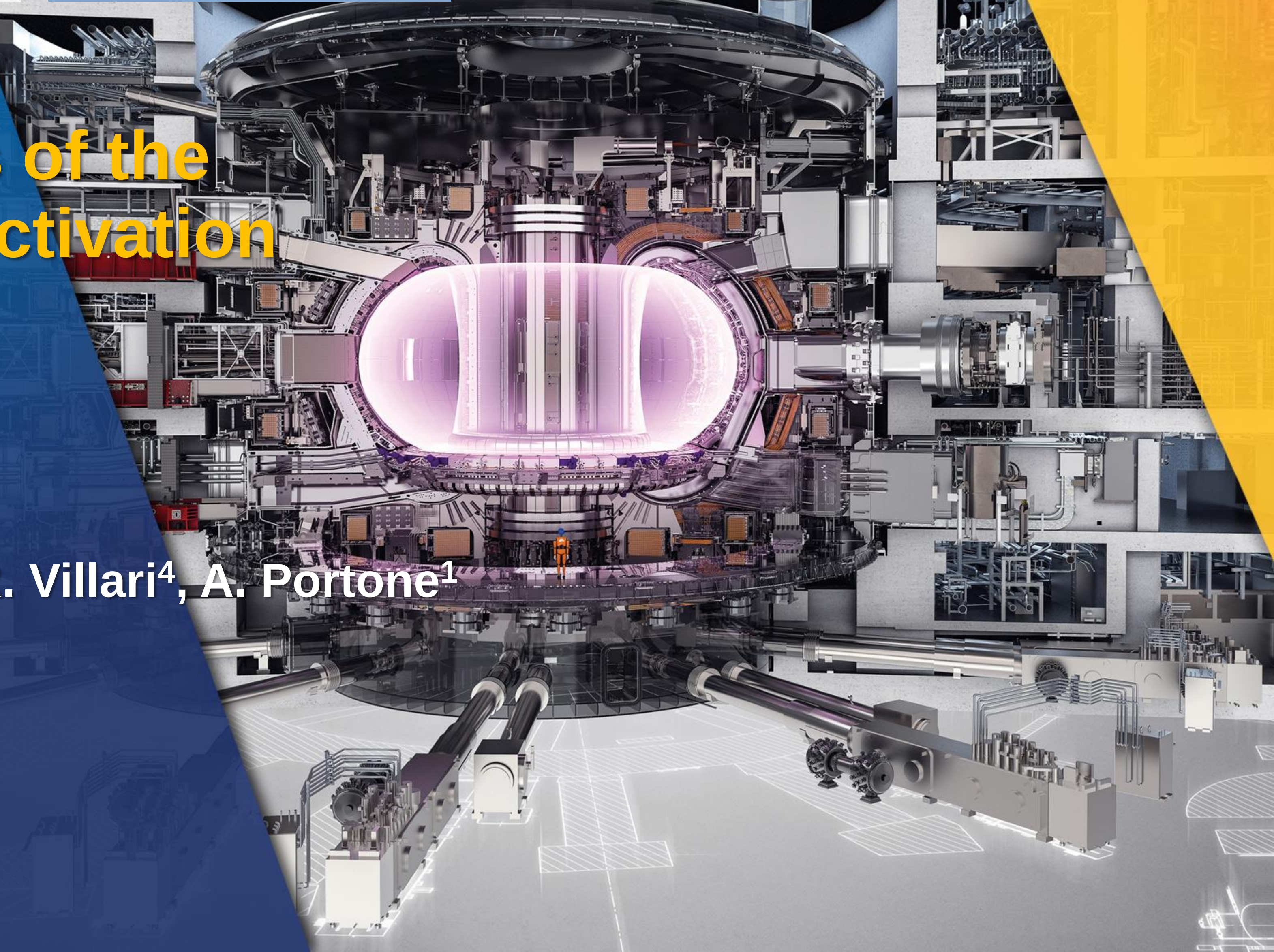
FUSION FOR ENERGY

Jožef Stefan Institute

EUROfusion

BRINGING THE POWER OF THE SUN TO EARTH

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



Raul Pampin[1]

E. Masia[2], F. Cau[1], D. Kotnik[3], R. Villari[4], A. Portone[1]

(1) F4E (2) ATG (3) JSI (4) ENEA - EUROfusion

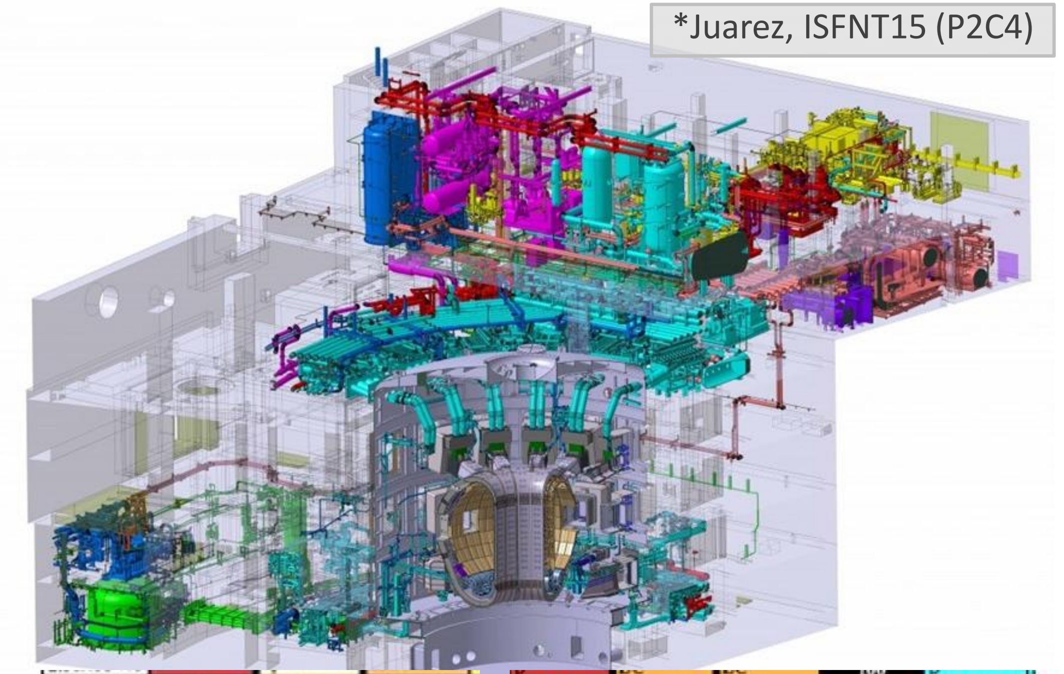
ISFNT-15

Gran Canaria, 11-15 Sep 2023

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)

*Juarez, ISFNT15 (P2C4)



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

Introduction

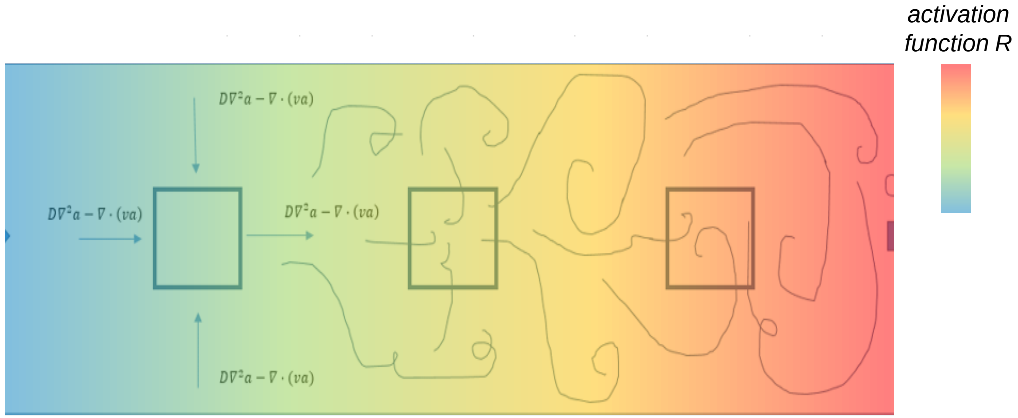
- Traditionally, activation methods developed for static conditions applicable to most problems (structures).
- Simulation of irradiated flowing fluids in generic conditions requires coupling of CFD & activation physics models.
- No such tools available until recently: the Radio-Species Transport Model (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

