

Mechanical properties of pre-hydrogenated (600 – 5000 wppm) cladding segments

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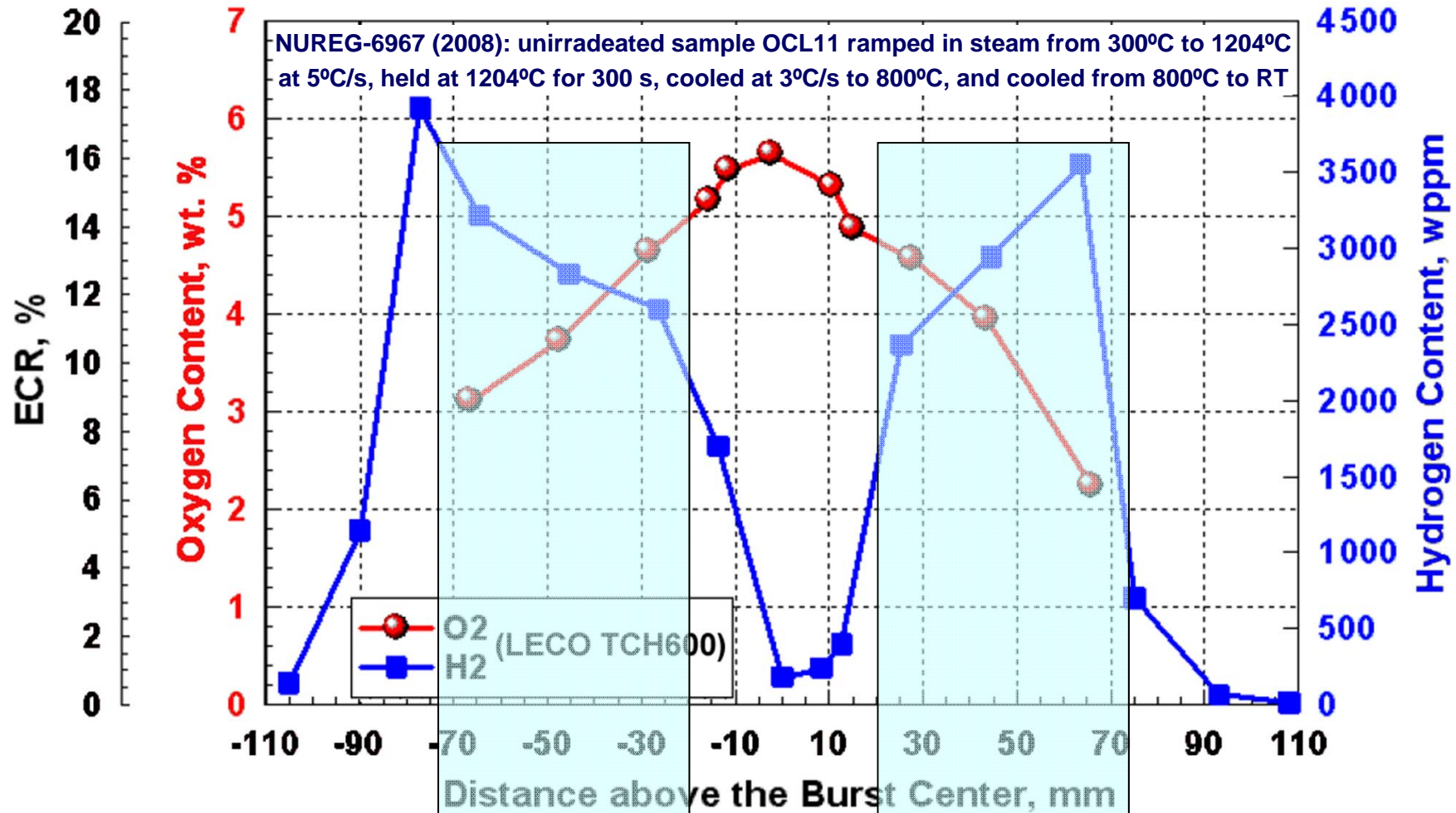
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Objectives

