as fill gas.



Influence of gap on fuel temperature

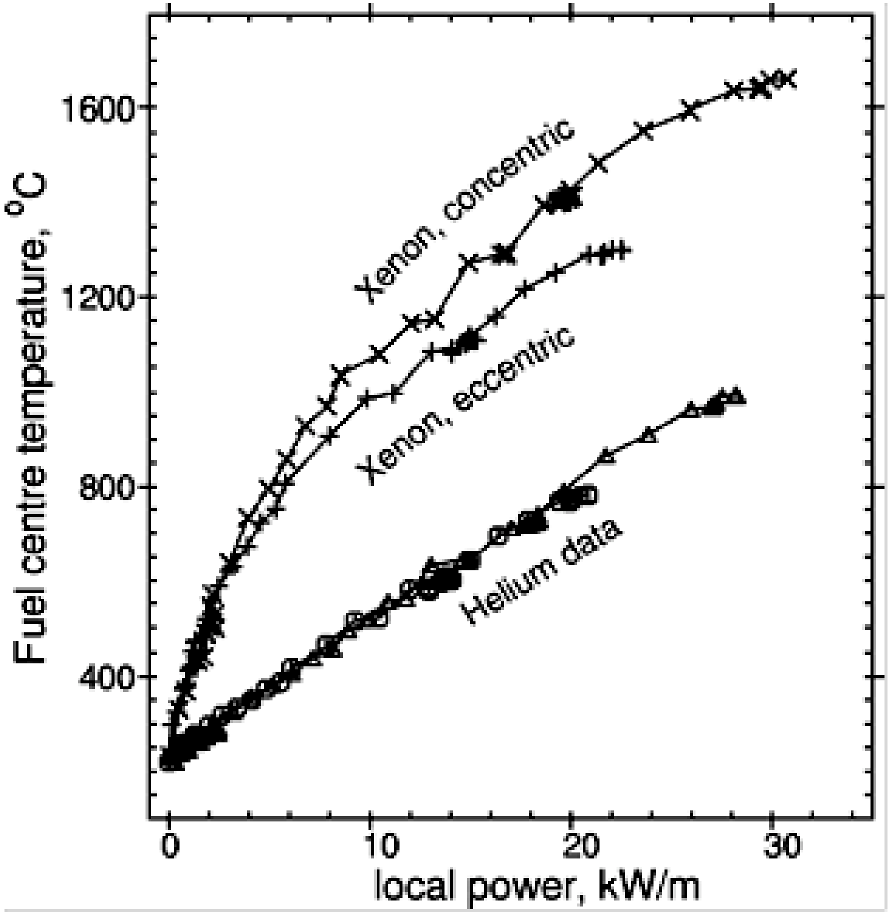
Variation of surface roughness

Surface roughness is a parameter in gap conductance models (effective gap width, contact conductance). The parameter was investigated in IFA-562.1. Although an effect could be identified, it was not as clear and pronounced as predicted.



Assessment of pellet eccentricity

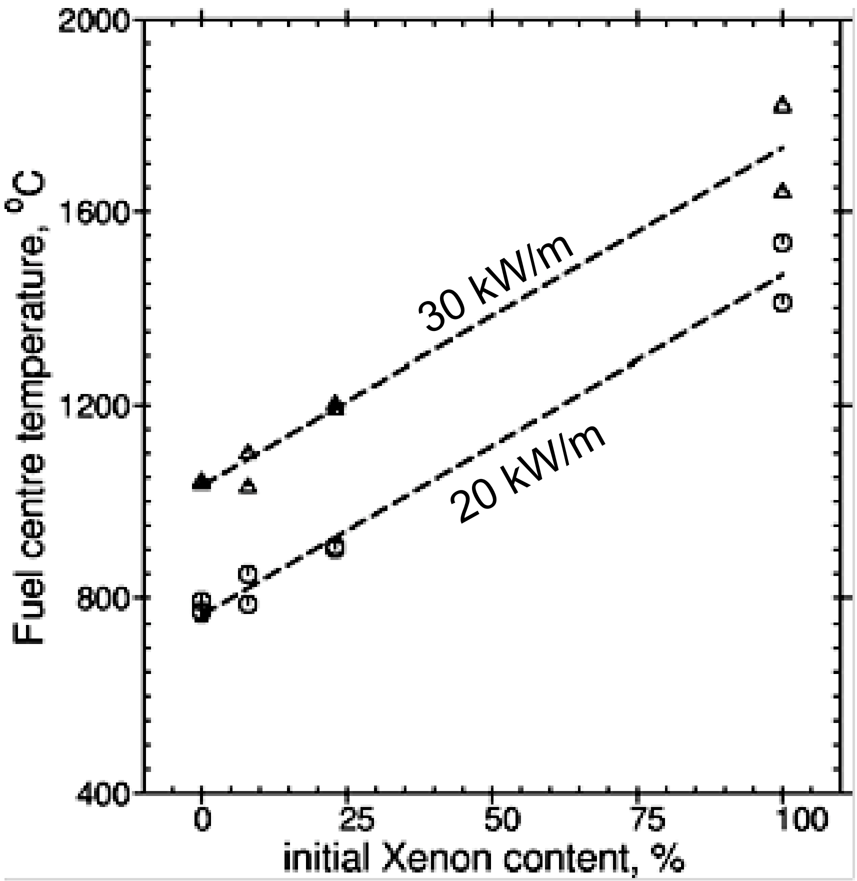
- Fuel pellets assume an eccentric position in the cladding tube.
- The asymmetric heat transfer should lead to overall lower average fuel temperatures compared to the ideal concentric case.
- The effect was investigated in HBWR experiments which provided some corroboration of the expected outcome.
- The nonlinear relation of temperature vs. power is typical of Xe or fission gas filled rods.



