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SIMULATIONS OF CORROSION PRODUCT TRANSFER WITH THE OSCAR V1.2 CODE

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ABSTRACT

Activated Corrosion Products (ACPs) generate a radiation field in PWRs, which is the major contributor to the dose absorbed by nuclear power plant staff working during shutdown operations and maintenance. Therefore, a thorough understanding of the mechanisms that control the corrosion product transfer is of the highest importance. Since the 1970's, the R&D strategy in France has been based on experiments in test loops representative of PWR conditions, on in-situ gamma spectrometry measurements of the PWR primary system contamination and on simulation code development.

The simulation of corrosion product transfers in PWR primary circuits is a major challenge since it involves many physical and chemical phenomena including: corrosion, dissolution, precipitation, erosion, deposition, convection, activation... In addition to the intrinsic difficulty of multi-physics modelling, the primary systems present severe operating conditions (300 °C, 150 bar, neutron flux, fluid velocity up to 15 m.s⁻¹ and very low corrosion product concentrations).

The purpose of the OSCAR code, developed by the CEA in cooperation with EDF and AREVA NP, is to predict the PWR primary system contamination by corrosion and fission products. The OSCAR code is considered to be not only a tool for numerical simulations and predictions (operational practices improvements and new-built PWRs design) but also one that might combine and organise all new knowledge useful to progress on contamination. The OSCAR code for Products of Corrosion, OSCAR PC, allows researchers to analyse the corrosion product behaviour and to calculate the ACP volume and surface activities of the primary and auxiliary systems.

In the new version, OSCAR PC V1.2, the corrosion product transfer in the particulate form is enhanced and a new feature is the possibility to simulate cold shutdowns. In order to validate this version, the contamination transfer has been simulated in 5 French PWRs with different operating and design characteristics. After a description of the models of the main transfer mechanisms, the paper presents the calculated ACP surface and volume activities, the calculated concentrations of metallic elements and their comparisons with on-site measurements for one of the 5 validation cases. The simulations of a steam generator replacement and a cold shutdown are also presented.

There is a good agreement between the OSCAR PC V1.2 results and the measured values during power operation and cold shutdown as well. Furthermore, the variations with operating cycle of the surface activities are correctly reproduced. Compared to the previous versions, these improvements are mainly due to the improvement of the thermodynamic database of the OSCAR chemistry module, PHREEQCEA, and to the enhancement of the corrosion product transfer in the particulate form.

1 INTRODUCTION

Activated Corrosion Products (ACP) generate a radiation field in PWRs which is the major contributor to the dose absorbed by nuclear power plant staff working during shutdown operations and maintenance. Therefore, a thorough understanding of the mechanisms that control the corrosion product transfer is of the highest importance. Since the 1970's, the R&D strategy in France has been based on experiments in test loops representative of PWR conditions, on in-situ gamma spectrometry measurements of the PWR primary contamination and on simulation code development.

The simulation of corrosion product transfers in PWR primary circuits is a major challenge since it involves many physical and chemical phenomena including: corrosion, dissolution, precipitation, erosion, deposition, convection, activation... In addition to the intrinsic difficulty of multi-physics modelling, the primary systems present severe operating conditions (300 °C, 150 bar, neutron flux, water velocity up to 15 m.s⁻¹ and very low corrosion product concentrations).

The purpose of the OSCAR¹ code, developed by the CEA in cooperation with EDF and AREVA NP, is to predict the contamination of the PWR primary system in power operating and cold shutdown conditions. The OSCAR code is the merging of two contamination codes: PACTOLE for corrosion products and PROFIP for fission products and actinides. The OSCAR code is a new version of these contamination transfer codes developed by the CEA since the 1970's [1], [2], [3], [4], [5], [6], [7].

In order to validate the new version of the simulation code OSCAR for Products of Corrosion, OSCAR PC V1.2, the contamination transfer has been simulated in 5 French PWRs with different operating and design characteristics. After a description of the models of the main transfer mechanisms, for one of the 5 PWR cases this paper presents the calculated ACP surface and volume activities, the calculated concentrations of metallic elements and their comparisons with in-situ measurements. In the last part, simulations of a cold shutdown and a steam generator replacement are also presented.

2 PRESENTATION OF THE SIMULATION CODE OSCAR PC V1.2

2.1 CORROSION PRODUCT TRANSFER MODELLING

The corrosion product transfer modelling of OSCAR PC V1.2 is almost identical to the previous versions [7], briefly:

- The PWR systems (RCS, CVCS, RHRS)² are discretized into several control volumes or regions (typically around 100 regions) defined according to the geometric, thermal-hydraulic, neutronic, material and operating characteristics.
- Seven media can be taken into account in each control volume: the base metal, the inner oxide layer, the outer oxide layer, the deposit, the particles and ions and the purification system (filter and resins) for particles and ions.
- The metallic elements taken into account are those composing the main alloys found in any primary system that generate the main ACPs: Ni, Co, Fe, Cr, and Mn. Their radioisotopes, which generate the dose rates around the primary systems, are: ⁵⁸Co, ⁶⁰Co, ⁵⁹Fe, ⁵¹Cr and ⁵⁴Mn. They are produced by the following neutron reactions: ⁵⁸Ni(n,p)⁵⁸Co, ⁵⁹Co(n,γ)⁶⁰Co, ⁵⁸Fe(n,γ)⁵⁹Fe, ⁵⁴Fe(n,p)⁵⁴Mn and ⁵⁰Cr(n,γ)⁵¹Cr.
- The mass balances are calculated for each isotope (stable and radioactive) of these metallic elements in each medium of each region using the following equation:

$$\frac{\partial m_i}{\partial t} + (\dot{m}_{out} - \dot{m}_{in}) = \sum_{Source} J_m - \sum_{Sink} J_m$$

with m_i being the mass of the isotope (i) in a given medium [kg], t the time [s], $(\dot{m}_{out} - \dot{m}_{in})$ the convection term [kg.s⁻¹] and J_m the mass flux between 2 media (except for nuclear reactions that represent a mass transfer inside the same medium) [kg.s⁻¹]. The transfer mechanisms taken into account are: corrosion-release, dissolution, precipitation, erosion, deposition, diffusion, convection, activation and radioactive decay.

2.2 MAIN TRANSFER MECHANISMS

In addition to the corrosion mechanism which is the source term, the main mechanisms involved in the corrosion product transfer are dissolution/precipitation and erosion/deposition.

¹ OSCAR : Outil de Simulation de la Contamination en Réacteur (tOol of Simulation of Contamination in Reactor)

² RCS : Reactor Coolant System – CVCS : Chemical and Volume Control System – RHRS : Residual Heat Removal System

2.2.1 Dissolution/Precipitation

The dissolution of a deposit occurs when the concentration of a soluble species in the coolant is less than its equilibrium concentration. The dissolution flux of the element *elt*, J_{dissol}^{elt} [kg.s⁻¹], may be written:

$$J_{dissol}^{elt} = \frac{S}{1/h + 1/V_{dissol}} \cdot (C_{equil}^{elt} - C^{elt})$$

with *S* being the wet surface proportional to the mass of the element *elt* of the deposit [m²], *h* the mass transfer coefficient of ions in the fluid [m.s⁻¹], V_{dissol} the dissolution velocity (dissolution surface reaction rate coefficient) [m.s⁻¹], C_{equil}^{elt} the equilibrium concentration of the element *elt* [kg.m⁻³] and C^{elt} the bulk concentration of the element *elt* [kg.m⁻³].

