Italian National Agency for New Technologies,
Energy and Sustainable Economic Development

DTT S.c.a.r.l.

BORATED WATER CHEMISTRY CONTROL FOR DTT VACUUM VESSEL

Technical Meeting on Compatibility Between Coolants and Materials for Fusion Facilities and Advanced Fission Reactors

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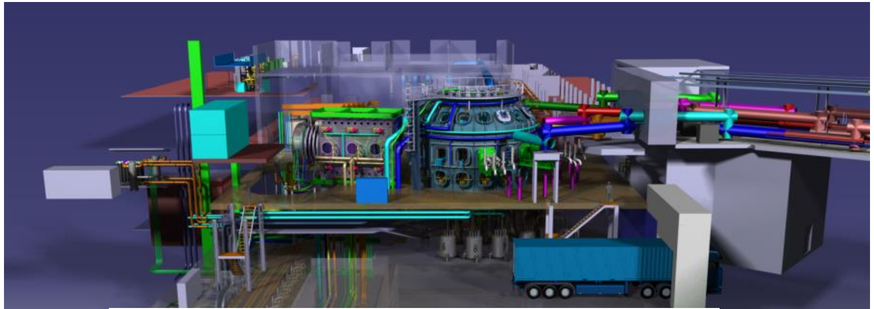
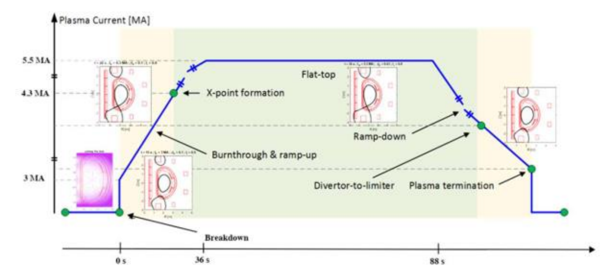
Outline

- Introduction
- WCS of the DTT - VV
- Borated water corrosion
- VV Steels Stress Corrosion Cracking
- Numerical Analysis of Activated Corrosion Products
- Conclusion

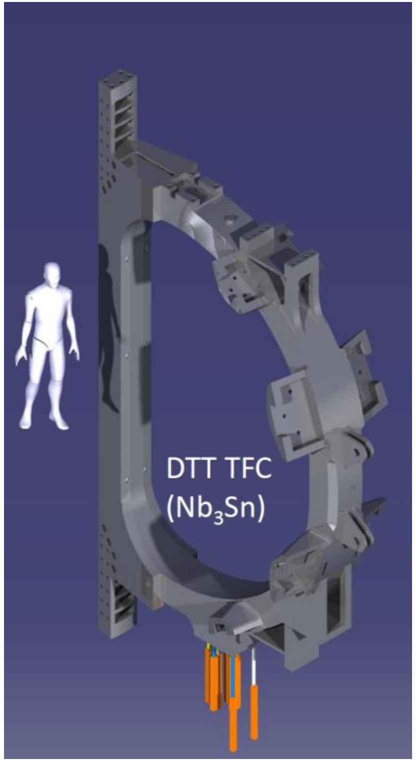
DTT facility

The Divertor Tokamak Test (DTT) facility is an experimental tokamak devoted to investigating the systems for the treatment of heat exhaust (divertor, configuration control system, diagnostics) to be used in Controlled Thermonuclear Fusion reactors. The facility will be installed in Frascati.



