Ageing Management and LTO of NPP’s in Switzerland
Status 2019

NRC Internat. Workshop on Age-Related Degradation of RPV and Internals
Rockville, MD, 23-24 May 2019
Presentation outline

- Nuclear power plants in Switzerland
- Regulatory framework related to Ageing & LTO
- OpEx: Fatigue & Embrittlement
- OpEx: NPP Beznau & Safety Case (RPV Inclusions)
- OpEx: NPP Mühleberg, Core Shroud Cracking
- Research activities
- Summary
- OpEx: NPP Leibstadt (to be presented by J. Heldt)
## Nuclear facilities in Switzerland

<table>
<thead>
<tr>
<th>NPP</th>
<th>Type</th>
<th>Year</th>
<th>$\text{MW}_{\text{e}}$</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beznau I</td>
<td>PWR</td>
<td>1969</td>
<td>365</td>
<td>Westinghouse</td>
</tr>
<tr>
<td>Beznau II</td>
<td>PWR</td>
<td>1971</td>
<td>365</td>
<td>Westinghouse</td>
</tr>
<tr>
<td>Mühleberg</td>
<td>BWR</td>
<td>1971</td>
<td>373</td>
<td>General Electric</td>
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<tr>
<td>Gösgen</td>
<td>PWR</td>
<td>1979</td>
<td>985</td>
<td>Siemens-KWU</td>
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<tr>
<td>Leibstadt</td>
<td>BWR</td>
<td>1984</td>
<td>1165</td>
<td>General Electric</td>
</tr>
</tbody>
</table>
Nuclear Power Plants in Switzerland

Early Prototypes:
- Magnox
- Dresden
- VAKL

Commercial Power:
- 2L Westinghouse
- BWR 3
- AGR
- CANDU

General Design Criteria:
- 4L Westinghouse
- BWR 6
- KWU Konvoi

Evolutionary Designs:
- AP1000
- ABWR
- EPR
- CANDU 6

Revolutionary Designs:
- Sustainable
- Physically secure
- Proliferation resistant

1965 1975 1995 2025
Gen I Gen II Gen II+ Gen III Gen IV
# Nuclear Power Plants in Switzerland

<table>
<thead>
<tr>
<th></th>
<th>KKB 1</th>
<th>KKB 2</th>
<th>KKG</th>
<th>KKL</th>
<th>KKM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal output [MW]</strong></td>
<td>1130</td>
<td>1130</td>
<td>3002</td>
<td>3600</td>
<td>1097</td>
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<tr>
<td><strong>Net electric output [MW] (2017)</strong></td>
<td>365</td>
<td>365</td>
<td>1010</td>
<td>1220</td>
<td>373</td>
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<tr>
<td><strong>Reactor supplier</strong></td>
<td>WE</td>
<td>WE</td>
<td>KWU</td>
<td>GE</td>
<td>GE</td>
</tr>
<tr>
<td><strong>Reactor type</strong></td>
<td>PWR</td>
<td>PWR</td>
<td>PWR</td>
<td>BWR</td>
<td>BWR</td>
</tr>
<tr>
<td><strong>Reactor model</strong></td>
<td>1(^{st}) Gen. 2 loop</td>
<td>1(^{st}) Gen. 2 loop</td>
<td>2(^{nd}) Gen. 3 loop (Pre-Konvoi)</td>
<td>BWR-6</td>
<td>BWR-4</td>
</tr>
<tr>
<td><strong>Main heat sink</strong></td>
<td>River water</td>
<td>River water</td>
<td>Cooling tower</td>
<td>Cooling tower</td>
<td>River water</td>
</tr>
<tr>
<td><strong>Commenced commercial operation</strong></td>
<td>1969</td>
<td>1972</td>
<td>1979</td>
<td>1984</td>
<td>1972</td>
</tr>
<tr>
<td><strong>Final shutdown (assumption)</strong></td>
<td>(2029 ... 2031)</td>
<td>(2029 ... 2031)</td>
<td>( (\geq 2039) )</td>
<td>( (\geq 2044) )</td>
<td>2019</td>
</tr>
<tr>
<td><strong>Expected lifetime</strong></td>
<td>( (\approx 60) )</td>
<td>( (\approx 60) )</td>
<td>( (\geq 60) )</td>
<td>( (\geq 60) )</td>
<td>48</td>
</tr>
</tbody>
</table>
**Current LTO Status, 2019**

Unlimited operating life time for NPP’s but **conditions for preliminary taking out of service, Periodic Safety Review + LTO safety evaluation (10 year interval)**

**1st generation NPPs in Switzerland**
- Beznau-1 (1969), LTO approved for the period 2008 until 2018
- Beznau-2 (1971), LTO approved for the period 2010 until 2020
- Second LTO (Unit 1&2) project submitted to ENSI in 2018 for the next 10 year period
- Mühleberg (1972), LTO approved until shut down in 2019

**2nd generation NPPs in Switzerland**
- Gösgen (1979), LTO project submitted to ENSI end of 2018
- Leibstadt (1984), LTO project in 2023 / 2024
After 40 years of operation:

- Unlimited operating life time for NPP’s but **conditions for preliminary taking out of service**

- **Continued backfitting measures** to improve nuclear safety or reduce nuclear risks

- Periodic Safety Review + **LTO safety evaluation based on licensees’ safety cases**

  - 2010, *Report on Life Management for LTO NPP Beznau*
  - 2012, *Report on Life Management for LTO NPP Mühleberg*
Time Limited Ageing Analysis (TLAA) & Safety Analyses

