Activity inventories and decay heat of ITER material samples after long-term irradiations with 14 MeV fusion neutrons at JET

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Andrius Tidikas and JET Contributors
LEI contribution to FUSION

• **Lithuanian Energy Institute** signed association agreement and became involved in EFDA since 2007.

• In the beginning, most of activities in EFDA were devoted to safety assessment of W7-X
  • LOCA analysis
  • Strength analysis of the port welds
  • RAMI assessment

• Since 2012 LEI become involved in activities related to DONES, DEMO and JET neutronics.

• In 2014 LEI became a member of Fusenet (Fusion education network) association
LEI contribution to FUSION

• In EUROfusion project LEI is involved in the following work packages:
  • JET1 – JET campaigns
    • Participation in JET Campaigns C35, C36 (Bolometer data analysis)
  • JET3 – Technological Exploitation of DT Operation for the ITER preparation
    • Calculation of activation and dose rates of ITER sample materials
  • SAE – Safety
    • Assessment of computer codes for fusion application
    • Deterministic analysis of events
    • FFMEA analysis of systems
    • WCLL DEMO concept neutronics calculations
  • ENS – Early Neutron Source IFMIF-DONES
    • Neutronics analysis of High Flux Test Module (HFTM)
Background

Activity inventories and decay heat of ITER material samples after long-term irradiations with 14 MeV fusion neutrons at JET

• **Irradiations with 14 MeV fusion neutrons** are planned at JET in DT operations with the objective to validate the activation of structural materials and the radiation damage in functional materials expected in ITER and fusion plants.

• The study describes the activation and dose rate calculations performed for materials irradiated during the complex and long-term irradiation sequence for **DD+HH+TT+HH+DD** phases, which was taken into consideration where the samples of ITER sample materials are irradiated.

• In the frame of **EUROfusion project** at JET, samples of real ITER materials samples used in the manufacturing of the main in vessel components will be irradiated at JET such as **W, Be, CuCrZr, 316L(N)**, but also **functional materials** used in diagnostics and **natural water** for heating systems that, if strongly activated, may release **high dose levels to critical components**.

• The neutron induced activities and dose rates at shutdown were calculated by the **FISPACT-II** code, using the neutron fluxes and spectra that were provided by the **MCNP** neutron transport calculations.
Objectives, methods and calculations

- The main objective is to estimate the activity and the dose rates of the material samples like W [divertor], SS AISI 316(F) [vacuum vessel] and SS304(borated) [in-wall shield] irradiated in the JET resulting from neutron irradiation after complex DD+HH+TT+HH+DD campaigns.

- The materials will be irradiated throughout the campaign in an Outer Long Term Irradiation Station (OLTIS) located inside the JET vacuum vessel where the maximum neutron fluence will be achieved.

- Neutron induced activities and dose rates at shutdown are calculated by means of the FISPACT code with EAF-2010 library using the neutron flux densities and spectra obtained from MCNP neutron transport calculation using FENDL nuclear data library.
Irradiation scenario

- This complex irradiation scenario assumes a JET operation with the duration of the campaign is the following:

<table>
<thead>
<tr>
<th></th>
<th>DD1</th>
<th>H1</th>
<th>TT</th>
<th>H2</th>
<th>DD2</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD</td>
<td>150 days</td>
<td>60 days</td>
<td>90 days</td>
<td>60 days</td>
<td>90 days</td>
</tr>
<tr>
<td>HH</td>
<td>4,00E+17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TT</td>
<td>8,00E+19</td>
<td>4,00E+19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH</td>
<td>4,50E+17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DD</td>
<td>5,40E+19</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After the end of irradiation, the activities and dose rates are calculated at the cooling time of: 0 sec. 1 min. 1 hour, 1 day, 1 week, 1 month and 1 year.

Neutron fluxes and spectra provided by the MCNP neutron transport calculation were estimated for DT which confirmed the peak fusion neutron energy at 14 MeV.

