Investigation of the Impact of In-Reactor Short-Term Dry-Out Incidents on Fresh and Pre-Irradiated Fuel Cladding

by

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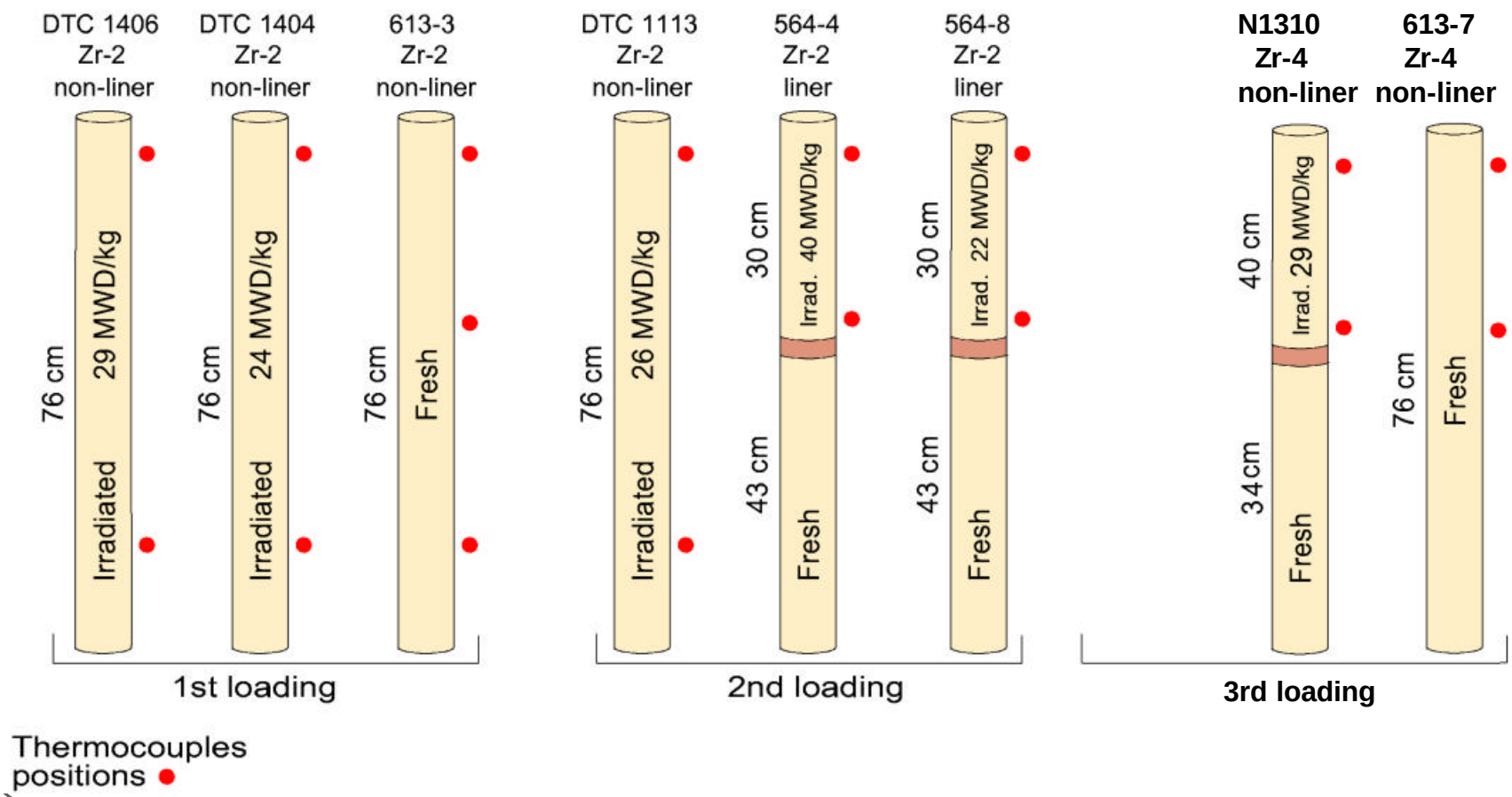
Outline

- Background
- In-Pile Testing
  - Rig and test rods
  - Dry-out simulation
- PIE Results
  - Visual inspection and profilometry
  - Mechanical testing and fractography
  - Microstructural investigation
- Summary and Conclusions

Background

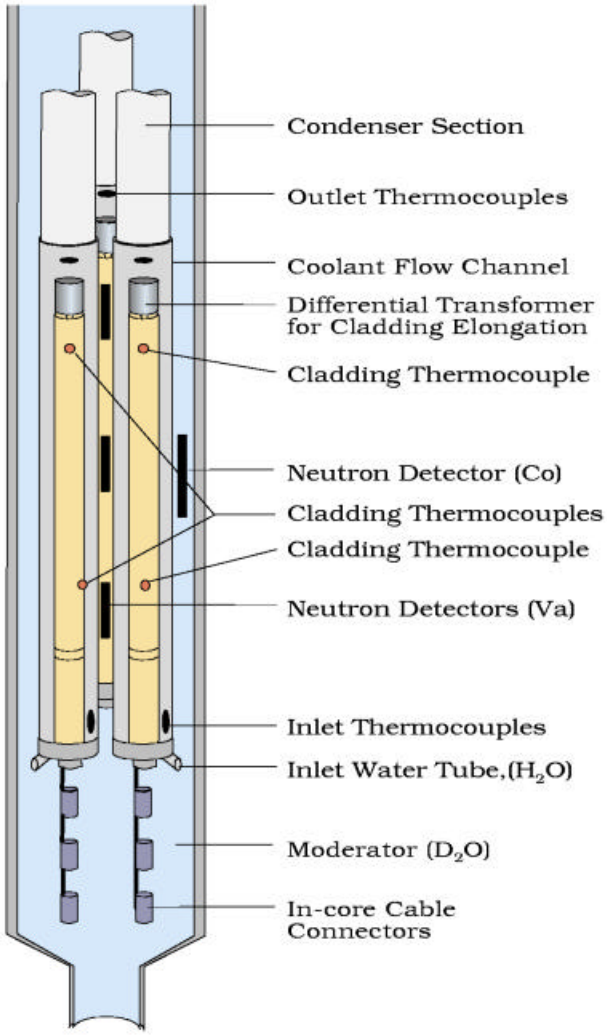
- BWR thermal-hydraulic transients result in short-term dry-out: clad temp ➔ 550-750°C
- Safety requirement: fuel integrity maintained post dry-out and quench until shutdown
- Halden Joint Programme dry-out fuel behaviour test series, IFA-613, initiated to assess consequences of short-term dry-out
  - By in-pile simulation of a pump trip
  - By PIE investigation of physical, mechanical and microstructural changes to cladding

