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Fuel Temperature Modelling and Phenomena

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Fuel Temperature Modelling and Phenomena (I)

Cladding temperature and pellet-clad heat transfer

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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

- Why temperature calculation?
- Coolant and cladding heat transfer
- Conductance through pellet-clad gap
  - open gap, gas conduction
  - closed gap, contact conductance
  - geometrical changes influencing gap size
- Fuel temperature distribution
  - Principal formulation
  - fuel conductivity
  - power distribution

Fuel rod temperature distribution

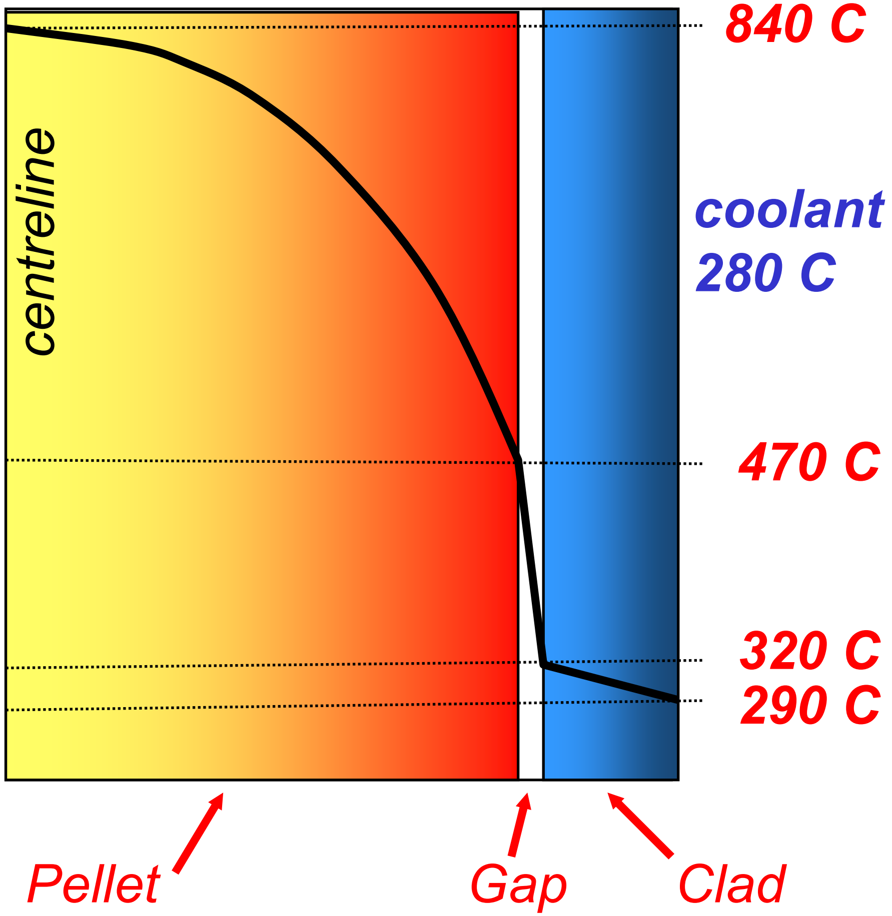
- Many properties are exponentially dependent on temperature. Therefore, accurate temperature estimates are important.
- The fuel temperature is strongly linked to
  - stored energy that must be removed in LOCA
  - thermal expansion of the fuel pellet as strong contribution to pellet-clad mechanical interaction and rod failure
  - fission gas release and thus rod pressure
- The fuel temperature distribution depends on design parameters, materials properties and on many phenomena which develop during irradiation.
- **The fuel temperature is important for many safety criteria**

Practical influences and data

- The steady state temperature distribution can be calculated from outside to inside, starting from the fixed coolant temperature
- Knowledge of the conditions (material properties, temperature) inside is not required!!!
- In the following sections, the various influences will be visited one by one (from outside to inside)
- Their effect will be illustrated by experimental data where possible

Typical temperature distribution

(20 kW/m)



Heat flow resistances

1. coolant – cladding
2. oxide/crud layer
3. cladding wall
4. inner oxidation / bonding layer
5. fuel – cladding gap
   - numerous influences
6. fuel
   - conductivity
   - general porosity
   - high burnup porous rim
   - cracks

1. Coolant – clad heat transfer

- **PWR conditions:** Dittus - Boelter correlation
  $h = 0.023 * k/D_E * Re^{0.8} * Pr^{0.4}$
  k = water conductivity, D_E = equivalent diameter,
  Re = Reynolds number, Nu = Nusselt number,
  $\Delta T_C = q'/(\pi D \cdot h)$
- **BWR conditions:** Jens - Lottes correlation
  $T_{wall} - T_{sat} = 0.79 * \exp(-p/62) * (q'')^{0.25}$
  p = pressure (bar); q'' = heat flux,W/m^2

typical ΔT_C at 250 W/cm = 25 K for PWR
8 K for BWR

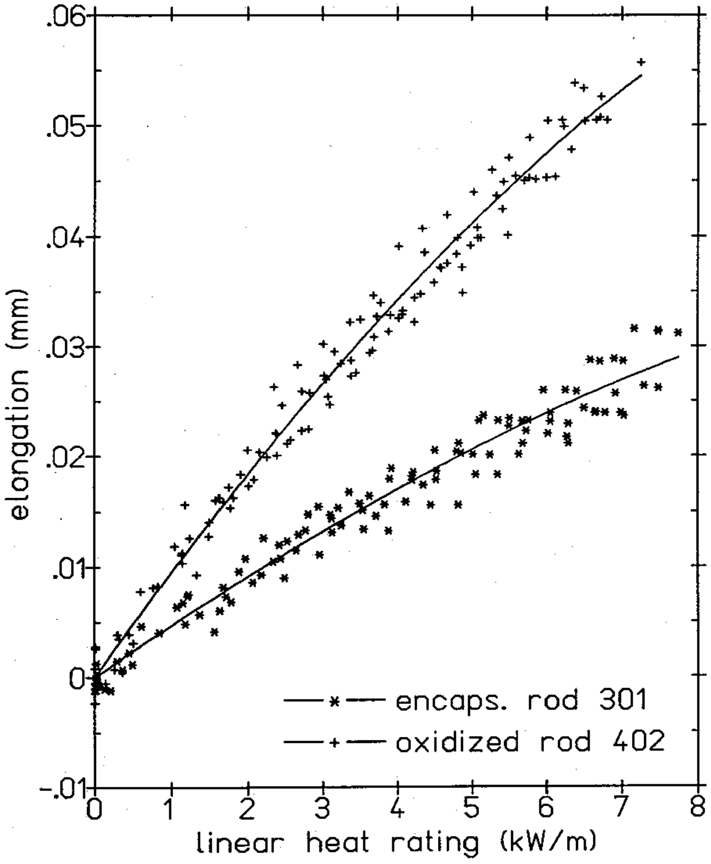
2. Crud and oxide layer

- Outer oxide layer
  - $\Delta T_{OX} = q' / (\pi D \cdot k_{OX} / w_{OX})$
  - $k_{OX} = 0.015 \pm 0.005$ W/cm·K;
    $w_{OX} = 50\text{-}100 \mu m$ for PWR fuel at high burn-up
    (a factor of ~3 lower for BWR fuel).
  - **$\Delta T_{OX} = 20 - 80°C$ for $q' = 250$ W/cm in PWR**
- Crud layer
  - constitutes a heat transfer barrier.
  - the crud thickness is normally moderate (some tens of µm at most)
  - conductivity is comparable to oxide conductivity.