- **Preparation of hydrogenated probes for mechanical tests**
- **Hydrogen uptake under hydrogen starvation conditions to achieve axial hydrogen gradient in the cladding**
- **Tension and ring compression tests with hydrogenated probes**

Short term secondary hydrogenation after ballooning and burst: hydrogen uptake increased rapidly up to 4000 ppm (significant higher than ductility limit of 500 ppm)



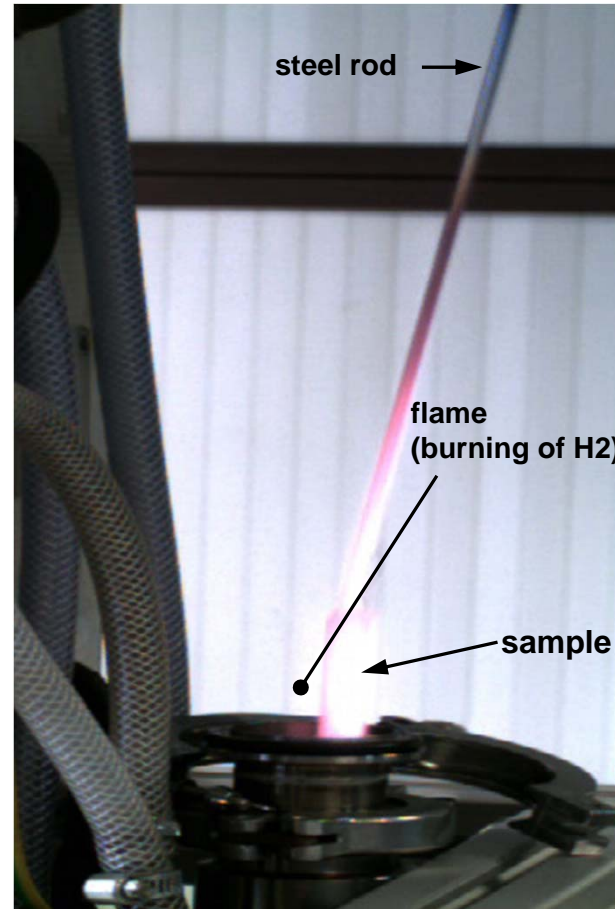
sample OCL11 (Zircaloy-2):



Hydrogenation facility



vertical 3-zones tube furnace LORA
(height 60 cm)



sample extraction
at furnace top



sample
15 cm

Test matrix

probe	temperature	H2 partial pressure	hydrogenation duration	dissolved hydrogen (weight gain)	hydrogen solubility limit
#	°C	mbar	min	wppm	wppm
H11Z4	700	90	2	2473	16770
H12Z4	700	90	6	5417	16770
H13 Z4	700	37	2	681	10820
H14 Z4	700	37	4	1819	10820
H15 Z4	700	37	6	2746	10820
H16 Z4	700	37	8	4810	10820
H18 Z4	800	37	2	827	5150
H19 Z4	800	37	4	1625	5150
H20 Z4	800	37	8	2783	5150
H21 Z4	800	37	16	4420	5150
H29Z4	900	37	1	400	2770
H31Z4	900	37	4	1215	2770
H33Z4	900	37	8	1689	2770

Post-test probe appearance:

probe bending at $T < 800^\circ\text{C}$ due to phase transition $\alpha\text{-Zr}$ to $\beta\text{-Zr}$