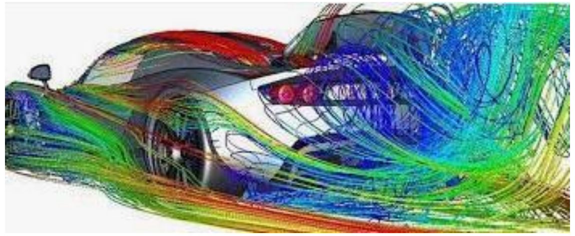
- General equation for the concentration of a radio-isotope in an elemental volume of fluid subject to a neutron field, a:

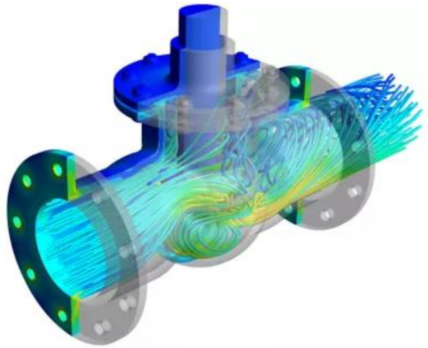
$$\frac{\partial a}{\partial t} = D\nabla^2 a \; - \nabla.(va) - \lambda a + R$$

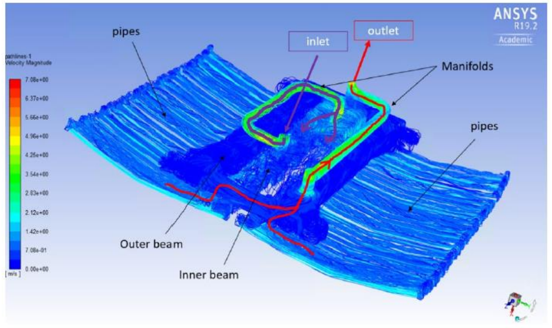
diffusion | convection | decay | production



- 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) → Radio-STM (RSTM).
  - Use of same powerful numerical solver of CFD root equations: Navier-Stokes, turbulence, species…
- Cooling circuits' particular case…







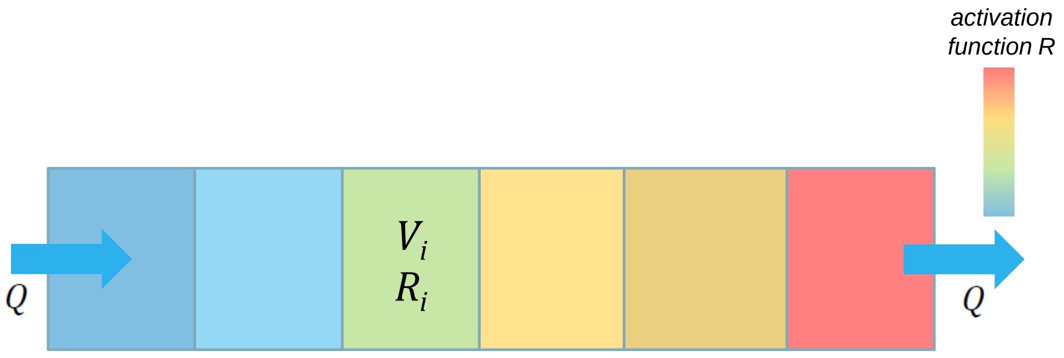
Methods for fluid activation
The conventional or circuit method

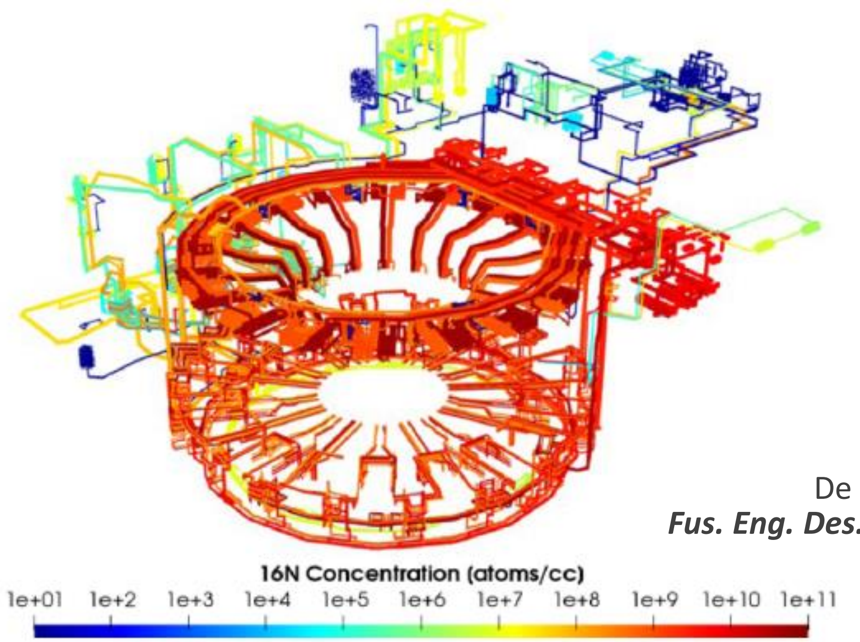
- …fluid moves under irradiation in linear fashion @ constant flowrate Q: no splitting, mixing, recirculation, stagnation.
- Fluid domain modelled as a series of discrete volumes V_i of single residence time t_i & constant neutron field (R_i).
- Analytical solution for a_i → *conventional* or *circuit*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

$$A_i = \lambda a_i \qquad t_i = V_i \,/\, Q$$

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

- 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.





De Pietri, *Fus. Eng. Des.* 2021

Developments timeline

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2000… | 2019 | 2020 | 2021 | 2022 | 2023

ITER cooling water activation calculations with circuit method.
- Polunovskiy, ***ITER report*** 2020

iter

Design & commissioning of JSI water activation loop.
- Kotnik, ***Fus. Eng. Des.*** 2023

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FW mock-up water activation experiment @ FNG & circuit calcs.

Nobs, ***Fus. Eng. Des.*** 2020

Re-analysis using RTD from Fluent's Species Transport Model (STM).

Pampin, ***Nuc. Fus.*** 2021

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Developments under EUROFusion by University of Palermo, UNED & CCFE.
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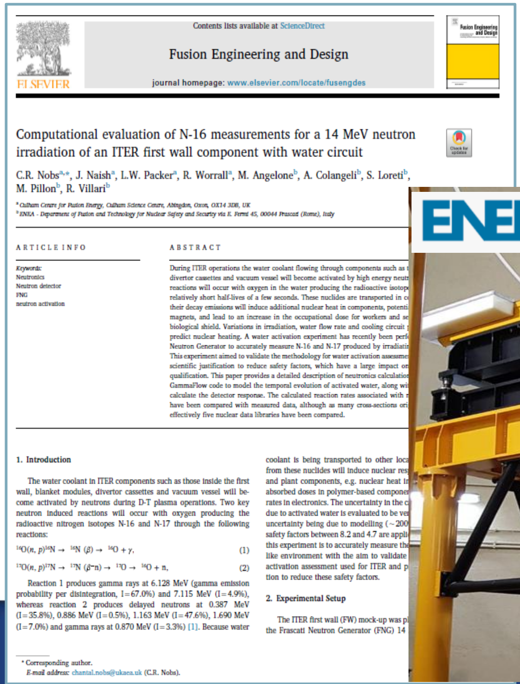
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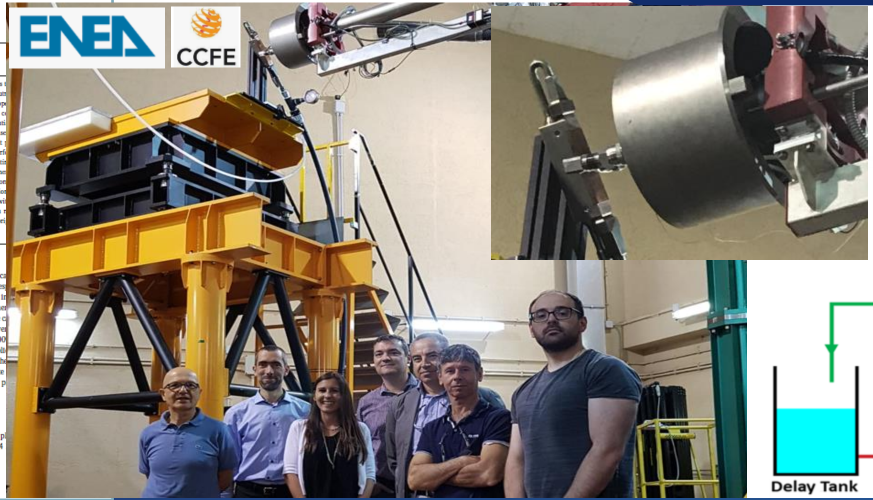
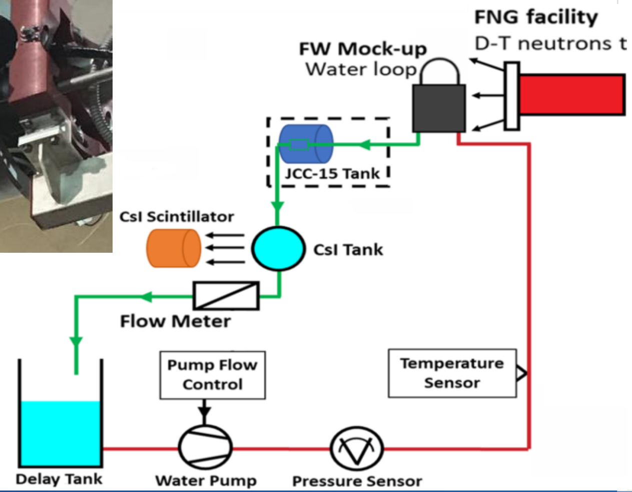
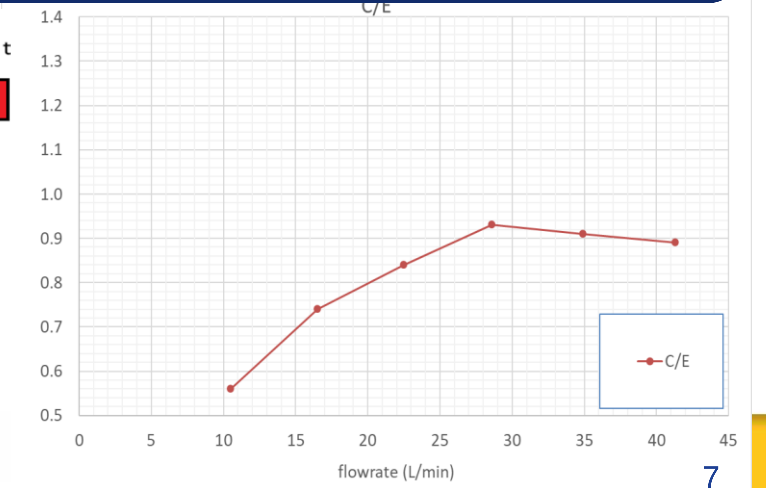
Computational evaluation of N-16 measurements for a 14 MeV neutron irradiation of an ITER first wall component with water circuit