Cladding temperature / oxide layer

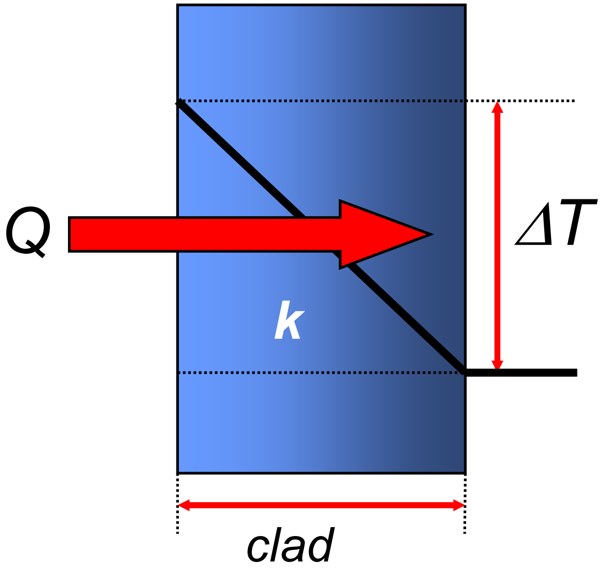
Measurement of the cladding temperature is normally not within the scope of the HRP experimental programme. However, if PCMI can be eliminated, details of cladding elongation behaviour can be used to qualify

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

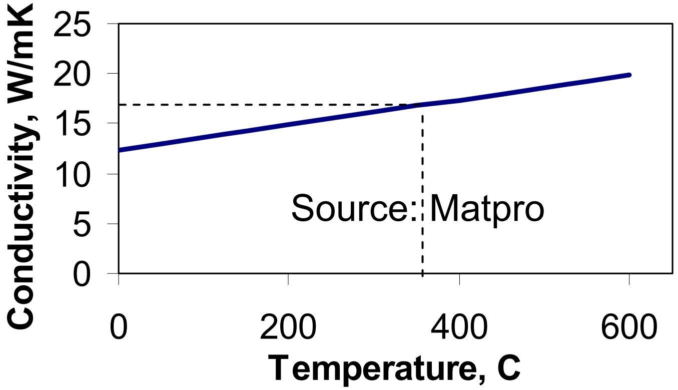


Elongation of cladding with and without outer oxide layer

3. Temperature increase in the cladding



Thermal conductivity of zircaloy



$$\Delta T = \frac{1}{k}\frac{q'}{2\pi}\ln(\frac{R_o}{R_i})$$

k = average conductivity (W/m·K)

q' = linear heat rating (W/m)

R_o, R_i = outer, inner cladding radius (m)

- for typical wall thickness 0.6 - 0.9 mm, the problem can also be approximated in 1 dimension
- k ≈ 17 W/m·K (linear function of T)
- Example:

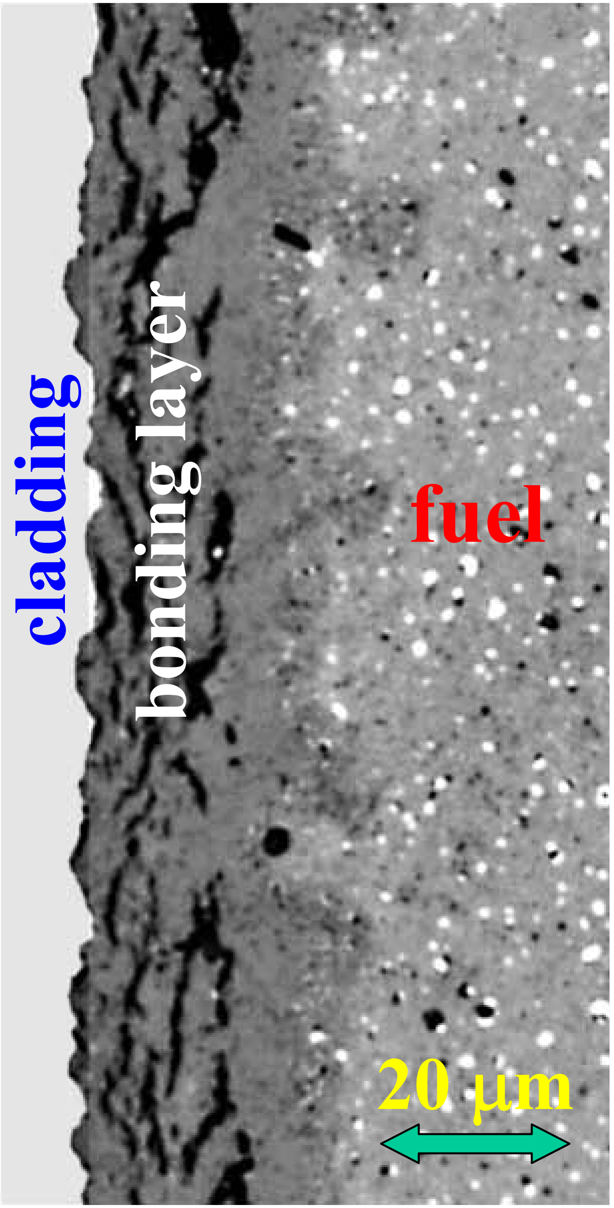
ΔT for 0.6 mm thick cladding with

R_i = 4.2 mm at 20 kW/m?

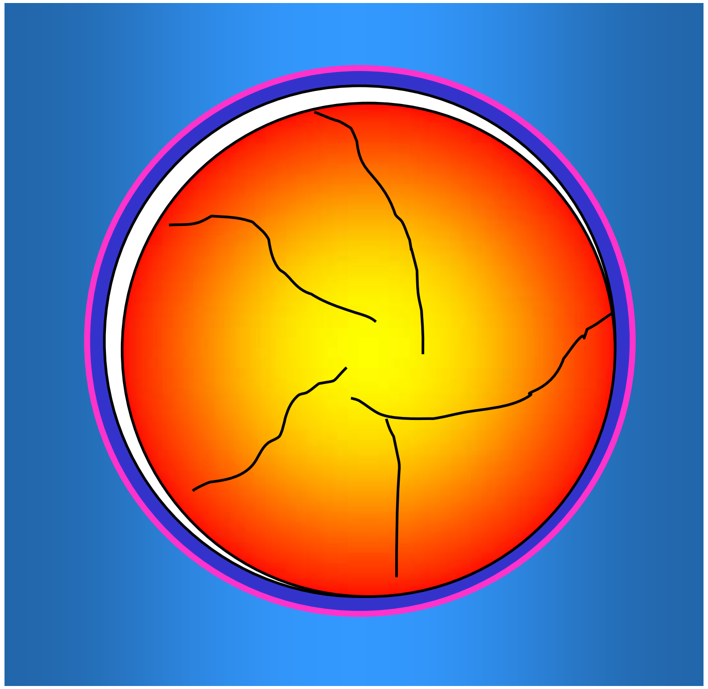
ΔT ~ 25 K

4. Inner oxidation and bonding layer

- At burnup >35 MWd/kg, a bonding layer develops between fuel and cladding
- Fuel-cladding contact (pressure) is essential for the formation
- It consists of oxides of Zr and U and fission products (e.g. Cs)
- The conductivity is similar to that of ZrO_2 and UO_2
- The gap is effectively closed



