In-Pile Research

Instrumentation and Methods

Lecture 8.4

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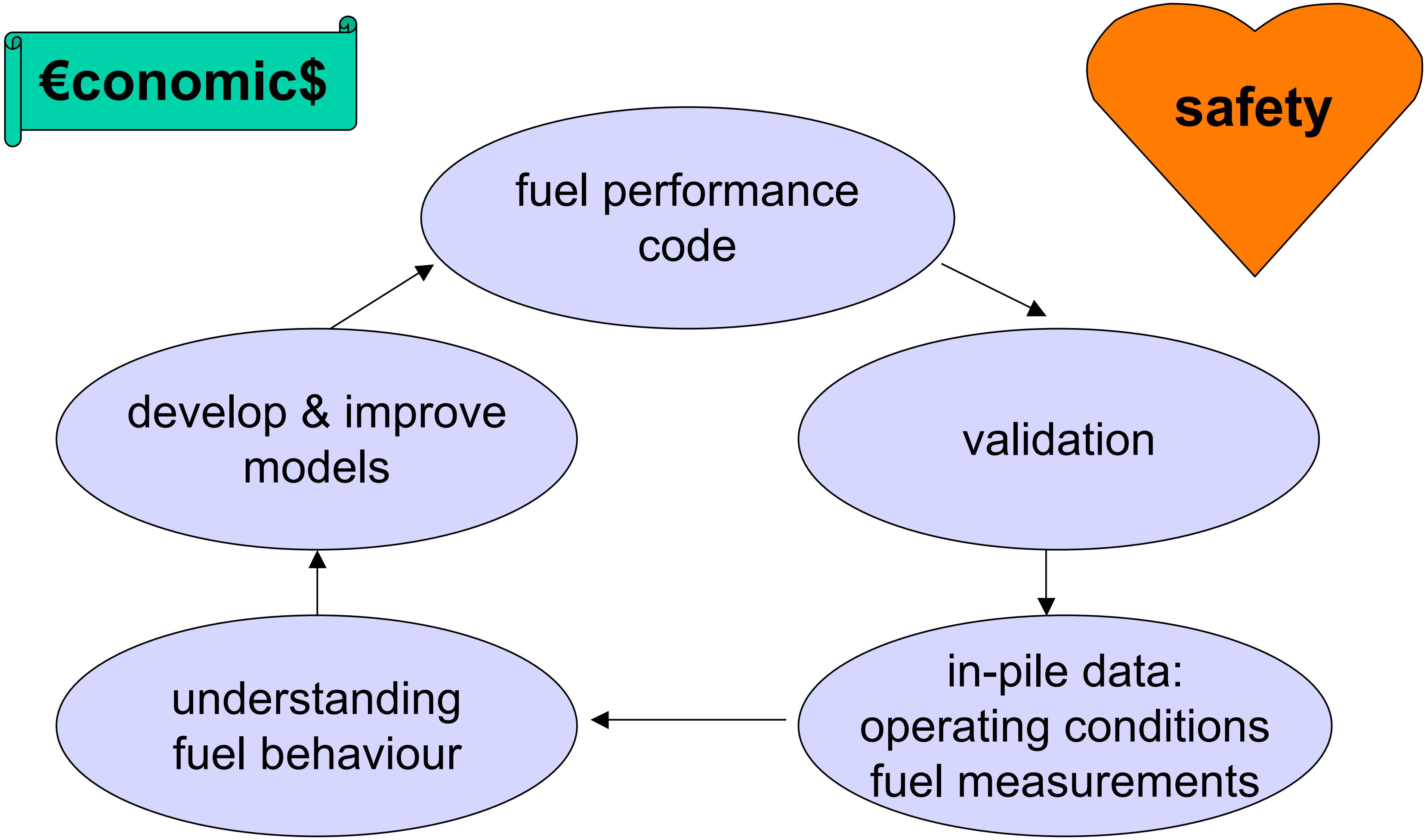
Overview

- Why make in-pile measurements on fuel rods?
- What can be measured?
  - temperature
  - pressure
  - dimensional changes
  - secondary measurements

Why make in-pile measurements on fuel rods?



In-core instrumentation ...

... is essential for fuel performance studies and provides

- direct insight into phenomena while they are going on
- cross-correlations between interrelated phenomena

However, the conditions in the core of a (research) reactor are not conducive for instrument performance and the ability to survive for a long time. Factors contributing to failure are

- high neutron and gamma fluxes
- high temperatures
- high pressures

Temperatures, pressures, stresses, strains, dimensional changes, electrochemical potential and other important parameters can be measured in various ways, **but:**

Only robust methods will endure in-core conditions for longer times.

What can be measured on a fuel rod and to what fuel performance issue does the measurement relate?

