nToF Target #3
Structural calculations on the vessel and moderators

Production Readiness Review

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3. Summary of calculations
1. Scope of analysis
## 1.1. Models

|   | 1. Horizontal moderator  
<table>
<thead>
<tr>
<th></th>
<th>(EN AW-5083 H111)</th>
</tr>
</thead>
</table>
|   | 2. Vertical moderator  
<table>
<thead>
<tr>
<th></th>
<th>(EN AW-5083 H111)</th>
</tr>
</thead>
</table>
|   | 3. Vessel assembly + horizontal moderator  
|   | (304L, 316L, 316LN and EN AW-5083 H111) |
1.2. Load cases and assumptions

Assumptions:
- room temperature in operating and testing cases
- no fatigue
- linear elastic materials
- small displacements and strains
- pressure test factor = 1.43
## 1.3. Materials and maximum allowable stresses

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield strength $R_{p0.2}$</th>
<th>Yield strength $R_{p1.0}$</th>
<th>Tensile strength $R_m$</th>
<th>Max. allowable stress $f$ in operating $f_d$</th>
<th>Max. allowable stress $f$ in testing $f_{test}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>in all body except weld</td>
<td>in full penetration butt welds</td>
</tr>
<tr>
<td>EN AW 5083 (1)</td>
<td>125 MPa</td>
<td>-</td>
<td>270 MPa</td>
<td>83 MPa</td>
<td>58 MPa</td>
</tr>
<tr>
<td>(H111)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>304L (2)</td>
<td>200 MPa</td>
<td>240 MPa</td>
<td>500 MPa</td>
<td>167 MPa</td>
<td>117 MPa</td>
</tr>
<tr>
<td>(1.4306/1.4307)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>316L (2)</td>
<td>220 MPa</td>
<td>260 MPa</td>
<td>520 MPa</td>
<td>173 MPa</td>
<td>121 MPa</td>
</tr>
<tr>
<td>(1.4404)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>316LN (2)</td>
<td>280 MPa</td>
<td>320 MPa</td>
<td>580 MPa</td>
<td>213 MPa</td>
<td>149 MPa</td>
</tr>
<tr>
<td>(1.4429)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Aluminium properties according to EN 12392

(2) Stainless steels properties according to EN 10028-7 and EN 10088-1

(3) Maximum allowable stresses according to EN 13445-3 and EN 13445-8
1.4. Assessment methodology

• Stress assessment
  • Stress linearization in the thickness direction according to the method based on stress categories in EN 13445-3
  • Requirements to satisfy:
    • Max. equiv. principal membrane stress: \((\sigma_{eq})_{pm} \leq f\)
    • Max. equiv. local membrane stress: \((\sigma_{eq})_{PL} \leq 1.5 \times f\)
    • Max. equiv. total stress (membrane+bending): \((\sigma_{eq})_p \leq 1.5 \times f\)
    • Full-penetration butt welds: \(f_{weld} = z \times f\), with \(z=0.7\) in operating condition and \(z=1\) in testing conditions
    • Equivalent stress according to the maximum shear stress theory (Tresca)

• Stress assessment on welded joints (not full penetration)
  • According to the directional method given in EN 1993-1-8 (Eurocode 3)
  • Decomposition in normal/shear stresses parallel/perpendicular to the axis of the weld
  • Requirements to satisfy:
    \[
    \sqrt{\sigma_\perp^2 + 3(\tau_\parallel^2 + \tau_\perp^2)} \leq \frac{f_u}{\beta_{WM2}} \quad \text{and} \quad \sigma_\perp \leq 0.9 \frac{f_u}{\gamma_{M2}}
    \]
    with: \(f_u\) the nominal ultimate tensile strength of the weaker part joined (\(R_m\))
    \(\beta_w\) the appropriate correlation factor (1 in this study)
    \(\gamma_{M2}\) the partial safety factor for joints (1.5 in this study)
  • Assessment expressed through the Weld Utilization Factor (percentage representing how much of the weld capacity is used):
    \[
    W_{uf} = \max \left[ \frac{\sigma_{eq}}{f_{uEqv}}, \frac{\sigma_\perp}{f_{u\perp}} \right]
    \]
2. Results of simulations
2.1. Horizontal moderator

Numerical model details:

- Symmetries xy and xz considered
- Mesh ~ 325 000 hexagonal elements (size 2 mm in the insert, 1 mm in the welding areas)
- Bonded contacts used in welded areas