Test Fuel Segments

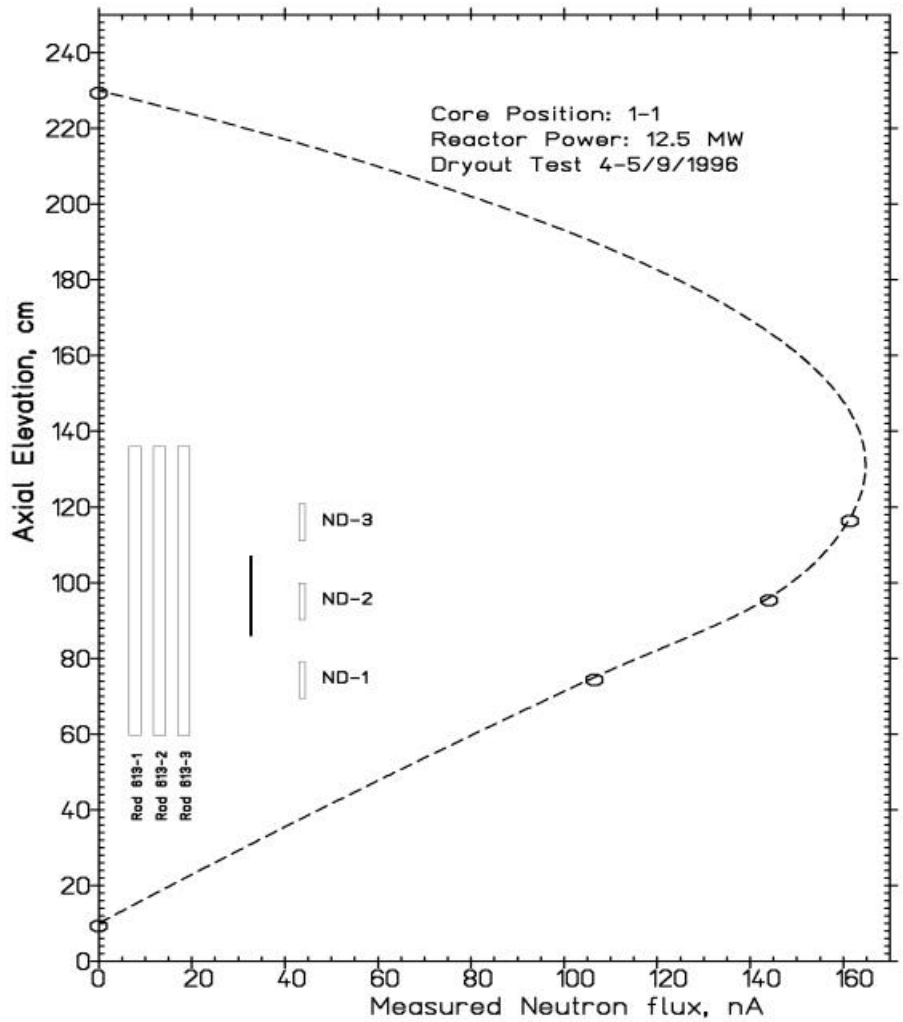


Thermocouples positions ●

Test Assembly IFA-613



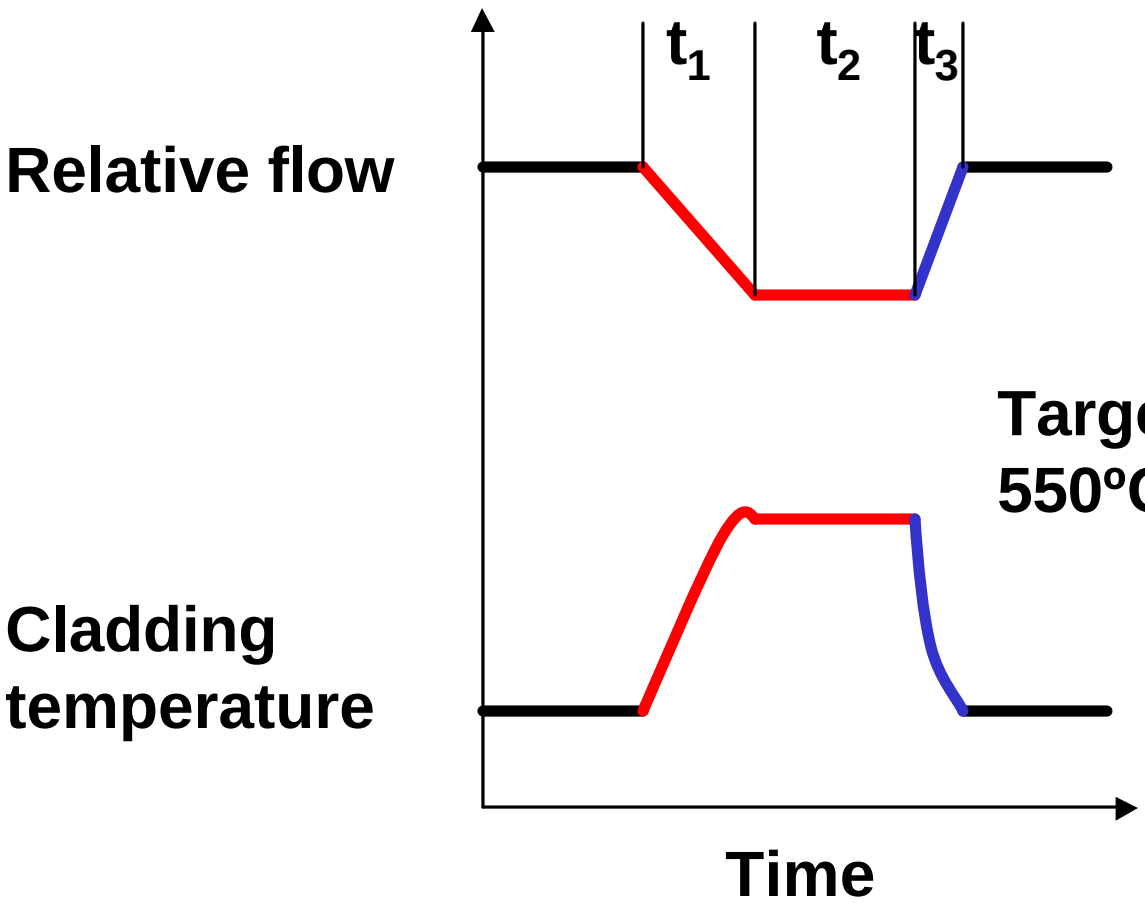
3 individually controlled flow channels
each containing one instrumented fuel rod



