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ENERGY**



Jožef
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EUROfusion

BRINGING
THE **POWER**
OF THE **SUN**
TO **EARTH**

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

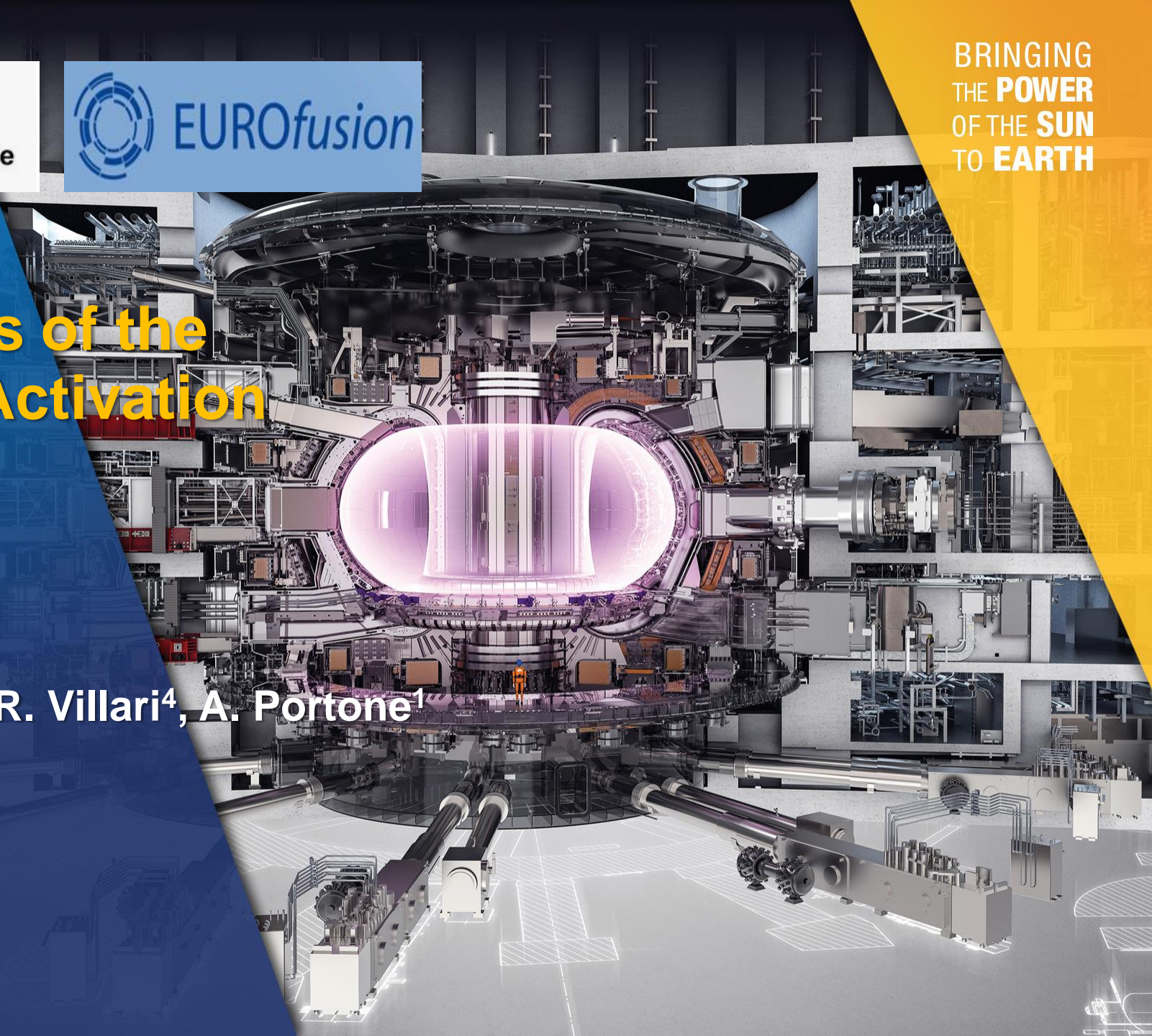
Raul Pampin¹

E. Masia², F. Cau¹, D. Kotnik³, R. Villari⁴, A. Portone¹

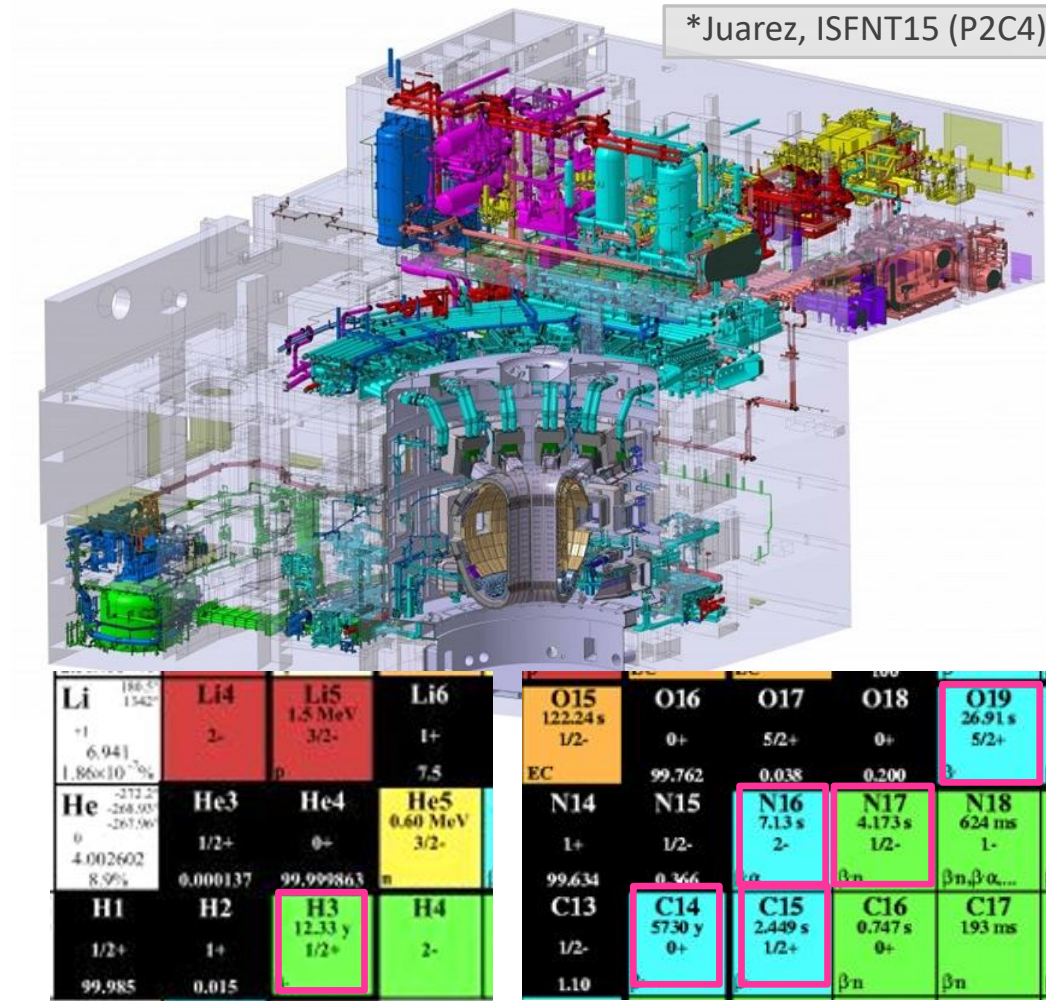
(1) F4E (2) ATG (3) JSI (4) ENEA - EUROfusion

ISFNT-15

Gran Canaria, 11-15 Sep 2023

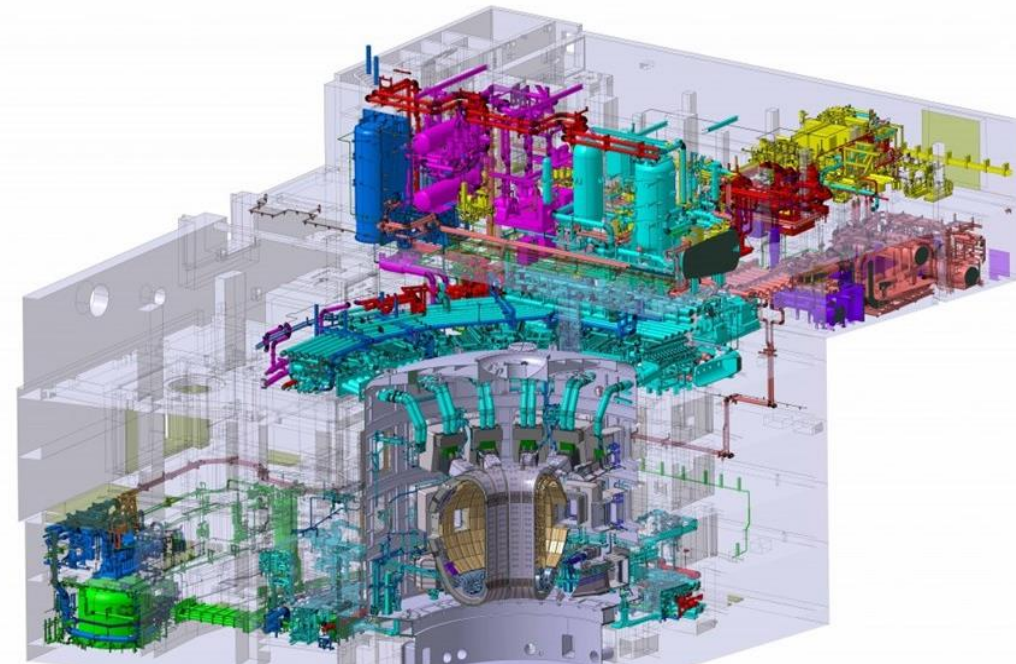


- ITER cooling water will carry throughout the plant two significant secondary* radiation sources:
 - water activation,
 - activated corrosion products (not in this talk*).
- Which have a number of implications in terms of:
 - Need for confinement barriers.
 - Nuclear pressure equipment & effluent regulations.
 - 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.