5. Temperature step in the pellet-cladding gap

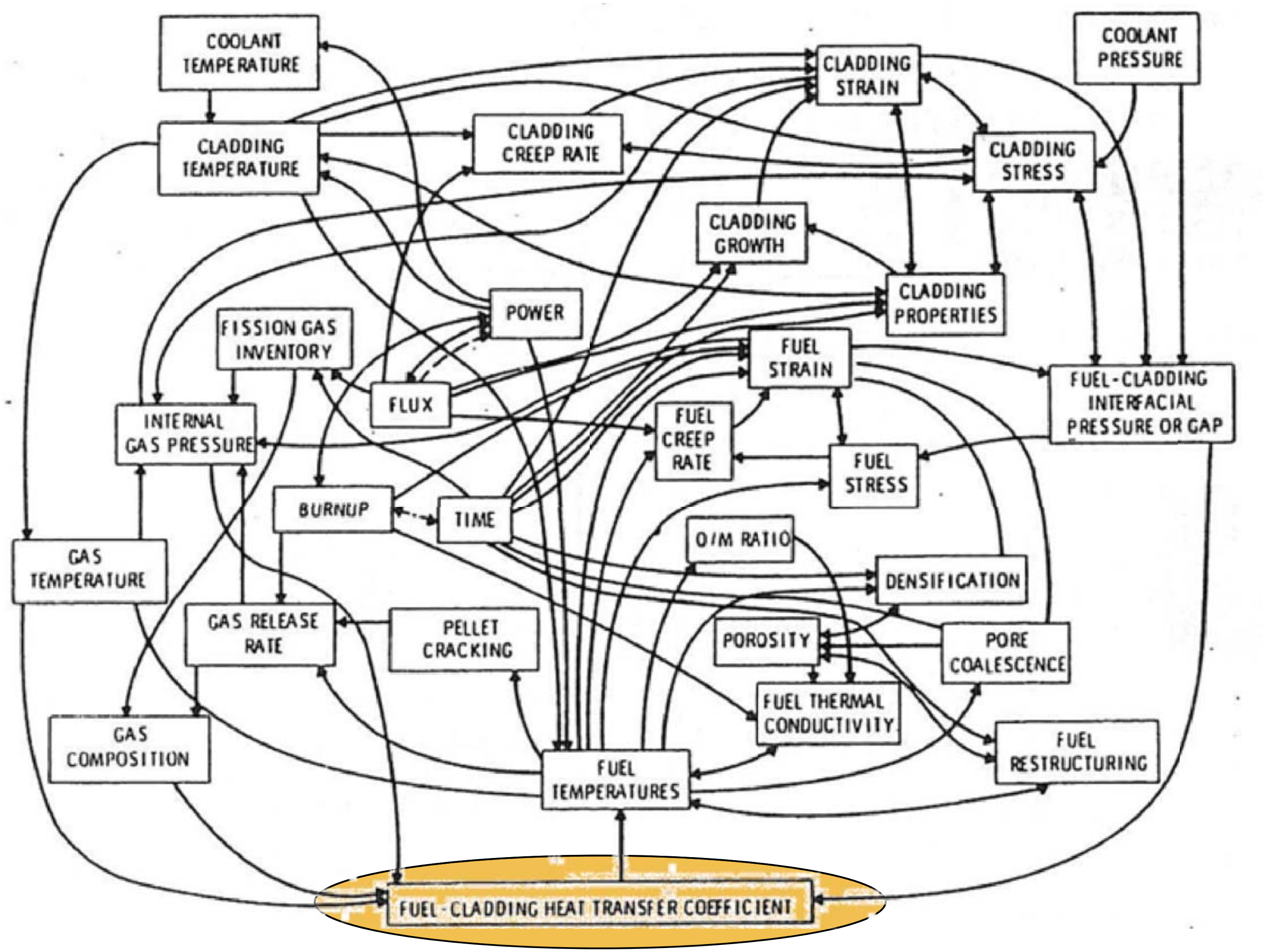


- Heat transfer routes:
  1. h_{rad} – by radiation
  2. h_{cont} – through areas of contact
  3. h_{gas} – through the gas gap
- the pellet is usually eccentrically located in the cladding tube
- treatment in one dimension with effective heat transfer coefficient

$$h_{eff} = h_{rad} + f(h_{cont}\ ,\ h_{gas})$$

- proper averaging (f) of contact and gas conductance is important for good results
- model details depend on numerous properties and results from other parts of a fuel modelling code

... and interactions may be quite complicated



Gap conductance

- Gap conductance models usually contain a number of parameters that are experimentally accessible. Halden reactor separate effects experiments include:
  - Systematic variation of gap size (50 – 400 µm)
  - 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
  - Determination of gap size by different techniques
- The associated data are indispensable for the verification of correct modelling of basic phenomena in fuel-clad gap heat transfer

5.1 Radiative heat transfer

Stefan-Boltzmann constant
($5.672 \cdot 10^{-8}$ W/m$^2 \cdot$K)

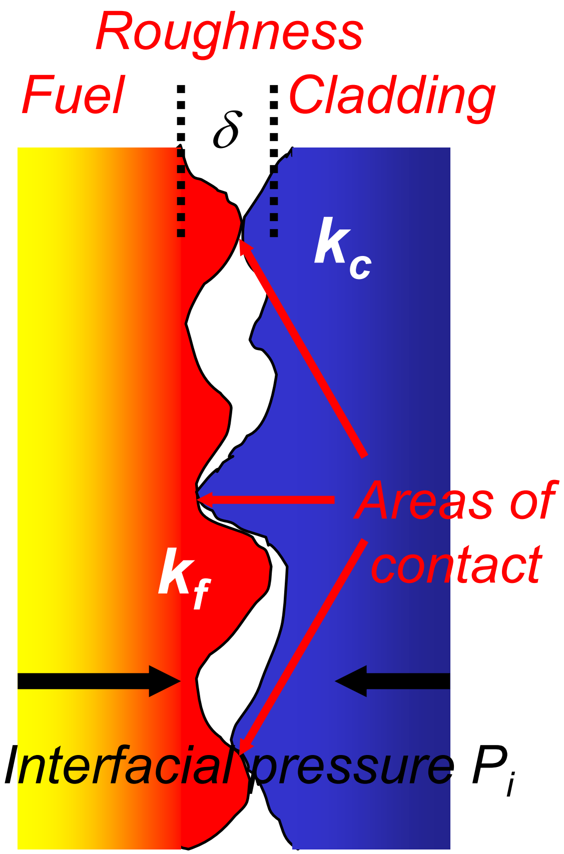
Surface temperature
fuel & cladding (K)

$$h_{rad} = \frac{\sigma \cdot (T_f^2 + T_c^2)(T_f + T_c)}{\left(1/\varepsilon_f\right) + \left(1/\varepsilon_c\right) - 1}$$

Fuel & clad emissivities

- typical emissivities:
  - $\varepsilon_f = 0.7856 + 1.5263 \times 10^{-5}\ T$ (= 0.8 at 500 °C)
  - ε_c = 0.3 (shiny metal) – 0.8 (oxidised)
- no dependence on gap size since ratio of inner and outer radii is practically 1 (small gap)
- Small contribution in normal operation
  - 1-2 % of total heat transfer

5.2 Contact conductance



Occurs even for open gaps due to eccentric location of pellets

Several theories mostly based on circles of contact whose number or area increases with interfacial pressure

A typical equation has the form:

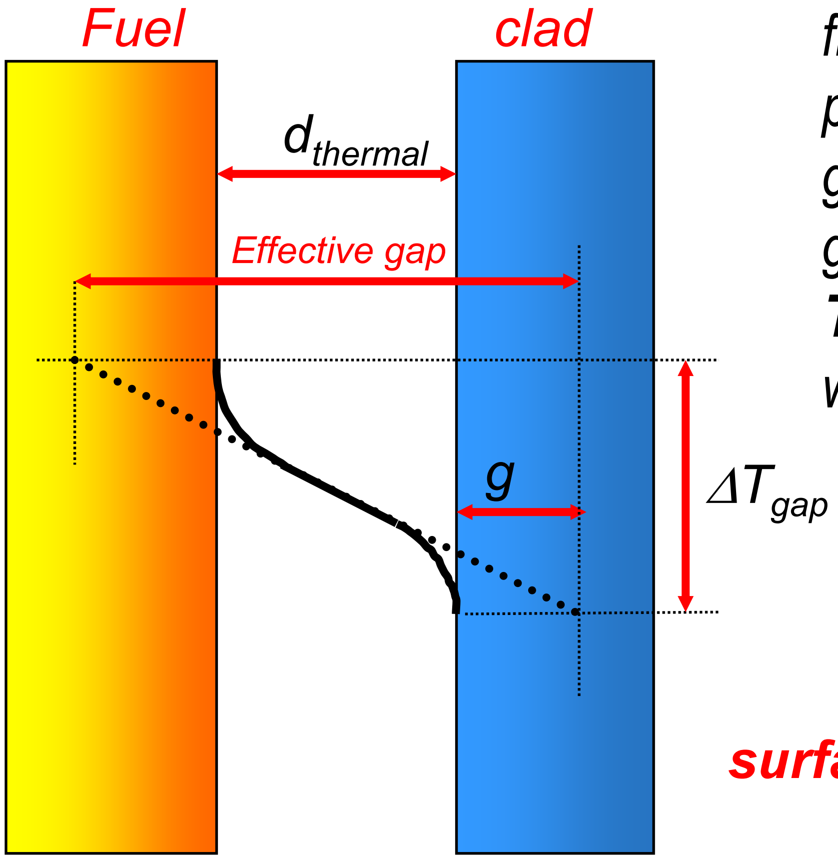
$$h_{cont} = \underset{\uparrow}{Const}\left(\frac{2k_f k_c}{k_f + k_c}\right)^{\beta} \cdot \frac{P_i}{\delta^{1/2} \cdot \underset{\uparrow}{H}}$$

0.7 – 1

Fitted to data

Meyer hardness

5.3 Gas conductance through the gap



Energy transfer (conductance) through a gas is independent of gas pressure if the mean free path is small compared to the conduction path. This is not the case for the pellet-clad gap. Imperfect heat transport across the solid-gas interface leads to the concept of the ***Temperature Jump Distance (g)*** *which effectively increases the gap size:*

$$h_{gas} = \frac{k_{gas}}{\underset{\uparrow}{\delta} + \underset{\uparrow}{d}_{thermal} + 2\underset{\uparrow}{g}}$$

