High Temperature Zr Cladding Oxidation, Hydriding and Embrittlement

Presented by
Mikhail S. VESHCHUNOV
Nuclear Safety Institute (IBRAE)
Russian Academy of Sciences

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Outline:

- **Introduction**: Mechanistic Code SFPR for Modelling Single Fuel Rod Performance under Various Regimes of LWR Operation, including Design-Basis and Severe Accidents
  - High Temperature Zr Cladding Oxidation
  - High Temperature Zr Cladding Hydriding
  - High Temperature Zr Cladding Embrittlement
  - Zr Cladding Embrittlement under LOCA Conditions
  - SFPR Code: Development Plan
Introduction:
Mechanistic Code SFPR for Modelling Single Fuel Rod Performance under Various Regimes of LWR Operation, including Design-Basis and Severe Accidents
SFPR code

**Single Fuel Rod ↔ Performance**

**SVECHA code**
- Mechanistic modeling thermo-mechanical and physico-chemical behavior of a single LWR fuel rod
- Initially designed for SA regimes, extended to normal operation conditions
- Collaboration of IBRAE with IRSN (France), FZK (Germany) JRC/IE, US NRC.

**MFPR code**
- Mechanistic modeling fission product release from irradiated UO₂ fuel
- Various regimes of reactor operation, including severe accidents (SA), and high burnups
- Collaboration of IBRAE with IRSN (France).
Single-Rod Code SVECHA
Development and Assessment

Objectives
advanced mechanistic models for oxidation, hydriding and chemical interactions of LWR fuel rod materials and thermo-mechanical deformations of cladding and pellet, tightly coupled within the code initially designed for modeling single-rod tests

Development
IBRAE with support of FZK, IRSN and JRC/IE in the framework of European projects:
4th FP (COBE & CIT Projects), 5th FP (COLOSS);
ISTC Projects #1648 & #2936, bi-lateral projects

Validation
QUENCH Rig (FZK: COBE & CIT), BOX Rig (FZK: COLOSS), AEKI Rod Degradation (COLOSS), QUENCH Bundle (FZK: ISTC), Phebus FPT0 and FPT1 interpretation (JRC/IE: SARNET)

Applications
after verification and subsequent simplification, specific separate-effect models were implemented in integral codes:
ICARE2 (collaboration IRSN),
SCDAP/RELAP (collaboration US NRC),
SOCRAT (collaboration ATOMENERGoproject and ROSATOM)
Important features:

• Mechanistic simulation of clad multi-layered structure + core degradation (eutectic interactions, molten pool formation, oxidation and relocation, etc.)

• Initially designed for SA, the code inherited the mechanistic approach in application to normal operation conditions.
High Temperature
Zr Cladding
Oxidation
Cladding Oxidation Kinetics

ANL oxidation tests train assembly (from Yan et al., JNM, 2009)
Cladding Oxidation Kinetics

Oxidation of Zry-4 alloy at temperatures of 700-950°C:
a) 700 °C;  b) 800 °C;  c) 900 °C;  d) 950 °C
Oxidation of Zry-4 alloy at temperatures of 1000-1200°C:

a) 1000 °C;  b) 1050 °C;  c) 1100 °C;  d) 1200 °C
Cladding Oxidation Kinetics

Post-transition oxidation (break-away effect)

Appearance of E110 alloy after steam oxidation for:

a) 5s at 1000 °C;  
b) 290s at 950 °C;  
c) 400s at 1000 °C
Cladding Oxidation Kinetics

Oxidation rate exponent of Zr alloys with temperature
(Baek et al., KAERI, JNM 335 (2004) 443)

$\Delta G = K \cdot t^{1/n}$
Cladding Oxidation Kinetics

Parabolic ZrO$_2$ scale growth according to literature sources

$L_{ox} = K_{ox} t^{1/2}$
Cladding Oxidation Kinetics

Comparison of mass gain rates

\[ G_{ox} = K_T t^{1/2} \]
## Cladding Oxidation Kinetics

**Parabolic correlations**

\[
G_{ox} = K_T t^{1/2} \quad K = A \cdot \exp\left(-\frac{Q}{RT}\right)
\]