- 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.



Li 186.5 1342 +1 6.941 1.86x10 ⁻⁹ %	Li4 2-	Li5 1.5 MeV 3/2-	Li6 1+ 7.5	O15 122.24 s 1/2-	O16 0+	O17 5/2+	O18 0+	O19 26.91 s 5/2+
He -212.2 -268.93 -267.90 0 4.002602 8.95%	He3 1/2+	He4 0+	He5 0.60 MeV 3/2-	N14 1+	N15 1/2-	N16 7.13 s 2-	N17 4.173 s 1/2-	N18 624 ms 1-
H1 1/2+	H2 1+	H3 12.33 y 1/2+	H4 2-	C13 1/2-	C14 5730 y 0+	C15 2.449 s 1/2+	C16 0.747 s 0+	C17 193 ms βn
99.985	0.015	99.999863		99.634	0.366	100	βn	βn,β ⁺ α...

Methods for fluid activation

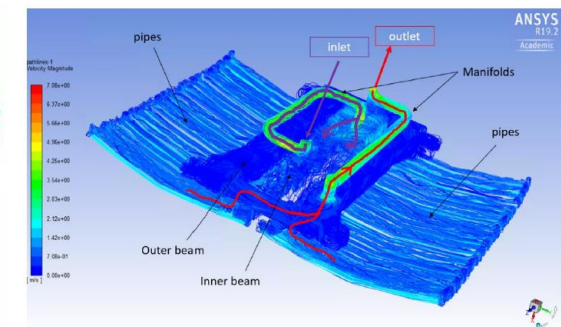
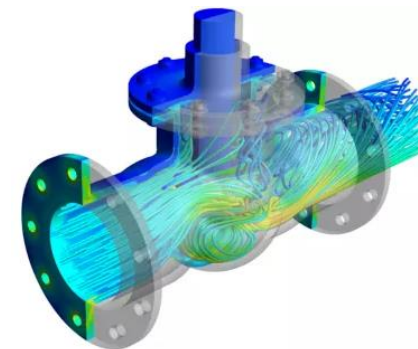
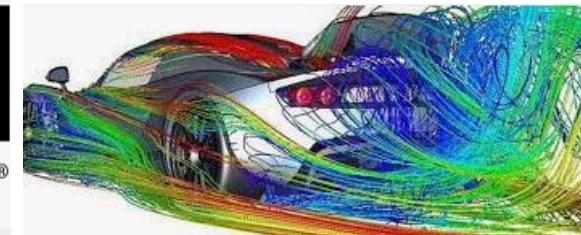
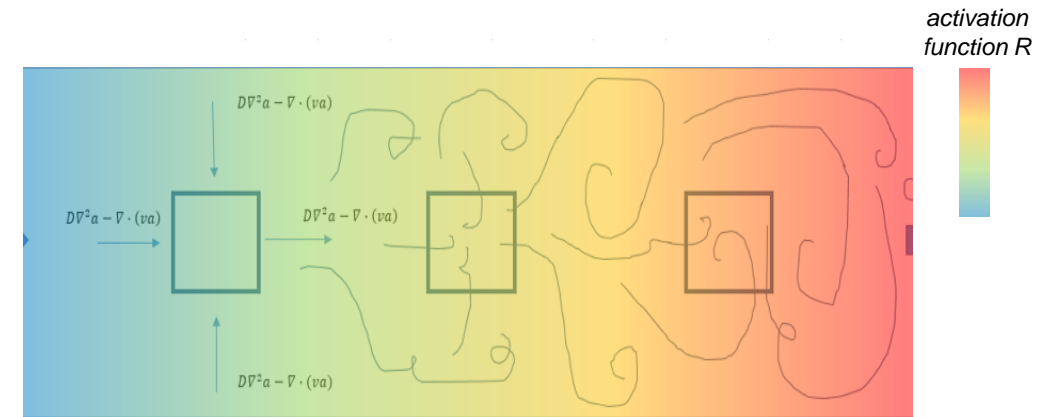
General governing equation

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

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

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

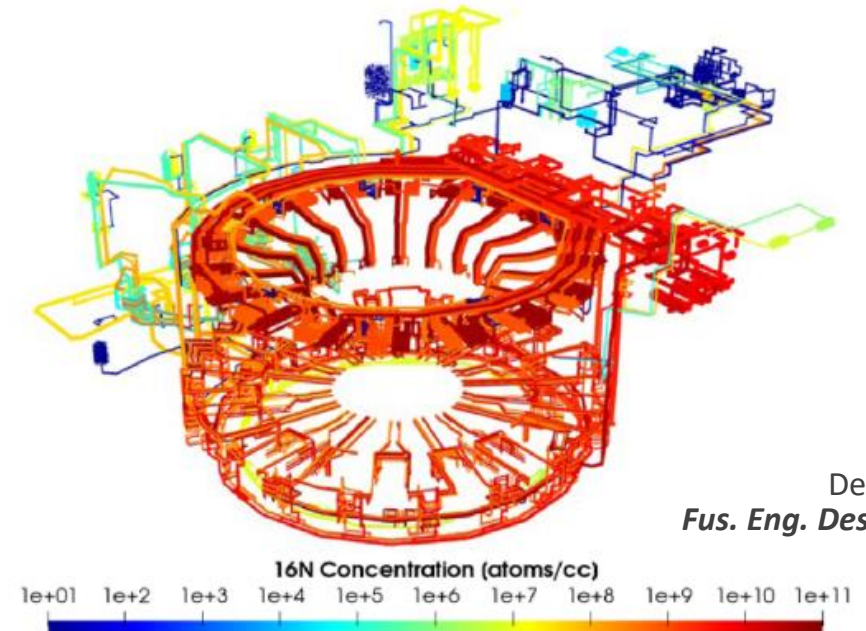
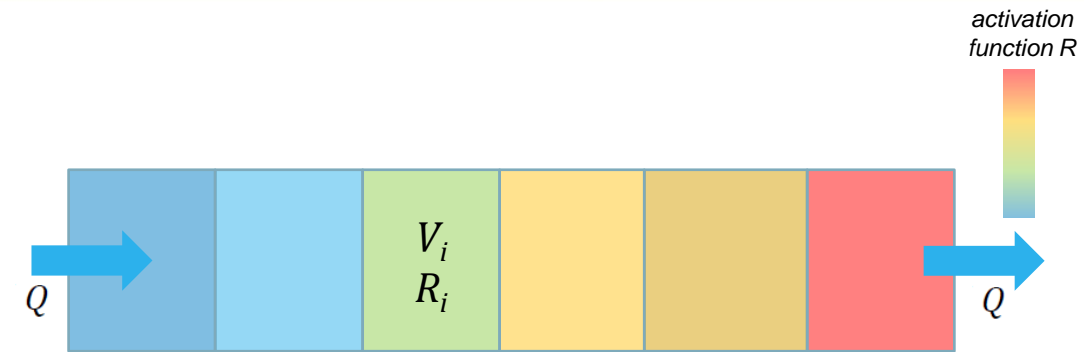
The conventional or circuit method

- ...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 $a_i \rightarrow$ *conventional* or *circuit* method:

$$A_i = \lambda a_i' \quad t_i = V_i / Q$$

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

- 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

2000...

2019

2020

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ITER cooling water activation calculations with circuit method.

- Polunovskiy, *ITER report* 2020



Design & commissioning of JSI water activation loop.

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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).



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Moreno, *Fus. Eng. Des.* 2022

RSTM application to JSI water activation loop.



Developments under EUROfusion by University of Palermo, UNED & CCFE.

- Chiovaro, *Fus. Eng. Des.* 2020
- De Pietri, *Comp. Phys. Comms.* 2023
- Berry, *Fus. Eng. Des.* 2021



Developments timeline

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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^{a,*}, J. Naitoh^b, L.W. Packer^c, R. Worrall^d, M. Angelone^e, A. Colangelo^f, S. Loreti^g, M. Pillon^h, R. Villariⁱ

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^b NIES - Department of Physics and Technology for Nuclear Safety and Security via S. Jorini 45, 00144 Pratica di Mare, Italy

1. Introduction

The water coolant in ITER components such as those inside the first wall, blanket modules, divertor cassettes and vacuum vessel will be activated by neutrons during D-T plasma operations. Two key neutron induced reactions will occur with oxygen producing the radioactive nitrogen isotopes N-16 and N-17 through the following reactions:

