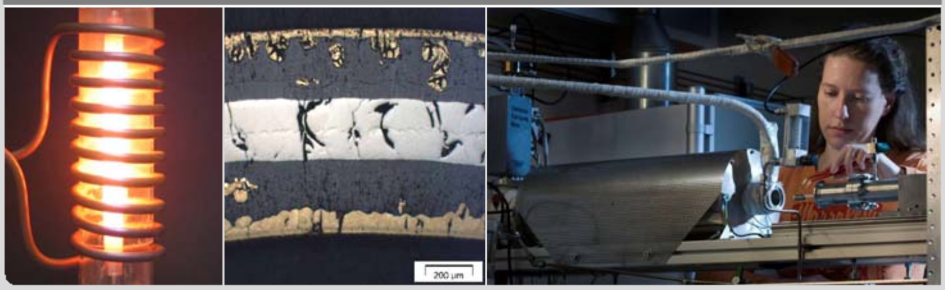
Separate-effects tests on high-temperature behavior of Zircaloy-2

Martin Steinbrück

Third Meeting of the Programme Review Group of the OECD-NEA SFP Project
Albuquerque, NM, 15-16 May 2011

Institute for Applied Materials - Program NUKLEAR



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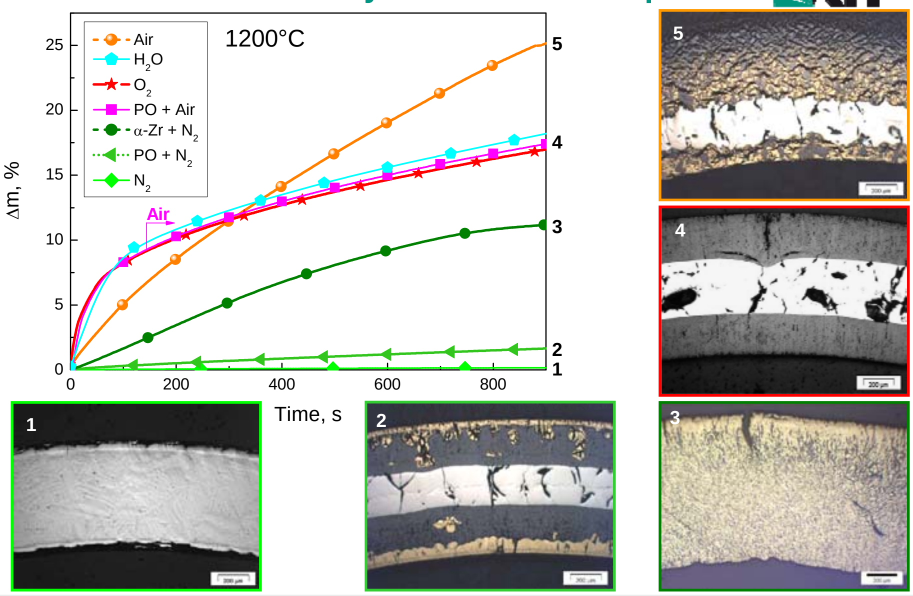
Preface: Oxidation of Zry in various atmospheres



Proposal on separate-effects tests with Zircaloy-2
Objective

- Proof the similarity of high-temperature oxidation and mechanical properties of Zircaloy-2 and Zircaloy-4
- Investigation of the influence of the swage-down process during manufacturing of the Zircaloy-2 heater rods
- Simulation of pre-ignition and SFP I test phases

➪ Report distributed Nov 2010

Composition of Zircaloy-2 and Zircaloy-4

ATI Wah Chang
Allegheny Technologies
TECHNICAL DATA SHEET

COMPOSITION (WEIGHT PERCENT)

Name	Zircaloy-2	Zircaloy-4
UNS Grade	R60802	R60804
Tin	1.20-1.70	1.20-1.70
Iron	0.07-0.20	0.18-0.24
Chromium	0.05-0.15	0.07-0.13
Nickel	0.03-0.08	---
Niobium	---	---
Oxygen	Per P.O.	Per P.O.
Iron + Chromium + Nickel	0.18-0.38	---
Iron + Chromium	---	0.28-0.37