1.	Fuel Temperature	Heat transfer (fuel thermal conductivity, gap conductance)
2.	Rod Internal Pressure Change	Fission gas release, fuel densification & swelling
3.	Fuel Stack Length Change	Fuel densification & swelling
4.	Fuel Cladding Length Change	PCMI, (or when no PCMI, surface heat transfer, growth)
5.	Fuel Rod Outer Diameter Change	PCMI, (or when no PCMI, creep & growth, corrosion)

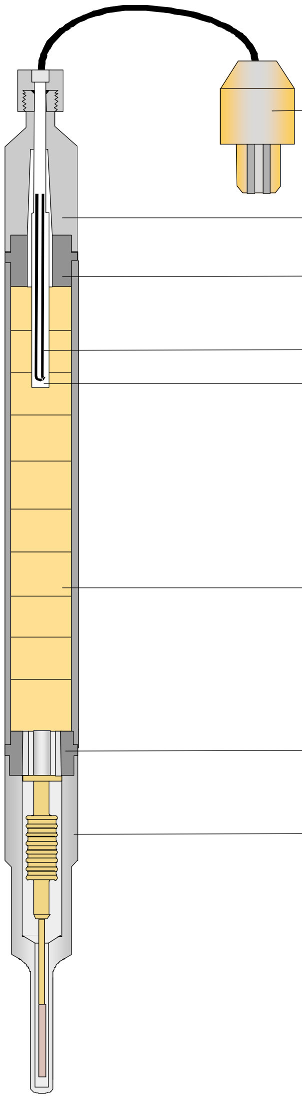
1. Fuel Temperature

- A good prediction of fuel temperature is an essential requirement for any fuel performance code
- Fuel centreline temperature at a single point within an annular fuel pellet can be measured with a thermocouple
- Average fuel centreline temperature can be measured with an expansion thermometer running the length of an annular fuel stack
- Fuel centreline temperature measurements enable modellers to test their code predictions with respect to:
  - Fuel thermal conductivity and its degradation with burn-up
  - Gap conductance / gas composition (fission gas release)
  - Gap width (fuel densification & swelling, cladding creep)
  - Fuel pellet surface roughness
  - Eccentricity in the fuel stack

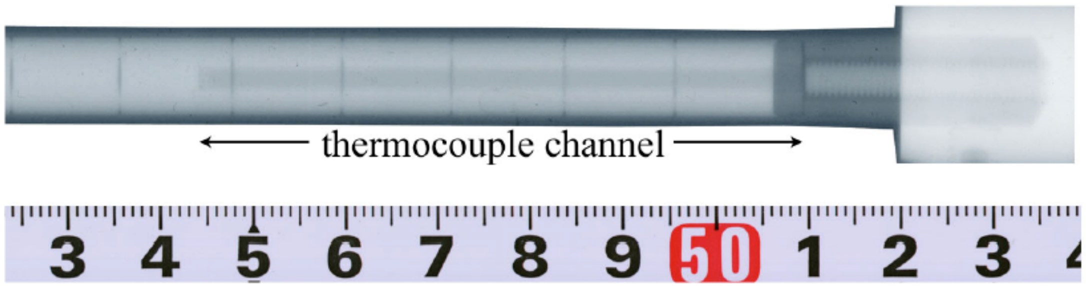
Measuring Fuel Temperature with a Thermocouple

- High temperature thermocouples suitable for measuring inside a fuel stack are:
  - W / Re
  - Nicrosil / Nisil
- Strengths of thermocouples
  - Reliable measurement: up to 1400 - 1600°C, thermocouples can last several years and will even manage a few hours at 2000°C
  - Accurate measurement: easy to calculate from measured to solid fuel pellet temperature
- Weaknesses of thermocouples
  - Tendency to premature failure at high fuel temperatures or in failed rods
  - Need to account for de-calibration due to transmutation at high fluence

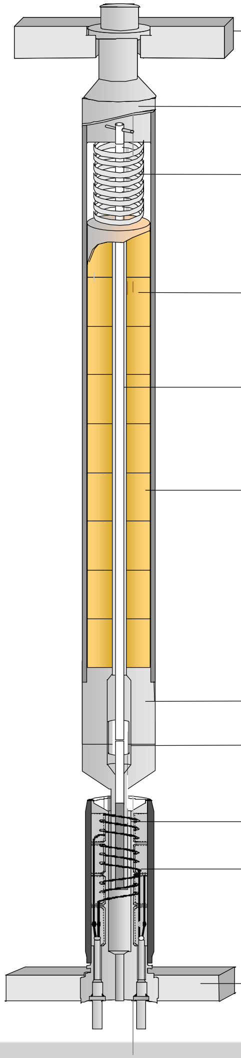
Measuring Fuel Temperature with a Thermocouple



- Both fresh and irradiated fuel pellets in a stack can be drilled to allow insertion of a thermocouple (Mo tube)
- Neutron radiography can show exactly where thermocouple tip (hot junction) is positioned