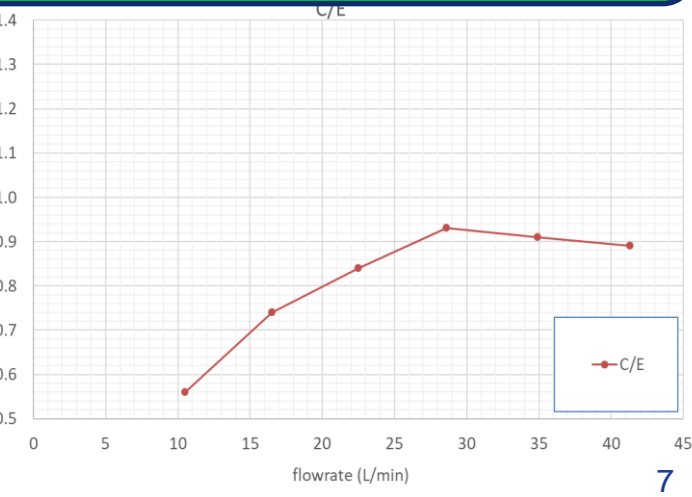
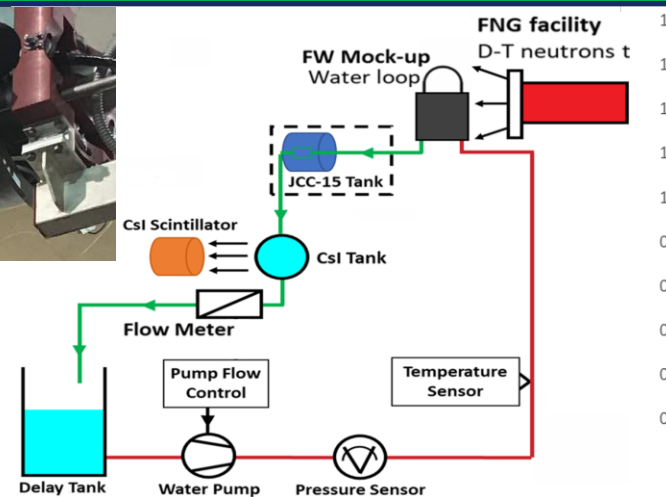
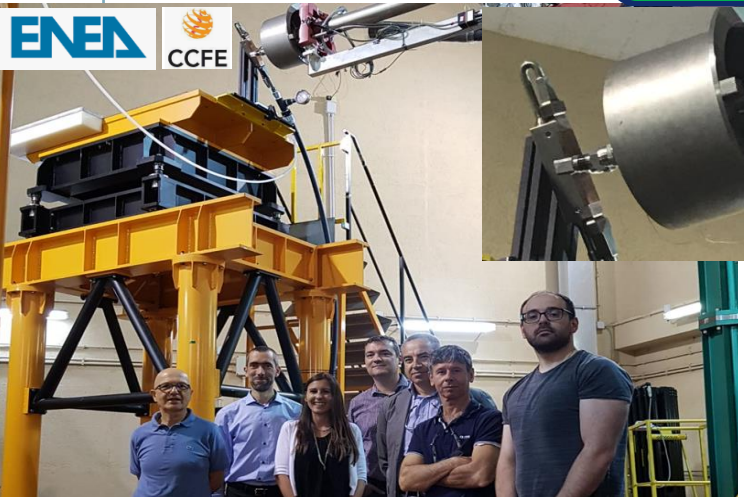
$$^{16}\text{O}(n,p)^{16}\text{N} \rightarrow ^{16}\text{N}(\beta^-) \rightarrow ^{16}\text{O} + \gamma \quad (1)$$

$$^{17}\text{O}(n,p)^{17}\text{N} \rightarrow ^{17}\text{N}(\beta^-) \rightarrow ^{17}\text{O} + \gamma \quad (2)$$

Reaction 1 produces gamma rays at 6.128 MeV (gamma emission probability per disintegration, I=67.0%) and 7.115 MeV (I=4.9%), whereas reaction 2 produces delayed neutrons at 0.387 MeV (I=25.9%), 0.886 MeV (I=0.5%), 1.163 MeV (I=47.8%), 1.690 MeV (I=7.0%) and gamma rays at 0.870 MeV (I=3.3%) (1). Because water coolant is being transported to other locations from these modules will induce nuclear activation and plant components, e.g. nuclear heat exchangers, will be activated by neutrons during D-T plasma operations. Two key neutron induced reactions will occur with oxygen producing the radioactive nitrogen isotopes N-16 and N-17 through the following reactions:

2. Experimental Setup

The ITER first wall (FW) mock-up was part of the Frascati Neutron Generator (FNG) 14



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Nucl. Fusion 61 (2021) 026003 (5pp)
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Improving the estimation of activation levels in flowing liquids under irradiation and decay

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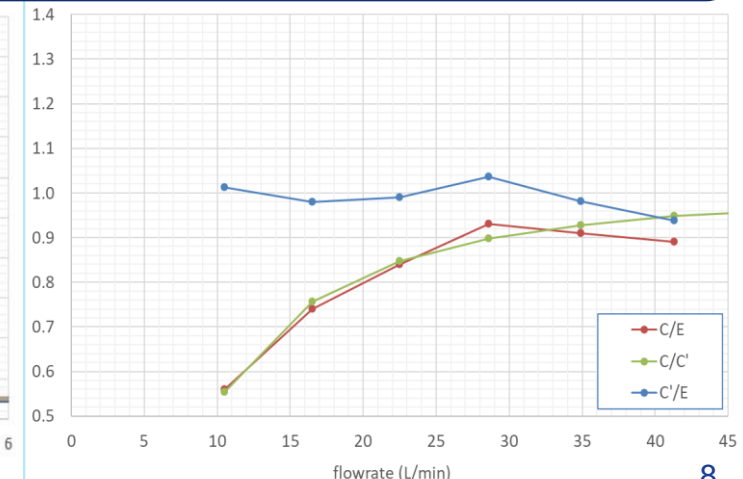
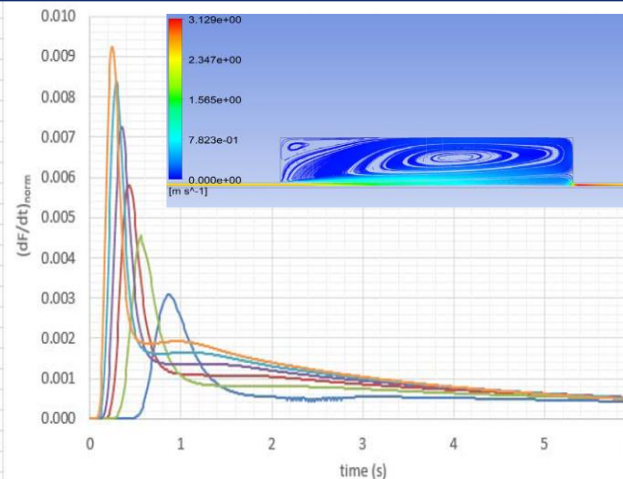
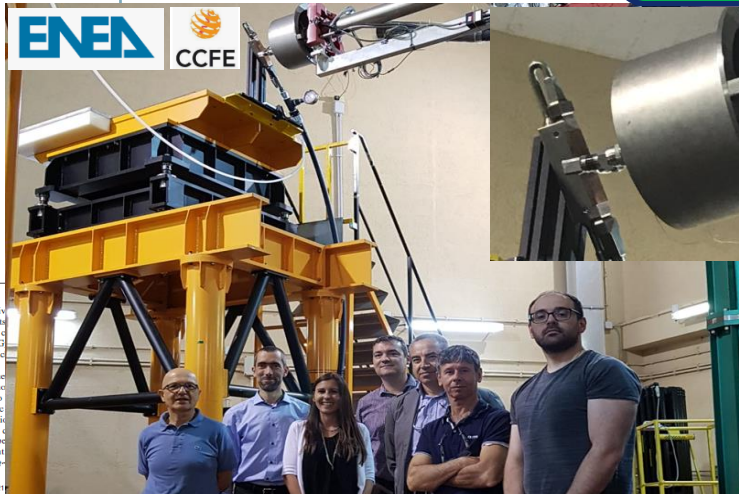
Abstract
A new methodological approach is proposed to calculate activation levels of flowing liquids under irradiation by coupling CFD analyses with activation physics. It overcomes the limitations of the conventional one, which assumes a simple linear dependency of residence times with flowrate that 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)

1. Introduction

Accurate prediction of the activation of liquids flowing under irradiation is important for the timely development of fusion technology. One of the major current interests in the cooling water of the ITER in-vessel components, which will become highly activated by plasma neutrons during DT operations. Of special concern are the reactions $O-16(n, p)N-16$ (≈ 5 MeV) and $O-17(n, p)N-17$ (≈ 7.9 MeV) because the radioactive products are intense, albeit short-lived, decay gamma and neutron emitters respectively. When pumped out of the vessel, the decay emissions from $N-16$ and $N-17$ will

induce nuclear responses in sensitive points (superconducting magnets, electronics and maybe others). The α indicate levels of up to tens of MG of ex-vessel locations, a level which industry qualification standards. F4E has sponsored an experiment confidence in the calculation methods [1, 2]. The objective was to in water flowing in fluid-dynamic ITER cooling water after irradiation first wall (FW) mock-up, and to results with calculations. The exp of the FW mock-up located in front error and 10^{-10} non-time w




* Author to whom any correspondence should be addressed.