### Assessed parabolic coefficients

<table>
<thead>
<tr>
<th>Oxygen mass gain (kg/m²/s¹/²)</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urbanie–Heidrick</td>
<td>(1.908 \times \exp\left(-0.70 \times 10^5/RT\right))</td>
<td>±30%</td>
</tr>
<tr>
<td>Cathcart–Pawl</td>
<td>(6.02 \times \exp\left(-0.836 \times 10^5/RT\right))</td>
<td>±6%</td>
</tr>
<tr>
<td>Leistikow–Schanz</td>
<td>(7.24 \times \exp\left(-0.871 \times 10^5/RT\right))</td>
<td>±10%</td>
</tr>
<tr>
<td>Urbanie–Heidrick</td>
<td>(3.289 \times \exp\left(-0.691 \times 10^5/RT\right))</td>
<td>±50%</td>
</tr>
<tr>
<td>Prater–Courtright⁹</td>
<td>(57.4 \times \exp\left(-1.1 \times 10^5/RT\right))</td>
<td>±40%</td>
</tr>
</tbody>
</table>

### Oxide scale growth (m/s¹/²)

<table>
<thead>
<tr>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urbanie–Heidrick</td>
<td>(3.6 \times 10^{-4} \times \exp\left(-0.565 \times 10^5/RT\right))</td>
</tr>
<tr>
<td>Cathcart–Pawl</td>
<td>(1.5 \times 10^{-3} \times \exp\left(-0.751 \times 10^5/RT\right))</td>
</tr>
<tr>
<td>Leistikow–Schanz</td>
<td>(2.8 \times 10^{-3} \times \exp\left(-0.840 \times 10^5/RT\right))</td>
</tr>
<tr>
<td>Urbanie–Heidrick</td>
<td>(1.4 \times 10^{-3} \times \exp\left(-0.665 \times 10^5/RT\right))</td>
</tr>
<tr>
<td>Prater–Courtright</td>
<td>(0.0546 \times \exp\left(-1.182 \times 10^5/RT\right))</td>
</tr>
</tbody>
</table>

⁹ Based on deduced values. \(R = 8.31 \text{ J/K/mol}\).
Cladding Oxidation Model

- Simulates kinetics of fuel cladding oxidation and physico-chemical interactions with fuel pellet (UO₂/Zr/steam)
- Based on numerical treatment of oxygen diffusion through multi-layered structure of the interaction system – up to 7 layers
- Best-estimate diffusion coefficients for ZrO₂, α-Zr(O) and β-Zr for Zry-4 and Zr1%Nb (E110)
- Tightly coupled with cladding thermo-mechanical module
Cladding Oxidation Model

\[
\frac{\partial c_i}{\partial t} + v_i(r,t) \frac{\partial c_i}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left( rD_i(r,t) \frac{\partial c_i}{\partial r} \right)
\]

Diffusion equation

\[
(c_i^{(1)} - c_i^{(2)}) \frac{dr_i}{dt} = D_{i-1} \frac{\partial c_{i-1}}{\partial r} \bigg|_{r=r_i} - D_i \frac{\partial c_i}{\partial r} \bigg|_{r=r_i} + c_i^{(1)}v_i^{(1)} - c_i^{(2)}v_i^{(2)}
\]

\[
(\rho_i - \rho_{i-1}) \frac{dr_i}{dt} = \rho_i v_i^{(1)} - \rho_{i-1} v_{i-1}^{(2)}
\]

Flux matches

**Diagram**

- **BETA**
- **ALPHA**
- **OXIDE**

- \( C_{\beta/\alpha} \)
- \( C_{\alpha/\beta} \)
- \( C_{\alpha/f} \)
- \( C_{f/\alpha} \)
- \( C_{f/\omega} \)
- \( \phi \)
- \( r_1 \)
- \( r_2 \)
- \( r_3 \)
- \( r \)
Cladding Oxidation Model

Microstructural changes of Zry-4 during oxidation
Boundary conditions

Binary phase diagram Zr-O, assessed in (Abriate et al., 1986)
Cladding Oxidation Model