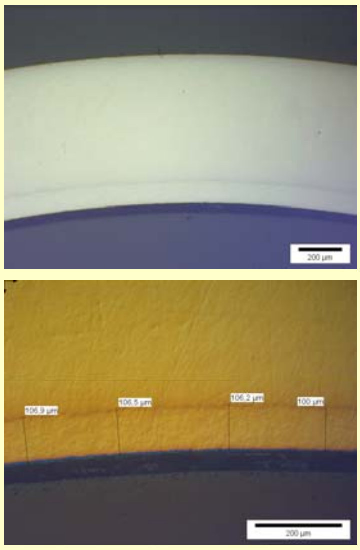
MAXIMUM IMPURITIES, WEIGHT %

Name	Zircaloy-2	Zircaloy-4
Aluminum	0.0075	0.0075
Boron	0.00005	0.00005
Cadmium	0.00005	0.00005
Carbon	0.027	0.027
Chromium	---	---
Cobalt	0.0020	0.0020
Copper	0.0050	0.0050
Hafnium	0.010	0.010
Hydrogen	0.0025	0.0025
Iron	---	---
Magnesium	0.0020	0.0020
Manganese	0.0050	0.0050
Molybdenum	0.0050	0.0050
Nickel	---	0.0070
Nitrogen	0.0080	0.0080
Phosphorus	---	---
Silicon	0.0120	0.0120
Tin	---	---
Tungsten	0.010	0.010
Titanium	0.0050	0.0050
Uranium (total)	0.00035	0.00035

⇒ Very similar composition of both alloys

Specimens

As-received Zry-2 and prototype heater rods



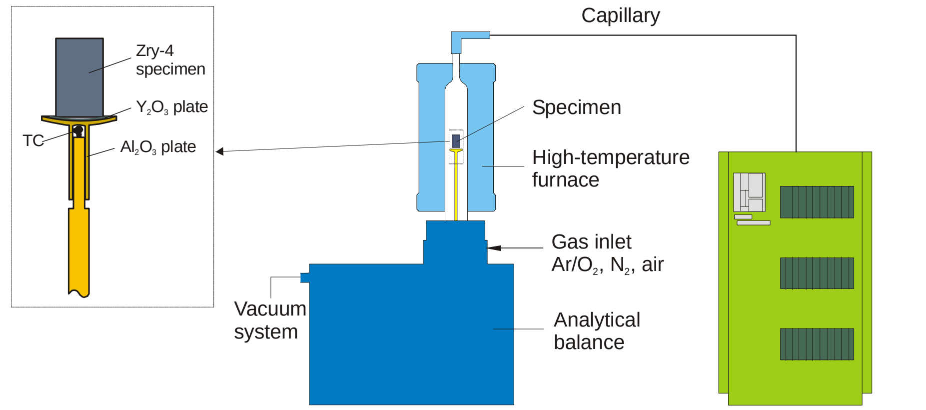
Cross-section of as-received Zry-2 with 100 µm inner Zr liner

Specimen dimensions

	Zry-2 as-received	Zry-2 reamed	Zry-4 as-received	Zry-4 reamed	Heater tube
Outer diameter (mm)	11.14	11.13	10.74	10.73	9.5-9.6
Inner diameter (mm)	9.82	10.22	9.37	9.83	8.1
Wall thickness (mm)	0.660	0.455	0.682	0.451	0.75
Removal (mm)		0.205		0.231	