Failure criteria:

- Operating case:
  - Deformation max = 1 mm
  - \((\sigma_{eq})_{pm} \leq f_d \) ( = 83 MPa)
  - \((\sigma_{eq})_p \leq 1.5 \times f_d \) ( = 125 MPa)

- Testing cases:
  - \((\sigma_{eq})_{pm} \leq f_{test} \) ( = 119 MPa)
  - \((\sigma_{eq})_p \leq 1.5 \times f_{test} \) ( = 178 MPa)
2.1. Horizontal moderator

**A. Operating condition**

Def. max. = 0.62 mm

\[
(\sigma_{eq, P_{max}}) = 24 \text{ MPa} < 83 \text{ MPa}
\]

\[
(\sigma_{eq, P_{max}}) = 94 \text{ MPa} < 125 \text{ MPa}
\]

\[W_{uf, ext} = 3\% \quad W_{uf, int} = 6\%\]

**B. Moderator pressure test condition**

Def. max. = 0.28 mm

\[
(\sigma_{eq, P_{max}}) = 24 \text{ MPa} < 119 \text{ MPa}
\]

\[
(\sigma_{eq, P_{max}}) = 90 \text{ MPa} < 178 \text{ MPa}
\]

\[W_{uf, ext} = 4\% \quad W_{uf, int} = 4\%\]
2.1. Horizontal moderator

C. Moderator vacuum test condition

- Def. max. = 0.07 mm

\[ (\sigma_{eq})_{Pm}^{\text{max}} = 4 \text{ MPa} < 119 \text{ MPa} \]
\[ (\sigma_{eq})_{P}^{\text{max}} = 23 \text{ MPa} < 178 \text{ MPa} \]

Wuf_{ext} = 2 \%
Wuf_{int} = 2 \%

D. Vessel vacuum test condition

- Def. max. = 1.13 mm

\[ (\sigma_{eq})_{Pm}^{\text{max}} = 36 \text{ MPa} < 119 \text{ MPa} \]
\[ (\sigma_{eq})_{P}^{\text{max}} = 150 \text{ MPa} < 178 \text{ MPa} \]

Wuf_{ext} = 7 \%
Wuf_{int} = 8 \%
2.2. Vertical moderator

Numerical model details:

- Symmetries xz considered
- Mesh ~ 500 000 hexagonal elements (size 1 mm in the insert)
- Bonded contacts used in welded areas

Failure criteria:

- Operating case:
  - Deformation max = 1 mm
  - \((\sigma_{eq})_{pm} \leq f_d \) (= 83 MPa)
  - \((\sigma_{eq})_p \leq 1.5 \times f_d \) (= 125 MPa)

- Testing cases:
  - \((\sigma_{eq})_{pm} \leq f_{test} \) (= 119 MPa)
  - \((\sigma_{eq})_p \leq 1.5 \times f_{test} \) (= 178 MPa)
2.2. Vertical moderator

A. Operating condition

- Def. max. = 0.25 mm

- $W_{uf_{ext}} = 3\%$
- $W_{uf_{int}} = 4\%$

C. Moderator vacuum test condition

- Def. max. = 0.08 mm

- $W_{uf_{ext}} = 2\%$
- $W_{uf_{int}} = 2\%$

$\left(\sigma_{eq}\right)_{P_{max}} = 16\text{ MPa} < 83\text{ MPa}$

$\left(\sigma_{eq}\right)_{P_{max}} = 88\text{ MPa} < 125\text{ MPa}$

$\left(\sigma_{eq}\right)_{P_{max}} = 6\text{ MPa} < 119\text{ MPa}$

$\left(\sigma_{eq}\right)_{P_{max}} = 32\text{ MPa} < 178\text{ MPa}$
2.2. Vertical moderator

B. Moderator pressure test conditions
   • $P_{\text{test}} = 1.43 \times P_{\text{service}} = 3.575 \text{ barg}$
   • Under the assumption of linear elastic behaviour, design verification in test conditions is equivalent to design verification in nominal conditions:
     \[
     \frac{P_{\text{test}}}{P_{\text{service}}} = 1.43 \quad \frac{f_{\text{test}}}{f_{\text{service}}} = \frac{R_{p0.2/1.05}}{R_{p0.2/1.5}} = 1.43
     \]

D. Vessel vacuum test conditions
   • Not impacted

E. Vessel pressure test conditions
   • Not impacted
2.3. Vessel assembly

Numerical model details:

