EFFECTS OF ADDITIONAL UNCERTAINTIES AND HANDLING AND MITIGATION OF UNCERTAINTIES

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- SOTERIA related work
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- Summary and conclusions
SOTERIA WP 3 “Evaluating uncertainties in fracture toughness measurement on irradiated RPV steels and mitigation approaches”

- Objective: To improve the prediction of radiation induced ageing phenomena in RPV steels from an end-user perspective by improvement of the applicability of the use of
  - modelling tools and ETCs
  - surveillance data
Referring to surveillance data the uncertainties in determination of RPV fracture toughness under irradiation have to be known in terms of a reliable safety assessment. Examples of scatter from publications:

**Chemical composition**

P in wt %

Brillaud et al, “Vessel Investigation Program of "CHOOZ A" PWR Reactor after shutdown,” ASTM STP 1405, 2001

**MTR (T) vs. surveillance (S) data**

Fluence (10^19/cm²)

Todeschini et al, “Revision of the irradiation embrittlement correlation used for the EDF RPV fleet,” Fontevraud 9, Avignon, 2010

**Measured Charpy energy**

Some additional factors affecting radiation embrittlement in surveillance specimens exist due to the specifics of irradiation conditions, like:

- Effect of initial heterogenities including segregations
- Testing conditions and number of specimens in one test group
- Thermal ageing
- Neutron flux (i.e. lead factor) and neutron energy spectrum
- Neutron fluence distribution within one test group
Two specific tasks in SOTERIA (I)

- T3.4: Effects of additional uncertainties in RPV surveillance data
  - Overview of the effects that can affect surveillance test data
    - initial conditions (location of specimens etc.)
    - irradiation conditions (uncertainties in neutron fluence, neutron spectrum, neutron flux, scatter between specimens etc.)
    - microstructural effects
  - Effect of testing conditions
    - testing procedure
    - standard vs. small size specimens
    - number of specimens
  - Effect of thermal ageing on radiation embrittlement
    - comparison of short and long term irradiations
    - effect of microstructure and chemical composition
  - Charpy notch impact vs. static fracture toughness (Master curve) testing
    - comparison of transition temperatures for different materials
Two specific tasks in SOTERIA (II)

- **T3.5:** Applications and guidance for handling and mitigation of uncertainties
  - Guidance for analysis of scatter in RPV surveillance data considering sources of uncertainties
  - Identification of microstructural parameters relevant for predictive models
  - Evolution of nano-features with neutron fluence
  - Evaluation of impact of testing conditions on transition temperature uncertainty
  - Assessment and validation of Embrittlement Trend curves (ETC)

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Materials

- 19 RPV materials which are representative for European LWR are being examined by appropriate mechanical tests, chemical analyses and microstructural techniques.

<table>
<thead>
<tr>
<th>Material ID</th>
<th>Material</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANP-2</td>
<td>S3NiMo1/OP41TT</td>
<td>WM, outlier observed at 4.97 n/cm²</td>
</tr>
<tr>
<td>ANP-3</td>
<td>22NiMoCr3-7</td>
<td>BM, Kloeckner</td>
</tr>
<tr>
<td>ANP-4</td>
<td>22NiMoCr3-7</td>
<td>BM, reference material JSW</td>
</tr>
<tr>
<td>ANP-5</td>
<td>NiCrMo1/LW320, LW330</td>
<td>WM, test weld seam, high Cu</td>
</tr>
<tr>
<td>ANP-6</td>
<td>S3NiMo/OP41TT</td>
<td>WM, Uddcomb, high Ni</td>
</tr>
<tr>
<td>ANP-10</td>
<td>22NiMoCr3-7</td>
<td>BM</td>
</tr>
<tr>
<td>ANP-15</td>
<td>22NiMoCr3-7</td>
<td>BM, Kloeckner, 30 years thermally aged</td>
</tr>
<tr>
<td>CIE-01</td>
<td>SA-508 Cl.3</td>
<td>BM</td>
</tr>
<tr>
<td>EDF-4</td>
<td>16MnD5</td>
<td>BM</td>
</tr>
<tr>
<td>FZD-1b</td>
<td>A533B Class 1</td>
<td>JPC (Japanese A533B Class 1 material), low P</td>
</tr>
<tr>
<td>FZD-2</td>
<td>10Kh2MFT</td>
<td>WM (WWER-440/V-230) Greifswald unit 4, Ishora, $K_{Jc}$ scatter T-S</td>
</tr>
<tr>
<td>FZD-3</td>
<td>15Kh2MFA</td>
<td>BM (WWER-440/V-230) Greifswald unit 4, Ishora, $K_{Jc}$ scatter L-S</td>
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<tr>
<td>FZD-4</td>
<td>15Kh2MFAA</td>
<td>BM (WWER-440/V-213) Greifswald unit 8, Skoda, $K_{Jc}$ scatter</td>
</tr>
<tr>
<td>JRQ</td>
<td>A 533-B</td>
<td>BM (IAEA reference steel)</td>
</tr>
<tr>
<td>JRQ UJV-2</td>
<td>Sv 12Kh2N2MAA or 15Kh2NMFA</td>
<td>WWER steel</td>
</tr>
<tr>
<td>UJV-2</td>
<td>15Kh2NMFA</td>
<td>WM (WWER-1000)</td>
</tr>
<tr>
<td>VFAB 1</td>
<td>S3NiMo/OP41TT</td>
<td>WM, Uddcomb, high Ni</td>
</tr>
<tr>
<td>VTT-1</td>
<td>10KhMFT</td>
<td>WM (WWER-440), high Cu</td>
</tr>
<tr>
<td>VTT-MW1</td>
<td>10KhMFT</td>
<td>WM (mock-up weld, WWER-440), high P content</td>
</tr>
</tbody>
</table>
### Chemical composition measurements