Typical Axial Power Profile

Thermal flux peaks towards top of the fuel rods

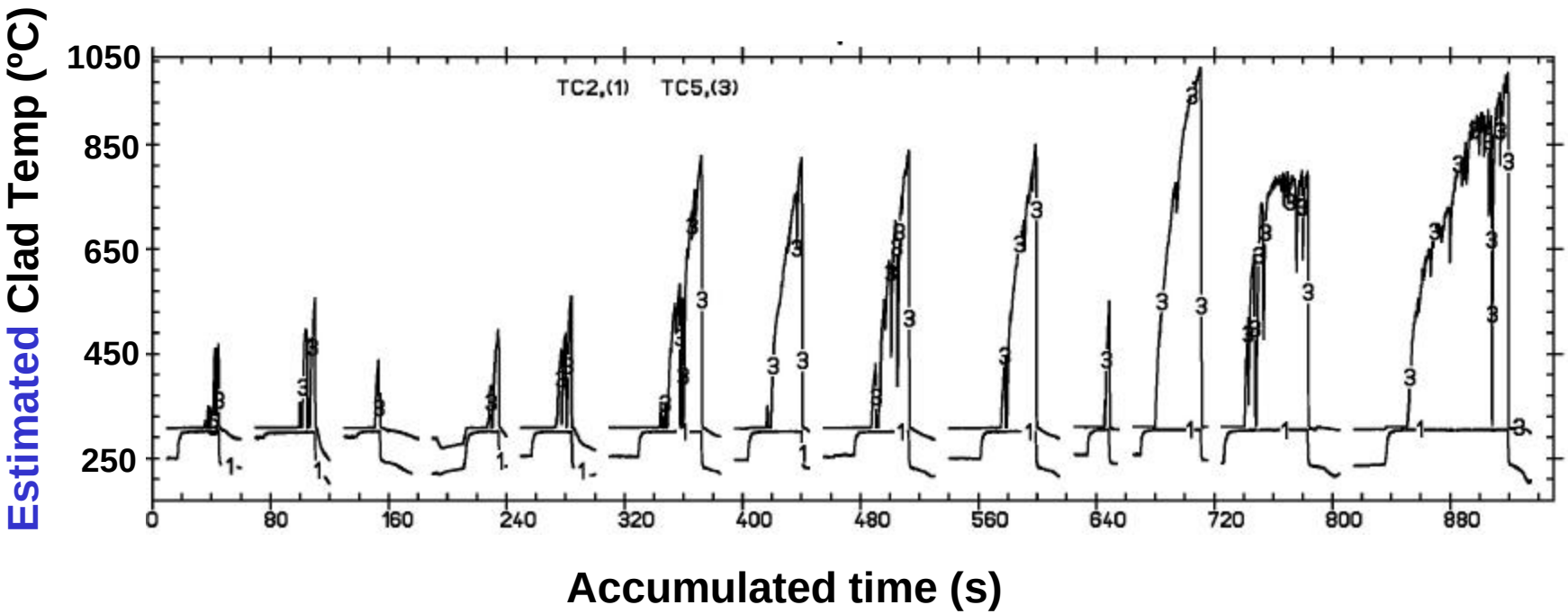
Target In-Pile Dry-Out Transient



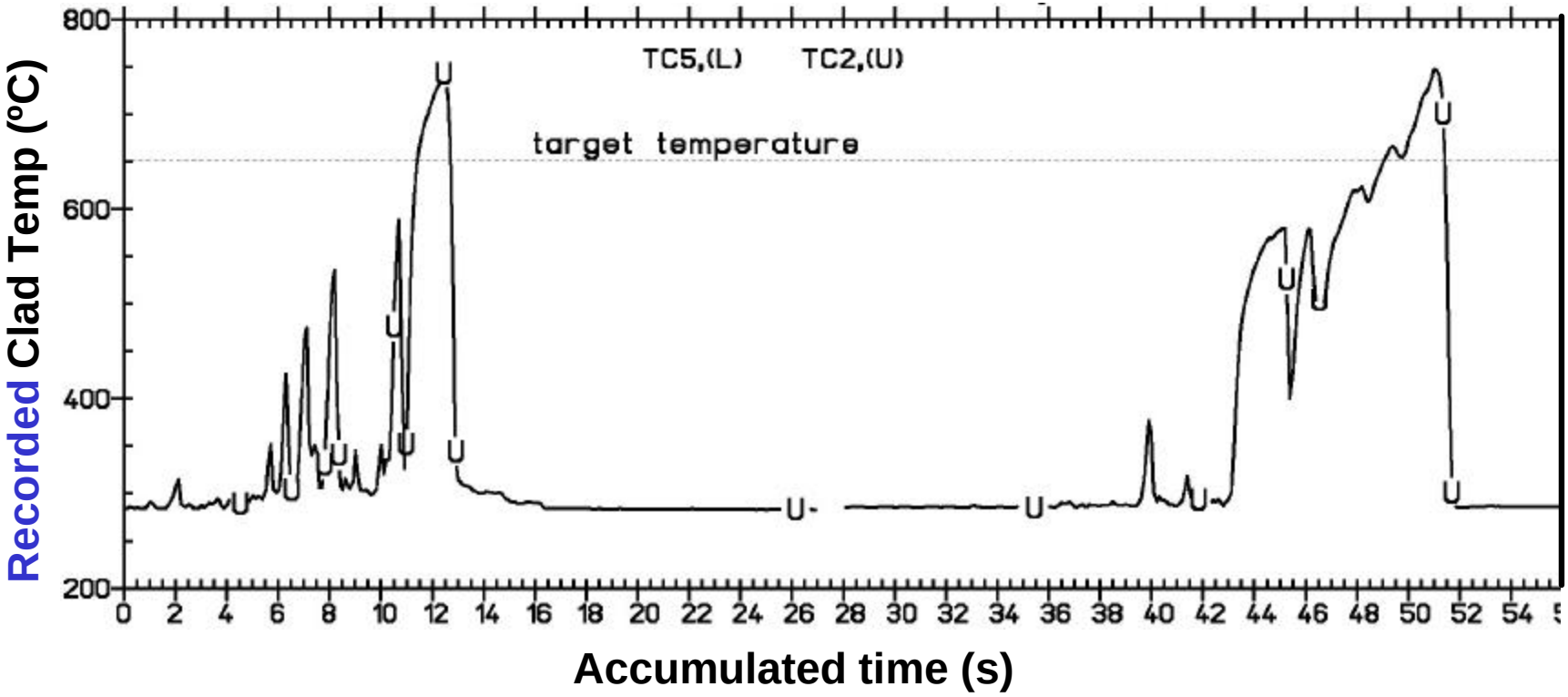
t_1 = 5 – 30 s
t_2 = 5 – 10 s
t_3 < 5 s

Target PCT
550ºC or 650ºC

Achieved In-Pile Transient DTC1404



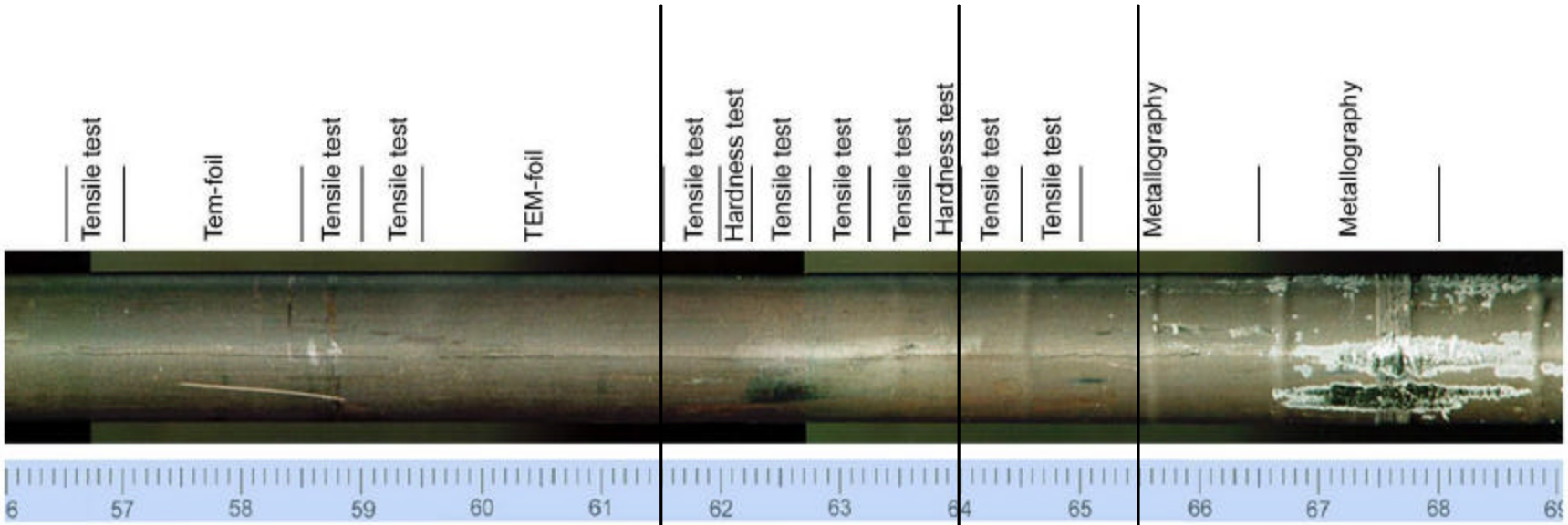
Achieved In-Pile Transient N1310



PIE Programme

- NDT of complete fuel rods (visual inspection and profilometry)
  - to get indication of where dry-out occurred
  - to aid in making cutting plan
- Destructive testing at selected axial regions (ring tensile, fractography, metallography, microhardness, hydrogen content, TEM)
  - to assess the impact of in-pile dry-out on cladding
  - to aid estimate of axial temperature profile and PCT

Visual Inspection DTC1404 (1)