Effect of eccentric pellets on temperature

Fill gas type and composition

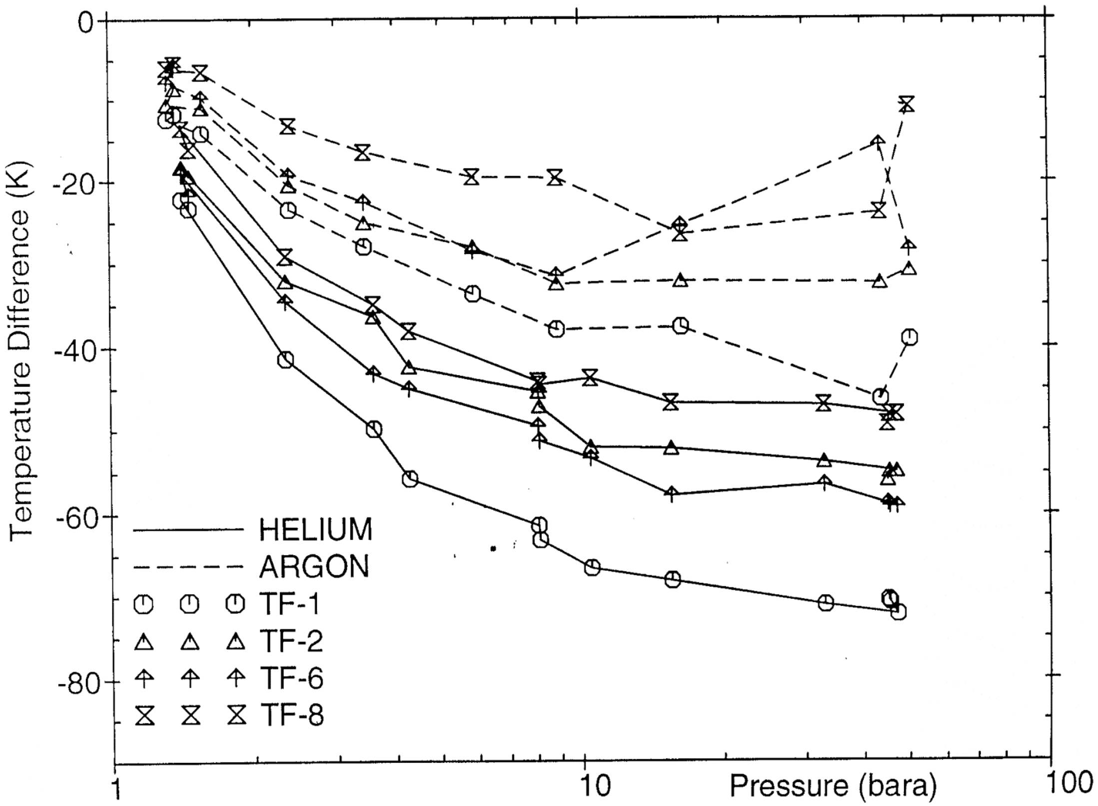
The initial fuel rod helium fill gas is diluted by released fission gas resulting in decreased gap conductance. The effect and the feedback on temperatures and further gas release needs accurate modelling. A number of experiments were conducted in the past where xenon or argon were added to simulate various degrees of fission gas release. The results from several IFAs are summarised in the figure.



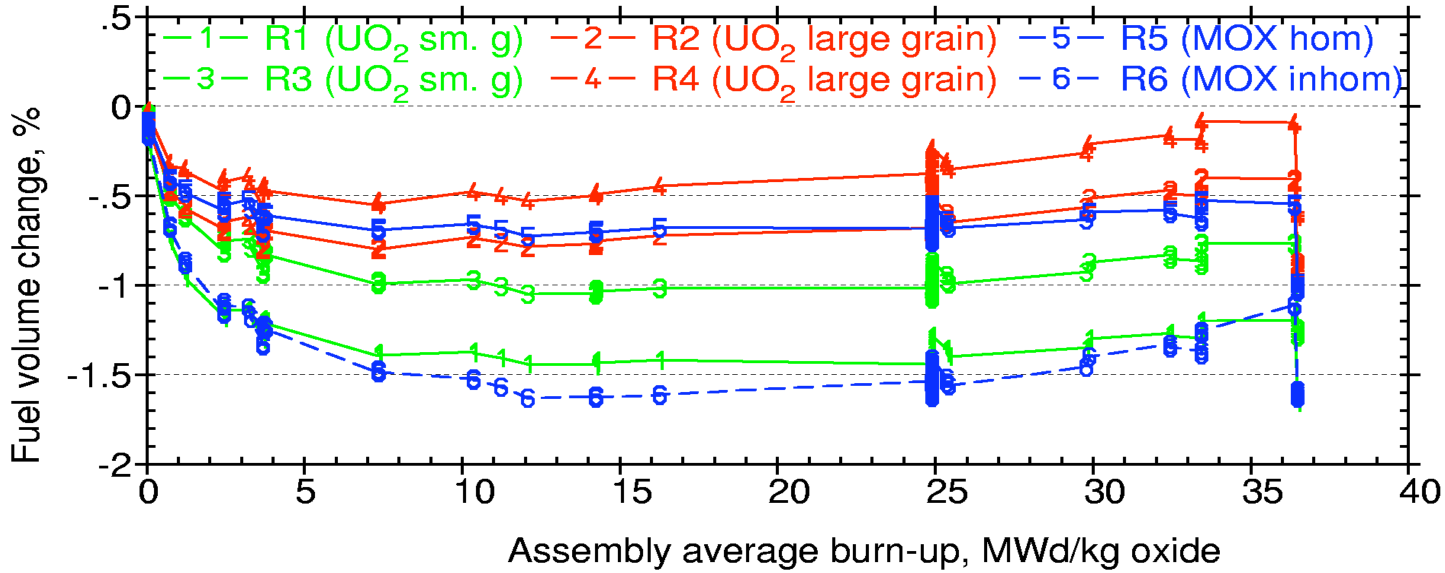
Influence of fill gas on fuel temperature

Fill gas pressure, extrapolation length

- Gap conductance models employ the concept of 'extrapolation length' to account for imperfect heat transfer between gas and solid
- The correction depends on pressure
- The effect has been assessed experimentally
- It shows some burnup dependence, possibly due to changes in number of fuel cracks