- RPV Integrity (irradiation surveillance program, neutron fluence assessment, PTS analyses)
  (ENSI-B01, Reg.-Guide 1.99 Rev. 2, KTA 3203)
- Pressure vessels and piping, mechanical and thermo-mechanical fatigue analysis
  (ENSI-B01, 10 CFR 50.54, NUREG-1800, NUREG-6909)
- Pressure vessels and piping, leak before break analysis
  (NUREG 0800 SRP 3.6.3, NUREG-1061, Reg.-Guide 1.45 KTA3206)
- Safety Analyses for NSSS
- Steel containment, corrosion monitoring and corrosion assessment
- Structural analysis of the concrete parts of the containment
Regulatory Timeline of AMP in Switzerland

- 1991 HSK enforced requirement for AMP
- 2004 RegGuide HSK-R-51 – Ageing Management (AMP)
- 2005 Nuclear Energy Act, Nuclear Energy Ordinance
- 2008 DETEC Ordinance “Preliminary shut down of NPP”
- 2008 RegGuide ENSI-B02 – Periodic Reporting
- 2009 IAEA NS-G-2.12, Safety Guide for AMP
- 2011 RegGuide ENSI-B01 – Ageing Management
- 2012 IAEA OSART Mission (with LTO module) Mühleberg NPP, 2014 OSART follow-up visit
- 2014 RegGuide ENSI-A03 – PSR for NPP (incl. LTO),
- 2017 Swiss Participation on ENSREG Topical Peer Review 2017,
- 2018 ENSI guide manual for AM of storage tanks
Key legal documents and guidelines, NEA, NEO

- **Nuclear Energy Act**
  - Art. 22: Maintenance, PSR, AMP and Backfitting

- **Nuclear Energy Ordinance**
  - Art. 32  Maintenance, in-service inspection and functional testing,
  - Art. 33  Systematic safety and security assessments
  - Art. 34  Comprehensive safety review for nuclear power plants
  - Art. 35  Ageing management
  - Art. 36  Monitoring the state of the art in science and technology and the operating experience in comparable installations
  - Art. 44  Conditions for the taking out of service and backfitting of nuclear power plants
Key legal documents and guidelines, Ordinances

- **Ordinance for safety classified vessels and piping**
  - During design, fabrication and construction of mechanical components, materials with highest quality shall be used to minimize the impact of ageing effects.

- **DETEC Ordinance “Preliminary shut down of NPP”**
  - A NPP has to shut down if the integrity of the physical barriers is compromised by ageing mechanisms (definition of acceptance criteria).
  - RPV embrittlement: - adjusted reference temperature > 93 °C
    - upper shell Charpy energy < 68 J
  - Wall thickness of primary piping < original design thickness
  - Cracking of primary piping < allowable limits (fracture mechanics)
  - Wall thickness of primary containment < original design thickness
  - For LTO: Demonstrate compliance with these criteria for ageing over the expected operation time by TLAA.
Key legal documents and guidance, RegG ENSI-B01

- Guideline ENSI-B01 (specific requirements for AMP)
  - Scope of the SSCs to be covered in the AMP
    - All safety classified structures and electrical components
    - All safety class 1-3 vessels and piping and related mechanical components (e.g. pumps, valves, supports and attachments)
  - Methods used for the verification of the embrittlement resistance of the RPV (Mandatory TLAA, Appendix 5)
  - Scope of the components to be covered in the fatigue monitoring and assessment program (Mandatory TLAA, Appendix 6)

- AMP basic documents (to prepare by licensees)
  - Plant-specific or generic guidelines (GSKL, Swiss NPP owners group),
  - KATAM (since 1991, periodical update): compendium of potential materials ageing mechanisms for mechanical Equipment in NPP (GSKL),
  - Fact sheets (“Steckbriefe”): basic data, tables of ageing mechanisms relating to the affected components, component history, periodical update (licensee),
Key legal documents and guidance, RegG ENSI-B02, -A03

Guideline ENSI-B02 (annual reporting)
- Overview of changes performed in the AM-documents
- Results of the fatigue surveillance program
- Results of the review of the operating experience and the follow-up of the current state of science and technology
- Description of the consequences of these results on the AMP
- Evaluation of the efficiency of the AMP based on failure statistics and maintenance indications

Guideline ENSI-A03 (additional reporting within the PSR)
- Review of the qualification status of the in-scope SSCs
- Assessment of technological obsolescence
- Review of existing time limited ageing analyses with respect to LTO
The regulatory body ENSI (2019)

Swiss Federal Safety Inspectorate ENSI at all has around 150 employees

Mechanical Engineering Group
8 (6) employees

Supported by SVTI (TSO)
with 26 employees

SVTI reviews and supervising In-service inspections, manufacturing, installation and repair activities.

NDT Qualification body

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Main degradation mechanisms

- Fatigue (LCF, HCF, TF, TMF, EAF)
- Irradiation Embrittlement
- Stress Corrosion Cracking (SCC)
- FAC
- Other (corrosion, wear, erosion, thermal ageing, ...
Fatigue Monitoring in Swiss NPP (1)

- 3 of 4 Swiss NPP using fatigue monitoring systems
  - KKL: “Fatigue Pro”, since 2007 (installed 2003), EPRI / Structural Integrity
  - KKG: “FAMOSi”, since 2014, Framatome
  - KKB: “WESTEMS”, since 2002, Westinghouse
  - KKM: Manual recording and assessment of fatigue

- Selection of monitoring positions based on recommendations and experience of manufacturer

- Typically around 25 - 30 positions are permanently monitored, including nozzles of RPV, steam generators and pressurizer and some piping like main cooling line and surge line.
Fatigue Monitoring in Swiss NPP (2)

- Measurement of temperature-time histories to identify transients (stress based approach)
- Baseline fatigue (before installing monitoring systems) is estimated from counted transients based on design specification (cycle based approach)
- Environmental effects on fatigue have to be considered according to ENSI-B01 and NUREG/CR-6909
- Annual fatigue report submitted to regulator about the current and extrapolated fatigue usage factors for 60 operation years (or EOL).
Fatigue Monitoring, annual reporting

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Fatigue Monitoring, backfittings & modifications

- **KKM**
  - 1995 to 1996, the RPV head bolts were replaced, replacement bolts having rolled threads and optimized thread geometry (calculated fatigue life 90 Y, bolts are the leading position for RPV)
  - In 1997, based on results from the fatigue monitoring measures, the RPV nozzles were modified by the installation of double thermo-sleeves.
  - A blind flange was fixed on RPV nozzle N9 in 2004. This modification largely eliminated fatigue loadings on this nozzle.