The equilibrium concentration of each chemical element and the oxide speciation of the deposit are calculated by the OSCAR chemistry module, PHREEQCEA (a version of the PHREEQC code [8] extended to the PWR temperature range) in combination with a thermodynamic database developed by the CEA [9]. PHREEQCEA determines the composition of the ideal solid solution (mixed oxides and any pure solid phases possibly in excess) and the equilibrium concentration of each element in relation to the chemical conditions (pH, H₂, O₂), the coolant temperature and the masses of the metallic element of the deposit in each control volume.

As the dissolution velocities are not well known in PWR conditions, they are calibrated in OSCAR. However, in order to have data of dissolution velocities, an experimental program is underway in the CEA to determine the oxide dissolution kinetics [10].

Soluble species precipitate when their concentration in the coolant reaches their equilibrium concentration. The expression of the precipitation flux is similar to that of the dissolution flux considering that the limiting phenomenon is the mass transfer in the fluid and not the precipitation surface reaction rate coefficient. The expression of the precipitation flux, J_{precip}^{elt} [kg.s⁻¹], is thus:

$$J_{precip}^{elt} = h \cdot S \cdot (C^{elt} - C_{equil}^{elt})$$

with *h* being the mass transfer coefficient of ions in the fluid [m.s⁻¹], *S* the wet surface [m²], C^{elt} the bulk concentration of the element *elt* [kg.m⁻³] and C_{equil}^{elt} the equilibrium concentration of the element *elt* [kg.m⁻³].

2.2.2 Erosion/Deposition

The erosion term of a deposit results from the coolant friction forces. The model assumes that a deposit can be eroded above the laminar sub-layer. In a volume control, the erosion flux, J_{eros} [kg.s⁻¹], is given by:

$$J_{eros} = \frac{m^{dep} - e_{lim} \cdot \rho^{dep} \cdot S^{dep}}{T_{eros}}$$

with m^{dep} being the mass of the deposit [kg], e_{lim} the thickness of the laminar sub-layer, ρ^{dep} the density of the deposit [kg.m⁻³], S^{dep} the surface of the deposit [m²] and T_{eros} the erosion characteristic time [s] which is a calibration parameter.

The particle deposition rate takes into account 1) the turbulent diffusion and the effects of inertia [11], 2) the sedimentation for horizontal ducts [12] and 3) the thermophoresis for temperature gradients between the coolant and the wall [13]. In a volume control, the deposition flux, J_{depos} [kg.s⁻¹], may be expressed as follows:

$$J_{depos} = \frac{4 \cdot V_{depos}}{D_h} \cdot m^{part}$$

with V_{depos} being the deposition velocity of particles [m.s⁻¹], D_h the hydraulic diameter [m] and m^{part} the mass of particles in the fluid [kg].

2.2.3 Calibration

For OSCAR V1.2, we have reassessed the relative influences of the ionic and particulate forms in the corrosion product transfer. Compared to the previous versions, the corrosion product transfer in the particulate form is enhanced. To achieve this goal, the thickness of the laminar sub-layer e_{lim} has been reduced by a factor of 5 and the deposition velocity of particles has been reduced by a factor of 10 [14].

With ⁵⁸Co and ⁶⁰Co contributing by over 90% on the average to the dose rates around primary systems, the parameters V_{dissol} , T_{eros} , e_{lim} , and V_{depos} have been calibrated by focusing on these two radioisotopes with respect to typical surface activities, volume activities and ion concentrations measured in PWR primary systems.

The results obtained with this new configuration are presented in the next paragraph.

3 SIMULATIONS USING OSCAR PC V1.2

In order to validate OSCAR PC V1.2, the corrosion product behaviour has been simulated in 5 French PWRs (DAMPIERRE-1, CRUAS-1, CHINON-B1, CATTENOM-2 and GOLFECH-2) which have different operating and design characteristics (900/1300 MWe PWRs, Inconel 600MA/600TT/690TT SGs, Inconel 718/Zry grids, pH of 7.0/7.2, different fuel managements ...). The results have been compared to on-site measurements: surface activities (EMECC campaigns [15] [16]), volume activities (total, ionic and particulate forms) and chemical element concentrations. We present the simulation of one of the 5 validation cases below (CATTENOM-2).

Like the previous versions, OSCAR takes into account the refuelling and a steam generator replacement if necessary. Cold shutdowns can be simulated using OSCAR PC V1.2, which is a major improvement of this new version, or only the effects of cold shutdowns can be taken into account (like in the previous versions). The simulations of DAMPIERRE-1 which underwent a Steam Generator Replacement (SGR) and of a cold shutdown of GOLFECH-2 are also presented in this part.

3.1 MAIN INPUT DATA

To run the OSCAR PC code, it is necessary to provide a set of input data:

- The geometric parameters of a control volume are the hydraulic diameter and the wet surface.
- The thermal-hydraulic data, which includes the velocity, the flowrate, the bulk and wall temperatures of the coolant.
- The materials are defined by their density, their composition and their roughness. Any possible surface treatment is taken into account via the experimental corrosion and release rates.
- As the activation of the corrosion products is directly proportional to the neutron flux, the power fraction is specified in each part of the core. The neutron reaction rates, as a function of PWR type, fuel burnup, ²³⁵U enrichment and Pu content, are extracted from a nuclear database interfaced with OSCAR.
- In terms of operating data, a cycle is defined by its duration, its power history and its concentration levels in boron, lithium, hydrogen and oxygen.
- The refuelling of fuel assemblies at each end of cycle.

3.2 SIMULATION OF CATTENOM-2

Unit 2 of the nuclear power plant of CATTENOM is a 1300 MWe PWR commissioned in 1988. It is equipped with Inconel 600TT SG tubes. From the 3rd cycle, the fuel assembly grids made of 718 alloy have been replaced by Zircaloy grids. For every cycle, one-third of the fuel was removed and replaced. The RCS and CVCS are described by 83 regions including 48 for the core (see Figure 1).