Densification & swelling



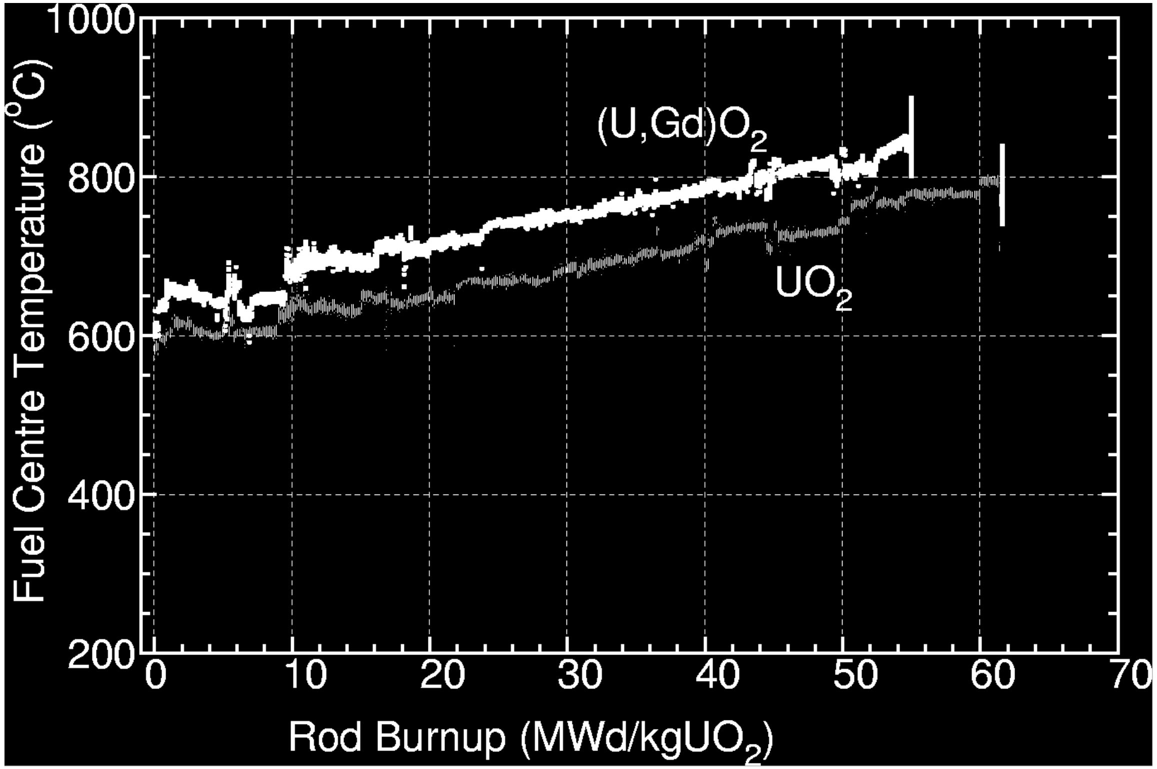
Numerous experiments address fuel densification and swelling. The primary instrument is the fuel stack elongation detector. Densification information can also be derived from rod pressure measurements.

The data of the example stem from a disk fuel irradiation and show a dependence on

- grain size (small vs. large grain)
- irradiation temperature
- fuel fabrication (for MOX fuel)

Thermal Conductivity, Degradation

Development of Temperature in UO_2 and $(U,Gd)O_2$ Fuel



The comparative irradiation shows the conductivity difference of the two types of fuel as well as the change of conductivity with burnup.

Measured fuel centre-line temperatures are linked to the thermal conductivity of the fuel. Numerous fuel rods equipped with thermocouples (UO_2, MOX, Gd-fuel, IMF…) constitute a large data base for the evaluation of various effects influencing conductivity.

Fission gas release overview

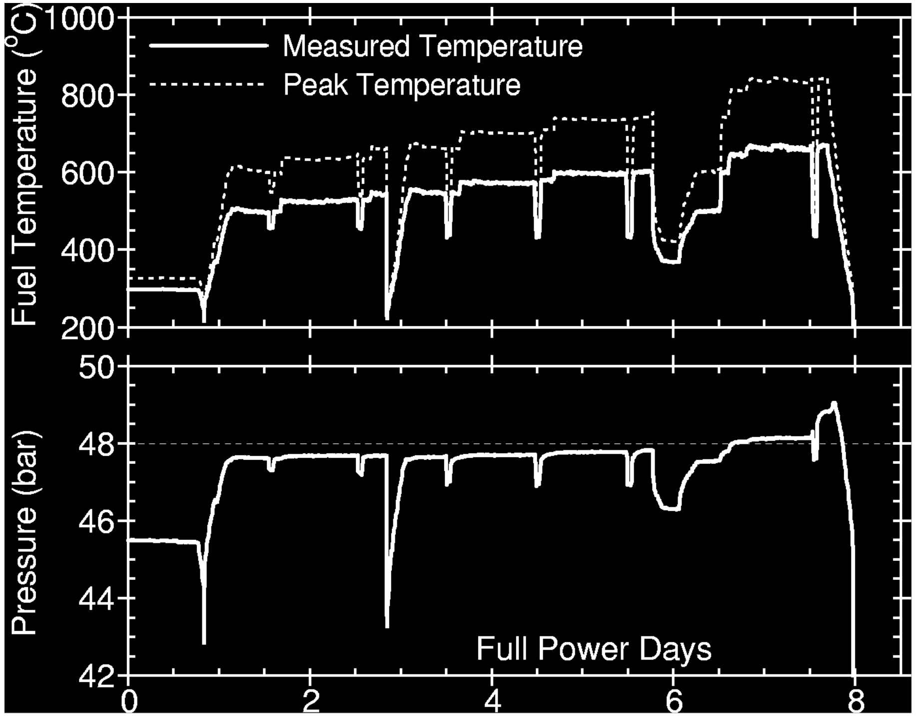
- Release onset
- Release kinetics
- Grain size
- Gas mixing

Measurements:

