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PWR circuit contamination assessment tool. Use of OSCAR code for engineering studies at EDF

Moez Benfarah[1*], Meddy Zouiter[1], Thomas Jobert[1], Frédéric Dacquait[2], Marie Bultot[2], and Jean-Baptiste Genin[2]

[1] EDF, SEPTEN, 12-14 avenue Dutrievoz, 69628 Villeurbanne, France
[2] CEA Cadarache, 13108 Saint-Paul-Lez-Durance, France

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Abstract. Normal operation of PWR generates corrosion and wear products in the primary circuit which are activated in the core and constitute the major source of the radiation field. In addition, cases of fuel failure and alpha emitter dissemination in the coolant system could represent a significant radiological risk. Radiation field and alpha risks are the main constraints to carry out maintenance and to handle effluents. To minimize these risks and constraints, it is essential to understand the behavior of corrosion products and actinides and to carry out the appropriate measurements in PWR circuits and loop experiments. As a matter of fact, it is more than necessary to develop and use a reactor contamination assessment code in order to take into account the chemical and physical mechanisms in different situations in operating reactors or at design stage. OSCAR code has actually been developed and used for this aim. It is presented in this paper, as well as its use in the engineering studies at EDF. To begin with, the code structure is described, including the physical, chemical and transport phenomena considered for the simulation of the mechanisms regarding PWR contamination. Then, the use of OSCAR is illustrated with two examples from our engineering studies. The first example of OSCAR engineering studies is linked to the behavior of the activated corrosion products. The selected example carefully explores the impact of the restart conditions following a reactor mid-cycle shutdown on circuit contamination. The second example of OSCAR use concerns fission products and disseminated fissile material behavior in the primary coolant. This example is a parametric study of the correlation between the quantity of disseminated fuel and the variation of Iodine 134 in the primary coolant.

1 Introduction

In a PWR, the release, the activation and the transfer of corrosion products generate radiation fields which cause occupational dose rates. In addition, the cases of fuel failures can cause the dissemination of actinides and fission products in the primary coolant. The fuel damages are the sources of the contamination of the PWR circuits by alpha emitters. To optimize reactor design and to reduce risks during reactor operations, it is essential to understand the behavior of corrosion products, fission products and actinides in PWR circuits.

In France, since 1970s, many R&D studies have been carried out by using test loops to simulate the behavior of contaminant species in PWR conditions. Furthermore, many engineering studies of PWR contamination have been based on the examination of data from plant measurements. The test loops and the data are key to understanding the contamination phenomena in PWR. Nevertheless, to thoroughly understand and control the mechanisms of the PWR contamination, it is strongly advised to develop and use tools for the numerical simulations of the contamination of the PWR circuits.

The simulation of PWR contamination is an important challenge for the following reasons:

- PWR contamination is the consequence of many physical and chemical phenomena impacted by a large number of design and operation parameters. It is difficult to clearly identify the individual impact of a specific parameter by just analyzing the plant data;
- the concentrations of the species generating the contamination are very low. Some species, which could represent a very low concentration, could paradoxically generate significant activities. However, it is very difficult to reproduce and control the behavior of species at very low concentrations in the test loops;
- PWR primary circuit presents high operating conditions regarding temperature, pressure, neutron flux and fluid velocity. Measuring chemical and physical data in these conditions is not an easy matter.

* e-mail: moez.benfarah@edf.fr

Since 1970s, CEA, EDF and Areva have been cooperating for the development of a contamination transfer code [1]. The OSCAR v1.3 code is a new version that incorporates the most recent advances on corrosion products, fission products and actinides modeling.

The code has been qualified by comparing the simulation results to measured contamination data from EDF fleet [2,3]. It is used by CEA, EDF and Areva to assess contamination of operating PWRs and to optimize new plant design.

The aim of this paper is to describe the OSCAR code and to illustrate its use at EDF through two examples of EDF engineering studies:

– the study of the impact of restart conditions on contamination by activated corrosion products following a reactor mid-cycle shutdown;
– the study of the connection between the quantity of disseminated fuel and the evolution of Iodine 134 in the primary coolant in the case of fuel damage.