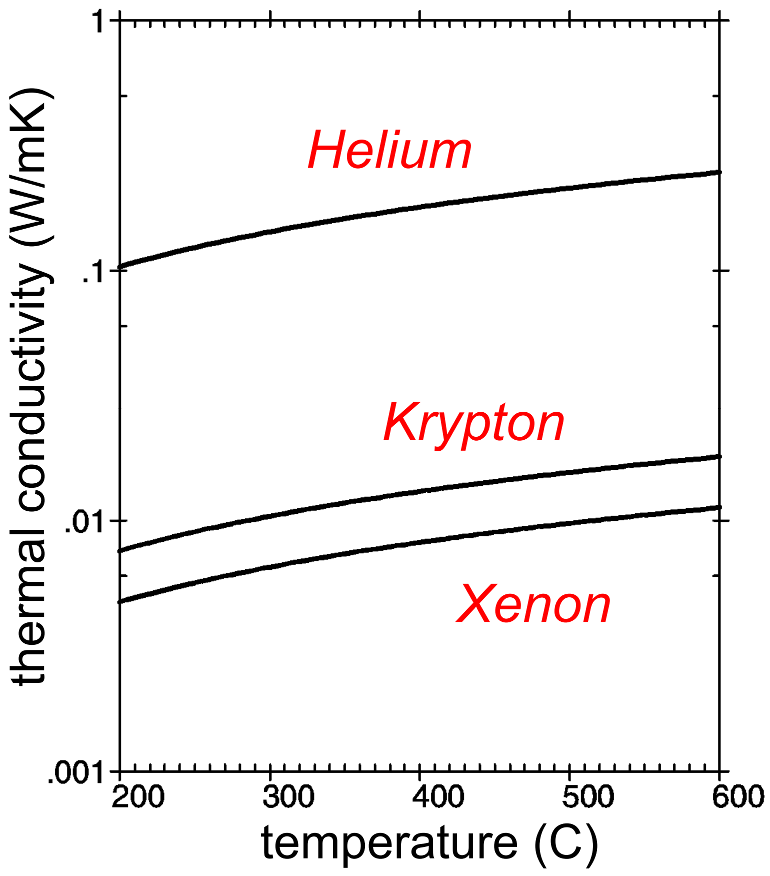
surface roughness

thermal gap

temperature jump distance

k_{gas} – gas conductivity

Gases are bad heat conductors (good insulation)



$$k_{gas} = A \cdot 10^{-4} \cdot T^{0.79}$$

k_{gas} (W/mK) and T(K)

A =	*15.8*	*He*
	1.15	*Kr*
	0.72	*Xe*

Note: independent of pressure

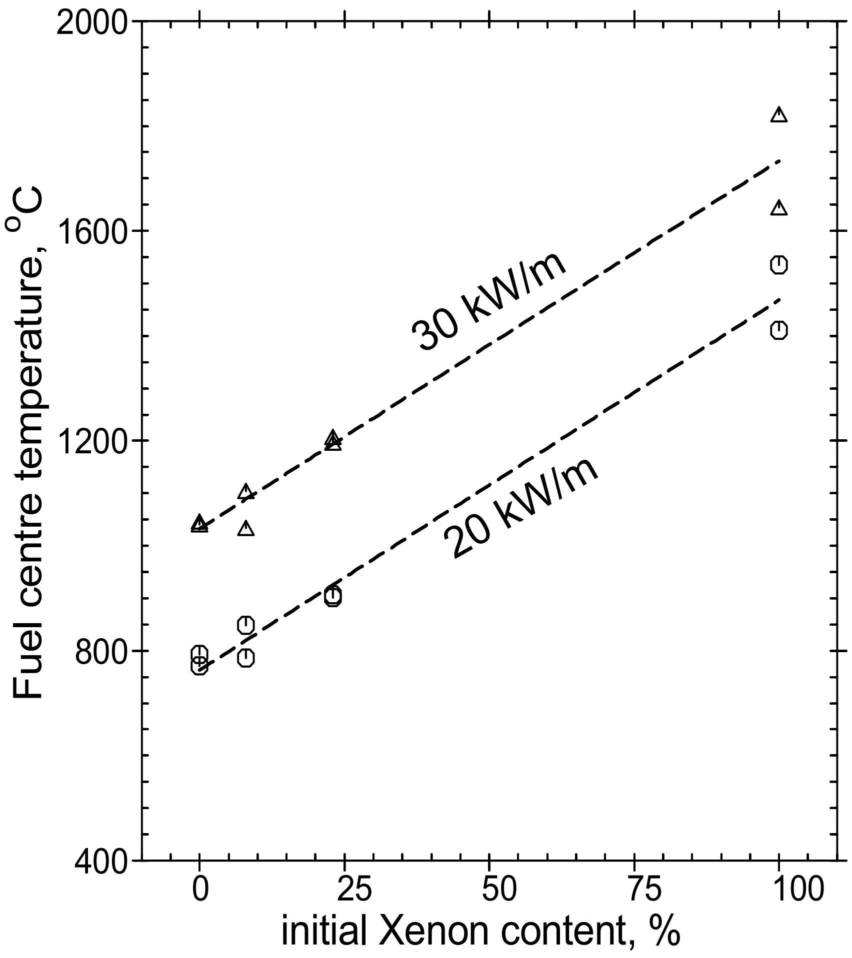
For a gas mixture: x·He and (1-x)·Xe

$$k_{mix} = (k_{He})^{x} \cdot (k_{Xe})^{(1-x)}$$

(von Ubisch rule, more complicated formulations exist)

In-core effect of fill gas composition

- The initial fuel rod fill gas (helium) 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



Influence of fill gas on fuel temperature

2g – temperature jump distance

The Halden FTEMP code uses this empirical expression:

$$2g(\mu m) = \frac{(10 - 9 * x_{Xe})}{p}$$

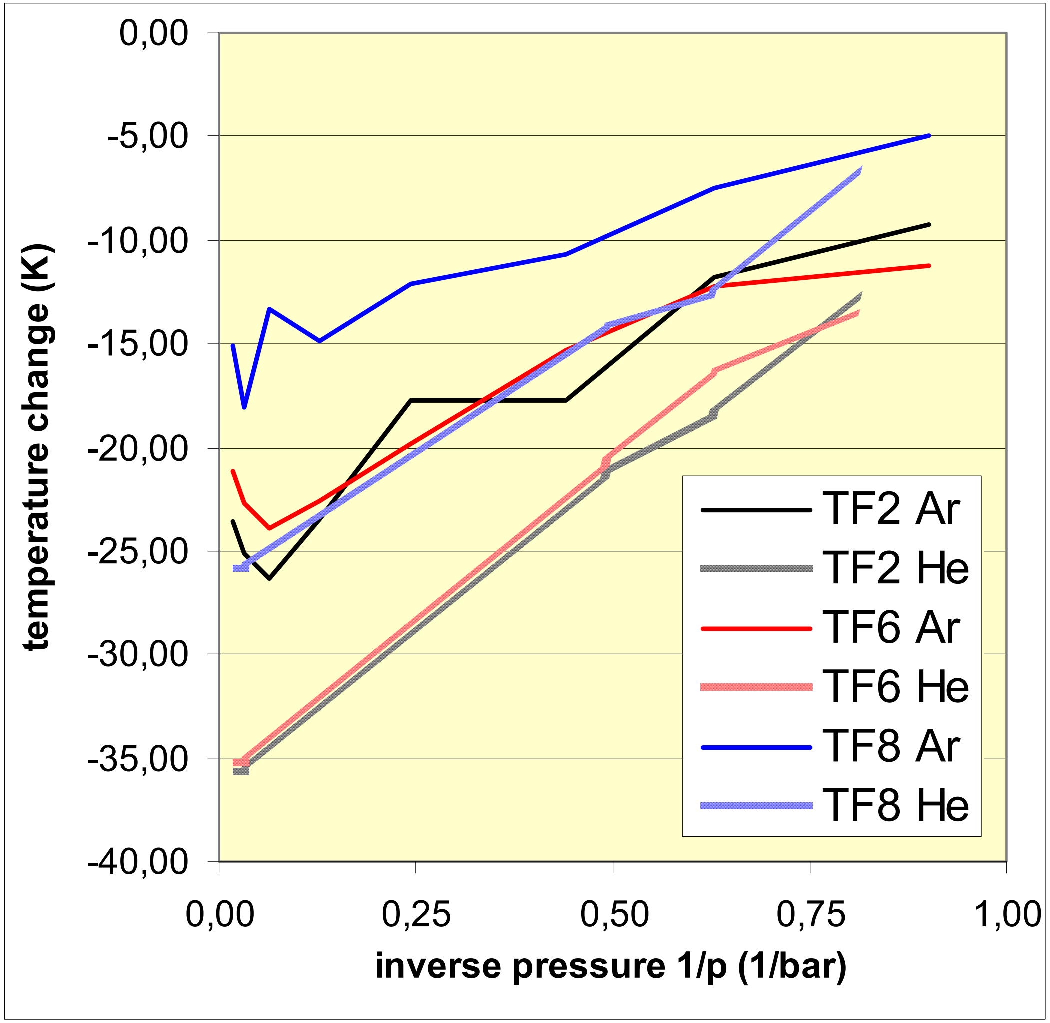
x_{Xe} = *fraction of Xe in He*
p = *gas pressure (bar)*