- Rod pressure
- Gamma spectroscopy
- Rod puncturing and gas analysis

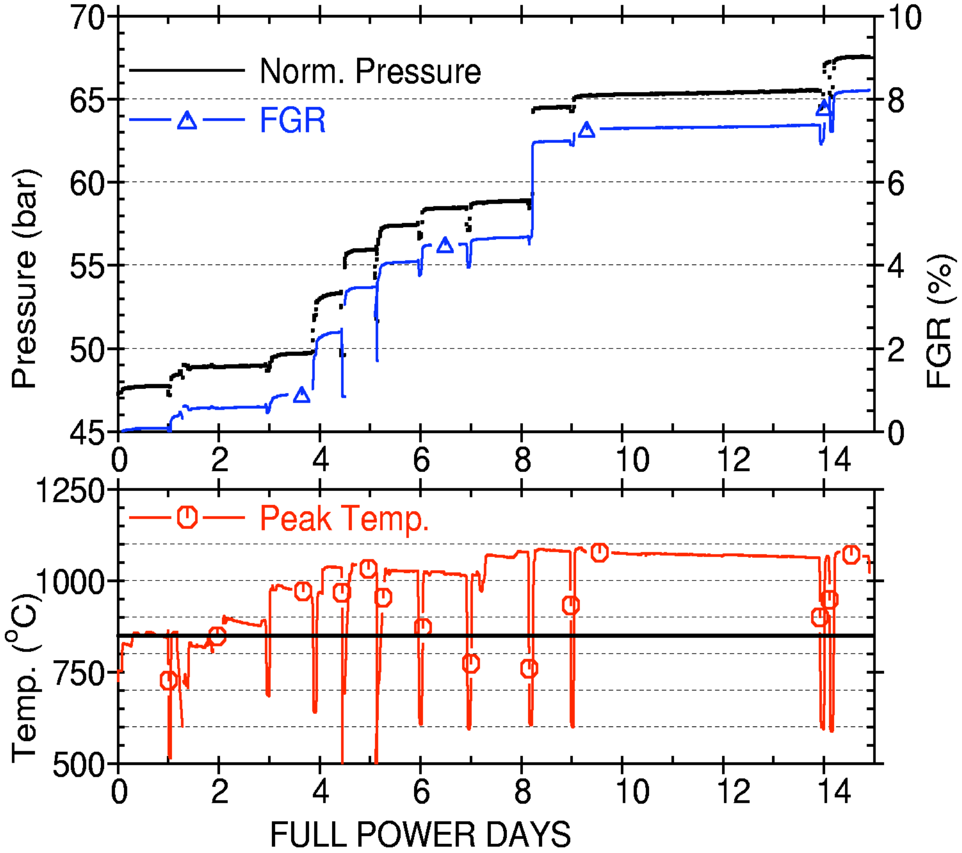
Fission gas release onset

- Irradiation of fresh and high burnup fuel (segments from LWRs)
- Instrumentation:
  - fuel thermocouple
  - rod pressure sensor
- Stepwise power / temp. increase to establish onset of fission gas release
- Simultaneous measurement of fuel temperature (most important parameter)



Temperature history and measured rod pressure (fission gas release)

Fission gas release kinetics

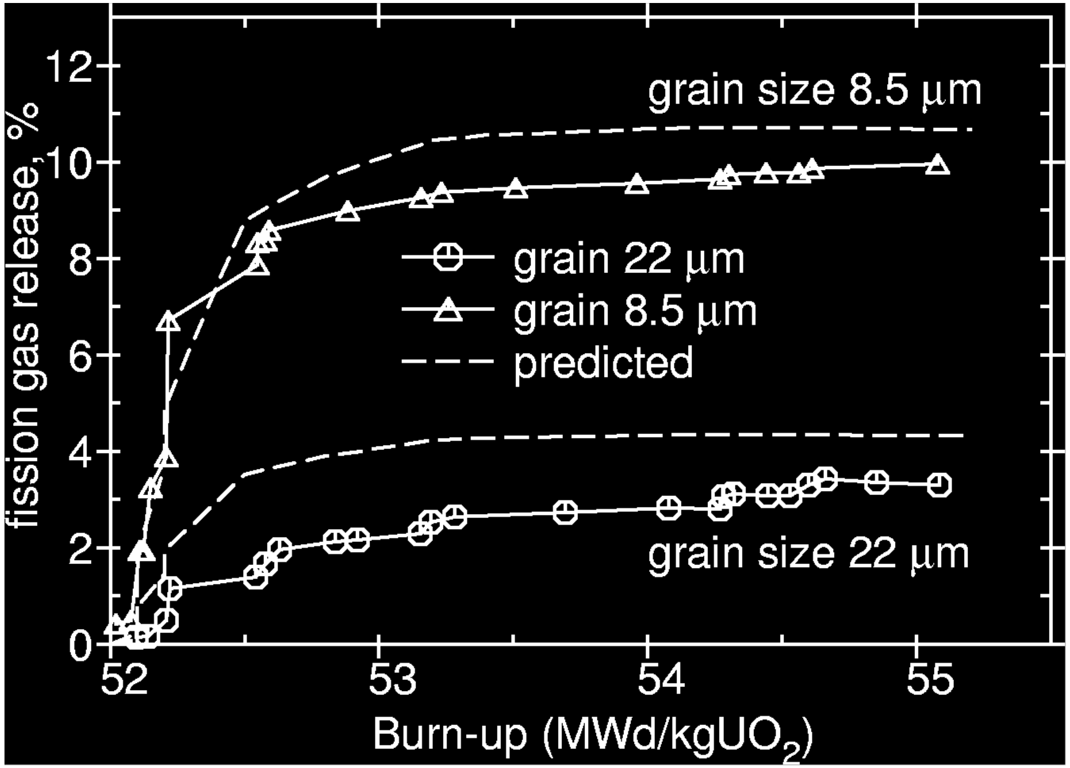


Temperature and FGR history

- Steady state power for long-term kinetics
- For high burnup fuel, power dips are necessary in order to obtain communication with the plenum (tight fuel column)
- Envelope of release curve indicates diffusion controlled release

Influence of grains size on gas release

- According to diffusion model, in general an increased grain size will result in reduced fission gas release
- At higher power and FGR >10%, grain size increase is less effective
- Satisfactory prediction with diffusion-based FGR model (Turnbull)

