The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2137-19

Joint ICTP-IAEA Advanced Workshop on Multi-Scale Modelling for Characterization and Basic Understanding of Radiation Damage Mechanisms in Materials

12 - 23 April 2010

Special experiments and their evaluation

W. Wiesenak

OECD Halden Reactor Project
Halden
Norway

6

Special Experiments and their Evaluation

Wolfgang Wiesenack

OECD Halden Reactor Project, Norway

Joint ICTP-IAEA Workshop on

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

Trieste, April 12-23, 2010

Overview

- Fuel conductivity degradation
- Cladding creep
- Rod overpressure – clad lift-off
- Hydraulic diameter & LOCA

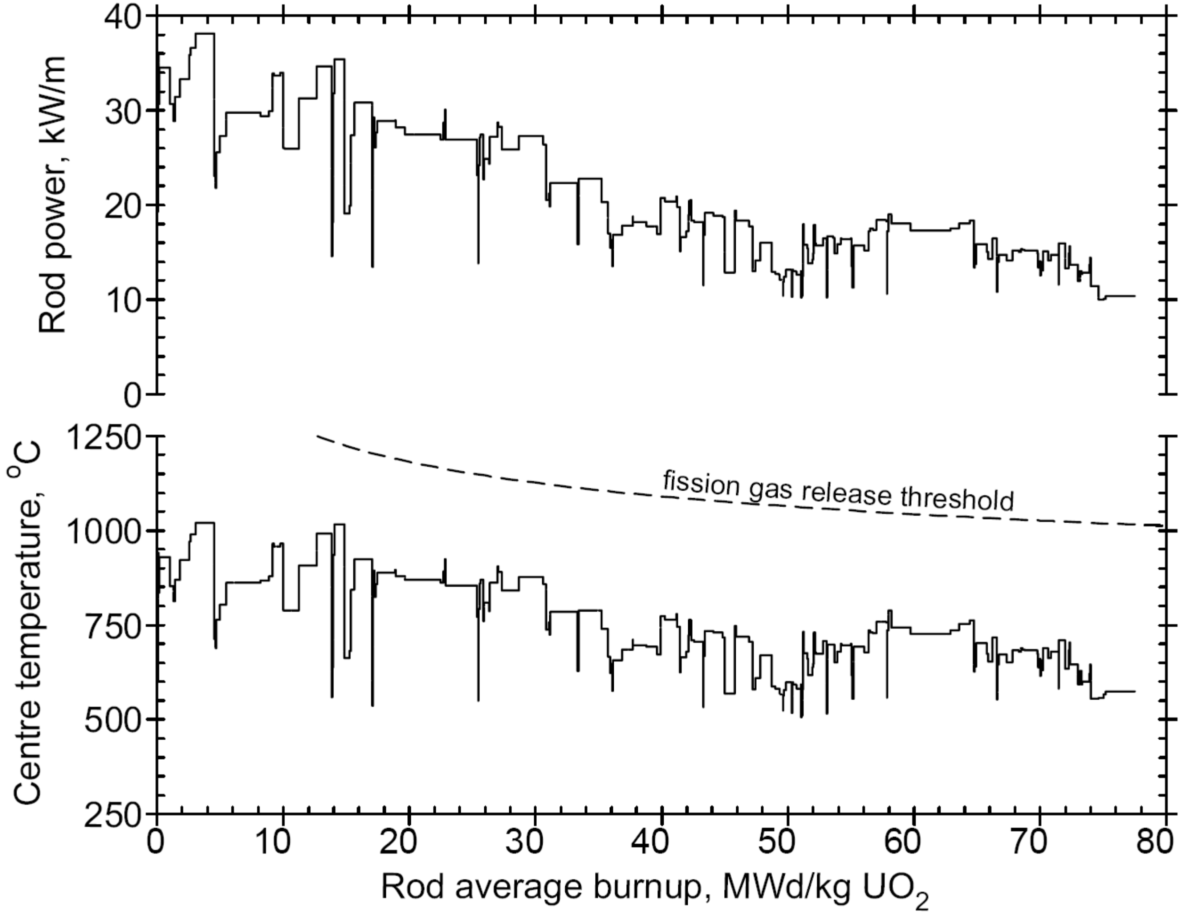
Fuel conductivity degradation

- Ultra-high burnup test -

- Four UO_2 fuel rods irradiated to 77 MWd/kgUO_2
- Instrumentation
  - expansion thermometer
  - rod pressure transducer
- Minimise gap conductance changes
  - Small fuel-clad gap (100 μm)
  - Temperature kept below fission gas release threshold
  - 10 bar helium to further minimise effect of fission gas release

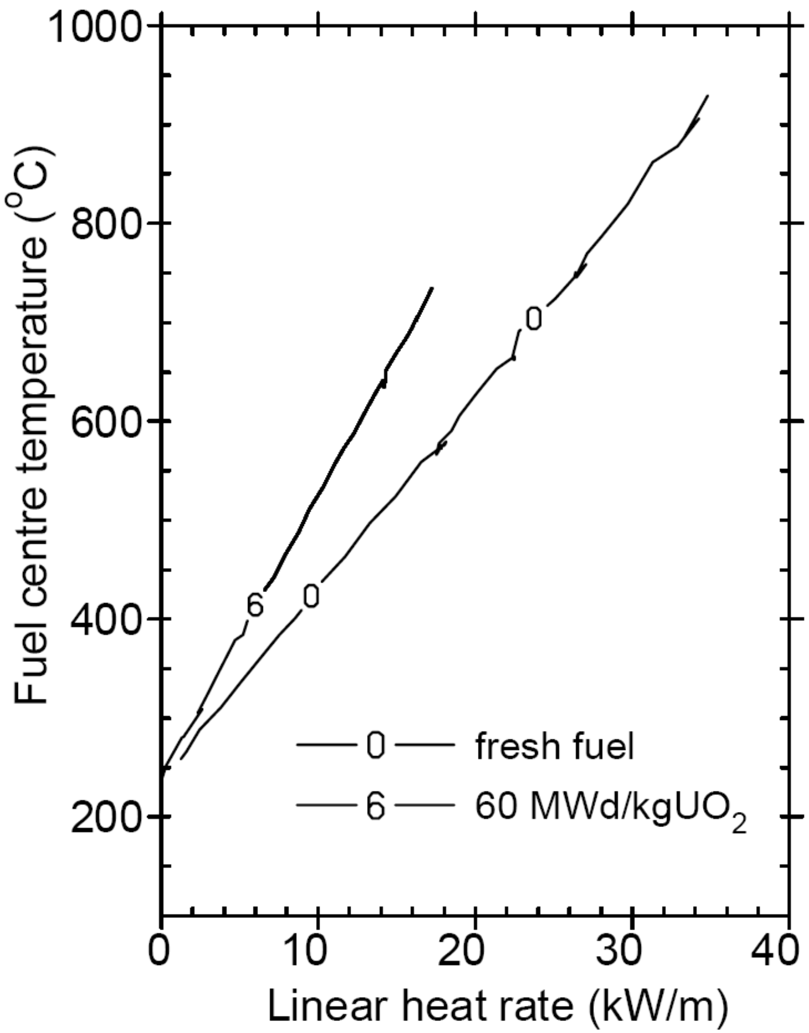
Raw data: power / temperature history

- Temperatures follow power changes
- Gradually decreasing temperature due to fuel depletion
- Temperatures stay well below the FGR threshold

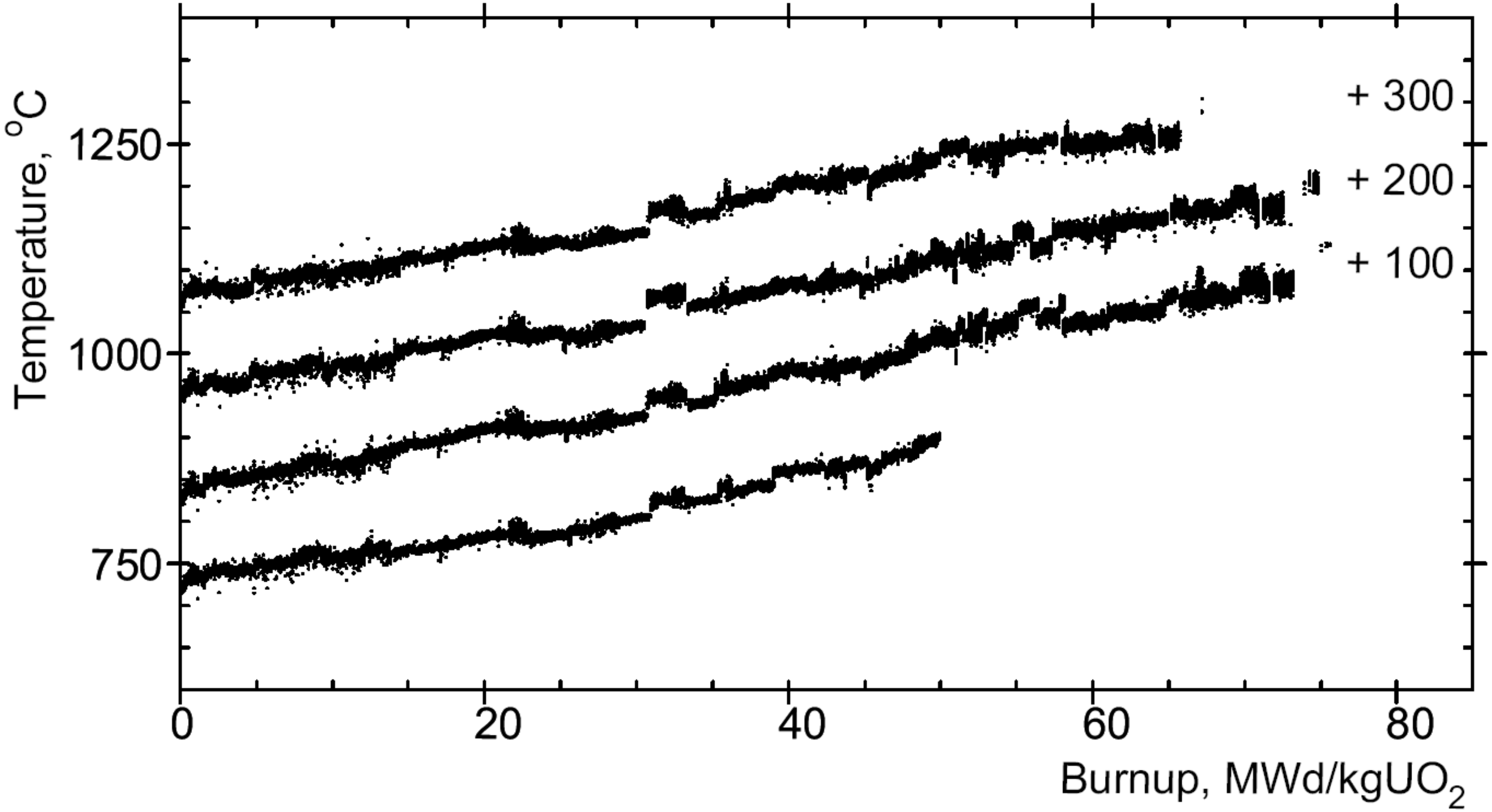


Temperature at 0 and high burnup

- Although gap conductance must have improved due to gap closure ...
- temperatures at 60 MWd/kg UO_2 and 17 kW/m are about 160 °C higher than at first start-up
- Linear temperature/power relationship is typical of fuel with He-filled gap