- **KKG**
  - 2005 PISA-project (TMI follow-up action), backfitting of primary pressure relief system, reduction of fatigue usage factors on surge line and pressurizer nozzles due to these system modifications and replacements of some pipe-sections

- **KKB**
  - 2013 New shafts for primary reactor water pumps (new material, optimized geometry, modified seal water flow)
Fatigue Monitoring, conclusions

- The results of the fatigue monitoring in the form of current fatigue usage factors and the corresponding levels extrapolated to 60 years of operation are submitted to ENSI in an annual report.

- The existing results show that the long-term operation of the Swiss NPP is not subject to any limitations as a result of RPV material fatigue.

- Potential future challenges:
  - Prevention of fatigue damages caused by vibrations (small piping, rotating equipment),
  - Load flexible operation
Program for assessment of irradiation embrittlement

- Neutron fluence assessment (Reducing of fluence by low leakage core configuration)
- Testing of surveillance specimens
- Determination of ART based on requirements of Guideline ENSI-B01 (U.S.-NRC 1.99 Rev. 2 / ASTM E 1921 Master Curve Concept)
- Embrittlement have to comply with “DETEC Criteria” (ART < 93°C in ¼ wall depth, Charpy energy ≥ 68 J)
- PTS analyses by deterministic FM (PWR)
- P-T limiting curves
Background of "DETEC Criteria" for RPV embrittlement

3. REQUIREMENT FOR NEW PLANTS

For beltlne materials in the reactor vessel for a content of residual elements such as copper, phosphorus, and vanadium should be controlled to low levels. The test should be such that the calculated adjusted reference at the 1/4T position in the vessel wall at end of life shall be 200°F. In selecting the optimum amount of nickel the deleterious effect on radiation embrittlement should be considered against its beneficial metallurgical effects and its tenacity the initial RTNDT.
# Status of surveillance programmes, March 2019

4 reactors have finished the surveillance programmes. Continued in Leibstadt NPP, 3\textsuperscript{th} capsule will be removed in 2020.

<table>
<thead>
<tr>
<th></th>
<th>KKB1</th>
<th>KKB2</th>
<th>KKG</th>
<th>KKL</th>
<th>KKM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested specim.</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>3*</td>
</tr>
<tr>
<td>last removed</td>
<td>2010</td>
<td>2010</td>
<td>2006</td>
<td>2008</td>
<td>2002</td>
</tr>
<tr>
<td>Coverage by tested specim.</td>
<td>&gt; 60 Y</td>
<td>&gt; 60 Y</td>
<td>&gt; 100 EFPY</td>
<td>&gt; 24 Y</td>
<td>&gt; 30 Y (BM, v3) 78 EFPY (weld v2)</td>
</tr>
<tr>
<td>Remaining spec. in RPV</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>5</td>
<td>1*  (reinstalled in 2004)</td>
</tr>
<tr>
<td>coverage 2019</td>
<td>-</td>
<td>&gt; 80 Y</td>
<td>-</td>
<td>&gt; 35 Y</td>
<td>≈ 50 Y (BM, v3)</td>
</tr>
</tbody>
</table>

* All specimens provided to PSI for future research activities.
### Adjusted reference temperatures for 54 EFPY / 60 Y

<table>
<thead>
<tr>
<th></th>
<th>KKB1</th>
<th>KKB2</th>
<th>KKG</th>
<th>KKL</th>
<th>KKM</th>
</tr>
</thead>
<tbody>
<tr>
<td>ART [°C] Method I</td>
<td>104</td>
<td>76</td>
<td>33</td>
<td>9</td>
<td>61 (V2)</td>
</tr>
<tr>
<td>inner wall / 1/4T</td>
<td>98</td>
<td>70</td>
<td>28</td>
<td></td>
<td>17 (BM)</td>
</tr>
<tr>
<td>RT_{ref} [°C] Meth. IIA</td>
<td>80</td>
<td>51</td>
<td>-16</td>
<td>-18</td>
<td></td>
</tr>
<tr>
<td>inner wall / 1/4T</td>
<td>74</td>
<td>46</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. upper shelf</td>
<td>137</td>
<td>120</td>
<td>118</td>
<td>&gt;119</td>
<td>125</td>
</tr>
<tr>
<td>Charpy energy [J]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>BM</td>
<td>BM</td>
<td>BM II</td>
<td>BM</td>
<td>Weld V2</td>
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<tr>
<td></td>
<td>Ring C</td>
<td>Ring C</td>
<td></td>
<td></td>
<td>BM</td>
</tr>
</tbody>
</table>

(KKG has installed ex-vessel dosimetry. It allows a more precise fluence calculation.)
Alternative assessment methods for RT<sub>ref</sub>:

- **Method I** (US NRC Regulatory Guide 1.99 Rev. 2):
  \[ RT_{ref} = ART \]

