Modelling the corrosion product transfer in fusion systems: the OSCAR-Fusion code

F. Dacquait, C. Cherpin, F. Broutin, C. Chalons

CEA/DES/IRESNE/DTN/SMTA/LMCT Laboratory for Mastering Contamination and Chemistry of Coolants and Tritium – Cadarache

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

30 Oct - 3 Nov 2023 | Vienna (Austria)

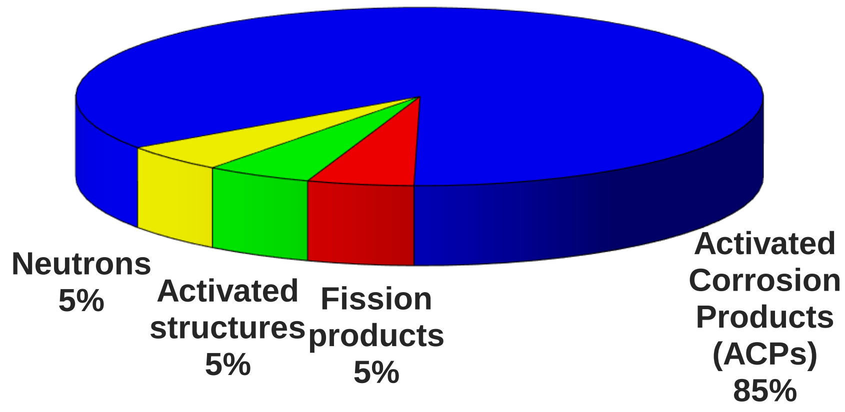
Outline

1. **OSCAR code**
2. **Challenges related to the interactions between coolants and materials**
3. **Conclusion**

1. OSCAR code

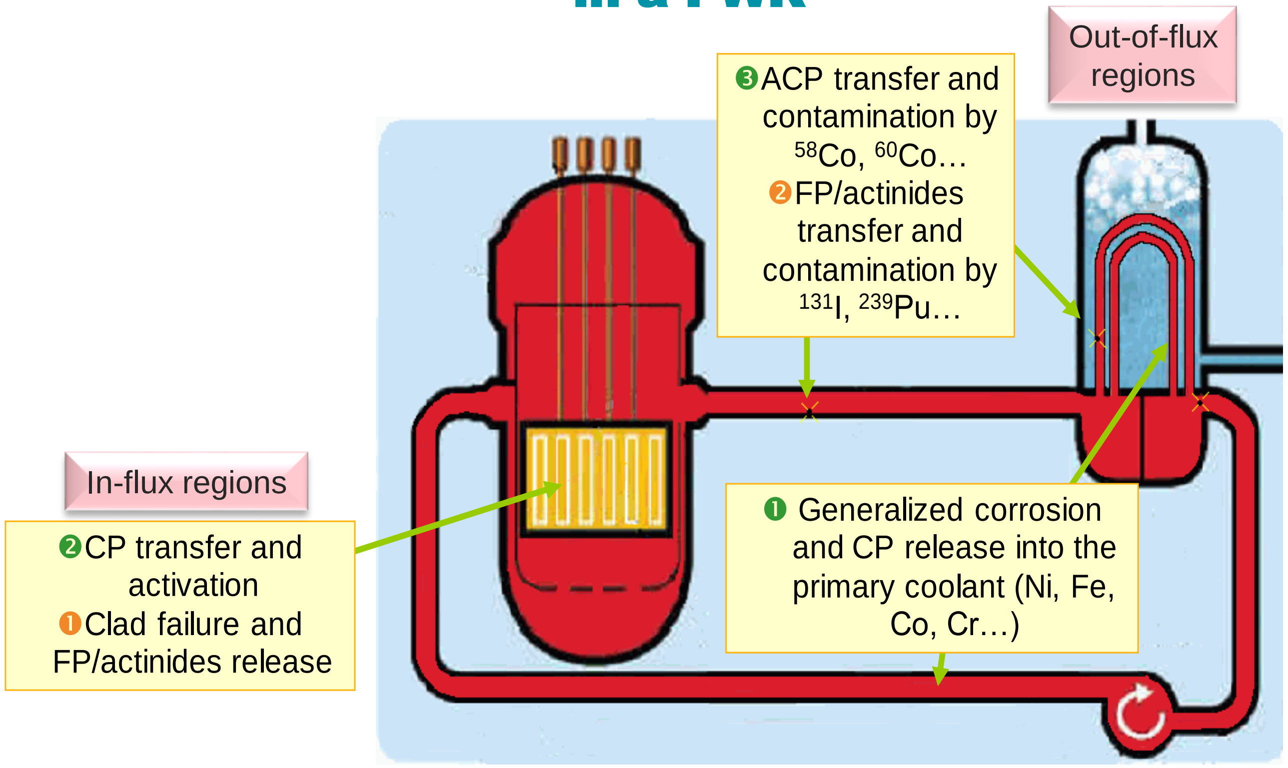
Principle and stakes

Collective dose for operation and maintenance of PWRs



For other types of reactor, especially fusion reactors, mainly due to ACPs as well (fundamental safety function for DEMO)

Principle of contamination transfer in a PWR



Industrial stakes:

- Radioprotection: Reduction of Occupational Radiation Exposure (ORE)
- Environment: Minimization of release/waste – Optimization of dismantling process
- Availability: Optimization of reactor operation
- Safety: Source term in case of accident/incident

OSCAR Outil de Simulation de la ContAmination en Réacteur
tOol for Simulating ContAmination in Reactors