Developed methodology will allow to foreseen irradiated equipment handling means (remote handling, gloves, etc..)
## Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Stoichiometry</th>
<th>Purity</th>
<th>Impurities (ppm)</th>
<th>Density, (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapphire</td>
<td>Al$_2$O$_3$</td>
<td>99.99%</td>
<td>Na, Si, Ca, Fe, Ga, Mg, Ti, Mn, Pb, Cu, Zn, Ni, Cr</td>
<td>3.96</td>
</tr>
<tr>
<td>YAG</td>
<td>Y$_3$Al$<em>5$O$</em>{12}$</td>
<td>99.999%</td>
<td>Unknown</td>
<td>4.55</td>
</tr>
<tr>
<td>ZnS</td>
<td>ZnS</td>
<td>99.999%</td>
<td>Unknown</td>
<td>4.09</td>
</tr>
<tr>
<td>Spinel</td>
<td>MgAl$_2$O$_4$</td>
<td>99.99%</td>
<td>Unknown</td>
<td>3.6</td>
</tr>
<tr>
<td>ALON®</td>
<td>Al${64+x}/3$O$_{32-x}$N$_x$; where 2 \leq x \leq 5</td>
<td></td>
<td></td>
<td>3.7</td>
</tr>
<tr>
<td>New KS-4V(*)</td>
<td>SiO$_2$</td>
<td></td>
<td>Fe &lt;0.05, Al &lt;0.055, Ti &lt;0.051, Ca&lt;0.04, Cr &lt;0.017, Li &lt;0.016, Na &lt;0.04, K &lt;0.2</td>
<td>2.2</td>
</tr>
<tr>
<td>New KU1(*)</td>
<td>SiO$_2$</td>
<td></td>
<td>Fe &lt;0.12, Al &lt;0.028, Ti &lt;0.01, Ca &lt;0.1, Cr &lt;0.002, Li &lt;0.01, Na &lt;0.03, K &lt;0.2</td>
<td>2.2</td>
</tr>
<tr>
<td>ZrO$_2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Vessel</td>
<td>SS316L(N)-IG, SS316L</td>
<td>Plates, Forgings, Piping</td>
</tr>
<tr>
<td>In-wall shield</td>
<td>SS304 (borated), Alloy 660</td>
<td></td>
</tr>
<tr>
<td>First Wall</td>
<td>CuCrZr</td>
<td></td>
</tr>
<tr>
<td>First Wall</td>
<td>316L(N)-IG</td>
<td></td>
</tr>
<tr>
<td>Be armor</td>
<td>Be (S-65C)</td>
<td>Qualified for ITER; also from RF/CN</td>
</tr>
<tr>
<td>Divertor (inner target)</td>
<td>W, OF-Cu, CuCrZr</td>
<td>Bar, plates, Plates, Rods, Pipes</td>
</tr>
<tr>
<td>Divertor (cassette body)</td>
<td>SS316L(N)-IG, XM-19, Al-bronze</td>
<td>Plates, Plate forgings, Forgings</td>
</tr>
<tr>
<td>Divertor rails</td>
<td>SS316L(N)-IG, Alloy 660</td>
<td>No prototypes</td>
</tr>
<tr>
<td>TF coils, PF coils</td>
<td>Nb3Sn, NbTi, 316L, 316L(N), SS316L, SS316L(N)</td>
<td>TF and PF conductor jacket (under qualification), Cover plates for radial plates, Radial plates</td>
</tr>
<tr>
<td>TF coils, PF coils</td>
<td>SS316L(N)</td>
<td>TF coil case</td>
</tr>
<tr>
<td>Blanket manifolds</td>
<td>SS316L</td>
<td></td>
</tr>
<tr>
<td>Tokamak building</td>
<td>Various concrete formulas</td>
<td></td>
</tr>
<tr>
<td>TBM structure</td>
<td>EUROFER</td>
<td></td>
</tr>
</tbody>
</table>
ZnS – activation, dose rate

- **S 33%**
- **Zn 67%**

**Pie Chart**
- **Activation**
- **Contact Dose**
- **30cm from Point Source**

**Graphs**
- Activity (Bq/kg)
- Dose rate (Sv/hour)
CuCrZr – activation, dose rate

- **Zr**: 0.1%
- **Cr**: 0.8%
- **Cu**: 99.1%

**Graphs**

- **Activation**: Activity (Bq/kg) over time (DD1, H1, HT, H2, DD2, 0 sec, 1 min, 1 hour, 1 day, 1 week, 1 month, 1 year).
- **Contact Dose**: Dose rate (Sv/hour) over time (0 sec, 1 min, 1 hour, 1 day, 1 week, 1 month, 1 year).
- **30cm from point source**: Dose rate (Sv/hour) over time (0 sec, 1 min, 1 hour, 1 day, 1 week, 1 month, 1 year).