**H14Z4: annealed at 700 °C
with H₂ (37 mbar); $\Delta t=240$ s
 $\Delta m_H=1800$ wppm**

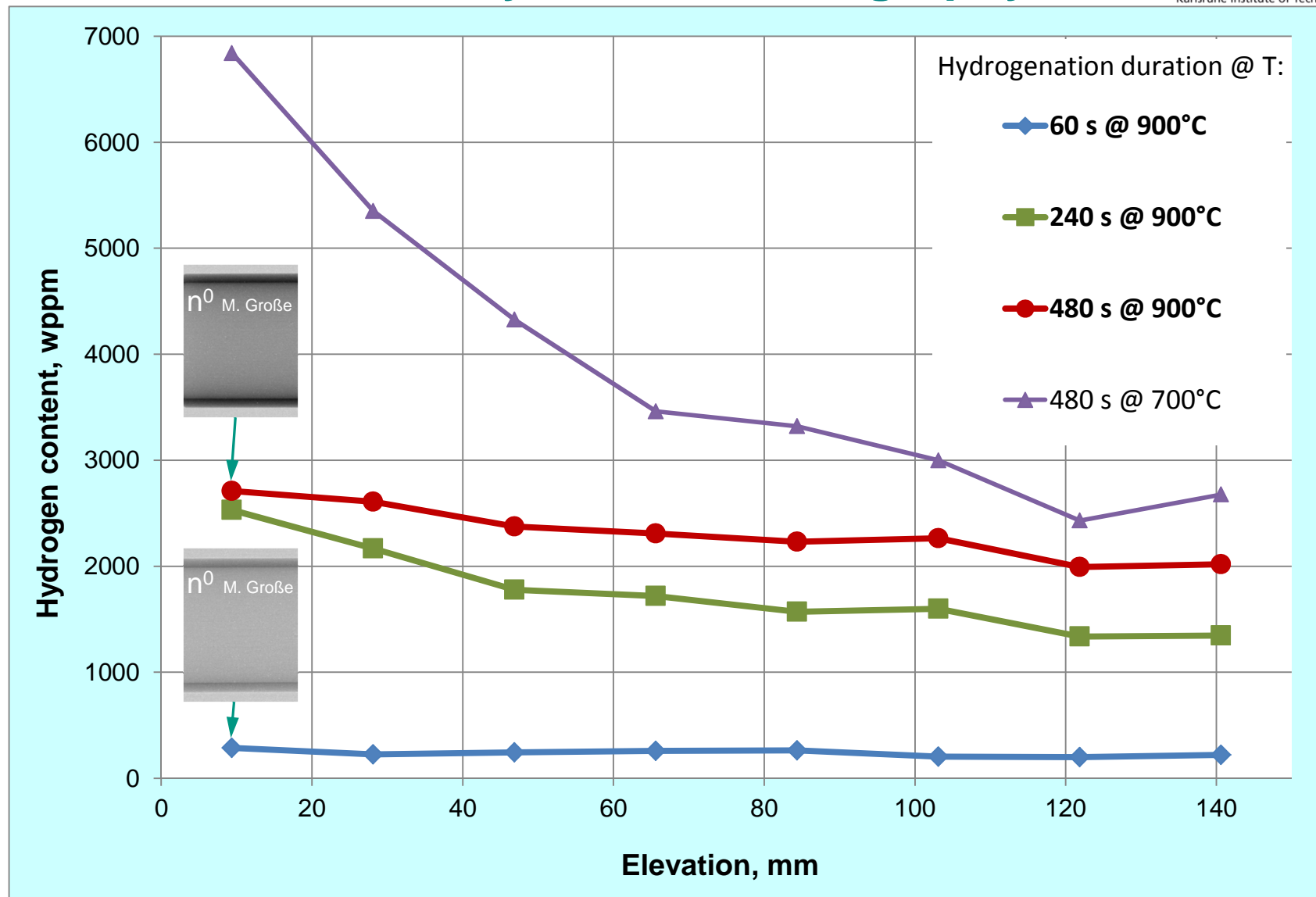


**H19Z4: annealed at 800 °C
with H₂ (37 mbar); $\Delta t=240$ s