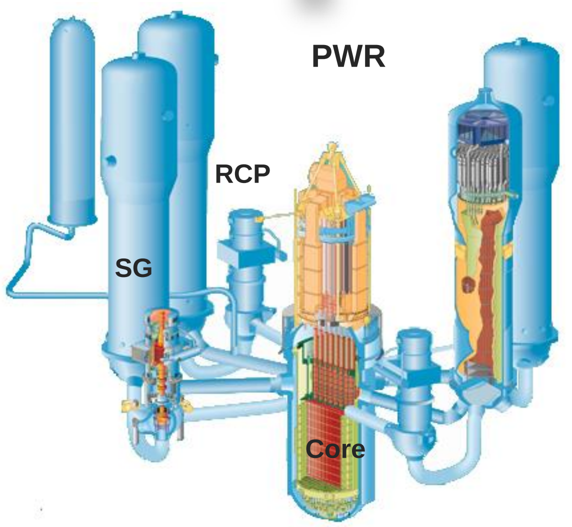
- Simulation of contamination transfer in nuclear reactor systems during power operation and shutdown (PWR: 20 → 350 °C - reducing/oxidizing - acid/alkaline)
  - Calculation of masses/activities of CPs, ACPs, Coolant Activation Products (CAPs), Actinides and FPs (AFPs) in solid, liquid and gaseous phases of nuclear circuits as a function of time (normal operation over several decades and transient events of a few minutes/seconds within a reasonable calculation time)
  - Development of calculation codes for PWRs since 1970's by CEA in collaboration with EDF and Framatome:
    - **PACTOLE** (ACPs) and **PROFIP** (AFPs) codes
    - **OSCAR** code since 2008 (merger of PACTOLE and PROFIP)
      - Modular code (easy evolving tool / C++ / Linux OS)
      - Input/output Graphical User friendly Interfaces (Salome/Python/QT)
  - Validation based on an extensive and world-unique OPEX:
    - >430 contamination expertise assessments in 76 different PWR units: EMECC campaigns (γ measurements of ACP surface activities)

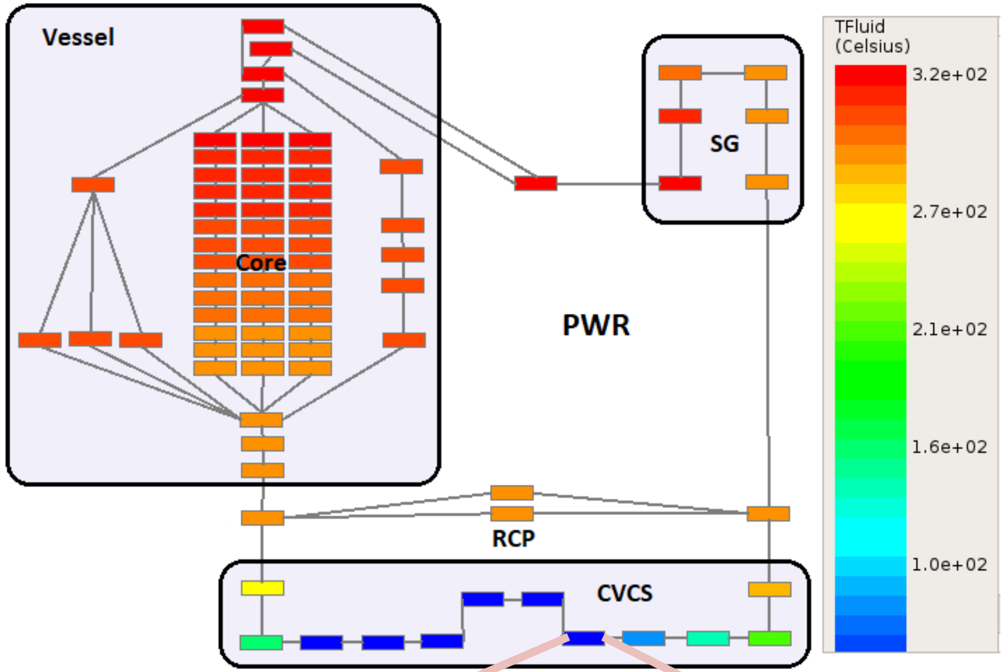
EMECC measurement of a hot leg of a PWR RCS

  - Application to SFRs: **OSCAR-Na** (2012) → **see C. Latge's presentation**
  - Application to Fusion reactors: **PACTOLE-ITER** (1995) → **PACTITER** (1998) **(see L. Di Pace's presentation)** → **OSCAR-Fusion** (2012)