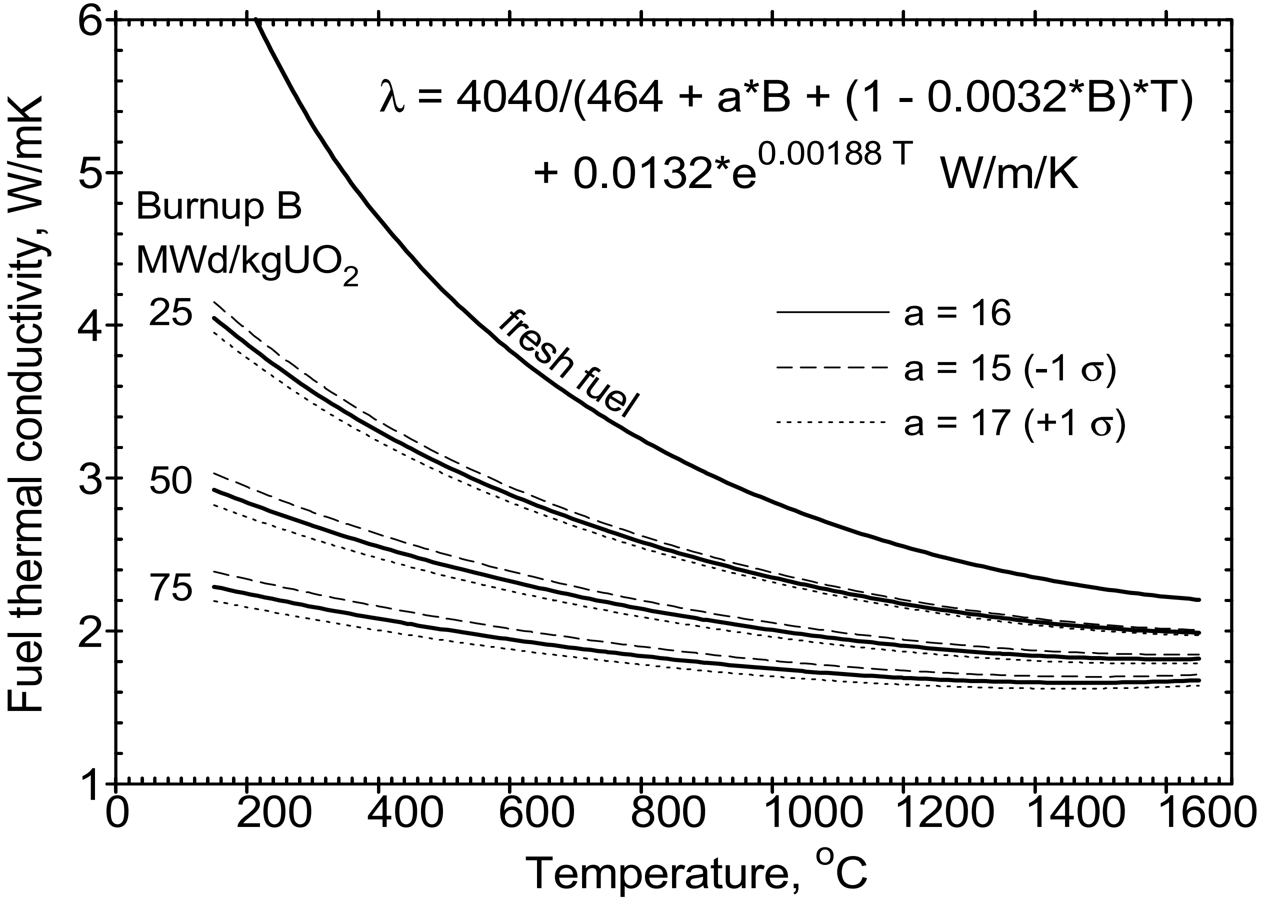


Normalising temperatures to constant power



At constant power, a clear trend becomes visible for all rods: temperatures increase approximately linearly with burnup

(temperature curves are offset by 100 K for clarity)

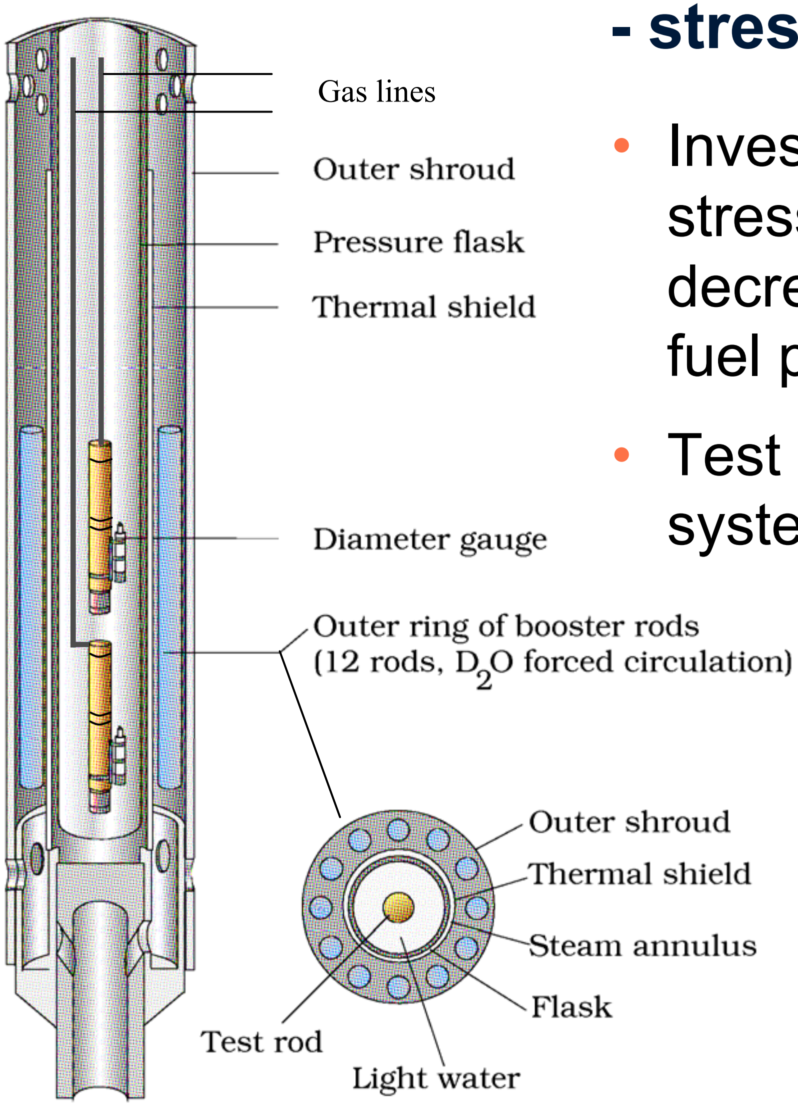


Change of UO_2 thermal conductivity derived from Halden reactor fuel temperature measurements

(see lecture on “fuel temperature” for more details)

Cladding creep

- stress reversal experiment -



- Investigate creep behaviour following stress reversals, increments and decrements, generating data for use by fuel performance code modellers
- Test rods connected to high pressure gas system to control applied hoop stress
  - PWR loop for system pressure and temperature
  - Booster fuel rods for fast flux
  - Contact scanning diameter gauge for monitoring change of rod outer diameter