- **ANP-2, -4 (low Cu/Ni/P):** OES for Cu, Ni, P, C, … of 5 samples each

<table>
<thead>
<tr>
<th>Average measured by OES</th>
<th>Mn (%)</th>
<th>P (%)</th>
<th>S (%)</th>
<th>Ni (%)</th>
<th>Cu (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANP-2</td>
<td>0.0607</td>
<td>1.052</td>
<td>0.0167</td>
<td>0.0054</td>
<td>1.020</td>
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<tr>
<td>s (%)</td>
<td>4.06</td>
<td>2.46</td>
<td>6.49</td>
<td>3.58</td>
<td>1.20</td>
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<tr>
<td>Heat at manufacture</td>
<td>0.05</td>
<td>1.08</td>
<td>0.019</td>
<td>0.009</td>
<td>1.01</td>
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<tr>
<td>Relative deviation (%)</td>
<td>21.4</td>
<td>-2.6</td>
<td>-12.2</td>
<td>-40.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average measured by OES</th>
<th>Mn (%)</th>
<th>P (%)</th>
<th>S (%)</th>
<th>Ni (%)</th>
<th>Cu (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANP-4</td>
<td>0.182</td>
<td>0.925</td>
<td>0.0045</td>
<td>0.0045</td>
<td>0.886</td>
</tr>
<tr>
<td>s (%)</td>
<td>1.47</td>
<td>0.51</td>
<td>4.44</td>
<td>24.02</td>
<td>1.28</td>
</tr>
<tr>
<td>Heat at manufacture</td>
<td>0.21</td>
<td>0.85</td>
<td>0.006</td>
<td>0.006</td>
<td>0.84</td>
</tr>
<tr>
<td>Relative deviation (%)</td>
<td>-13.2</td>
<td>8.8</td>
<td>-25.0</td>
<td>-25.0</td>
<td>5.5</td>
</tr>
</tbody>
</table>

- **VFAB-1 (high Ni):** OES, ICP

### Non-negligible deviations for Cu, Ni and P may affect ETC predictions
Removal position of specimens (I)

- ANP-2
  - Measured material properties confirmed by SANS and APT results
  - Reason of the unexpected irradiation behaviour?

Material testing

SANS

<table>
<thead>
<tr>
<th>Neutron fluence (E &gt; 1 MeV) [cm⁻²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>T₀</td>
</tr>
<tr>
<td>T₄₁</td>
</tr>
</tbody>
</table>

Mn/Ni/Si/Cu enriched clusters in ANP-2 irradiated to 5x10¹⁹ n/cm²

APT

H. Hein et al, “Some recent research results and their implications for RPV irradiation surveillance under long term operation,” IAEA Technical Meeting, 5-8 November 2013, Vienna, Austria
Removal position of specimens (II)

- ANP-2
  - Too low $T_0$ might be caused by use of specimens from weld root area
  - $\geq 10$ K higher $T_0$ if specimens from weld root area are omitted
 Thermal aging

- Role of thermal aging in RPV irradiation surveillance programs
- ANP-15 (low Cu/Ni/P forged base material) ~30 years aged on PWR MCL at 290 °C
- $T_0 = -120 ^\circ C$ → no indication of thermal aging

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>SPECIMEN</th>
<th>B</th>
<th>W</th>
<th>$T_0$</th>
<th>KJCmed1T</th>
<th>s</th>
<th>n</th>
<th>r</th>
<th>FP</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANP-15</td>
<td>PCCV</td>
<td>10</td>
<td>10</td>
<td>-120.27</td>
<td>91.89</td>
<td>6.27</td>
<td>10</td>
<td>9</td>
<td>1.55</td>
</tr>
</tbody>
</table>

**Selected preliminary results**

07/05/2018

SOTERIA Midterm Workshop in Prague │ 9 & 10 April, 2018
Material heterogeneities

- Role of non-metallic inclusions
- Role of specimen thickness if the specimen size is smaller than the distance between the heterogeneities (if any)

For ANP-3/-4 the primary initiation site is not characterized by a specific microstructural feature (precipitate or inclusion), whereas for VTT-1 the initiation sites of two specimens revealed a brittle Si and Mn rich particle.
Impact of the testing procedure on the uncertainty of the ductile to brittle transition temperatures (I)