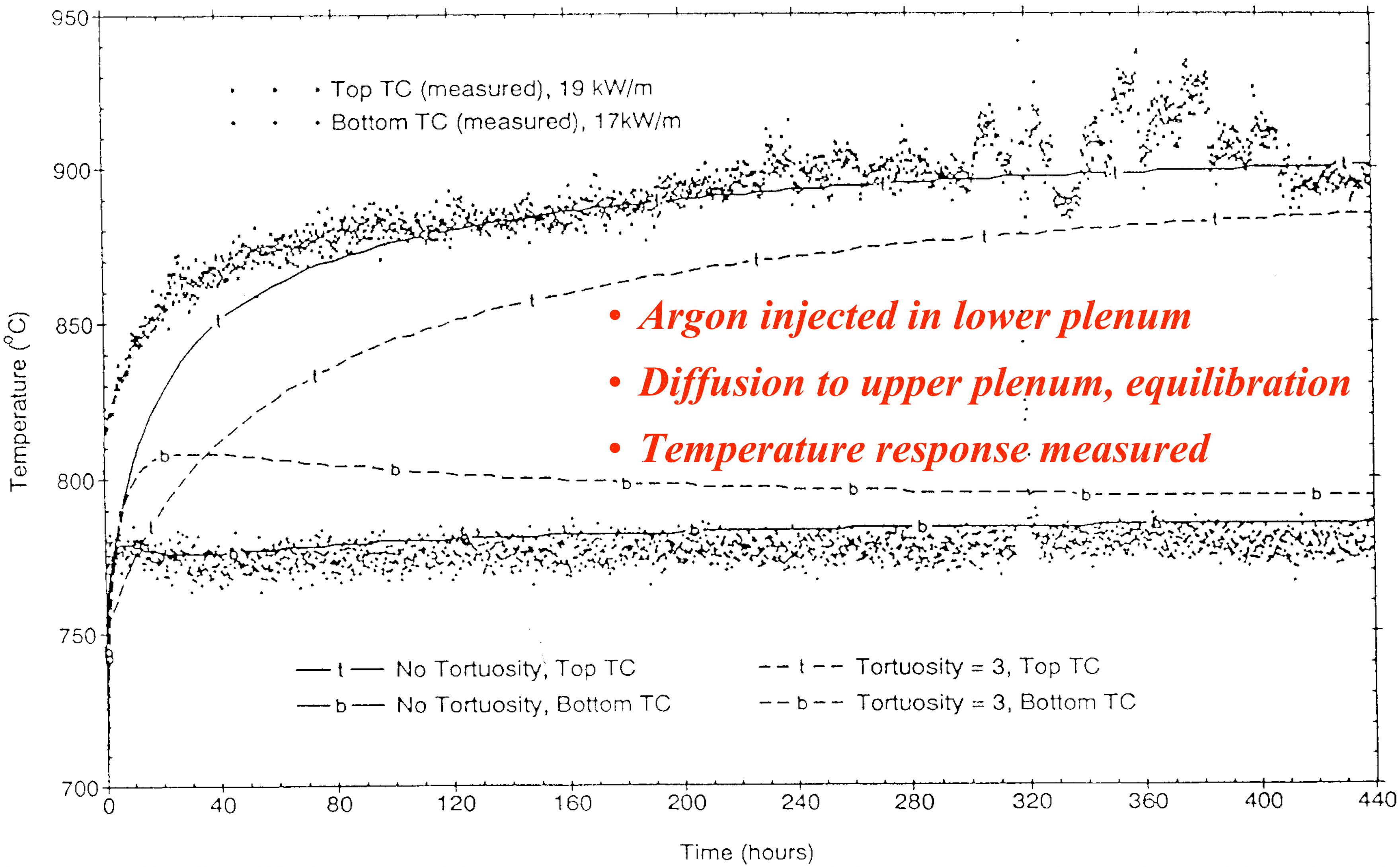


Measured and predicted FGR for UO_2 fuel with different grain sizes

Gas mixing in a fuel rod (I)

- Released fission gas has to diffuse to the rod plenum
- A temporary strong dilution of the fill gas in the fuel column may result …
- ... and cause increased fuel temperatures and positive feedback on fission gas release.
- Gas mixing behaviour and feedback has been investigated in different ways:
  - Injection of argon at one end and tracing the equilibration
  - Causing FGR and monitoring of the temperature response

Gas mixing in a fuel rod (II)



- ***Argon injected in lower plenum***
- ***Diffusion to upper plenum, equilibration***
- ***Temperature response measured***

PCMI overview

- How to measure PCMI and fuel stack properties
- Development of onset of interaction (fresh, low to medium, high burnup fuel)
- Long-term PCMI
  - cladding elongation and fuel swelling
  - Axial ratcheting

Possibilities to measure PCMI and fuel stack properties

- Primary measurements
  - Diameter gauge, 3-point feeler moving along the length of the rod, μm sens.
  - Cladding elongation sensor, LVDT principle, frequent measurements, reliable
- Secondary measurements
  - Gas flow, hydraulic diameter
  - Noise analysis (elongation and neutron detector)

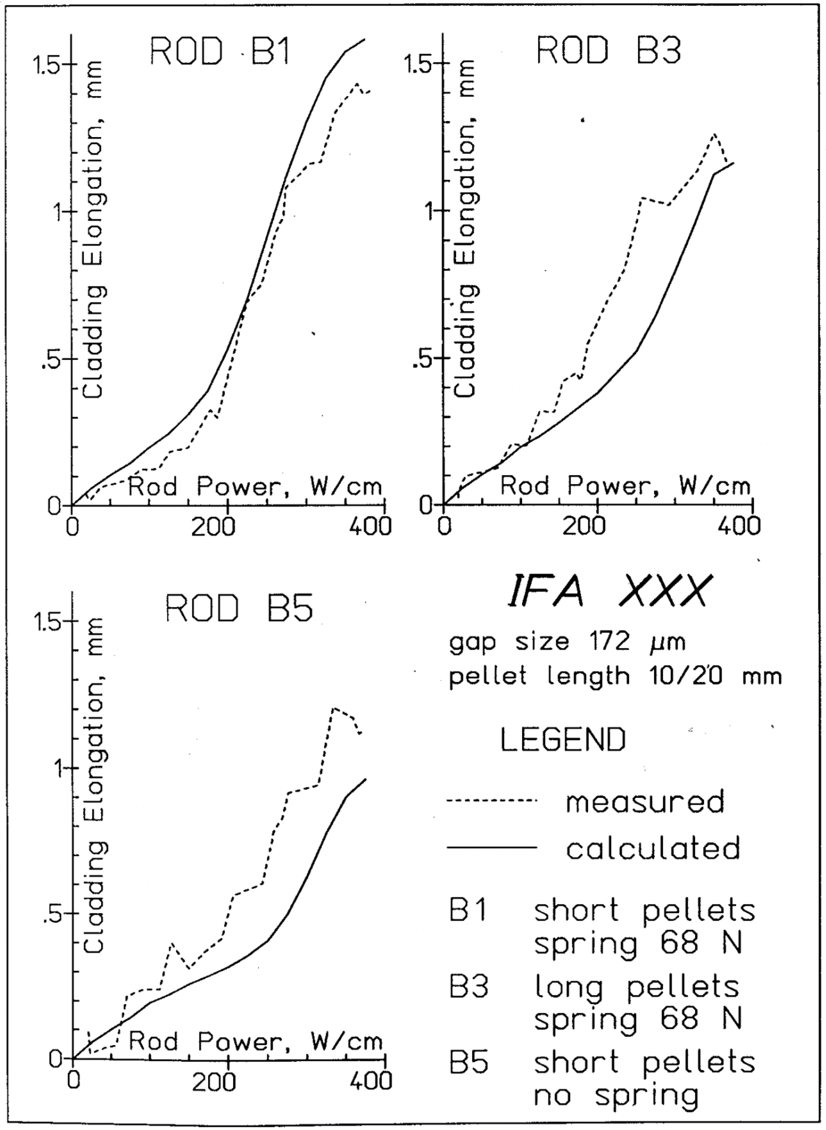
Axial and diametral deformation show similar trends in small gap rods