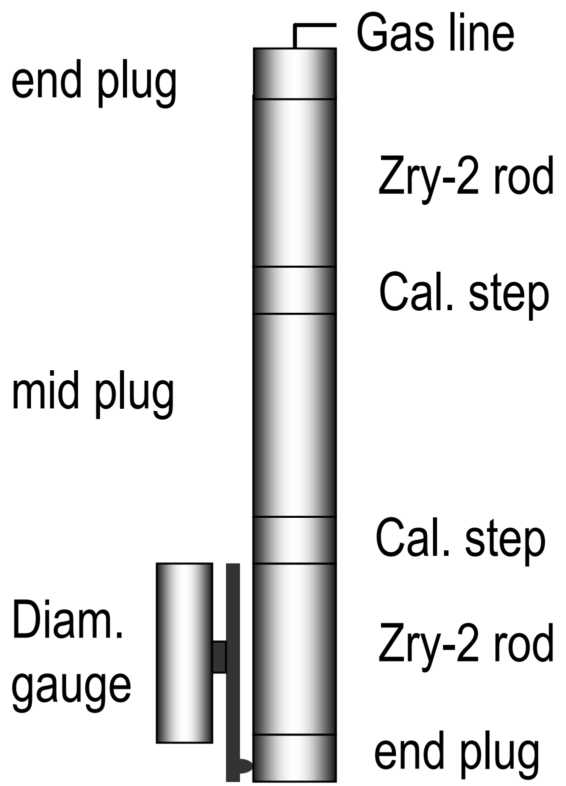
Background and Objectives

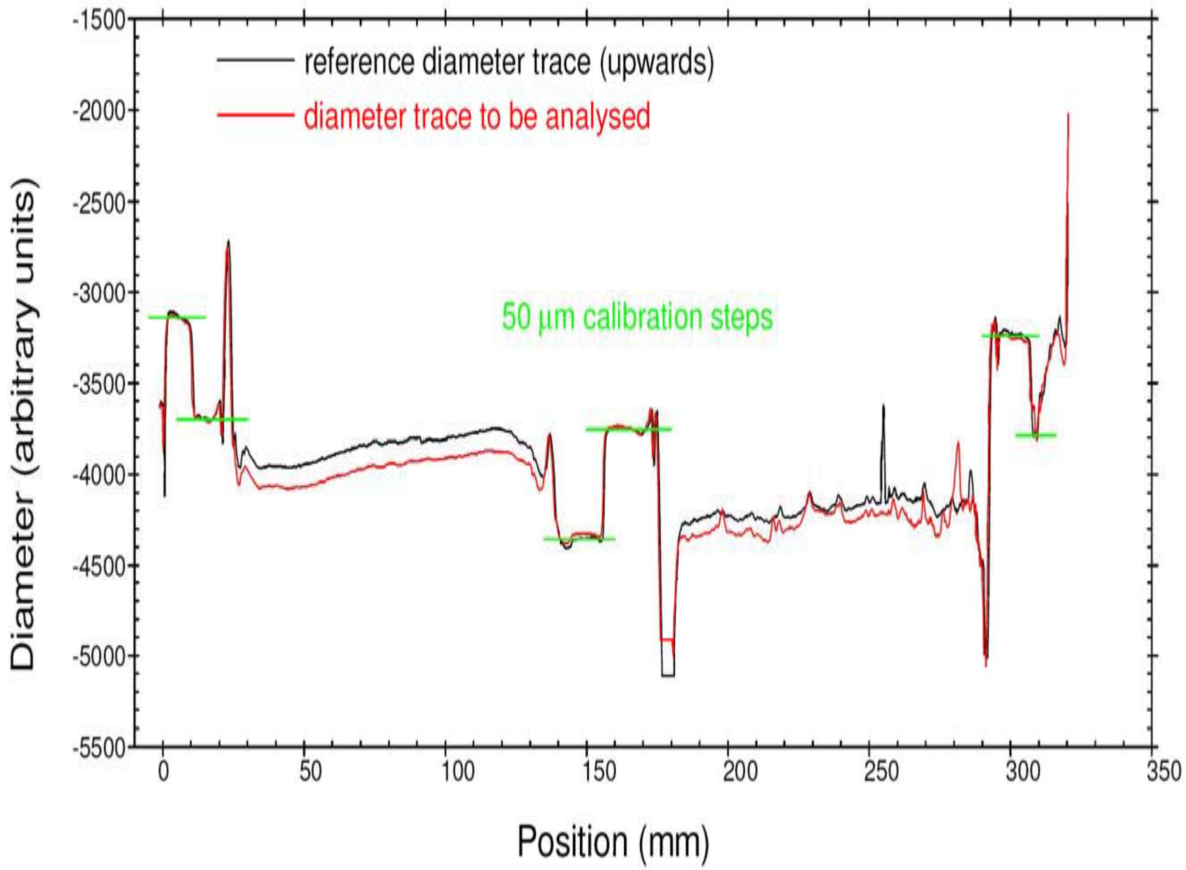
- Clad thermal and irradiation creep affects the fuel-clad gap
- Fuel-clad gap affects thermal performance of fuel
- In-pile creep data needed to validate clad creep models in fuel performance codes for modern fuel clad materials under variable loading conditions
- Addressed in several creep studies in the Halden reactor using different cladding alloys exposed to BWR and PWR conditions
- (How) does primary creep recur after stress change?

Measurements

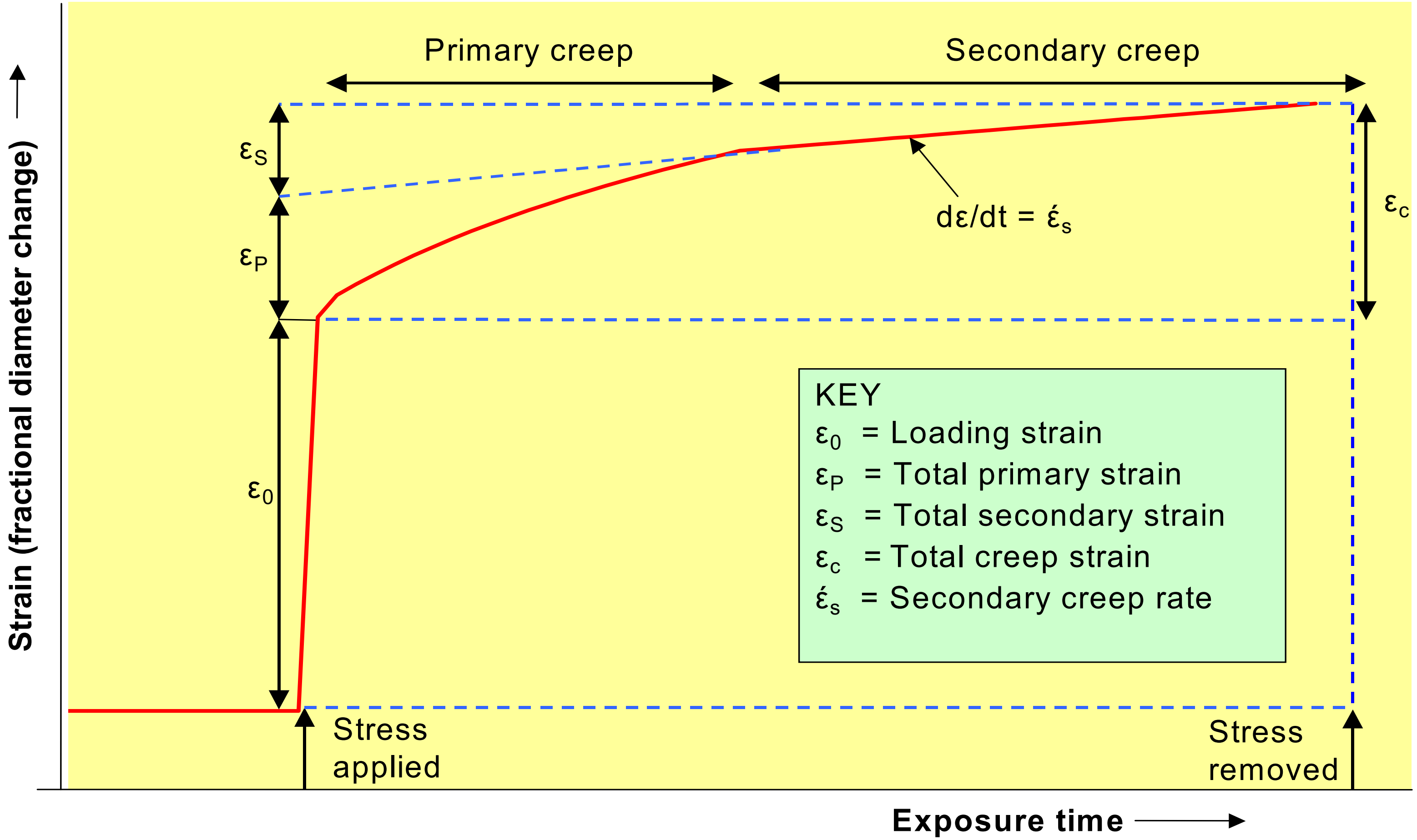
The diameter gauge is repeatedly run up and down the rod string

Diameter traces are aligned at the calibration steps and compared to the reference trace taken at the beginning of a stress period

