ZIRLO™ Irradiation Creep Stress Dependence in Compression and Tension
16th ASTM Zirconium Symposium
Chengdu, China, 9-12 May 2010

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INTRODUCTION

- Data are from the Vogtle Unit 2 PWR Creep/Growth Program
- Results for SRA ZIRLO show:
  - In-reactor creep compliance is the same in tension and compression
  - If total in-reactor strain is split into growth and creep components:
    - Deviatoric hoop stress is the driving force for irradiation creep
    - Irradiation creep in tension is the same as compression
EXPERIMENTAL
Test Samples

• SRA ZIRLO
• 168 mm long
• Samples are either He pressurized or open on both sides to water
## Irradiation Schedule

<table>
<thead>
<tr>
<th>Cycle</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
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</thead>
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<td>Fall 02</td>
<td>Spring 04</td>
<td>Fall 05</td>
<td>Spring 07</td>
<td>Fall 08</td>
<td>Spring 10</td>
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</table>

### Assembly

<table>
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<tr>
<th>Assembly</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
<th>A5</th>
<th>A6</th>
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</tbody>
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Test Overview

- Test samples are irradiated in guide thimble positions using segmented insert rods
  - Test samples do not contain fuel
  - Samples are placed in outer row guide thimble positions
- Six assemblies
- Samples discharged for measurement are not reinserted
- Disassemble samples by shearing after the refueling outage in the pool and shipped to Hot Cell for examination
  - Measured by laser micrometer
Irradiation Conditions

- Data are available for 1 and 2 cycles (~17 months irradiation/cycle)
  - Temperature range 300-318 °C
  - No axial or radial fast flux gradient
    - Confirmed with retrospective dosimetry measurements
  - Cycle-to-cycle fast fluxes are approximately constant
    - Range between $9.3-9.7 \times 10^{13}$ n/cm$^2$-sec E$>1$ MeV
Stress Analysis

- $\sigma_\theta$, $\sigma_r$ and $\sigma_z$ stresses calculated with the thick-wall equations
- Deviatoric hoop stress,
  \[
  \sigma_\theta = \sigma_\theta(\text{deviatoric}) + \sigma(\text{hydrostatic})
  \]
  \[
  \sigma(\text{hydrostatic}) = (\sigma_\theta + \sigma_r + \sigma_z)/3
  \]
  - Deviatoric stress results in plastic strain (creep)
  - Hydrostatic stress does not result in plastic strain (creep)
Sample Design

SOLID CYLINDER INTERNAL MANDREL

- Black = Sample
- White = He Gas
- Red = Internal Mandrel

TUBE INTERNAL MANDREL

- Solid cylinder internal mandrel generates more heat than the tube internal mandrel
RESULTS and DISCUSSION
Gamma Heat Generation Rate [1/2]

Total Dia. Strain vs. Deviatoric Hoop Stress for Gamma Heat Gen. Rate of $1.60 \times 10^6$ Btu/h-ft$^3$
SRA STD ZIRLO, Vogtle Unit 2 Cycle 10 (Test Assembly A1)

- Linear behavior
- Calculated regression
  $R^2$ coefficient for different $\gamma$-heat rates
- Fit associated with highest $R^2$ coefficient
Gamma Heat Generation Rate

Regression $R^2$ Coefficient versus the Gamma Heat Generation Rate
SRA STD ZIRLO, Vogtle 2 Cycle 10 (Test Assembly A1)

- Determined gamma heat generation rate
- Calculated internal pressures and stresses using the gamma heat generation rate
RESULTS and DISCUSSION
In-Reacto r Creep Compliance (1 Cycle, Cycle 10) [1/3]

- Linear behavior
- In-reactor creep compliance (slope of the line) is the same in tension & compression
• Linear behavior

• In-reactor creep compliance (slope of the line) is the same in tension & compression

• Same $\Delta D/D_0$ vs. $\sigma_{\theta}\text{ (dev.)}$ behavior as Cycle 10 data
In-Reactor Creep Compliance (2 Cycles, Cycles 10-11)

[3/3]

Total Dia. Strain vs. Deviatoric Hoop Stress for Gamma Heat Gen. Rate of $1.20 \times 10^6$ Btu/h-ft$^3$
SRA STD ZIRLO, Vogtle Unit 2 Cycles 10 & 11 (Test Assembly A3)

- Linear behavior
- In-reactor creep compliance (slope of the line) is the same in tension & compression
Split Total In-Reactor Strain into Growth & Creep Components

$$\Delta D/D_o(\text{creep}) = \Delta D/D_o(\text{measured total}) - \Delta D/D_o(\text{growth})$$
Irradiation Growth

- Linear behavior
- Data includes samples open to water on both sides
- Determined irradiation growth strain by regression analysis
Irradiation Creep Hoop Stress Correlation

- Linear behavior
- Between -16 and 0 MPa, $\sigma_\theta$ is negative & $\Delta D/D_o$ is positive (the red line) – physically unrealistic
- $\sigma_\theta$ is not the correct driving force for irradiation creep
Irradiation Creep Deviatoric Hoop Stress Correlation (1 Cycle/Cycle 10)

- Linear behavior
- Data pass through the origin
- Deviatoric $\sigma_\theta$ is the driving force for irradiation creep
- Tension = compression
Irradiation Creep Deviatoric Hoop Stress Correlation (1 Cycle/Cycle 11)

- Linear behavior
- Data pass through the origin
- Deviatoric $\sigma_\theta$ is the driving force for irradiation creep
- $\Delta D/D_o$ vs. $\sigma_\theta$(dev.) same as Cycle 10 data
Irradiation Creep Deviatoric Hoop Stress Correlation (2 Cycle/Cycles 10-11)

- Linear behavior
- Data pass through the origin
- Deviatoric $\sigma_\theta$ is the driving force for irradiation creep
- Tension = compression
CONCLUSIONS

• For SRA ZIRLO,
  – In-reactor creep compliance is the same in tension and compression
  – If total in-reactor strain is split into growth and creep components:
    – Deviatoric hoop stress is the driving force for irradiation creep
    – Irradiation creep in tension is the same as compression
Thank you for your attention
PUBLICATIONS

- Initial 1 cycle results were reported in 15th International Symposium of Zirconium in the Nuclear Industry
- Initial 1 cycle dosimetry results were reported in Proceedings of the 13th International Symposium on Reactor Dosimetry