The Effects of Microstructure and Operating Conditions on Irradiation Creep of Zr-2.5Nb Pressure Tubing

17th International Symposium on Zirconium in the Nuclear Industry
L. Walters, G. Bickel and M. Griffiths
February 2013
Outline

• Zr-2.5Nb pressure tubes in the CANDU® reactor.
• In-service pressure tube deformation.
• The empirical data obtained to characterize pressure tube deformation
• The functional relationships between:
  – operating conditions (including temperature, stress, fast flux)
  – microstructure parameters (including texture, grain size)
  – and cold work
  on pressure tube deformation.
CANDU6 Reactor and the Zr-2.5Nb Pressure Tube

- The Zr-2.5Nb pressure tube resides in the reactor core and it is the pressure boundary surrounding the fuel
- The pressure tubes are 6.3 m long, 104 mm ID and 4.2 mm wall thickness

- CANDU6 design has 380 horizontal fuel channels in the reactor core
The concentration of basal plane normals in pressure tubes are predominantly (90%) oriented in the radial/transverse plane mostly in the transverse direction.
• Pressure tubes operate at $265^\circ$C to $310^\circ$C
• Initial hoop stresses of 140 MPa
• Maximum 40 dpa with flux $4 \times 10^{17} \text{n} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ ($E > 1 \text{ MeV}$)
• 30 year in-service life
A series of irradiation deformation tests were conducted using bi-axially stressed creep capsules in the French OSIRIS test reactor.

- 10 mm diameter Zr-2.5Nb capsules
- The CANDU equivalent of the fast flux in the OSIRIS experiments is $1.8 \times 10^{18} \text{n} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ (E > 1 MeV) ~5x CANDU.
- Nominal operating temperatures 280°C to 340°C
- Hoop stresses 0 to 160 MPa
- Texture $f_R = 0.334$ to 0.56, $f_T = 0.596$ to 0.37, $f_L < 0.1$
- Irradiated up to a maximum of 26.5 dpa
Each experimental insert:
• 7 creep capsules
• Growth specimens
• Thermocouples and flux monitors
• NaK filled
Summary of OSIRIS Zr-2.5Nb Creep Capsule Experiments

• **Trillium-2 and 3** *(April 1989-January 1999)*
  
  designed to provide deformation behaviour data on Zr-2.5Nb pressure tube material to fluences \( \approx \) half CANDU pressure tube life for:
  
  - two temperatures 280\(^\circ\)C and 310\(^\circ\)C
  - two different textures \((f_T>f_R)\) and \((f_R>f_T)\)

• **Trillium-5** *(February 2001-March 2003)*
  
  performed to evaluate in-reactor deformation as a function of cold work (6\%, 12\%, 18\%, and 26\%) at 140 MPa and nominal temperature of 310\(^\circ\)C

• **Cardinal-1 and 2** *(October 2004 – December 2007)*
  
  performed to characterize the strain rate behaviour at extended temperatures, 320\(^\circ\)C and 340\(^\circ\)C
OSIRIS Zr-2.5Nb Creep Capsule Experiments

• Early results from the OSIRIS experiments (Trillium-2&3) were used as a basis for assumptions regarding CANDU pressure tube deformation.


• These results have now been supplemented with more recent data which provide new insights regarding temperature dependence (Cardinal-1&2), the effect of cold work (Trillium-5) and the effect of texture and grain size on Zr-2.5Nb pressure tube deformation.
• Diametral and axial strain increase approximately linearly with fluence and increase with increasing hoop stress.

• Theoretical single-crystal growth anisotropy exhibits expansion in the basal plane and contraction along the c-axis.
OSIRIS Creep Capsule Experiment: Strain Rate vs Hoop Stress

- Diametral strain rate increases with increasing temperature.
- Axial strain rate appears to be less affected by temperature.

- The stress dependence of irradiation creep rate on these capsule materials up to 160 MPa is shown to be approximately linear.
• Diametral strain rate increases with temperature while the axial strain rate has a relatively weaker temperature dependence.
• Irradiation creep anisotropy appears to be temperature dependent.
NRU Loop Tube Experiment: Effect of Cold Work

- The lower creep strength (higher creep rate) of material which has been cold-worked was rationalized to be the result of enhanced glide of dislocations.