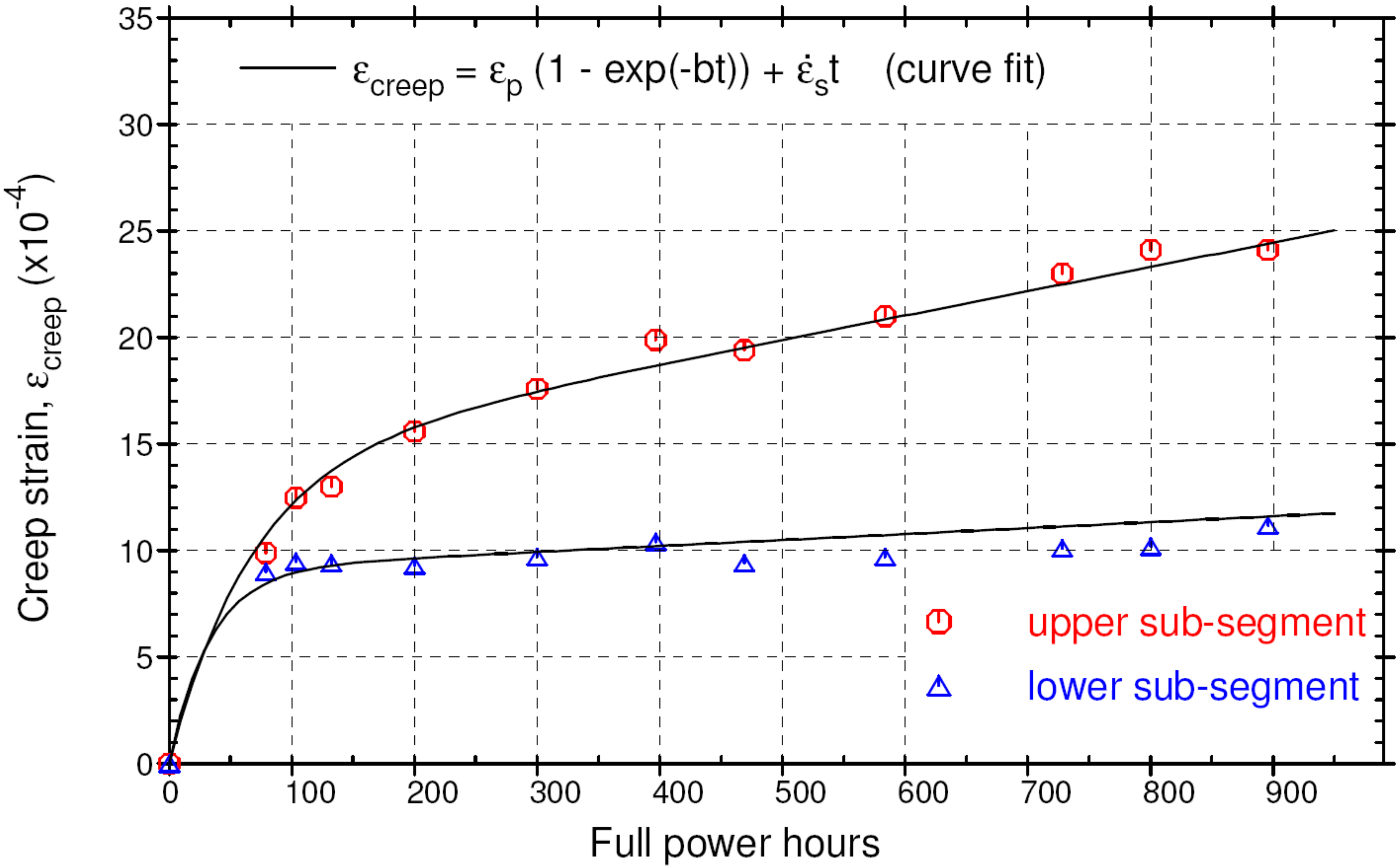




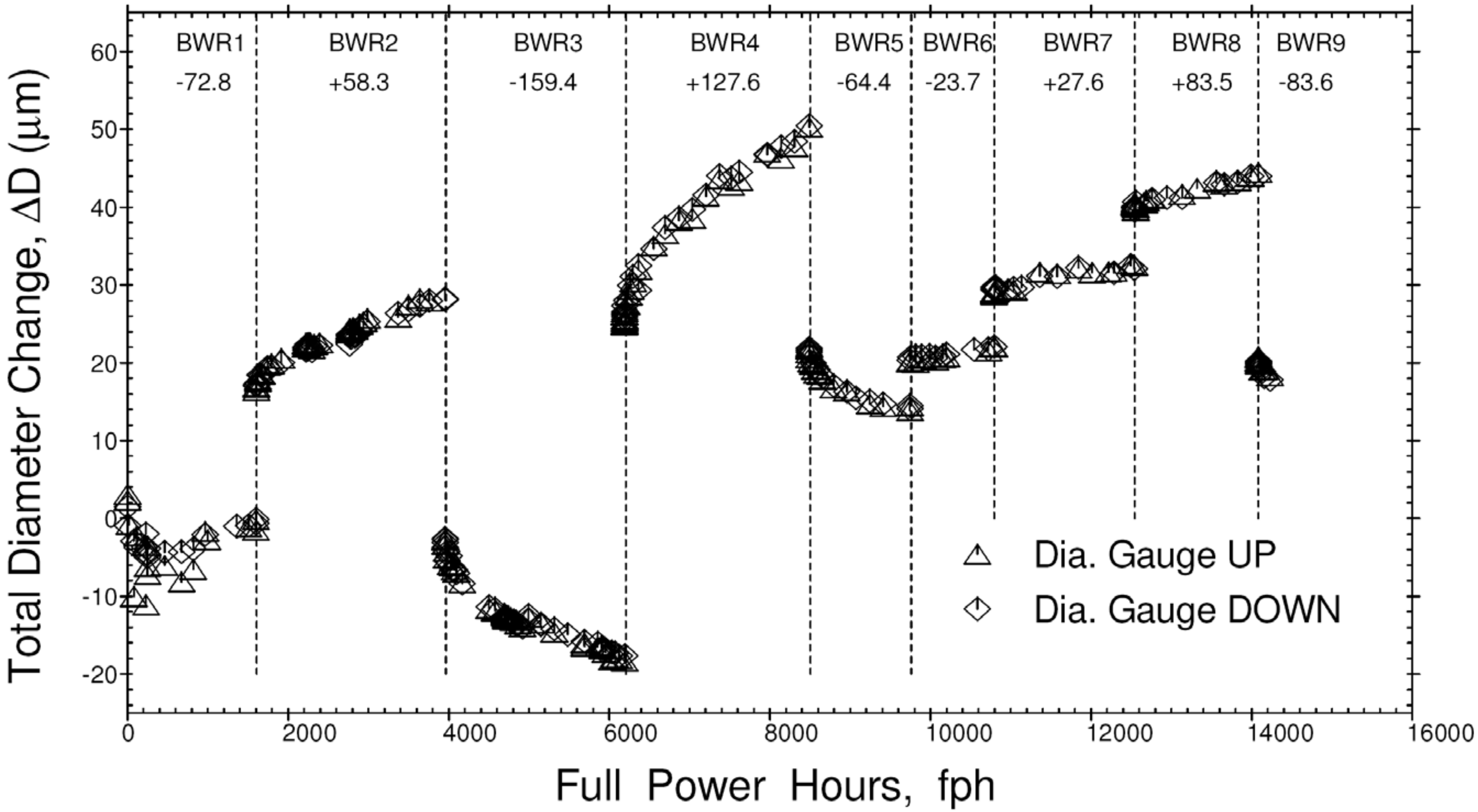
Goal: for a given material determine
- primary creep increment
- secondary creep rate



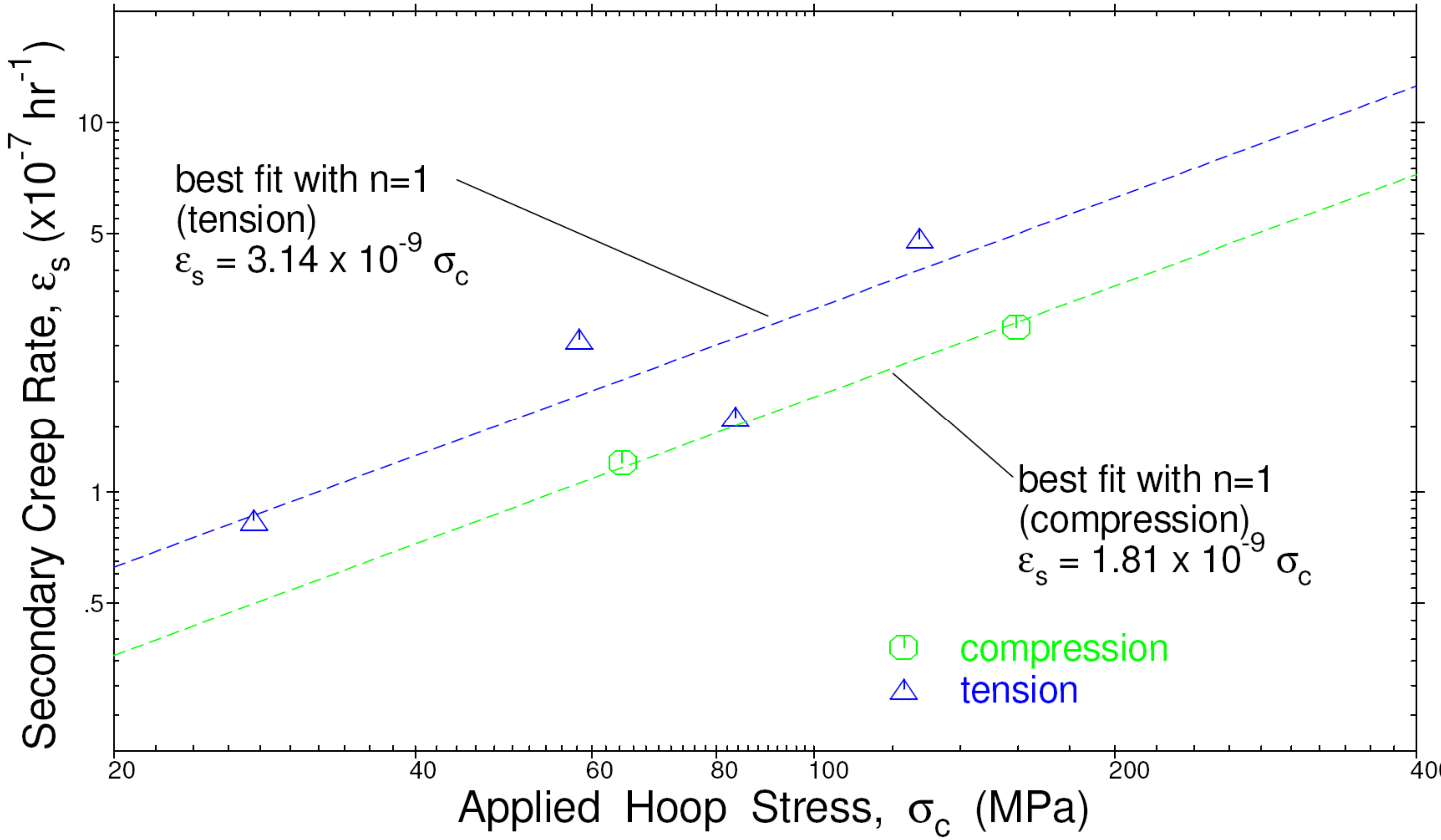
Measurements evaluated for a stress period