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 Fusion Engineering and Design
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Radio-species transport model for coupled fluid dynamics-neutron activation calculations
 Carlos Moreno Carrero^a, Francesca Gau, Raúl Pampin

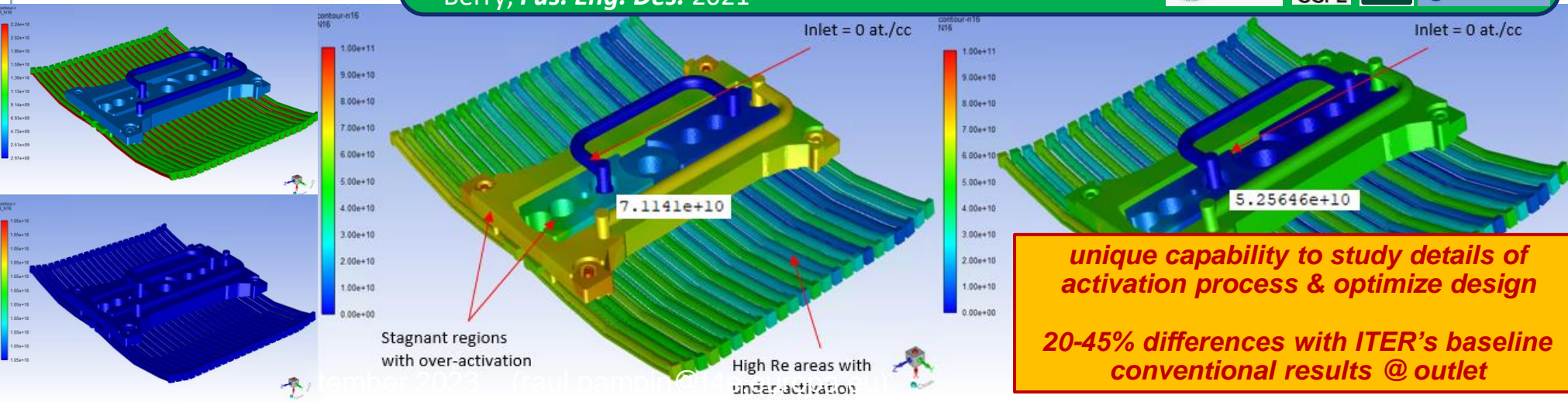
ARTICLE INFO

ABSTRACT
 A coupled methodological approach was developed for the modelling of fluid activation on ITER relevant components, using Computational Fluid Dynamics (CFD), based on ANSYS Fluent's general transport mathematical model, built in equations (EQS) were contained to represent radioactive species' activation and decay processes, fully embedded in field transport equations. Such model, so called Radioactive Species Transport Model (RSTM) was benchmarked against previous approaches on this field. Additionally, two applications relevant for ITER in-Vessel design are reported: (1) a complete FW06 and (2) a complete FW18 with its Shielding Blank (SB18). These results provide new availability on the effects of flow stagnation and recirculation under real activation rate fields for in-Vessel components. This implementation shows that previous approaches may have overestimated the activation levels expected on downstream FWs by the order of 20-40%, depending on the characteristics of the FW parts.

Keywords:
 Water activation
 CFD
 ANSYS Fluent
 Two defined nuclei
 First wall
 In-vessel
 ITER

1. Introduction
 Calculation of neutron-activated species on flowing fluids is a relevant activity in the context of ITER design. It particularly concerns In-Vessel components, which are subjected to excessive radiation from the plasma operation. Water activation models are important for downstream protection dimensioning [1, 2].
 The coupled effect of neutron flux energy spatial distribution and fluid transport (particularly stagnation and recirculation) are known to play a significant role on the activated species' concentration of cooling water at the outlet of in-Vessel components. The pattern of each fluid particle's voyage across the neutron domain lead to a range of different residence times and outlet activation levels. The precise interaction between these phenomena is still a field of active research [3-7].
 The most simple and common approach to this problem assumes a constant and uniform residence time along the fluid domain. Earlier work on experimental analyses and ITER water activation level estimations consisted of modelling a series of conceptual circuit sections (i.e. "compartments") each having one single residence time and activation rate. These conditions may be applicable for components where fully developed turbulent pipe flow regime and almost constant residence times are acceptable. However, this is not the case when benchmarking the analysis domain, for instance to consider complete In-Vessel component under real neutron flux distributions. Divergences are expected the larger the geometry scope of the analysis, where the effect of stagnation and recirculation on residence times cannot be neglected. Certainly, activation rates should not be assumed to be homogeneous either.
 Previous work in [8] substantially improved the prediction of experimental results by the calculation of actual residence-time distributions using the transient simulation of a tracer flow. Unfortunately, the CFD and the integral activation models were uncoupled, so to calculate the activated species' outlet concentration this approach assumed a constant activation rate field across the fluid domain, which is usually not accurate on the simulation of complete in-Vessel components. This model was based on ANSYS Fluent's Species Transport Model (STM).
 A more thorough modelling approach, named Radio Species Transport Model (RSTM), was developed within Fusion for Energy to extend the calculation of activated species concentration to larger geometries under any complex activation rate field [9]. This approach is an embedded formulation of species activation and decay processes into the

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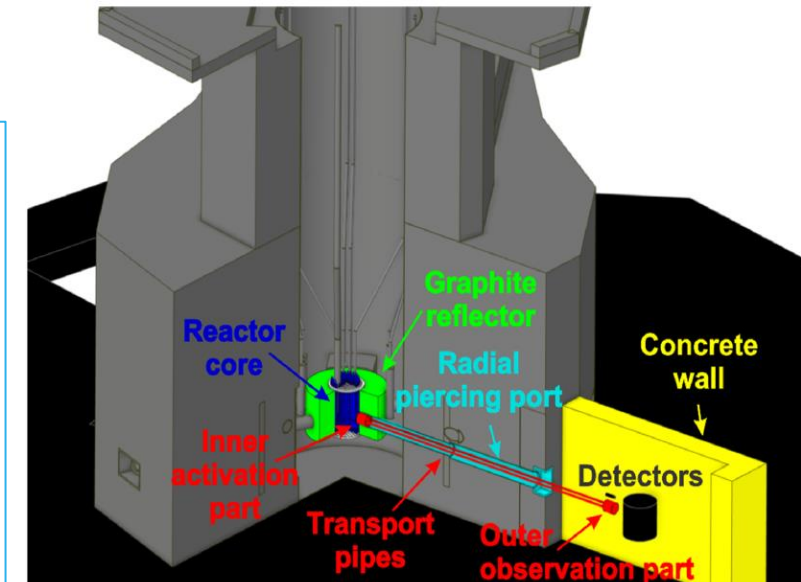
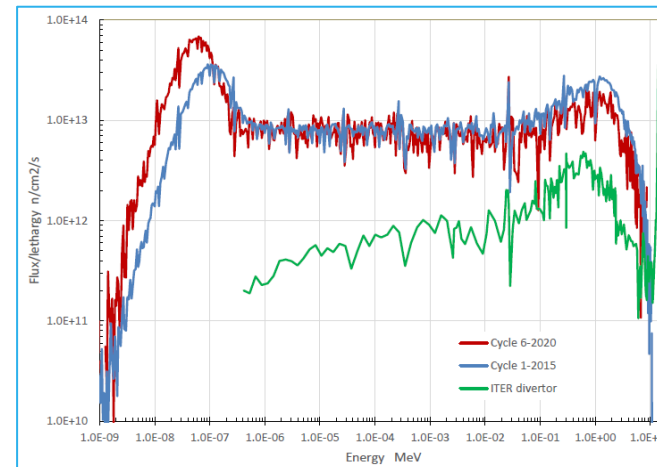
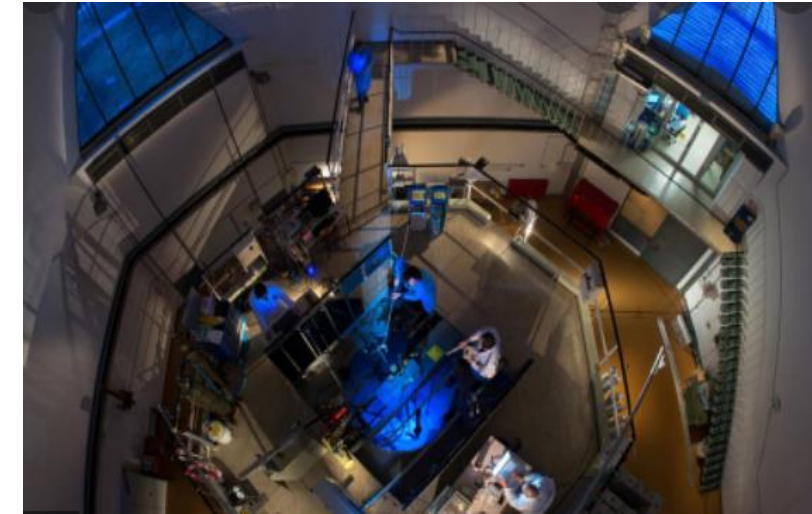


*Pampin, this talk

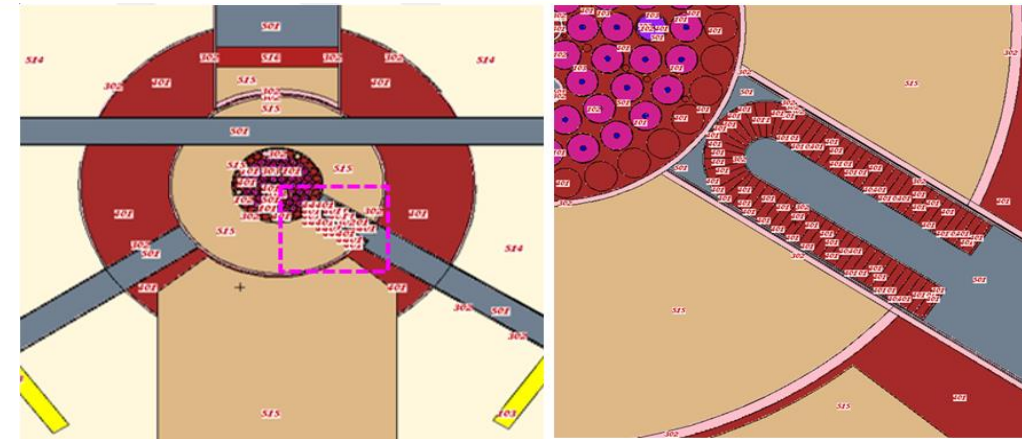
*Villari, ISFNT15 (PL1)

*Kotnik, ISFNT15 (PS2-113)

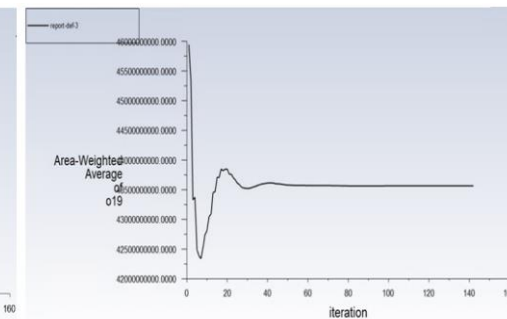
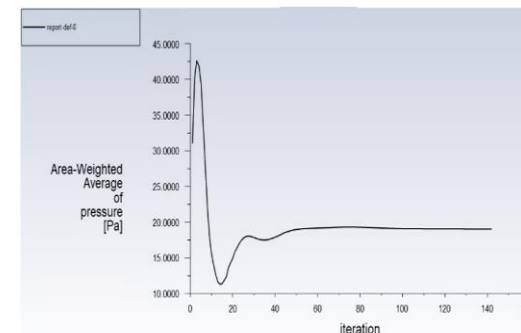
- Water activation reactions also in fission spectrum.
- Dedicated loop designed & commissioned at JSI TRIGA under EUROfusion sponsorship. Objectives:
 - First phase: stable flux of highly energetic decay photons for shielding experiments.
 - Second phase: validation of calculation methods in ITER-relevant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



- 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.