- Entire model considered
- Mesh ~ 900 000 hexagonal elements (global size: 5 mm, refined areas: 2 mm)
- Cradle assembly and lead blocks represented by point masses
- Standard earth gravity considered
- Bonded contacts used in welded areas

Failure criteria:

- Deformation max = 1 mm (in operating case)
- Max. allowed stress values in st. steel bodies:
  - \( f_d = 167 \) MPa (operating case)
  - \( f_{\text{test}} = 250 \) MPa (testing cases)
  (considering the weaker stainless steel: 304L)
2.3. Vessel assembly

A. Operating condition

• Stress analysis
  • Stress levels < $f_d$ everywhere except in front plate weld
  • Stress linearization:
    • $(\sigma_{eq})_{P\text{max}}^{\text{max}} = 47$ MPa < $f_d$ (= 167 MPa)
    • $(\sigma_{eq})_{P}^{\text{max}} = 123$ MPa < 1.5 x $f_d$ (= 250 MPa)
2.3. Vessel assembly

- Stress assessment on welded joints in **operating condition**

<table>
<thead>
<tr>
<th>Description</th>
<th>Weld type</th>
<th>Analysis method (1)</th>
<th>Limit value</th>
<th>Ratio to limit (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wedge support to vessel</td>
<td>Full penetration butt weld 5 mm</td>
<td>A</td>
<td>f_{d_{304L}} = 117 MPa</td>
<td>77 %</td>
</tr>
<tr>
<td>Vessel longitudinal weld</td>
<td>Full penetration butt weld 10 mm</td>
<td>A</td>
<td>f_{d_{316L}} = 121 MPa</td>
<td>25 %</td>
</tr>
<tr>
<td>Bi-metallic transition to vessel</td>
<td>Full penetration butt weld 5 mm</td>
<td>A</td>
<td>f_{d_{316L}} = 121 MPa</td>
<td>54 %</td>
</tr>
<tr>
<td>Bi-metallic transition</td>
<td>Explosion bonding</td>
<td>A</td>
<td>f_{d_{alu}} = 58 MPa</td>
<td>74 %</td>
</tr>
<tr>
<td>H moderator to bi-metallic transition</td>
<td>Partial penetration butt weld 5 mm</td>
<td>B</td>
<td>f_{uEqv_{alu}} = 180 MPa</td>
<td>8 %</td>
</tr>
<tr>
<td>Front plate to vessel body</td>
<td>Partial penetration butt weld 2 mm</td>
<td>B</td>
<td>f_{u_{316L}} = 347 MPa</td>
<td>7 %</td>
</tr>
<tr>
<td>H moderator insert to body (ext)</td>
<td>Partial penetration butt weld 3.5 mm</td>
<td>B</td>
<td>f_{u_{alu}} = 180 MPa</td>
<td>8 %</td>
</tr>
<tr>
<td>H moderator insert to body (int)</td>
<td>Partial penetration butt weld 3.5 mm</td>
<td>B</td>
<td>f_{u_{alu}} = 180 MPa</td>
<td>5 %</td>
</tr>
<tr>
<td>N2 outlet tubes to vessel</td>
<td>2x fillet weld (int/ext) with a=1.4 mm</td>
<td>A</td>
<td>f_{d_{316L}} = 121 MPa</td>
<td>55 %</td>
</tr>
<tr>
<td>N2 inlet tubes to front plate</td>
<td>2x fillet weld (int/ext) with a=1.4 mm</td>
<td>A</td>
<td>f_{d_{316L}} = 121 MPa</td>
<td>33 %</td>
</tr>
<tr>
<td>Feedthrough tube to front plate</td>
<td>2x fillet weld (int/ext) with a=1.4 mm</td>
<td>A</td>
<td>f_{d_{316L}} = 121 MPa</td>
<td>27 %</td>
</tr>
</tbody>
</table>

(1) Analysis method:
- A = stress intensity with joint coefficient z
- B = directional method according to Eurocode 3

(2) Ratio to limit:
in method A, ratio = \( \frac{\sigma_{\text{max}}}{f_d} \)
in method B, ratio = \( \max \left[ \frac{\sigma_{\text{Eqv}}}{f_{u\text{Eqv}}}, \frac{\alpha_1}{f_{u1}} \right] \)
2.3. Vessel assembly