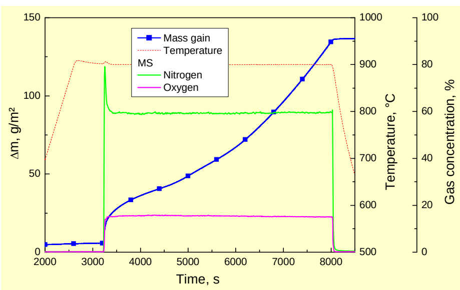
Sample height: 20 mm

Thermal balance

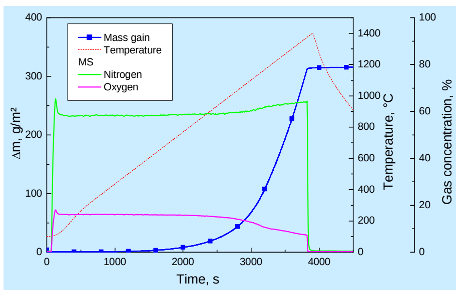


TG measuring head | **Thermobalance** NETZSCH STA 409 | **Mass spectrometer** NETZSCH Aeolos

Typical test conducts

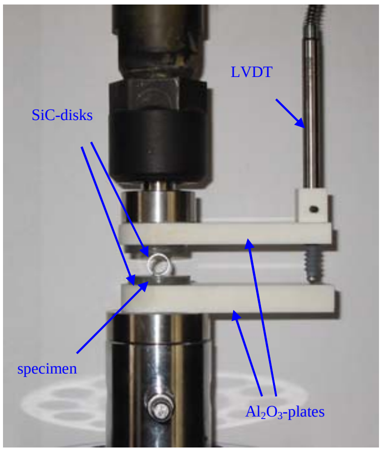


Isothermal

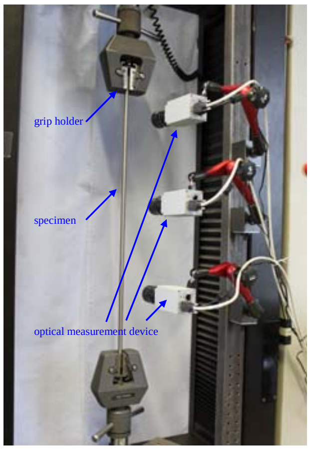


Transient

Mechanical test setups



Ring compression test

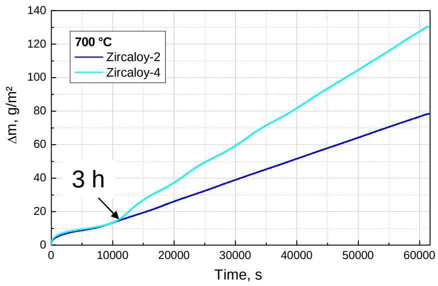


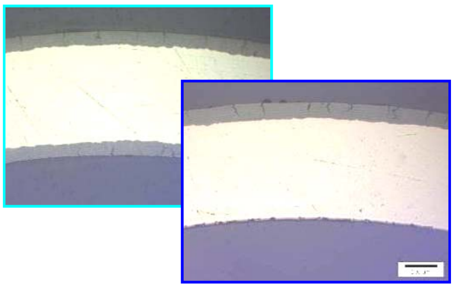
Tensile test

Test matrix

- Isothermal oxidation
  - Specimens: As-received, swaged-down, reamed
  - Temperatures: 600 - 1400 °C
  - Durations: 10 min - 70 h → partial oxidation
- Transient oxidation
  - Temperature: RT – 1400 °C
  - Heating rates: 5 – 50 K/min
  - According to SFP pre-test calculation results
- Mechanical testing
  - Ring compression tests
  - Tensile tests
  - Comparison between Zry-2, Zry-4, swaged-down heater cladding