 $\Delta m_H=1600$ wppm**

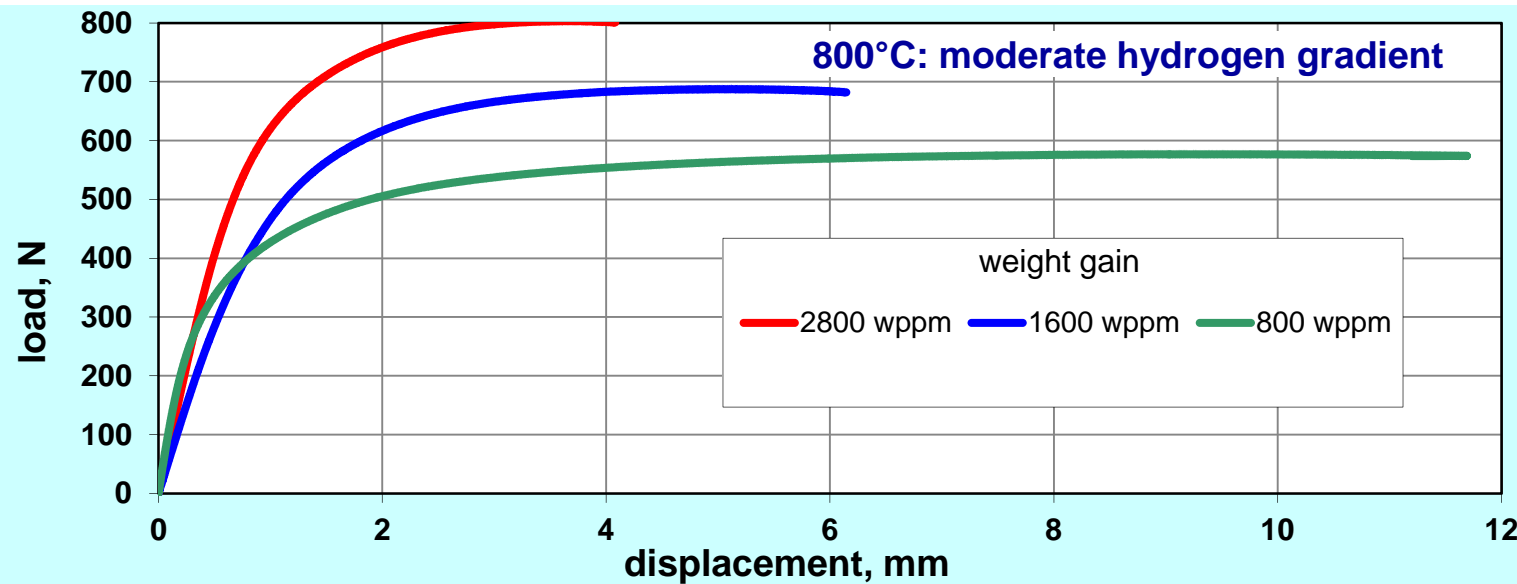
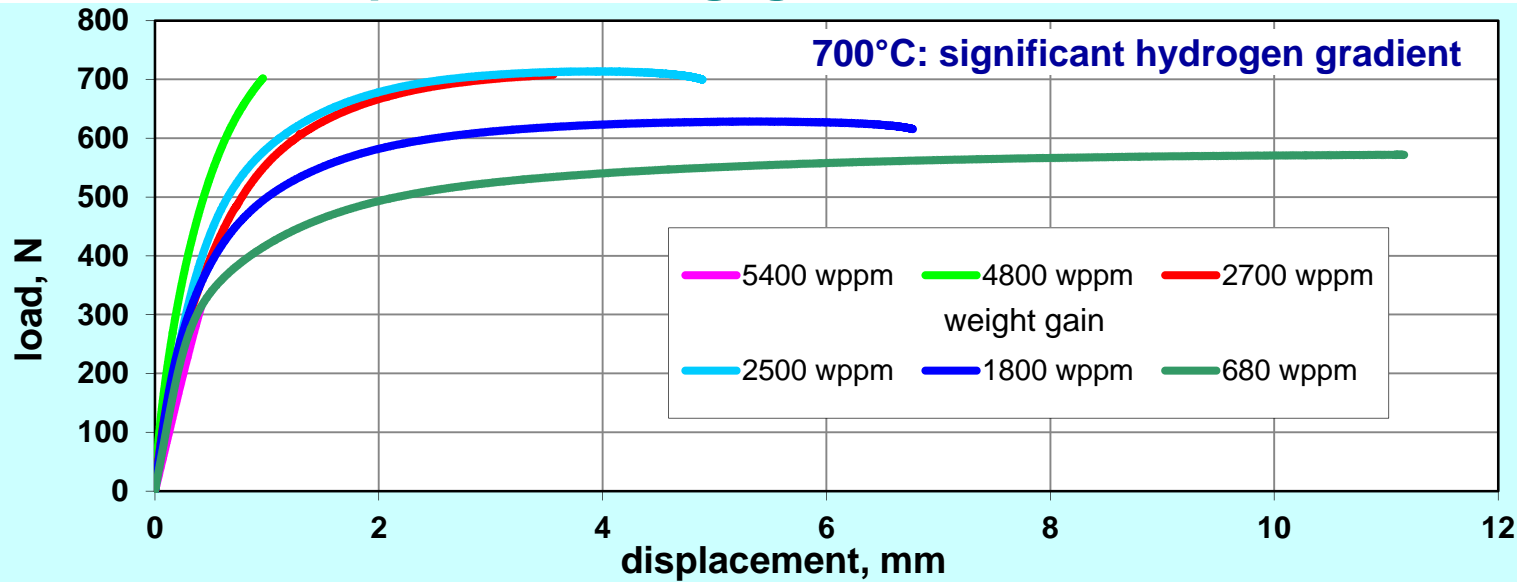