C.R. Nobs, J. Naish, L.W. Packer, R. Worrall, M. Angelone, A. Colangeli, S. Loreti, M. Pillon, R. Villari







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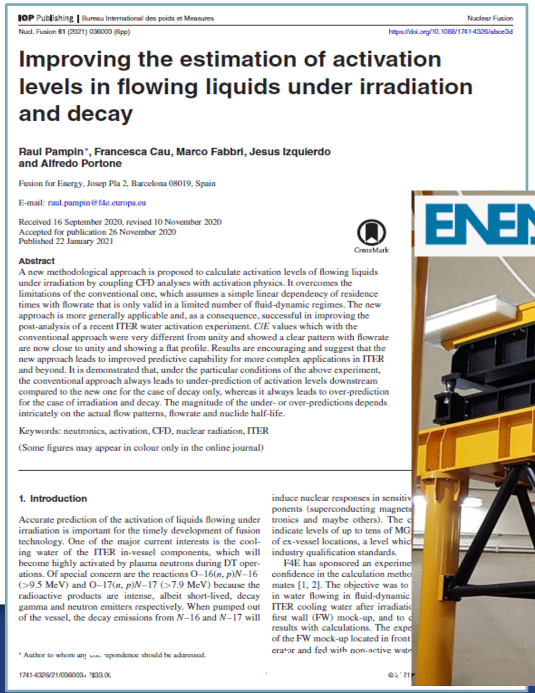
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Nucl. Fusion 61 (2021) 036003 (6pp) — https://doi.org/10.1088/1741-4326/abce3d

Improving the estimation of activation levels in flowing liquids under irradiation and decay

Raul Pampin*, Francesca Cau, Marco Fabbri, Jesus Izquierdo and Alfredo Portone

Fusion for Energy, Josep Pla 2, Barcelona 08019, Spain

E-mail: raul.pampin@f4e.europa.eu

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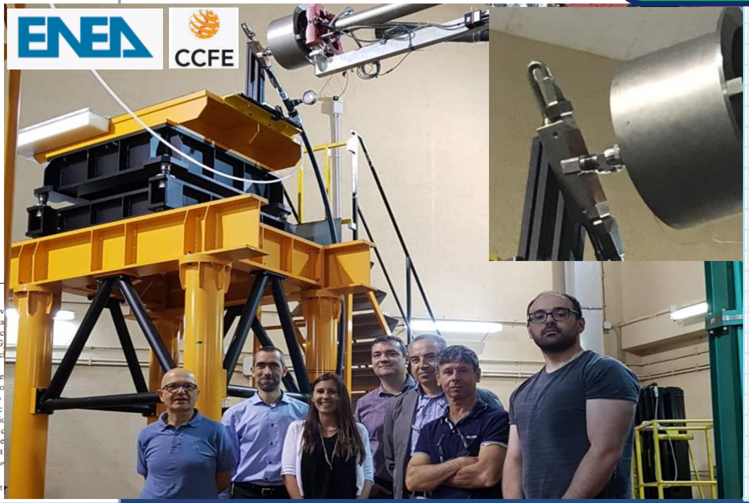
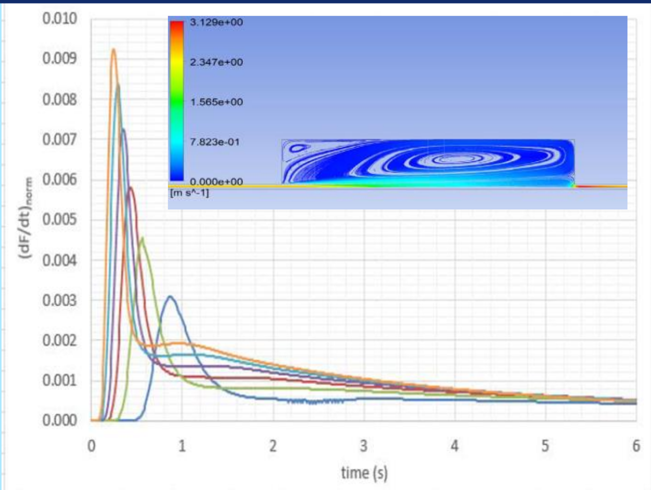
Abstract

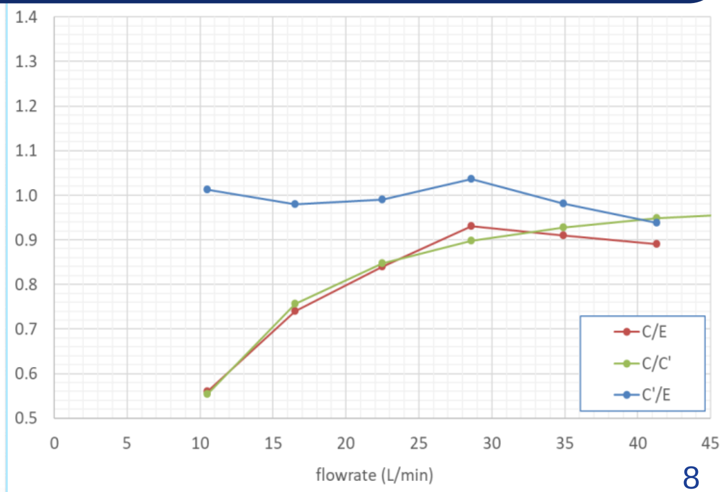
A new methodological approach is proposed to calculate activation levels of flowing liquids under irradiation by coupling CFD analyses with activation physics. It overcomes the limitations of the conventional one, which assumes a simple linear dependency of residence times with flowrate that is only valid in a limited number of fluid-dynamic regimes. The new approach is more generally applicable and, as a consequence, successful in improving the post-analysis of a recent ITER water activation experiment. *C/E* values which with the conventional approach were very different from unity and showed a clear pattern with flowrate are now close to unity and showing a flat profile. Results are encouraging and suggest that the new approach leads to improved predictive capability for more complex applications in ITER and beyond. It is demonstrated that, under the particular conditions of the above experiment, the conventional approach always leads to under-prediction of activation levels downstream compared to the new one for the case of decay only, whereas it always leads to over-prediction for the case of irradiation and decay. The magnitude of the under- or over-predictions depends intricately on the actual flow patterns, flowrate and nuclide half-life.