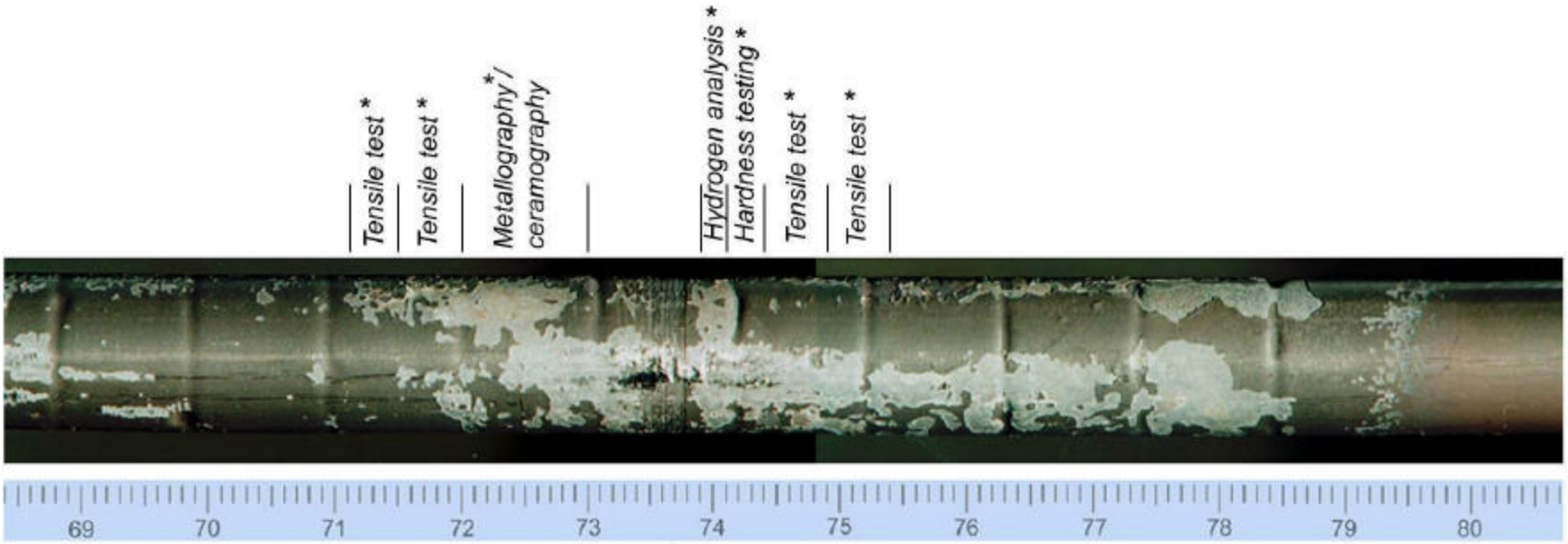
Unaffected Zone

Transient Zone 1

Trans. Zone 2

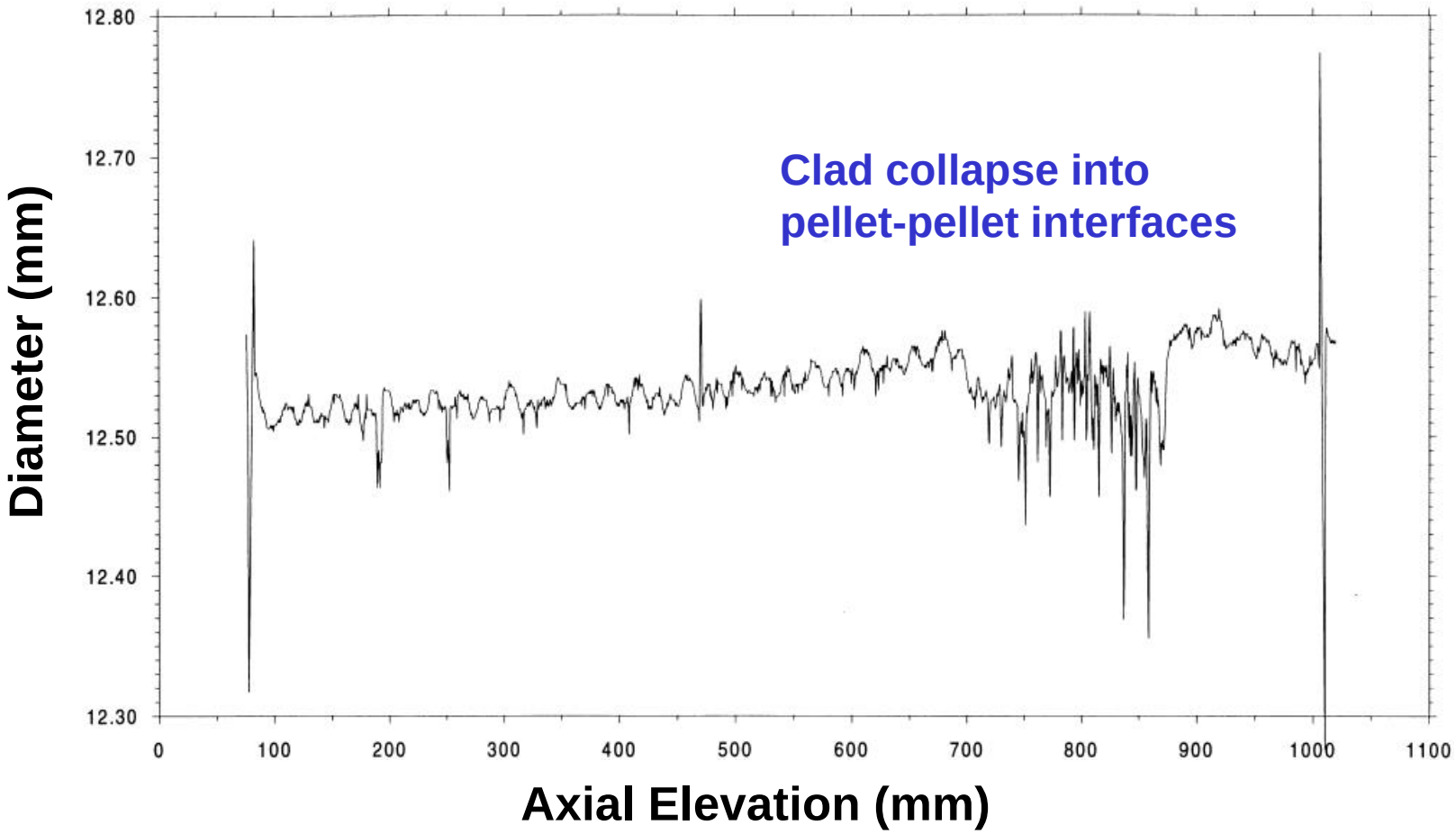
Peak Temp Zone

Visual Inspection DTC1404 (2)