**H33Z4: annealed at 900 °C
with H₂ (37 mbar); $\Delta t=480$ s
 $\Delta m_H=1700$ wppm**

Axial distribution of hydrogen content measured by neutron radiography

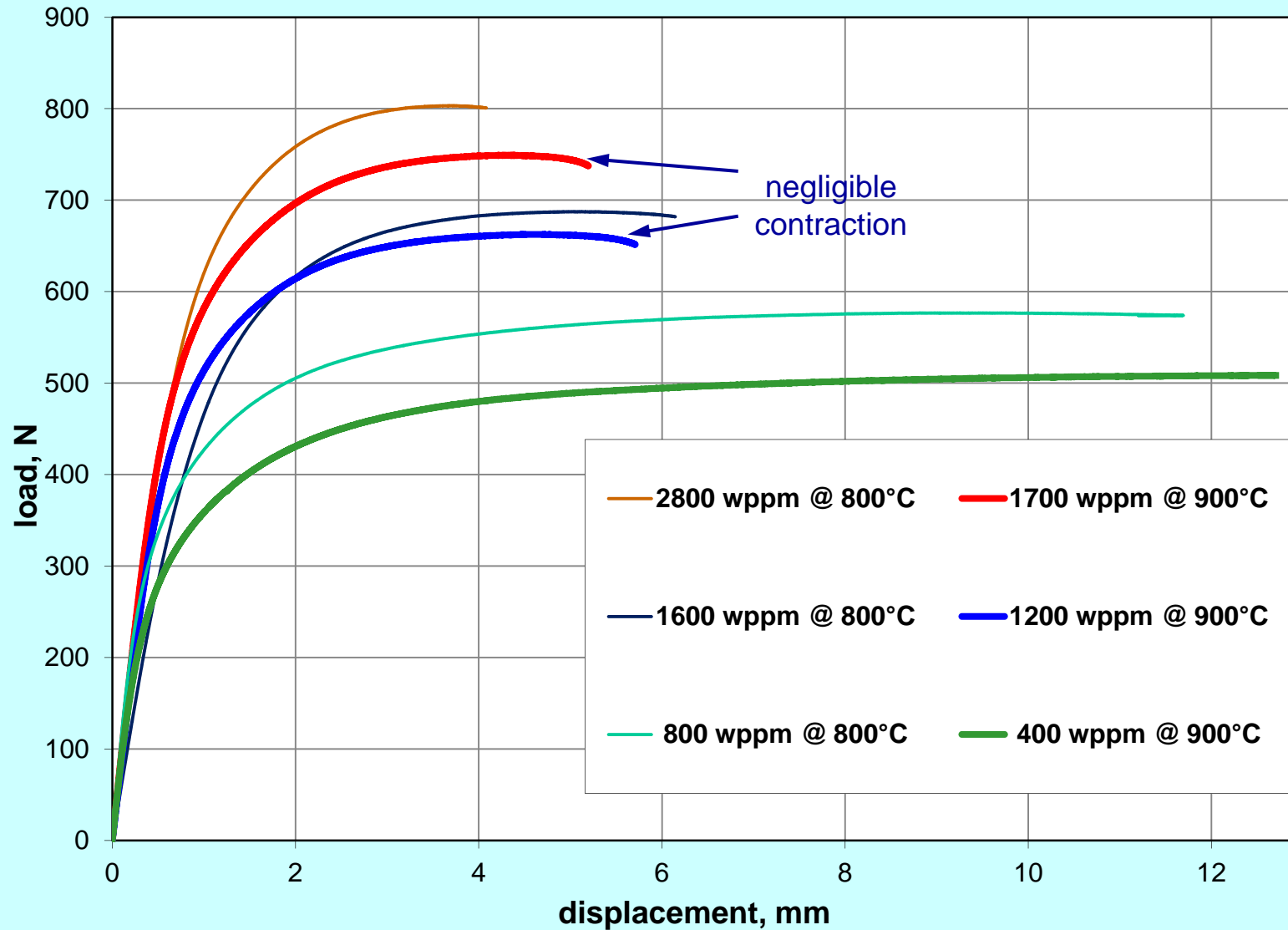


Tension tests with probes hydrogenated at 700 and 800°C: rupture with negligible contraction