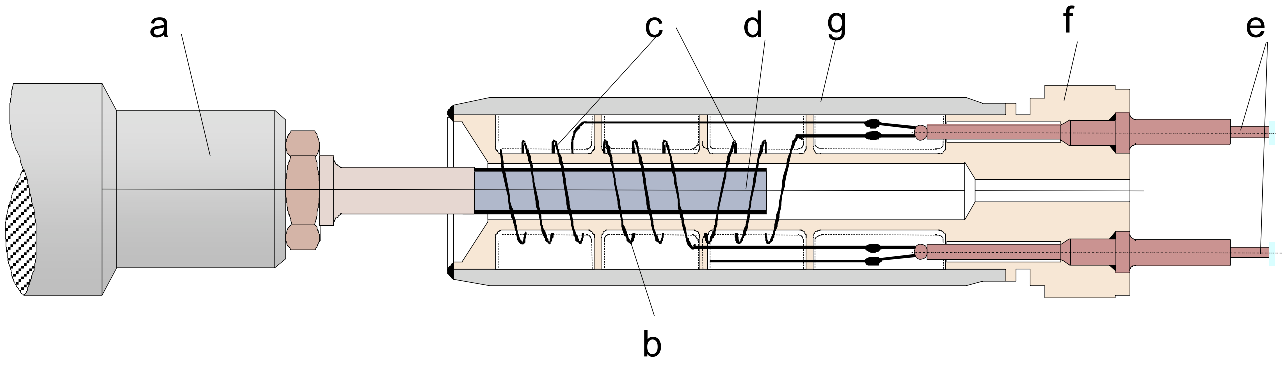


Measuring Fuel Temperature with an Expansion Thermometer



- A thin tungsten rod is inserted through a centre hole drilled in the entire fuel stack
- One end of W-rod fixed to fuel rod end-plug, other end is free and fitted with a magnetic core, movement of core sensed by an LVDT (Linear Variable Differential Transformer)
- Average centreline temperature in fuel stack derived from measured axial expansion of tungsten rod

Linear Variable Differential Transformer (LVDT)



a: Test rod end plug assembly
b: Primary coil
c: Secondary coils
d: Ferritic core
e: Twin-lead signal cables
f: Body
g: Housing

- Developed for measuring fuel rod pressure, temperature, fuel stack and cladding elongation
- Primary coil with two secondary coils connected in opposition. Movable magnetic core concentrically located inside coil system
- Core movement affects the balance of the secondary coils and generates the signal output

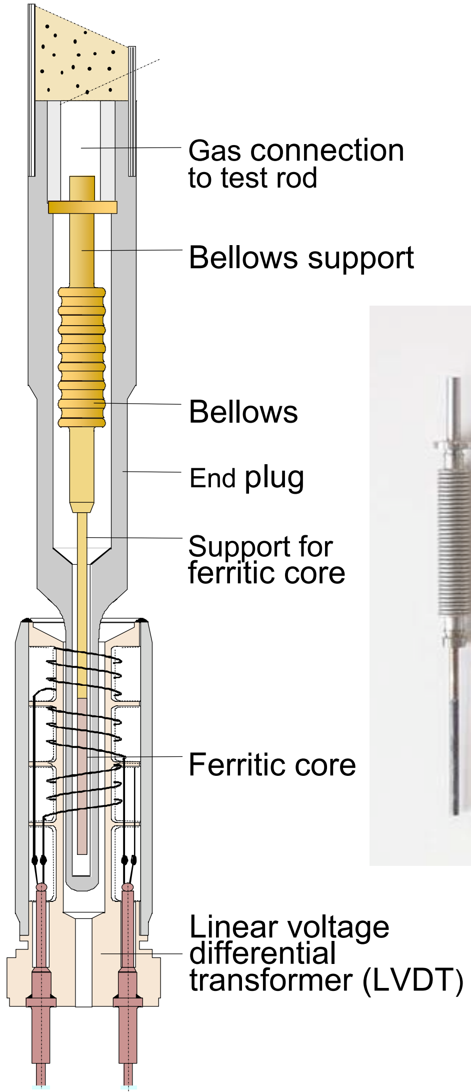
Measuring Fuel Temperature with an Expansion Thermometer

- Strengths of expansion thermocouples
  - Suitable alternative to thermocouples for high-temperature measurements
  - No de-calibration with time
  - Expected lifetime is longer than that of a thermocouple
- Weaknesses of expansion thermocouples
  - Accuracy of the measurement due to the interpretation of the signal that is needed is not as good as the accuracy of a thermocouple
  - There is also a risk that mechanical interaction between the fuel and the tungsten rod will affect the performance of the instrument

2. Fuel Rod Internal Pressure Change

- Measuring changes in rod internal pressure provides data on
  - Fission gas release
  - Fuel stack densification and swelling (in absence of FGR)
- Understanding or being able to adequately model fission gas release mechanisms is important especially for development of new fuel types for better fuel performance
  - Rod pressure measurements often combined with fuel temperature measurements e.g. investigating threshold temperature for FGR onset
- Fuel rod internal pressure is a key issue for extending the discharge burn-up of fuel for power reactors - most licensing bodies limit allowable fuel rod internal pressure to not exceed system pressure

Measuring Fuel Rod Internal Pressure Change



- Small stainless steel or Inconel sealed bellows unit inserted in a fuel rod end-plug
- Gas pressure in fuel rod acts on bellows
- One end of bellows fixed to end-plug, other end is free and fitted with a magnetic core, movement of core sensed by an LVDT
- In-pile calibration at start of life (know rod pressure), then subsequent signal gives change in rod pressure
- Different bellows used for different expected measuring ranges: up to 15, 30 or 70 bar ΔP