Keywords: neutronics, activation, CFD, nuclear radiation, ITER

(Some figures may appear in colour only in the online journal)







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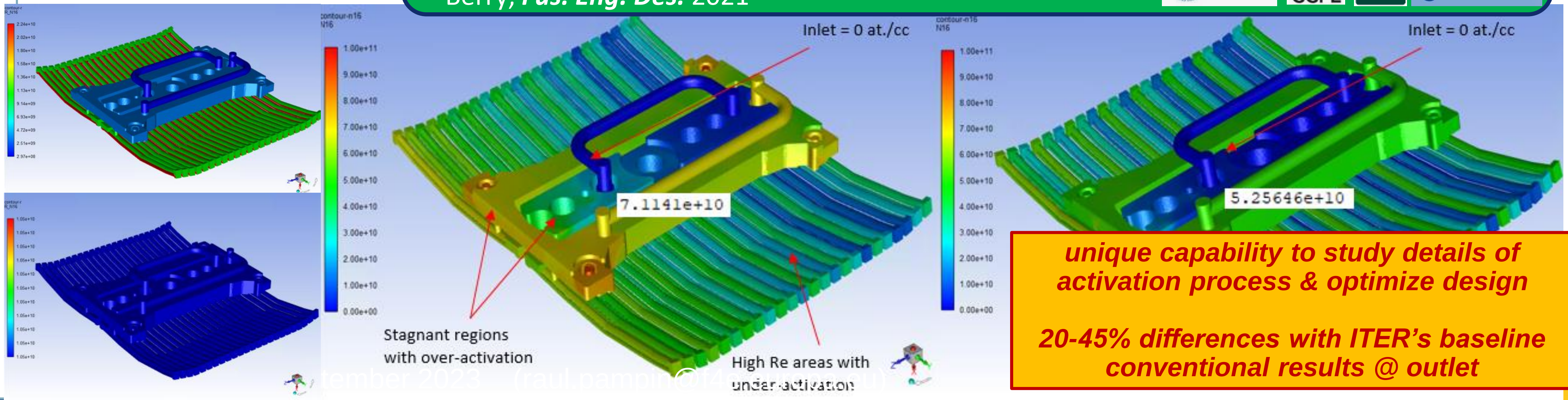
Radio-species transport model for coupled fluid dynamics-neutron activation calculations

Carlos Moreno Carrero, Francesca Cau, Raúl Pampin

ARTICLE INFO

ABSTRACT

1. Introduction



unique capability to study details of activation process & optimize design

20-45% differences with ITER's baseline conventional results @ outlet

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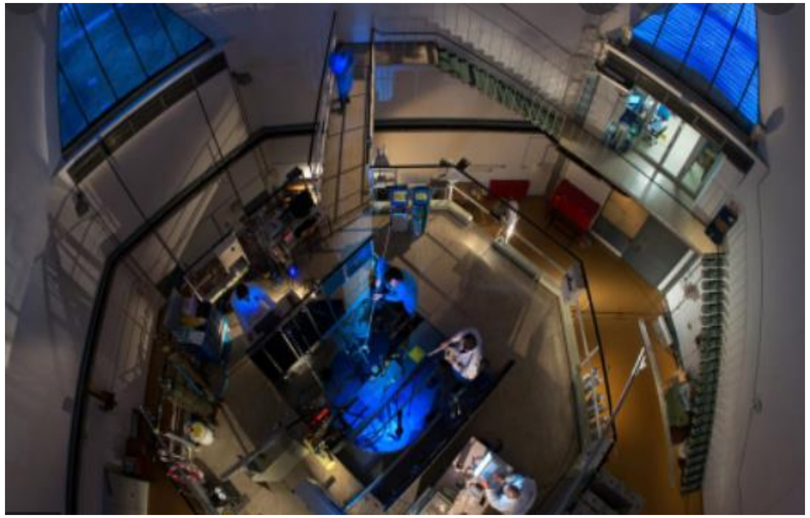
*Pampin, this talk

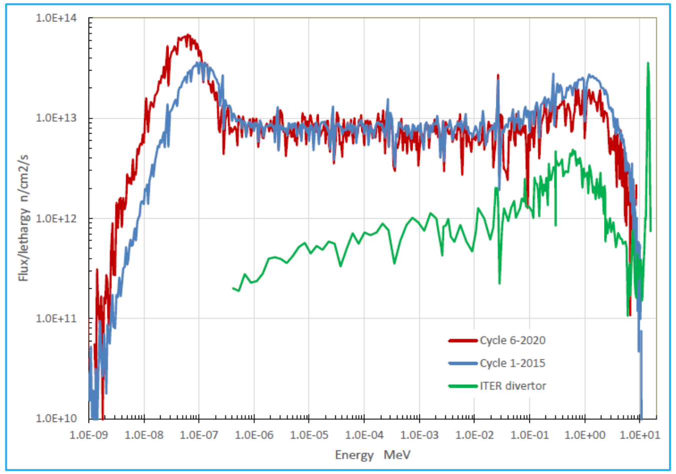
*Villari, ISFNT15 (PL1)

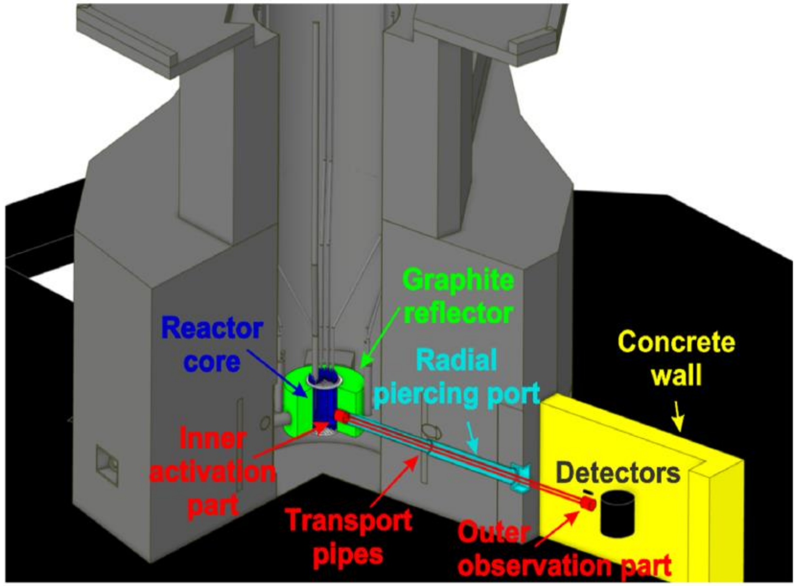
*Kotnik, ISFNT15 (PS2-113)

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.