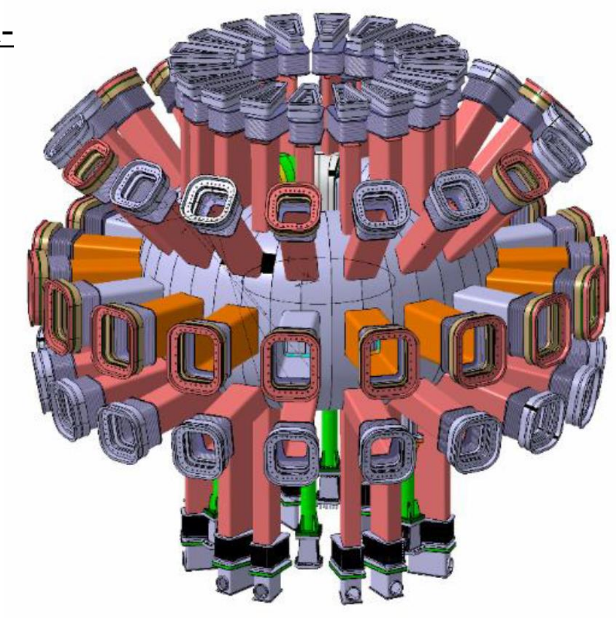


Parameter	**Value**
R (m)	2.19
A (m)	0.7
I_p (MA)	5.5
B_T (T)	6
$<n_e>$ (10^{20} m^{-3})	1.7
$<T_e>$ (KeV)	6.2
CS, PFC 1/6, TFC	Nb_3Ns
PFC 2/3/4/5	NbTi
P_{set}/R (MW/m)	15



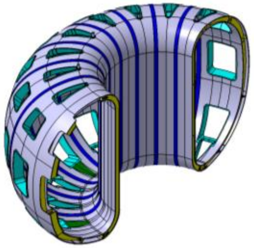
DTT- Vacuum Vessel

The tokamak element named “Vacuum Vessel” (VV) of fusion nuclear reactor has the functions of neutron shielding superconducting magnets, provides a high-vacuum environment for the plasma, allows the plasma stability and act as primary confinement barrier for radioactivity.

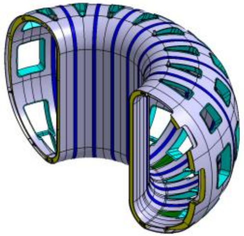


DTT Vacuum Vessel (VV)

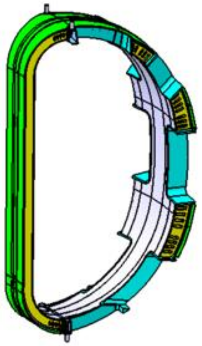
In DTT the neutron shielding of the superconducting coils is obtained with the use of borated water circulating through the vessel’s double steel walls ensuring neutrons heating below 1 mW/cm3.



Vacuum vessel 170°A



Vacuum vessel 170°B



Last Sector 20°

DTT- Vacuum Vessel

- ☐ The borated water of the “Vacuum Vessel” has to circulate inside the VV sectors at 60°C.
- ☐ The VV and pipes connections will be manufactured in Stainless steel.
- ☐ Two different water qualities have to be considered depending on the three modes of operations foreseen:
  - ➢ Low Performance Phase (starting from day-0): Demi water (conductivity <0.1 µS/cm)
  - ➢ High Performance Phase (starting from day-2): Bored Water
  - ➢ Baking: every three / six months using Nitrogen

Parameters	**VV**
Fluid	Demi water/Boron Water/Nitrogen
Installation phase	Phase 1
Mass flow rate [kg/s]	23.8
Power to be supplied [MW]	0.2 Max
Tin VV [°C]	**60**
Tout VV [°C]	**59**
Pin [MPa]	0.4
Max Pressure losses [MPa]	0.2
T baking [°C]	120

Borated Water corrosion

Borated water, at 60°C, is obtained in DTT via the addition of boric acid, H_3BO_3 (4.58 wt%H3BO3).

8000 ppm B in the water means that, if a 95% ^{10}B enrichment is used the **pH_{60C} = 3.6** that increase susceptibility of 316L to SCC.

2002 Davis-Besse reactor pressure vessel head degradation knowledge digest, US NRC, https://www.nrc.gov/docs/ML1403/ML14038A119.pdf

The Water Cooling System of the VV has to additional scope:

- ✓ ensures minimum radiation field to operators;
- ✓ protect the material, the VV shells and pipes, from corrosion and stress corrosion cracking (SCC);
- ✓ minimize out-of-core radiation fields due to formation and redeposition of activated corrosion products (ACPs) from general corrosion of steel surfaces.

DTT use boric acid at high concentrations in the Vacuum Vessel (VV) cooling loop, the requirement was set to 8000 ppm in B enriched to 95% in ^{10}B, which is well above the operational experience of nuclear power plants, such as pressurized water reactors (PWRs).