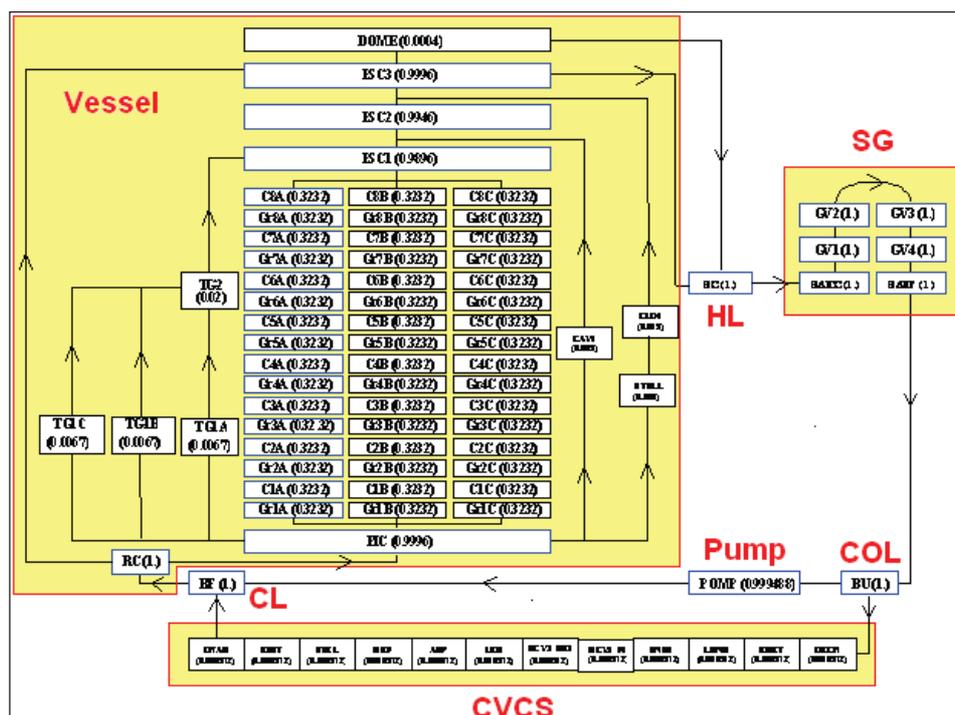


Figure 1: CATTENOM-2 – Control volumes (HL : Hot Leg / COL : CrossOver Leg / CL : Cold Leg)

The first 11 operating cycles have been simulated using OSCAR PC V1.2. CATTENOM-2 operated according to coordinated boron-lithium chemistry at $\text{pH}_{300^\circ\text{C}}$ of 7.0 for the first 7 cycles and then at $\text{pH}_{300^\circ\text{C}}$ of 7.2 with a maximum lithium concentration of 3.5 ppm (modified chemistry). The operating parameters are given in Figure 2 and the $\text{pH}_{300^\circ\text{C}}$ calculated using OSCAR/PHREEQCEA in Figure 3.

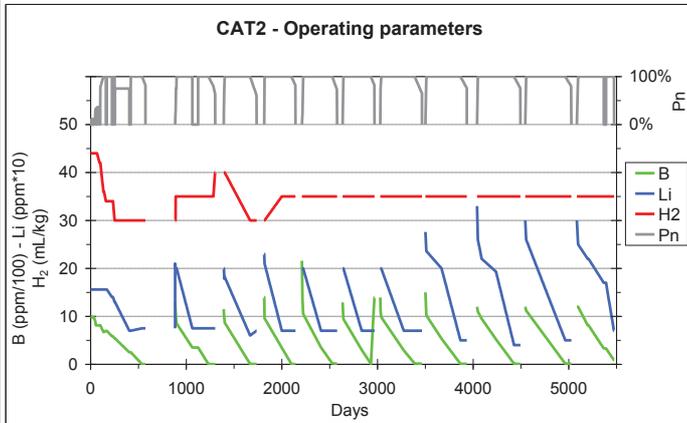


Figure 2: CATTENOM-2 – Operating parameters

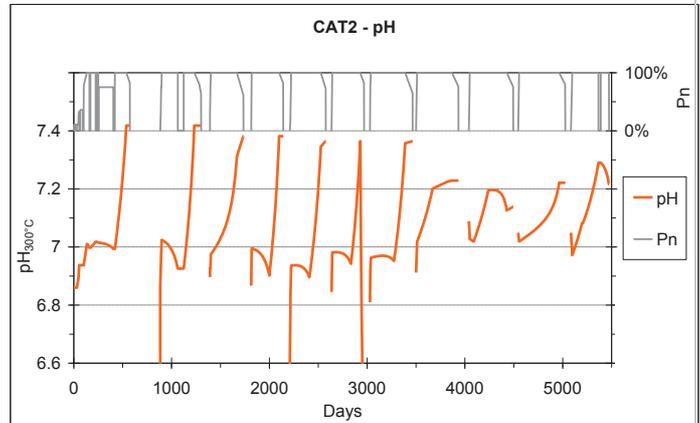


Figure 3: CATTENOM-2 – $\text{pH}_{300^\circ\text{C}}$

3.2.1 Surface activities

Figure 4 and Figure 5 compare the ^{58}Co , ^{60}Co , ^{51}Cr , ^{59}Fe and ^{54}Mn surface activities calculated using OSCAR V.1.2 with the surface activities measured at the beginning of some unit outages (cycles 3 to 5 and 7 to 11) using the EMECC system for the hot legs and the cold side of steam generator tubes.