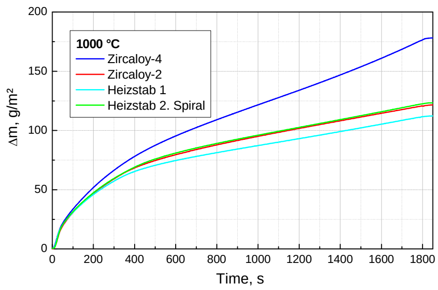
Oxidation of as-received claddings

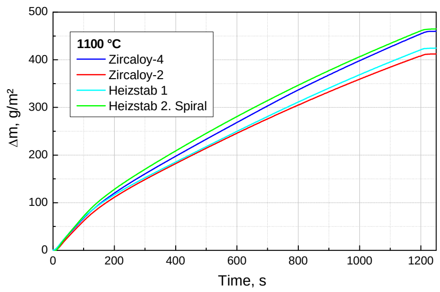




- Positive effect of inner Zr layer (but no effect in SFP tests)
- Comparable external oxidation
- Breakaway after ca. 3 hours

Oxidation of heater rods

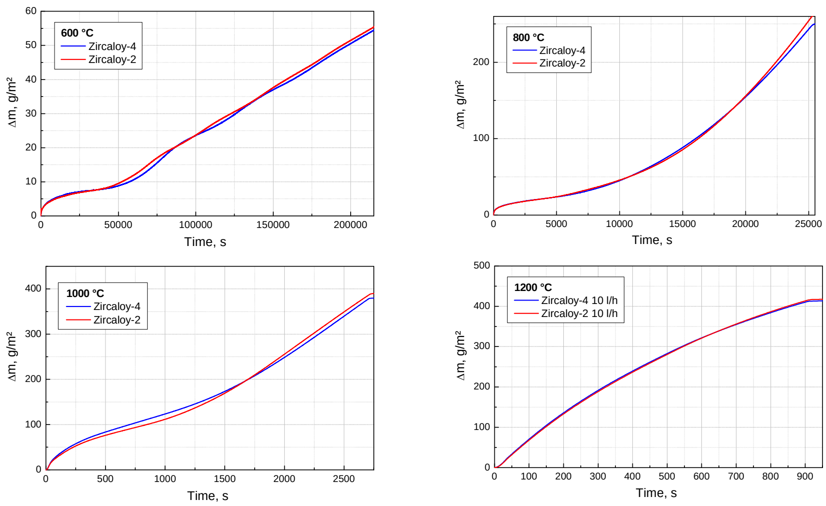




➡ No effect of swage-down process on oxidation behavior of Zircaloy-4

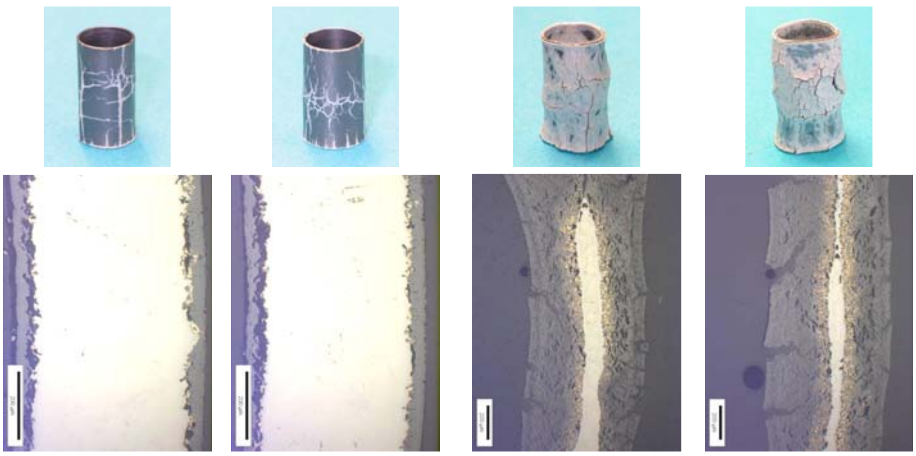
Oxidation of reamed claddings