Corrosion and SCC are complex phenomena influenced by the materials (microstructure, alloy elemental composition and surface finish), residual stress and strain, and the water cooling circuit environment (water chemistry, contaminants, dissolved oxygen, and temperature).

C. Gasparrini et al., IEEE Transactions on Plasma Science, 2022

Water Coolant – Water Chemistry control

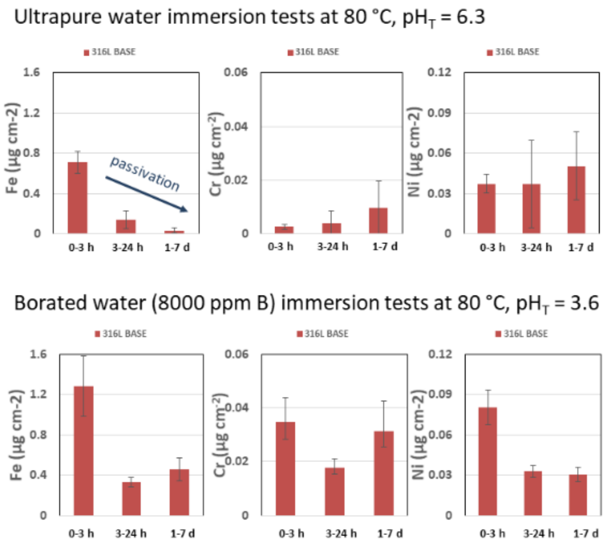
Water chemistry control for Fusion reactor was developed on the basis of LWRs chemistry control in order to reduce corrosion, SCC, et. The main solution adopted are summarized:

- Pressurized Water Reactors (PWRs) have a controlled water chemistry regime that mainly uses boric acid and a base (LiOH or KOH) for maintaining an optimum pH, typically for boron concentration below 2400 ppm B (naturally enriched boron).
- Reducing conditions and a very pure water (free from contaminants) have proven to be beneficial to counteract corrosion problems such as pitting, crevice corrosion and SCC in PWRs.
- Hydrogen usually is inserted in the coolant to suppress the formation of oxidising species induced by water radiolysis. In PWRs, 15-50 cm^3 (STP) H2/kg H_2O are usually inserted.

Similar water chemistry options are now being considered for **DTT** water cooling loop by choosing through the addition of LiOH or KOH.

VV Steels General corrosion and Stress Corrosion Cracking due to borated water

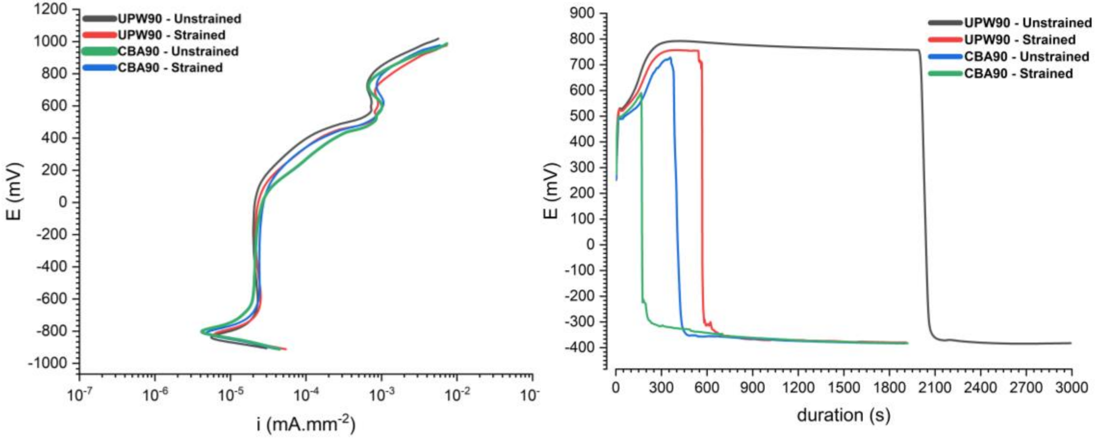
Experimental analysis was carried out in order to determine the effect borated water with 8000ppm B and UPW on VV materials (316L and welds) and therefore the amount of corrosion product generated.