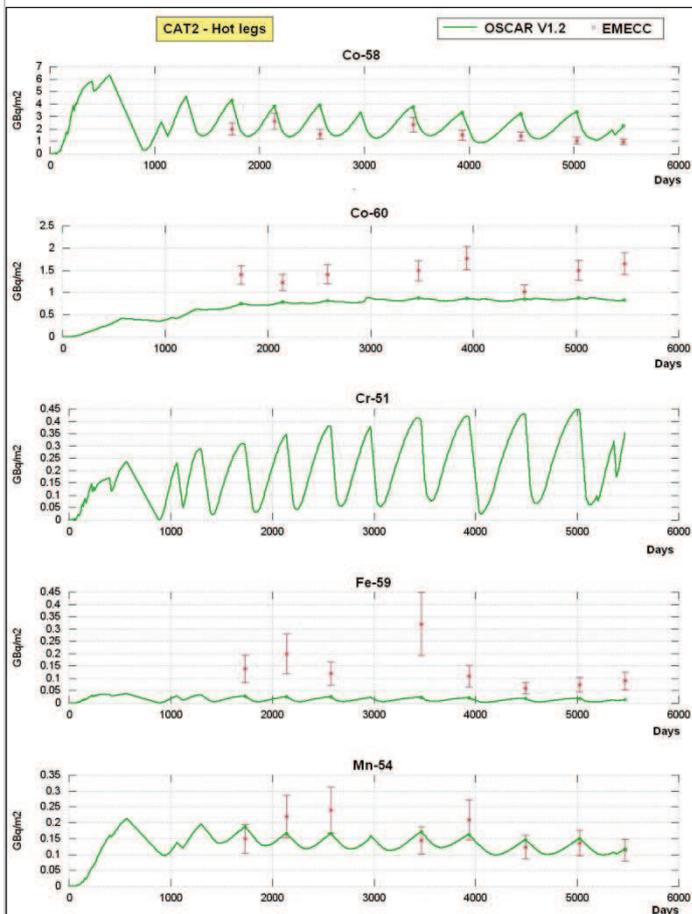


Figure 4: CATTENOM-2 – Activities deposited on the hot legs

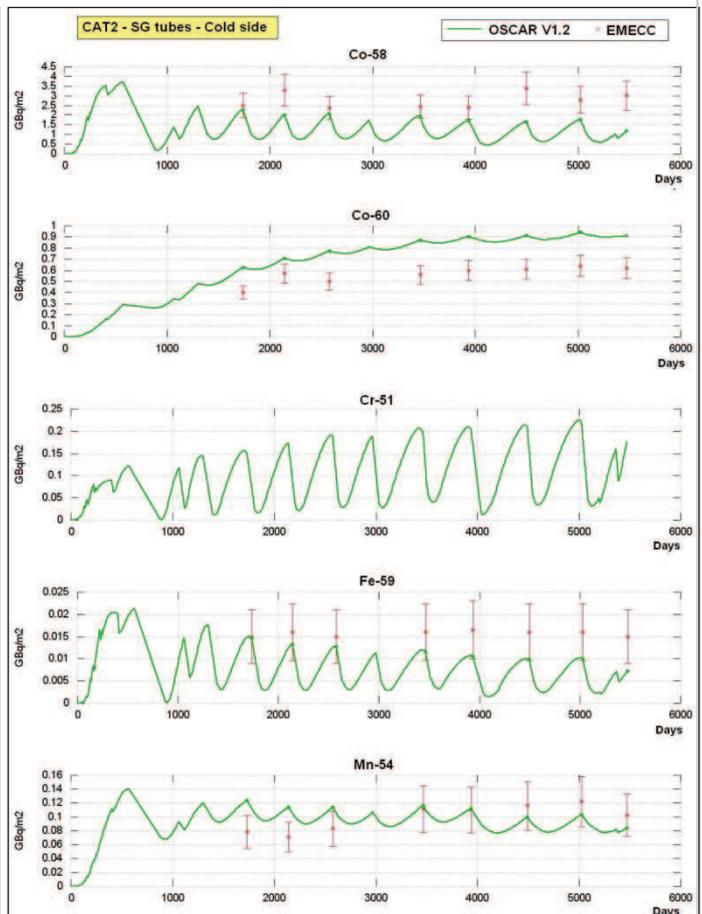


Figure 5: CATTENOM-2 – Activities deposited on the SG tubes (cold side)

The simulation reproduced the levels and the trends of the surface activities of the primary system correctly:

- The average differences over the cycles between the calculated and measured activities are less than a factor of 2.2 for ^{58}Co , 2.0 for ^{60}Co , 6.5 for ^{59}Fe and 1.3 for ^{54}Mn .
- The ^{58}Co surface activities tend to decrease for the first cycles and then stabilize.
- The ^{60}Co surface activities increase for 6 to 8 first cycles and then stabilize.

In general, ^{51}Cr deposited inside the primary system cannot be measured due to its low gamma energy of 320 keV and the great thicknesses of the primary coolant pipes and steam generator shell. However, EMECC measurements of some auxiliary systems (SG by-pass or CVCS letdown pipe) allow us to estimate the ^{51}Cr surface activities of the primary system of the order of a few tenths of GBq/m² to a few GBq/m² [17]. The calculated range between 0.2 and 0.5 GBq/m² is of the same order of magnitude.

In Figure 6, we have plotted the calculated and measured ^{58}Co and ^{60}Co surface activities on the SG cold and hot sides. The calculated surface activities on the cold side and on the hot side of the SG tubes of CATTENOM-2 are in good agreement with the EMECC measurements. The differences of measured contamination between the hot and cold sides of the SG tubes are low (less than 20%) or even zero. The measured ^{60}Co surface activity is higher on the cold side than on the hot side from cycle 7 (about 3,500 days) whereas the levels were similar at cycle 3 (about 1,700 days). In agreement with the measurements, the results obtained with OSCAR V1.2 show differences less than 15% between the two sides and the same trends: no difference for ^{60}Co contamination at cycle 3 and a higher contamination on cold side at cycle 7 and later. However in some cases after SGR, the temperature impact on the contamination levels of the hot and cold sides is very marked [18], reflecting a strong chemistry effect which is not reproduced by OSCAR PC V1.2.

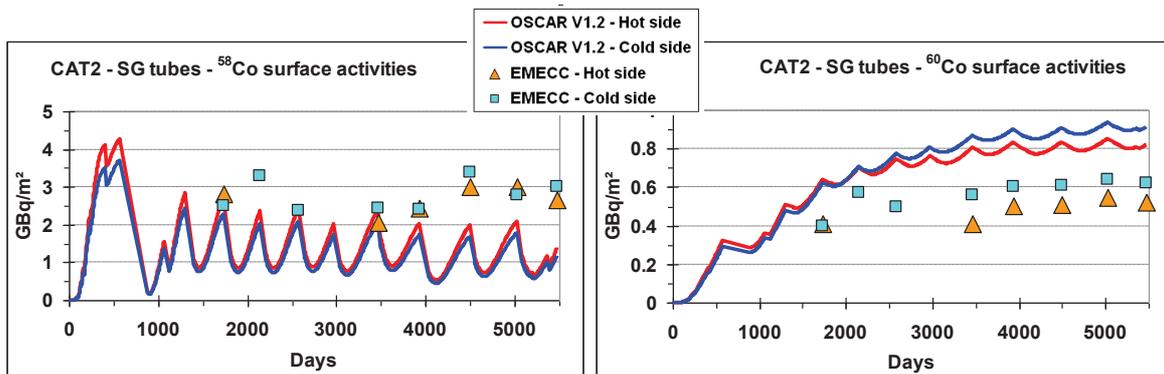


Figure 6: CATTENOM-2 – ^{58}Co and ^{60}Co activities deposited on the SG tubes (cold and hot sides)

3.2.2 Volume activities

Figure 7 and Figure 8 compare the ^{58}Co , ^{60}Co , ^{51}Cr , ^{59}Fe , ^{54}Mn volume activities calculated by OSCAR PC V1.2 with the volume activities measured by EDF.

The calculated volume activities are in relative good agreement with the measured volume activities for ^{60}Co and ^{54}Mn , they are relatively close for ^{58}Co but they are underestimated for ^{51}Cr and ^{59}Fe . The difference for ^{51}Cr is due to an underestimation of the particulate activities and the difference for ^{59}Fe is probably due to an underestimation of soluble and particulate activities (see Figure 9).