This equates to 2g values at STP (1 bar) of:

~10. µm	*He*
~1.0 µm	*Xe*

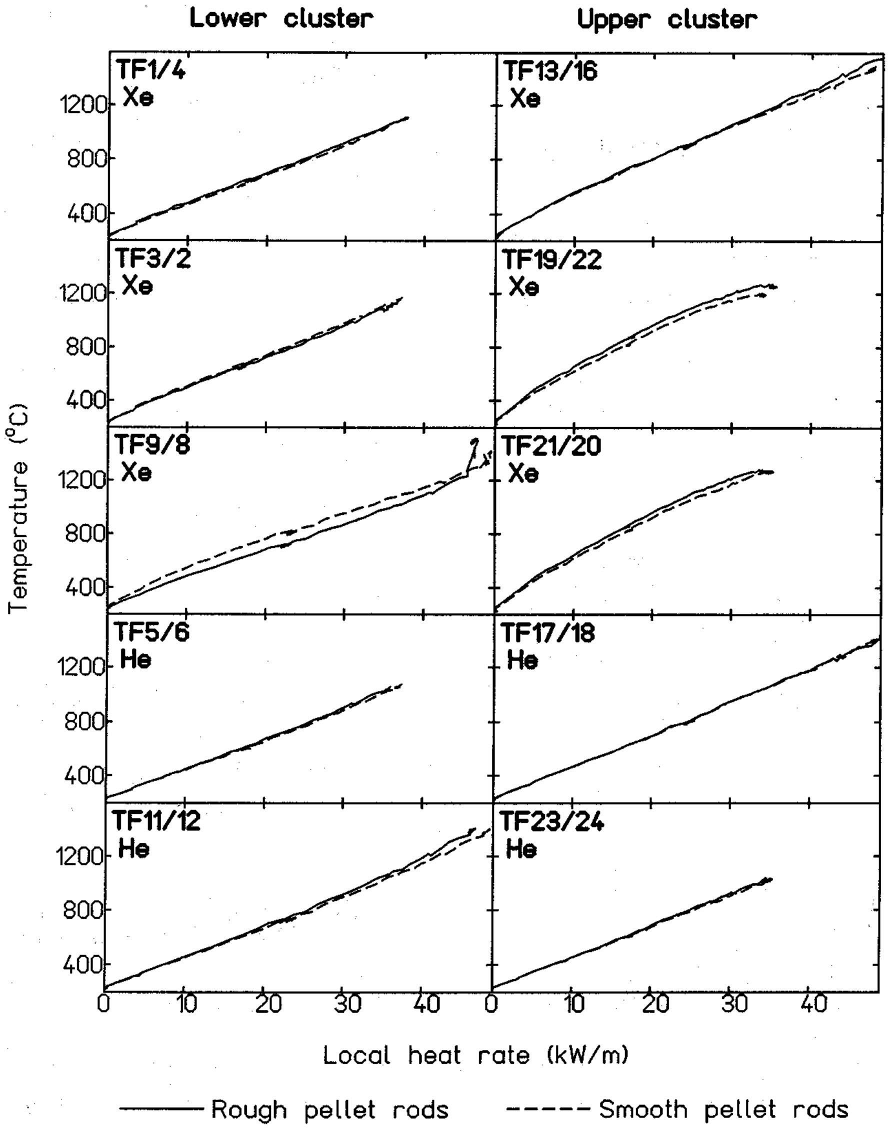
2g – in-core effect of temperature jump distance

- Gap conductance models employ the concept of ‘extrapolation length’ to account for imperfect heat transfer between gas and solid
- The correction depends on pressure (and temperature)
- The effect has been assessed experimentally
- It is stronger than calculated with *2g* in the gap only and includes fuel cracks (a heat flow resistance as well)
- It shows some burnup dependence, possibly due to changes in number of fuel cracks



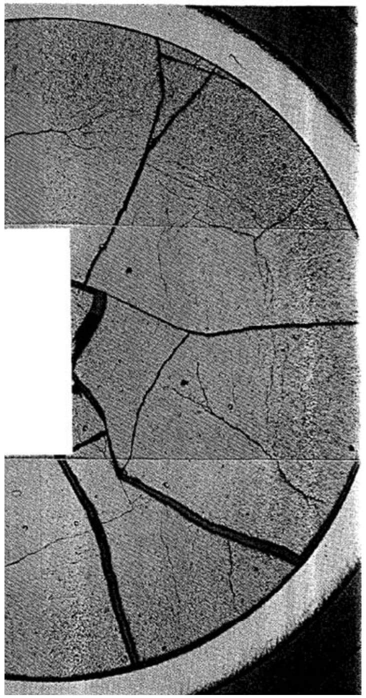
δ – surface roughness

- 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



... and the gap ($d_{thermal}$)?

- The phenomena and properties mentioned before (with complexity of description ranging from constants and empirical equations to formulations based on first principles) are important parts of gap heat transfer modelling. However
- the most important quantity is the **pellet-clad gap**. It depends on
  1. differential thermal expansion of fuel and cladding
  2. fuel cracking and relocation
  3. distribution of open and closed gap
  4. fuel densification and swelling
  5. clad creep-down
- Many of these phenomena
  - are stochastic and cannot be calculated exactly
  - depend in complicated ways on other phenomena
- **The calculation of the heat transfer between pellet and cladding remains a source of uncertainty**



5.3.1 Differential thermal expansion

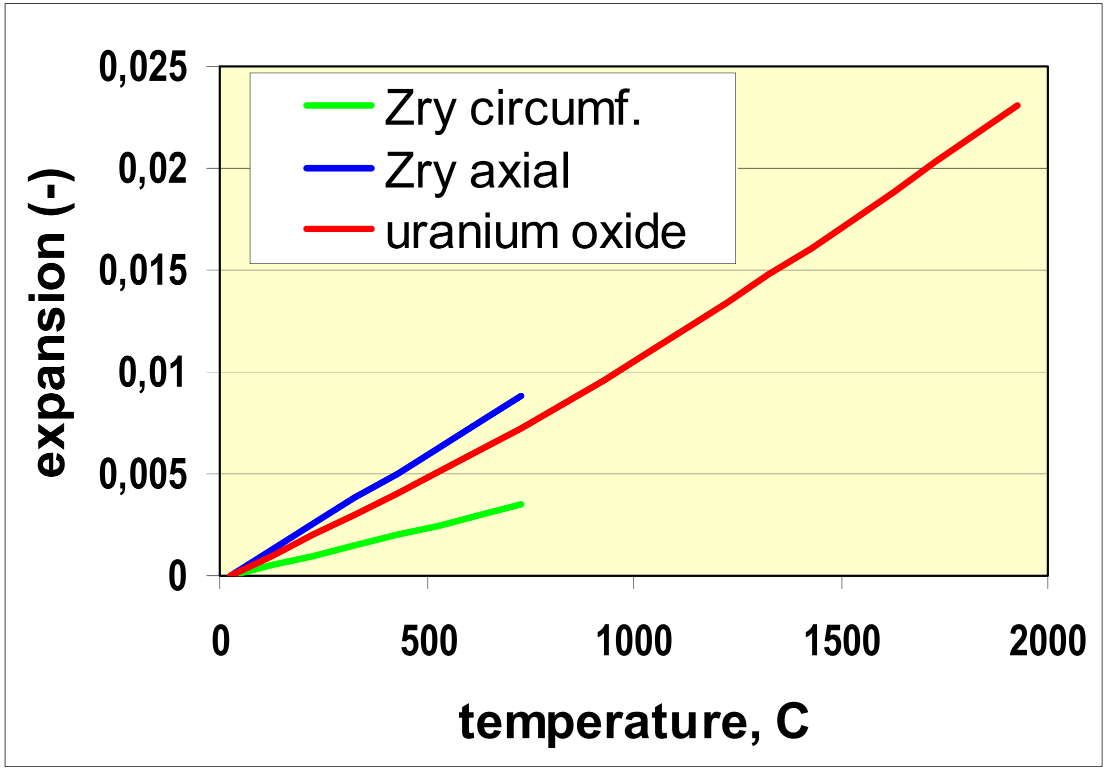
- MATPRO → recommendations for Zry and UO_2

$$\varepsilon_{clad,circ} = 4.95\times10^{-6}T - 1.485\times10^{-3}$$

$$\varepsilon_{clad,axial} = 1.26\times10^{-5}T - 3.780\times10^{-3}$$

$$\varepsilon_{urania} = 1.00\times10^{-5}T - 3.000\times10^{-3} + 0.04\cdot e^{-5000/T}$$