PCMI & fuel design

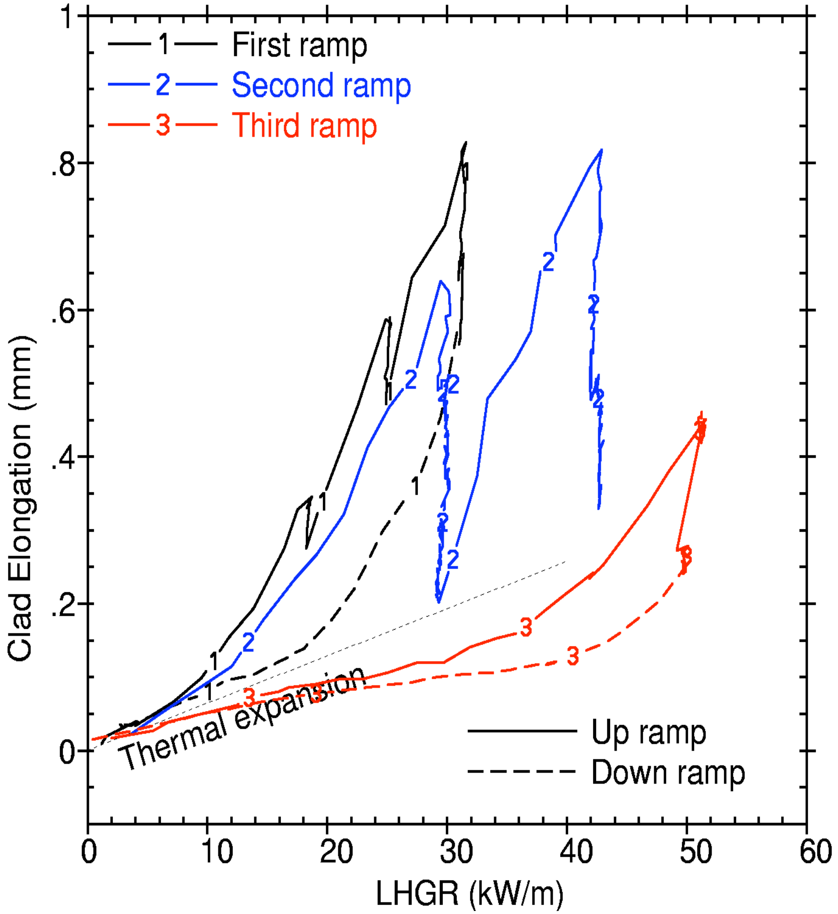
PCMI is influenced by a number of fuel design parameters, e.g.:

- Pellet end shape (dished, flat ended, chamfered)
- Pellet length (L/D)
- Hold-down spring force

A number of experiments have addressed these and other parameters. Other experiments deal with ridge formation and ramping behaviour.