E.F. Ibrahim, Deformation of Cold-Drawn Tubes of Zr-2.5wt%Nb After 7 Years In-Reactor, JNM 118 (1983) 260-268.
NRU Loop Tube Experiment: Effect of Cold Work

- The extrusion process resulted in a high concentration of basal poles in the axial direction which were subsequently reduced by cold-drawing.
- Tensile twinning flipped the grains towards the radial-transverse plane.
- Texture and cold work varied.

E.F. Ibrahim, Deformation of Cold-Drawn Tubes of Zr-2.5wt%Nb After 7 Years In-Reactor, JNM 118 (1983) 260-268.
• The effect of cold work appears to have a more significant effect on axial strain rate than on diametral strain rate.
OSIRIS Trillium-2 Experiment:
Strain vs Hoop Stress for Different Textured Capsules

Zr-2.5Nb material with two textures:
- pressure tube (PT) typical textured material where the concentration of basal plane normals are predominantly oriented in the tranverse direction ($f_T > f_R$)
- fuel sheath (FS) typical textured material ($f_R > f_T$)
Axial and diametral strain rate appear to have a strong texture dependence.
OSIRIS Creep Capsule Experiment: Creep Compliance vs Texture

- Were it not for the fuel-sheath textured capsules, a strong dependence on texture would not be evident for diametral strain rate.

**Creep Compliance**
- \( (m^2 \cdot n^{-1} \cdot MPa^{-1}) \)
- \( 1 \times 10^{-30} \)
- \( @ T=310^\circ C \)

**Graph**
- Plot of Creep Compliance vs. \( f_R \) for PT Diametral and FS Diametral samples.
OSIRIS Creep Capsule Experiment: Effect of Grain Size Aspect Ratio

Significant differences between the fabrication methods for the fuel sheath and pressure tube textured capsules resulted in different grain sizes:

Fuel sheath textured capsules:
• 0.8 μm radial grain thickness
• 1.1 μm transverse grain width
• radial/transverse aspect ratio is 0.7

Pressure tube textured capsules
• 0.4 μm radial grain thickness
• 5.0 μm transverse grain width
• radial/transverse aspect ratio is 0.08
• the PT grains are thinner and wider in the R-T plane
The high diametral strain of the fuel sheath textured capsules may not be explained by texture alone as grain size aspect ratio may also have an effect.
• These Zr-2.5Nb pressure tubes had a slightly different manufacturing route but have similar texture, dislocation density and operated at the same temperatures, hoop stress, axial location yet diametral strain is distinct.
TEM Micrographs of H and HM-series CANDU Pressure Tubes

H0081M

H1852

UNRESTRICTED / ILLIMITÉ
TEM Micrographs of H and HM-series CANDU Pressure Tubes

H0081M

H1852

UNRESTRICTED / ILLIMITÉ
TEM Micrographs of H and HM-series CANDU Pressure Tubes

LT

H0081M

H1852

R

UNRESTRICTED / ILLIMITÉ

L O T

Radial

Transverse

Radial

Transverse
CANDU Pressure Tube Data: Diametral Strain vs Grain Size Aspect

- Diametral strain appears to have a strong dependence on aspect ratio consistent with the results from the OSIRIS creep capsule data.
- An irradiation creep mechanism where diffusion of interstitials and vacancies to grain boundaries causes deformation.
Summary

The analysis of OSIRIS data combined with data from in-service CANDU tubes has revealed some significant observations regarding pressure tube deformation:

(i) diametral strain rate increases with temperature while the axial strain rate has a relatively weaker temperature dependence, i.e., irradiation creep anisotropy varies with temperature,

(ii) that whereas cold-work correlates with the axial strain rate of the capsules, there appears to be no statistically significant dependence of diametral strain rate on cold-work

(iii) texture appears to have a significant effect on axial strain rate and

(iv) diametral strain rate appears to have a strong dependence on grain size aspect ratio.

These results are consistent with a mass transport type mechanism for pressure tube deformation which is described in the paper.
Acknowledgements

Past and present members of the Deformation Technology Branch at Chalk River Laboratories.

Contributions to this paper and presentation were made by:

• Andrew Buyers (AECL-CRL)
• Stephen Donohue (AECL-CRL)
• Wenjing Li (AECL-CRL)
• Amy Fluke (AECL-CRL)
• Eric Nicholson (AECL-CRL)
• Nick VanDenBrekel (Ontario Power Generation)