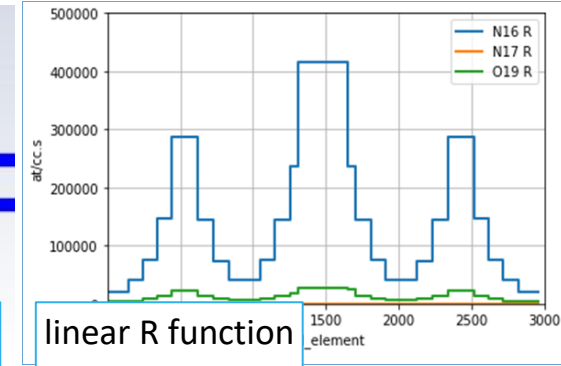
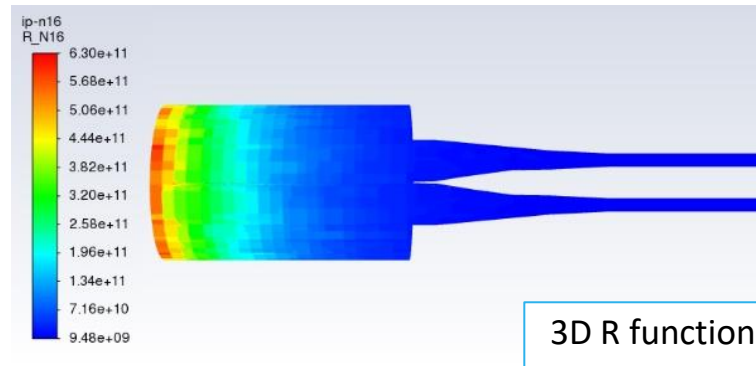
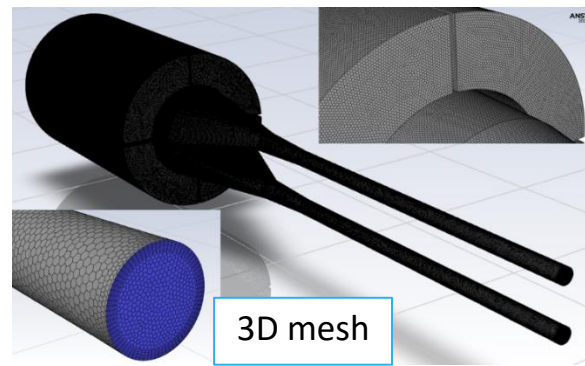
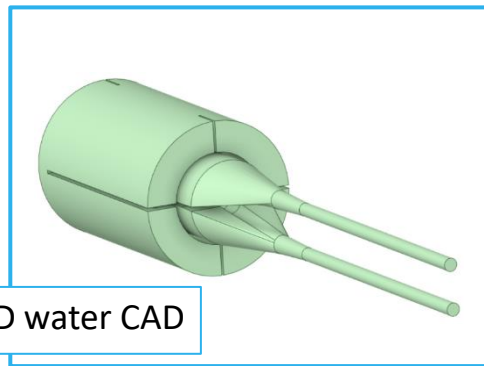
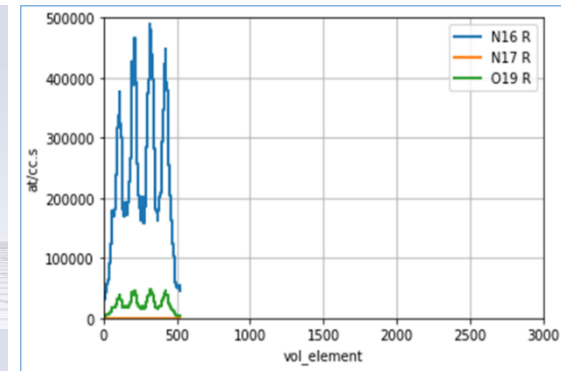
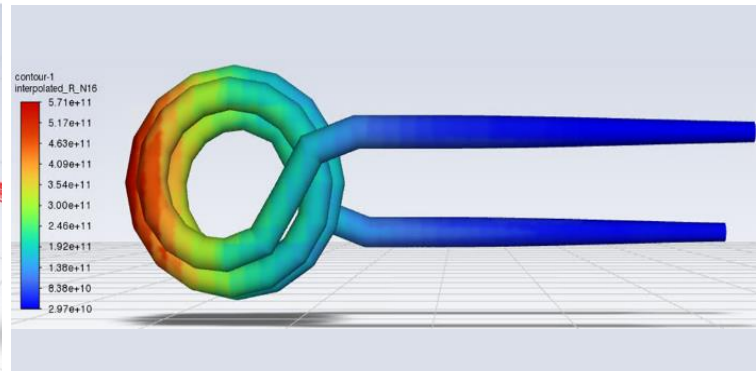
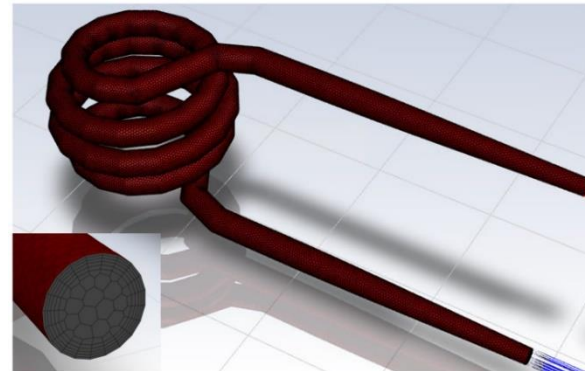
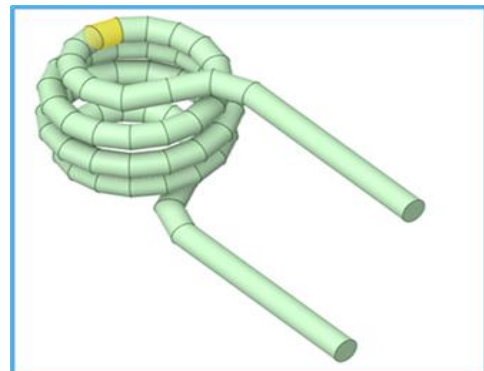
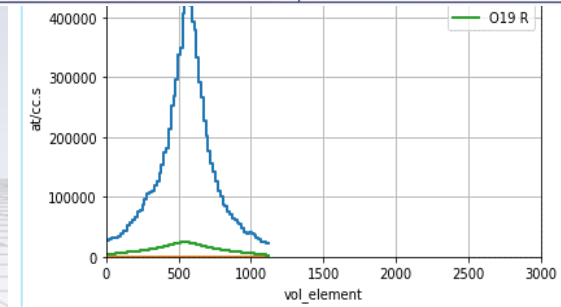
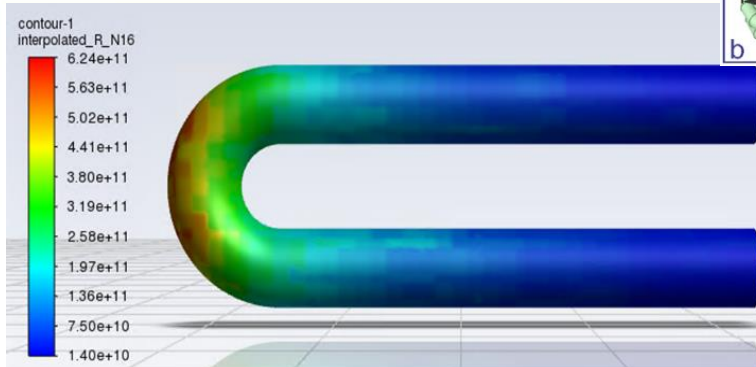
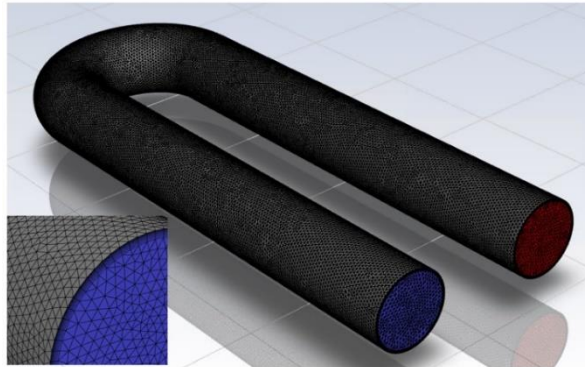
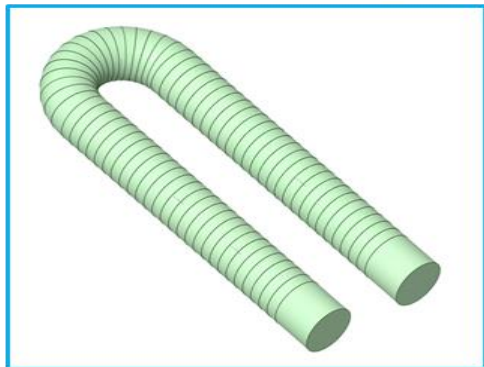
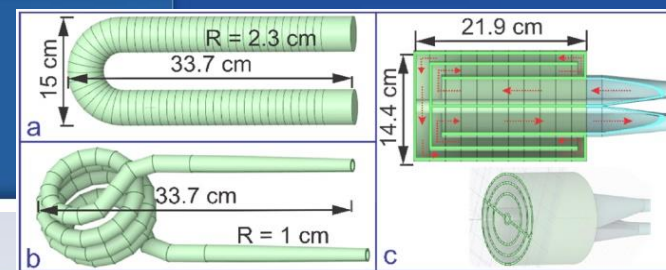