Release metals from 316L and TIG welds samples exposed to UPW and borated water H_3BO_3 (8000 ppm in B) at 80°C. h stands for hours and d stands for days.

C. Gasparrini et al., IEEE Transactions on Plasma Science, 2022

UPW: samples passivated for 12 weeks in UPW
CBA: samples passivated for 12 weeks in 8000 ppm B



Potentiodynamic polarization curves : better performance of passivated samples in UPW than the 8000 ppm B passivated samples in passive layer breakdown zone. Galvanostatic polarization results confirms better performance of passive layer in unstrained condition for UPW compared to 8000 ppm B.

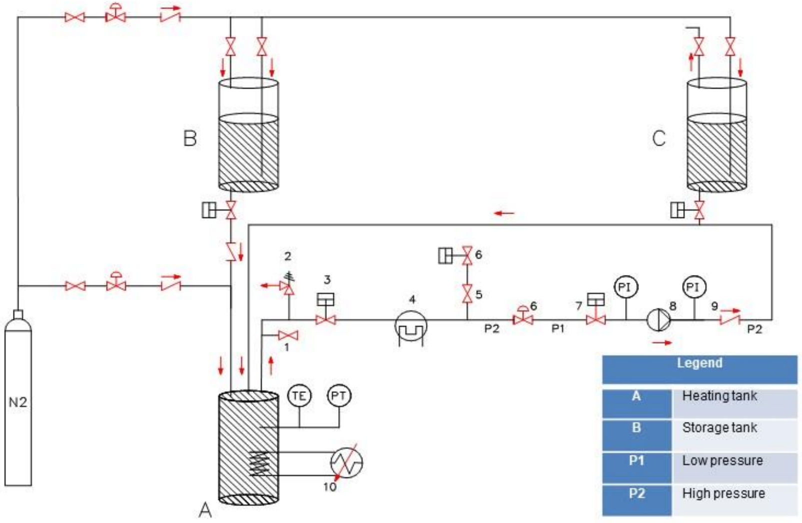
C.Gasparrini et a., unpublished work

Stress Corrosion Cracking (SCC)

The effect of high B concentration in water solution is to reduce pH at the range of 3-4, creating a potential de-passivation of the stainless steels, which can generate pitting and/or crevice corrosion. Cracking initiation can be generated from the pits when the component is under loading condition or for residual stress due to cold working effect.

Slow Strain Rate Testing allows to assess the degradation of mechanical performance of the metal alloy when exposed to the corrosive environment under tensile stress.
Stress corrosion cracking (SCC) initiation tests were also performed on 316L in CSM-Rina Consulting (CSM) laboratories.

The This apparatus consisted in a autoclave equipped by a HPHT loop, in which the solution is moved by a pump.



Stress Corrosion Cracking (SCC)

- Stress corrosion cracking (SCC) initiation tests performed on 316L showing that steels passivated in 8000 ppm B were more prone to SCC initiation than the ones passivated in UPW over 12 weeks.
- 316L irradiated with 3 dpa Ni ion was exposed in water with 8000 ppm B (same condition of Gasparrini et al. IEEE Trans. Plasma Sci., pp. 1–5, 2022). <u>Results showed that Fe and Ni releases were higher from the ion irradiated samples compare to the unirradiated one after 1 week of exposure</u>.
- Trace metal analyses measured indicated that releases were larger on samples exposed to 8000 ppm B and 5.7 ppm Li compared to 8000 ppm B and 57 ppm Li showing the importance of the choice of a correct water chemistry.

C. Gasparrini et al., IEEE Transactions on Plasma Science, 2022

Activated Corrosion Product assessments

ACPs (Activated Corrosion Product) are an important «source term» (hazard) with a potential impact on Occupational Radiation Exposure (**ORE**) , **waste** management, **decommissioning**, **accidental scenarios**.

Activated Corrosion Products (ACPs) formation has SAFETY concerns:

- **Radioprotection**: Reduction of the occupation dose;
- **Environment**: Minimization of release/waste – Optimization of dismantling process – Source term in case of accident/incident
- **Availability**: Optimization of reactor operation

From FFMEA (Functional Failure Mode and Effect Analysis), source term identification and quantification including ACPs have been required.

