Operating experience of a Swiss BWR (KKL)

Jens Heldt
Leibstadt NPP
Contents

Introduction

Indications of EAC in Reactor Water

SCC of DMW

Concluding Remarks
Introduction
Leibstadt Nuclear Power Plant (KKL)

- BWR/6, 1275 MWe
  
  **EPU of 114% accomplished in 2003**
  + LP turbine refurbishment in 2010
  + new turbine generator in 2012
  + new moisture separator reheater in 2017
  + new condenser in 2020
  
- Mark III containment

- Commercial operations: 1984

- Newest and largest NPP in Switzerland

- Located at the River Rhine on the border between Switzerland & Germany
EAC in Reactor Water
KKL EAC in Reactor Water

Findings

Three different kinds of indications so far:

- Recirculation loop piping
- Core shroud (horizontal weld)
- Dissimilar Metal Weld (DMW) of feed water nozzle to safe end
Recirculation Loop Piping

- Made out of 316 NG
  low carbon content < 0.02 % (from 0.007 to 0.018%)

- Most of all indications found at shop welds made by Hitachi
  acceptable according ASME Code Sect. XI

- Augmented inspections by UT

- All indications did not show growth since 2001
  in accordance with the observations made for Japanese recirc. piping

* = e.g. K.Kumagai et.al. Proceedings of ASME-PVP 2004: 2004 ASME/JSME Pressure Vessels and Piping Conference
San Diego, California, July 25 – 29, 2004
Core Shroud

- Made out of 304L / 308L
- OD of Weld SD-007: two small indications found by VT in 2012
  maximum length of 22 mm
- Reinspection after 2 und 5 years revealed no apparent change of both indications
Indications in Core Shroud

2012

2014

~ 10 mm
Indications in Core Shroud

Qualified IVVI

~ 10 mm
SCC of DMW
DMW of Feed Water Nozzle to Safe End

- Ferritic nozzle and safe end
- DMW: Alloy 182 (Butter) / Alloy 82
- No Mechanical Stress Improvement (MSIP)
- ID-connected axial indication found in 2012
- Reevaluation of prior UT-inspection in 2004
  - ~1.5 mm/year crack growth
- Full Structural WOL with Alloy 52
RPV Nozzle Dissimilar Metal Welds (DMW)
Outage 2012: Indication overlaid at N5-nozzle

- Axial orientation
- Found in weld metal
- Length 22 mm (*shorter at base?*)
- Depth 26 mm (~93% wall thickness)
- Multifaceted and branched
- Emanating from edge of ID weld repair
- Clear ID connection
- Flaw is indicative of interdendritic stress corrosion cracking

Axial orientation (schematic)
After WOL Repair: Additional Laboratory Tests

Material Alloy 52 tested with the identical:

- Chemical composition
- Welding parameters

Test conducted:

- Elevated temperature tension tests in air
- Fracture toughness tests in air
- SCC tests under simulated BWR-conditions
Elevated Temperature Tension Tests

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sp. #1</th>
<th>Sp. #2</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E [GPa]</td>
<td>171</td>
<td>167</td>
<td>169</td>
</tr>
<tr>
<td>YS₀.₂ [MPa]</td>
<td>260</td>
<td>262</td>
<td>261</td>
</tr>
<tr>
<td>UTS [MPa]</td>
<td>430</td>
<td>440</td>
<td>435</td>
</tr>
<tr>
<td>FS = (UTS+YS)/2 [MPa]</td>
<td>345</td>
<td>351</td>
<td>348</td>
</tr>
<tr>
<td>UE [%]</td>
<td>31</td>
<td>32.5</td>
<td>31.8</td>
</tr>
<tr>
<td>EF [%]</td>
<td>45.4</td>
<td>45.7</td>
<td>45.6</td>
</tr>
<tr>
<td>RA [%]</td>
<td>77.2</td>
<td>82.9</td>
<td>80.1</td>
</tr>
</tbody>
</table>

T = 288 °C, ds/dt ~ 10⁻³ s⁻¹
KKL Alloy 52

Necking outside extensometer in Sp 2
Sp 2, post necking with compl. corr. trav. displ
Sp 2, with extensometer
After WOL Repair: Additional Laboratory Tests

