Status & Applications of the RSTM Tool for CFD-Activation Simulation of Fluids

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Introduction

- ITER cooling water will carry throughout the plant two significant secondary* radiation sources:
  - water activation,
  - activated corrosion products (not in this talk*).

- Which have a number of implications in terms of:
  - Need for confinement barriers.
  - Nuclear pressure equipment & effluent regulations.
  - Radiological protection (zoning & ORE management).
  - Degradation of sensitive critical equipment (magnets, insulators, polymers, electronics).

- In fact, activation of fluids flowing under neutron irradiation is important in many fusion applications:
  - cooling systems
  - service fluids
  - fluid breeders (LiPb)

(*) Radioactive isotopes produced by transmutation reactions occurring under neutron irradiation (a.k.a. "activation") during plasma operation.
Introduction

- Traditionally, activation methods developed for static conditions applicable to most problems (structures).

- Simulation of irradiated flowing fluids in generic conditions requires coupling of CFD & activation physics models.

- No such tools available until recently: the Radio-Species Transport Model (RSTM) is one developed by F4E.

- Here we review:
  - Methods for fluid activation analysis.
  - History of RSTM development & applications along other similar tools.
  - Design & commissioning activities of an experimental water activation loop at the JSI reactor.
  - RSTM applications to this experiment.
  - A look ahead.
Methods for fluid activation
General governing equation

- General equation for the concentration of a radio-isotope in an elemental volume of fluid subject to a neutron field, \( a \):

\[
\frac{\partial a}{\partial t} = D \nabla^2 a - \nabla \cdot (v a) - \lambda a + R
\]

- Solution for arbitrarily complex geometry, fluid regimes & neutron fields: fit CFD codes with activation physics.
- RSTM is one such tool conceived and developed at F4E:
  - Built on ANSYS Fluent® UDF tools: extended Species Transport Model (STM) \( \rightarrow \) Radio-STM (RSTM).
  - Use of same powerful numerical solver of CFD root equations: Navier-Stokes, turbulence, species…
- Cooling circuits’ particular case…
Methods for fluid activation
The conventional or circuit method

- Fluid moves under irradiation in linear fashion @ constant flowrate $Q$: no splitting, mixing, recirculation, stagnation.
- Fluid domain modelled as a series of discrete volumes $V_i$ of single residence time $t_i$ & constant neutron field $(R_i)$.
- Analytical solution for $A_i \rightarrow$ conventional or circuit method:

$$
A_i = \lambda a_i \quad t_i = \frac{V_i}{Q}
$$

$$
A_i = A_{i-1}e^{-\lambda t_i} + R_i(1 - e^{-\lambda t_i})
$$

- Historically used for ITER cooling water systems (tool also available at F4E for this type of calculation).
- Validity subject to linearity of flow patterns (absence of non-linearities affecting residence time vs. half-life) and homogeneity of neutron field in volumes.
### Developments timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000...</td>
<td>ITER cooling water activation calculations with circuit method.</td>
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Developments under EUROFusion by University of Palermo, UNED & CCFE:
- De Pietri, *Comp. Phys. Comms.* 2023
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    - De Pietri, *Comp. Phys. Comms.* 2023

- **2022**
  - Design & commissioning of JSI water activation loop.  

- **2023**
  - Unique capability to study details of activation process & optimize design
  - 20-45% differences with ITER's baseline conventional results @ outlet
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Development of Radio-STM & application to ITER representative FWs.