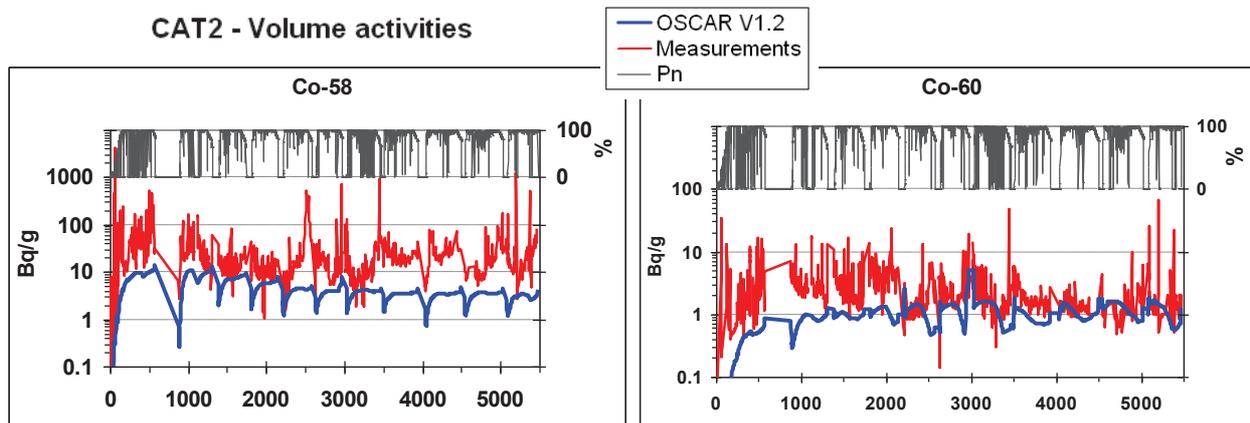


Figure 7: CATTENOM-2 – ^{58}Co and ^{60}Co volume activities

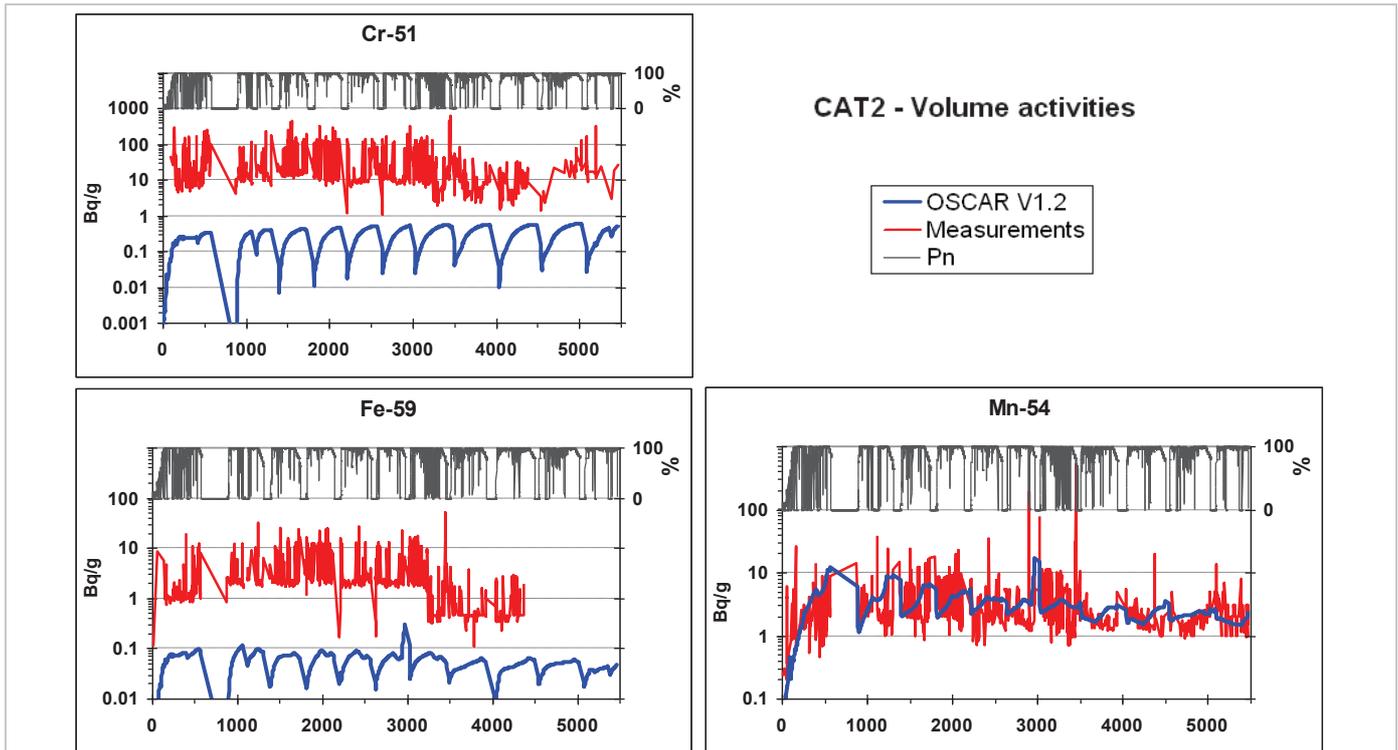


Figure 8: CATTENOM-2 – ⁵¹Cr, ⁵⁹Fe and ⁵⁴Mn volume activities

In accordance with the EDF experimental feedback, the calculated ⁵⁸Co and ⁵⁹Fe particulate activities are close to the ionic activities or even higher for ⁵⁸Co. The ⁶⁰Co and especially ⁵⁴Mn volume activities are mainly in the soluble form and the ⁵¹Cr volume activity is mainly in the particulate form (see Figure 9).

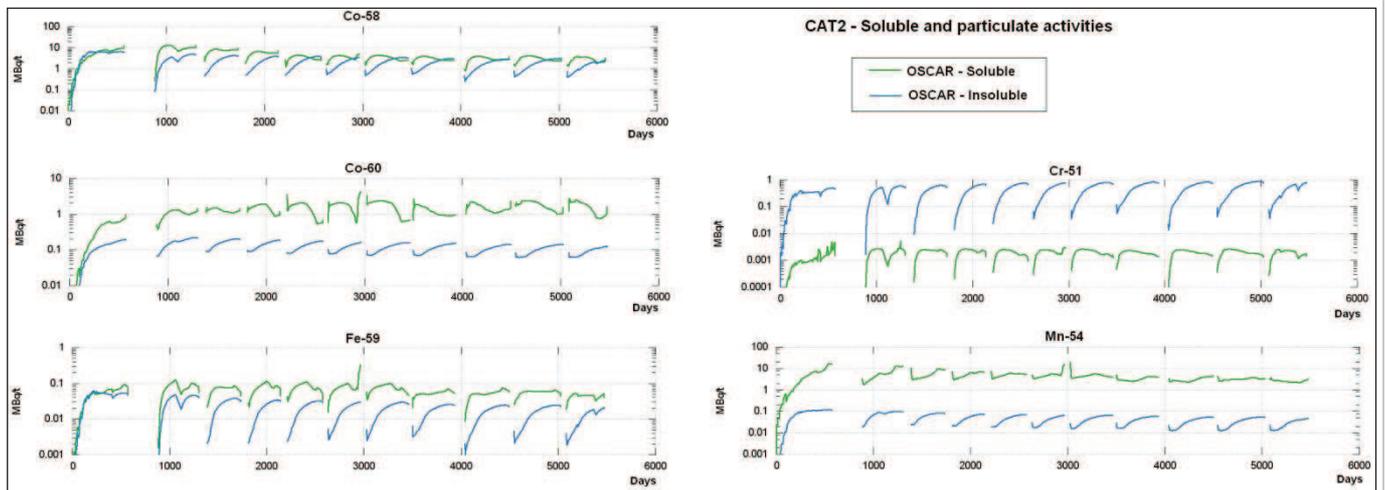


Figure 9: CATTENOM-2 – Soluble and particulate activities

3.2.3 Concentrations of metallic elements

The total concentrations of Ni, Co, Fe, Mn and Cr and their concentrations in soluble and particulate forms calculated by OSCAR PC V1.2 are presented in Figure 10.