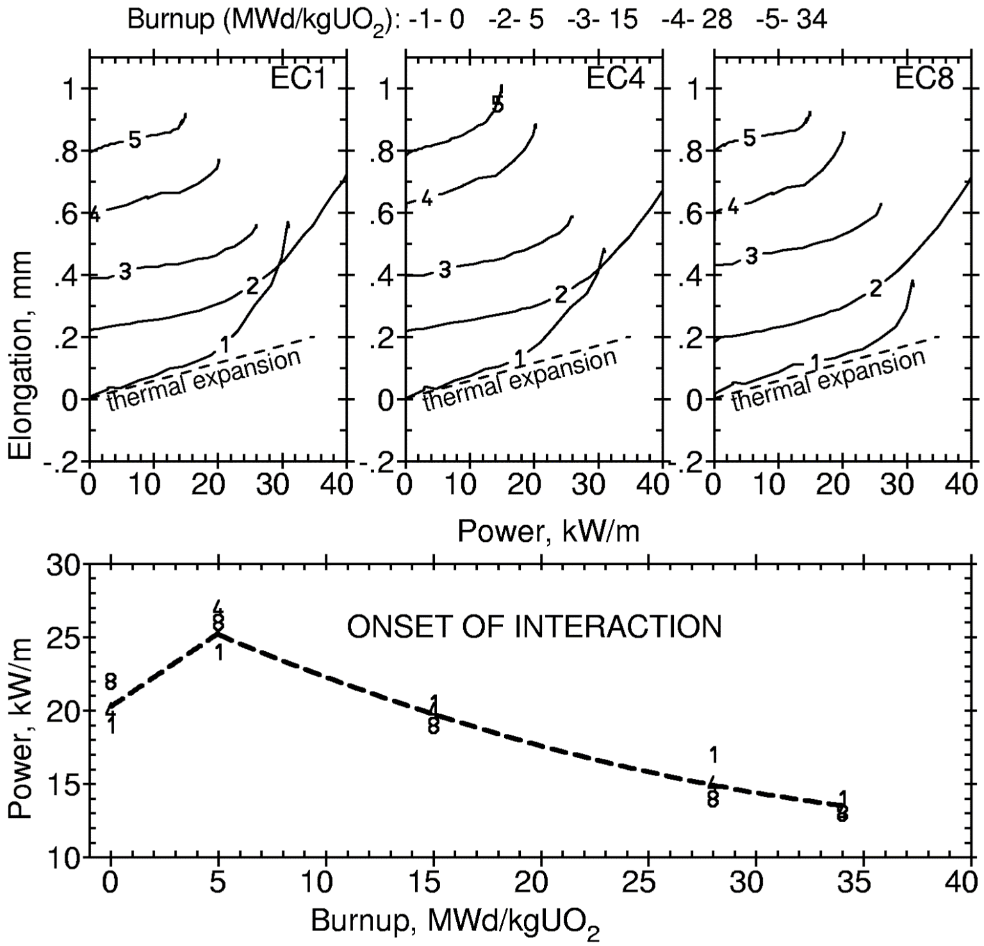
Onset of interaction
– fresh fuel –



Features of early-in-life PCMI

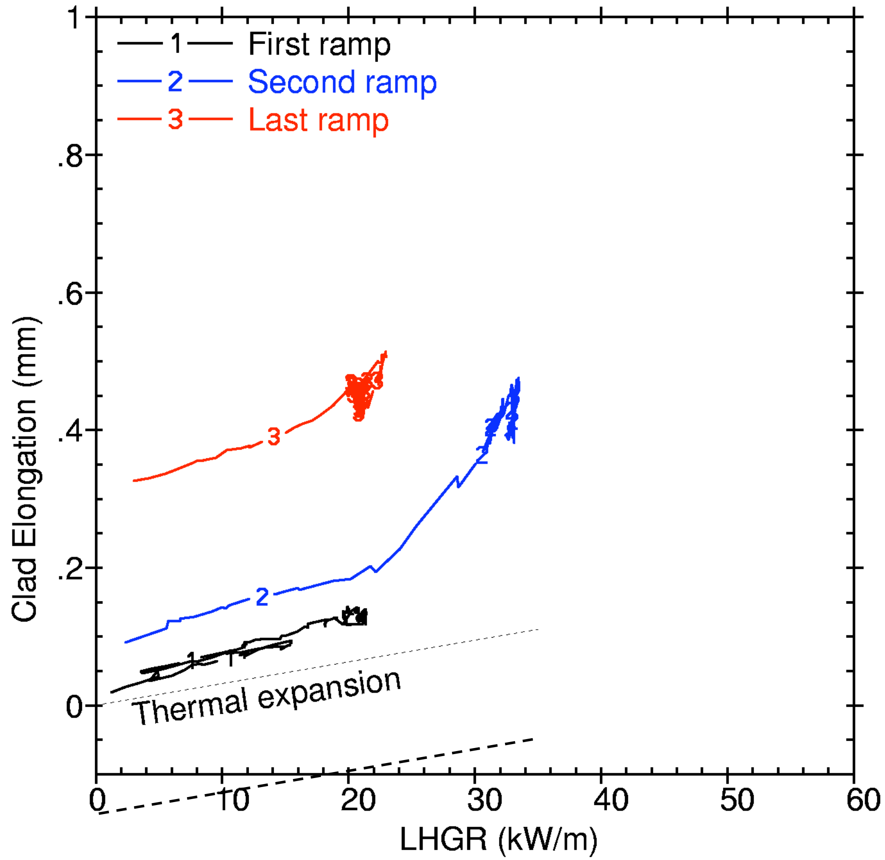
- First power ramp: very early onset of interaction
- Following power ramps: shift of PCMI onset to higher power
- Relaxation of axial strain during power holds (sliding, densif., creep)
- Immediate continuation of elongation when power increases (strong contact)

Onset of interaction
Fuel-clad accommodation



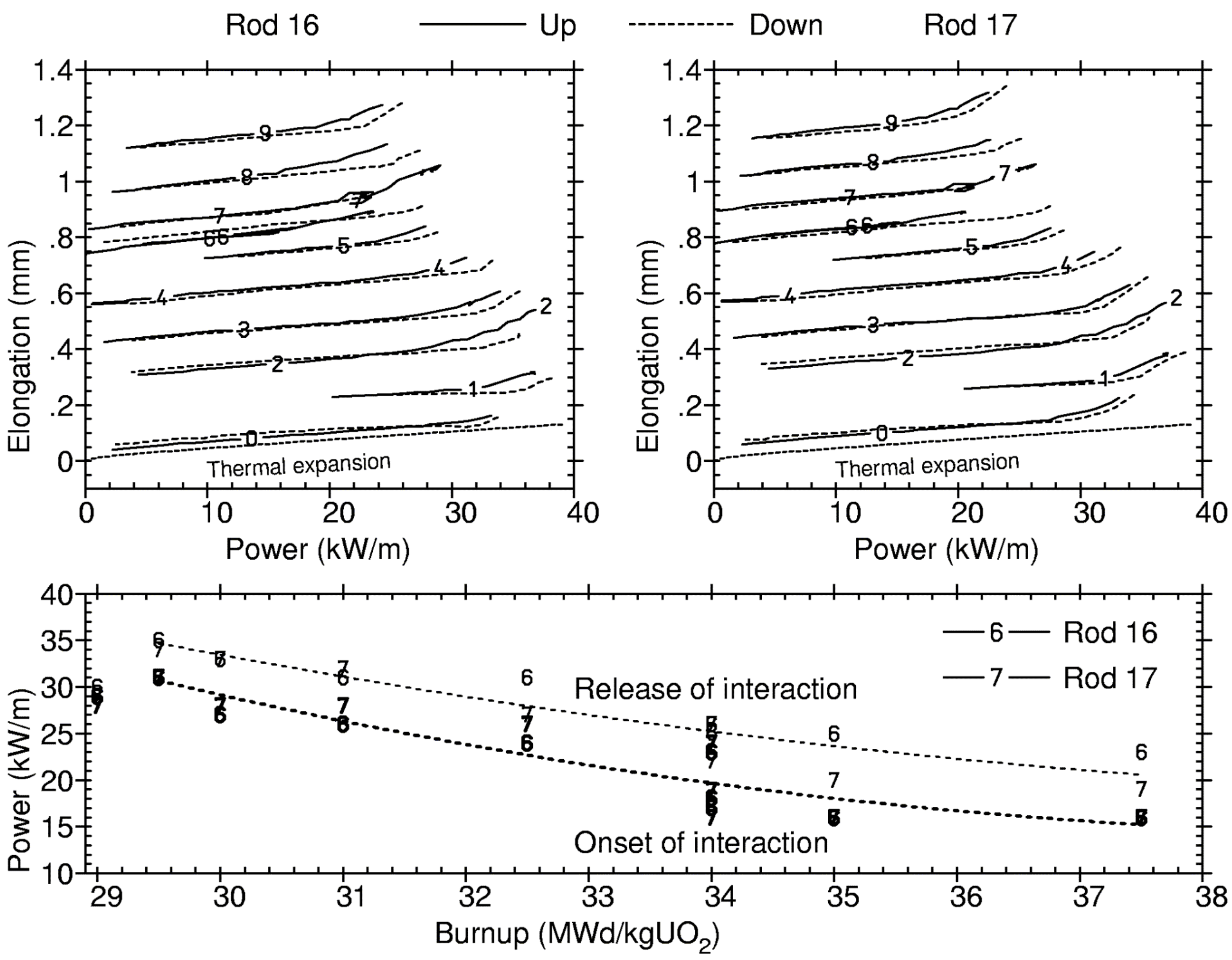
- The onset of interaction moves to lower power with increasing burnup and decreasing power
- The accommodation of fuel and cladding to each other result in small ‘interaction tails’ as long as power does not exceed previously reached levels.