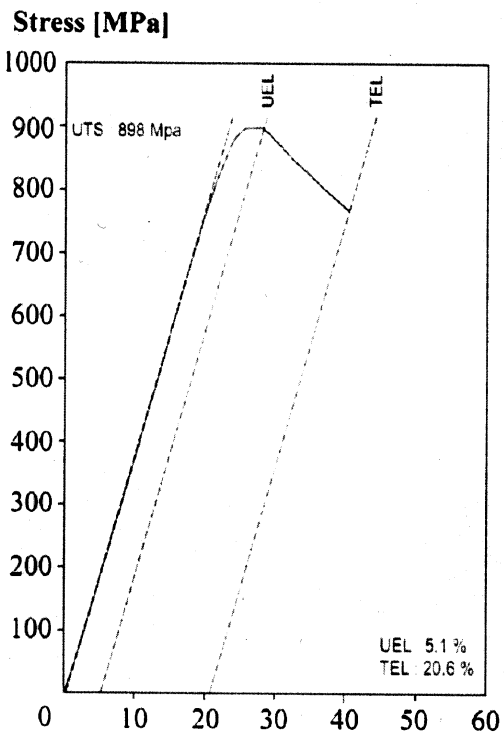
Peak Temp Zone

Diameter Trace DTC1404

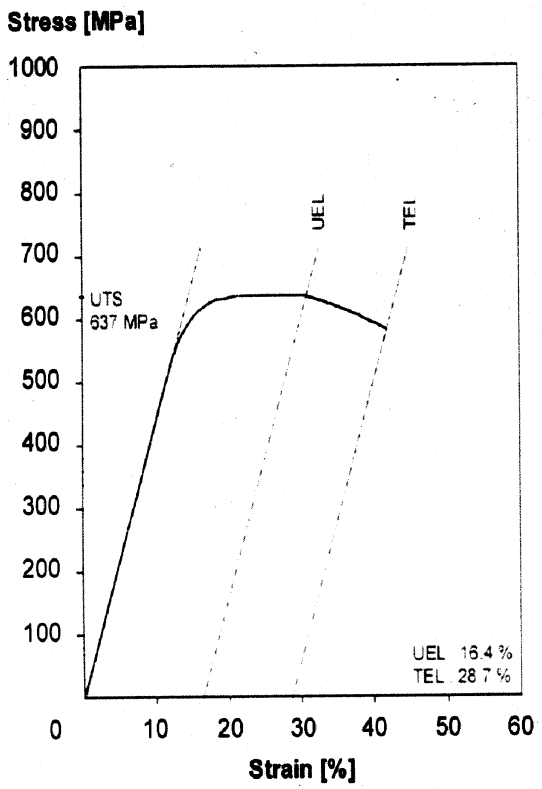


Tensile Testing DTC1404

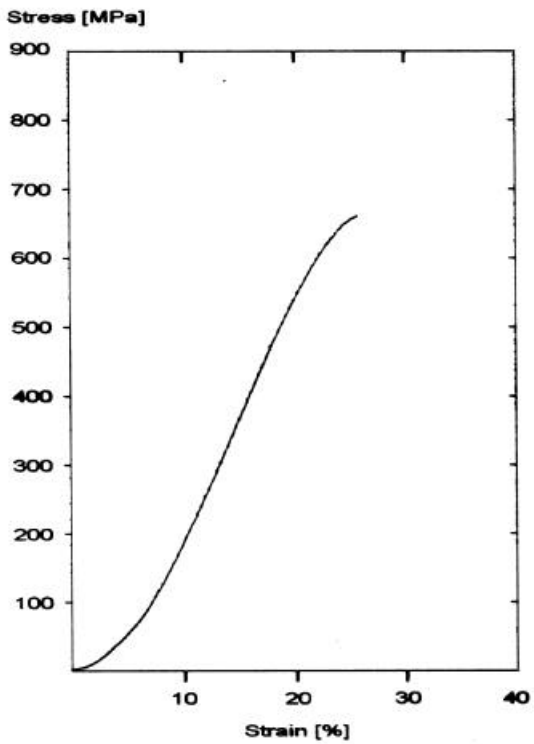
Unaffected Zone



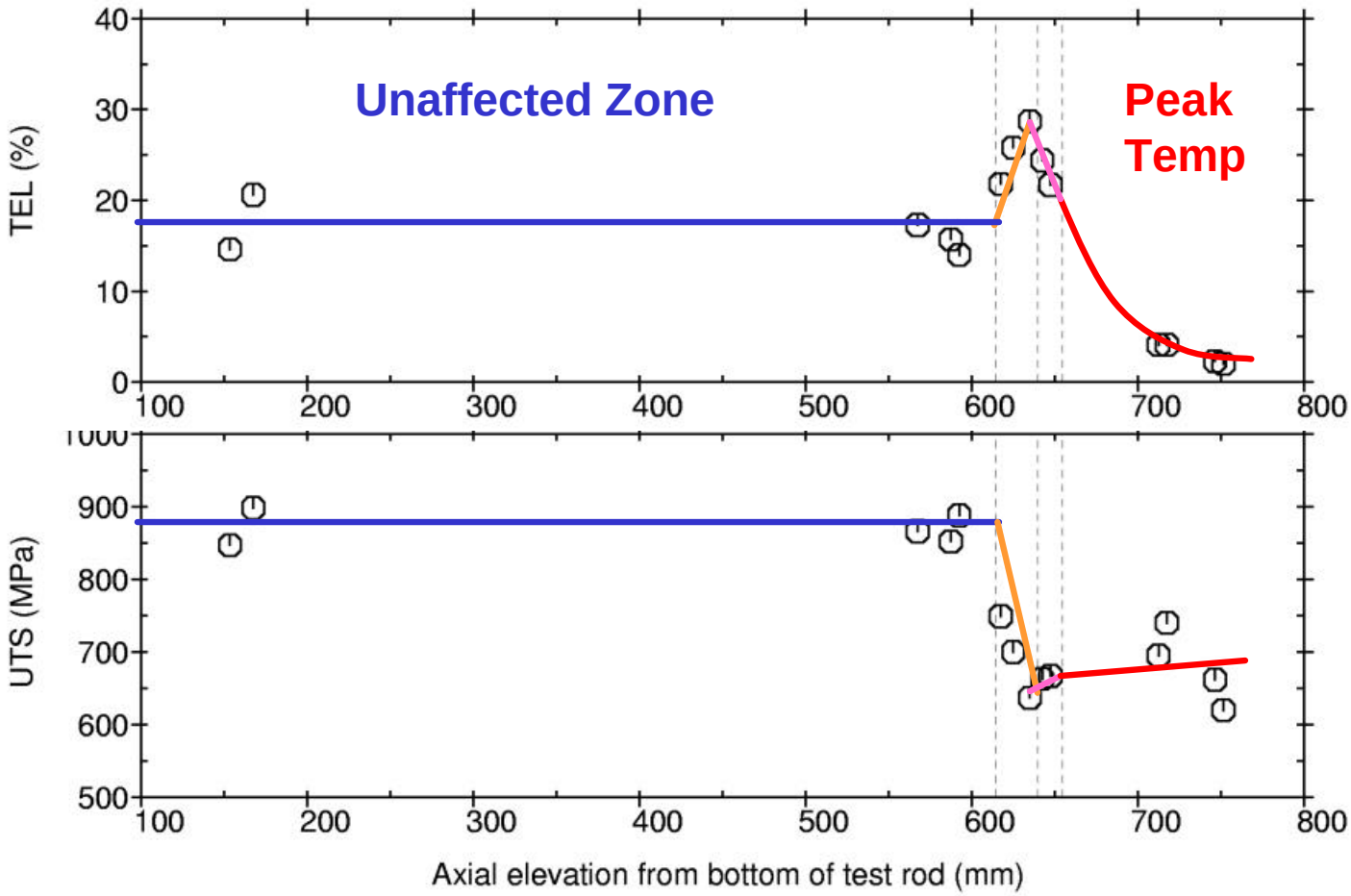