**Legend**

- Total
- Cu 64
- Cu 66
- Cr 51
- Ni 65
- Cr 55
- Co 60
- Co 60m
- Others
SS316L – activation, dose rate

Activation:
- Total
- Mn 56
- Cr 51
- Fe 60m
- Tc 99m
- Mn 99
- Mo 99
- Fe 59
- Co 58
- Others

Contact dose:
- Total
- Mn 56
- Ta 182
- Co 60
- Fe 59
- Cr 51
- Others

30cm from point source:
- Total
- Mn 56
- Cr 51
- Fe 59
- Co 60
- Others
Radionuclides are mainly produced by \((n,\gamma)\) reactions (neutron capture) with low energy neutrons. The dominant nuclides that contribute to the decay heat are Co-60, 58 after the decay of Mn-56.
Calculation of material damage

In addition to the activation, the radiation damage at the same position in sample materials was calculated.

Two methods have been applied for the study of the radiation damage, which is represented by the Displacement per Atom (DPA) quantity:

- Calculation with MCNP; the spectrum was calculated and folded with the appropriate damage cross-section (reaction number MT 444).

- Calculation of the spectra with MCNP and insertion into FISPACT (the DPA value is calculated automatically).

MCNP calculations were performed with use of the FENDL 3.0 data library. For calculations with FISPACT II the TENDL 2015 library was used (the reason is in the unavailability of the FENDL library in the format used by FISPACT and due to the fact, that TENDL library was provided with FISPACT II as the default).
Calculation of material damage

- The values of the DPA for the total duration of the DT (neutron yield of $1.7 \cdot 10^{21}$ DT neutrons) and for materials, irradiated at the position of the irradiation holder:

<table>
<thead>
<tr>
<th>Material</th>
<th>DPA [yield of $1.7 \cdot 10^{24}$ DT neutrons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALON x=2</td>
<td>4.59E-06</td>
</tr>
<tr>
<td>ALON x=5</td>
<td>4.64E-06</td>
</tr>
<tr>
<td>Sapphire Al$_2$O$_3$</td>
<td>5.03E-06</td>
</tr>
<tr>
<td>Diamond</td>
<td>1.65E-06</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>3.16E-06</td>
</tr>
<tr>
<td>Spinel MgAl$_2$O$_4$</td>
<td>5.29E-06</td>
</tr>
<tr>
<td>YAG</td>
<td>4.67E-06</td>
</tr>
<tr>
<td>ZnS</td>
<td>2.70E-05</td>
</tr>
</tbody>
</table>

For the studied compounds the calculated radiation damage is of the order of $10^{-5}$ DPA when irradiated at the selected position for the duration of the DT.

As observed form Table above, the values calculated with FISPACT II are, with the exception of ZnS, for a factor of around two higher than those calculated with MCNP only. Discrepancies are being investigated.
The key nuclides are several with short half-life (up to 20 min.) are produced from oxygen isotopes. Especially, N-16 ($T_{1/2}=7.13$ sec, produced from $^{16}$O($n,p$) reaction, $B^-$ decay with releasing high energy 6.13-MeV gammas) and O-15 ($T_{1/2}=2.037$ min, produced from $^{16}$O($n,2n$) reaction, $B^+$ decay).

Such results are very important and should be taken into account and the possible contribution to the final assessment of radiological description of the water cooling system should be considered.
Summary

The objective of the study is to estimate the activity and the contact dose rate in foils and functional material samples, in **Outer Long Term Irradiation Stations** as resulting from neutron irradiation after irradiation in DD/DTE2 campaign. Neutron induced activities and dose rates after shutdown are calculated by means of the **MCNP and FISPACT** codes using the irradiation scenario specified for JET.

- Several types of **ITER sample materials** were considered.

- One irradiation scenario with complex and long-term irradiation sequence for **DD+HH+TT+HH+DD** phases was assumed.

- Neutron induced activities and dose rates at shutdown and other time intervals using the neutron flux densities and spectra were calculated.

- **SS-304 (Borated), Nb₃Sn, ZnS, SS316L, XM-19** showed the highest activation of investigated ITER sample materials.

- The study of investigated types of steels identified the Mn-56 and Cr-51 as the largest contributors to the total activity while Mn-56, Co-60, Fe-55 and Fe-59 were found to be the major contributors to the dose rate.

- Damage on the order of $10^{-5}$ DPA is estimated for the considered materials at the in-vessel irradiation position for the whole the DT campaign which is sufficient to identify physical changes in observed materials.

- The analysis performed within this study refers to JET experimental conditions.
THANK YOU!

“A day without FUSION is a day without SUNSHINE !”

Gediminas Stankūnas

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