Oxygen diffusion coefficient in oxide

$D_f, \text{cm}^2/\text{s}$

$T, \text{C}$

- Zry-4 calc. from [6]
- Zry-4 calc. from [7] by metallography
- Zry-4 calc. from [7] by weight gain
- Zr-1%Nb present work

Calculated oxygen diffusion coefficients in $\text{ZrO}_2$ for Zr1%Nb и Zircaloy-4
Calculated oxygen diffusion coefficients in $\alpha$-Zr for Zr1%Nb и Zircaloy-4
Cladding Oxidation Model
Isothermal conditions

Analysis of KfK tests with Zry-4

Calculation results for oxide thickness (solid lines) in comparison with experimental results (dashed lines)

S. Leistikow, G. Schanz (KfK, 1978)
Cladding Oxidation Model
Isothermal conditions

Analysis of RIAR tests with Zr-1%Nb

Simulation of the $\alpha$-Zr and ZrO$_2$ layers growth kinetics in the RIAR isothermal tests on Zr-1%Nb cladding oxidation in steam at 1000 and 1100ºC
Cladding Oxidation Model
Isothermal conditions

Analysis of RIAR tests with Zr-1%Nb

Simulation of the $\alpha$-Zr and ZrO$_2$ layers growth and weight gain kinetics in the RIAR isothermal tests on Zr-1%Nb cladding oxidation in steam at 1200ºC
Validation of Oxidation Model against transient oxidation tests

FZK tests (P. Hofmann)

**Conclusion**: being developed on the base of steady-state isothermal oxidation tests, the model demonstrates good agreement with transient tests data owing to:

- mechanistic approach (diffusion equations, \( D(T(t)) \));
- coupling with Mechanical Deformation model (influence of oxide microcracking)
Oxidation kinetics under steam starved conditions

Oxygen flux

Boundary conditions

Evolution of layer structure

Mole fraction of water in H₂O - H₂ gas mixtures in equilibrium with hypostoichiometric ZrO₂ (from Olander, 1994)
High Temperature
Zr Cladding
Hydriding
Zr-H Equilibrium Phase Diagram

E. Zuzek et al.
Bulletin of Alloy Phase Diagrams
Vol. 11, No.4 (1990) 385-395

Zr-H binary phase diagram
Hydrogen solubility in Zr

\[ 2\text{H}_2\text{O} + \text{Zr} \leftrightarrow \text{ZrO}_2 + 2\text{H}_2 + \Delta_r H \]

\[ \text{H}_2\text{(gas)} \leftrightarrow 2\text{H}_\text{(abs)} + \Delta_s H \]

\[
\left( \frac{\text{H}}{\text{Zr}} \right)_{\text{at}} = K_S \cdot \sqrt{p_{\text{H}_2}}
\]

\[ K_S = \exp \left( \frac{\Delta_s S}{R} - \frac{\Delta_s H}{RT} \right) \]

- Sieverts law
- Sieverts constant
Hydrogen solubility in Zr
Experimental studies

M. Steinbrueck (FZK, 2004)
Gaseous Hydriding Model

Zr-H₂ interaction kinetics

- Dissolution of hydrogen in Zr metal as neutral atoms:
  \[ H_2(g) = 2H_{ab}(m) \]

- Sieverts law:
  \[ C_H(s) = K_S P_H^{1/2}(s) \]

- Hydrogen transport:
  \[ 2k_{H_2} \left( P_{H_2}(b) - P_{H_2}(s) \right) = -D_H \frac{\partial C_H}{\partial r} \left| \frac{P_{tot} - P_{H_2}(s)}{P_{tot}} \right| \]

- Thin Zr layer: \( \tau_D \approx L^2 / D_H << t_{exp} \)
  \[ \frac{L}{2} \frac{dC_H}{dt} = \frac{k_{H_2}}{RT} \left( P_{H_2}(b) - \frac{C_H^2}{K_S^2} \right) \]
Model Verification

FZK tests on hydrogen uptake by Zry-4 cladding in H₂ atmosphere
(M. Steinbrueck, 2004)

\[ C_H(t) = K_S P_{H_2}^{1/2} (b) \frac{1 - \exp(-2t\gamma)}{1 + \exp(-2t\gamma)} \]

\[ C_H(t) = \frac{C_{H,0}}{1 + \gamma_1 t} \]