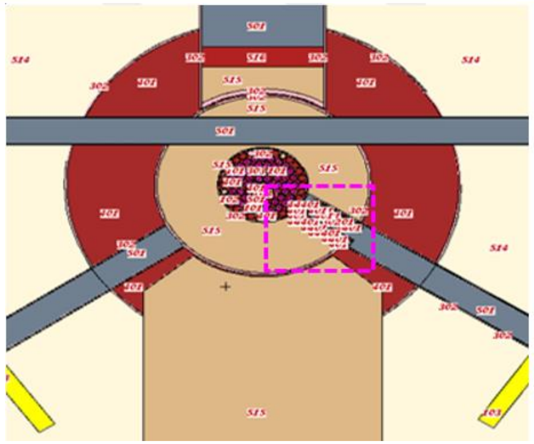


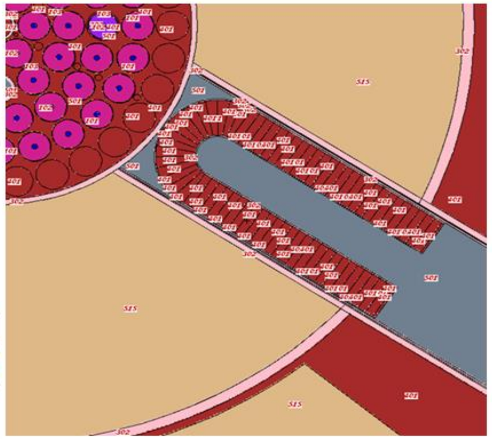




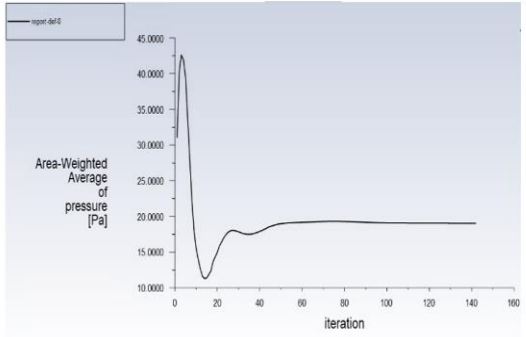
RTSM application

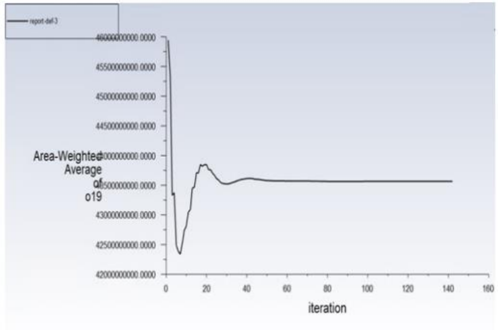
- F4E contributions to JSI water activation experiment:
  - Extension & debugging of RSTM capabilities.
  - Conventional & RSTM of conceptual inner head.
  - Conventional & RSTM of final inner & outer heads.
  - Conceptual design of ITER-relevant alternative head.
- Range of flowrates: 1.5 L/s to 0.1 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-ω turbulence model solver & typical residual-based & outlet stability convergence criteria.



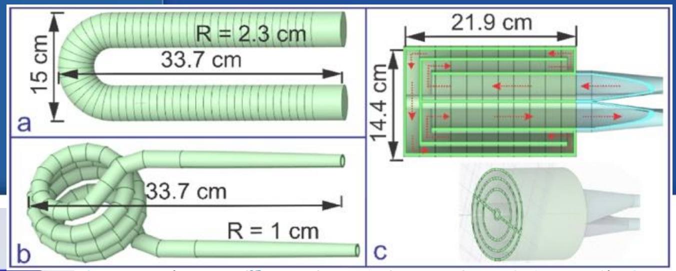


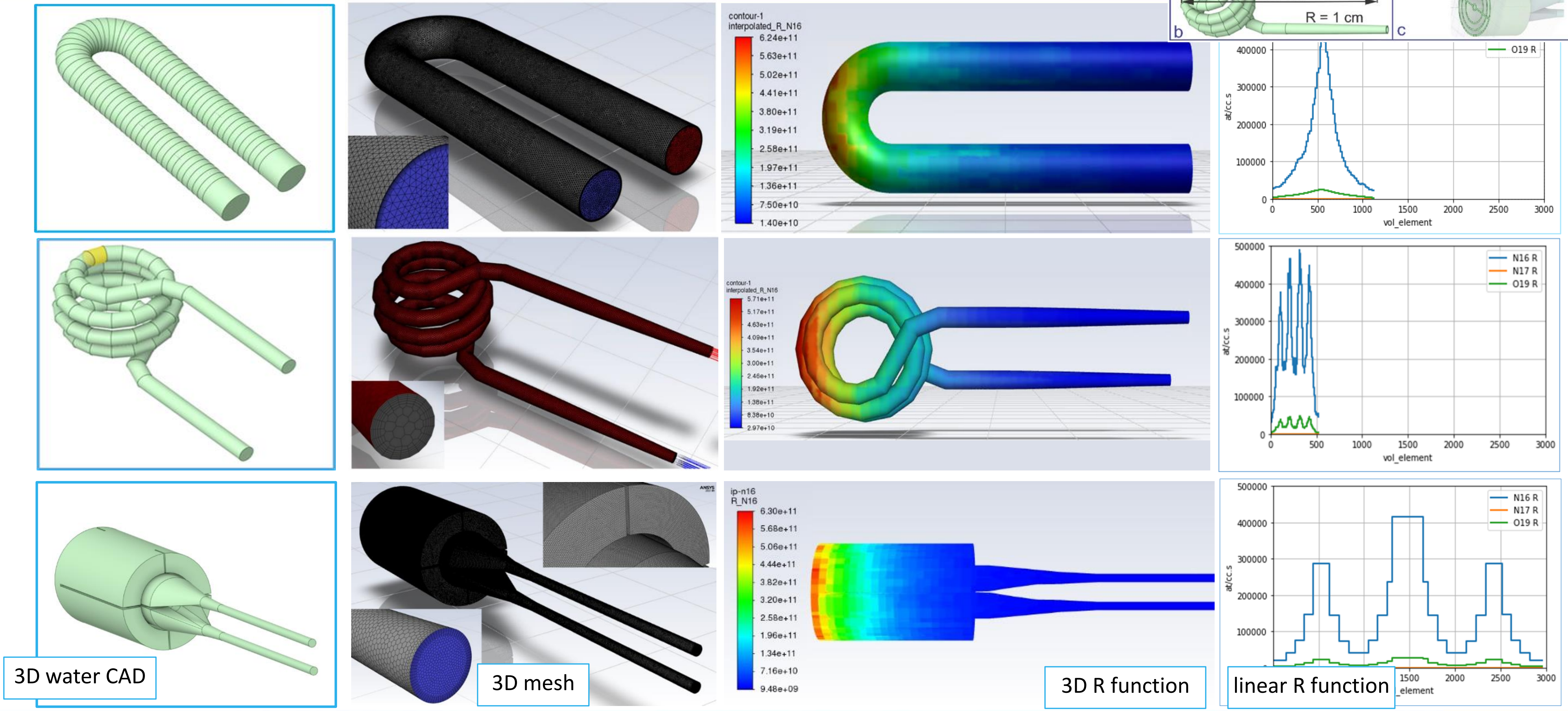
	U-turn	Spiral	Snail
Element type	tetrahedral	polyhedral	polyhedral
Base size	1 mm	1.5 mm	1 mm
Maximum size	N.A.	N.A.	2.5 mm
Growth rate	1.2	1.2	1.2
No. elements	1.68 M	0.27 M	6.61 M
Boundary layer 1st layer thickness	0.1 mm	0.25 mm	0.1 mm
Boundary layer no. layers	8	5	8
Boundary later growth rate	1.2	1.2	1.2
Boundary layer total thickness	1.65 mm	1.86 mm	1.65 mm