- **Method II-A:**
  \[ RT_{ref} = T_0 + 14.4K + \Delta T_s + \sqrt{324/n + 16 + \Delta T_M^2 + \Delta T_T^2} \]
  - \( T_0 \): reference temperature acc. to ASTM E 1921 (Master curve approach)
  - \( n \): number of valid tests
  - \( \Delta T_s \): =0 for 1T-C(T) specimens; =10K for 0.4T-SEN(B) specimens
  - \( \Delta T_M \): =0 for base material; =6K for weld material
  - \( \Delta T_T \): =0 for 1T-C(T) specimens; =5K for 0.4T-SEN(B) specimens

- **Method II-B:**
  \[ RT_{ref} = RT_{ref}^{(o)} + \Delta T_j \]
  - \( RT_{ref}^{(o)} \): reference temp. acc. to equation of method II-A for unirradiated material
  - \( \Delta T_j \): temperature shift according to NRC Regulatory Guide 1.99 Rev. 2
Embrittlement KKB 1&2, ENSI-B01 Method-IIA (MC)

KKB, Unit 1

KKB, Unit 2
## Embrittlement KKB 1, Ring C, ENSI-B01, 54 EFPY / 60 Y

<table>
<thead>
<tr>
<th>Material</th>
<th>RPV position</th>
<th>Neutron fluence [cm(^{-2})]</th>
<th>(\text{RT}_{\text{ref}}) [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Method I</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charpy</td>
<td>surface</td>
<td>5.59E+19</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>¼ wall thickness</td>
<td>3.55E+19</td>
<td>98</td>
</tr>
<tr>
<td><strong>Method II-A</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Master Curve</td>
<td>surface</td>
<td>5.59E+19</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>¼ wall thickness</td>
<td>3.55E+19</td>
<td>74</td>
</tr>
<tr>
<td><strong>Method II-B</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(T_0 + \text{Charpy-shift})</td>
<td>surface</td>
<td>5.59E+19</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>¼ wall thickness</td>
<td>3.55E+19</td>
<td>83</td>
</tr>
</tbody>
</table>

\(\text{DETEC} \leq 93^\circ\text{C}\)

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$R_{\text{NDT}}$ and the ART best fit curves for Beznau Unit 1 core weld, compared to Westinghouse US PWRs of same design

ENSi-B01 Method-I
(RG 1.99 Rev. 2)
(Source: ORNL-Report to ENSI)
$R_{NTD}$ and the ART best fit curves for Beznau Unit 1 Ring C, compared to Westinghouse US PWRs of same design

ENSI-B01 Method-I (RG 1.99 Rev. 2)
(Source: ORNL-Report to ENSI)
PTS-Analyses based on deterministic FM

\[ K_I = \sigma \cdot \sqrt{\pi a} \]

- Werkstoff
- Beanspruchung

Spannungsintensitätswert in MPa/\sqrt{m}

- Bruchzähigkeit K_c bzw.

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PTS-Analyses based on deterministic FM

For PWR’s a PTS-Analysis is required which include following tasks:

- Thermo-hydraulic Analyses (RELAP5, KWU-Mix, optional CFD) for a comprehensive load case matrix:
  - different leak sizes from 3 cm² up to 2F-break,
  - leak locations in hot and cold leg, different injection temperatures,
  (For Swiss NPP the medium size LOCA’s are leading.)

- Fracture Mechanics Analyses for:
  - Different crack locations (Nozzle corner, core region),
  - Different crack orientations (axial / circumferential),
  - Different crack types (surface / undercladding),
  - Different crack depths, aspect ratio is given by code (1/5 or 1/6)
  - Possible options with/without WPS,
  - Additional options, but not used for Swiss NPP PTS analyses: constraint effects, crack arrest, PFM to demonstrate conservatisms

PTS-Analyses for Beznau and Gösgen NPP based on KTA 3203 methology.
Irradiation embrittlement, conclusion

- The results of the surveillance programs in the form of fluence calculations and the corresponding levels of irradiation embrittlement extrapolated to 60 years of operation are submitted to ENSI.

- Highest embrittlement of all Swiss Reactors have the Base Material of Ring C in Beznau unit 1. It fulfils the requirements of 93°C shut down criteria of the DETEC Ordinance.

- The existing results show that the long-term operation of the Swiss NPP is not subject to any limitations as a result of RPV irradiation embrittlement.

- PTS-Analyses showed for all Swiss PWR that the allowable $RT_{PTS}$ (with consideration of WPS effect) is higher than the 93°C DETEC shut down criteria.
KKB 1, UT Indications in 2015

- Indications identified as Al2O3-Inclusions
- Not Ageing, manufacturing problem (insufficient discard rate from ingot)
KKB 1, Safety Case

Area of high density of inclusions

\[ \rho_{EA600} = 2.3 \text{ ind./cm}^3 = E1 \]

Dim. 560 x 130 x 21 mm

Area of high PTS load

\[ \rho_{EA740} = 1.0 \text{ ind./cm}^3 = E3 \]

Dim. 485 x 34 x 19 mm
KKB 1, Replica of Ring C based on manufacturing records

metallurgical bottom
KKB 1, Master Curve by 1 CT-Specimen from Replica

\[ T_0 = -82^\circ C, \quad \sigma = 5,7^\circ C \left( \sigma_{\text{exp}} = 4^\circ C \right) \]

\[ T_0 \text{ Determination according to ASTM E1921-15a} \]

Master Curve Testing of the replica shell C material: Specimens with inclusions show no difference to specimens without inclusions.
KKB 1, Master Curve by 0.5 CT-Specimen from Replica

A standard MC analysis indicate that specimens with large or small inclusions in the fracture process zone are homogeneous based on the log-likelihood criterion.