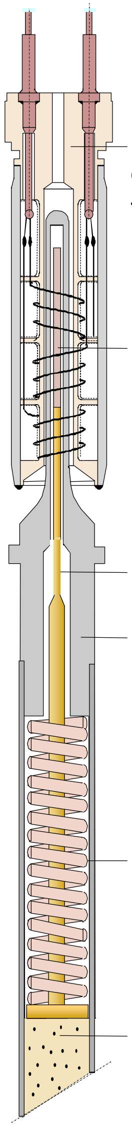
Measuring Fuel Rod Internal Pressure Change

- Bellows experience creep due to the high temperature, stress and radiation environment
    - Use pressurised bellows (to reduce stress)
    - Carry out "re-calibrations" with data obtained from periods of cool-down and heat-up (no nuclear heating) using gas law
- Measuring fuel rod pressure in the plenum (end-plug) is subject to accessibility of gas released from the fuel stack
    - No problem with fresh fuel (fuel-clad gap open at power)
    - For fuel rods with a tight gap at power, brief power reductions can be made allowing the fuel-clad gap to re-open and gas to percolate to the plenum

3. Fuel Stack Length Change

- Measuring changes in fuel stack length provides data on
  - Fuel densification and swelling (fuel-clad gap open)
- Fuel densification and swelling are of interest because of the way they affect the development of the fuel-clad gap e.g. as fresh fuel densifies initially, the gap size increases inducing an increase in the fuel temperature
- Dimensional stability behaviour varies between different fuel types and this is something that fuel models need to capture
  - Fuel density
  - Pellet shape (flat ended versus dished, hollow versus solid)
  - MOX fuel, Gd-doped fuel, other additive fuels

Measuring Fuel Stack Length Change

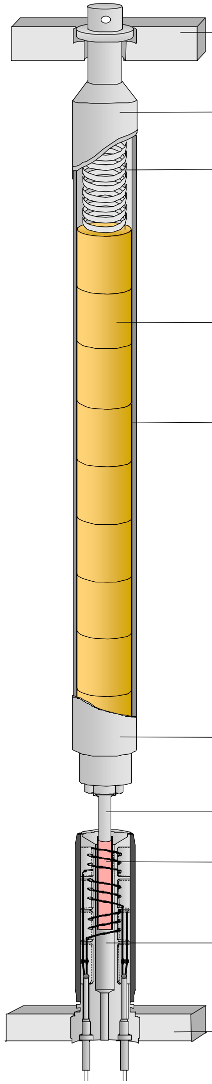


- Magnetic core holder fitted in fuel rod end-plug and spring loaded against fuel stack end
- Axial densification / swelling of the fuel stack acts on spring so magnetic core holder position moves
- Core movement sensed by LVDT
- In-pile calibration at start of life (zero point), then subsequent signal gives change in fuel stack length
- Stops being relevant once fuel-clad gap closes
- Because of connection between fuel dimensional changes and fuel temperature, fuel thermocouple often inserted at other end of same fuel rod

4. Fuel Cladding Length Change

- Measuring changes in fuel cladding length can provide data on cladding strain from fuel pellet to cladding mechanical interaction (PCMI) under different conditions which can be used for
  - model development
  - predicting the outcome of situations where clad integrity may be jeopardised
- When there is no PCMI, measurements can provide data on
  - Heat transfer properties of surface layers (oxide, crud)
  - Irradiation growth of cladding
  - Onset of dry-out (in dry-out testing)