RSTM application
Conceptual design options for irradiation head





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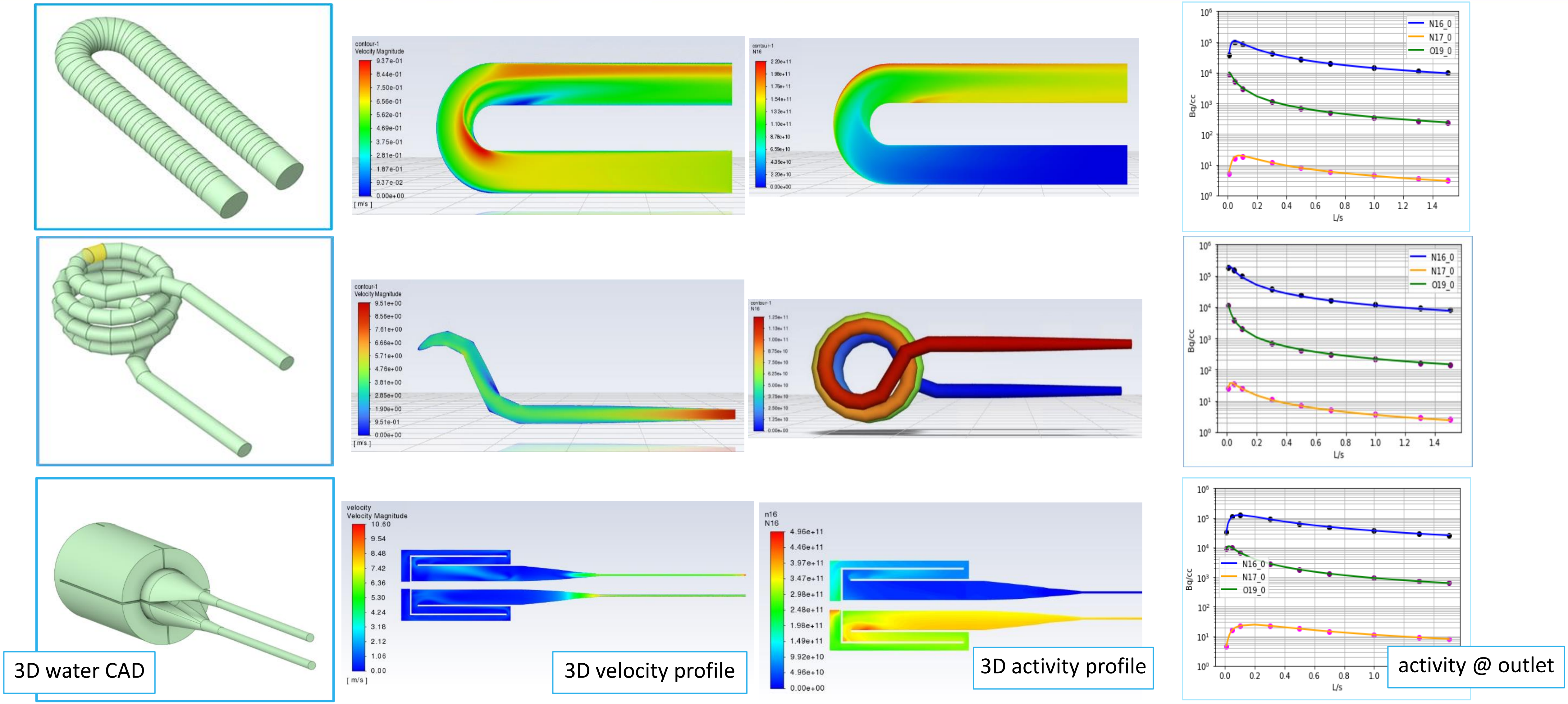
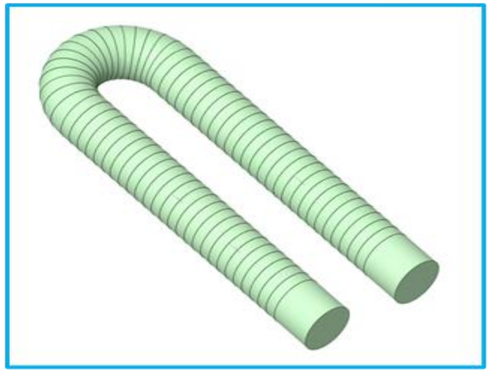
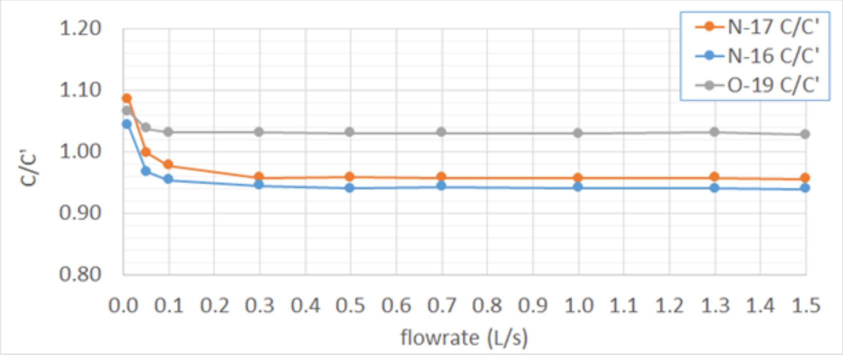
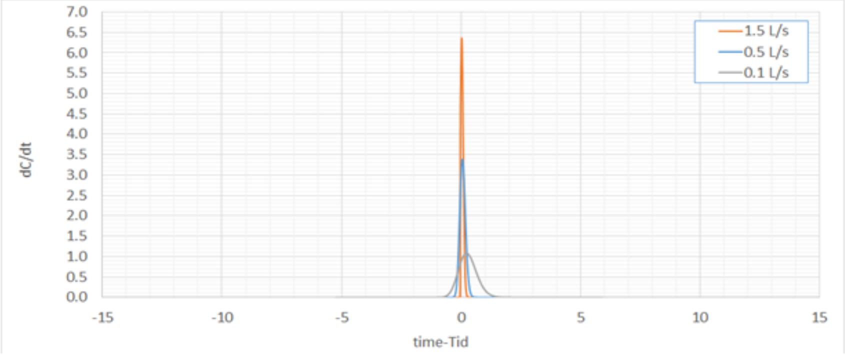
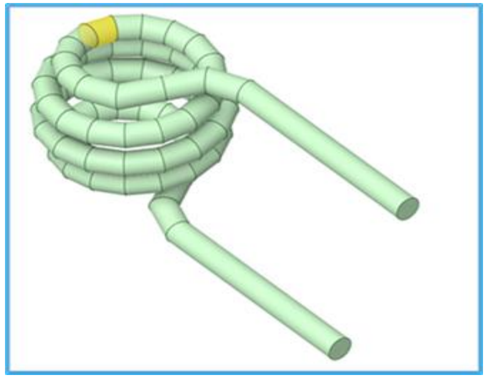


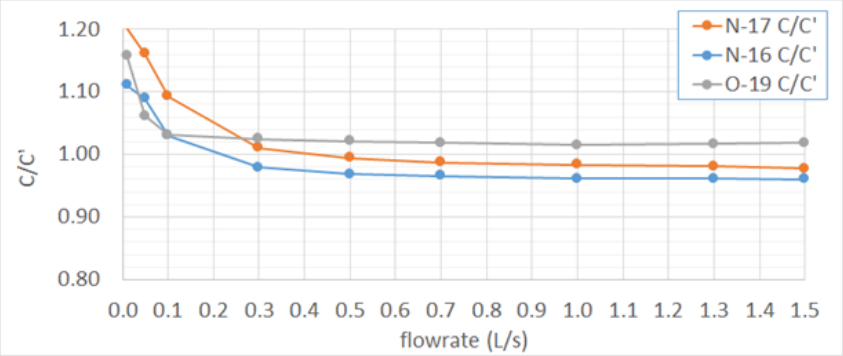
RTSM application
Conceptual design options for irradiation head

