Materials Data Requirements For High Power Target Design

E. Noah, C. Kharoua, F. Plewinski, P. Sabbagh
ESS Target Division

4th HPTW
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Outline

- ESS Baseline Parameters
- Irradiation environments
- Motivation for engineering design codes
- RCC code description
- Adding material data to code
ESS baseline parameters

Proton beam
- 2.5 GeV proton linac
- 2 mA average beam current
- 1.3 ms pulse length
- 16.67 – 20 Hz rep. frequency

Target options:
- Molten LBE
- Solid Tungsten (or W alloy)
Sweden, Denmark and Norway
50% of construction costs

17 Partners
today
ESS target station sketch (LBE)

Instrument hall

Proton beam line

Main tank

TMR Cell

High bay

Target vault

Hot cell

Activated utilities vault

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Irradiation environments


<table>
<thead>
<tr>
<th></th>
<th>dpa</th>
<th>H &amp; He</th>
<th>Temperature</th>
<th>Corrosion</th>
<th>Pulsed</th>
<th>Codes &amp; Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spallation Source</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>ADS</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fusion</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>F.R. (Na)</td>
<td>+</td>
<td>---</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>
Motivation for design codes

**Basic design requirements:**
- Safety
- Reliability of components

**Motivation for codes and standards:**
- Contractual: client/contractor/supplier
- Consistency: tendering/safety authorities
- Efficiency: documents/practices simplification
- Sharing applied practice: tech. transfer/localisation of manufacturing/international exchange.
- Integration of industrial experience.
Safety considerations

- Functional requirements of the process
- Human activities
- Natural events
- Site conditions

Safety analysis: OGS

Behavioral requirements

Situations: I to IV

1. Operating conditions
   - Internal Hazard
2. External Hazard

Loads = combination of actions
  = Permanent + variable + incidental/accidental

Design and analysis of the structure

F. Plewinski

Codes and Standards

Criteria

Check

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RCC code description

> **The RCC-MRx:**
> - Merging of RCC-MR with RCC-MX.
> - RCC-MR: equipments for use at nuclear installations (also ITER, except PWR): 12 materials.
> - RCC-MX: mechanical equipment at research reactors (JHR): Aluminium and Zirconium alloys specific.

> **RCC describes requirements on:**
> - materials procurement.
> - design.
> - analysis.
> - construction qualification.
> - examinations.
RCC irradiation scales

> **Non-alloy and low-alloy steels:**
  - Fast neutrons > 1 MeV / cm².

> **Austenitic stainless steels:**
  - Displacements per atom using NRT model.

> **Aluminium alloys:**
  - % radiogenic silicon: conventional thermal neutron flux (0.0254 eV).

> **Zirconium alloys:**
  - Fast neutrons > 1 MeV / cm².
RCC irradiation range

Negligible irradiation

Significant irradiation

Maximum allowable irradiation
### Material properties covered in code

**RCC Properties Group**

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>elastic</th>
<th>inelastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>coefficient of thermal expansion</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Young modulus</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>density</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>specific heat capacity</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>thermal conductivity</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>thermal diffusivity</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

**border lines**

| Values of $S_m$ (linked with $S$ in RCC) | Not supplied |
| Values of $S_m$ (linked with $S_m$ in RCC) | Not supplied |
| Tensile Stress-Strain curves: For plastic strain limited to x% | Not supplied |
| Tensile Stress-Strain curves: For total strain attaining maximum elongation | Not supplied |

**Analysis data 1**

| Cyclic curves | x | x |
| Coefficient $K_c$ | x | x |
| Coefficient $K_v$ | x | x |
| Symmetrisation coefficient $K_s$ | x | x |
| Fatigue curves | x | x |
| Values of $J_{lc}$ | x | x |

**Analysis data 2**

| THERMAL AGEING COEFFICIENT | x |
| VALUES OF $K_T$ | x |
| Creep rupture stress $S_R$ | x |
| Creep strain rules: primary creep | x |
| Creep strain rules: secondary creep | x |
| FATIGUE-CREEP INTERACTION DIAGRAM | x |
| Maximum allowable strain DMAx | x |

**Analysis data 3**

| conventional yield stress at 0.2 % offset $R_{0.2}$ | Not supplied |
| Tensile strength $R_m$ | Not supplied |
| Values of $S_m$ | Not supplied |
| Values of $S_m$ | Not supplied |
| Ductility characteristics (after and before irradiation) | Not supplied |
| Tensile Stress-Strain curves: For plastic strain limited to x% | Not supplied |
| Tensile Stress-Strain curves: For total strain attaining maximum elongation | Not supplied |

**Cyclic curves**

| VALUES OF $K_c$ | Not supplied |
| VALUES OF $K_v$ | Not supplied |
| VALUES OF $K_s$ | Not supplied |
| Fatigue curves | Not supplied |
| Values of $J_{lc}$ | Not supplied |

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Adding material data to code

> **Material listed in code:**
  - Data in (RCC standard) non-negligible irradiation domain needed.
  - Data in new irradiation needed.