- Uranium oxide expands more than Zircaloy (circumferentially)
- The fuel gets much hotter than the cladding
- → the gap closes due to thermal expansion



5.3.2 Fuel cracking and relocation

- A fuel pellet will start cracking at 50-60 W/cm due to thermal stresses induced by the temp. gradient
- Cracks are irregular, but with a predominantly radial direction
  - hollow pellets tend to develop “nice” radial cracks
- The fuel fragments are assumed to relocate slightly
  - evidence is essentially indirect through temperature meas.
- Fuel modelling codes employ the “relocation” concept to improve fuel temperature predictions by decreasing the thermally effective gap size

Extent of relocation

- Relocation can be regarded as a parameter to bring about agreement between measured and calculated fuel centre temperatures
- As a modelling concept, it is thus not independent of other models and correlations employed in a code
- Typical values (code dependent)
  - 20-40% reduction of cold gap
  - slight increase with power
  - slight increase with burnup
- It is reasonable to assume that a fragment can be found anywhere in the available relocation space
  - 50% reduction of hot gap on average
  - effective circumferential crack component (heat flow resistance in the fuel) should reduce the overall conductance improvement

5.3.3 Modelling alternative: Distribution of open and closed gap

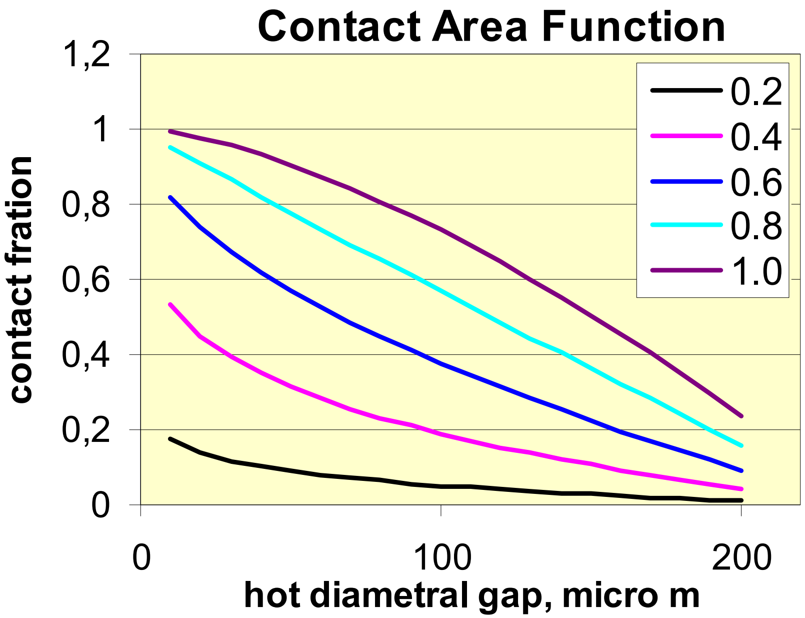
- Instead of reducing the thermal gap, it can also be assumed that a certain fraction of the fragments is in contact with the cladding while the rest keeps a maximum separation
- Such a concept, the *contact area function,* is employed in the Halden Project’s temperature analysis code FTEMP
- In ENIGMA, gap conductance is improved by a contact component that is always present

$$CA = 1 - \left(\frac{\delta}{\delta_0 + 40}\right)^{1.5 \cdot \varepsilon^2}$$

$CA =$ contact area function

$\delta =$ diametral gap (hot)

$\varepsilon =$ eccentricity parameter

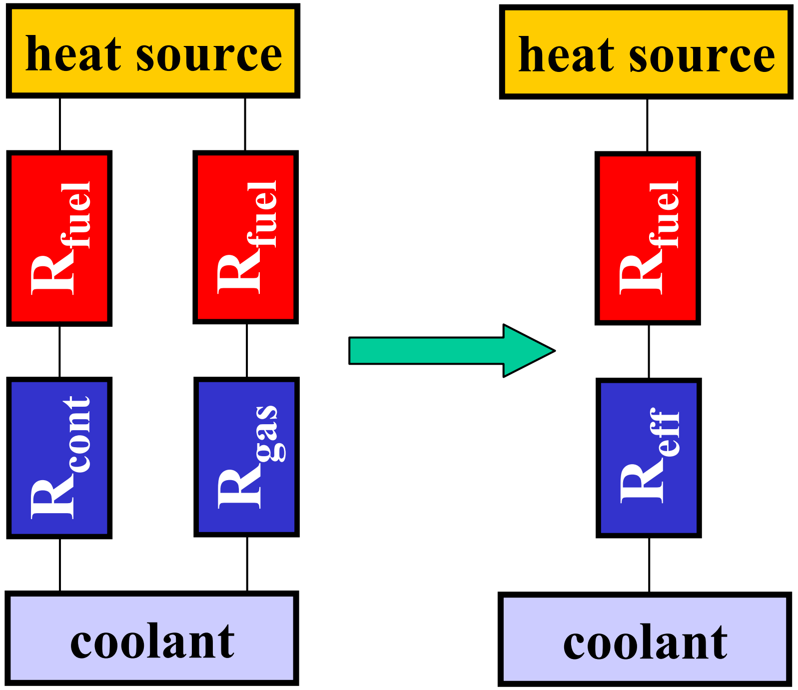


Average heat transfer coefficient

- A 1-D treatment requires a proper averaging to derive an effective heat transfer coefficient from the components:

  $h_{eff} = h_{rad} + f(h_{cont}, h_{gas})$

- Various concepts for *f* are employed i fuel modelling codes
- The Halden Project FTEMP uses the electrical analogy of parallel resistances between a common potential difference

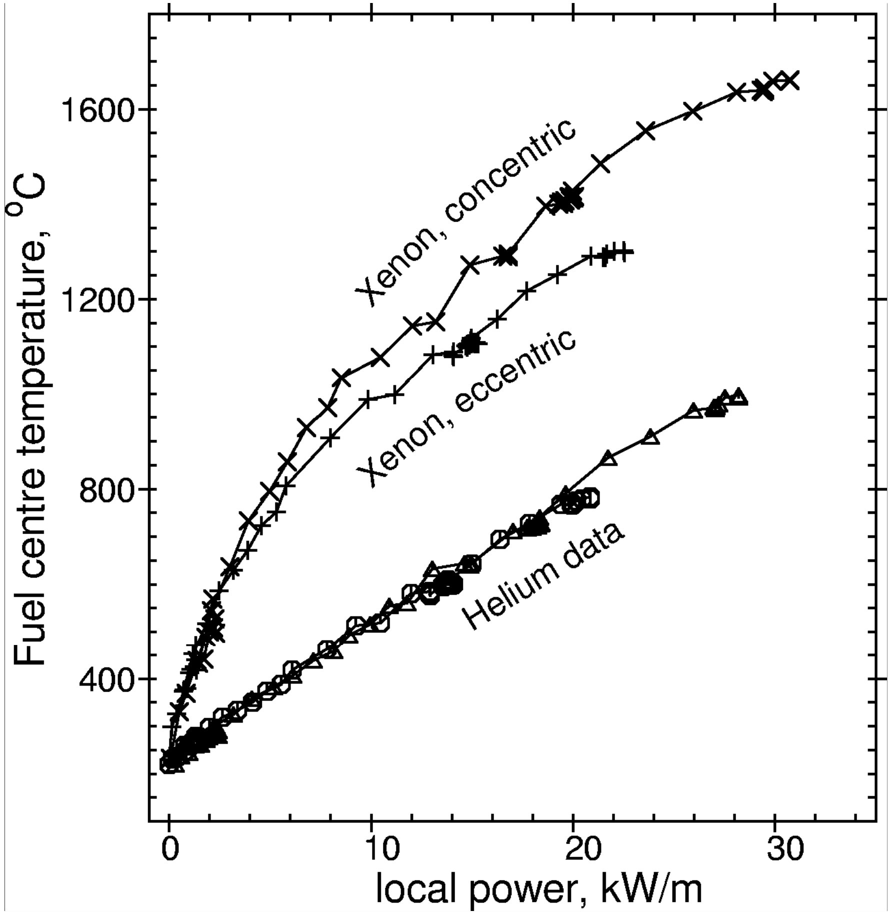


$$R_{eff} = \left(\frac{CA}{R_{fuel} + R_{cont}} + \frac{1 - CA}{R_{fuel} + R_{gas}} \right)^{-1} - R_{fuel}$$

$$h_{eff} = 1 / R_{eff}$$

Effect of eccentrically located pellet on fuel centre temperature

- 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.