Transient Zone 1



Peak Temp Zone

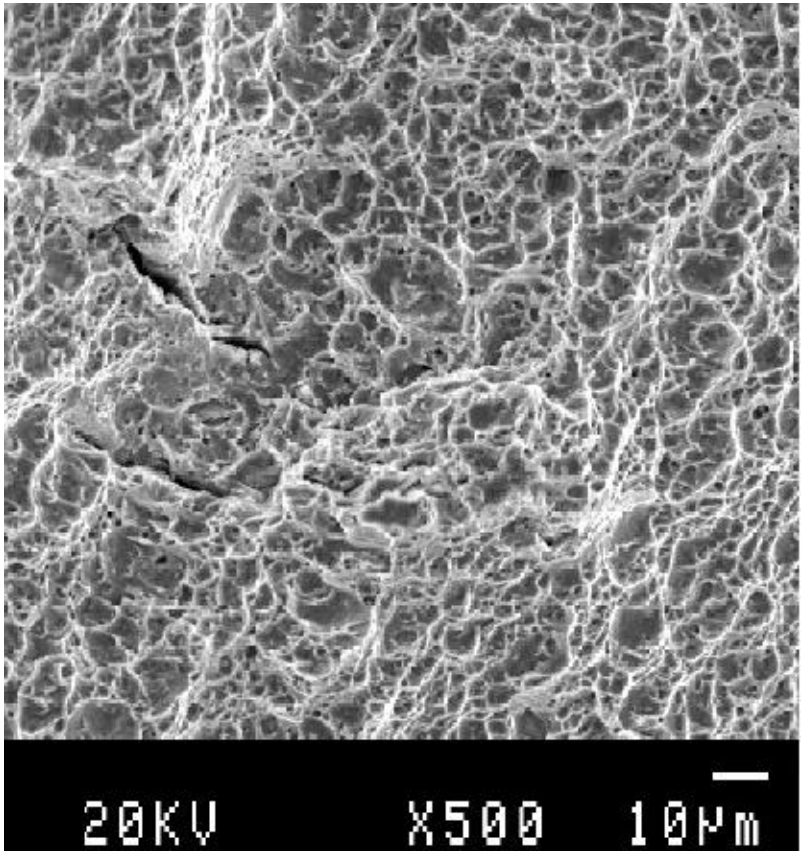


Tensile Testing Summary DTC1404

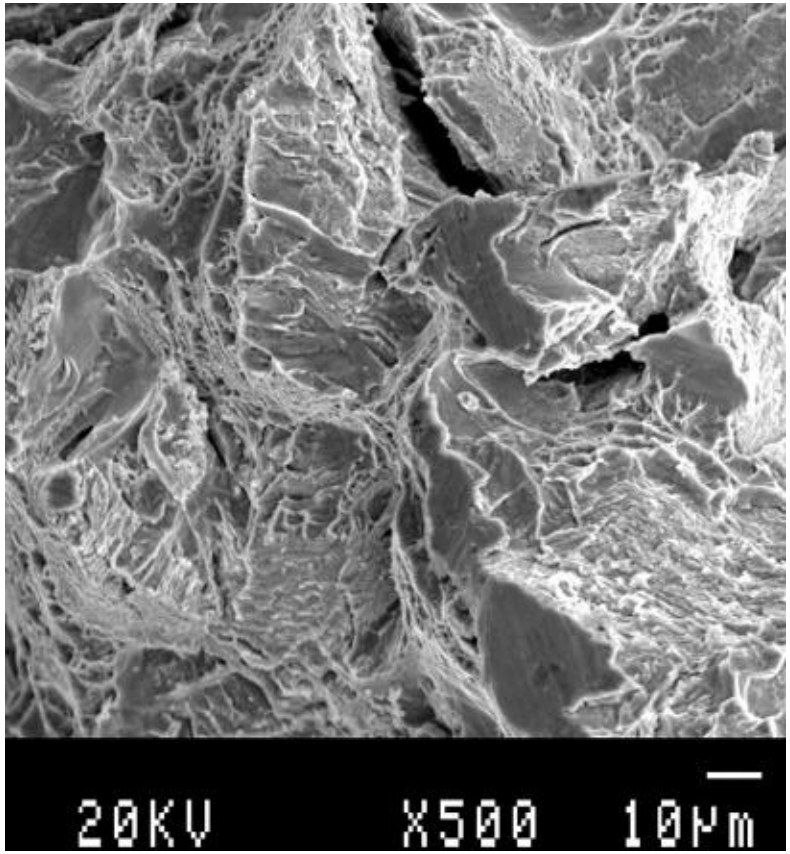


Fracture Faces DTC1404

Unaffected Zone

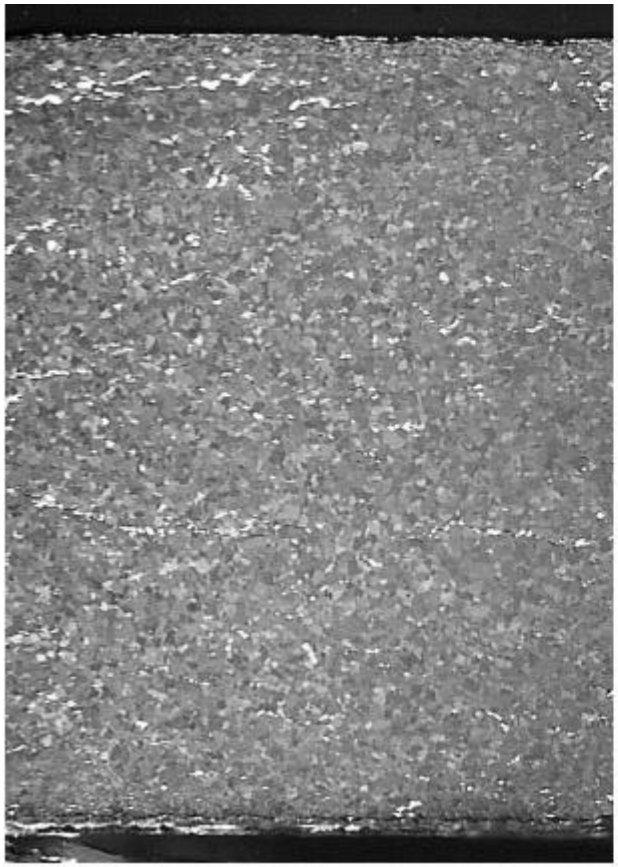