MAIN GOALS:

- To have the most precise ACP estimation to understand if ACPs pose safety concerns.
- To guide design of the cooling circuit in terms of water replacements, filter design, etc.

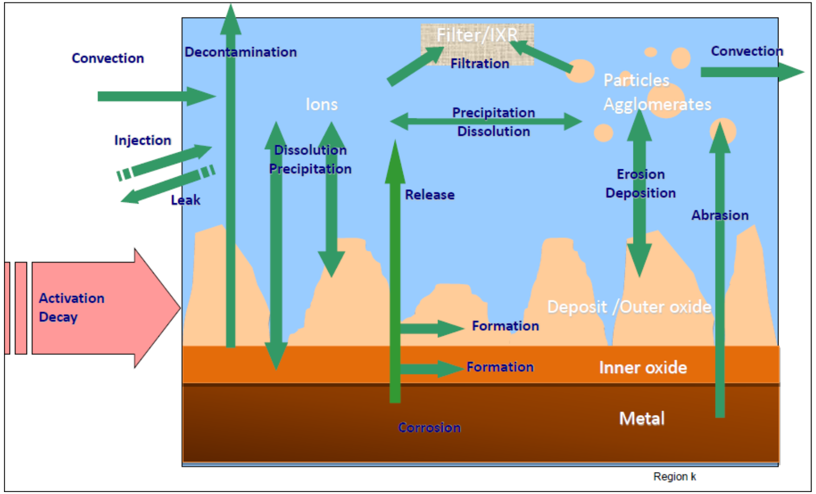
Numerical Analysis of Activated Corrosion Products

The water corrosion (electro-chemical process) codes were mostly developed for predicting ACPs formation and transport in the nuclear fission power reactors cooling loop, the main codes are:

- **TRACT** (used in ITER) simulates the flow and mass transport of isotopes inside a network of 1-D channels (corrosion and activation of products). The code handles liquid or gaseous coolants encountered in fusion devices.
- **CATE** was developed to simulate the production and transport process of ACPs in the cooling loops of fusion reactor, especially for CFETR of China in the future.
- **PACTITER** and **OSCAR-Fusion** codes were derived for fusion applications from their analogous codes developed for PWRs. **POTHY** is a chemistry subroutine of PACTITER v2.1 simulated the water pH and solubility of the main elements of stainless-steel during corrosion processe;
- **PHREEQCEA** calculates the values of the parameters of the OSCAR water dissolution/precipitation model

OSCAR-Fusion v1.4a: The simulation tool for ACP determination

OSCAR-Fusion v1.4a (developed by CEA) **is the reference tool for EUROfusion Safety and Environment Work Package (EUROfusion WPSAE) and for ITER-IO Nuclear Safety .**



- The cooling system is discretized in control volumes depending on geometry, thermal-hydraulic, neutronics, material and operation.
- Balance equations are solved for 6 media: base metal, inner oxide, deposit/outer oxide, particles, ions and filters+resins
- Ni, Co, Fe, Cu, Mn, Ag, Zn and Zr are the elements that are simulated

$$\frac{\delta m_i}{\delta t} + (\dot{m}_{out} - \dot{m}_{in}) = \sum_{source} J_m - \sum_{sink} J_m$$

For each control volume and medium.

$$J_{corr}^{el} = V_{corr}^{el} \cdot S_w \cdot \alpha_{met}^{el}$$

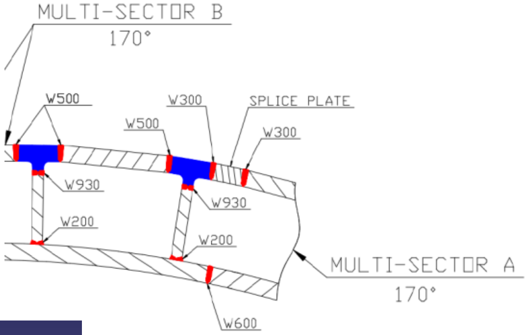
$$J_{rel}^{el} = V_{rel}^{el} \cdot S_w \cdot \alpha_{rel}^{el}$$