	U-turn	Spiral	Snail
Element type	tetrahedral	polyhedral	polyhedral
Base size	1 mm	1.5 mm	1 mm
Maximum size	N.A.	N.A.	2.5 mm
Growth rate	1.2	1.2	1.2
No. elements	1.68 M	0.27 M	6.61 M
Boundary layer 1 st layer thickness	0.1 mm	0.25 mm	0.1 mm
Boundary layer no. layers	8	5	8
Boundary later growth rate	1.2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



3D water CAD

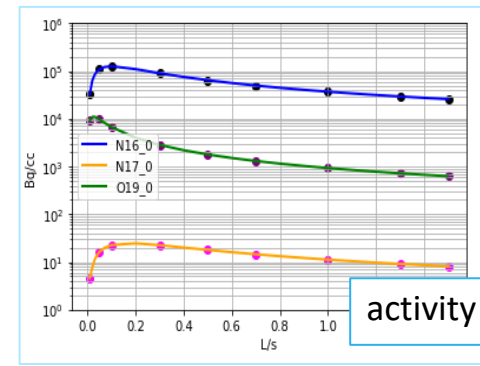
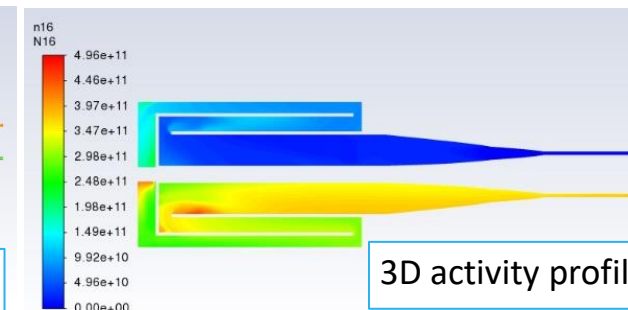
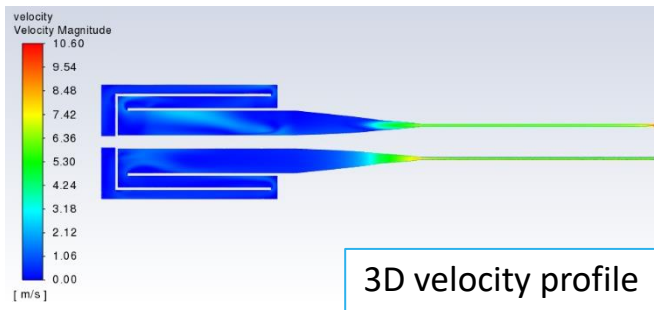
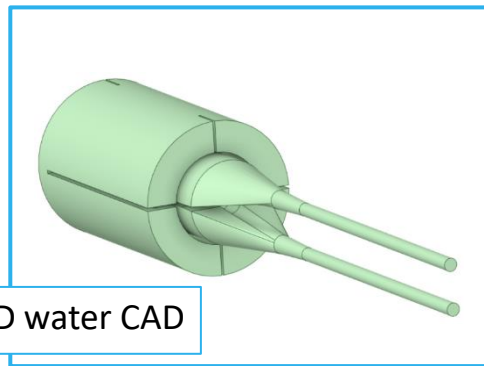
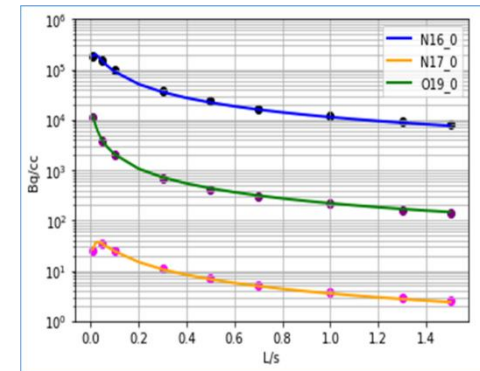
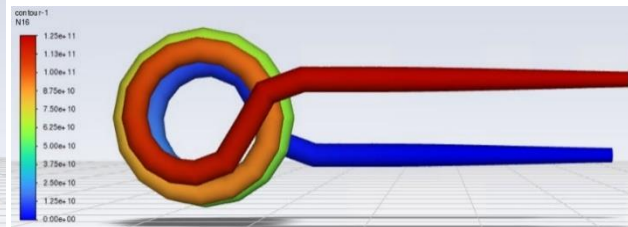
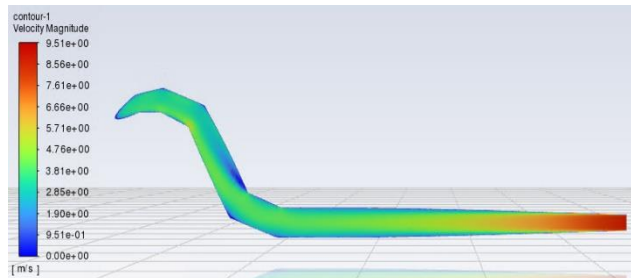
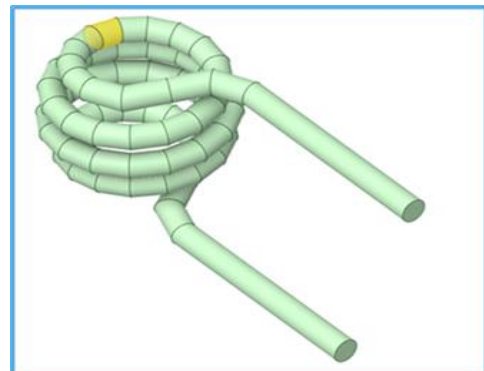
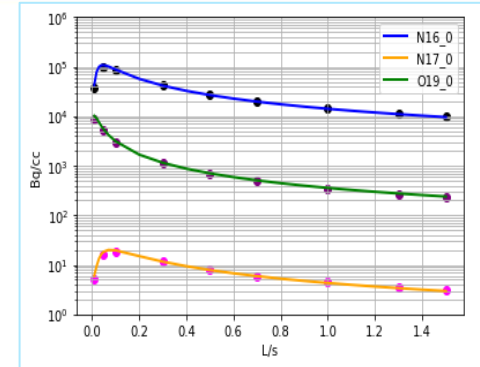
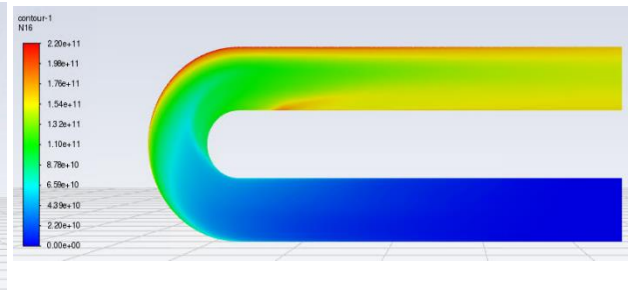
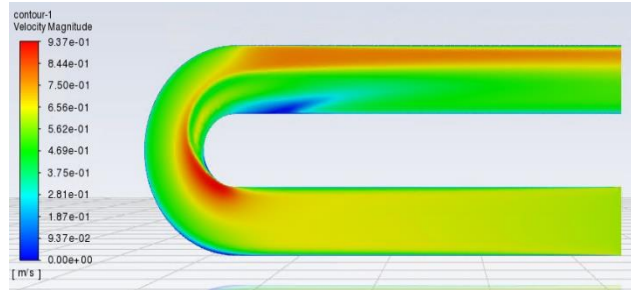
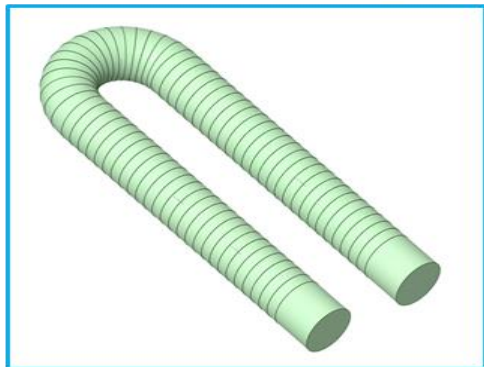
3D mesh

3D R function

linear R function

RSTM application

Conceptual design options for irradiation head



3D water CAD

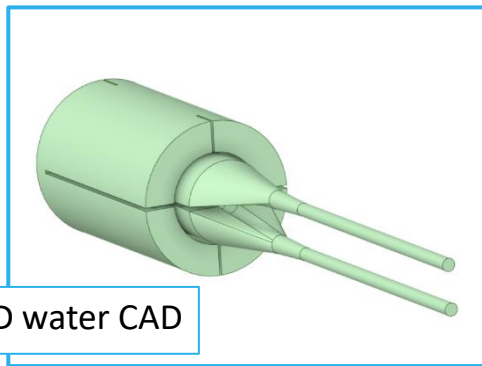
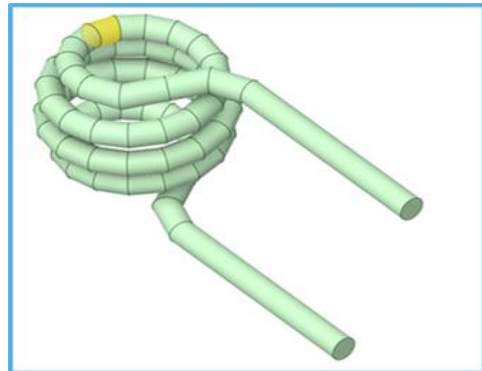
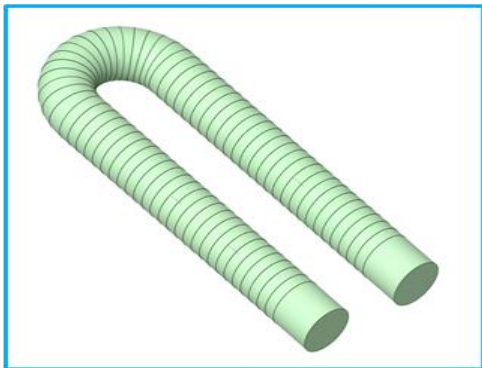
3D velocity profile