Fracture Toughness Tests according to ASTM E1820-13

<table>
<thead>
<tr>
<th>Sp</th>
<th>Type</th>
<th>$a_0$ [mm]</th>
<th>$\Delta a$ [mm]</th>
<th>$\Delta a_{ULC}$ [mm]</th>
<th>$J_Q$ [kJ/m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2b</td>
<td>0.5T C(T)</td>
<td>12.37</td>
<td>3.06</td>
<td>3.10*</td>
<td>1089**</td>
</tr>
<tr>
<td>2c</td>
<td>0.5T C(T)</td>
<td>13.20</td>
<td>1.30</td>
<td>1.30</td>
<td>1118</td>
</tr>
<tr>
<td>2d</td>
<td>0.5T C(T)</td>
<td>13.35</td>
<td>2.65</td>
<td>1.97</td>
<td>948</td>
</tr>
<tr>
<td>1a</td>
<td>1T C(T)</td>
<td>26.80</td>
<td>2.80</td>
<td>2.81</td>
<td>1420</td>
</tr>
<tr>
<td>1b</td>
<td>1T C(T)</td>
<td>26.80</td>
<td>4.10</td>
<td>3.53</td>
<td>914</td>
</tr>
</tbody>
</table>

High toughness confirmed
SCC Tests in a high-temperature water loop
SCC Tests in a high-temperature water loop

KKL Alloy 52
PPU & constant load
2 ppm DO, 50 ppb SO$_4^{2-}$

Load [kN]

Time [h]

Δ$a_{EAC}$ [μm]

Sp1: 2e
~ 32.9 MPa·m$^{1/2}$

Sp2: 2f
~ 21.6 MPa·m$^{1/2}$
SSC Tests in a High-Temperature Water Loop

Alloy 52 (KKL)
288 °C, 2 ppm DO, 50 ppb SO$_4^{2-}$
increased environmental acceleration due to dilution zone or residual stress?
range of GE SCC data
no environmental acceleration?
High SCC resistance confirmed

CL  PPU  LCF
Sp1 $\sim$ 32.9 MPa$\cdot$m$^{1/2}$
Sp2 $\sim$ 21.6 MPa$\cdot$m$^{1/2}$

---

Kernkraftwerk Leibstadt AG
Folie 19 | 23.05.2019 | International Workshop on Age-Related Degradation of Reactor Vessels and Internals; NRC Headquarters, Rockville, May 2019
After WOL Repair: Analysis on SCC Susceptibility

- **Assessment of all RPV DMW’s**
  + Operational experience
  + OLNC / HWC mitigation
  + ID-repairs of DMW’s
  + Operational loads at DMW’s
    → supported by a fracture mechanics analysis

- **Provide qualification of a MSIP pilot application to the Swiss regulator**
### RPV Nozzle DMW

DMW: Alloy 182 (Butter) / Alloy 82

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Safe End (SF)</th>
<th>SF to Safe End Extension (SFE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2 Recirculation Outlet</td>
<td>SA-508 CL2</td>
<td>SA-336 CL F8</td>
</tr>
<tr>
<td>N3 Recirculation Inlet</td>
<td>SA-508 CL2</td>
<td>SB-166</td>
</tr>
<tr>
<td>N5 Feedwater</td>
<td>SA-508 CL2</td>
<td>SA-508 CL 1</td>
</tr>
<tr>
<td>N6 Core Spray</td>
<td>SA-508 CL2</td>
<td>SB-166</td>
</tr>
<tr>
<td>N7 RHR/LPCI</td>
<td>SA-508 CL2</td>
<td>SB-166</td>
</tr>
<tr>
<td>N10 JP Instrument.</td>
<td>SA-508 CL2</td>
<td>SA-336 F8</td>
</tr>
<tr>
<td>N11 CRD Return</td>
<td>SA-508 CL2</td>
<td>SA-336 F8</td>
</tr>
</tbody>
</table>
BWRVIP-75-A

"Technical Basis for Revisions to Generic Letter 88-01 Inspection Schedules"

- Re-assessment of Inspection schedules required by Generic Letter 88-01
- BWRVIP-75-A issued in 2005 and accepted by USNRC

<table>
<thead>
<tr>
<th>Category</th>
<th>Weld Description</th>
<th>Existing Inspection Frequency of GL 88-01</th>
<th>Proposed Inspection Frequency (Note 1, 2, 3(b))</th>
<th>Scope Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Non-Resistant Materials Stress Improved after 2 years of Operation</td>
<td>All within 2 cycles of SI, then all within 10 years, at least 50% within 1&quot; 6 years</td>
<td>25% every 10 years (Note 5) 10% every 10 years (Note 5)</td>
<td>Section 3.3.1</td>
</tr>
<tr>
<td>D</td>
<td>Non-Resistant Materials, No Stress Improvement</td>
<td>Every 2 refueling Cycles</td>
<td>100% every 6 years</td>
<td>100% every 10 years, at least 50% in 1&quot; 6 years</td>
</tr>
<tr>
<td>E</td>
<td>Cracked - Reinforced by Weld Overlay</td>
<td>Every 2 refueling Cycles</td>
<td>25% every 10 years, at least 12.5% in 1&quot; 6 years</td>
<td>10% every 10 years</td>
</tr>
</tbody>
</table>
Assessment of Operational Experience
since 2005 to complete information found in BWRVIP-75-A