OSCAR modelling for ACPs

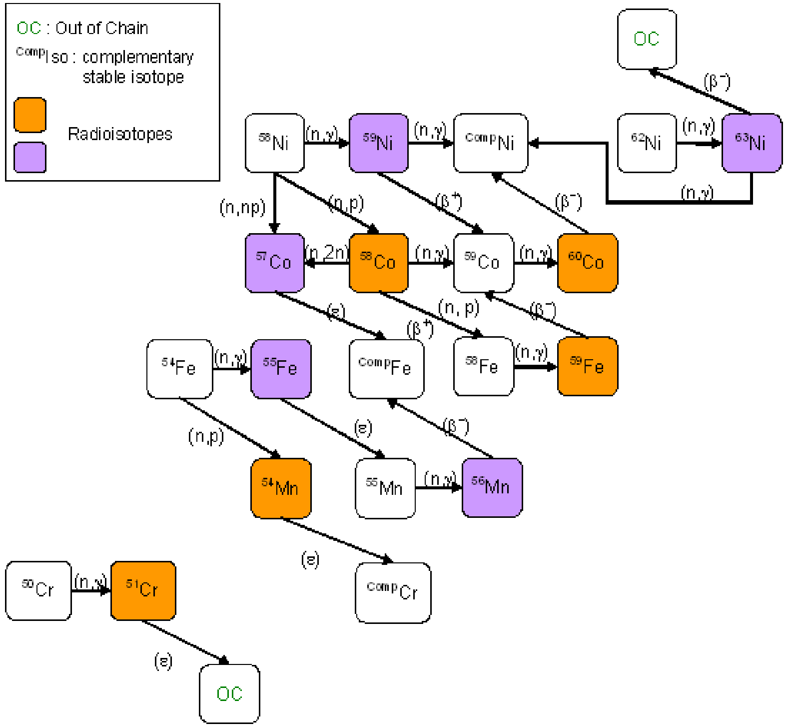
Nodalization



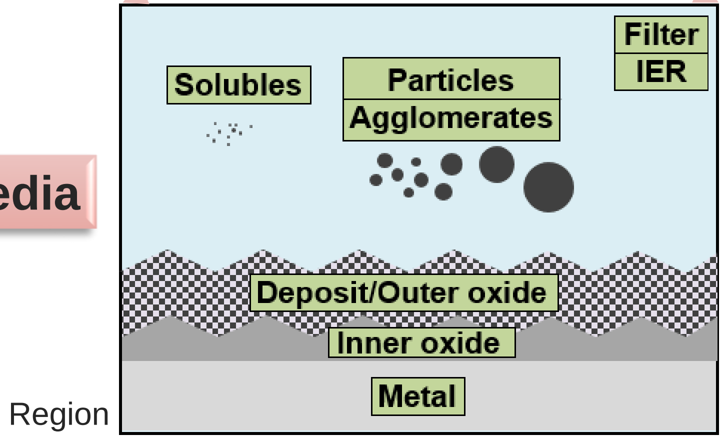


Elements/Isotopes

Co, Cr, Cu, Fe, Mn, Ni
Ag, Sb, Zn, Zr

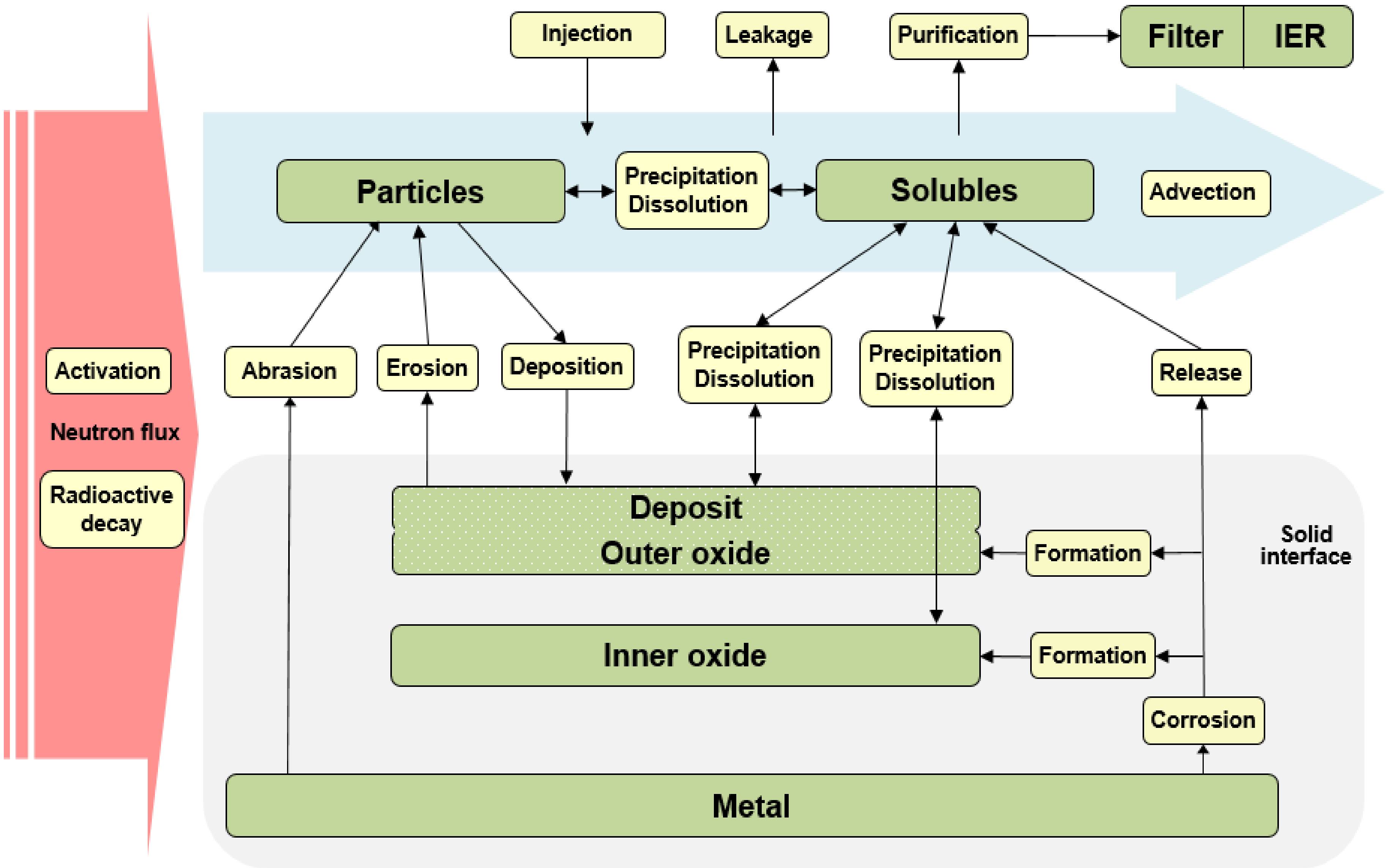


Media



OSCAR modelling

Transfer mechanisms



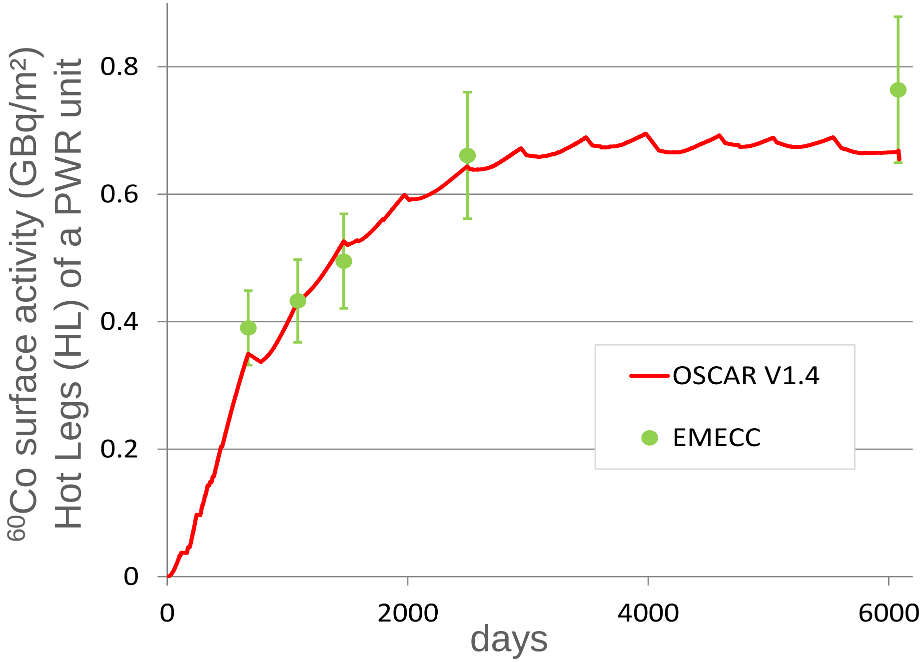
OSCAR modelling