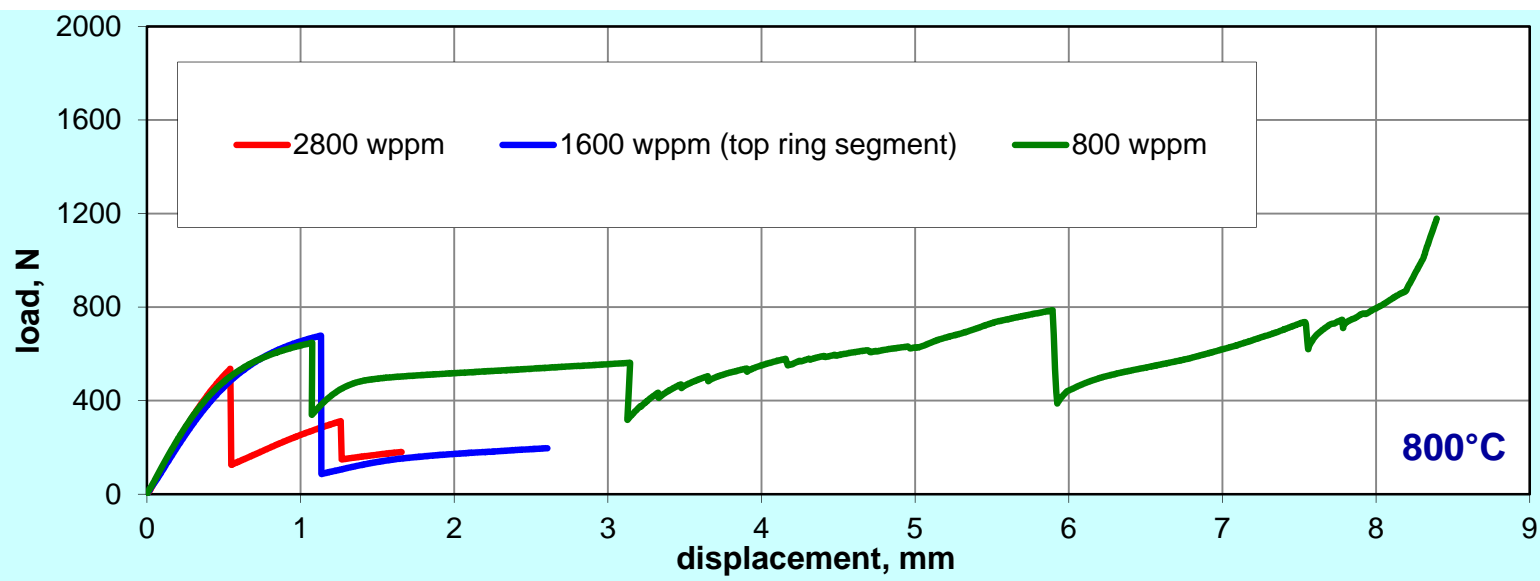
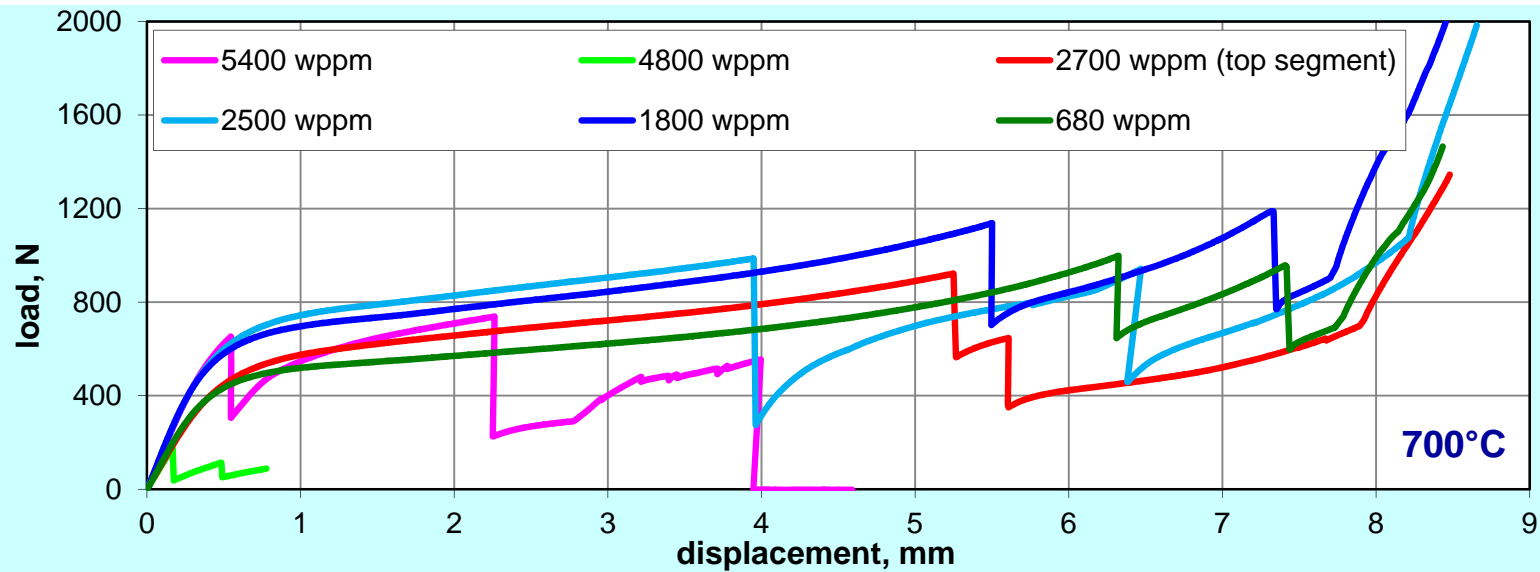
ductile not hydrogenated probe with pronounced contraction

Tension tests with probes hydrogenated at 800°C (moderate H gradient) and 900°C (small gradient)