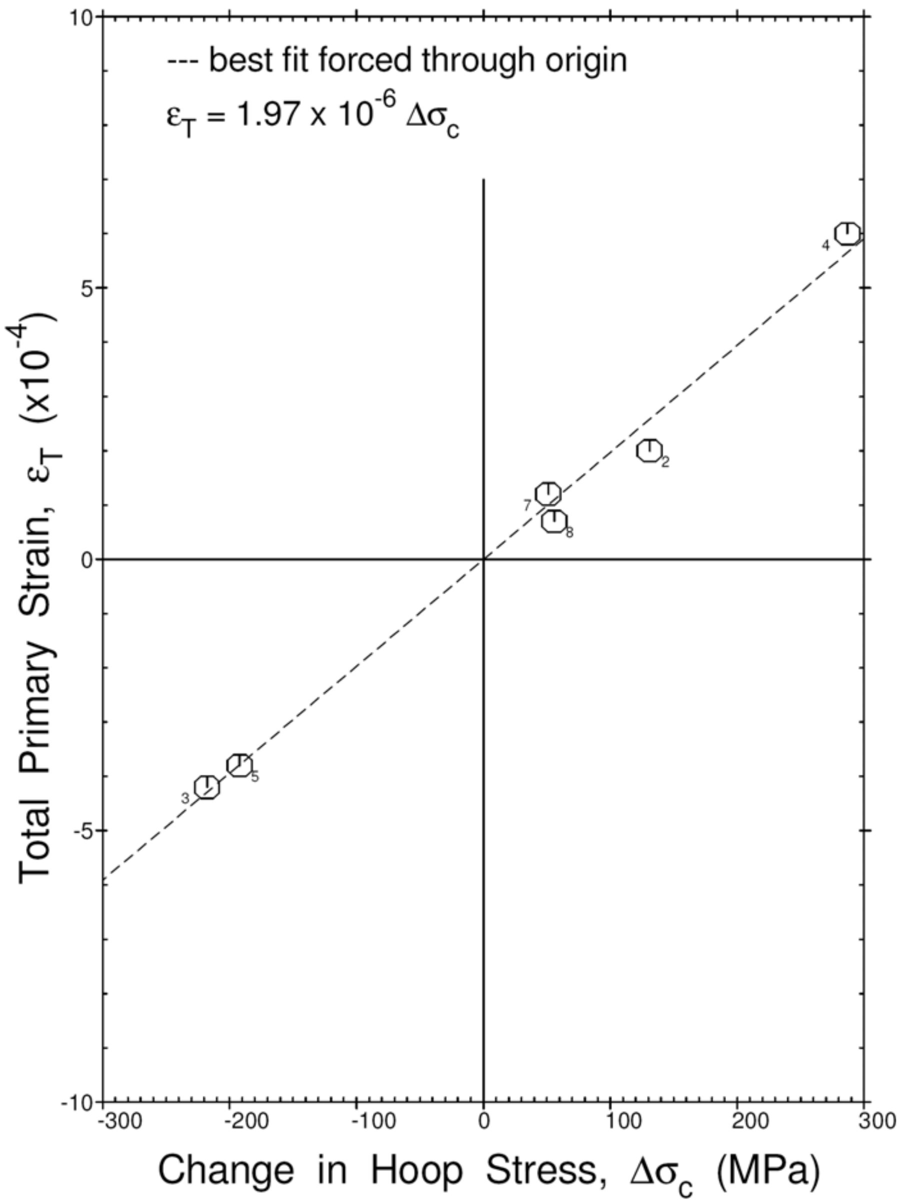


Entire set of measurements



Secondary creep rate depends on stress level and is greater in tension than compression





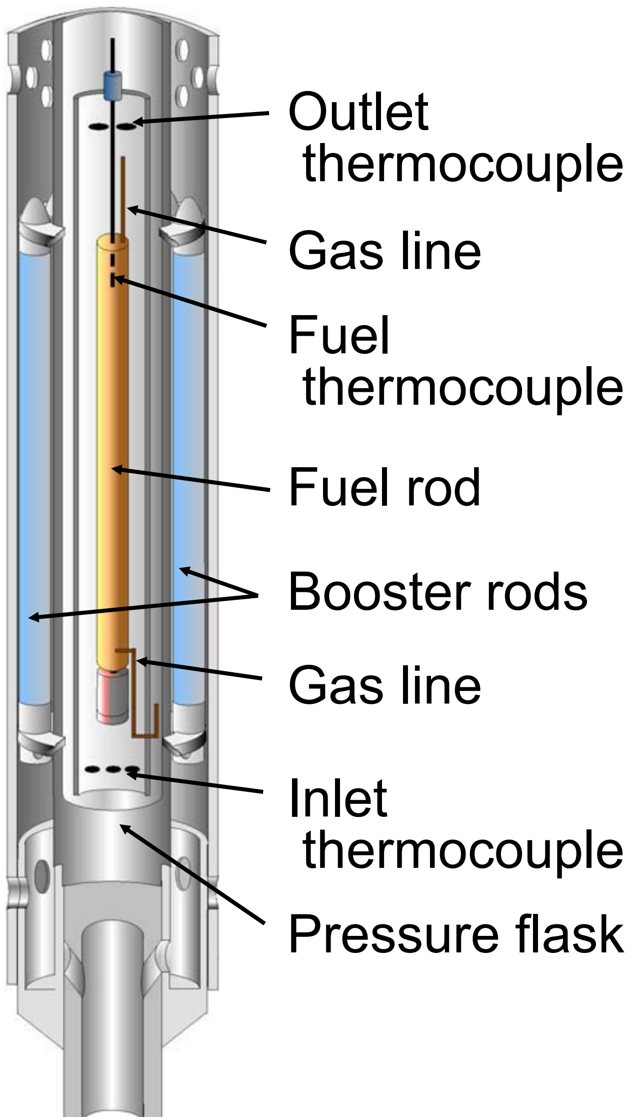
Primary creep

- Recurs with every stress change
- Depends on amount of stress change
- No difference in absolute value between tension and compression

Rod overpressure – clad lift-off

- Excessive fission gas release and the reduction of the free rod volume due to fuel swelling can cause the rod pressure to rise beyond system pressure. The consequences are investigated in a Halden Project experimental series to:
  - establish the overpressure leading to onset of increasing fuel temperature
  - investigate the temperature response at different overpressure levels
  - assess different combinations of fuel and cladding
- High burnup instrumented fuel segments are used for these investigations

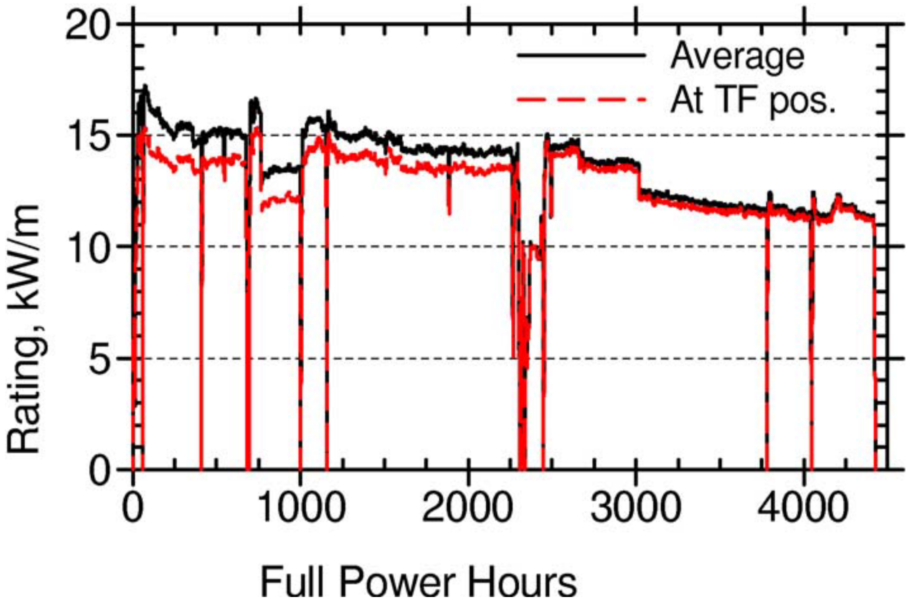
HBWR irradiation rig

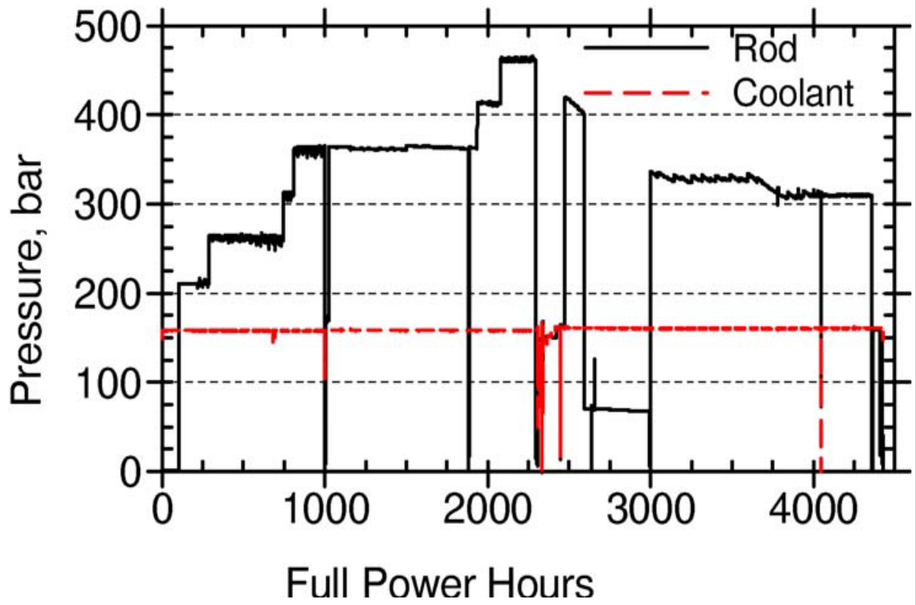


Measurement Possibilities

- Fuel centreline temperature and its change as primary clad lift-off indicator
- Temperature response to fill gas change (argon versus helium) during operation
- Fission gas release by means of gamma-spectroscopy
- PCMI and fuel swelling by means of clad elongation measurements
- Hydraulic diameter
- Coherence between fast response neutron detector (power) and clad elongation