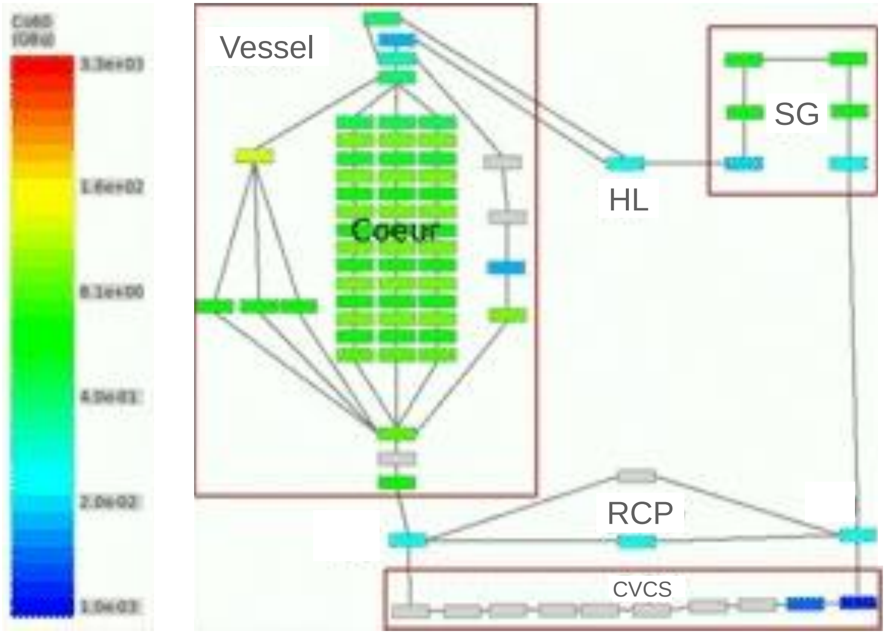
Solver

$$\frac{\partial m^i}{\partial t} + \left(\dot{m}^i_{out} - \dot{m}^i_{in}\right) = \sum_{sources} J^i_m - \sum_{sinks} J^i_m$$

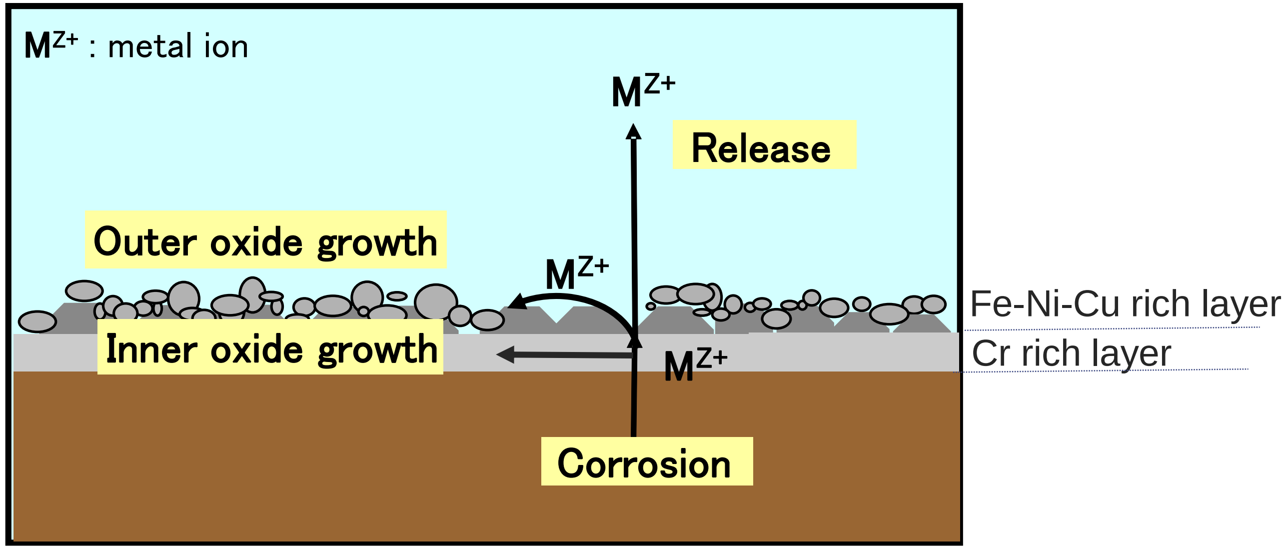
Applications of OSCAR-Fusion:
see D. Carloni's presentation (ITER IBED PHTS)
and C. Gasparrini's presentation (DTT)