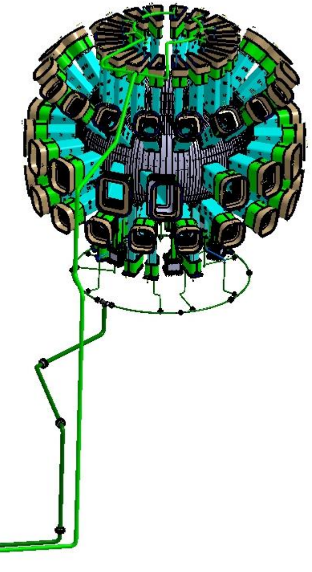
V's are the surface corrosion and release rates [kg.m-2.s-1], calculated by an empirical model as a function of chemistry, temperature and material;

S_w is the wet surface area

Numerical Analysis: VV- WCS Activated Corrosion Products

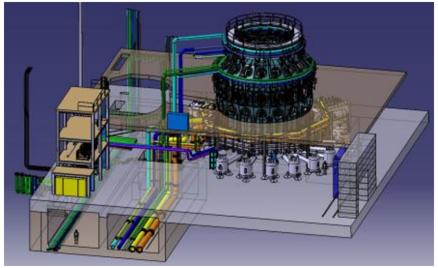
The operative conditions of the DTT-VV-WCS fall outside the validation domain of OSCAR-Fusion, which relies on a solid and extensive experimental database derived from French PWRs. To mitigate this issue, the corrosion laws employed in the simulation have been interpolated using the last experimental data from C. Gasparrini et al.(borated water 8000ppm, water temperature 80°C).





The operative conditions evaluated are:

- Water chemistry: borated water H_3BO_3 (8000 ppm in B) at 80°C;
- Stagnant water
- Base material: 316L
- Neutron Flux: PWR conditions



Results on ACPs: Surface activity per component

```
<< -----irradiation phase----- >>
WALL   3.805E-06
TIME    182.5  DAYS  ATOMS
WALL   0.000E+00
TIME    182.5  DAYS  ATOMS
WALL   2.854E-05
TIME    182.5  DAYS  ATOMS
WALL   0.000E+00
TIME    182.5  DAYS  ATOMS
WALL   1.903E-04

[………]

WALL   6.559E-04
TIME    150.0  DAYS  ATOMS
WALL   9.838E-04
TIME      5.0  DAYS  ATOMS
WALL   0.000E+00
TIME      2.0  DAYS  ATOMS
WALL   9.838E-04
TIME      5.0  DAYS  ATOMS
WALL   0.000E+00
TIME      2.0  DAYS  ATOMS
WALL   9.838E-04
TIME      5.0  DAYS  ATOMS
WALL   0.000E+00
TIME      2.0  DAYS  ATOMS
WALL   0.000E+00
TIME   28800.0  SECS  ATOMS
WALL   1.687E-03
TIME   50400.0  SECS  ATOMS
WALL   0.000E+00
TIME   36000.0  SECS  ATOMS
WALL   1.687E-03

[…………]

WALL   0.000E+00
TIME   3600.0  SECS  ATOMS
WALL   1.000E+00
TIME     50.0  SECS  ATOMS
```