3D activity profile

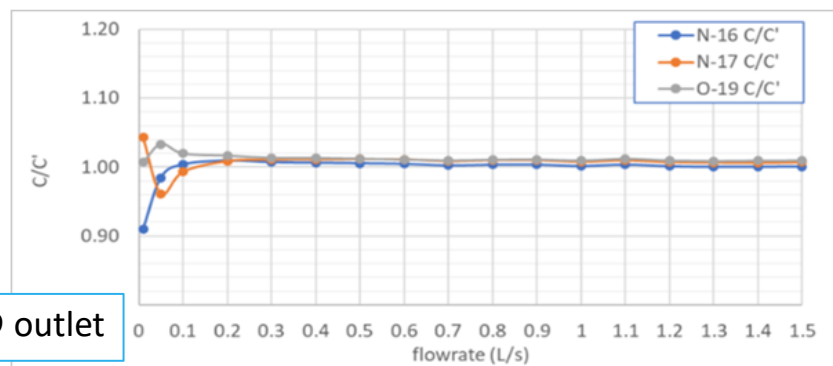
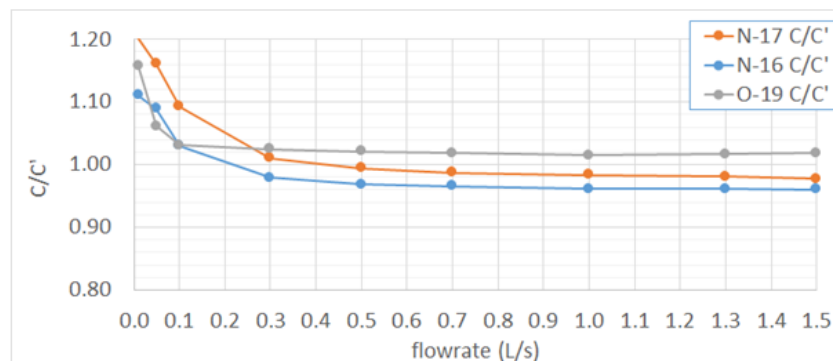
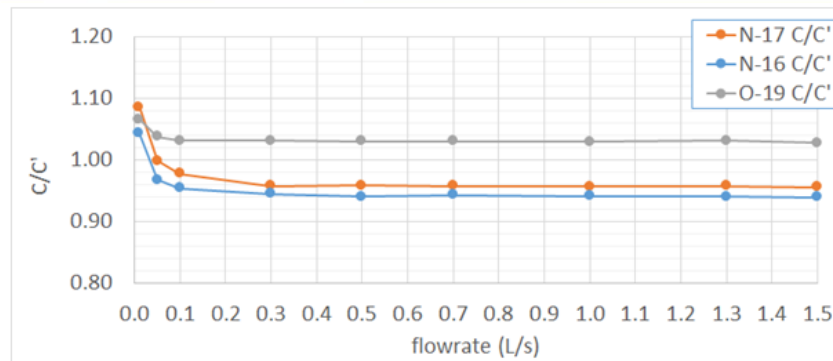
activity @ outlet

RSTM application

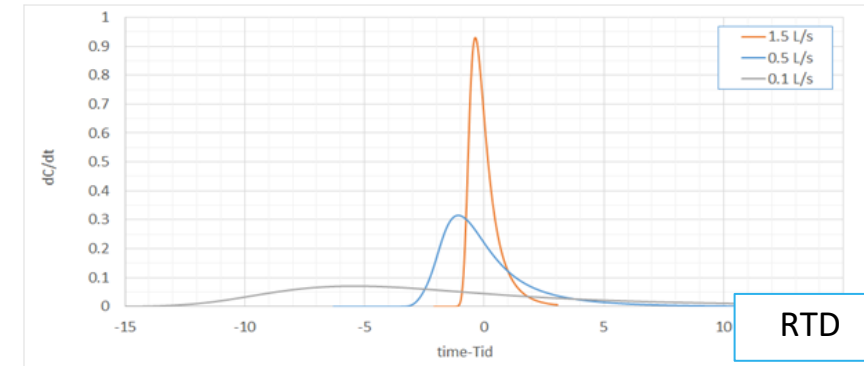
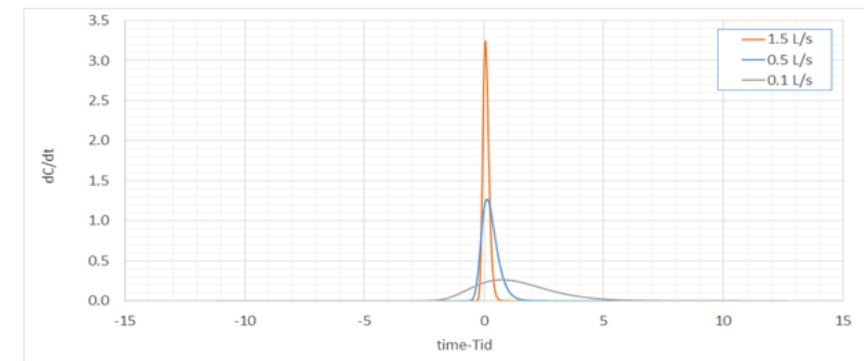
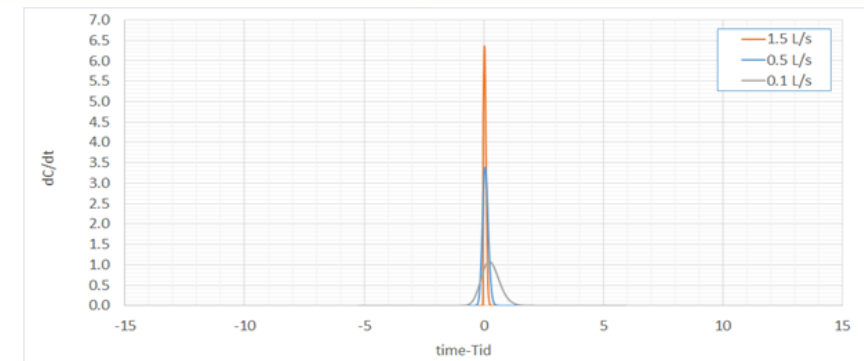
Conceptual design options for irradiation head



3D water CAD



C/C' @ outlet

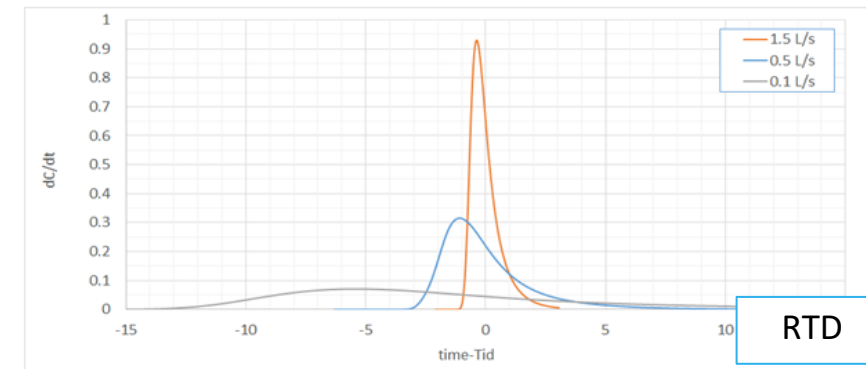
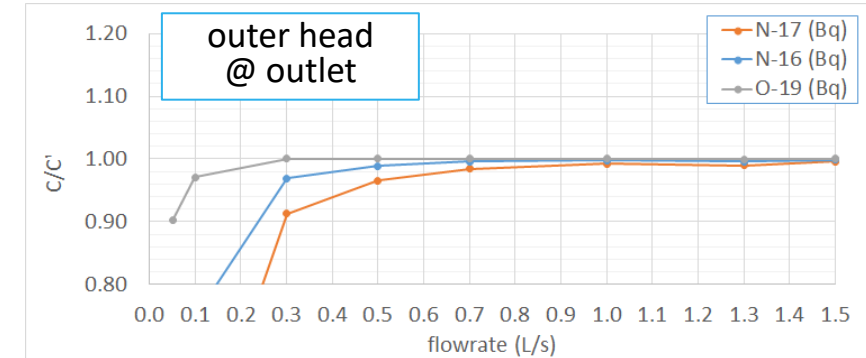
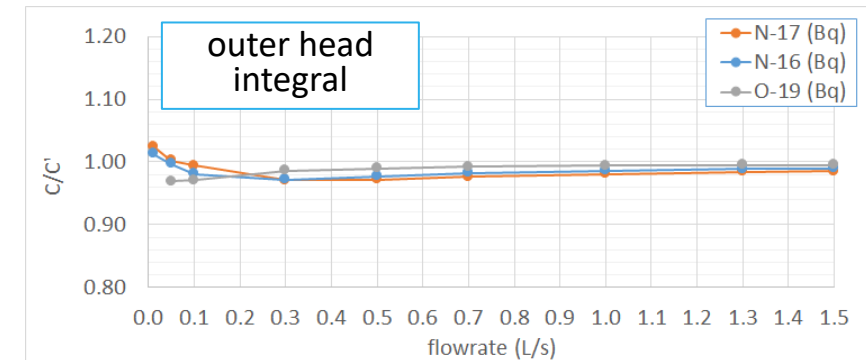
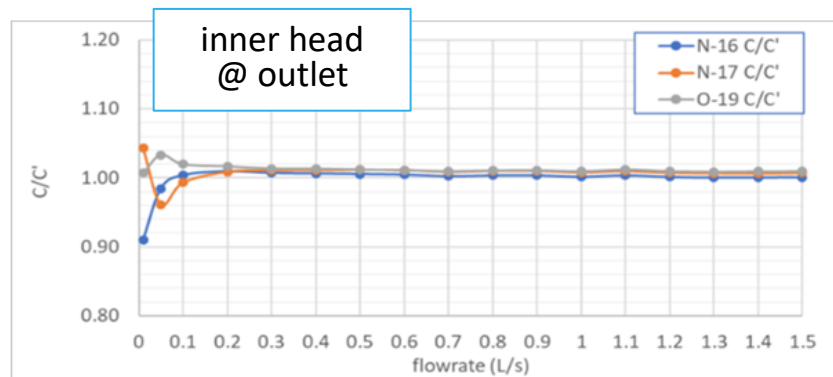
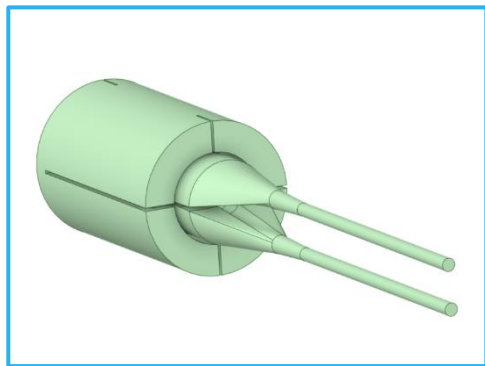