D. Vessel vacuum test condition

• Stress analysis
  • Stress levels < $f_{test}$ everywhere except in the groove of the vessel body (~300 MPa)
  • Stress linearization:
    • $(\sigma_{eq})_{P_{max}}^{max} = 83$ MPa < $f_{test}$ (= 250 MPa)
    • $(\sigma_{eq})_{P_{max}}^{max} = 209$ MPa < 1.5 x $f_{test}$ (= 375 MPa)

Deformation max = 1.4 mm ⇒ acceptable for testing case
### 2.3. Vessel assembly

- Stress assessment on welded joints in **vacuum test condition**

<table>
<thead>
<tr>
<th>Description</th>
<th>Weld type</th>
<th>Analysis method (1)</th>
<th>Limit value</th>
<th>Ratio to limit (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wedge support to vessel</td>
<td>Full penetration butt weld 5 mm</td>
<td>A</td>
<td>$f_{\text{test}_{304L}} = 250$ MPa</td>
<td>84 %</td>
</tr>
<tr>
<td>Vessel longitudinal weld</td>
<td>Full penetration butt weld 10 mm</td>
<td>A</td>
<td>$f_{\text{test}_{316L}} = 260$ MPa</td>
<td>20 %</td>
</tr>
<tr>
<td>Bi-metallic transition to vessel</td>
<td>Full penetration butt weld 5 mm</td>
<td>A</td>
<td>$f_{\text{test}_{316L}} = 260$ MPa</td>
<td>31 %</td>
</tr>
<tr>
<td>Bi-metallic transition</td>
<td>Explosion bonding</td>
<td>A</td>
<td>$f_{\text{test}_{alu}} = 119$ MPa</td>
<td>58 %</td>
</tr>
<tr>
<td>H moderator to bi-metallic transition</td>
<td>Partial penetration butt weld 5 mm</td>
<td>B</td>
<td>$f_{\text{uEqv}_{alu}} = 180$ MPa</td>
<td>11 %</td>
</tr>
<tr>
<td>Front plate to vessel body</td>
<td>Partial penetration butt weld 2 mm</td>
<td>B</td>
<td>$f_{\text{uEqv}_{316L}} = 347$ MPa</td>
<td>15 %</td>
</tr>
<tr>
<td>H moderator insert to body (ext)</td>
<td>Partial penetration butt weld 3.5 mm</td>
<td>B</td>
<td>$f_{\text{uEqv}_{alu}} = 180$ MPa</td>
<td>7 %</td>
</tr>
<tr>
<td>H moderator insert to body (int)</td>
<td>Partial penetration butt weld 3.5 mm</td>
<td>B</td>
<td>$f_{\text{uEqv}_{alu}} = 180$ MPa</td>
<td>7 %</td>
</tr>
<tr>
<td>N2 outlet tubes to vessel</td>
<td>2x fillet weld (int/ext) with a=1.4 mm</td>
<td>A</td>
<td>$f_{\text{test}_{316L}} = 260$ MPa</td>
<td>48 %</td>
</tr>
<tr>
<td>N2 inlet tubes to front plate</td>
<td>2x fillet weld (int/ext) with a=1.4 mm</td>
<td>A</td>
<td>$f_{\text{test}_{316L}} = 260$ MPa</td>
<td>33 %</td>
</tr>
<tr>
<td>Feedthrough tube to front plate</td>
<td>2x fillet weld (int/ext) with a=1.4 mm</td>
<td>A</td>
<td>$f_{\text{test}_{316L}} = 260$ MPa</td>
<td>27 %</td>
</tr>
</tbody>
</table>

(1) **Analysis method:**
- A = stress intensity with joint coefficient $z$
- B = directional method according to Eurocode 3

(2) **Ratio to limit:**
- in method A, ratio = $\sigma_{\text{max}} / f_d$
- in method B, ratio = $\max \left[ \frac{\sigma_{\text{Eqv}}}{f_{\text{uEqv}}}, \frac{\sigma_{\text{a}}}{f_{\text{u}}} \right]$
3. Summary of calculations

<table>
<thead>
<tr>
<th></th>
<th>Vertical moderator</th>
<th>Horizontal moderator</th>
<th>Vessel assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Operating condition</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>B. Moderators pressure test</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>C. Moderators vacuum test</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>D. Vessel vacuum test</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>E. Vessel pressure test</td>
<td></td>
<td>under investigation</td>
<td>under investigation</td>
</tr>
</tbody>
</table>

⇒ Static structural analysis validated for cases A, B, C, D
⇒ Study of Case E in progress
⇒ Buckling analysis in progress
Thank you for your attention