Experimental comparison of the behavior of E110 and E110G claddings at high temperature


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Introduction

E110 cladding (1%Nb) produced on electrolytic basis (traditional)

E110G produced from sponge material (new)

Preliminary information from fuel supplier:
• The excellent corrosion behaviour during normal reactor operation will not change
• Much better behaviour under accident conditions (no breakaway, slow embrittlement)
Motivation for Hungarian tests

- Execution of independent tests
- Covering wide ranges of parameters
- Use of facilities and expertise applied earlier for the investigation of E110 cladding at high temperatures
- Support licensing of new cladding for the Paks NPP, Hungary
Test program

- determination of the composition of the alloys
- phase transition studies
- ballooning and burst of tube samples with inner pressurization
- oxidation in steam atmosphere
- oxidation in hydrogen rich steam atmosphere
- investigation of breakaway effect
- mechanical testing of oxidized cladding samples
- determination of the hydrogen content of oxidized samples
- post-test examination of samples by optical and scanning electron microscopy
### Composition / by SSMS

<table>
<thead>
<tr>
<th>Element</th>
<th>E110</th>
<th>E110G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg (ppm)</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Al (ppm)</td>
<td>0.5</td>
<td>10</td>
</tr>
<tr>
<td>Si (ppm)</td>
<td>1</td>
<td>35</td>
</tr>
<tr>
<td>Cr (ppm)</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Mn (ppm)</td>
<td>0.1</td>
<td>5</td>
</tr>
<tr>
<td>Fe (ppm)</td>
<td>45</td>
<td>500</td>
</tr>
<tr>
<td>Ni (ppm)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Cu (ppm)</td>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td>Hf (ppm)</td>
<td>100</td>
<td>10</td>
</tr>
</tbody>
</table>

Russian data: C, Si, Ni, P, Cl, N, F, Al

99% Zr + 1% Nb
Phase transition studies

- calorimetric (DSC/DTA) és termomechanic measurements (TMA)
- temperature increase rates: 2.5–20 °C/min
- determination of onset and end of phase transition
- no change of phase transition temperatures compared to E110
Phase transition studies

Phase transition temperature (°C) vs Heating rate (°C/min)

- Red circle: onset E110G
- Red diamond: end E110G
- Blue dot: onset E110
- Blue diamond: end E110
Oxidation facility

- Parallel oxidation of E110 and E110G samples
- Steam + 12 vol% Ar
- Steam + 65 vol% H
- 600-1200 °C
Oxidation in steam

800 °C

Cathcart-Pawel

E110G

E110

ECR (%) vs Oxidation time (s)
Oxidation in steam

**Similar behaviour at**
- 600 °C
- 700 °C
- 1100 °C
- 1200 °C
Oxidation in steam

![Graph showing the oxidation of materials E110, Cathcart-Pawel, and E110G at 1000 °C over different oxidation times.](image)
Oxidation in steam

1000 °C

Similar behaviour at 900 °C
Oxidation in steam

\[ \begin{align*}
\text{900°C - 1200°C: } & \quad y = 8948.4e^{-1.4014x} \\
\text{600°C - 900°C: } & \quad y = 64.24e^{-0.8173x}
\end{align*} \]
Oxidation in steam

5000 s
900 °C

E110G  E110
H-uptake during oxidation

1000 °C

High H content of E110 after breakway

Below 100 ppm H for E110G
Oxidation in H-rich steam

- E110G 900 °C steam
- E110 900 °C steam
- E110 900 °C steam+H₂
- E110G 900 °C steam+H₂

ECR (%) vs Oxidation time (s)
Breakaway oxidation

1000 °C

TCD signal (mV)

time (s)
Balloonning and burst tests

- Isothermal conditions (700-1200°C) in argon atmosphere
- Linear pressurization with 0.007-6 bar/s rates
- Pre-oxidation at 900°C-on (selected samples)
Ballooning and burst

The graph shows the relationship between burst pressure (in bar) and pressurization rate (in bar/s) for different temperatures:

- 800°C
- 900°C
- 1000°C
- 1200°C
- 700°C

The burst pressure increases significantly with an increase in pressurization rate, especially at higher temperatures.
Ballooning and burst

![Graph showing the relationship between temperature (°C) and burst pressure (bar) for two different materials, E110 and E110G. The graph indicates a burst pressure of 0.08 bar/s.](image-url)
Ring compression tests

Mechanical load bearing capability

Determination of ductile-to-brittle transition

- INSTRON 1195 tensile test machine
- crosshead: 0,5 mm/min
- 20 °C and 135 °C
- load-displacement curves
Ring compression tests

After oxidation at 1000 °C for 3600 s
Fracture surface

E110G

E110

After oxidation at 1000 °C for 3600 s
Ductile-to-brittle transition

\[ t \sim \exp \left( \frac{Q}{T} \right) \]

Oxidation time (s)

10000
1000
100

brittle
ductile

1000/T (1/K)

0.6 0.7 0.8 0.9 1.0 1.1 1.2

E110
Ductile-to-brittle transition

Oxidation time (s)

10000

1000

100

0.6 0.7 0.8 0.9 1.0 1.1 1.2

1000/T (1/K)

ductile-to-brittle transition

brittle

ductile

E110G
The behaviour of E110 and E110G claddings was studied in high temperature experiments.

The non-oxidised E110 and E110G samples showed similar behaviour:

- Phase transition
- Ballooning and burst

Significant difference in oxidising conditions, better behaviour of E110G compared to E110

- Oxidation kinetics
- Breakaway oxidation
- Hydrogen uptake
- Mechanical load bearing capabilities, ductile-to-brittle transition
Thank you for your attention