Results





OSCAR modelling - Corrosion-Release



- Corrosion/release rates : $J^i_{cor/rel} = f^i_{met}\, S_w\, V_{cor/rel}$
  - Empirical laws (material, chemistry, temperature, time)
  - User data (time power law, time logarithmic law, constant value per stage)

OSCAR modelling - Dissolution/Precipitation

- Dissolution/precipitation rate: $J^{i}_{dissol/precip} = \frac{S_{dissol/precip}}{R^{elt}_{solid-fluid}+R^{fluid}_{wall-bulk}}\left|f^{i_{elt}}_{solid}C^{elt}_{eq} - f^{i_{elt}}_{fluid}C^{elt}\right|$

  - $S_{dissol/precip}$: dissolution/precipitation surface
  - $R^{elt}_{solid-fluid}$: transfer resistance of element elt at interface solid-fluid $\left(= 1/\frac{M_{elt}}{C^{elt}_{eq}}\sum_n \alpha_n\, \nu_n k_n (10^{-pH})^{\mu_{H^+,n}} \left(p_{H_2/O_2}\right)^{\mu_{H_2/O_2,n}}\right)$
  - $R^{fluid}_{wall-bulk}$: transfer resistance in fluid between wall and bulk ($= 1/h$ for Dep/OE-Part. or $= L_{dep}/D^{elt}_{dep} + 1/h$ for IO)
  - C^{elt}_{eq} : equilibrium concentration of element *elt*
  - C^{elt} : bulk concentration of element *elt*
  - $f^{i_{elt}}_{solid/fluid}$: isotopic mass fractions of isotope i of element elt in solid/fluid

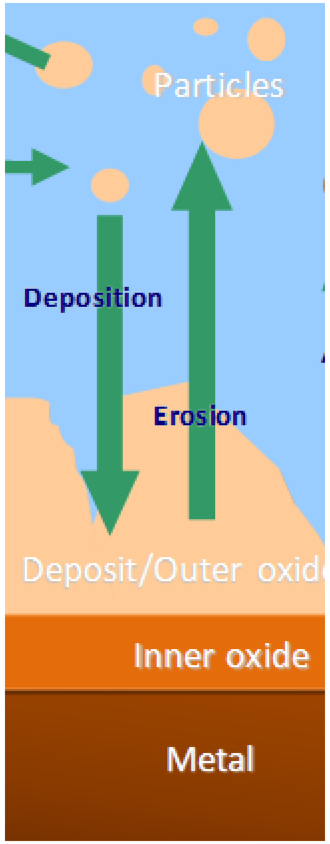
Equilibrium concentrations and composition of solid solution:

- *Calculated by PHREEQCEA (OSCAR chemistry module) (version of PHREEQC code extended to 350 °C) and its thermodynamic database developed by CEA-Saclay →* **For more information, ask M. Roy**
- *Depend on chemical conditions (pH, redox), bulk/wall temperature and masses of each medium in each region*

OSCAR modelling – Erosion & Deposition

- Erosion rate: $J^i_{erosion} = f^i_{dep} m_{eros} E_{eros} / \Psi_{eros}$
  - m_{eros} : mass of the deposit that can be eroded
  - E_{eros} : erosion coefficient (based on Cleaver & Yates model)
  - Ψ_{eros} : erosion resistance

- Deposition rate: $J^i_{deposition} = f^i_{part} S_w v_{depos} C_{part}$
  - v_{depos} : deposition velocity taken into account laminar and turbulent (Beal model)
    diffusion, sedimentation, thermophoresis, boiling deposition, flow disturbances
  - C_{part} : particle concentration

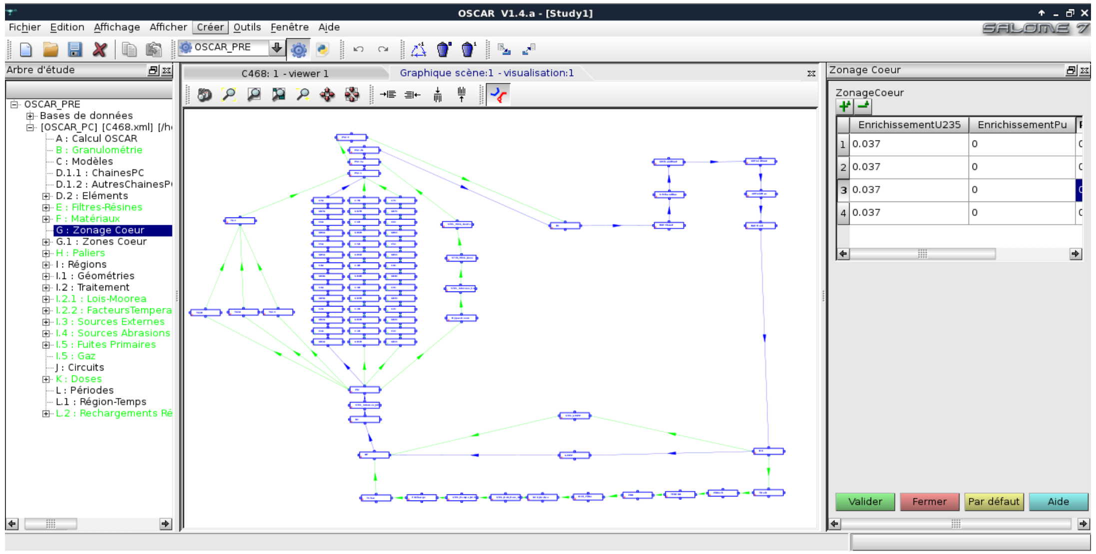


OSCAR Input/Output

❑ Input data file (.xml)