• **Information was hard to compile:**
  - different lists, private communications etc.
  - part of information missing (category C / D, inspection history)

• **Input and assistance from EPRI (C. Wirtz) and additional input from utilities** (provided by Sierra Technologies)

• **Assessment by KKL**
  - Crack initiation in Alloy 182 but also crack growth in Alloy 182
  - No (significant) crack growth in base material (nozzle, SF and SFE)
  - Very few indications with > 0.75 t since 2005

  **Most important: encoded qualified UT-inspection method**
Water Chemistry

Low concentration of chloride and sulfate

Outage in August / September every year
Assessment of OLNC / HWC Mitigation according to BWRVIP-219

Not mitigated:
- N5: Feed Water
- N6: Core Spray (HPCS / LPCS)
- N7: RHR / LPCI
- N11: CRD-Return

Mitigated:
- N2: Recirc Out
- N3: Recirc Inlet
- N10: Jet Pump Instrumentation
Assessment of ID-Repairs

All N5 nozzle to safe end DMW have ID-repairs

- 30°, max. depth of 5 mm
- 150°, max. depth of 4 mm
- 90°, depth of 3 mm

Two other ID-repairs found:

- N2 SF
- N7 SFE (shop weld)
## Operational Stresses

**E.g.: hoop stresses $\sigma_h$ (axial crack growth)**

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>DMW</th>
<th>Outer Dia [mm]</th>
<th>Thickness [mm]</th>
<th>$\sigma_h$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>SF</td>
<td>600</td>
<td>46</td>
<td>57</td>
</tr>
<tr>
<td>N3</td>
<td>SF</td>
<td>358</td>
<td>31</td>
<td>49</td>
</tr>
<tr>
<td>N5</td>
<td>SF</td>
<td>374</td>
<td>28</td>
<td>58</td>
</tr>
<tr>
<td>N6</td>
<td>SF</td>
<td>342</td>
<td>33</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>SFE</td>
<td>335</td>
<td>23</td>
<td>65</td>
</tr>
<tr>
<td>N7</td>
<td>SF</td>
<td>354</td>
<td>30</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>SFE</td>
<td>335</td>
<td>23</td>
<td>65</td>
</tr>
<tr>
<td>N10</td>
<td>SF</td>
<td>140</td>
<td>21</td>
<td>27</td>
</tr>
<tr>
<td>N11</td>
<td>SF</td>
<td>136</td>
<td>21</td>
<td>25</td>
</tr>
</tbody>
</table>
Qualitative Assessment

Important Factors:

- Operational experience
- Water chemistry
- ID-repairs
- Operational stresses
- Qualified UT-technique

Important Factors:

- BWRVIP-75A inspection frequencies
- Good practice at KKL
- Impact on initiation and growth of SCC
- For SFE > SF («wall thickness»)
- Very important

Approach:

- BWRVIP-75A as a «base line»
- Shorter UT-intervalls for welds:
  - (a) with ID-repair
  - (b) SFE (if not mitigated by HWC)
Fracture Mechanics Analysis

Calculation of «residual live time»

- Welding Residual Stresses (FE-Analysis*) and operational stresses
- Crack growth by SCC (>> Fatigue CGR)
- Circumferential and axial crack growth
  - Axial cracks: «natural flaw growth»; crack growth in Alloy 182/82
  - Circumferential cracks: crack growth in SS and in Alloy 182/82
- Crack growth rates according to BWRVIP-59-A / BWRVIP-114-A
- Acceptable flaw dimensions according ASME Sect. XI, Appendix C
- Initial crack depth: 10% of wall thickness

* As described in:
## Shortened UT-Inspections Intervals

<table>
<thead>
<tr>
<th>DMW</th>
<th>Inspection [y]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2 Recirc. Outlet SF</td>
<td>10 / 5</td>
<td>Mitigated by HWC 5 years interval because of ID-repair at one weld</td>
</tr>
<tr>
<td>N5 Feedwater SF</td>
<td>3</td>
<td>Not mitigated by HWC ID repairs</td>
</tr>
<tr>
<td>N6 Core Spray SFE</td>
<td>4</td>
<td>Not mitigated by HWC</td>
</tr>
<tr>
<td>N7 RHR/LPCI SFE</td>
<td>4 / 3</td>
<td>Not mitigated by HWC 3 years for one weld with ID-repair</td>
</tr>
</tbody>
</table>
Concluding Remarks
Concluding remarks

Important for the assessment of SCC EAC / SCC

- Understanding of the mechanisms / phenomena
- Disposition lines for crack growth
- Operational Experience
- Fabrication History
- NDE capability
Thank you very much for your attention

Jens Heldt
Leibstadt NPP