Only the specimens without inclusions show an indication of inhomogeneity.
Fracture surface (SEM) of broken CT-specimens, replica C material
Result: No influence of Al$_2$O$_3$ inclusions on crack initiation
### KKB 1, Comparison of Chemical Composition

<table>
<thead>
<tr>
<th>Sample</th>
<th>P</th>
<th>Ni</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring C</td>
<td>0.014</td>
<td>0.71</td>
<td>0.092</td>
</tr>
<tr>
<td>Replica ⊙</td>
<td>0.014</td>
<td>0.70</td>
<td>0.100</td>
</tr>
<tr>
<td>MQ1965 min</td>
<td>0.013</td>
<td>0.68</td>
<td>0.093</td>
</tr>
<tr>
<td>MQ1965 max</td>
<td>0.014</td>
<td>0.72</td>
<td>0.099</td>
</tr>
<tr>
<td>65CT41E3</td>
<td>0.010</td>
<td>0.70</td>
<td>0.090</td>
</tr>
<tr>
<td>65CT20E1</td>
<td>0.014</td>
<td>0.70</td>
<td>0.092</td>
</tr>
</tbody>
</table>

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KKB 1, Local Chemical Composition near Inclusions

C7-B154 Inclusion 1, BSE
Al Kα, element distribution
O Kα, element distribution
Cu Kα, element distribution
P Kα, element distribution
Ni Kα, element distribution
KKB 1, Safety Case Summary and Conclusions

- UT indications found in 2015 in RPV Base material were identified as non-metallic aluminium oxide inclusions.
- Fracture mechanics testing on specimen from replica ring C did not show an influence of these inclusions.
- Fractographic analyses never showed crack initiation at Al₂O₃-Inclusions.
- Inclusions do not have a negative effect on fracture toughness.
- According to chemical analyses, Inclusions do not influence irradiation embrittlement behaviour.
- Large inclusions or inclusion clusters, so called “high amplitude indications”, were conservatively assumed as flaws. These assumed flaws are covered by the ASME XI, IWB-3000 acceptance standards as well by the postulated cracks for PTS analyses.
- An alternative multiple flaw combination rule was proposed, now Code Case N-877. Acceptance criteria met with CC N-877 as well with standard rules according to Section XI, IWA-3000.
Examples of IASCC Incidents in LWRs

- Replacement of baffle former bolts at Beznau unit 1&2 in 2009 and 2010
- 192 bolts (unit 2)
- 195 bolts (unit 1)
- Replacement in an optimized pattern
- New material (AISI 316 CW)
- Optimized notch contour to reduce stresses
KKB, (HERA) 2015/16 RPV Head Replacement

- New RPV closure heads with a series of small improvements
- Inconel 600 replaced by Inconel 690 and 52 (head penetration seal welds),
- No control rod thermal sleeve wear issue (no thermal sleeve),
- A small boric acid cavity at unit 1 removed.
KKM, Overview core shroud cracking

- 1990 cracks in HAZ of H4 weld discovered by VT inspections, 1991 UT on H4, IGSCC driven by weld residual stresses, starting from inner surface
- 1992/93 conductivity of reactor water optimized (to around 0.1 μS/cm), 2" Plug sample removed
- 1993 on HSK request, start of qualified systematic (1 or 2-year) VT and UT (GE from ID)
- 1994 Simplified FM-model (screening criteria)
- 1996 installation of pull rods and radial stabilizers at 4 positions, precautionary safety action against unexpected fast crack growth. VT of rods
- 2000 HWC & NobleChem, 2005 OLNC (platinum injection),
- 2011 3D FE-model for FM analyses to LTO
- 2011 New UT-System (WE, from OD with measurement of depth), enhanced coverage
- 2013 New FE-model with circumferential cracks, 60 % wall thickness, acoustic loads, further optimization of Pt feed-in strategy
- 2014 replacement of pull rods planned, 6 rods new design, cancelled because of shut down
- 2014 first detection of transversal cracks (off-axis flaws), FE-model adapted
- 2015 & 2016 inspections H4 (UT, VT)
- 2018 last inspection (VT, H4 and the off axis cracks), no propagation
KKM, Core Shroud Cracks, 2011
KKM, systematic Core Shroud measurements since 1993
KKM, Core Shroud Crack, Indication 1, Weld H3

![Graph showing the growth of a crack over time, indicating a rate of 14.1 mm/a between 2009 and 2011.](image)
KKM, Core Shroud Model with through wall cracks, 2011
**KKM, Results of FM analyses of core shroud cracks**

**LC 6.3.1: SSE von 102°, 3 Zuganker, Δp Recirc-Bruch, Eigengewicht, ΔT**

<table>
<thead>
<tr>
<th></th>
<th>( K_{1,\text{max}} ) [MPa(\sqrt{\text{m}})]</th>
<th>( K_{1,c} ) [MPa(\sqrt{\text{m}})]</th>
<th>( \text{SF}_{\text{erf}} )</th>
<th>( \text{SF} )</th>
<th>( \text{Marge} )</th>
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<tbody>
<tr>
<td>H1</td>
<td>15.8</td>
<td>165</td>
<td>1.39</td>
<td>10.4</td>
<td>&gt; 3 x</td>
</tr>
<tr>
<td>H2</td>
<td>33.9</td>
<td>165</td>
<td>1.39</td>
<td>4.9</td>
<td>&gt; 3 x</td>
</tr>
<tr>
<td>H3</td>
<td>41.4</td>
<td>165</td>
<td>1.39</td>
<td>4.0</td>
<td>2.9 x</td>
</tr>
<tr>
<td>H4</td>
<td>39.5</td>
<td>123</td>
<td>1.39</td>
<td>3.1</td>
<td>2.2 x</td>
</tr>
<tr>
<td>H5</td>
<td>---</td>
<td>165</td>
<td>1.39</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>H6</td>
<td>24.7</td>
<td>165</td>
<td>1.39</td>
<td>6.7</td>
<td>&gt; 3 x</td>
</tr>
<tr>
<td>V3</td>
<td>15.1</td>
<td>123</td>
<td>1.50</td>
<td>8.1</td>
<td>&gt; 3 x</td>
</tr>
<tr>
<td>V4</td>
<td>3.9</td>
<td>123</td>
<td>1.50</td>
<td>&gt; 15</td>
<td>&gt; 3 x</td>
</tr>
<tr>
<td>V7</td>
<td>25.7</td>
<td>165</td>
<td>1.50</td>
<td>6.4</td>
<td>&gt; 3 x</td>
</tr>
</tbody>
</table>

SSE according to “PEGASOS” (increased seismic hazards), 2013 acoustic loads added
KKM, Core Shroud Model with circumferential cracks, 2013

Modelling: 3D-Finite Element Modeling of whole Core Shroud: Enveloping 360° cracks at H3 and H4 with crack depth of 75% resp. 66% of wall thickness.