- Geometry and Thermal-hydraulic (D_H, S_w, flow rate, $T_{wall/bulk}$,)
- Material (initial composition and thickness, ρ, Ra, porosity, tortuosity)
- Neutronic (nuclear power fraction & activation rates)
- Operating data (Pn, B, Li, H_2, O_2 = f(t), Zn injection rate)
- Purification efficiency
- Dose rate coefficients
- Replacement of components

➢ **Input GUI**

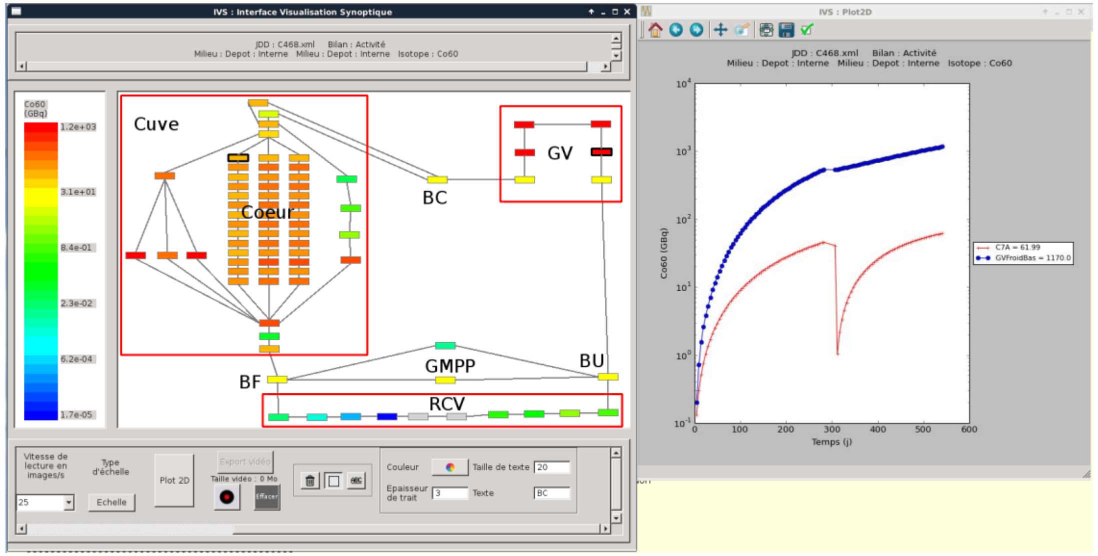


OSCAR

❑ Output files (.csv)

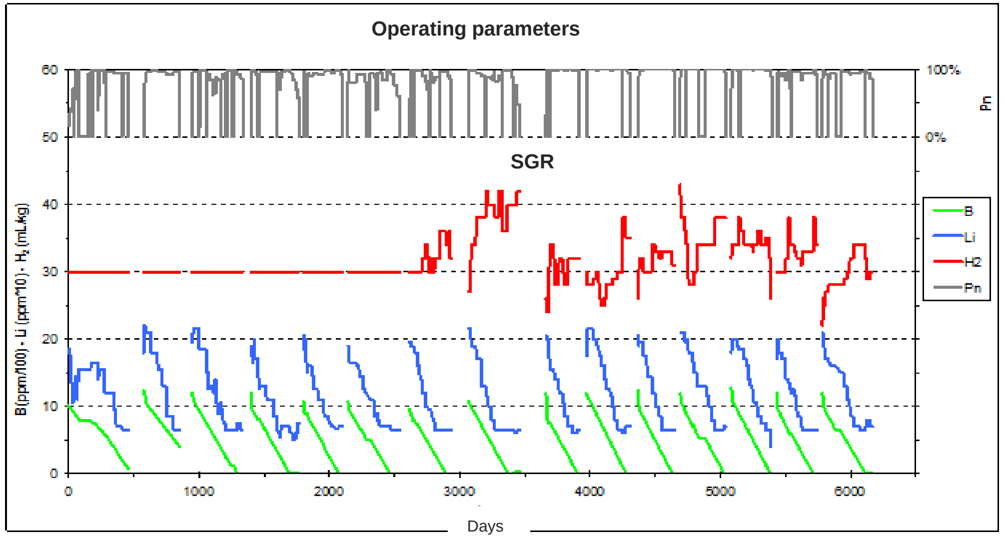
- Masses of isotopes/elements (kg)
- Activities of radioisotopes (Bq, Bq/m², Bq/m³, Bq/kg)
- Dose rates (Sv/h)
- Transfer mass rates (corrosion, dissolution, deposition… rates in kg/s)
- Chemical data (pH, pe, Ceq, speciation…)
- Thermal-hydraulic data (density, viscosity, Re, Sc…)
- Region characteristics (thicknesses of IO & Dep/OE)
- Operating data