Power and pressure history





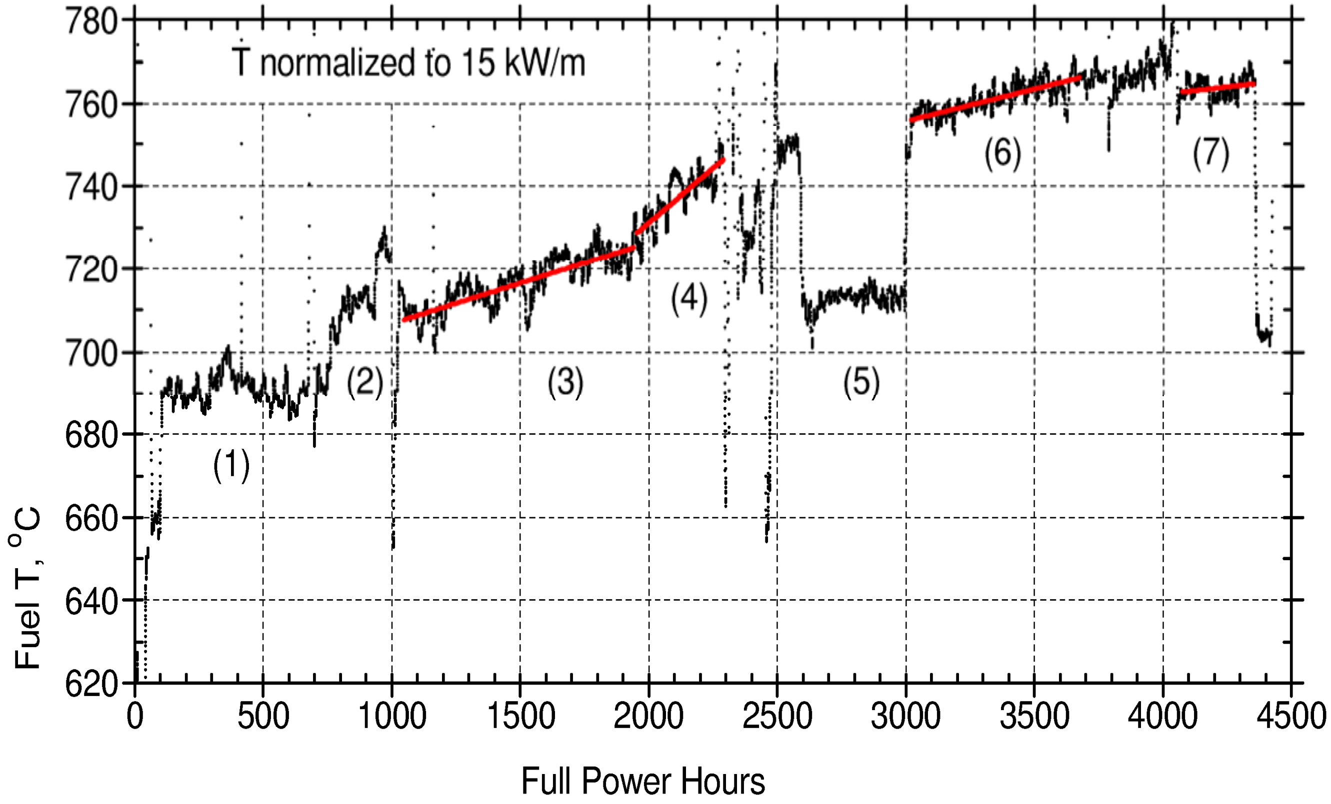
Rod power

- 1st cycle 15 kW/m average
- 2nd cycle 12 kW/m average

Rod pressure

- Increased in steps of ca. 50 bar
- maximum 470 bar

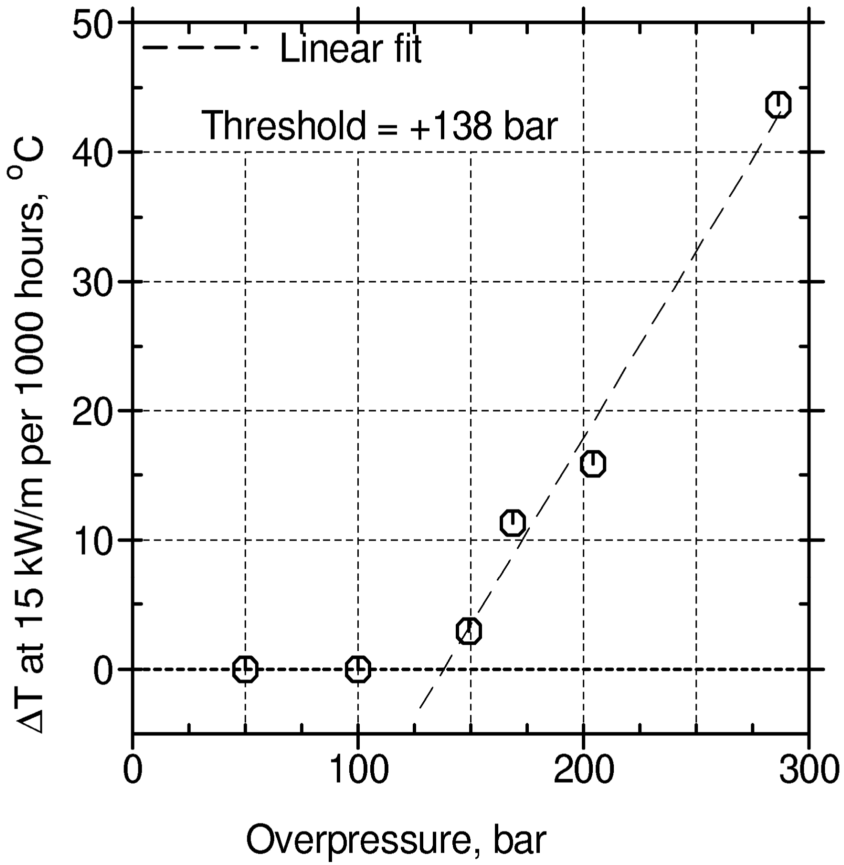
Response to fuel rod overpressure



Normalised fuel temperature

- Shows clear response to level of overpressure and
- direct effect of pressure step

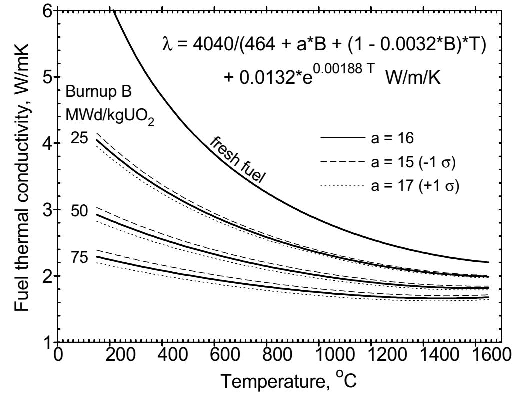
Summary of measurements



- The rate of temperature increase is correlated with the overpressure
- The onset of thermal feedback occurs at about 138 bar overpressure
- This represents the lift-off threshold for the particular combination of fuel and cladding utilised in the test
- Below this threshold, any clad creep-out is sufficiently compensated, e.g. by fuel swelling, such that no net thermal feedback becomes apparent

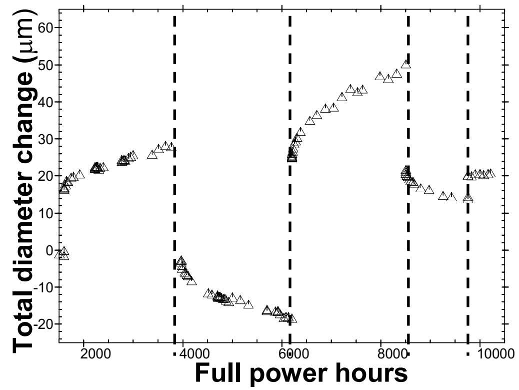
Data evaluation (I)

- Influence of conductivity degradation corrected according to Halden model
  $\Delta T_{degrad} = 14\ K$

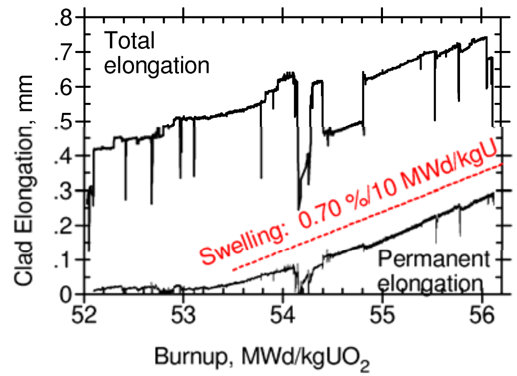


- Cladding creep based on evaluation of clad creep test and Franklin's model

$$\Delta D_{creep} = 0.177 \times t^{0.33} \times \sigma_{\Theta}^{0.579} = 40\,\mu m$$

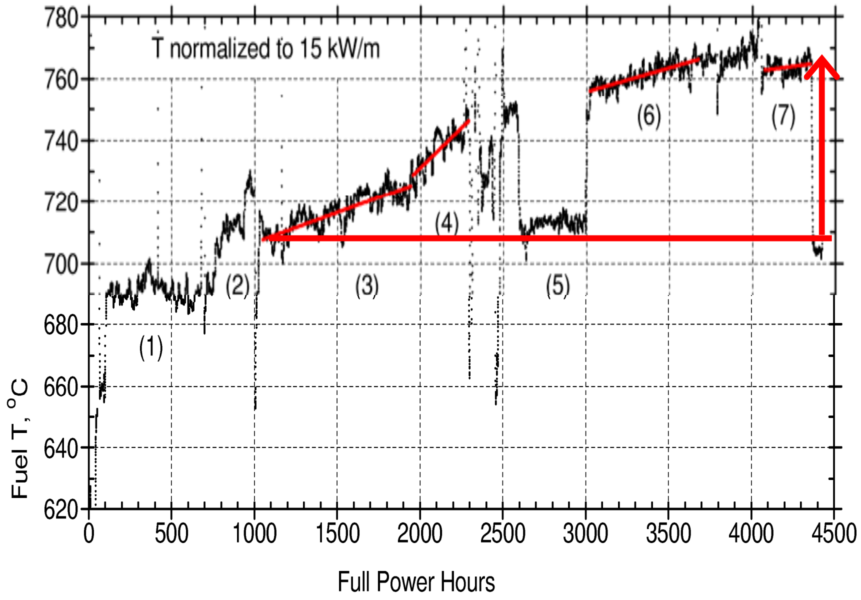


- Fuel swelling according to measurements in lift-off experiment
  $\Delta D_{swell} = 9\ \mu m$



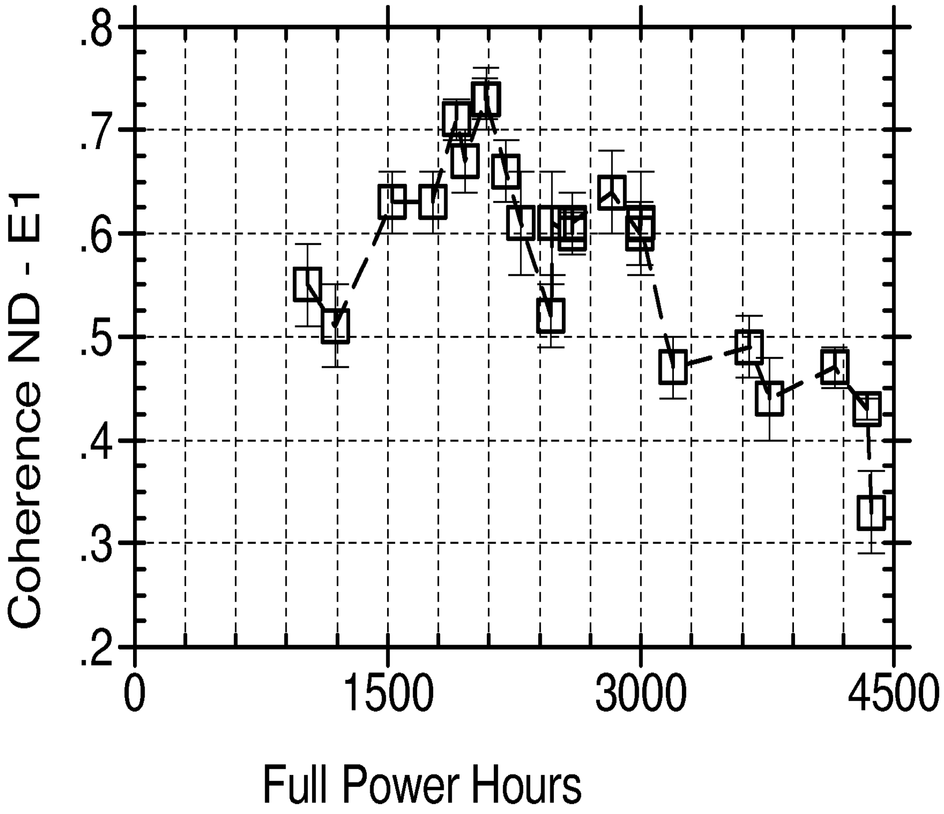
Data evaluation (II)