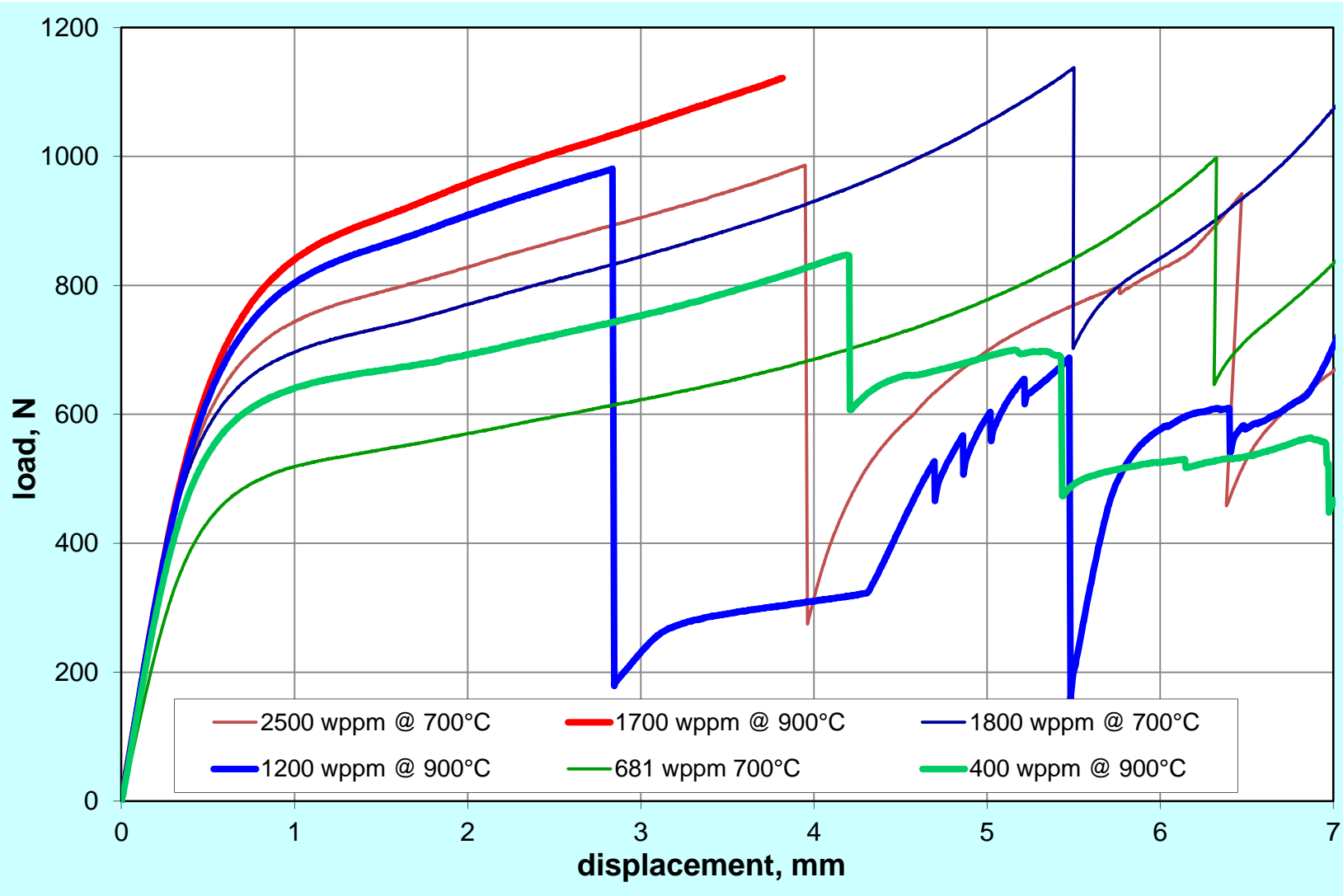


ductile not hydrogenated probe with pronounced contraction

Compression tests with rings from bottom of probes hydrogenated at 700 and 800°C



Compression tests with rings from bottom of probes hydrogenated at 700 and 900°C: hardening and embrittlement increase at higher annealing temperature



Summary

- **Twelve Zry-4 cladding specimens with length of 150 mm were hydrogenated in Ar + H₂ atmosphere at temperatures 700, 800 and 900 C**
- **Average hydrogen content was measured with probe weighing between 600 and 5000 wppm. Axial hydrogen distribution was measured by neutron radiography.**
- **No macroscopic hydrides were observed by means of optical microscopy.**
- **Tension and ring compression tests showed clear hardening and embrittlement increase with increased hydrogen content and annealing temperature.**

The authors would like to thank Ms Peters, Ms Baudin, Ms C. Goulet and Ms Wozniak

Thank you for your attention