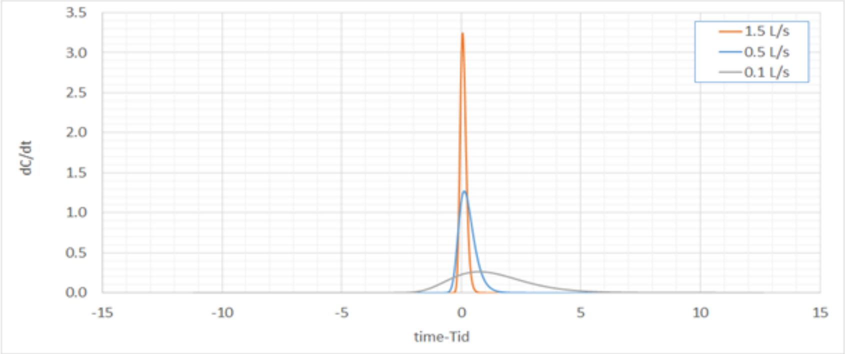


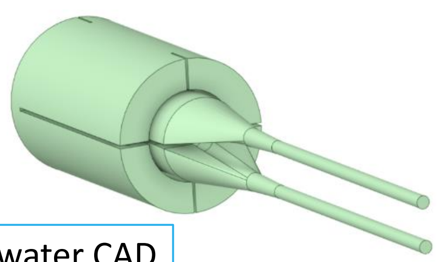


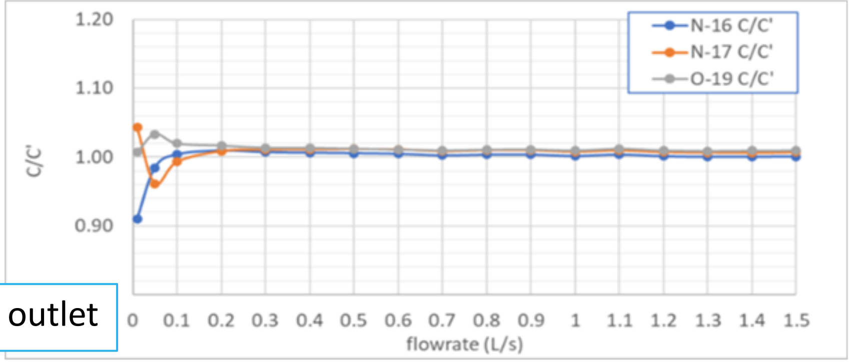


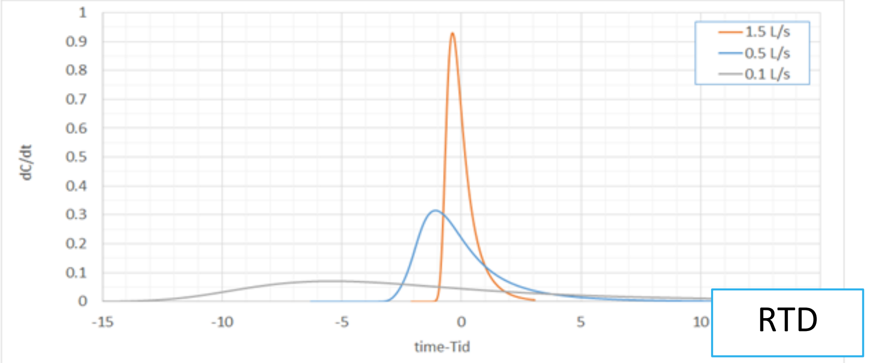












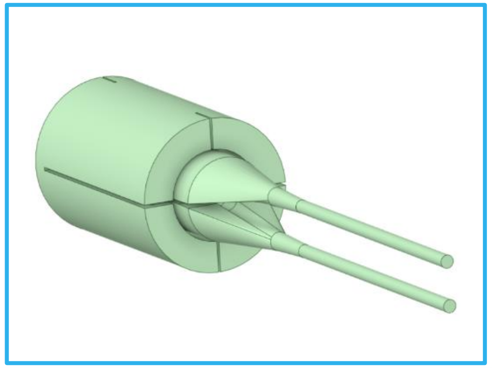
3D water CAD

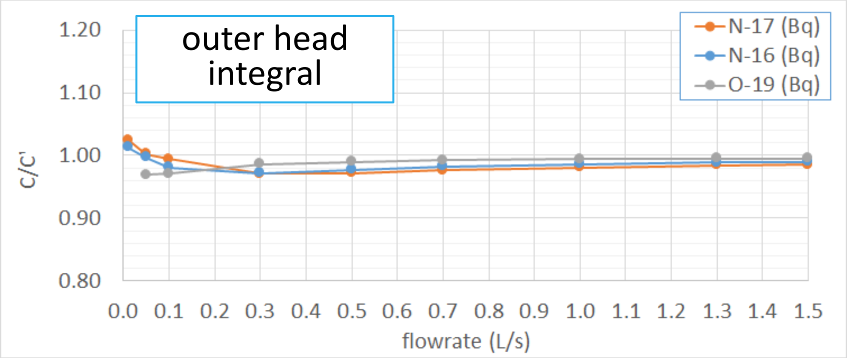
C/C' @ outlet

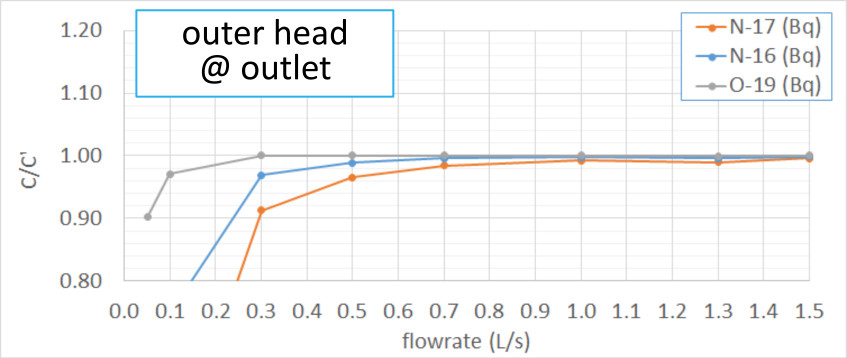
RTD

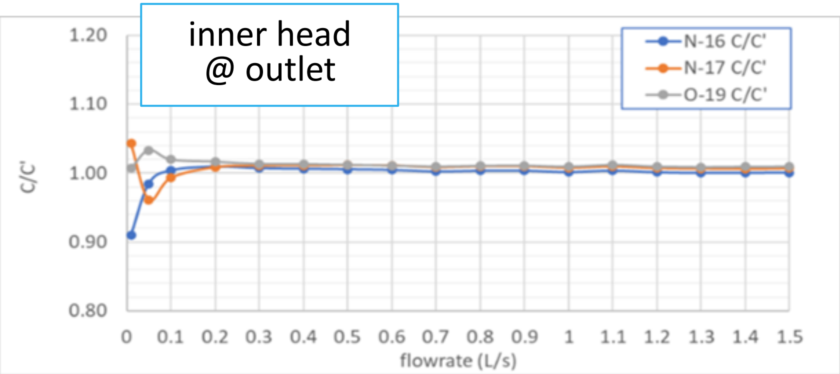
RTSM application
Final design of irradiation & observation heads

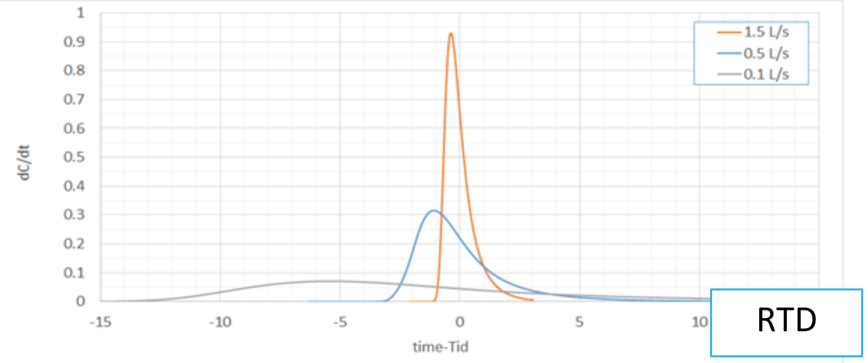
- First phase (shielding tests): snail's superior activity chosen for inner head final design & implementation → flat C/C'.
- Same design for outer head, where R=0 (decay only).
- Then C/C' depends only on flow non-linearities which, from the RTD, can be significant → seen in results @ outlet.
- But: 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

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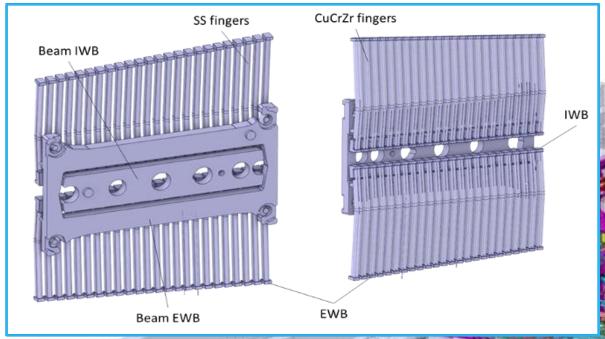
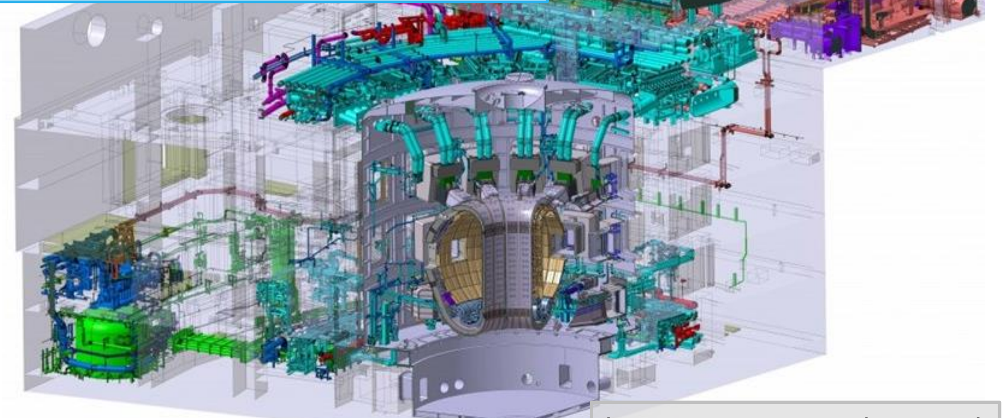
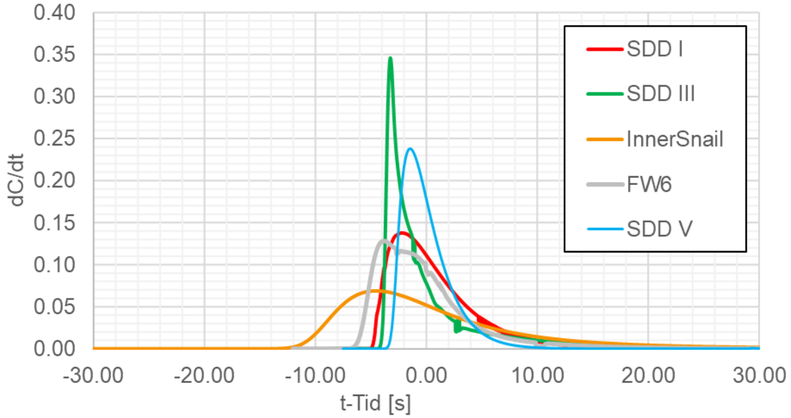
- Second phase (ITER-relevant validation tests): attempt to design inner head mimicking FW.
- Hindered by complex hydraulic routing & limited port size.
- Conceptual design premise is to preserve:
  - Hydraulic features: pipework, waterboxes, fingers.
  - Residence time: adjusted flowrate @ same regime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