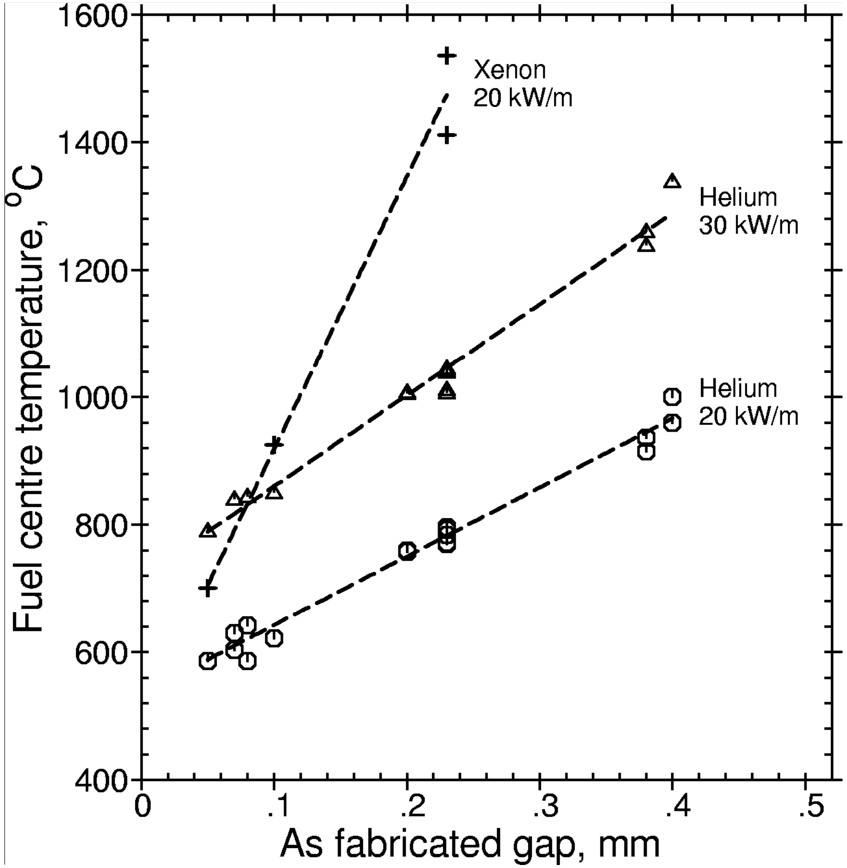
Effect of eccentric pellets on temperature

The pellet-clad gap is ...

- ... opened by
  - fuel densification
  - cladding creep (if overpressure)
- ... closed by
  - cladding creep
  - fuel swelling
- More about these in lecture on dimensional changes and pellet-clad interaction

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

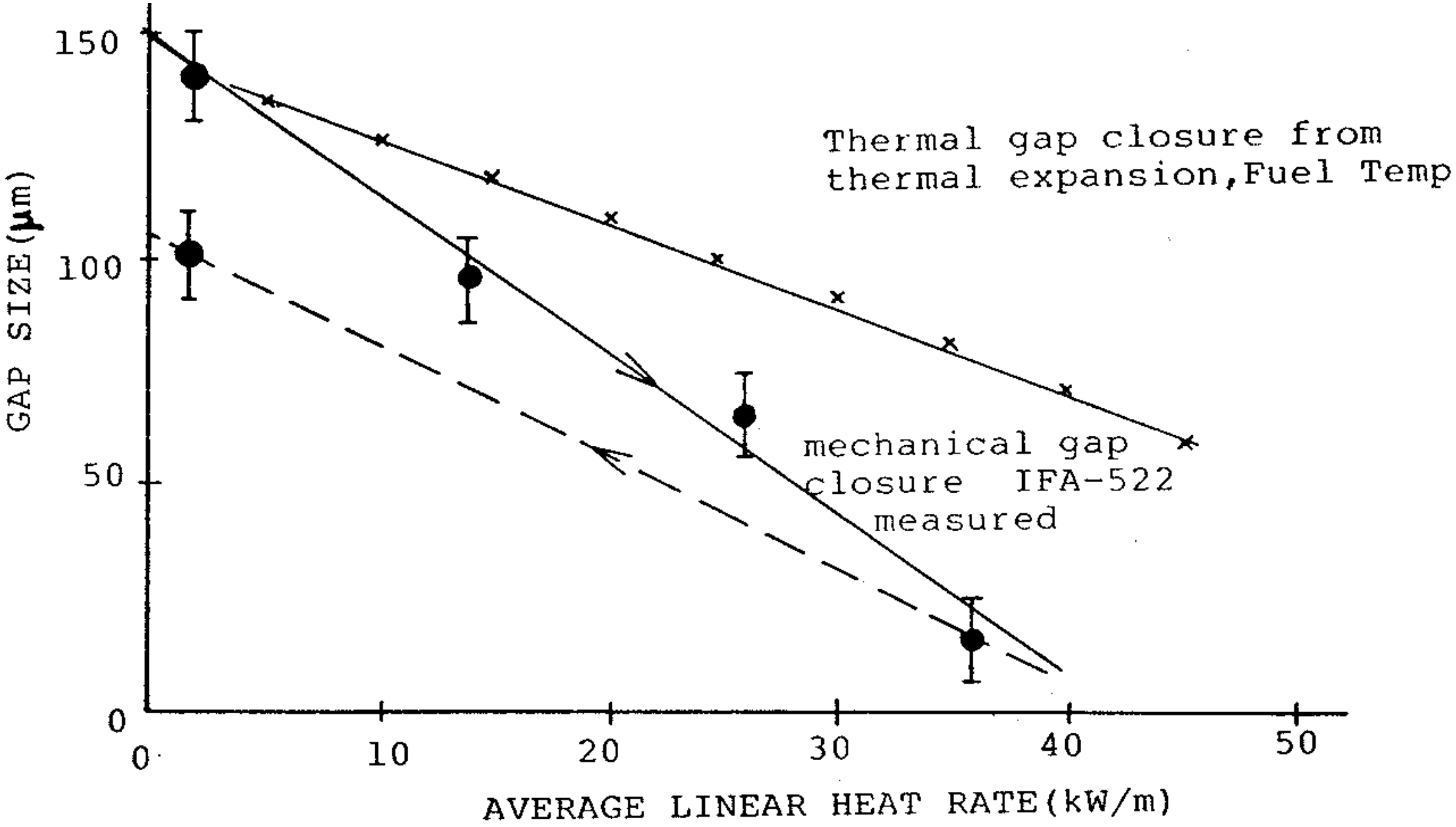


Influence of gap on fuel temperature

Gap size determination

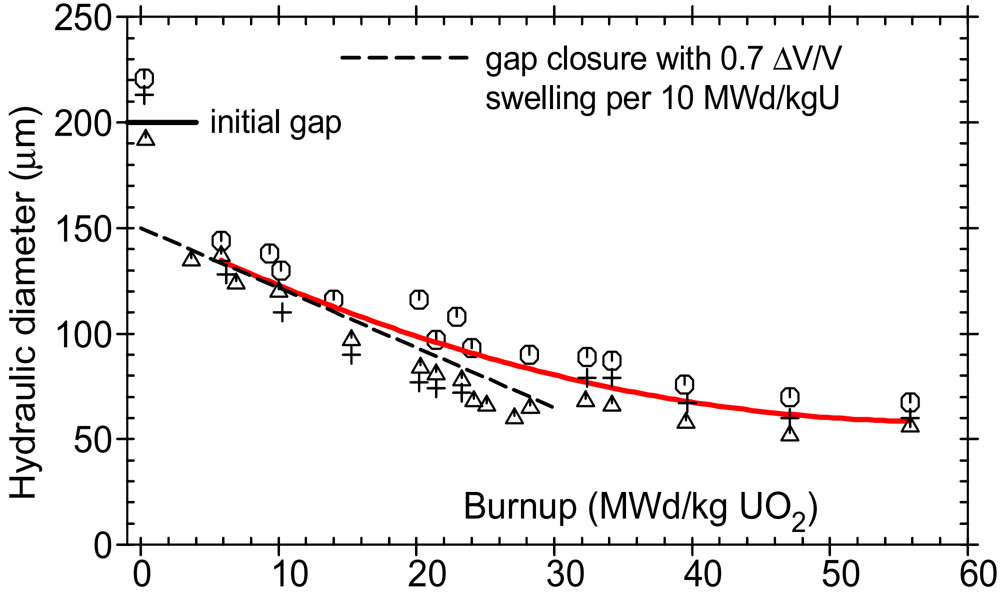
- The size of the gap between fuel pellet and cladding can be assessed by different direct and indirect techniques:
  - Clad squeezing (mechanical in-core device)
  - Hydraulic diameter measurements
  - Evaluation of onset of pellet-clad mechanical interaction
  - Gas exchange and effect on fuel temperature

Clad squeezing technique



Clad squeezing was used to determine the fuel-clad gap at power. A discrepancy between calculated thermal expansion and measured gap is apparent.