- Charpy data set for 16MND5 material
  - Focus on test matrix effects on uncertainty
  - Specimens machined from $\frac{3}{4}T$ to reduce micro/meso-segregation heterogeneities
  - MC simulation: 5000 random selections of test result sets according to conventional test matrices (Surveillance Program-like, RCC-M, ...)
  - Tanh fitting: determination of parameters w/o constraint
  - Computation of $T_{28}$, $T_{41}$, $T_{56}$ and $T_{68}$ transition temperatures
  - Standard deviation sigma and other statistical characteristics
  - Uncertainties defined at +/- 2 sigma for the chosen test matrix
Impact of the testing procedure on the uncertainty of the ductile to brittle transition temperatures (II)

- 12 tests for 16MND5 material
  - 3 tests each at -60 °C, -30 °C, -20 °C and 100 °C
Scatter between fracture toughness and Charpy impact shifts

- **Sources:**
  - Scatter due to heterogeneities within specimen group for one type of testing
  - Scatter due to heterogeneities between two groups of specimens
  - Scatter due to differences in irradiation of these two groups of specimens
  - Scatter due to uncertainties of test parameters
Uncertainty assessment of $T_{41}$ from Charpy tests by Bootstrapping is a promising tool (work still ongoing)

- Synergies from NUGENIA+ project AGE60+
  - Charpy testing in the upper and lower shelf rather than repeat in the transition region may reduce uncertainties
  - Bootstrapping during testing may optimize the choice of test temperatures

S. Ortner et al, “Applicability of ageing related data bases and methodologies for ensuring safe operation of LWR beyond 60 years,”
Embrittlement Trend Curves (I)

- Several well-known ETC models are applied for irradiation embrittlement of selected SOTERIA materials
  - ASTM E900-02, FIM RSE-M, RG 1.99 Rev 2, 10C FR50.61a, WR(5), Erickson CVE (Fit 6), JEAC 4201-2007

![Graphs showing predicted vs measured ΔT_41 for WR(5) and JEAC4201-2007 models]
Embrittlement Trend Curves (II)

- ETC predictions need careful application rules depending on material conditions.
Selected preliminary results

- Identification of microstructural parameters relevant for predictive models (I)

- Basic needs of experimental data for the same material:
  - Tensile curve at different temperature (ideally one near Tg and enough other temperatures to estimate change in properties with temperature) and irradiation dose (as tested).
  - Spatial & size distribution of carbides (assuming these are initiators)
  - Experimental toughness obtained at different temperatures and doses (for the identification of Beremin or MIBF parameters in function of the temperature)
  - Information on tests performed to determine toughness (i.e. specimen type, size, crack depth etc)

- Any unusual/extreme results:
  - Any unusual tensile behaviour / characteristics
  - Nature/size/location of the initiator
  - Any particles that didn’t fail that maybe should / any particles that failed and didn’t cause cleavage

- Some approaches include additional specific information:
  - Information on typical grain sizes (average/max/min)
  - Location of particles in proximity to the grain boundaries
  - Note that some models may consider variation in properties, so an idea of possible distribution of tensile properties, i.e. mean, max, min yield / UTS etc (for one temp / dose condition at a minimum)
Identification of microstructural parameters relevant for predictive models (II)

- Analysis techniques: Atom Probe Tomography (APT), Transmission Electron Microscopy (TEM), Electron Backscatter Diffraction (EBSD) and Small Angle Neutron Scattering (SANS):
  - Chemical composition of the solid solution (which determines the friction stress) – APT
  - The average dislocation density (responsible for the forest hardening) – TEM
  - The grain size of the material (inducing the Hall-Petch effect) – TEM
  - Grain size distributions and grain hierarchy – EBSD
  - Distribution of carbides or inclusions (for mechanical behavior but also for fracture models) – APT, TEM
  - Irradiation defects (in general) and evolution of nano-features with neutron fluence as a physical basis to ETCs – APT, TEM, SANS

Selected preliminary results

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Applications and guidance for handling and mitigation of uncertainties will cover following issues:

- **Material properties**
  - As-received micro and macrostructure and vessel manufacturing (heterogeneities)
  - Effects of inclusions
  - Chemical composition
  - Removal position

- **Environmental effects**
  - Neutron flux and fluence
  - Neutron spectrum
  - Irradiation temperature
  - Thermal aging

- **Synergistic effects**
  - Late irradiation effects

- **Surveillance programs**
  - Representativeness of specimens, neutron flux and fluence, irradiation temperature, specimen types

- **Experimental method and analysis**
  - Testing conditions
  - Evaluation of test results
  - Non-destructive characterization and techniques
  - Characterization of irradiation induced damage

- **Predictive models**
  - Embrittlement trend curves (ETC) and predictive models
  - Multiscale modeling
Summary and Conclusions

- Studies are ongoing in SOTERIA WP3 on effects of additional uncertainties and handling and mitigation of uncertainties.

- To improve the prediction of radiation induced ageing phenomena in RPV steels from an end-user perspective by improvement of the applicability of the use of modelling tools and ETCs, and surveillance data.

- A number of important effects of uncertainties were identified.

- Applications and guidance for handling and mitigation of uncertainties will be issued at the end of SOTERIA.

- A summary of obtained results will be given on international symposium Fontevraud 9, 17-20 September 2018 in Avignon, France.
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