> **Material not listed in code** (e.g. Ti alloy Ti6Al4V):
  - Data in negligible irradiation domain to be added.
  - Data in (RCC standard) non-negligible irradiation domain needed.
  - Data in new irradiation regime needed.
Adding material data to code

> **Phase I:**

- Identify origin of criteria for selection of data.
- Clarify use of code for elastic/inelastic design.
- Highlight applicability of code to ESS components.
- Draft list of components that can be designed with RCC.

> **Phase II:**

- Analyse damage modes for spallation environment.
- Establish whether spallation materials data can be included in code.
- Assess whether formal "modification request" can be drafted.
TMR structural materials environment

- Neutrons: $-200^\circ C < T < 100^\circ C$
e.g. Al6061, Zircaloy
- Neutrons: $T < 100^\circ C$
e.g. Al6061
- Protons + Neutrons: $30^\circ C < T < 400^\circ C$
  - Low-cycle fatigue (beam trips, LBE target)
  - High-cycle fatigue (rotating target)
e.g. T91, SS316

1.25 $\times 10^{16}$ protons/s
5.6 $\times 10^{17}$ neutrons/s
### LBE target structural materials

<table>
<thead>
<tr>
<th>LBE Target</th>
<th>Inner vessel</th>
<th>Middle vessel</th>
<th>Outer vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td>Martensitic steel T91</td>
<td>SS316</td>
<td>SS316</td>
</tr>
<tr>
<td>Material - Reference</td>
<td>Material - Alternative 1</td>
<td>AlMg3</td>
<td>AlMg3</td>
</tr>
<tr>
<td><strong>Physical characteristics and boundaries</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Contact fluid inner/outer</td>
<td>liquid LBE/helium</td>
<td>helium/water</td>
<td>water/helium-or-vacuum</td>
</tr>
<tr>
<td><strong>Operating temperature and pressure</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating temperature [°C]</td>
<td>200-400</td>
<td>20-400</td>
<td>20-400</td>
</tr>
<tr>
<td>Operating pressure [Bar]</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
Austenitic steel fission vs spallation


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Austenitic steel spallation data

No substantial differences for 316-type steels between fission reactors (US fusion program DB) and spallation sources under these conditions, $T > 100 ^\circ C$.

Austenitic steel spallation data


Saturation above 10 dpa?
Issue with TE margins for engineering design
Martensitic steel spallation data

9\%Cr-steels

dpa rate \approx 2.3 \times 10^{-6} \text{ dpa/s}
He/dpa ratio \approx 6400 \text{ appm He/dpa}
T_{irrad} = 325 \degree C
superposition law = quadratic

1250 \text{ appm He}

\begin{align*}
\Delta \sigma_y (\text{MPa}) \\
\text{neutron dose (dpa)}
\end{align*}

Data from:
- Jung et al. JNM 318 (2003) 241
- Jung et al. JNM 343 (2005) 275

R. Chaouadi et al. JNM386-388 (2009) 544-549
Martensitic steel spallation data

9%Cr-steels
$T_{\text{irrad}} = 300 - 325 \, ^\circ\text{C}$

- $\Delta \sigma_y$ (MPa)
- neutron dose (dpa)

- neutron irradiation
- proton irradiation
- He-implantation

R. Chaouadi et al. JNM386-388 (2009) 544-549
Elastic vs. inelastic design

- Seeking *less conservative* approach to:
  - *Reduce* typical *thicknesses* of *structural components*
  - *Irradiation* leads to severe *embrittlement*
  - Design code *not prescriptive*, only offers *guidelines*
  - *Data* on *irradiated properties* for *inelastic design* are scarce

<table>
<thead>
<tr>
<th>Target</th>
<th>Vacuum</th>
<th>H₂O</th>
<th>He/Vacuum</th>
<th>H₂O</th>
<th>He</th>
<th>LBE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderator + pre-mod</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>H₂</td>
<td>Al6061</td>
<td>Al6061/Zircaloy</td>
<td>Al6061/Zircaloy</td>
<td>SS316</td>
<td>T91/SS316</td>
</tr>
<tr>
<td></td>
<td>H₂O</td>
<td>Al6061</td>
<td>Al6061/Zircaloy</td>
<td>SS316</td>
<td>SS316</td>
<td></td>
</tr>
<tr>
<td></td>
<td>He</td>
<td>SS316</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LBE</td>
<td>T91/SS316</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Materials test requirements

> **Standards:**
- Samples (geometry, composition, manufacturing).
- Test procedures.

> **Environment:**
- Radiation/Temperature/Mechanical loads/Fluids.

> **Mechanical properties:**
- Tensile/Impact/Fracture toughness/Fatigue/Hardness/Swelling/Creep.

> **Activity & radiochemistry:**
- Diffusion/release.
- Gamma/alpha spectrometry.
- H/He conc.

> **Microstructure:**
- SEM/EDX, EPMA, TEM.
Summary

> Use of design codes strongly motivated by safety and reliability of components.

> Large number of ESS target station components already qualify for use of design codes.

> Critical components subjected directly to proton beam currently not covered by design codes.

> Large amount of data exists on structural materials from spallation community.

> Inclusion of spallation data in design code:
  - Review criteria for data inclusion used by code
  - Assess existing spallation data
  - Draft code modification requests