2 Code description

For corrosion products, the source term is the result of the corrosion of the base metals. The corrosion phenomenon leads to the formation of oxide layers and induces the release of ions in the primary coolant. The metallic elements taken into account are those composing the main alloys found in PWR primary system: Ni, Co, Fe, Cr and Mn.

In the case of fuel failure, the source term of disseminated fissile material is defined by the dissemination rate specified by the user in the input file. The code takes into account U, Pu, Am, Cm isotopes as alpha emitter. The fission products taken into account are I, Xe, Kr, Cs, Rb, Ba, La, Ru, Sr and Te isotopes.

The OSCAR modeling is based on the subdividing of the PWR circuits into elementary regions:

– each region is defined by its geometric, thermal, neutron and hydraulic characteristics and by its base metal. These characteristics are the main input data required for an OSCAR simulation;
– each region is characterized by six media: the base metal, the oxide layer, the deposit layer, particles, ions and purification media. These media have different concentrations of corrosion products, fission products and actinides.

The OSCAR calculation is based on the resolution of the mass balance equations for each isotope 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 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 two media [kg·s^{-1}].

The variations of the concentrations of the species in the six media result from corrosion, release, diffusion, convection, activation, purification, radioactive decay mechanisms and the exchange flux between the media (dissolution/precipitation and erosion/deposition). Figure 1 describes the different media and flux in an elemental region. The main mechanisms involved in the transfers between the six media are dissolution/precipitation and erosion/deposition. A detailed description of these mechanisms has been reported by Dacquait et al. [2]. The dissolution of a deposit occurs when the concentration of a soluble species in the coolant is less than its equilibrium concentration. Soluble species precipitate when their concentration in the coolant reaches their equilibrium concentration. The dissolution and the precipitation flux are calculated using the following equations:

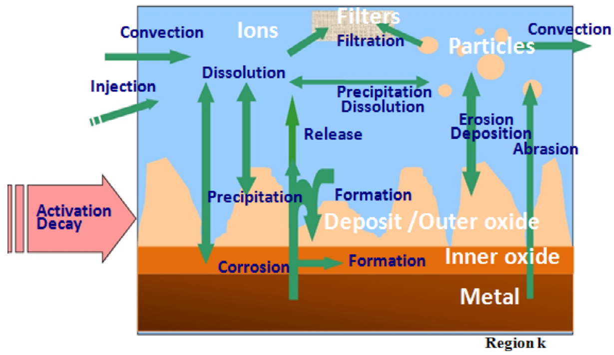

Fig. 1. Mass flux between the different media in an elemental region.

$$J^{elt}_{dissol} = \frac{S}{{}^{1}/_{h} + {}^{1}/_{V_{dissol}}} \cdot \left(C^{elt}_{equil} - C^{elm}\right),$$

$$J^{elt}_{precip} = h.S.\left(C^{elm} - C^{elt}_{equil}\right),$$

with S the wet surface [m^2], h the mass transfer coefficient of ions in the fluid [m·s^{-1}], V_{dissol} the dissolution surface reaction rate coefficient [m·s^{-1}], C^{elt}_{equil} the equilibrium concentration of the element elt [kg·m^{-3}] and C^{elm} the bulk concentration of the element elt [kg·m^{-3}].

It is important to note that the dissolution and the precipitation phenomena depend on the equilibrium concentration. The equilibrium concentration of each element and the oxide speciation are calculated by an OSCAR chemistry module: PHREEQCEA, a version of PHREEQC code [4], associated to a thermodynamic database developed by CEA [5].

For insoluble species, the deposition flux, J_{depos} [kg·s^{-1}], is calculated by:

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

with V_{depos} 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].

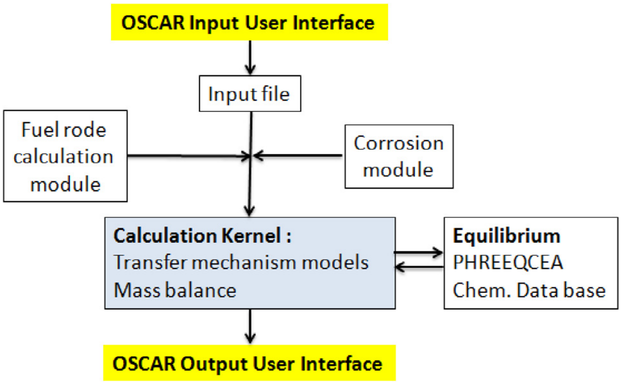

Fig. 2. Structure of the OSCAR code.