Acceptance Criteria based on LEFM: (defined by ENSI (Swiss regulator) for the specific KKM situation considering PCO 2019)

- $K_I \text{ max} < 75 \text{ MPa}\sqrt{\text{m}}$ (transversal cracks);
- $l$ transversal through-wall cracks $< 320 \text{ mm}$
KKM Core Shroud - UT inspection results 1993 - 2015

H4 indication @ azimuth 106° (top)

Strategy change:
Pt: 0.3 g/h, (100 + 80) g Pt per cycle, based on recommendations from NORA results

Provided by PSI (LNM)
ENSI research and related activities, overview

- RIKORR, FEVER, IASCC, DIAGNOSTIK
- KORA I & II
- PISA I
- NORA I
- NORA II
- NORA III
- MECOS
- OECD / NEA Benchmarks
- LEAD
- PISA II
- PROBAB
- PROACTIVE
- LBB & XFEM
- Leak rate
- RPV welds
- Fracture Mechanics
- Scap
- Opde
- Halde
- Codap
- Halden
- New NDT
- EAC, Fatigue
- RPV Integr.
- Chemistry
- OECD NEA
- IAEA
- Smile?

Other partner: B&H, MatTec, HZR, Swiss NPP

NKC International Workshop on Age-Related Degradation of RPV and Internals
Ralph Döring / ENSI (Switzerland), Rockville, MD, 23-24 May 2019
PROBAB (2016-18, ENSI): RPV Structural Integrity

• **SP-I (25 %): Systematic LOCA transients study by LTH and LRS**
  - Analysis of various LOCA scenarios (T, p, dm/dt, h) with system (LRS) and CFD codes (LTH)
  - Evaluation of cooling for various TH regimes (single & two-phase, plume & stripe cooling)
  - Uncertainties of transients & critical evaluation of transient matrix

• **SP-II (50 %): Probabilistic & deterministic PFM PTS analysis of a reference RPV by LNM**
  - Various LOCA and other transients (LTOP, …)
  - Consideration of plume & stripe cooling by engineering models
  - Material inhomogeneity’s (segregation, inclusion bands) and hydrogen flakes
  - Effect of cladding & residual stress (cladding, welds)
  - 3D FEM & XFEM analysis for various crack configurations, validation of XFEM

• **SP-III (25 %): Probabilistic integrity, lifetime & LBB assessment for material ageing by LNM**
  - Literature survey for active ageing mechanism (SCC, EAF, TMF) → state-of-the-art
  - Evaluation of potential codes (PRO-LOCA, X-LPRM, …) and selection of code → POR-LOCA
  - Application of code to a selected specific case (e.g., KKL feedwater nozzle) in a first pre-study
  - Participation in OECD XFEM & LBB benchmarks / round robins study & in PARTRIDGE project
PROBAB: RPV Integrity Assessment as Multi-Disciplinary Joint Effort of LNM, LRS & LTH

Safety assessment
\[ K_I < K_{IC} \]
Crack loading < fracture toughness

Mechanical loading of crack
\[ K_I = f(\text{crack, load path}) \]

Fracture toughness
\[ = f(\text{material, fluence}) \]

Axial Neutron Fluence

LNM & AHL

NDT & periodic ISI

LNM

LRS

LNM

LRS & LTH

System Codes & CFD
Loss of coolant accidents

Safety margin

Increasing operation time
3D SM & FM Simulations of LOCAs by LNM

LBLOCA

Peak $K_i$ at crack-tip in plume may be higher than in simplified 1D-models

Complex time course with significant reloading $\rightarrow$ WPS may be challenged
PRO-LOCA - Probabilistic LBB Analysis

- PRO-LOCA code is used for Leak-Before-Break (LBB) analysis (criteria: $2c_d < 2c_b$)
- Demonstration that LBLOCA is an extremely rare event
- Active degradation mechanisms:
  - PWSCC for PWR & IGSCC for BWR
  - TMF
- The scope of the LBB analysis includes
  - Primary coolant loop
  - Surge line
  - Main steam line
  - Safety injection line
  - Residual heat removal line
# PROACTIVE 2019 - 2021

PROACTIVE is the follow-up project of PROBAB

<table>
<thead>
<tr>
<th>part</th>
<th>topics</th>
<th>effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP-I</td>
<td>Probabilistic Integrity Assessments at critical RPV locations and piping under consideration of active degradation mechanisms (PARTRIDGE, PRO-LOCA, OECD-Benchmark „LBB“)</td>
<td>40 %</td>
</tr>
<tr>
<td>TP-II</td>
<td>Experimental Validation of Extended Finite Element Method (XFEM) with respect to application to crack growth simulations. (Experiments and participation at OECD-Benchmark „XFEM“)</td>
<td>40 %</td>
</tr>
<tr>
<td>TP-III</td>
<td>Fracture toughness evaluation of RPV-steels by using of small specimen (mini-CT?) (literature study to identify knowledge gaps + definition and start for a PhD-thesis)</td>
<td>20 %</td>
</tr>
</tbody>
</table>
### SP-I: SCC Initiation in Austenitic SS & Ni-Alloys
- **PhD thesis** of J. Bai: Effect of $H_2$ on SCC initiation in Alloy 182 under BWR/HWC conditions @ 274 °C
- International MICRIN+ / NUGENIA+ project with 9 partners: Accelerated screening–SSR-Tests (tapered specimens) on SCC initiation (critical strains & stresses) in CW & high Si SS and Alloy 182
- ICG-EAC Round Robin on SCC initiation (constant load tests)
- ECG-COMON Round Robin on ECN & EIS measurements in high-temperature water