Measuring Fuel Cladding Length Change

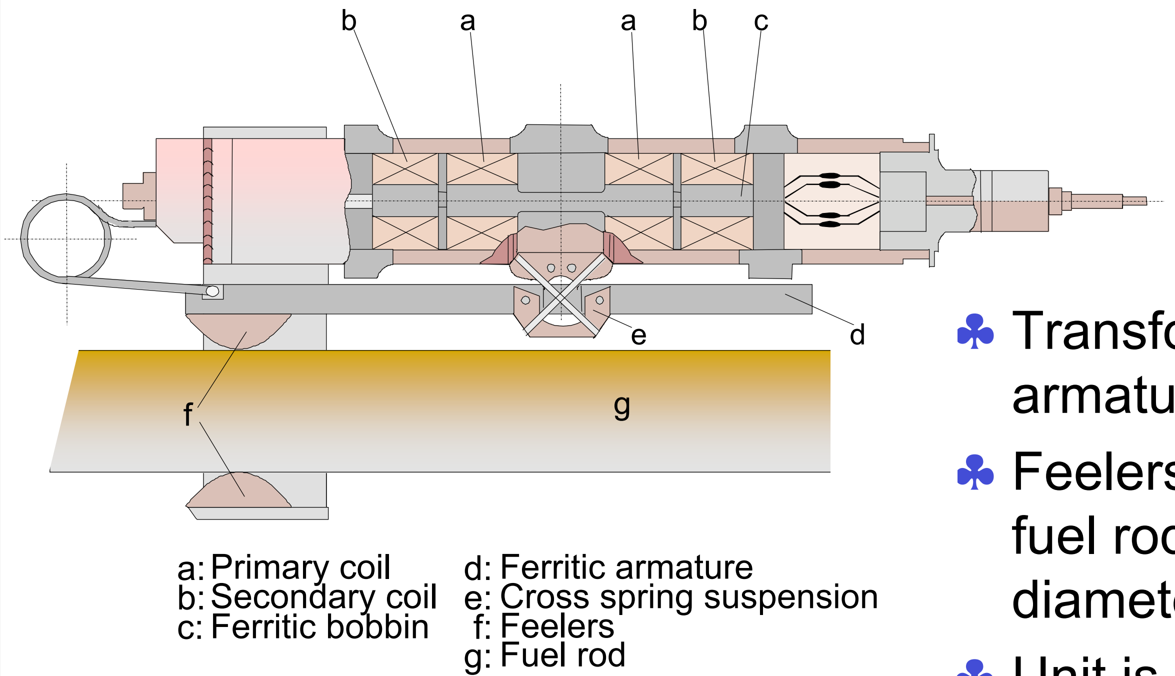


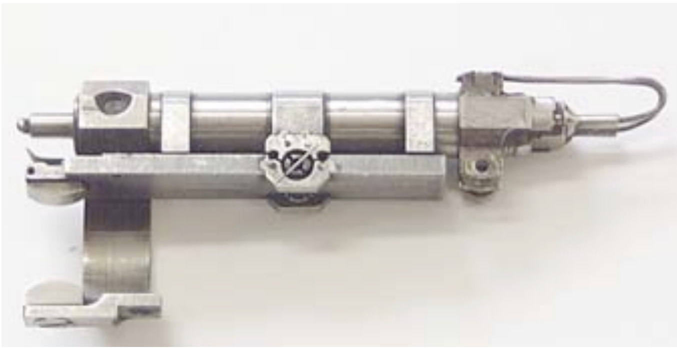
- Upper end of fuel rod fixed to test rig structure
- Magnetic core holder fitted to end-plug at lower (free) end of fuel rod
- Change in fuel cladding length causes core holder position to move relative to an LVDT
- In-pile calibration at start of life (zero point), then subsequent signal gives change in fuel cladding length

5. Fuel Rod Outer Diameter Change

- Measuring fuel cladding outer diameter changes can provide data on
  - PCMI during power transients (continuous measurement)
  - Cladding creep (measurement made once a week)
  - Oxide / crud build-up on a fuel rod (measurement made once a month)
- Monitoring diametral in addition to the axial components of PCMI enables better understanding of what occurs during power transients
- Most fuel performance codes contain models for cladding creep as this affects the development of the fuel-clad gap as well as influencing a fuel rod's PCMI behaviour
- Discharge burn-ups are often limited by the corrosion behaviour of the fuel rod cladding – so knowing how different claddings behave in different water chemistries in-pile is a vital part of alloy development

Measuring Fuel Rod Outer Diameter





Instrument based on the LVDT principle

- Transformer body connected to armature via a pivot point
- Feelers on opposite sides of the fuel rod trace the fuel rod outer diameter profile
- Unit is driven along the fuel rod by a hydraulic system
- Position sensor used to sense axial position of DG along the rod
- Calibration steps machined into the fuel rod end-plug surface

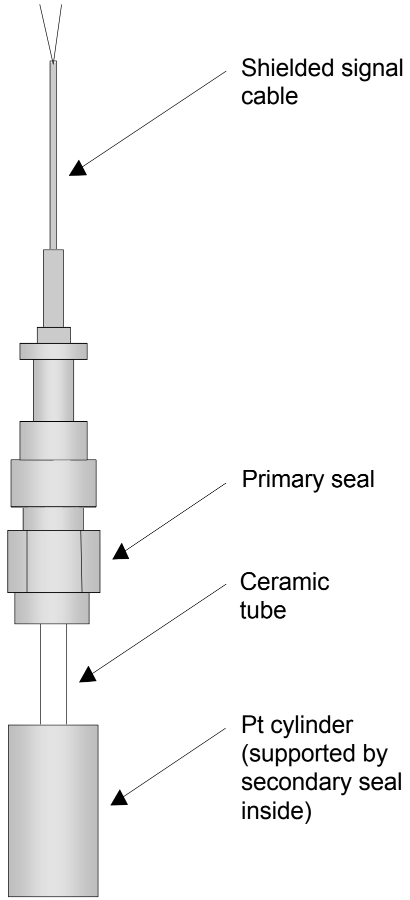
What else can be measured and to what fuel performance issue does the measurement relate?

- Thermal-hydraulic parameters
  - temperature, temperature increase
  - flow
  - pressure
- Nuclear conditions
  - neutron flux
  - gamma flux
- Water Chemistry parameters
  - Electrochemical Corrosion Potential (ECP)
  - High temperature coolant conductivity
  - On-line potential drop corrosion monitor
  - Electrochemical Impedance spectroscopy (EIS)

Electrochemical Corrosion Potential

- Electrochemical corrosion potential (ECP) of a corroding metal is the potential difference between it and the standard hydrogen electrode (SHE)
  - A key measurement when the corrosion performance of an in-reactor material is to be assessed or measures taken to optimise its performance
  - Arises from a combination of the surface conditions of the specimen and the concentrations of dissolved oxidants
  - Determined by measuring the potential between a sample and a reference electrode, and adding the (calculated) potential versus SHE of the reference electrode
  - A reference electrode is a half-cell that produces a stable and reproducible potential