The erosion flux, resulting from the coolant friction forces, is calculated by:

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

with m^{dep} 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 [m^2] and $T_{erosion}$ the erosion characteristic time [s].

The source term of the corrosion products results from the base metal corrosion leading to the formation of oxide layers and the release of ions in the primary coolant. In the OSCAR code, the release of corrosion products is modeled by a parametric law which has been determined from the results of test loops.

In the case of fuel damage, the dissemination rate must be specified by the user in the input file. The isotopic distribution of the disseminated fissile material is the same as at the surface of the fuel pellet. The isotopic distribution depends on the fuel burn-up of the damaged fuel and is calculated by a specific module integrated in the code.

The global code structure is schematically described in Figure 2. The code validation was reported in previous papers [2,3].

3 The use of the OSCAR code for engineering studies at EDF

3.1 First example: study of the impact of the primary coolant activities at reactor restart after a mid-cycle shutdown

The radiochemical specifications applied at EDF plants indicate two requirements concerning the activity of the primary coolant before the reactor restart: 7 GBq/t for ^{58}Co activity and 14 GBq/t for the total gamma activity. These specifications have been designed to reduce the risk of recontamination by precipitation of corrosion products at high temperature. The objective of this study is to examine the impact of the ^{58}Co coolant activity on the contamination of the reactor circuits. The study only concerns the reactor restart occurring after a mid-cycle shutdown.

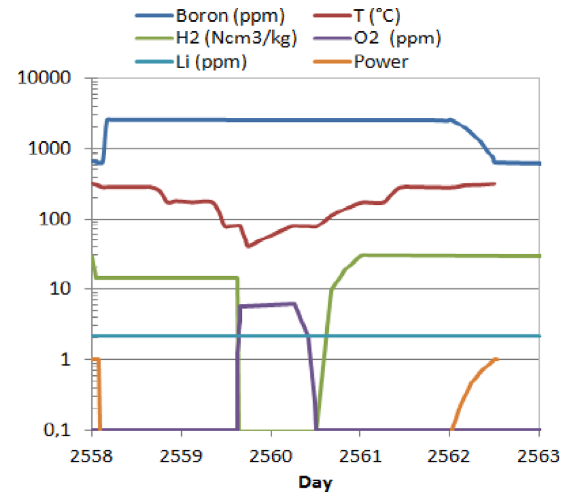

Fig. 3. Operating data used for the simulation of the mid-cycle shutdown and restart.

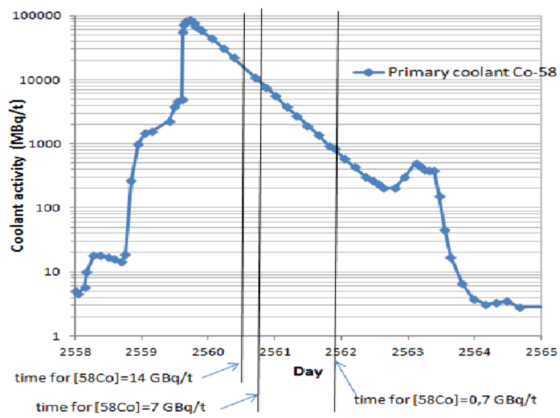

Fig. 4. Evolution of the activity of ^{58}Co in the primary coolant during a mid-cycle shutdown occurring 6 months before the end of cycle.

The input data used for the OSCAR simulation corresponds to the reference data for a 900 MWe PWR 3 loops reactor. Only the first 10 cycles have been simulated. The reference case refers to the case of 10 cycles without mid-cycle shutdown. The studied cases correspond to a mid-cycle shutdown and a restart occurring 6 months, 3 months or 1 month before the end of the 9th cycle. The operating data (power, temperatures, concentrations of boron, lithium, oxygen and hydrogen) from the beginning of the reactor shutdown to the end of the reactor restart are represented in Figure 3. The reactor restarts after oxygenation, during the purification phase, when the primary activity is decreasing (Fig. 4).