P_{H_2} = 0/0.5 bar

Uptake:

P_{H_2} = 0.2/0.6 bar

Release:
Hydrogen solubility in ZrO$_2$

Experimental studies

Park and Olander, 1991: gaseous H$_2$ hydriding of ZrO$_2$

Conditions: T=1300-1600°C, $P_{H_2} \approx$ 10 bar

Interpretation: $H_2(g) = 2H(ox)$ $\Rightarrow$ $[H] \propto P_{H_2}^{1/2}$

Sieverts law (in agreement with observations)

Results: H solubility: $[H] \sim 10^{-5}$,

H mobility: $\rightarrow 0$ (strong trapping)

Conclusion: ZrO$_2$ is impermeable for neutral H

Wagner, 1968: H$_2$O dissolution in Yt-stabilized ZrO$_2$

Conditions: T=900, 1000°C, $P_{H_2O} \approx$ 10$^{-2}$ bar

Interpretation: $H_2O(g) + V_0^{2+} = 2H_i^+(ox) + O(ox)$ $\Rightarrow$ $[H_i^+] \propto P_{H_2O}^{1/2}$; (in agreement with observations)

Results: H solubility: $[H_i^+] \sim 10^{-5}$, ($P_{H_2} \sim 10^{-8} \times P_{H_2}$ (Park & Olander) !)

H mobility: $D_{H^+} \sim 10^{-6}$ cm$^2$/s.

Conclusion: ZrO$_2$ is permeable for protons H$^+$

Fundamentally different dissolution mechanisms (neutral H / protons H$^+$)
Hydrogen uptake model  (1/2)

- Dissociation of water molecules in the gas phase:
  \[ 2H_2O(g) = O_2(g) + 2H_2(g) \]  (1)
- Dissolution of oxygen in oxide:
  \[ O_2(g) + 2V_{O}^{2+} + 4e^{-}(ox/g) = 2O_O(ox) \]  (2)
- Dissolution of hydrogen in oxide as neutral atoms:
  \[ H_2(g) = 2H_{ab}(ox) \]  (3)
- Dissolution of hydrogen in oxide as protons:
  \[ H_2(g) = 2H_{ab}^+(ox) + 2e^{-}(ox/g) \]  (4)

Eq. (3) corresponds to Park & Olander’s mechanism:
- gaseous H₂ hydriding of ZrO₂:
  \[ H_2(g) = 2H_{ab}(ox) \]

Superposition of (1), (2) and (4) corresponds to Wagner’s mechanism:
- dissolution of water molecules in oxide:
  \[ H_2O(g) + V_O^{+2+} = 2H_{ad}^+ + O_O(ox) \]

➤ Wagner’s mechanism of water molecules dissolution in ZrO₂ might be responsible for high hydrogen uptake during Zr oxidation in steam
Hydrogen uptake model  (2/2)

**Mass action laws**

\[ P_{H2O}(s)^2 = k P_{H2}(s)^2 P_{O2}(s) \]

\[ P_{O2}(s) C_v^2 C_e^4 = \beta \]

\[ \gamma P_{H2}(s) = C_{H+}^2 C_e^2 \]

\[ C_H = K_S P_{H2}(s)^{1/2} \]

**Solution**

\[ 2(\frac{k^{1/2} \beta^{1/2}}{\gamma}) C_{H+}^3 / P_{H2O}(s) + C_{H+}^2 - \gamma^{1/2} P_{H2}(s)^{1/2} = 0 \]

**Charge neutrality condition**

\[ 2C_v + C_{H+} = C_e \]

If \( P_{H2} \ll P_{H2O} \) \( \Rightarrow \)

\[ C_{H+} \propto P_{H2}(s)^{1/4} \gg C_H \propto P_{H2}(s)^{1/2} \]

➢ In steam atmosphere hydrogen is dissolved (and transported) in \( \text{ZrO}_2 \) mainly in the form of protons (with high mobility)
Hydrogen transfer in oxide phase

Steady-state approximation

\[ J_O(\text{ox}) = D_O^{(\text{ox})} \Delta C_O / \delta(t) \]

\[ J_H(\text{ox}) = D_H^{(\text{ox})} \Delta C_{H^+} / \delta(t) + D_H^{(\text{ox})} \Delta C_H / \delta(t) \]

Experimental data

B. Cox, 1976 (review): H\textsubscript{2} dissolution in thin layers of ZrO\textsubscript{2} on Zr substrate,
Results: \( \Delta^* \sim 1 \mu \text{m}, \) ZrO\textsubscript{2} becomes permeable for H.