Measuring ECP



- ♣ Mechanical seal in transition between ceramic parts and metal parts - no brazing
- ♣ Platinum reference electrode reliable – but does not give SHE values in oxygenated water
- ♣ Palladium reference electrodes show promise for use in BWR conditions
- ♣ Prototype Fe/Fe_3O_4 reference electrode developed - can be used in hydrogenated and oxygenated water

Methods
(secondary measurements)

- Gas flow through a fuel stack (hydraulic diameter)
- Gas flushing plus gamma spectroscopy (fission gas release)
- Noise analysis
- Fuel temperature response to scram

Secondary measurements

- **Hydraulic diameter** measurements determine the resistance that the fuel stack offers against gas flow and is applied to
  - map changes of the fuel-clad gap with increasing burnup
  - determine loosening of the fuel column in clad lift-off tests
  - find the resistance of the fuel stack against axial gas transport (e.g. in LOCA or from local fission gas release).
- **Gamma spectrometry** (fission gas release) allows assessing
  - low temperature fission gas release,
  - recoil component,
  - microstructural properties such as the surface-to-volume ratio
- **Fuel time constant** can be derived through evaluation of
  - rapid power changes (reactor scram)
  - noise analysis (fuel thermocouples + fast response ND)

Hydraulic diameter (HD)

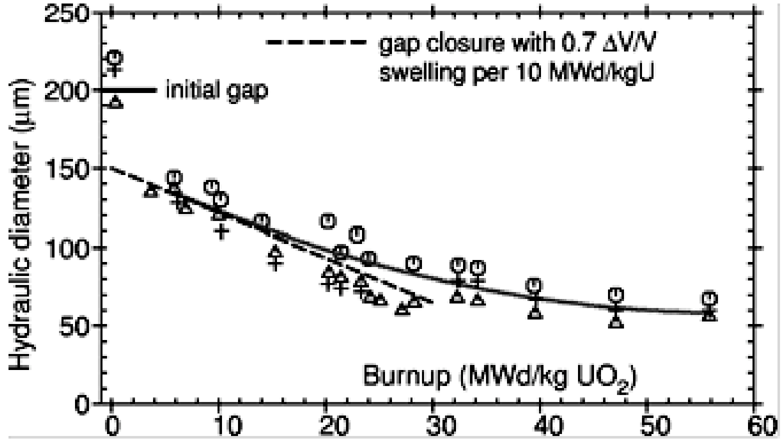
- Hydraulic diameter measurements determine the resistance that the fuel stack offers against gas flow and is applied to
  - map changes of the fuel-clad gap with increasing burnup
  - determine loosening of the fuel column in clad lift-off tests
  - find the resistance of the fuel stack against axial gas transport (e.g. in LOCA or from local fission gas release).
- Experimental set-up
  - direct measurement of gas flow driven by a pump
  - empty a reservoir of gas at overpressure through the fuel rod and measure pressure change in reservoir
- Due to pellet cracking and the convoluted flow path, the HD is a measure of permeability rather than an indication of the pellet-clad gap

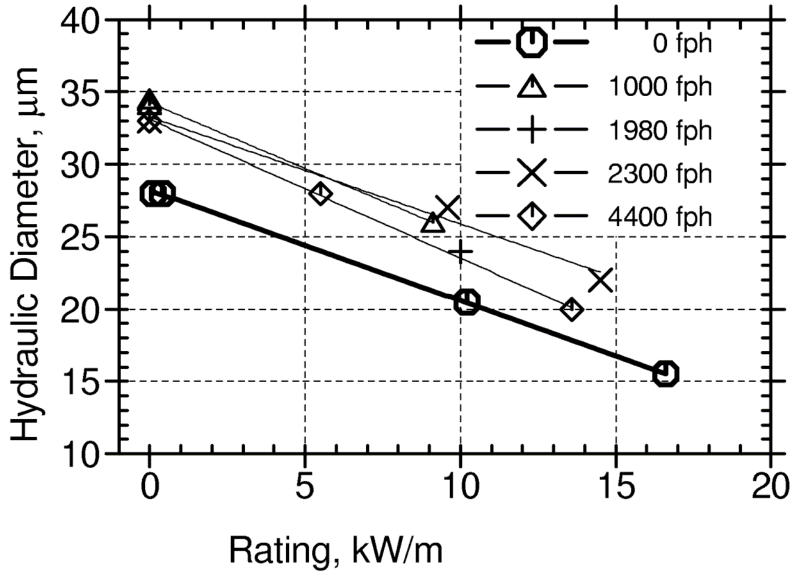
Hydraulic diameter measurements

$$D_H = \sqrt[4]{\frac{0.021 \cdot \eta \cdot L \cdot R \cdot T \cdot \dot{n}}{\pi \cdot D \cdot \left(p_1^2 - p_2^2\right)}}$$