Figures 5 and 6 illustrate the ^{58}Co activities deposited on the surfaces of the hot legs, the steam generators and the letdown lines during cycle 9 and 10. These figures compare the reference case to the cases with mid-cycle shutdown occurring 6 months and 1 month before the end of the 9th cycle. These figures also describe the cases of a restart when the ^{58}Co activity in the coolant reaches 0.7, 7 or 14 GBq/t.

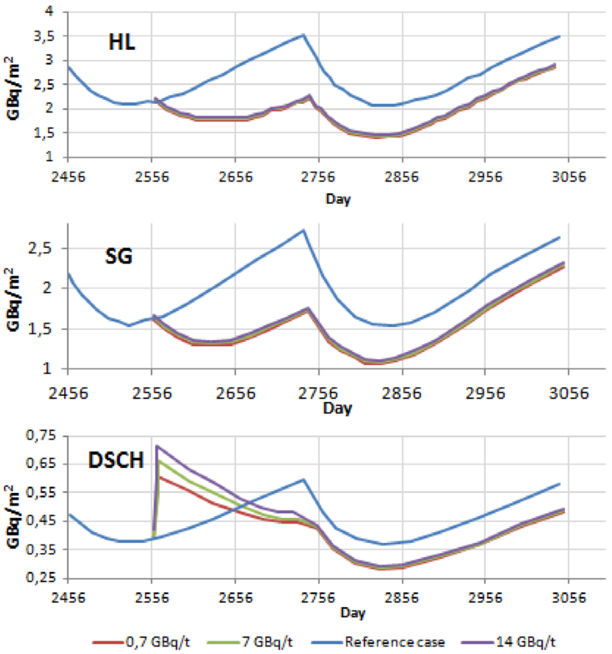

Fig. 5. ^{58}Co activities deposited on the hot legs (HL), the steam generators (SG) and the letdown lines (DSCH) in the case of a mid-cycle shutdown 6 months before the end of cycle.

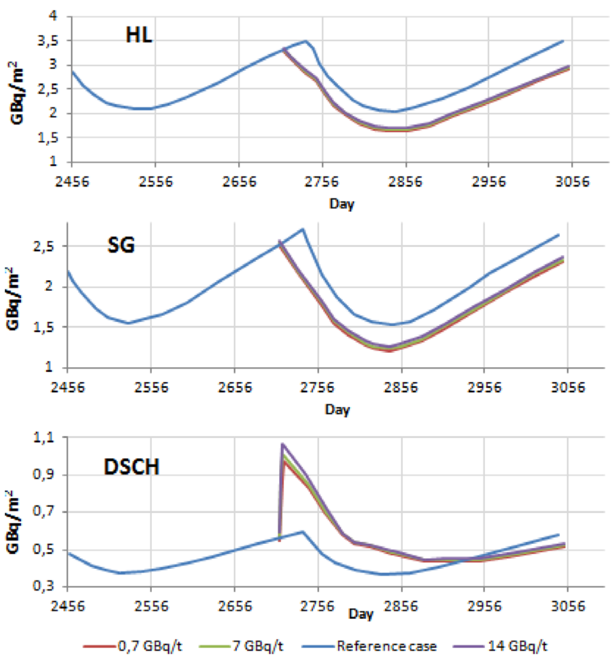

Fig. 6. ^{58}Co activities deposited on the hot legs (HL), the steam generators (SG) and the letdown lines (DSCH) in the case of a mid-cycle shutdown 1 month before the end of cycle.

The simulation results show that:

- the ^{58}Co activity in the primary coolant at reactor restart has no significant impact on the contamination of the main loop (legs and steam generators). The contamination of the main loop surfaces from the reactor restart to the end of the cycle remains lower than the reference case;
- for the letdown line, the ^{58}Co deposited activity increases at the reactor restart. The higher the ^{58}Co volume activity at the restart, the more significant the contamination. After the phase of the increase which occurs when the reactor restarts, the contamination of the letdown line decreases during the rest of the cycle. When the shutdown and the restart of the reactor occur 1 month before the end of the cycle, the contamination of the letdown line is notably higher than the reference case.