Design & commissioning of JSI water activation loop*

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- *Pampin, this talk*

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*Pampin, this talk
*Villari, ISFNT15 (PL1)
*Kotnik, ISFNT15 (PS2-113)
JSI water activation loop

- Water activation reactions also in fission spectrum.
- Dedicated loop designed & commissioned at JSI TRIGA under EUROFusion sponsorship. Objectives:
  - First phase: stable flux of highly energetic decay photons for shielding experiments.
  - Second phase: validation of calculation methods in ITER-relevant conditions.
- Experimental layout:
  - Radial piercing port:
    - Inner (irradiation) head.
    - Shield plug.
  - Inlet & outlet pipework.
  - Shielded experimental area:
    - Outer (observation) head.
    - Detectors, pumps & controls.
RSTM application

- F4E contributions to JSI water activation experiment:
  - Extension & debugging of RSTM capabilities.
  - Conventional & RSTM of conceptual inner head.
  - Conventional & RSTM of final inner & outer heads.
  - Conceptual design of ITER-relevant alternative head.

- Range of flowrates: 1.5 L/s to 0.1 L/s (extended to 0.01 L/s)

- Reaction rates with MCNP, FENDL3.1d & ENDF/B-VIII.0:
  - Conventional: linear series of volume-averages.
  - RSTM: 1 cm resolution 3D mesh-tallies.

- Fluent poly/tetra meshes with boundary layers.

- SST $k-\omega$ turbulence model solver & typical residual-based & outlet stability convergence criteria.
RSTM application
Conceptual design options for irradiation head

3D water CAD
3D mesh
3D R function
linear R function
RSTM application
Conceptual design options for irradiation head

3D water CAD

3D velocity profile

3D activity profile

activity @ outlet
RSTM application
Conceptual design options for irradiation head

3D water CAD

C/C' @ outlet

RTD
RSTM application
Final design of irradiation & observation heads

- First phase (shielding tests): snail’s superior activity chosen for inner head final design & implementation → flat C/C’.
- Same design for outer head, where R=0 (decay only).
- Then C/C’ depends only on flow non-linearities which, from the RTD, can be significant → seen in results @ outlet.
- But: in current layout, detector readings are for entire head → activity largely dominated by inlet from inner head.
- Then C/C’ flattened → seen in integral results.
- C/C’ discrepancies observable by tailoring detector layout.
RSTM application
Design of ITER FW relevant irradiation head

- Second phase (ITER-relevant validation tests): attempt to design inner head mimicking FW.
- Hindered by complex hydraulic routing & limited port size.
- Conceptual design premise is to preserve:
  - Hydraulic features: pipework, waterboxes, fingers.
  - Residence time: adjusted flowrate @ same regime (Re)
  - Orientation of neutron flux gradients.
- Several options based on spiral disk design concept (SDD)*

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<tbody>
<tr>
<td>SDD I</td>
<td>0.75</td>
<td>0.1</td>
<td>1.152</td>
<td>6941</td>
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<td>7.5</td>
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<tr>
<td>SDD III</td>
<td>0.87</td>
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<td>0.716</td>
<td>5624</td>
<td>9.3</td>
<td>8.7</td>
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<tr>
<td>SDD V</td>
<td>0.75</td>
<td>0.1</td>
<td>0.770</td>
<td>6048</td>
<td>7.7</td>
<td>7.5</td>
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<td>Snail</td>
<td>3.06</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>31.5</td>
<td>30.6</td>
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<td>FW06</td>
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<td>4.66</td>
<td>0.791*</td>
<td>17310*</td>
<td>11.9</td>
<td>11.8</td>
</tr>
</tbody>
</table>

* FW finger cooling channel.
Conclusions and further work

- Activation of fluids flowing under neutron irradiation important in many fusion technology applications.
- Water activation in ITER cooling systems is a currently impending one.
- Treatment of irradiated flowing fluids in arbitrary conditions requires coupling of CFD & activation physics.
- Since 2019, significant advances in development & application of such tools: e.g. RSTM.
- Conventional method assumptions can break down in parts of ITER systems:
  - Impact depends on flow non-linearities & neutron field heterogeneity.
  - May be conservative or not!
- Limited experimental data for validation.
- Future RSTM work:
  - Continued support to & validation with JSI experiments.
  - Validation with JET DTE3 water activation measurements*.
  - Extension of capabilities & application to F4E LiPb TBM.

*Villari, ISFNT15 (PL1)
Thank you!

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