- About 60K of the observed temperature increase can be attributed to the combined effect of increasing space in the fuel and thermal conductivity degradation (14K)
- The Halden Project's thermal analysis code calculates a 60K temperature increase when the gap size is increased by 28µm



- This is close to the evaluated effective increase of 31 µm which is the difference between clad creep-out and fuel swelling
- The analysis confirms that the observed temperature change is reasonable
- The model for cladding creep plays a critical role in the analysis
- Different cladding types will exhibit individual sensitivities to lift-off

Noise data - PCMI



Coherence between rod power and cladding elongation

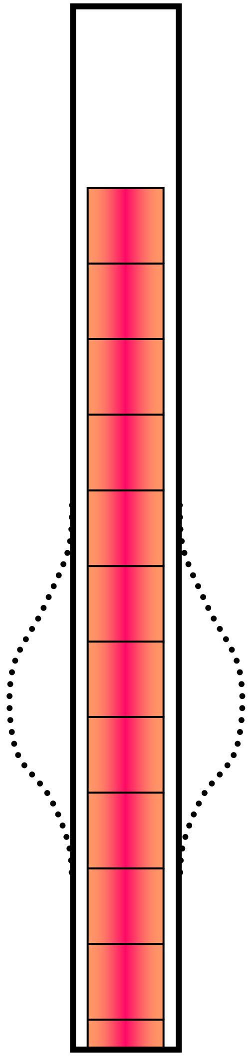
- The coherence between power (fast response neutron detector) and clad elongation increases slightly until the maximum overpressure is applied
- Then, it drops gradually until the end of irradiation
- Significance of coherence value:
  - <0.05 → PCMI free
  - >0.20 → PCMI developed
- Noise analysis supports the conclu-sion derived from steady state data that considerable fuel-clad contact is maintained also in the state of lift-off

Modelling of clad lift-off

- Modelling must take into account and calculate:
  - Instantaneous cladding distension (elastic, primarily in experiment)
  - Primary and secondary creep of the cladding (response to both pressure steps and gradual pressure increase)
  - Fuel swelling
  - Relocation/redistribution of fuel fragments into available space as cladding creeps outwards
  - Resulting temperature response
  - Fission gas release
- Different types of measurement indicate that pellets and cladding keep contact and that the pellet fragments follow clad creep-out by swelling and relocation
- A fuel model where (solid) pellet and cladding are separated by a gap will have problems to explain all of the observations in a satisfactory way

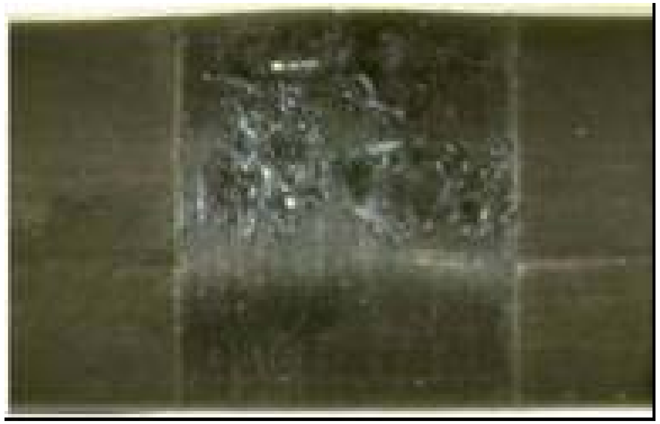
Hydraulic diameter & LOCA

- In a Loss-of-Coolant Accident (LOCA), the fuel rod balloons (and ruptures) for T > 750-800 °C
- The ballooning process is driven by the supply of gas from the fuel rod plenum
- However, the fuel column is a restriction between plenum and balloon and impedes axial gas transport
- The effect of restricted axial gas transport was investigated in the ’70s using fresh or low burnup fuel
- It was found that gas supply is still sufficient under the investigated conditions
- But what about high burnup, bonded fuel?



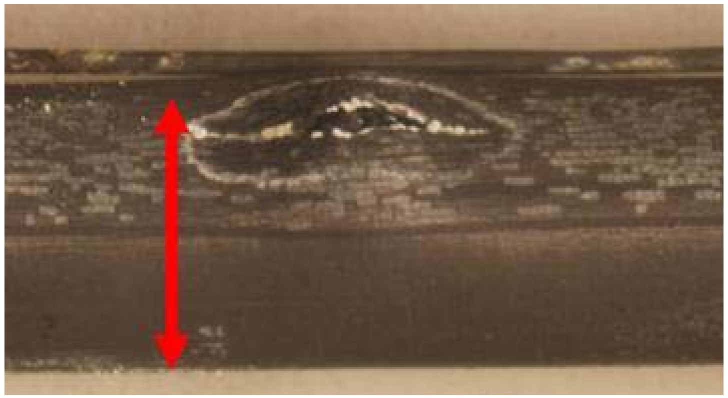
Three LOCA tests with high burnup fuel
- observations – visual inspection -