Schanz et al., 1984:
Zry interactions with H\textsubscript{2}/H\textsubscript{2}O mixtures
Conditions: T=800 - 1300°C
Interpretation: mass gain in the initial period can be attributed to the hydrogen absorption

Model assumption

Two different regimes of H (neutral) mobility in the oxide:

\[ \Delta > \Delta^* \sim 1 \mu \text{m}, \quad \Rightarrow \quad D_H^{(\text{ox})} << D_H^{(\text{ox})}. \]
\[ \Delta < \Delta^* \sim 1 \mu \text{m}, \quad \Rightarrow \quad D_H^{(\text{ox})} - \text{finite value} \]

Moalem and Olander, 1991:
Zry interactions with H\textsubscript{2}/H\textsubscript{2}O mixtures
Results: similar to G. Schanz
KIT Tests on Hydrogen Uptake by Neutron Radiography (M. Grosse et al.)

In-situ NeutronenRadiographie ReaktionsOfen

Scheme of INRRO furnace
KIT Tests on Hydrogen Uptake by Neutron Radography (M. Grosse et al.)

Fig. 4 Neutron radiographic image and normalized horizontal intensity distribution of specimens oxidized at 1,000 °C for 7,200 s
Tests simulations

KIT tests on hydrogen uptake by Zry-4 cladding during isothermal oxidation in steam (50 l/h Ar + 50 g/h H₂O )

- **Graph 1:**
  - Title: H₂ Concentration (vol. %)
  - X-axis: Time (h)
  - Y-axis: H₂ Concentration (vol. %)
  - Data points for T = 1373 K

- **Graph 2:**
  - Title: H/Z atomic ratio (%)
  - X-axis: Time (s)
  - Y-axis: H/Z atomic ratio (%)
  - Data points for T = 1373 K

- **Graph 3:**
  - Title: H/Z atomic ratio (%)
  - X-axis: Time (s)
  - Y-axis: H/Z atomic ratio (%)
  - Data points for T = 1473 K

- **Graph 4:**
  - Title: H/Z atomic ratio (%)
  - X-axis: Time (s)
  - Y-axis: H/Z atomic ratio (%)
  - Data points for T = 1673 K
Tests simulations

KIT tests on hydrogen uptake by Zry-4 cladding during isothermal oxidation in steam (30 l/h Ar + 30 g/h H₂O at 1473 K)
Hydrogen Uptake under normal operation conditions

**Coupling of 2 models:**

- Hydrogen absorption mechanism;
- Mass transfer through 2-phase zone (hydrides in metal Zr)

**Predictions:**

- Non-uniform distribution of hydrides (owing to oxygen concentration profile);
- Close to parabolic hydriding kinetics:

\[ M_H \propto t^{9/16} - t^{3/8} \approx t^{1/2} \]

Metallographic cut of the rod cladding
High Temperature
Zr Cladding
Embrittlement
Cladding Embrittlement Criteria

Criterion 17%-ECR (and T<1204°C)

Failure-nonfailure boundary for fully constrained Zircaloy-4 after oxidation in steam and quenching as function of oxidation time and temperature; total oxidation calculated with Baker-Just equation is also indicated (from Uetsuska et al., J. Nucl. Sci. Tech. 20, 1983, pp. 941-950).
Cladding Embrittlement Criteria

Criterion 17%-ECR (and T<1204°C)

Chung and Kassner (ANL, 1980)
Chung-Kassner advanced criterion

- Capability to withstand the different loading modes depends on thickness of and oxygen distribution in $\beta$-Zr layer:

1. **Capability to withstand thermal shock during LOCA reflooding:**
   Calculated thickness of the cladding with $\leq 0.9$ wt % oxygen should be greater than 0.1 mm.