Hydraulic diameter measurements



Change of hydraulic diameter (free fuel column volume)

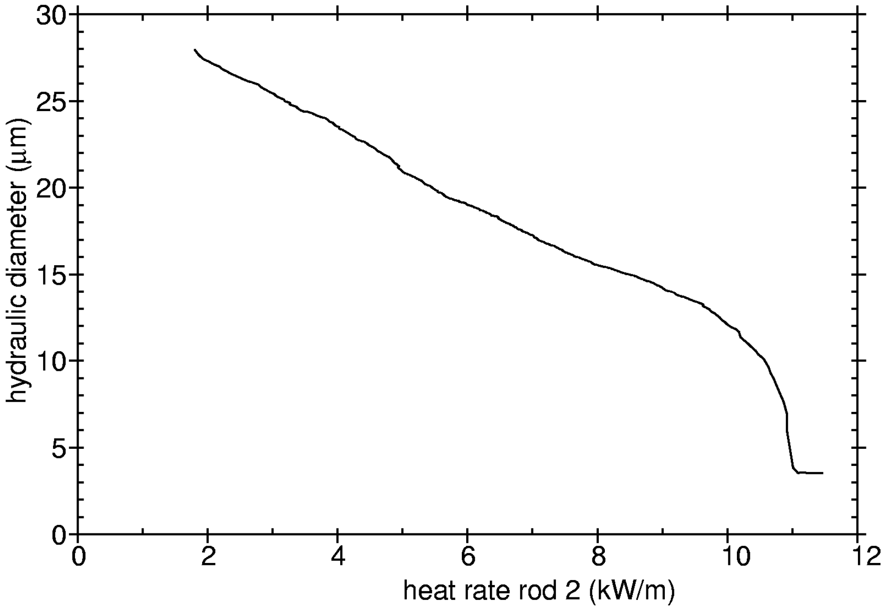
The hydraulic diameter reflects the free volume in the fuel column. Normal changes are:

- 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

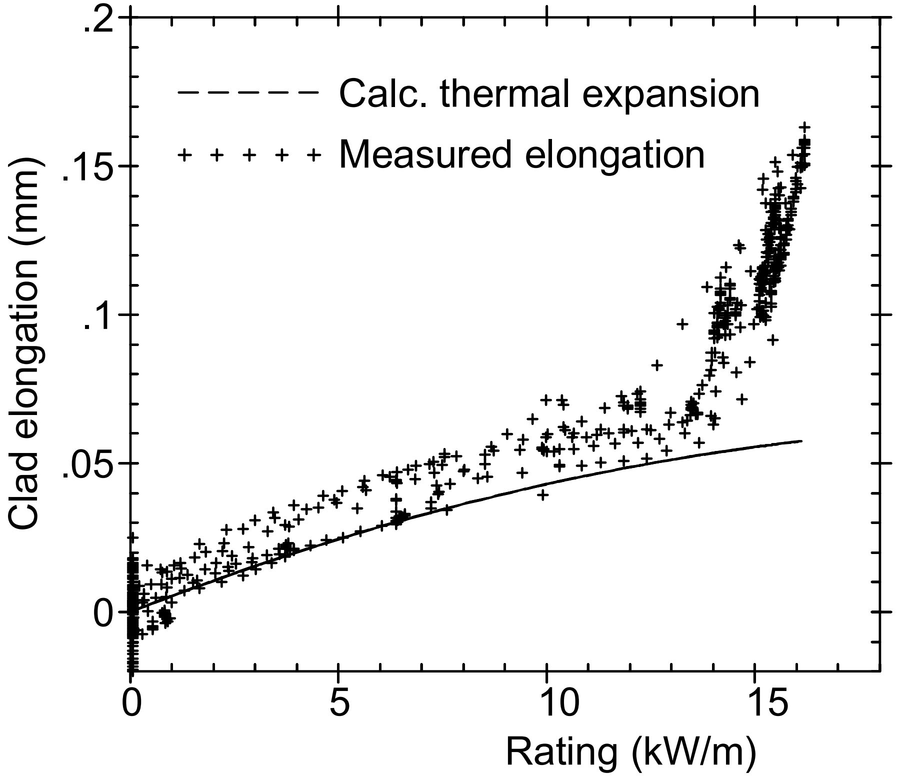
- At zero power, high burnup fuel typically has a “gap” size reflecting thermal contraction from the accommodation power level
- When the accommodation power level is approached, the hydraulic diameter decreases at a higher rate, similar to the onset of PCMI
- Regular measurements in a number of HBWR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

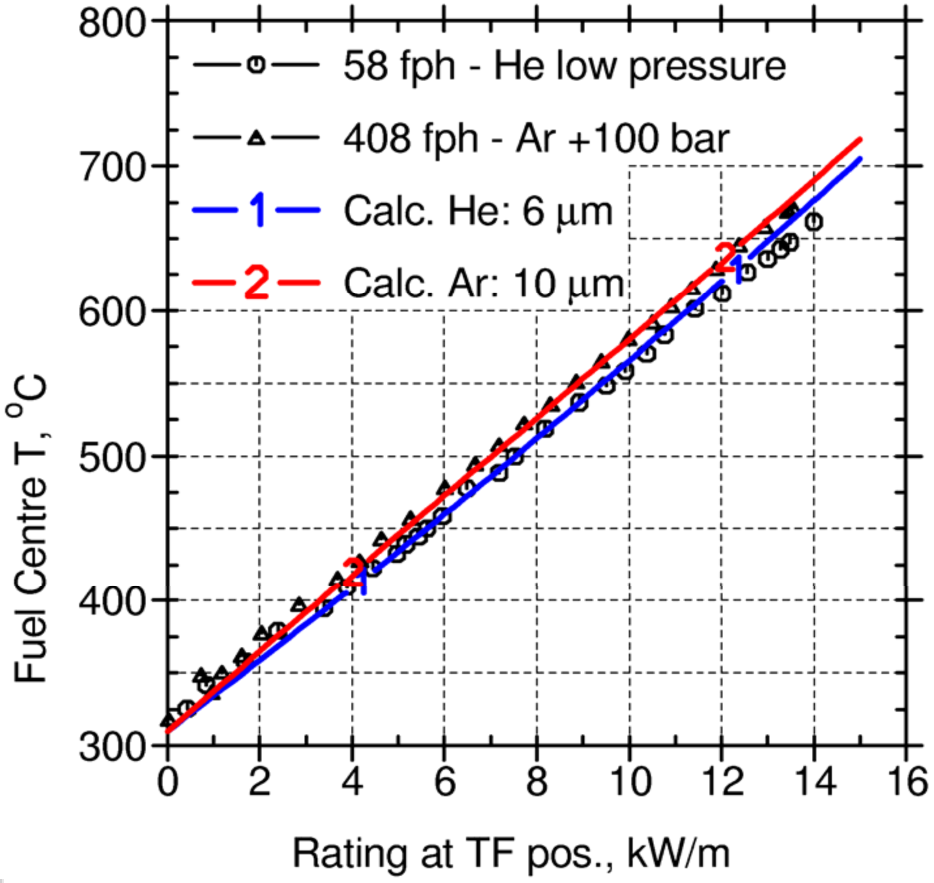
Pellet-clad mechanical interaction undergoes various phases. When the cracked fuel has accommodated to the cladding, the onset of appreciable PCMI indicates gap closure. The high burnup fuel example illustrates:

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

Gas exchange in irradiated fuel rods

- Experimental rigs with gas lines provide for a change of fill gas during in-core service
- This feature allows assessing the dependence of gap conductance on fill gas composition
- Other influences on gap conductance are (practically) unchanged
  - relocation
  - fuel cracking pattern

Change of fill gas and temperature response



Fuel temperatures with He and Ar fill gas

- The difference between Ar and He fill gas is small, reflecting an essentially closed gap
- The comparison with code calculations is satisfactory, but details differ:
  - the calculated temperature curve bends upwards, while
  - the measured data are best rendered by a straight or slightly downward bending curve
- Such subtle differences may indicate a different distribution of the thermal resistances (solid fuel, fuel cracks, fuel-clad gap) than commonly assumed in fuel modelling codes

The END