Peak Temp Zone

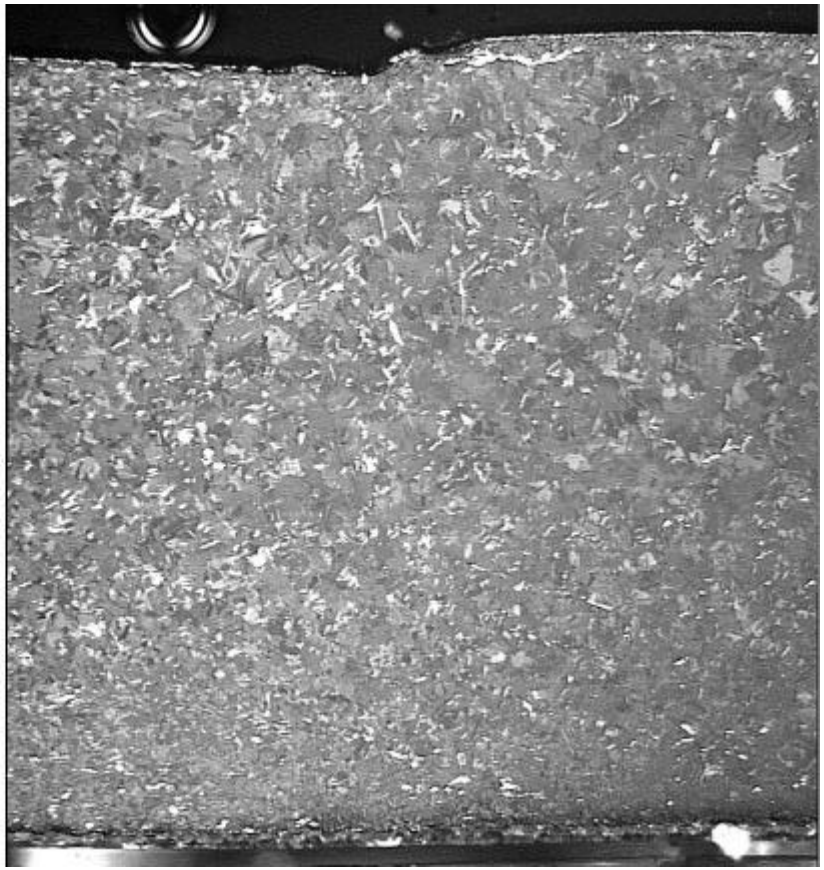


Microstructure DTC1404 (1)

Unaffected Zone a-grains 9 mm



Transient Zone 2 a+b grains



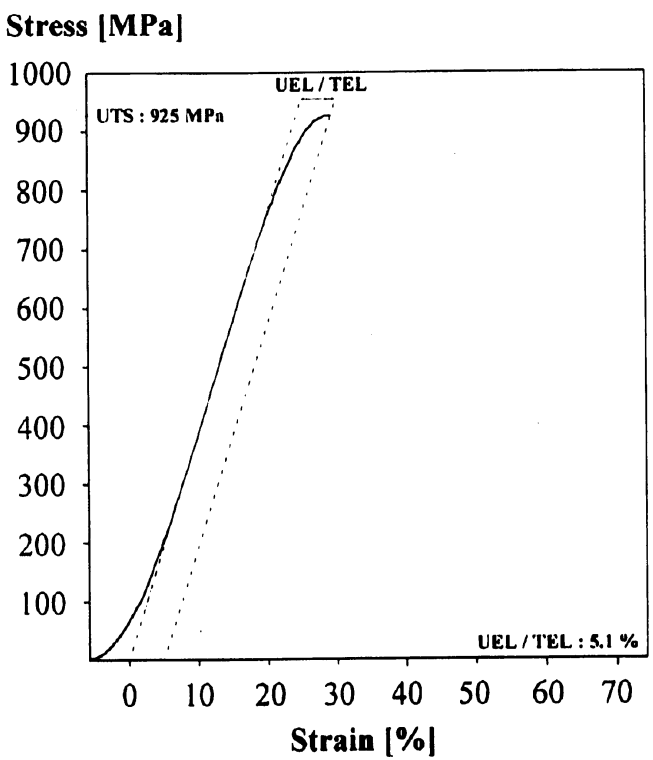
Microstructure DTC1404 (2)