RTD

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.



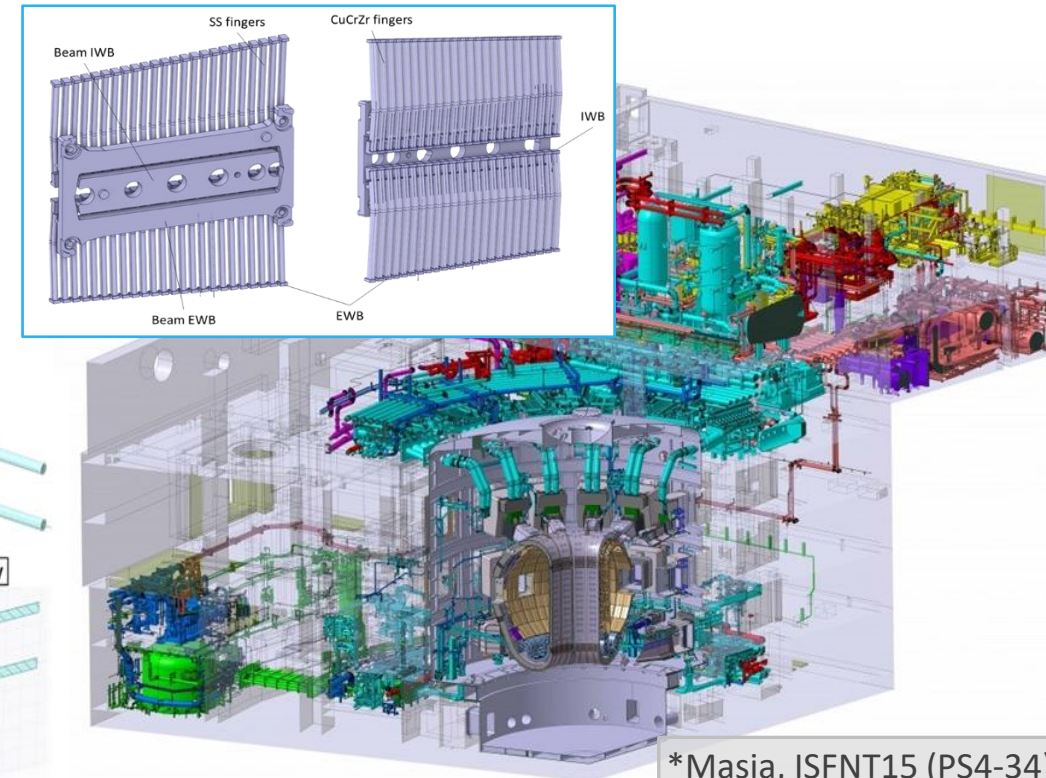
RSTM application

Design of ITER FW relevant irradiation head

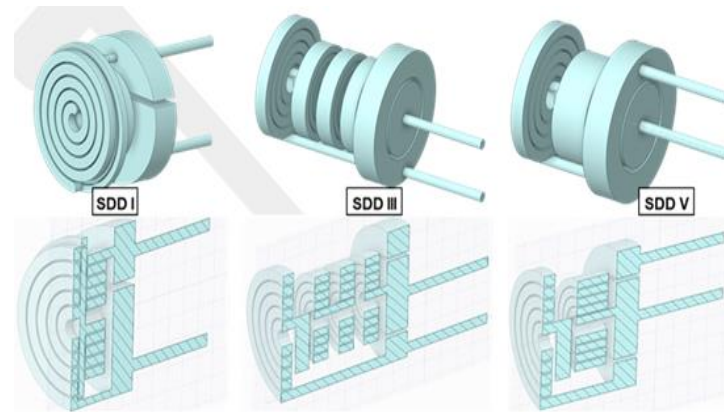
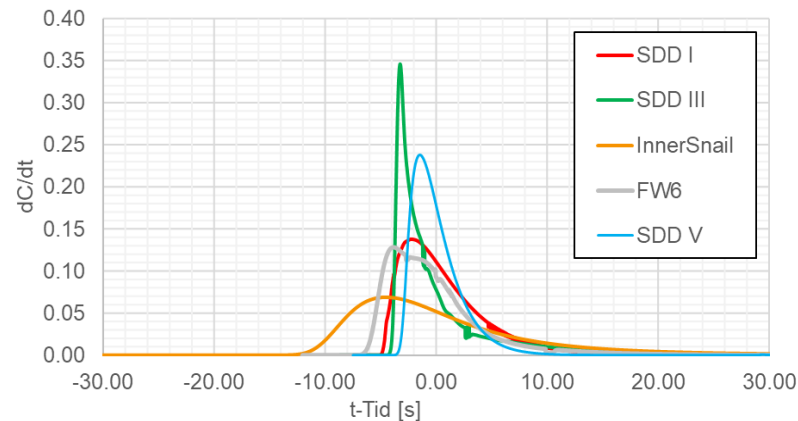
- Second phase (ITER-relevant validation tests): attempt to design inner head mimicking FW.
- Hindered by complex hydraulic routing & limited port size.
- Conceptual design premise is to preserve:
 - Hydraulic features: pipework, waterboxes, fingers.
 - Residence time: adjusted flowrate @ same regime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

Geom.	V [L]	Q [L/s]	v [m/s]	Re [-]	MRT [s]	T _{id} [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

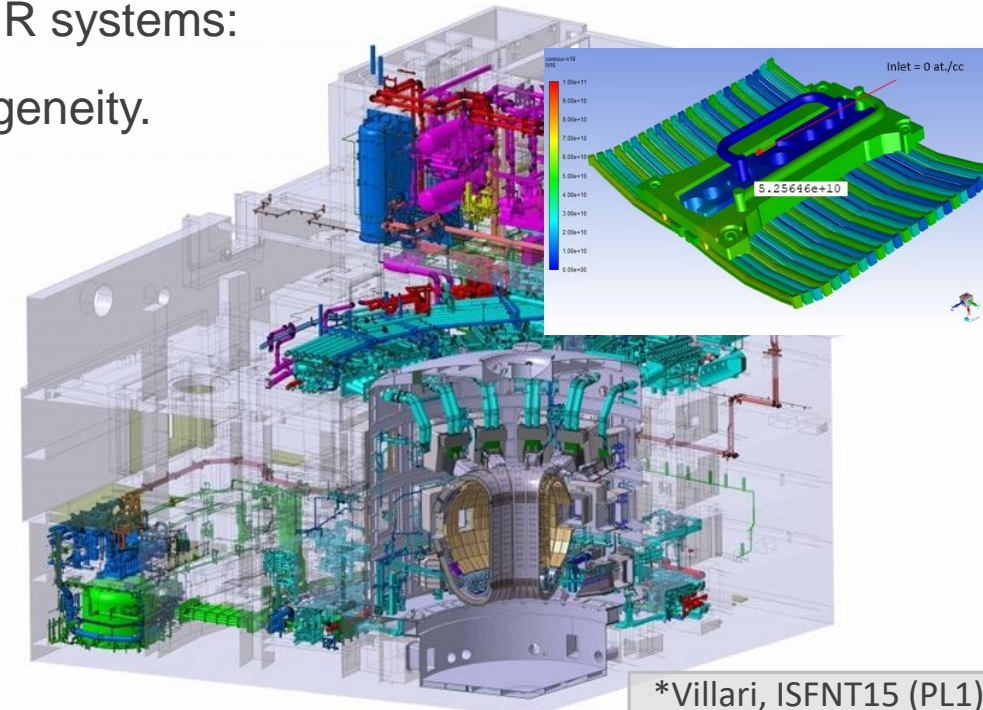
* FW finger cooling channel.



*Masia, ISFNT15 (PS4-34)



- 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.





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TO **EARTH**

Thank you!

Raul Pampin¹

E. Masia², F. Cau¹, D. Kotnik³, R. Villari⁴, A. Portone¹

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

ISFNT-15

Gran Canaria, 11-15 Sep 2023