Mass gain during isothermal oxidation in air



Oxidation of as-received and reamed claddings

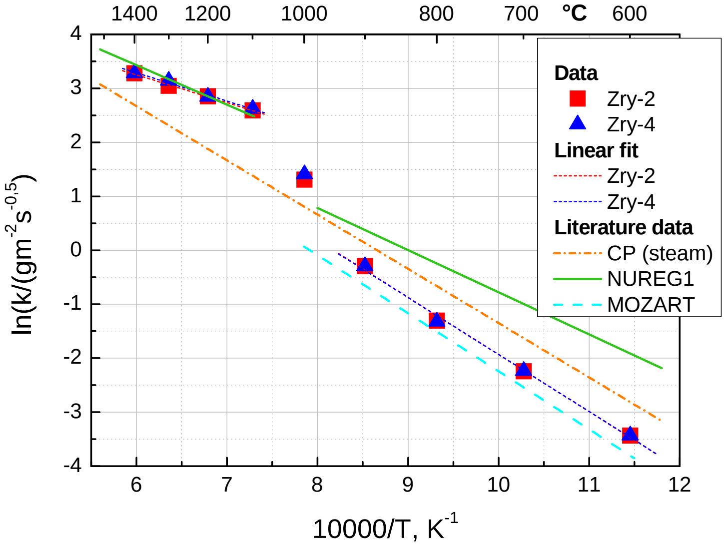
Post-test examinations (Example from 1100°C tests)



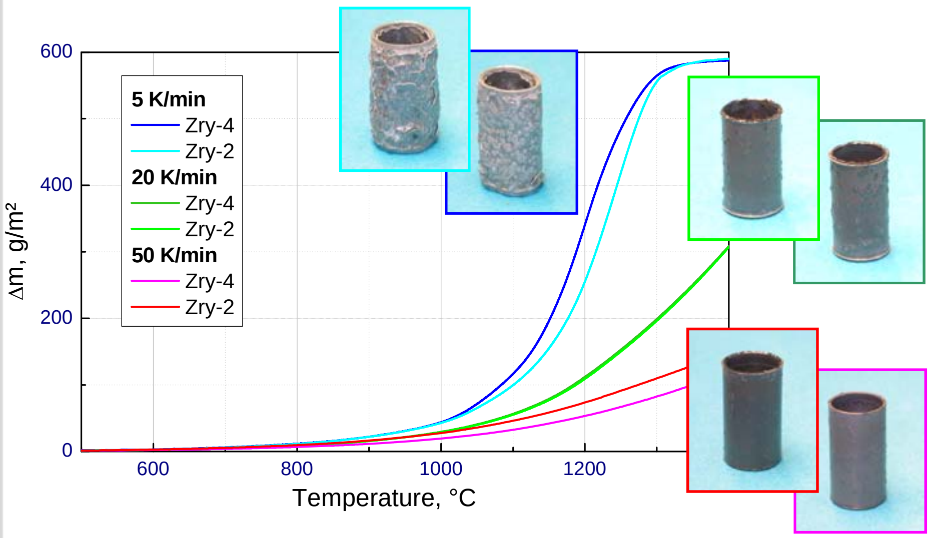
Zry-4, 15 min | Zry-2, 15 min | Zry-4, 45 min | Zry-2, 45 min

Oxidation of as-received and reamed claddings

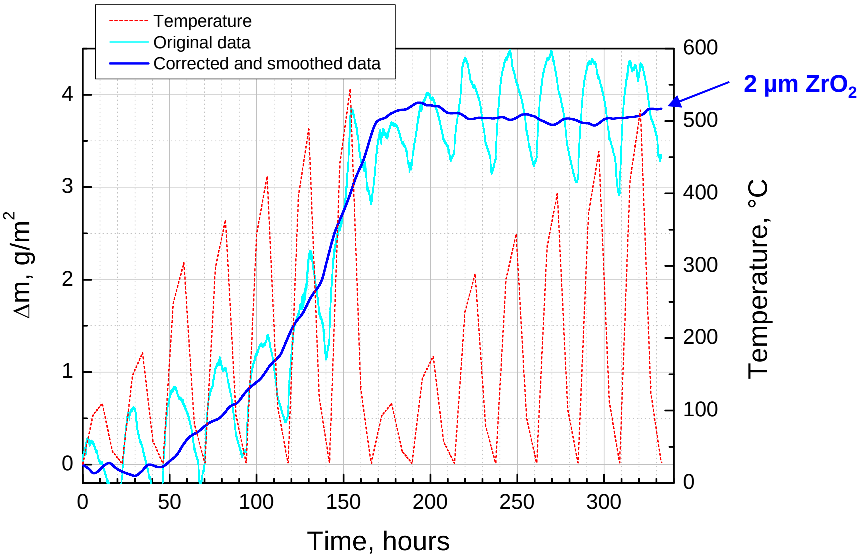
Parabolic rate constants, comparison with literature data