The calculated concentrations of Ni, Fe and Co are close to the typical concentrations measured in EDF PWRs:

- About 1 ppb for Fe, several tenth of ppb for Ni and several ppt for Co.
- Mainly in soluble form for Fe, Co and Mn, mainly in particulate form for Cr and equally distributed for Ni. However, the particulate Ni concentration seems to be overestimated.

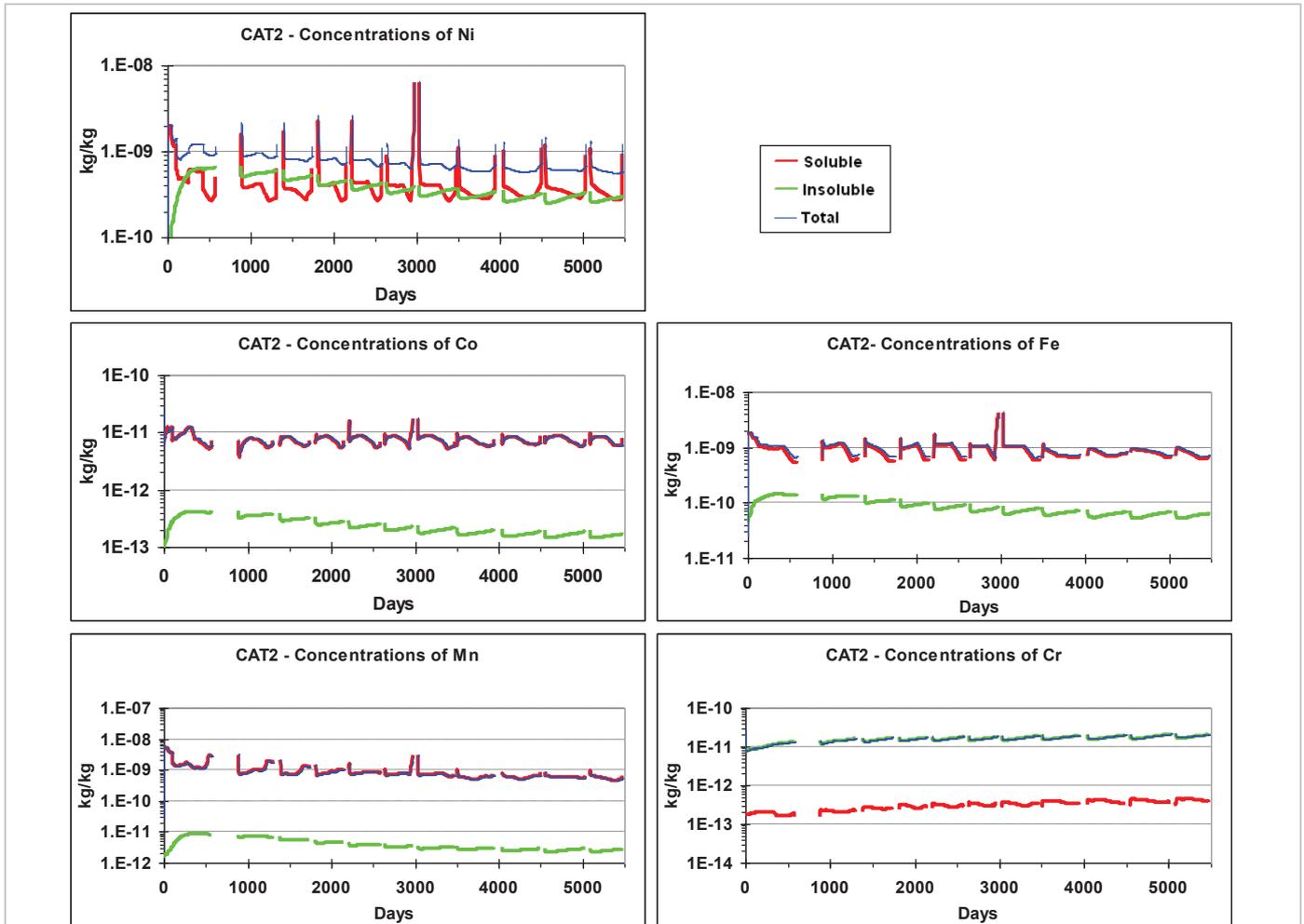


Figure 10: CATTENOM-2 – OSCAR results – Metallic element concentrations of the primary coolant (hot legs)

3.3 SIMULATION OF A SGR

DAMPIERRE-1, a 900 MWe PWR commissioned in 1980, underwent a Steam Generator Replacement (SGR) at the outage of cycle 8. The Inconel 600MA SGs have been replaced by Inconel 690TT SGs.

The average Co content of the SG tubes was 270 ppm before SGR and 130 ppm after SGR. From the 6th cycle, the fuel assembly grids made of 718 alloy were replaced by Zircaloy grids.

The first 15 operating cycles with an aimed $pH_{300^{\circ}C}$ of 7.0 have been simulated. The operating parameters are given in Figure 11 and the $pH_{300^{\circ}C}$ calculated using OSCAR/PHREEQCEA in Figure 12.

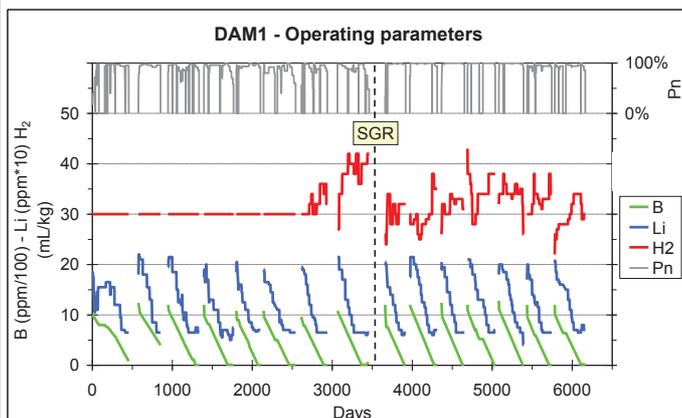


Figure 11: DAMPIERRE-1 – Operating parameters

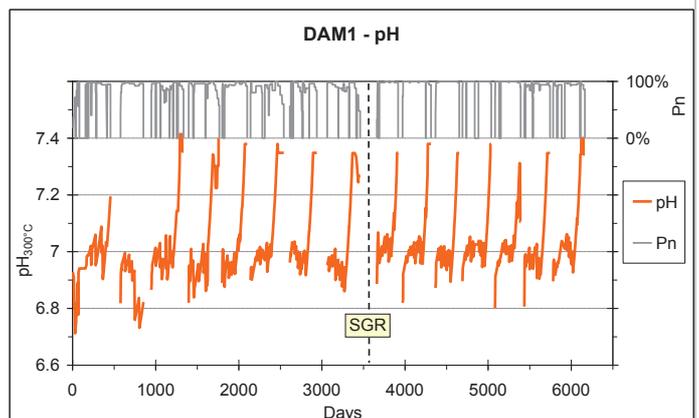


Figure 12: DAMPIERRE-1 – $pH_{300^{\circ}C}$

3.3.1 Surface activities

Figure 13 and Figure 14 compare the ^{58}Co , ^{60}Co , ^{59}Fe and ^{54}Mn surface activities calculated using OSCAR V.1.2 with the surface activities measured at the beginning of some unit outages (cycles 1 to 3, 6 to 13 and 15) using the EMECC system for the Hot Legs (HL) and the Steam Generator tubes (SG) (cold side).