2. **Capability to withstand fuel handling, transport and storage:**
   Calculated thickness of the cladding with $\leq 0.7$ wt % oxygen should be greater than 0.3 mm.

Low hydrogen content $< 700$ w. p.p.m. !!
Double-side oxidation
(interactions with UO$_2$ pellet)

- In the case of solid contact between pellet and cladding, Zry reduces UO$_2$ to form oxygen stabilized $\alpha$-Zr(O) (internal) and (U,Zr)-alloy.
- The external cladding interaction with oxygen or steam results in the formation of $\alpha$-Zr(O) (external) and ZrO$_2$.
- The internal and external $\alpha$-Zr(O) layers of the cladding grow $\approx$ with the same rates. Initially the reaction-layer growth obeys a parabolic rate law. After the disappearance of $\beta$-phase, the cladding tube is completely embrittled and no more mechanically stable.
Diffusion Model for Double-Side Oxidation

$T = 1700 \text{ K}$
Cladding Embrittlement due to “Fuel Bonding”

- Formation of Zr(O) layer at the inner surface of the cladding as a result of UO₂/Zr chemical interaction (“bonding”) can lead to cladding embrittlement even in the absence of oxidation atmosphere at the outer cladding surface.

Maximum extent of oxidation and fuel-pellet interaction to remain intact under thermal shock.
Cladding Embrittlement Criteria

Effect of hydrogen uptake

700 w.p.p.m.
Cladding Embrittlement Criteria

Combined effect of oxygen and hydrogen uptake

Chung & Kassner 1980

for fresh Zircaloy-4 burst and oxidized in steam near 1 atm. pressure

Post-quench ductility shown as function of oxidation (beta-layer centerline oxygen content) and total hydrogen content, from diametral compression test at 23°C on burst, oxidized, slow-cooled, and quenched Zircaloy-4 tubes (for database see Ref. 17).
Zr Cladding Embrittlement under LOCA Conditions
Observations in KIT Tests
(Stuckert et al., 2012)

Temperature escalation at different elevations and appearance of ballooned zones
Observations in KIT Tests
(Stuckert et al., 2012)

External and internal cladding oxidation

- Ballooning zone
- Non-deformed zone
Observations in KIT Tests
(Stuckert et al., 2012)

Secondary hydriding of cladding

Increased microhardness at positions of hydrogen rich bands
Observations in ANL Tests
(M. Billone et al., 2008)

Temperature and pressure histories

Post-test appearance
Axial distribution of oxygen and hydrogen content for:

- OCL#22 sample held at 1204°C for 1 s (left);
- OCL#17 sample held at 1204°C for 120 s (right).
Observations in JAERI Tests
(Uetsuka et al., 1981)

Distributions of hydrogen content, inner-diameter oxide layer thickness, and total deflection at 100°C of ring specimens sectioned from burst region (from Uetsuka et al., Refs. 32 and 33).
Modification of Gas Kinetics Module

Processes:

- Oxidation of clad outer surface and transport of gas mixture (H₂O-H₂-Ar) in channel
- Oxidation/hydriding of clad inner surface and transport of gas mixture in gap
- Flux matching at breach position
Modification of Gas Kinetics Module

Transport in gap:

\[ \frac{\partial n_i}{\partial t} = D_i \frac{\partial^2 n_i}{\partial z^2} - \frac{\partial}{\partial z} (n_i u) + Q_i(z,t) \]

\( n_i(z,t) \) - concentrations of gas components (1 = H₂O, 2 = H₂, 3 = Ar, 4 = ...)

\[ n = \sum_i n_i, \quad P(t) = n(t)kT(t), \quad D_k(P,T) = \left[ \sum_{i \neq k} \frac{x_i}{D_{k,i}(P,T)} \right]^{-1}, \quad x_i = \frac{n_i}{\mu_i} \left[ \sum_i \frac{n_i}{\mu_i} \right] \]

\( Q_{H_2O}(z,t) = -q_{H_2O}(z,t) \) - H₂O sink (calculated by oxidation kinetics module with consideration of steam starvation)

\( Q_{H_2}(z,t) = q_{H_2O}(z,t) - q_{H_2}(z,t), \quad \text{where} \]