Transient oxidation

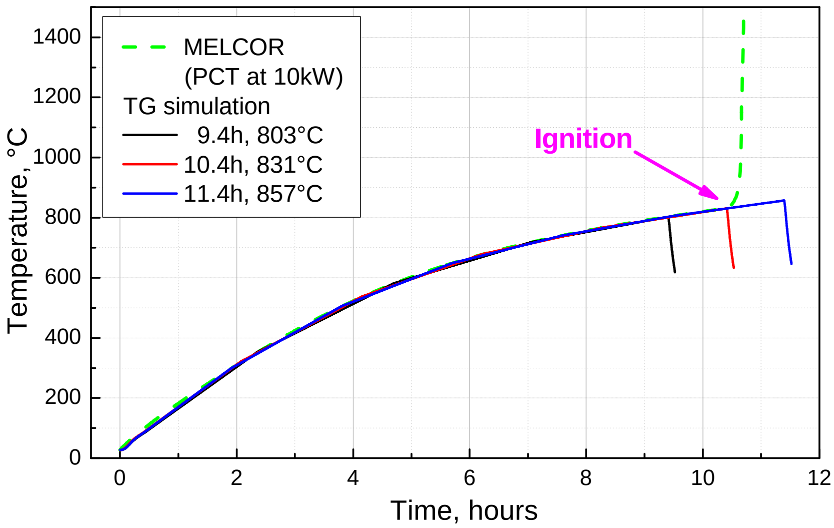


Simulation of SFP pre-ignition tests

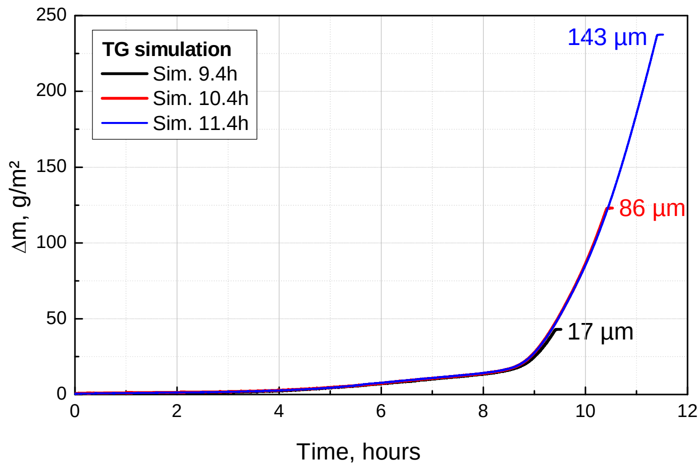


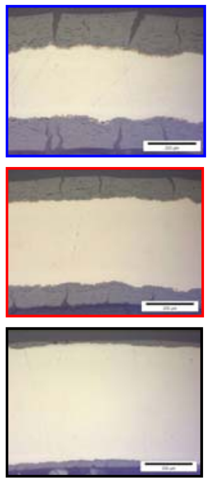
Simulation of SFP test phase I

Test conduct

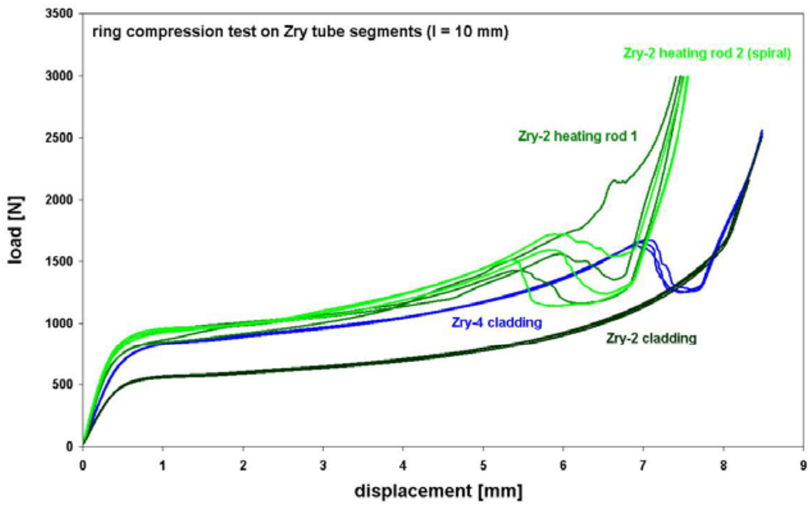


Simulation of SFP test phase I
Test results

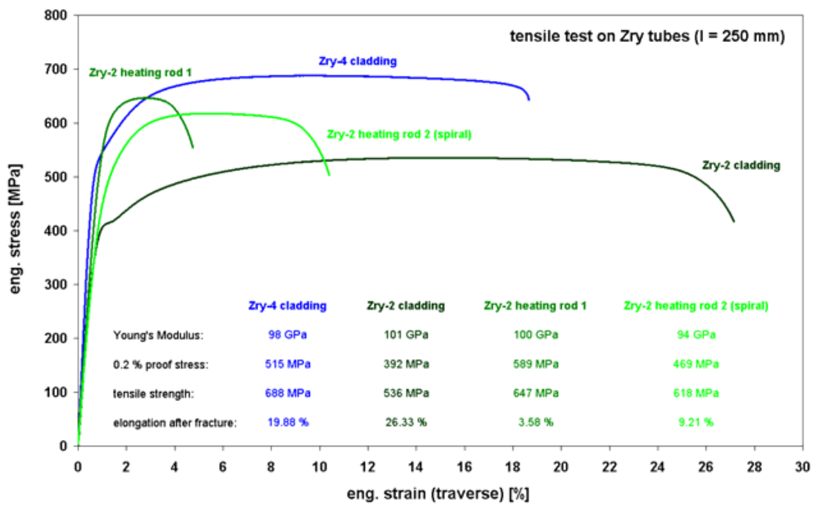




Mechanical properties
Ring compression tests



Mechanical properties
Tensile tests



	Zry-4 cladding	Zry-2 cladding	Zry-2 heating rod 1	Zry-2 heating rod 2 (spiral)
Young's Modulus:	98 GPa	101 GPa	100 GPa	94 GPa
0.2 % proof stress:	515 MPa	392 MPa	589 MPa	469 MPa
tensile strength:	688 MPa	536 MPa	647 MPa	618 MPa
elongation after fracture:	19.88 %	26.33 %	3.58 %	9.21 %

Summary

- Very similar oxidation behavior of the two alloys Zircaloy-2 and Zircaloy-4 and hence no concern regarding use of Zircaloy-2 for PWR tests
- No effect of swage-down process on oxidation
- Only very low oxidation (2 µm) of cladding during pre-ignition tests
- Strong influence of the time of self-ignition on the degree of pre-oxidation and thus on amount of metal left for further oxidation
- Mechanical properties of as-received Zircaloy-4, Zircaloy-2, and heater rods (Zry-2, swaged down) are different. The manufacturing of the heater rods caused increase of strength and decrease of ductility.

Finally…

- The financial support of this work by the SFP program is acknowledged
- Next QUENCH Workshop:
  - Nov 22-24, 2011
  - KIT, Karlsruhe, Germany
  - quench.forschung.kit.edu

Thank you for your attention!

Karlsruhe Institute of Technology

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