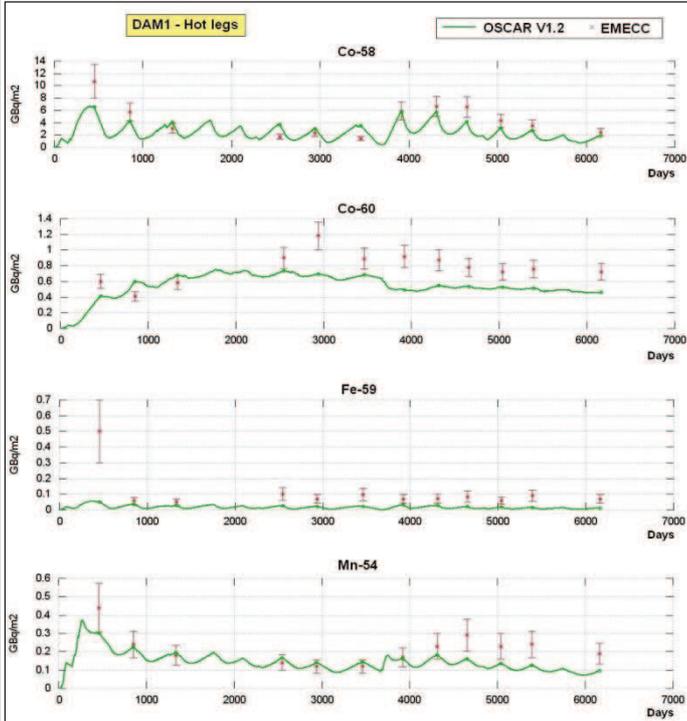


Figure 13: DAMPIERRE-1 – Activities deposited on the hot legs

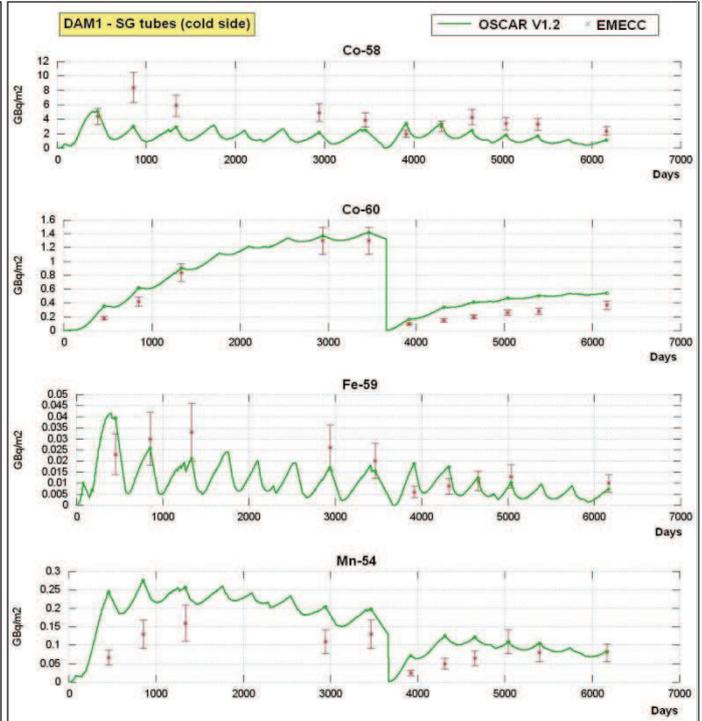


Figure 14: DAMPIERRE-1 – Activities deposited on the SG tubes (cold side)

The simulation correctly reproduces the levels and the trends of the surface activities of the primary system before and after SGR:

- The average differences over the cycles between the calculated and measured activities are less than a factor of 2.1 for ^{58}Co , 2.4 for ^{60}Co , 4.0 for ^{59}Fe and 2.5 for ^{54}Mn .
- Before SGR, the ^{58}Co surface activities tend to decrease with cycles. After SGR, they increase for two cycles and then decrease.
- Before SGR, the ^{60}Co surface activities increase for the first 5 to 7 cycles and then stabilize. After SGR, they are stagnant or even decrease on the primary pipes and they increase on the new SG tubes.

The SGR impact is quite suitably reproduced with OSCAR PC V1.2. The increase in the ^{58}Co surface activities for the first cycles after SGR is due to a high Ni release from the new SG tubes during the formation of an inner protective oxide layer on the fresh alloy surfaces and also due to the state of the circuit cleanliness after a SGR process [18]. After SGR, the decrease in the ^{60}Co surface activities on the primary pipes and the increase by a lower rate than before SGR on the SG tubes are due to the lower Co content and a lower corrosion rate of the replacement SG tubes.

3.4 SIMULATION OF A COLD SHUTDOWN

Physico-chemical conditions significantly vary during cold shutdowns: power, temperature and pH decrease and primary coolant oxygenation. These changes lead to corrosion product releases in the primary coolant. The RCS oxygenation in particular causes a large dissolving of the in-core Ni⁰ deposit. The metallic nickel deposit dissolution involves the dissolution of ^{58}Co coming from the neutron activation of ^{58}Ni . Ni peak concentration and ^{58}Co peak activity then appear, typically, of the order of several ppm and 100 GBq/Mg, respectively [19] (except for PWRs equipped with improved manufacturing process SG tubes [20]).

To simulate these releases, it is necessary:

- to know the solid speciation of the crud on fuel elements (calculated by OSCAR/PHREEQCEA),
- to vary the phase dissolution velocities (V_{dissol} , see §2.2.1) as a function of the temperature,

- to increase the dissolution flux of Ni° in oxidizing conditions by means of the increase in the dissolution velocity of the Ni° phase,
- to link the dissolution of the ⁵⁸Co coming from the Ni° activation to the dissolution of Ni°, which is done by a ratio.

We have simulated 5 operating cycles including the cold shutdown of the 2nd outage of GOLFECH-2, a 1300 MWe PWR equipped with Inconel 690TT SGs.

GOLFECH-2 operated according to coordinated boron-lithium chemistry at pH_{300°C} of 7.0 until cycle 3 and then at pH_{300°C} of 7.2 (see Figure 15 and Figure 16). From cycle 2, the fuel assembly grids made of 718 alloy were replaced by Zircaloy grids. The average differences over the 5 cycles between the calculated and measured surface activities on the primary system are less than a factor of 1.6 for ⁵⁸Co, 1.5 for ⁶⁰Co, 4.1 for ⁵⁹Fe and 1.9 for ⁵⁴Mn.