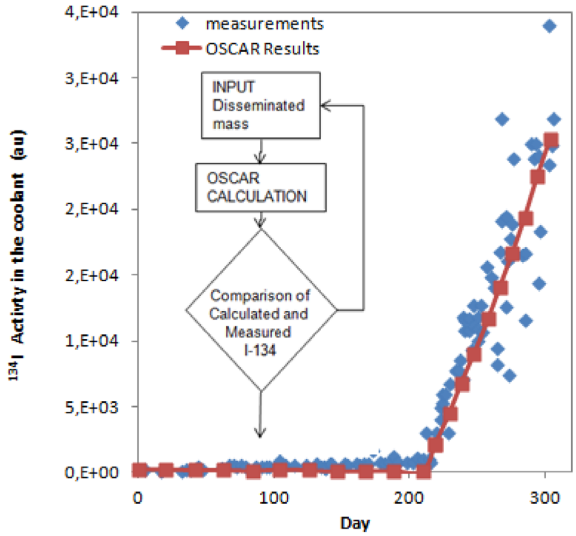

Fig. 7. Comparison of plant measurement and OSCAR calculation of ^{134}I variation in a case of fissile material dissemination.

In conclusion, this simulation has shown that the criterion concerning the ^{58}Co coolant activity at the reactor restart after a mid-cycle shutdown has no significant impact on the contamination of the main loop. This criterion could have an effect on the contamination of the letdown line especially when the shutdown and the restart of the reactor occur near the end of the cycle.

3.2 Second example: study of the connection between the quantity of disseminated fuel and the evolution of Iodine 134 in the primary coolant

In the case of fuel rod damage, the release of a small amount of fissile material can cause a serious risk of contamination of circuits by alpha emitters. Furthermore, actinides disseminated in the primary system essentially have a particulate behavior and they depose easily on the primary circuit surfaces [6]. The detection of actinides disseminated in the primary fluid is very difficult when the reactor is operating.

The solution is the indirect monitoring of the fissile material dissemination using the evolution of ^{134}I activity. ^{134}I is a product of the fission reactions which occur in the fissile material deposited under neutron flux. The OSCAR code allows us to calculate the activity of ^{134}I in the primary fluid which is generated by the release of a given quantity of fuel. Thus, in the case of an increase in ^{134}I activity

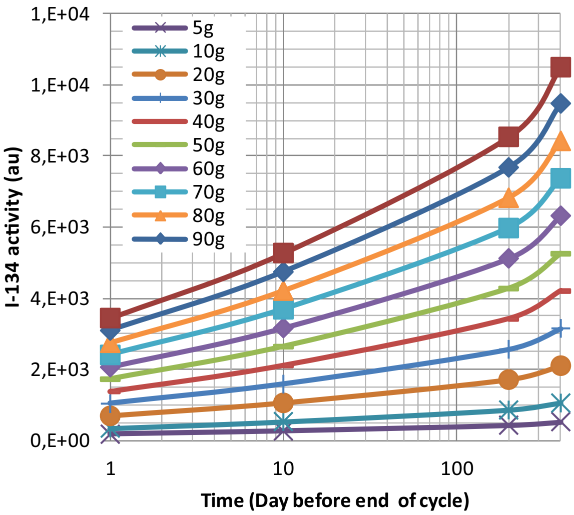

Fig. 8. Example of abacus developed using OSCAR code for the assessment of the quantity of disseminated fissile material in the case of fuel failure.

measured in the primary circuit, iterative calculations using the OSCAR code (Fig. 7) lead to the determination of the quantity of the released fissile material.

Thanks to the OSCAR code, we also managed to draw charts that may be easily used to estimate the amount of fuel disseminated in the PWR primary coolant in the case of fuel failure (Fig. 8). These charts aim at assessing the disseminated quantity by using the following criteria: (i) ^{134}I activity at the end of the cycle and (ii) the date of the ^{134}I increase.

4 Conclusions

OSCAR is a code that incorporates the French (CEA, EDF and Areva) scientific and industrial work focusing on the PWR circuit contamination phenomena. In addition to the loop experiments and the plant measurement campaigns, the use of a simulation tool such as OSCAR is also essential in predicting the contamination of the PWR circuits by corrosion products, fission products and actinides. Indeed, the two examples described above illustrate the usefulness of the OSCAR code in the study of PWR contamination for the improvement of PWR operating parameters, as well as the optimization of new plant design.

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