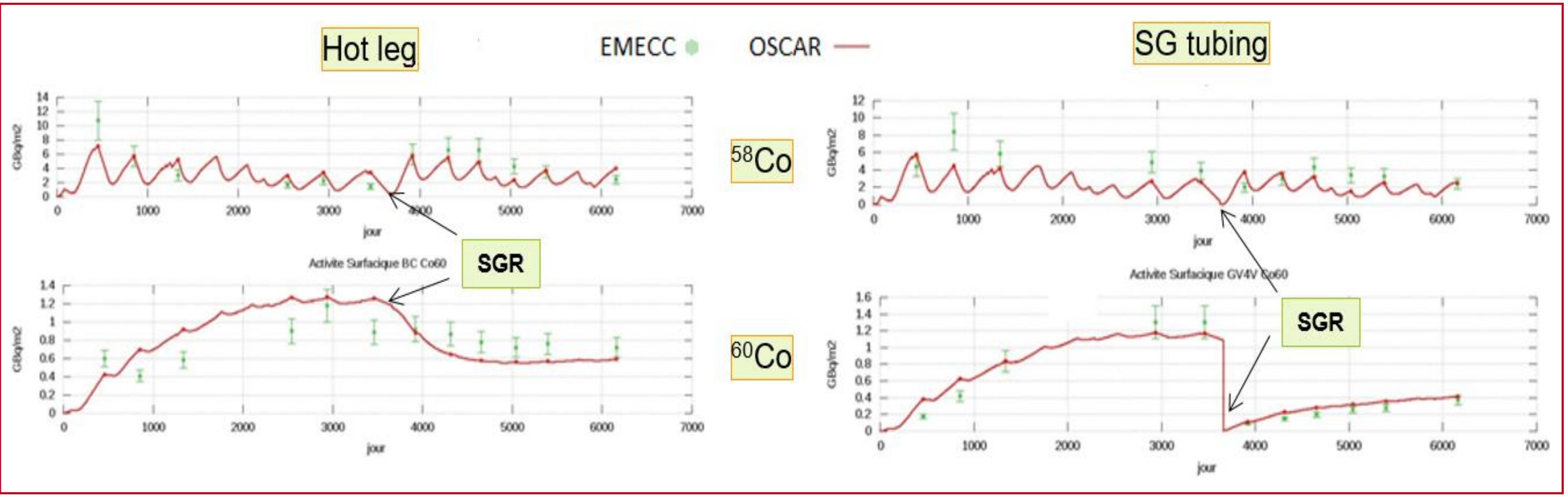
➢ **Output GUI**

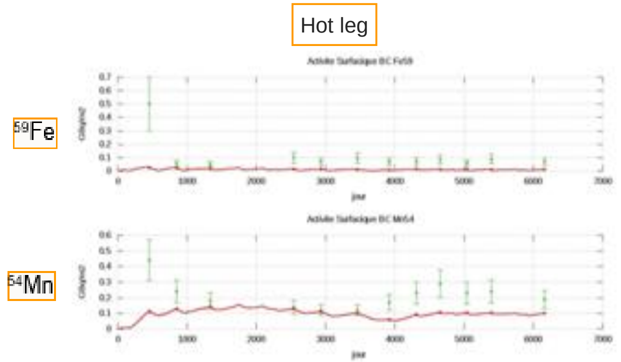


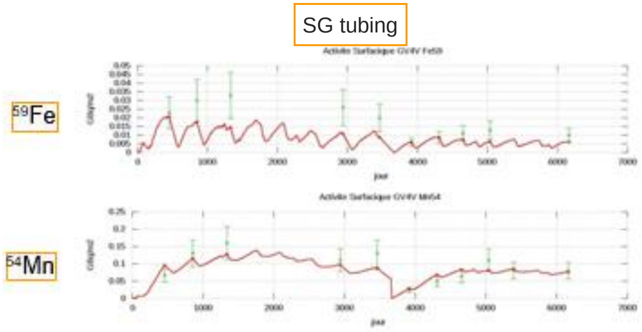
OSCAR validation

- Validation based on operational feedback from various PWRs (EMECC campaigns), e.g.:
  - 900 MWe PWR
  - Steam Generator Replacement during cycle 8 outage
    SG tubing 600MA → 690TT
  - First 15 cycles simulated









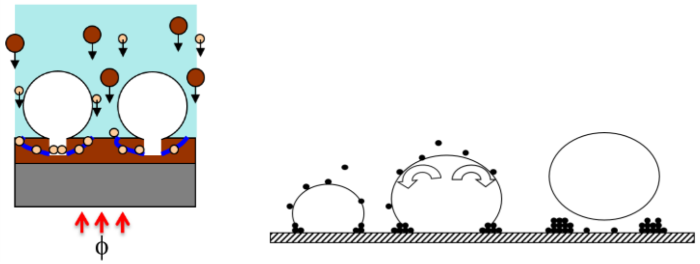
Good agreement between OSCAR and EMECC

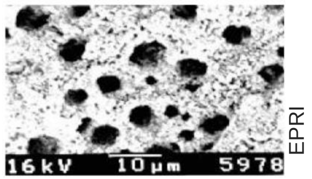
2. Challenges related to the interactions between coolants and materials

Challenges related to the interactions between coolants and materials

- Similarities between PHTS conditions in fusion reactors and PWRs (e.g; WCLL-BB PHTS of DEMO ≅ RCS of PWRs) → **OSCAR-Fusion leverages from the validation of OSCAR for PWRs (fission-fusion synergy)**

- But distinct characteristics for fusion reactors:
  - Materials: RAFM steels (Eurofer, F82H…) and Cu-base alloys
  - Higher thermal flux (up to 10-20 MW/m² for DEMO)
    - → Subcooled nucleate boiling ($T_{wall} > T_{sat} + \Delta T_{sat}$)
    - → Higher deposition rate (deposition by vaporization, deposition by trapping, enrichment = models already in **OSCAR**)
    - → Thicker deposit
    - → More formation of ACPs and higher T_{mat}
    - → Probably more out-of-flux contamination and localized corrosion (called CILC in PWRs - Crud-Induced Localized Corrosion)





→ Experiments to be conducted to measure corrosion rate of RAFM steels (different manufacturing processes) and Cu-base alloys up to T_{sat} (350 °C for Eurofer), even higher