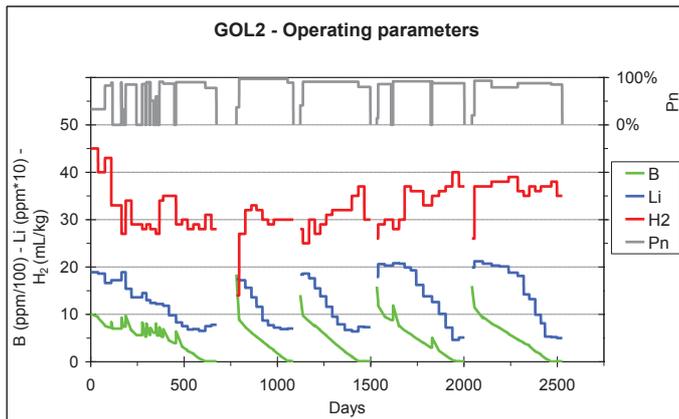


Figure 15: GOLFECH-2 – Operating parameters

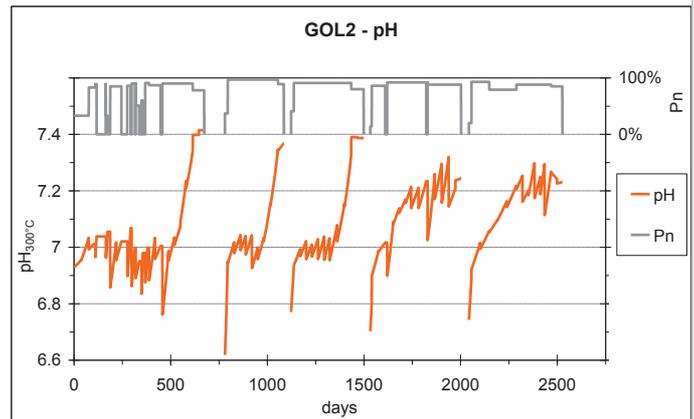


Figure 16: GOLFECH-2 – pH_{300°C}

The coolant temperature, the CVCS flowrate, the boron, dihydrogen and dioxygen concentrations during the cold shutdown of cycle 2 are presented in Figure 17. Figure 18 shows the comparison of the calculated and measured ⁵⁸Co volume activities.

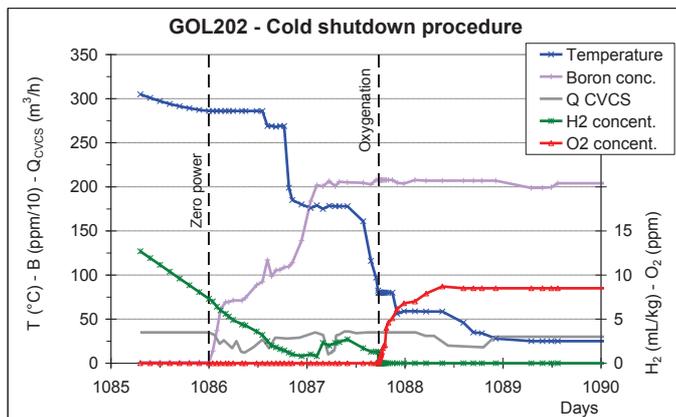


Figure 17: GOLFECH-2 – Cycle 2
Cold shutdown procedure

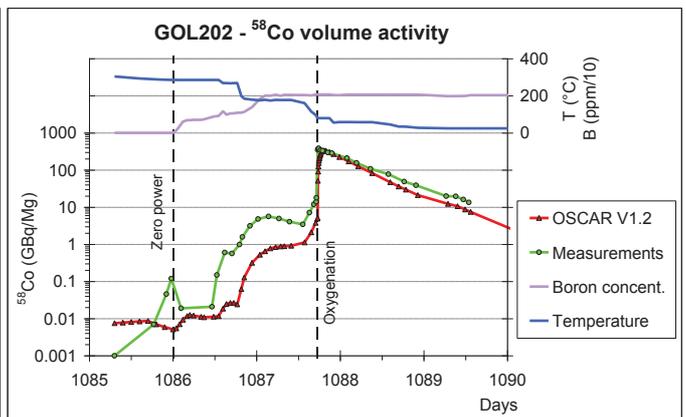


Figure 18: GOLFECH-2 – Cycle 2
⁵⁸Co volume activities

The changes of the Ni and ⁵⁸Co volume activities are well reproduced: the boron increase and the temperature drop lead to an increase in the volume activities considering that the corrosion product solubilities are higher at low temperature and in acid medium. The oxygenation causes the in-core Ni° deposits and thus ⁵⁸Co to dissolve quickly. To achieve the reproduction of the ⁵⁸Co peak activity, in our model the Ni° dissolution velocity at 80 °C is $1.9 \times 10^{-8} \text{ m.s}^{-1}$ in reducing medium and $4 \times 10^{-6} \text{ m.s}^{-1}$ in oxidizing medium (about 200 times higher) and the dissolution velocities of the other phases are lower. The calculated ⁵⁸Co peak activity is 337 GBq/Mg, which is close to the measured value of 385 GBq/Mg. The calculation underestimates the volume activity during the temperature plateaux. It will be corrected in the next version of OSCAR by a better calibration of the dissolution velocities of the different phases. The decrease after the peak activity is due to the purification by the CVCS. The purification rate is correctly simulated.

4 CONCLUSION

Tableau 1 summarises the comparison of the average values over the 5 validation PWR cases calculated by OSCAR V1.2 during power operation to the experimental feedback.

		Average over the 5 PWR cases
Surface activities	⁵⁸ Co	Over or underestimation by a factor of 1.6
	⁶⁰ Co	Over or underestimation by a factor of 1.7
	⁵¹ Cr	Low underestimation or even equivalent
	⁵⁹ Fe	Over or underestimation by a factor of 2.8
	⁵⁴ Mn	Over or underestimation by a factor of 1.5
Volume activities	⁵⁸ Co	Low underestimation or even equivalent
	⁶⁰ Co	Equivalent
	⁵¹ Cr	Underestimation by a factor < 10
	⁵⁹ Fe	Slight underestimation
	⁵⁴ Mn	Equivalent
Concentrations	Ni	Equivalent
	Fe	Equivalent
	Co	Equivalent

Tableau 1 : Summary of calculated/measured comparisons

There is a relative good agreement between the OSCAR PC V1.2 results and the measured values during power operation and cold shutdown as well. Furthermore, the variations with operating cycle of the surface activities are correctly reproduced.

The simulations of a French 1450 MWe PWR and of an US 1100 MWe PWR have also shown a good consistency with the measurements [21].

Compared to the previous versions, these improvements are mainly due to the improvement of the thermodynamic database of PHREEQCEA coupled to OSCAR and to the enhancement of the corrosion product transfer in the particulate form.

Nevertheless, further improvements are scheduled in the next version that will be released in 2013, OSCAR PC V1.3. Its objectives in particular will involve: finding a better balance between the corrosion product transfers in the ionic and particulate forms in order to reproduce some phenomena, focusing not only on ⁵⁸Co and ⁶⁰Co but also on the other radioisotopes, improving the cold shutdown simulation, reassessing the erosion and release mechanisms, modelling the crud growth under nucleate boiling conditions [22].

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