Peak Temp Zone b-grains

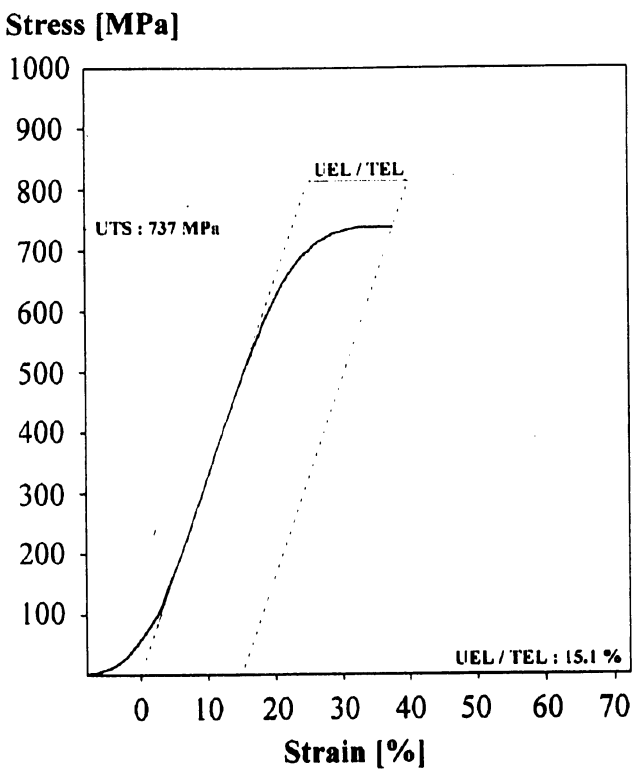
Peak Temp Zone hydrides

Tensile Testing N1310

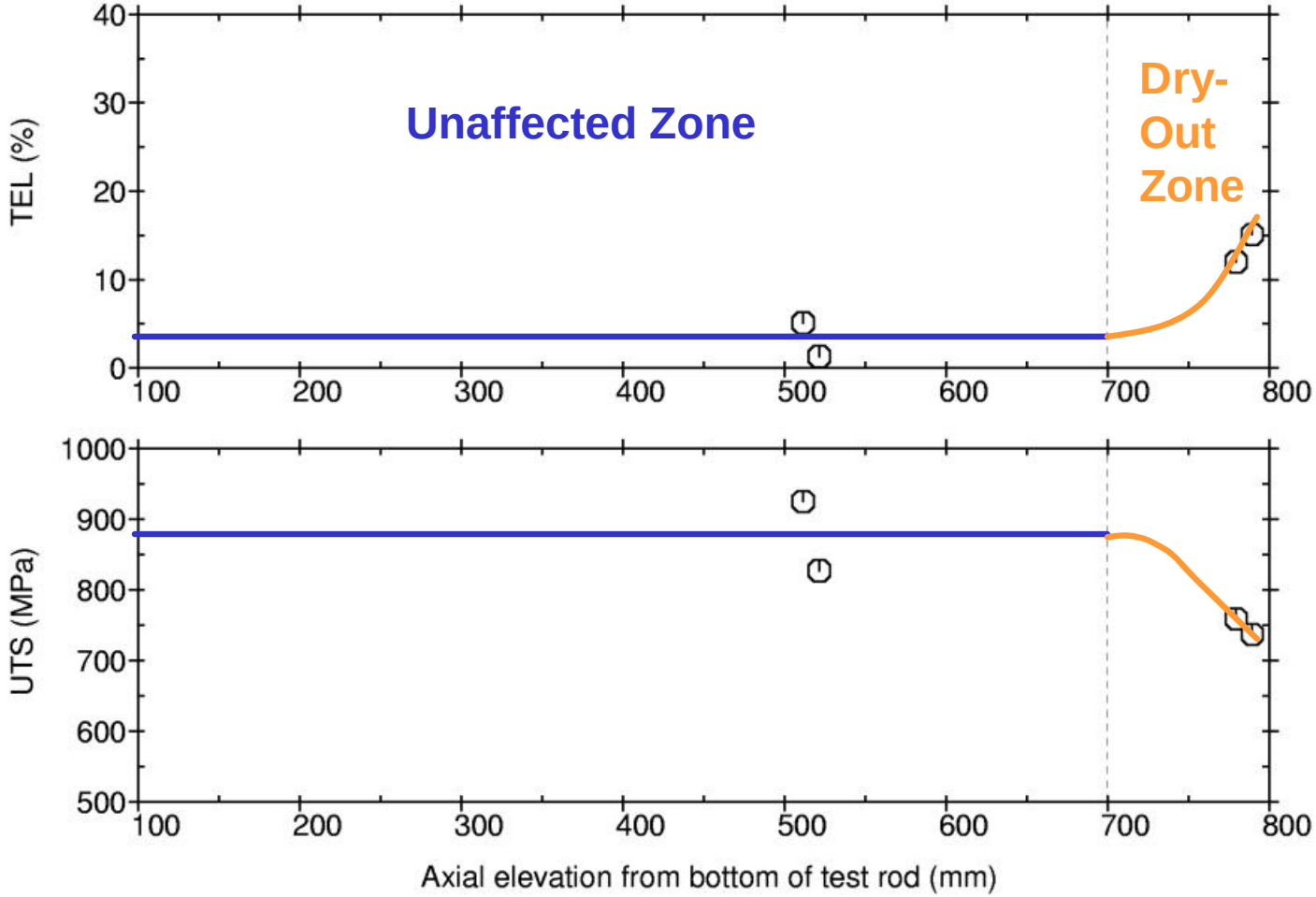
Unaffected Zone



Dry-Out Zone



Tensile Testing Summary N1310



Summary of PIE Results (1)

- The impact of in-reactor short-term dry-out incidents on fuel rods can be summarised

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- with a combined description of the physical, mechanical and microstructural changes induced by the temperature transients

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- which can be divided into four categories

1. Unaffected Zone

- Smooth adherent grey oxide
- No clad creep-down
- Relatively: high UTS, low TEL
- Ductile fracture
- Small α-Zr grains
- No hydrogen pick-up

2. Transient Zone 1

- Smooth adherent grey oxide
- Clad creep-down
- Relatively: ⬇UTS ⬆TEL
- Ductile fracture
- Small α-Zr grains
- -

3. Transient Zone 2

- Start of oxide spalling
- Clad collapse
- Relatively: low UTS ⬇TEL
- Ductile and brittle fracture
- Large α-Zr grains plus quenched ex-β-Zr
- -

4. Peak Dry-Out Zone

- Oxide spalling
- Clad collapse
- Relatively: low UTS ⬇TEL
- Brittle fracture
- Quenched ex-β-Zr
- Hydrogen pick-up

Conclusions

- **Significant improvement** in RT clad ductility occurs after in-pile transients where a small grained α-Zr structure is retained: max transient clad temp ~850°C
- **Clad RT ductility is severely reduced** after multiple exposures to >1000°C that result in quenched, former β-Zr grain structure with hydrides at former g.bs
- **Fuel rod integrity can be retained** even after in-pile dry-out transients that are sufficiently severe to induce an $\alpha \rightarrow \beta$ phase transformation, a significant reduction in RT clad ductility, clad collapse into pellet-pellet interfaces and oxide spalling