Multiscale integral analysis of non-operational tritium leakages in nuclear power plants

Tritium analysis team

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• Introduction
• Objective
• Multiscale integral analysis
• Tritium transport phenomena
Introduction

- Tritium leakages are currently a major concern regarding existing nuclear power plants.

- Future fusion reactors will breed tritium from other elements to use it as fuel. Hence, the need for preventing and containing tritium leakages turns out to be a key issue.

- A methodology for multiscale integral analysis of tritium leakages with dedicated computational tools will be a powerful tool from the design, operation and safety point of view.
Objective

- Develop an integral methodology as a decided step towards a standard for safety analysis regarding tritium leakages to the environment.

- Define all necessary interfaces between different scale analysis, e.g., CFD to System Codes to atmospheric transport.

- Assess tritium cloud patterns (cyclonic and anticyclonic circulations) including the definition of significant scenarios which lead to maximum concentrations in tritiated clouds at short range.

- Ensure the reliability and accuracy of future analysis with a robust methodology and best practices, focused on safety.
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- Need for interfaces between codes and a methodology on what, when and how these codes are coupled.
Multiscale Integral Analysis

Tritium transport phenomena

- Complex physics and sophisticated modelling is needed in order to assess tritium leakages from the component level to the atmospheric transport.

  - Convection
  - Diffusion (thermomigration, electromigration, trapping)
  - Tritium chemistry
  - Isotopic exchange
  - Recombination and deposition processes in the soil
  - Penetration in the underground
  - Re-emission and later conversion to organic bound tritium (OBT)
  - Dosimetry (inhalation, re-emission and ingestion (early and chronic doses)

*T transport phenomena under nuclear condition with He nucleation.*
Multiscale integral analysis

Time scale

Unburnt fuel and heat spreads toward the chamber.

Thermonuclear burn spreading compressed fuel.

$T$ transport phenomena under nuclear conditions for a solid FW and a liquid Blanket.

Simulation techniques:

- FD: Finite differences
- MD: Molecular Dynamics
- MC: Monte-Carlo
- SC: System Codes
- CFD: Computational Fluid Dynamics
- AT: Atmospheric Transport

Phenomena time scale:

- $10^{-9}$ s
- $10^{-8}$ s
- $10^{-7}$ s
- $10^{-5}$ s
- 1 h
- 1 d

Unburnt fuel and heat spreads toward the chamber.

The FW filling the chamber.

Thermonuclear burn spreading compressed fuel.

$T$ transport phenomena under nuclear conditions for a solid FW and a liquid Blanket.
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Spatial scale

Simulation techniques:
- MD: Molecular Dynamics
- MC: Monte-Carlo
- FD: Finite differences
- CFD: Computational Fluid Dynamics
- SC: System Codes
- AT: Atmospheric Transport

Ensemble of techniques:

- MD: trapping
- MC: Monte-Carlo

Tritium leakage at a tritium handling facility: HVAC system

Detailed HVAC system

Atmospheric transport tritium release zones

10^{-9}m \quad 10^{-6}m \quad 10^{-3}m \quad 10^{-6}m \quad 10^{-1}m \quad 10^{2}m

Tritium loop at system code level.
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**Blanket**

- Tritium transport on blanket systems can be modelled with 3D highly detailed CFD simulations.
- Current state of the art shows that whole sectors of a blanket can be analyzed.
Multiscale integral analysis
Blanket

Heat Transfer Coefficient (HTC) for the ITER Vacuum Vessel
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- MCNP data to CFD codes coupling
- Source term for tritium generation

ANSYS® FLUENT® Mesh

MCNP data as a VTK file

Idom software for VTK data mapping on an ANSYS® FLUENT® Mesh
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Blanket

MCNP data VTK file slice on Y axis

iMapper resulting ANSYS® FLUENT® Mesh
Multiscale integral analysis
Critical components

- Critical components can be modelled with CFD, including tritium transport phenomena, and even coupled to system codes.

Permeator against vacuum to extract tritium from breeding blankets (currently under development by Idom)

Coupled temperature across different materials and electric potential

Tritium transport phenomena with electro migration and thermal migration
Permeator against vacuum to extract tritium from breeding blankets.

Comparison of phenomena

Efficiency due to electric potential
Multiscale integral analysis
System code

- Idom is currently developing iMOL, a tritium transport parallel system code.
- Codes like MELCOR (fusion version), MAAP, GOTHIC, FATHOM, IMPULSE, TMAP... can also be used.
- iMOL can be coupled to these codes

Tritium loop model.
Multiscale integral analysis
System code

• ITER MELCOR model for the validation of the cryostat design

MELCOR nodalization
Multiscale integral analysis
Site analysis

- Tritium leakages and plume evolutions are studied locally taking into account building aerodynamics

Exhaust at a nuclear facility
Wind streamlines over a nuclear facility

IAEA meeting
### Source term

**Accident Event**

- Analysis of radiological releases in ITER GSRR/PRSR for licensing.