NB: Higher corrosion rate at 300 °C for Eurofer (low Cr content) compared to stainless steel **(e.g. see M. Molinari's presentation)**

Challenges related to the interactions between coolant and materials

- Colloidal behaviour in PHTSs of fusion reactors to be studied → **see C. Cherpin's presentation**

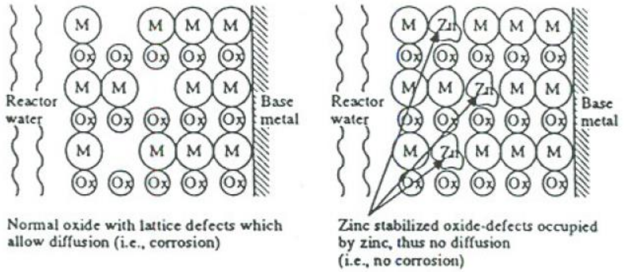
- Higher neutron flux (14 MeV)
  → Recoil energy for reaction products
  → Release of ACPs
  → Model to be introduced in **OSCAR-Fusion**, as was the case with **PACTITER**

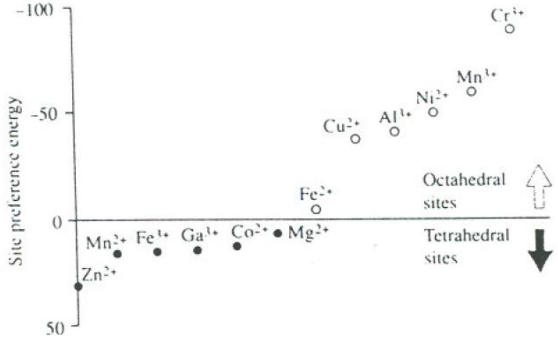
- Plasma pulsed mode + High neutron flux (high radiolysis) + High flow velocity (~14 m/s for CuCrZr)
  → Cyclic slightly oxidizing environment despite H_2 addition (to be studied)
  → Flow Assisted Corrosion (FAC) [Obitz, 2016]
  → Effects of erosion-corrosion can be taken into account in **OSCAR-Fusion**
  → Probably more out-of-flux contamination and impact on material integrity

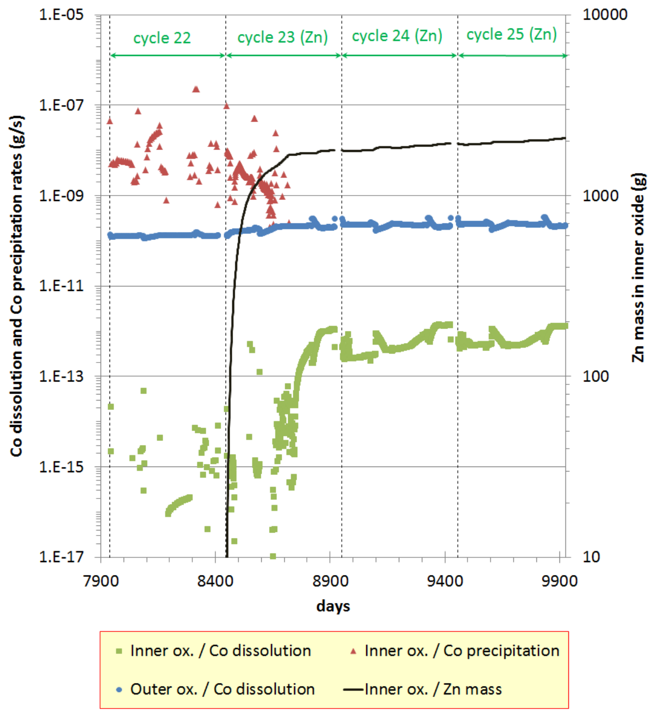
Challenges related to the interactions between coolant and materials

- Intense magnetic field
  - → Probably impact on corrosion and deposition of ferrimagnetic particles (ferrites)
  - → Study currently being conducted by **M. Molinari** (La Sapienza University) for **OSCAR-Fusion**

- Benefits of injecting Zn in PHTSs?
  - → Under certain conditions in PWRs, reducing corrosion and ^{60}Co incorporation into chromites
  - → Probably not for Eurofer and Cu-base alloys (low Cr content)
  - → Experiments to be conducted (Zn impact on corrosion rate)
  - → Zn simulated using **OSCAR**







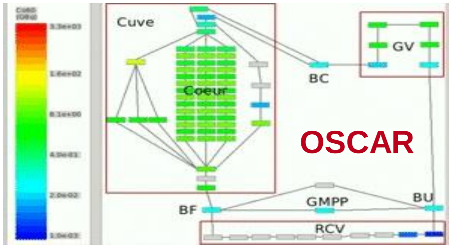
OSCAR calculation

3. Conclusion

- **OSCAR**: Tool for simulating contamination in primary and auxiliary systems of PWRs
- **OSCAR-Na**: **OSCAR** version for SFRs
- **OSCAR-Fusion**: **OSCAR** version for TCWS PHTSs of ITER and DEMO
- **OSCAR-Fusion** benefits from validation of **OSCAR** in a wide range of PWR conditions
- Distinct features of fusion reactors → Challenges related to the interactions between coolants and materials (RAFM steels and Cu-base alloys) to be addressed:
  - Subcooled nucleate boiling
  - High neutron flux
  - High coolant velocity
  - Plasma pulsed operation
  - Magnetic field
  - Colloidal transport

- Perspectives
  - **OSCAR-LiPb** (for DEMO – EUROfusion task)
  - **OSCAR-SMR** (for Nuward)
  - **OSCAR-MSR**

Thank you



CEA CADARACHE

13108 St-Paul lez Durance Cedex

France

frederic.dacquait@cea.fr

+ 33 4 42 25 75 74