3. High burnup fuel (82 MWd/kg), clad failure by a small crack; relatively fast pressure drop

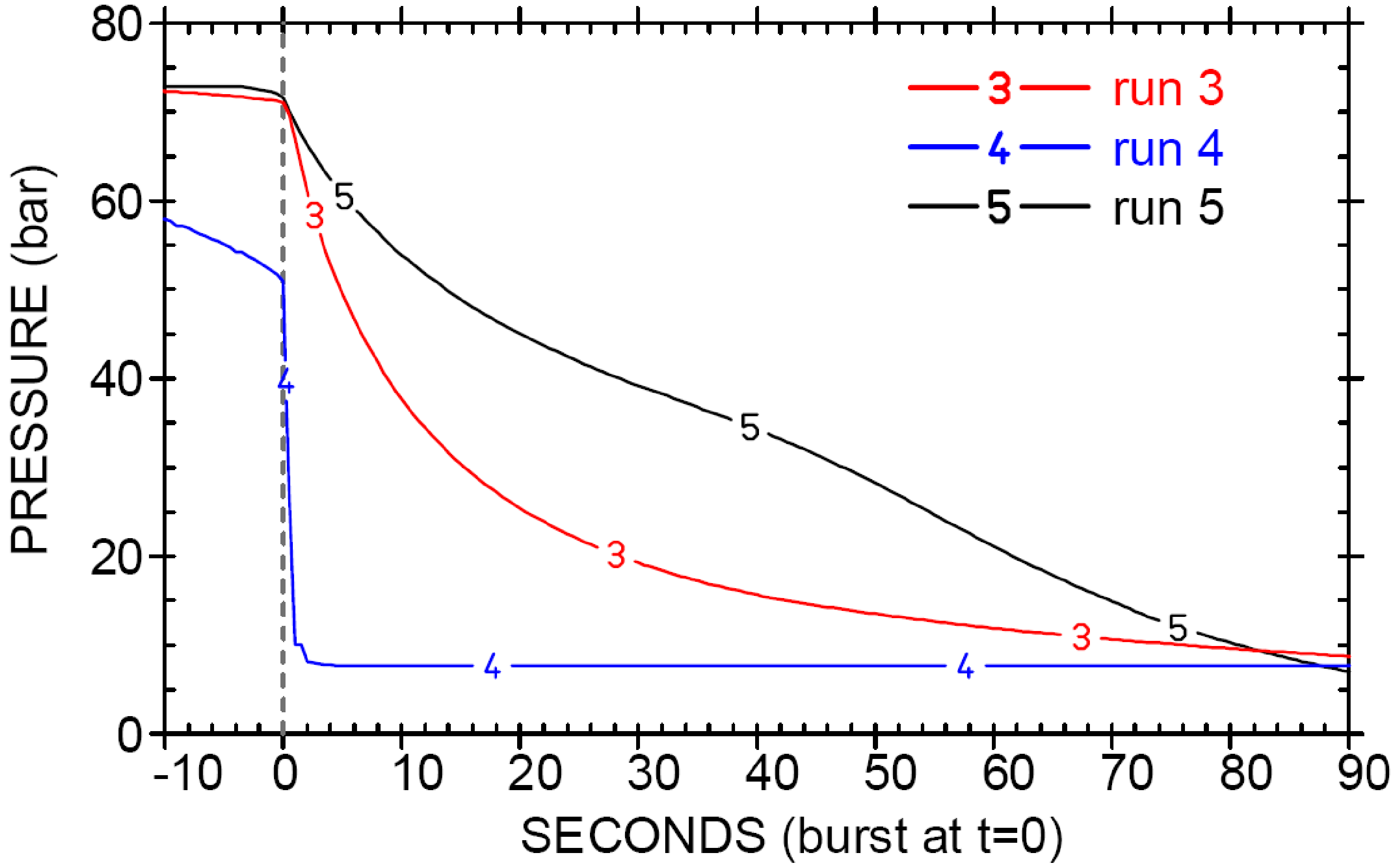


4. High burnup fuel (92 MWd/kg), ballooning, rupture and instantaneous loss of pressure

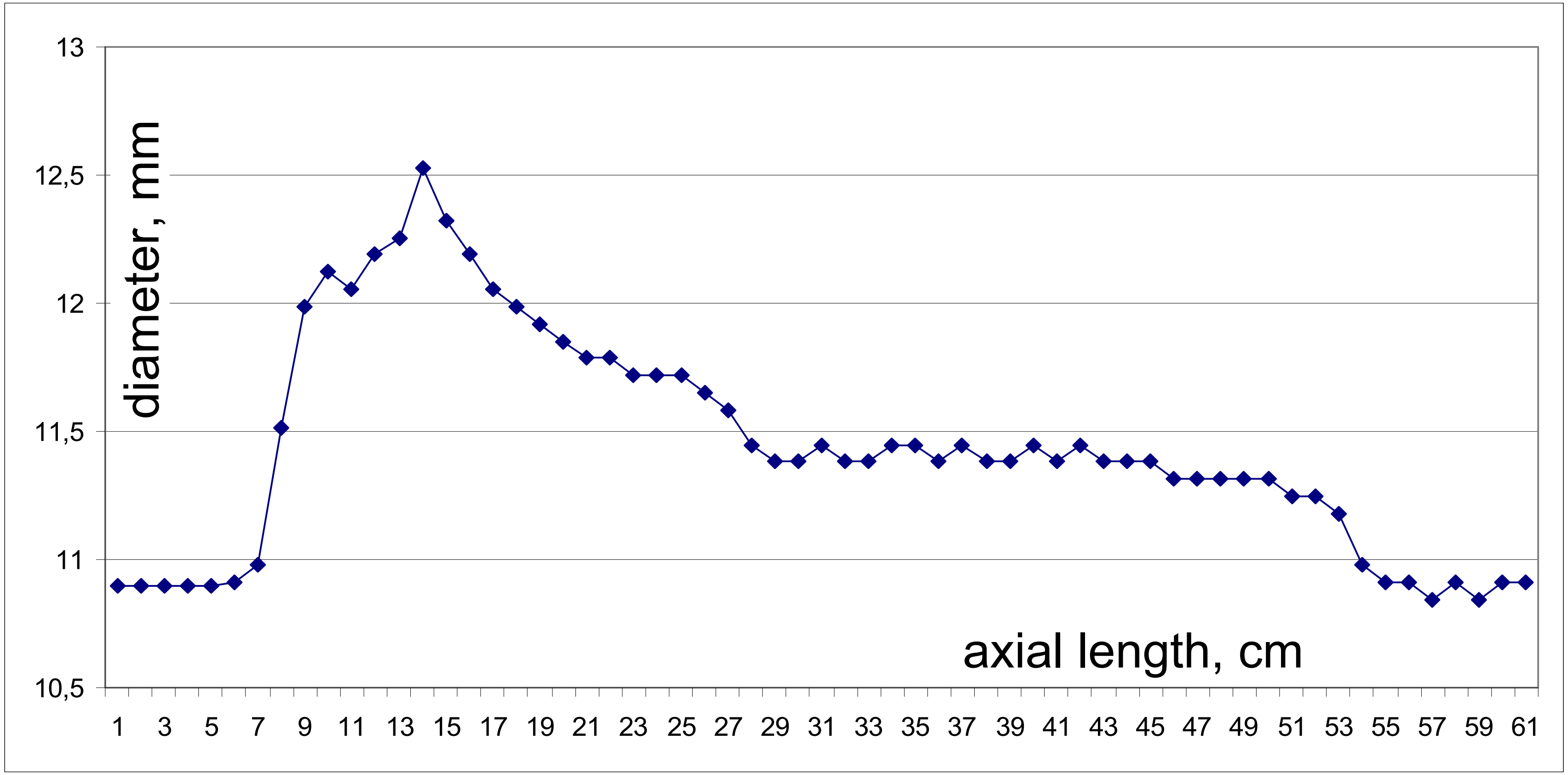
5. High burnup fuel (83 MWd/kg), small ballooning, rupture and very slow loss of pressure



Pressure drop measurements



Test #5 - cladding distension

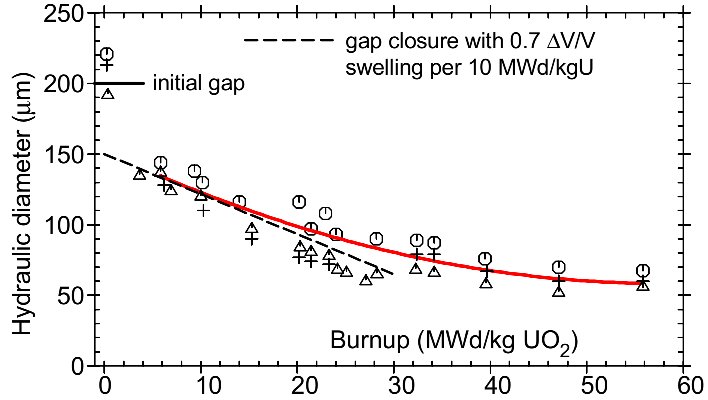


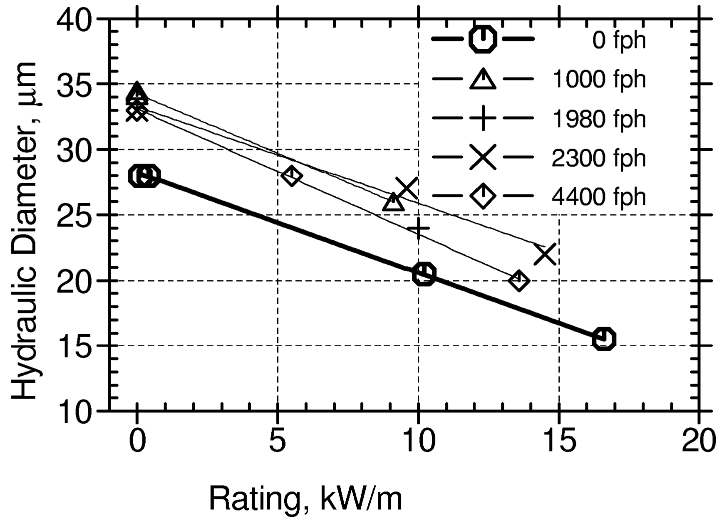
Strong contact at the upper half of the fuel segment impeded axial gas flow in test 5

Hydraulic diameter measurements

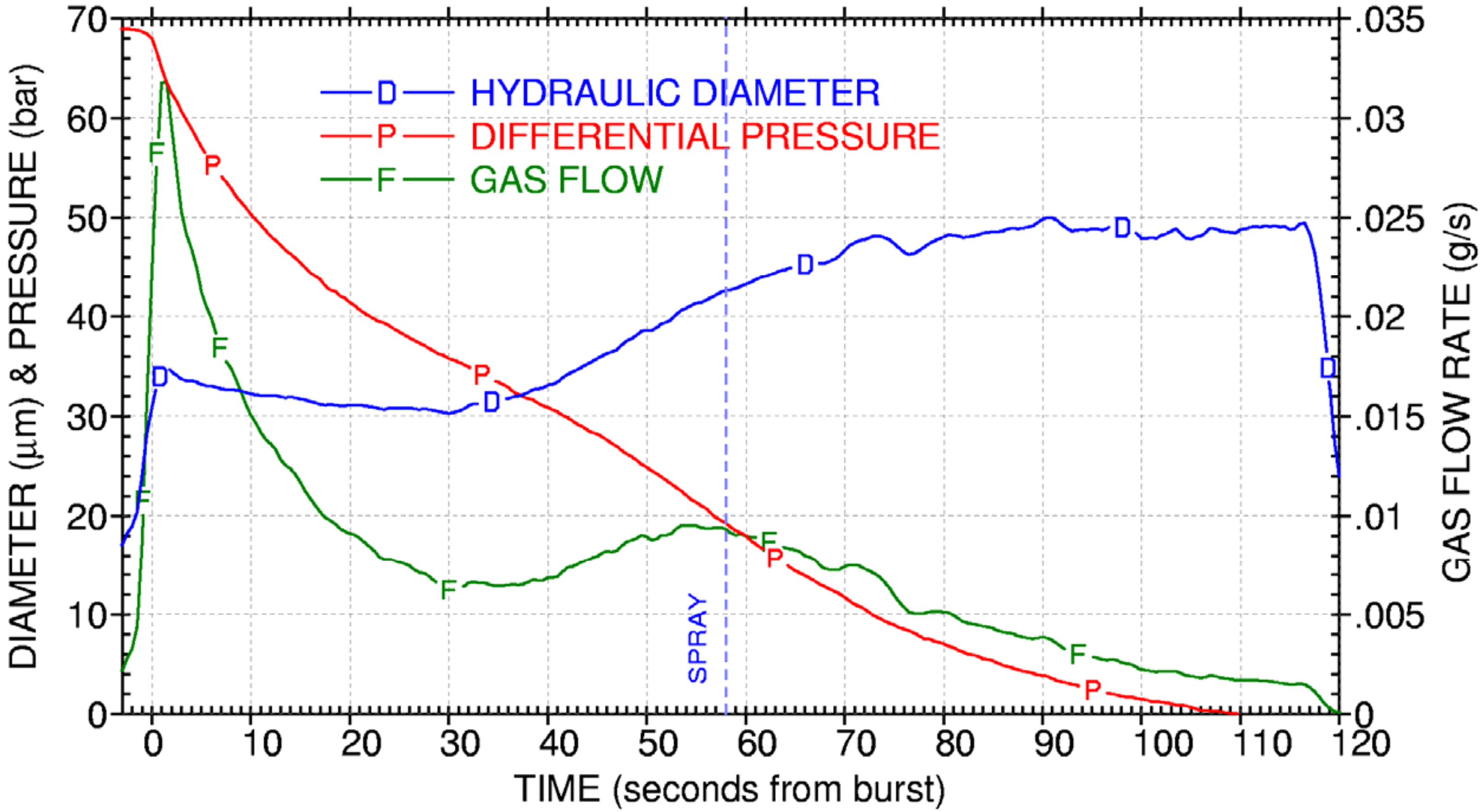
$$D_H = \sqrt[4]{\frac{0.021 \cdot \eta \cdot L \cdot R \cdot T \cdot \dot{n}}{\pi \cdot D \cdot \left(p_1^2 - p_2^2\right)}}$$

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





Application to LOCA experiment #5



Considerations for LOCA calculations

The “plug” of fuel at the upper end of the test segment limits the availability of high pressure gas for driving the ballooning. A full length fuel rod will exhibit a similar behaviour since there will be an axial temperature gradient because of the pre-transient power distribution and the heat losses from the core periphery. Two implications should be considered:

- *The ability to supply sufficient gas for driving the ballooning.* Starting with pressure equilibrium between plenum and fuel stack, a pressure difference for driving the gas flow will occur due to increasing volume. This difference is initially much smaller than the strong difference immediately after failure. Thus gas flow will also be small.
- *The driving force for axial fuel relocation is more limited* when it is mainly derived from the flow of locally available gas.

The equations for gas flow and hydraulic diameter provide a simple way to approximate the effect in LOCA code calculations.

The END