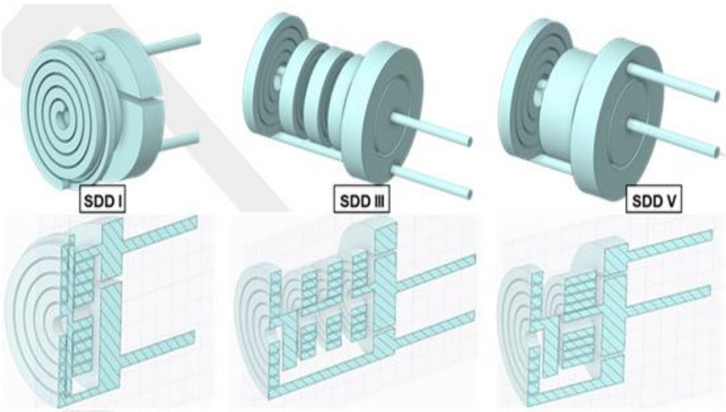
Geom.	V [L]	Q [L/s]	v [m/s]	Re [-]	MRT [s]	Tid [s]
SDD I	0.75	0.1	1.152	6941	8.1	7.5
SDD III	0.87	0.1	0.716	5624	9.3	8.7
SDD V	0.75	0.1	0.770	6048	7.7	7.5
Snail	3.06	0.1	-	-	31.5	30.6
FW06	55.13	4.66	0.791*	17310*	11.9	11.8

* FW finger cooling channel.





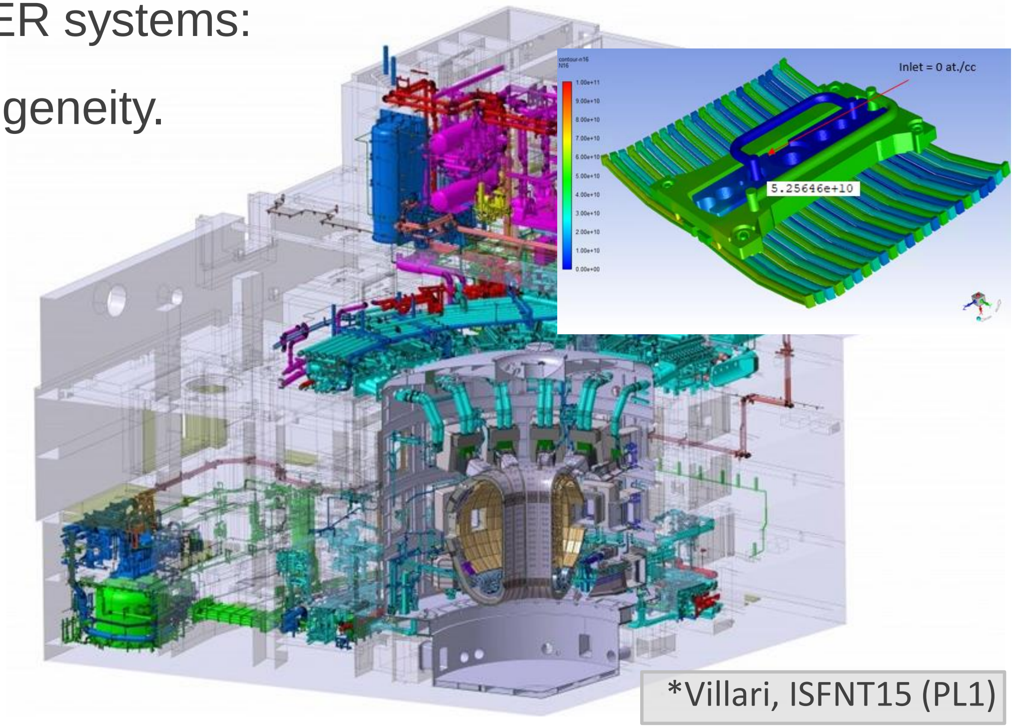




*Masia, ISFNT15 (PS4-34)

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)

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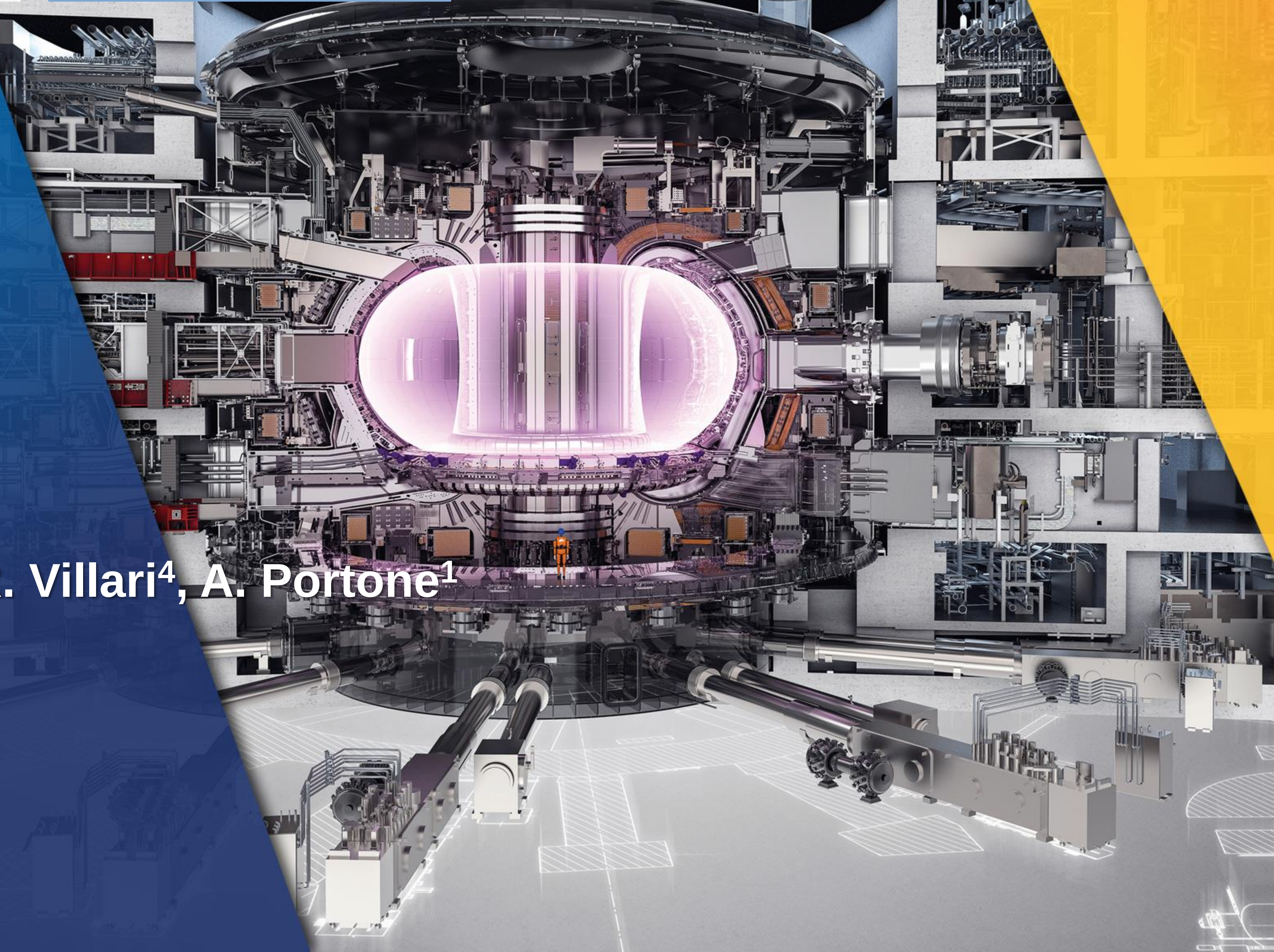
Thank you!



Raul Pampin[1]

E. Masia[2], F. Cau[1], D. Kotnik[3], R. Villari[4], A. Portone[1]

(1) F4E (2) ATG (3) JSI (4) ENEA - EUROfusion

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Gran Canaria, 11-15 Sep 2023

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