### SP-II: Environmental Effects on Fracture
- Systematic study & quantification of environmental & hydrogen effects on the fracture behaviour in the upper shelf & brittle to ductile transition region in different RPV steels.
  - **DBTT shifts** and reduction of resistance to brittle failure due to H and HTW?
  - Major factors of influence & critical system conditions
  - Underlying mechanism, synergies/interactions with other mechanism (EAC, DSA, …)
- **PhD thesis** (Z. Que) on high-temperature water effects & Post-Doc project (S. Rao) on H effects in air

### SP-III: Environmental Effects on Fatigue
- International EU HORIZON2020 INCEFA+ collaborative project, 2015 to 2020 (5 y), 14 partners
  - Effect of **mean stress**, long static load hold times & surface conditions on fatigue of SS in HTW
  - Development of European EAF analysis procedure, EAF data base (MATDB, JRC)
- **PhD thesis** (W. Chen) with focus to basic aspects of EAF (mean stress, stress state & mechanism)
**LEAD Project (ENSI, 2018 - 2020)**

**SP-I: SCC Initiation in Austenitic Ni-Alloys & SS (30 %)**
- Effect of surface conditions on SCC initiation & surface modification for SCC mitigation, LBB
- H2020 MEACTOS project, 2017-2020
- ICG-EAC Round Robin on SCC initiation (constant load tests) – phase II

**SP-II: Environmental Effects on Fracture (20 %)**
- PhD thesis (Z. Que), RPV steels (DSA, S, TE, HAZ), 2/2019

**SP-III: Environmental Effects on Fatigue (20 %)**
- International EU HORIZON2020 INCEFA+ collaborative project, 2015 to 2020 (5 y), 14 partners
  - Effect of mean stress, long static load hold times & surface conditions on fatigue of SS in HTW
  - Development of European EAF analysis procedure, EAF data base (MATDB, JRC)
- PhD thesis (W. Chen), 3/2020

**SP-IV: Synergies & Superposition of Ageing Mechanisms (25 %)**

**Part-I:** Environmental fracture & (IA)SCC of irradiated RPV steels (JRQ)

**Part-II:** Environmental fracture & SCC of thermally-aged Alloy 182 weld metal (short range ordering)
**PSI Corrosion Fatigue Crack Growth Model**

Superposition-model, \( \frac{da}{dt}_{CF} = \frac{da}{dt}_{ENV} + \frac{da}{dt}_{Air} \)

\( T = 240 - 288 \, ^\circ C \)

0.4 - 8 ppm \( O_2 \)

\(<1 \) or 65 ppb \( SO_4^{2-} \)

\( v = 3E-6 - 1E-1 \) Hz

\( R = 0.2 - 0.8 \)

\( \Delta K = 11 - 62 \, MPa\cdot m^{1/2} \)

SA 533 B Cl. 1 (0.018 % S)

20 MnMoNi 5 5 (0.004 % S)

20 MnMoNi 5 5 (0.015 % S)

\( \frac{da}{dt}_{Air} \) for high-sulphur steel and low-flow conditions

ECP = -500 mV\text{SHE}:
\( \frac{da}{dt}_{Air,crit} \approx 7E-10 \) m/s

ECP = -100 mV\text{SHE}:
\( \frac{da}{dt}_{Air,crit} \approx 8E-11 \) m/s

ECP = +200 mV\text{SHE}:
\( \frac{da}{dt}_{Air,crit} < 1E-13 \) m/s
BWRVIP-233 R.2 SCC Disposition Lines

- New SCC disposition lines for RPV steels for BWR/NWC, HWC & chloride transients
- ASME BPV Code Case, positive feedback from all code (sub-) committees, response to US NRC feedback done, final approval expected in May 2019
- Largely based on PSI results and suggestions
- Adjustment of AL 1 of EPRI BWR WC Guidelines for chloride to 3 ppb in 2016
PSI support to new ASME Code Cases for EAC

- Code Case N-XXX
  “Reference Crack Growth Rate Curves for SCC of Low Alloy Steels in BWR Environments”
  Draft close to final approval,
  (C&S Connect Record # 17-3016)

- Two new Code Cases for BWR Fatigue Crack Growth Rates are under preparation
  - for Low Alloy Steel (i.e., BWR Version of N-643-2)
    expected to use data provided by PSI
    (C&S Connect Record # 19-5)
  - for Stainless Steel (i.e., BWR Version of N-809)
    (C&S Connect Record # 19-6)
Non-Standard Fatigue Tests for Model Validation & Development
(supported by swissnuclear)

**TMF with biaxial pre-loading**

**HCF with micro notch (FIB)**

**Multiaxial HCF**
tension-torsion, proportional & non-proportional

- Crack arrest at 2 to 2.5 mm = f (frequency)
- Strong effect of surface conditions on initiation

Significant effect of small non-proportional noise on fatigue life!
1. IG SCC crack (BWR/NWC) in middle of bulk weld metal ~ 20% of wall thickness

2. Detailed UT characterization by SVTI

3. Cutting of weld segment & insert of segment in weld mock-up by minimally invasive welding
Detection and, in particular, sizing of SCC defects in DMWs represents a challenge and is related to relevant uncertainties. Crack depth is often significantly underestimated by NDT!