Long pulse and dwell periods

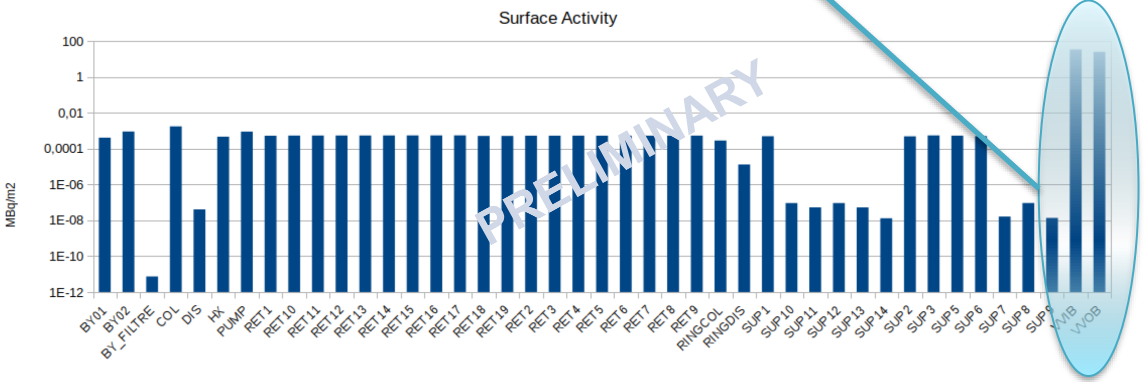
Short pulse and dwell periods

End of the scenario, 10030 days

A condensed scenario made of long pulses and dwells has been used as first approximation to represent the base metal activation in the VV cooling circuit (28yr long scenario, 6 months on and 6 months off, integral neutron fluence has been respected).

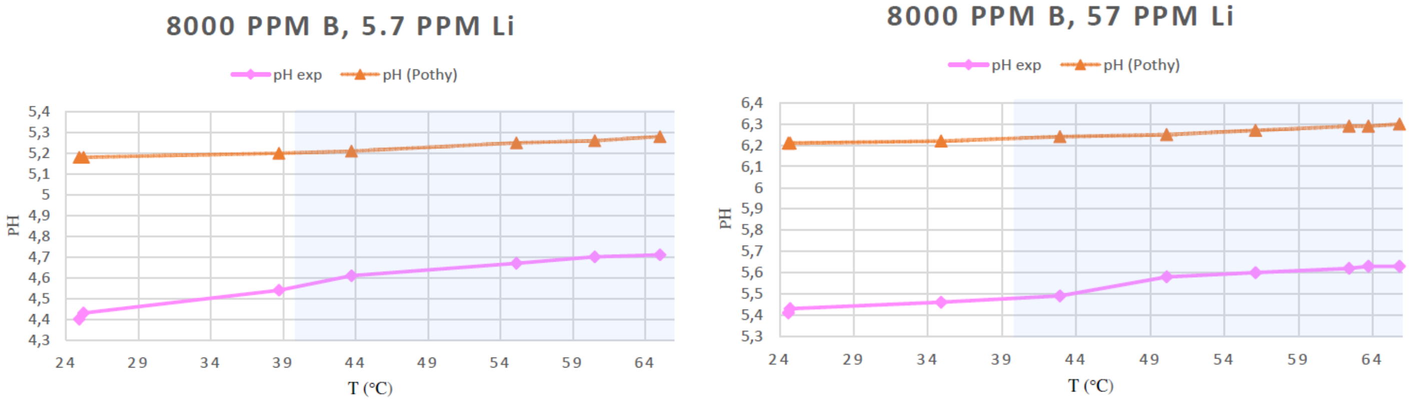
These preliminary results seem to indicate that the **deposits in the out-of-flux regions might not be problematic** for the occupational radiation exposure of the working personnel called to perform maintenance operation on the balance-of-plant components.

The components under neutron flux, hosted in the Tokamak Hall, show the largest surface activity (deposits + inner oxide), as expected.



Corrosion analysis with POTHY

Beyond a strict control on materials requirements and water chemistry (on contaminants, oxidizing/reducing conditions, oxygen scavengers) **the addition of additives** to increase water pH is envisaged since 8000 ppm B shows a $pH_{60C} = 3.6$ which makes 316L prone to SCC.
The effect of Bases addition of LiOH are evaluated with numerical code POTHY and compared with experimental data obtained.



Comparison between experimental measurements of pH_T at 8000 ppm B plus LiOH additions and simulation from POTHY, in blue the range of temperature of interest for DTT VV

C.Gasparrini et a., unpublished work

Conclusion

- Preliminary experimental analysis were caried out in order to identify the quantity of corrosion products generated in the borated water (8000 ppm B, pH = 3.6) of the VV;
- The results of the experiment were used in the Oscar code 1.4a to analyse the impact of Activated corrosion product on the personnel and waste management, preliminary analysis carried out without a full database, the result doesn’t show concern outside the VV;
- The preliminary experimental characterization of SCC effects induced by DTT-VV borated water on 316L material was investigated showing an increase of susceptibility also exposed to ion irradiation;
- Experimental validation of Corrosion, SCC, and mitigation strategy at relevant operative conditions is requested to generate a database for the numerical analysis.

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