\( q_{H_2}(z,t) \) - H₂ sink (calculated by hydriding kinetics module)

\( u(z,t) \) - gas net velocity, induced by:

1) pressure drop between inner and outer after breaching (~ 38s);
2) gas thermal expansion (during temperature escalation);
3) gas advection due to H₂ uptake by cladding (Stefan flow)

\[ Q_i = -D_i \frac{dn_i}{dx} \bigg|_{x=0} + u_i(0)n_i(0) = \alpha_i \left( n_i(0) - n_i^{(ext)} \right) \] - flux matching at breach position

\[ \alpha_i \approx K \frac{D_i S_d}{V_{cl} d}, \quad K \approx 50 \quad \text{- best fit} \]

Simulation of QL0 Test (1/6)

Temperature distribution

Temperature evolution at the burst position

Cladding temperature axial distribution at the calculation time moments 40 s, 60 s and 80 s
Simulation of QL0 Test (2/6)

Burst geometry

Axial distribution of rod dimensions at bundle elevations from 1150 to 850 mm
Simulation of QL0 Test (3/6)

Gas partial pressures in gap

Gap gas components partial pressures axial distribution at the time moments 40 s, 60 s and 75 s
Simulation of QL0 Test (4/6)

Internal oxidation

Specimen inner surface oxidation layers thicknesses axial distribution at the time moments 40 s, 60 s and 75 s
Simulation of QL0 Test (5/6)

Cladding oxygen content due to double-side oxidation

Axial distribution of total oxygen content at the calculation time moments 40 s, 60 s and 75 s
Simulation of QL0 Test (6/6)
Cladding hydriding

Axial distribution of cladding total hydrogen content at time 40 s, 60 s and 75 s.

<table>
<thead>
<tr>
<th>Exp. Rod</th>
<th>#1</th>
<th>#7</th>
<th>#3</th>
<th>#14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation period</td>
<td>~ 74 s</td>
<td>~ 71 s</td>
<td>~ 64 s</td>
<td>~ 32 s</td>
</tr>
<tr>
<td>Hydrogen (w.p.p.m.)</td>
<td>2560</td>
<td>2140</td>
<td>1940</td>
<td>1050</td>
</tr>
</tbody>
</table>
Simulation of ANL Test OCL #17

Temperature distribution

Temperature evolution at the burst position

Cladding temperature axial distribution at the calculation time moments 60 s, 80 s and 200 s
Simulation of ANL Test OCL #17 (2/7)

Burst geometry

Axial distribution of rod dimensions
Simulation of ANL Test OCL #17(3/7)
Gas partial pressures in gap

Gap gas components partial pressures axial distribution at the time moments 60 s, 80 s and 200 s
Simulation of ANL Test OCL #17(4/7)
Internal oxidation

Specimen inner surface oxidation layers thicknesses axial distribution at the time moments 60 s, 80 s and 200 s
Axial distribution of gap gas partial pressures (*left*)
and of outer surface oxidation layers thicknesses (*right*)
at the time moments 60 s, 80 s and 200 s
Simulation of ANL Test OCL #17 (6/7)
Cladding oxygen content due to double-side oxidation

Axial distribution of total oxygen content at the calculation time moments 60 s, 80 s and 260 s
Simulation of ANL Test OCL #17 (7/7)

Cladding hydriding

Axial distribution of cladding total hydrogen content at times 60 s, 80 s and 100 s in comparison with experimental measurements
SFPR Code: Development Plan

- The first version of the fuel performance code SFPR, designed by coupling of MFPR with the mechanistic thermo-mechanical module SVECHA, was released and tested in 2008.

- Validation (by IBRAE) and commercial applications to operation conditions of the new VVER-2006 reactor design (by ATOMENERGOPROECT) started in 2009.

- Implementation of SFPR module in the advanced version of the Russian integral best-estimate safety code SOCRAT (for LWRs), started in 2010 (Russian collaboration under IBRAE coordination).

- Extension to the Fast Reactor (FR) fuel and implementation in the new generation integral code EUCLID (developed under IBRAE coordination) for FR design and safety justification, within the new Russian Federal Target Program “Nuclear Power Technologies of a New Generation for the years 2010-2015 with a perspective to 2020”.