Initial PCMI – Re-instrumented PWR fuel 52 MWd/kgUO_2



- No appreciable PCMI for the first ramp since the conditioning power of 20 kW/m is not exceeded
- Linear elongation part is more than calculated for thermal expansion
- Some re-conditioning during 2.5 MWd/kg burnup increment between second and last ramp

Axial racheting

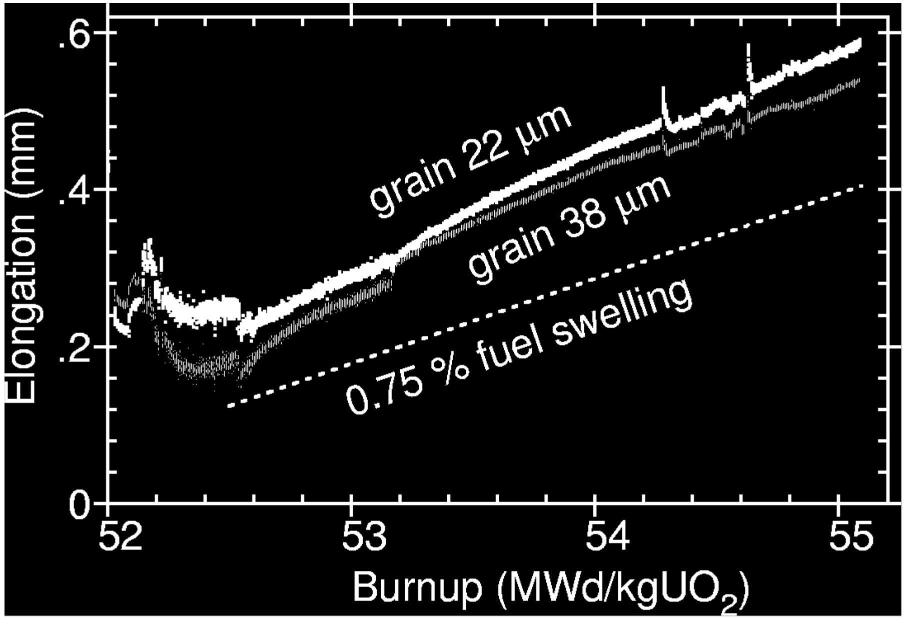


Burnup
MWd/kgUO$_2$

-0- 29.0
-1- 29.5
-2- 30.0
-3- 31.0
-4- 32.5
-5- 34.0
-6- 34.0
-7- 34.0
-8- 35.0
-9- 37.5

The slight mismatch between release and onset of interaction causes axial ratcheting and elongation peaks

PCMI behaviour of PWR fuel - high burnup -



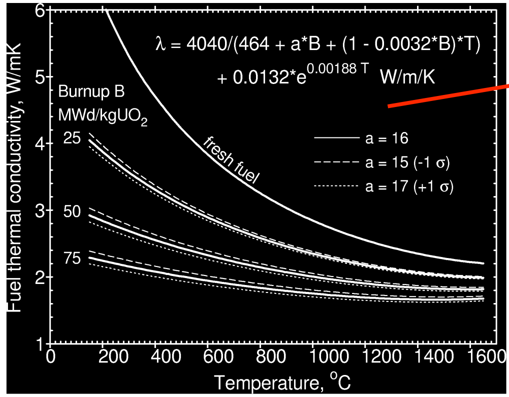
Cladding elongation response of re-instrumented PWR fuels (61 MWd/kgU) with different grain sizes during steady state periods.

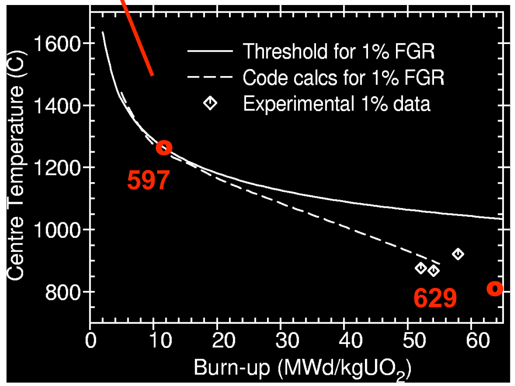
- *Permanent elongation*
  Clad elongation increase reflects fuel swelling
- *Ratcheting*
  Elongation peaks associated with shut-down / start-up (release/onset mismatch)
- *Relaxation*
  Inital relaxation of high power elongation. Stress caused by ratcheting is relaxed by fuel creep within a few days

Typical Results Fuels Testing

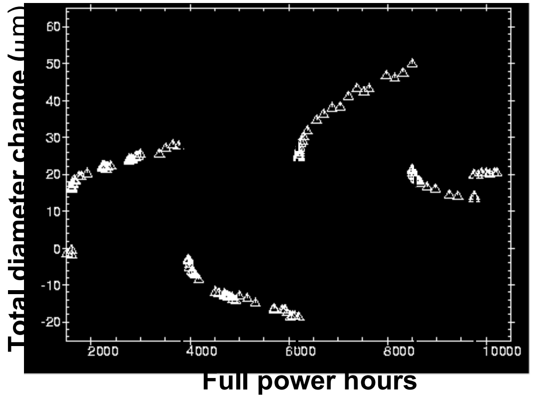
UO_2, MOX
Gd-UO_2

- Conductivity degradation

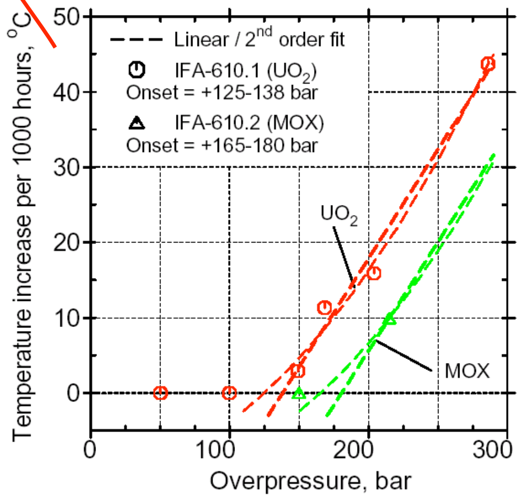




- Fission gas release



- Cladding creep



- Overpressure – clad lift-off

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