#### REFERENCE ACCIDENT EVENT

<table>
<thead>
<tr>
<th>REFERENT EVENT</th>
<th>SOURCE TERM</th>
<th>DOCS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of plasma control</td>
<td>$2.6 \times 10^{-4}$ g-T (HTO)</td>
<td>pp. VII-66</td>
</tr>
<tr>
<td>Multiple FW pipe break</td>
<td>$2.8 \times 10^{-4}$ g-T (HTO)</td>
<td>pp. VII-85</td>
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<td>Loss of vacuum through one VV / cryostat penetration line</td>
<td>0.55 g-T (HTO)</td>
<td>pp. VII-94</td>
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<td>Pump seizure in divertor</td>
<td>0.26 mg-T (HTO)</td>
<td>pp. VII-103</td>
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<tr>
<td>Heat exchanger tube rupture</td>
<td>18 mg-T (HTO)</td>
<td>pp. VII-106</td>
</tr>
<tr>
<td>Large VV coolant pipe break</td>
<td>2.1 mg-T (HTO)</td>
<td>pp. VII-109</td>
</tr>
<tr>
<td>Large DV ex-vessel coolant pipe break</td>
<td>1.5 g-T (HTO)</td>
<td>pp. VII-121</td>
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<tr>
<td>Air leakage into VV during maintenance</td>
<td>0.4 mg-T (HTO)</td>
<td>pp. VII-126</td>
</tr>
<tr>
<td>Stuck DV cassette and failure of cask</td>
<td>0.1 mg-T (HTO)</td>
<td>pp. VII-133</td>
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<td>Accident with transport hydride bed</td>
<td>45 mg-T ($T_2$ gas)</td>
<td>pp. VII-141</td>
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<td>Isotope separation system (ISS) failure</td>
<td>54 mg-T (mainly HT,DT)</td>
<td>pp. VII-146</td>
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<tr>
<td>Failure of fuelling line</td>
<td>0.17 g-T (HTO)</td>
<td>pp. VII-151</td>
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<tr>
<td>Cryostat water and helium ingress</td>
<td>1.8 μg-T (HTO)</td>
<td>pp. VII-174</td>
</tr>
<tr>
<td>Loss of confinement in hot cell</td>
<td>3.4 mg-T (HTO)</td>
<td>pp. VII-180</td>
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</tbody>
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Emission release of primary phase
Atmospheric Transport

- Real time forecast of tritium transport in air from off-site the fusion reactor towards far downwind distance

Release evolution
Primary phase

Plume rise

- Topological events
- Plume rise
- Building wake effects
- Shoreline fumigation
- Atmospherical conditions outlining the measures in real time
- Use of Spanish Meteorological Agency data
Primary phase
Boundary conditions

- Emission point of release to the atmosphere

- Dispersion in
  - Convective boundary layers
  - Stable boundary layers

- Topographic conditions
  - Urban terrain
  - Rural terrain

- Meteorological measures
  - Humidity
  - Insolation
  - Precipitation
  - Wind velocity
  - Change of wind direction
Deposition Rate

- The low solubility of the elementary tritium causes deposition, mainly in HTO form, under rainfall events. The deposition rate is essential for tritium removal process on the ground. This parameter is the great importance in all of the secondary phase, when the tritium is incorporated to the biological system.
The concentrations vary always depending on the process that take place.

- Recombination and deposition processes in the soil surface
- Wet and dry deposition at surface in different chemical forms
- The velocity of deposition is one order of magnitude higher for HTO than HT
- Oxidation of tritium by bacteriological process (water content, soil porosity and distribution of organisms)
- Re-emission to the atmosphere.
Secondary phase

- Remotion and penetration into the underground
- Tritium oxide absorption by plant root or deposition of tritium in the leaves
Biokinetic Models

Demographic, nutritional and agricultural data are used for the best approximation and adapted to entry-format of calculation tools.

- The probabilistic sampling scheme based on hourly data is detailed. These studies provide the real dynamics of the processes, which are different from deterministic case.

- Different soil type is considered.

- Three compartments levels of underground.

- Soil organic matter included in the components (non-humid substances).

- New parameters: LAI (Leaf Area Index), photosynthesis, respiration, water and organic matter content.
Dosimetric analysis

- Dosimetry in all tritium pathways to the environment:
  - Direct inhalation and skin absorption
  - Re-emission
  - Ingestion

- Early doses (7 days after the release) and chronic doses have been evaluated of the Most Exposed Individual (MEI)

- Quantitative numerical values of doses from tritium of different Equivalent Dose Effective (EDE)

- Experimental data compared with the computational simulation

- Non soluble tritium in form of OBT (Organically Bound Tritium) by exchange reactions or enzimatically-catalised reactions
• This tritium form that can remain long time in the organism: OBT has longer retention times than tritiated water (amino acids, sugars, protein, starches, lipids cell structural materials)

• Following OBT intake. Ingestion is more hazardous
  ▪ RBE (Relative Biological Effectiveness), wR
  ▪ Transmutation effects
  ▪ LET (Low-linear energy transfer for internal dosimetry, ionisation-density)
  ▪ Incorporation in DNA and RNA
  ▪ Distribution effects

• Level of safety required of the International Commission on Radiological Protection (ICRP)

• Recomendations concerning of the Committed effective Dose Equivalent for public, 1mSv/year

• All systems are needed to minimize chronic and accidental emissions
The tritium analysis team is a collaboration program between the Nuclear Fusion Institute (IFN) at UPM and Idom Nuclear Services with the aim of develop tools and methodologies for tritium transport phenomena.

Thank you!

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