PARENT: Program to Assess the Reliability of Emerging Nondestructive Techniques follow-on project to PINC: Program for the Inspection of Nickel Alloy Components

- Participation of Swiss consortium (ENSI, PSI, ALSTOM, SVTI, EMPA) in PARENT-Project
- International program including regulators, industrial groups and research institutions
- Assessment & quantification of established & new promising NDE techniques
- NDT tests bodies with well characterized SCC cracks for open round robin as PSI contribution
- Participation in open and closed round robin programs (ALSTOM, SVTI)
Background:
• Optimization of NDT methods for SCC detection in DMW and Ni-alloys
• Follow-up project of PARENT & PINC

Administrative issues:
• Contract of ENSI with US NRC (in-kind contributions), contract of PSI with ENSI

PSI Tasks:
• 2 (or 3) NDT specimens with real IG/ID SCC with short cracks (~ 20 % of wall thickness), NWC with chloride and high-purity water in final phase, interrupted with UT at Alstom & SVTI?
• 2 x 1T C(T) specimens for quantitative crack configuration characterizations: Crack openings, branching, un-cracked ligaments, surface roughness in loaded and unloaded conditions
• ~ 1 year of total testing time

Status:
• Specimens fabricated and pre-cracked, 3rd test is running,
• NDT pre-characterization of initial conditions at SVTI in December 2018
Research activities, OECD/NEA MECOS Benchmark

Mode 2, f = 5.9 Hz
(Structural Dynamic Analyses by B&H)

(Cyclic Quasi-static calculations on Elbow by ENSI)

\[
\varepsilon_{pl}^{eqv} = \int \sqrt{\frac{2}{3}} d\varepsilon_{pl} : d\varepsilon_{pl}
\]
Results of Fracture Mechanics RPV weld project

- Inclusion of MC-Concept to the RegGuide ENSI-B01, App. 5
- An Equation to convert $T_0$ (ASTM E-1921) to $R_{T0}$ was developed, which have to be used instead ASME CC-N-629 or N-631
- ENSI-B01, Method II:
  \[
  R_{T0} = T_0 + 14.4K + \Delta T + \sqrt{324/n + 16 + \Delta T_M^2 + \Delta T_T^2}
  \]
  - $T_0$: reference temperature acc. to ASTM E 1921 (MC approach)
  - $n$: number of valid tests
  - $\Delta T_s$: =0 for 1T-C(T) specimens; =10K for 0.4T-SEN(B) specimens
  - $\Delta T_M$: =0 for base material; =6K for weld material
  - $\Delta T_T$: =0 for 1T-C(T) specimens; =5K for 0.4T-SEN(B) specimens
- ASME CC-N-629, N-631:
  \[
  R_{T0}(^\circ C) = T_0 + 19.4K
  \]
  \[
  R_{T0}(^\circ F) = [T_0 + 35](^\circ F)
  \]
**NORA: Noble metal deposition behaviour in boiling water reactors**

**Objective:** Investigation of the Pt deposition behaviour in boiling water reactors and its possible impact on structural materials and fuel element performance.

Systematic Pt deposition tests in sophisticated high-temperature water loop with steel specimens and simulated fuel rods.

Exposure of steel specimens in the reactor system at nuclear power plant Leibstadt.

- **NORA-I to NORA-III** from 2010 to 2019
- Project partners: PSI, ENSI, KKL, KKM
- Independent expertise and world-wide unique capabilities
- Results of direct practical use (optimized OLNC procedure)
- Several additional small industry R&D and service projects acquired
- Cooperation between several labs at PSI (LNM, AHL, LTH, & others)

Characterization by high-resolution SEM, (S)TEM/EDS & LA-ICP-MS and development of non-destructive technique for radioactive components.

Modelling of Pt deposition (with LTH).
Experiments at PSI revealed that the Pt injection rate has an impact on the Pt particle size, whereas smaller particles are beneficial (more homogenous coverage with a low total amount of injected Pt).

These results were directly applied at KKL (as well as at KKM):

- The Pt injection rate was reduced from 1.50 to 0.75 g/h to generate and deposit smaller and therefore more nanoparticles.
HWC/OLNC: ECP-run Cycle 33

- Avg. Coreflow Cycle 32: 1580 kg/s
- Avg. Coreflow Cycle 33: 1420 kg/s

- ECP data from MMS/DAS switched to ANS+ (01. June 2017)

- OLNC Mainapplication: 0.75g/h 200g Platinum 26. Apr. - 07. May 2017 (during Application H2-Trip 2 h)

- OLNC Miniapplication: 0.75g/h 125g Platinum 14. - 21. June 2017

- OLNC Miniapplication: 0.75g/h 125g Platinum 03. - 10. August 2017
Summary

- In Switzerland the establishing of a systematic ageing management started in 1991

- From ENSI’s perspective, a comprehensive and effective ageing management is implemented for the RPVs in the Swiss nuclear power plants, with which relevant ageing effects are detected at an early stage and effective corrective actions are initiated.

- Within the AMP all relevant ageing mechanisms for the RPV components are identified and evaluated according to the current state-of-the-art of science and technology.

- Based on results of the extensive inspection programmes, specific corrective actions have been taken for identified ageing-related damage and degradation.

- With the existing AMP for the RPVs, safe long-term operation for an operating period of 60 years, or for KKM until the final shutdown in 2019, is ensured.
Acknowledgement

Special thanks to

Hans-Peter Seifert and colleagues (PSI)
Jens Heldt (KKL)
and to all colleagues from ENSI
supported this presentation

and for providing material.

Thank You for your kind attention.