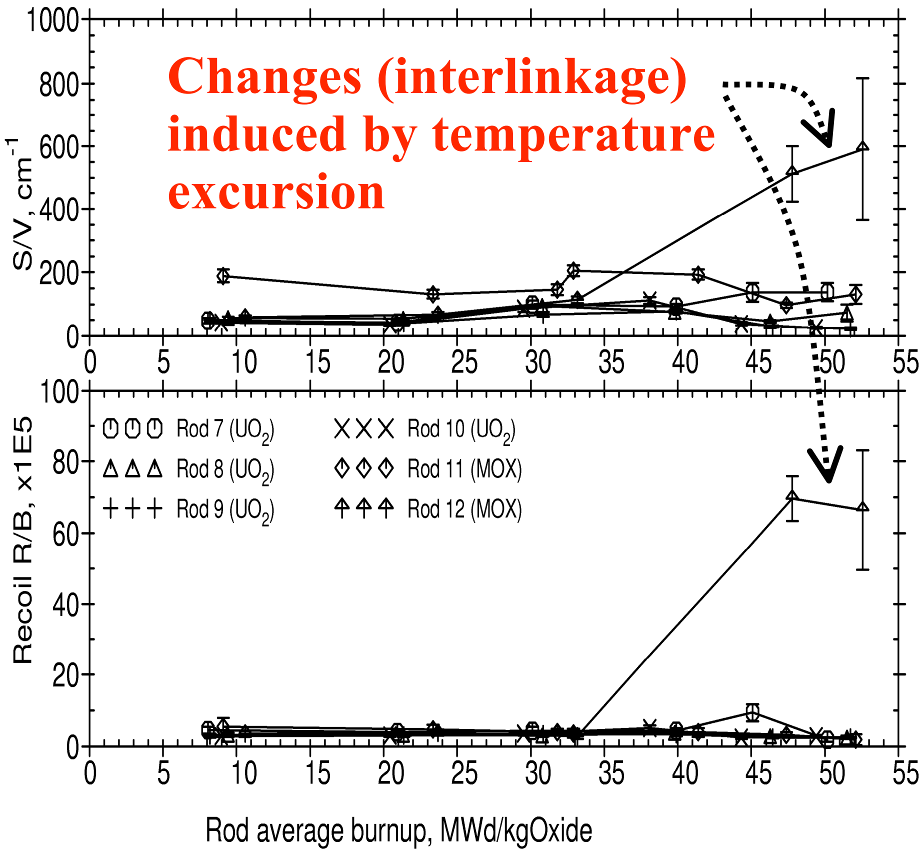
D_H = hydraulic diameter
D = mean fuel diameter
p_1 = gas pressure – supply side
p_2 = gas pressure – return side
Ha = Hagen number
η = dynamic viscosity
L = flow channel length
R = universal gas constant
T = gas temperature

The examples show long-term developments (upper right) and short-term changes (due to clad creep-out; lower right)





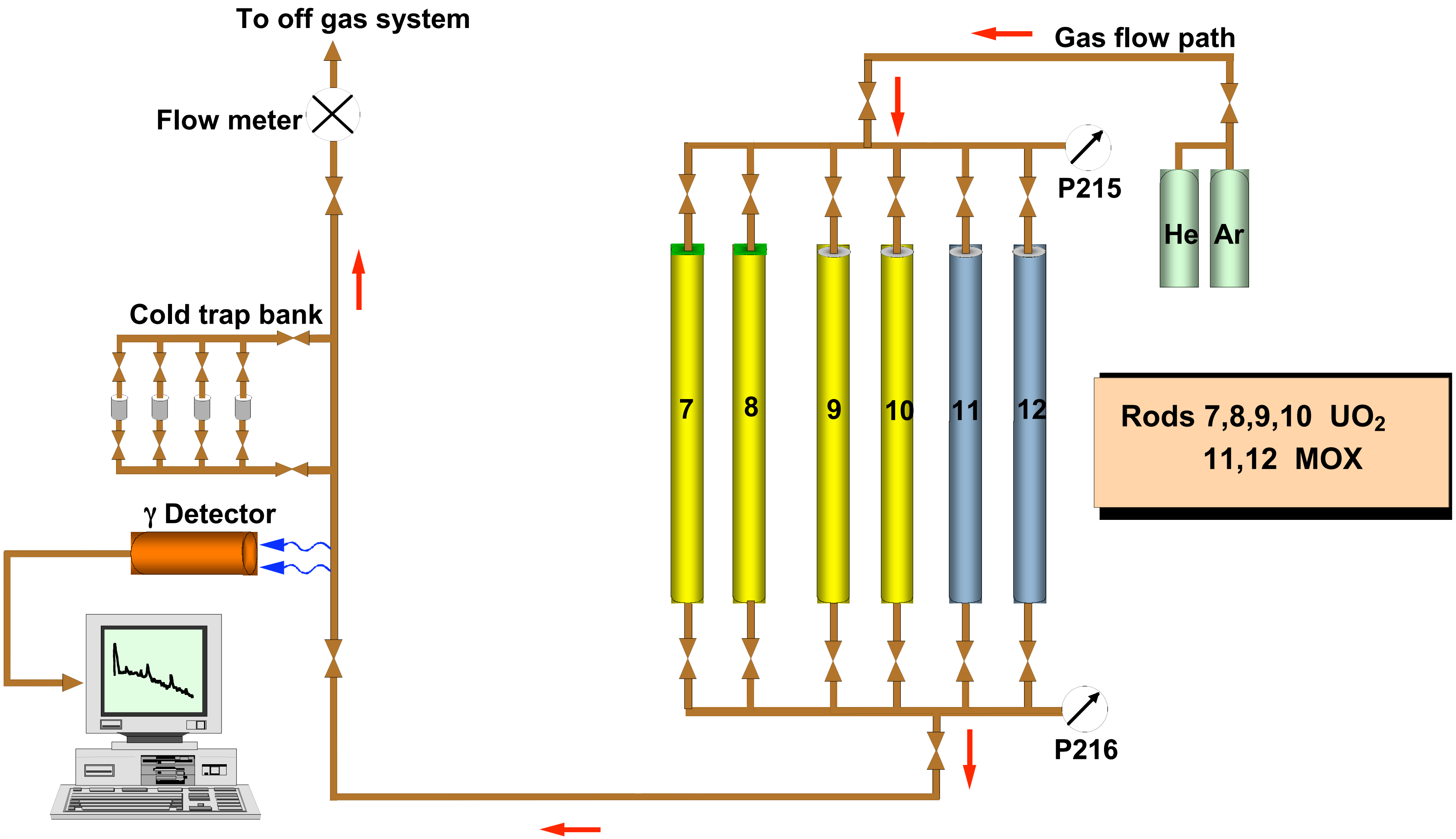
Gamma spectrometry



Gamma spectrometry (fission gas release) allows assessing

- low temperature fission gas release
- recoil component
- micro-structural properties such as the surface-to-volume ratio

Experimental setup



Gas flow analysis

Isotopic release rate from γ-spectrometry

Isotopic birth rate from fission yield calculations

Recoil release to birth rate

$$\frac{R}{B} = \frac{S}{V}\sqrt{D}\sqrt{\frac{\alpha}{\lambda}} + \frac{R}{B}_{recoil}$$

Surface area to volume ratio * square root of diffusion coefficient

Square root of precursor enhancement factor / decay constant

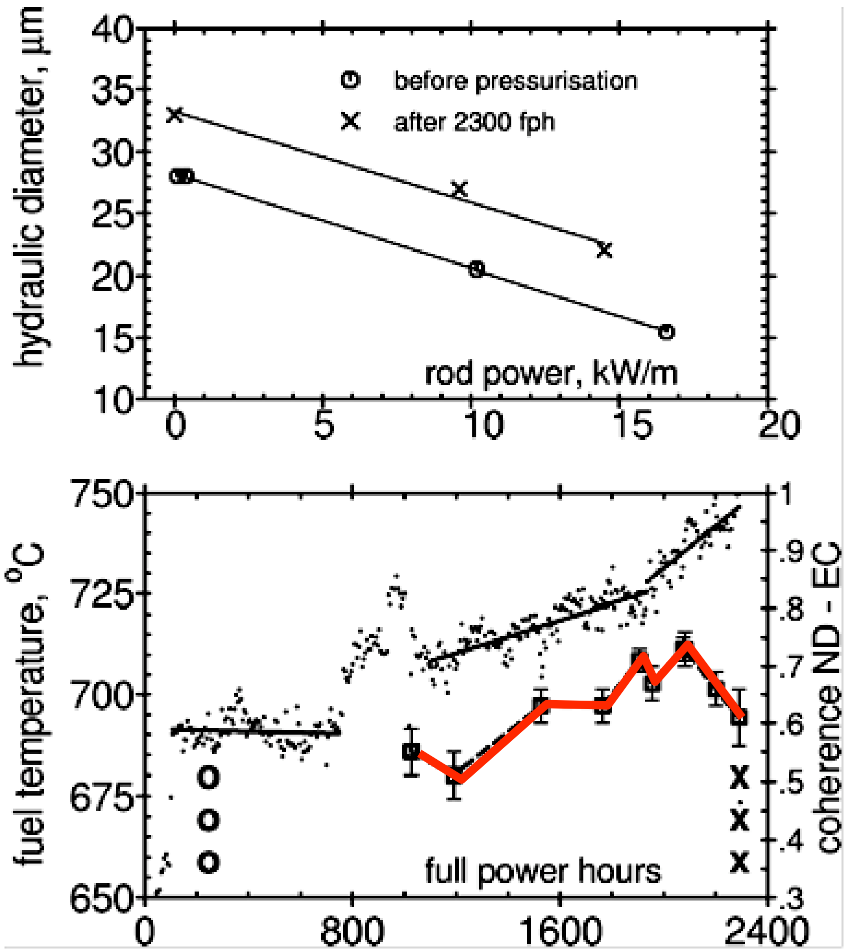
In start-up diffusivity analysis S/V fixed

In first cycle analysis D fixed

Noise Analysis Technique

- Used in studies of
  - thermal properties
  - pellet-clad mechanical interaction
  - fission gas release
- for determination of
  - fuel and thermocouple time constants
  - pellet-clad interaction coherence function
- by correlating two measurements
  - fast response neutron detector (power)
  - and
    - fuel thermocouple
    - cladding elongation detector

A practical example
PCMI and Rod Overpressure – Clad Lift-off



- Rod overpressure (>130 bar above system pressure) causes clad lift-off and a measurable temperature increase
- Clad lift-off causes the hydraulic diameter to increase
- Noise analysis (power – elongation) indicates continued contact between fuel and cladding

The END