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## **EXPERIMENTAL STUDY OF PARTICLE DEPOSITION KINETICS IN THE PRIMARY CIRCUIT OF THE CIRENE LOOP AND COMPARISON WITH OSCAR V1.2 CODE SIMULATIONS**

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### **ABSTRACT**

Within the framework of corrosion product contamination in PWR, the understanding of mass transfers and particularly the understanding of particle transfers in the primary circuit is of great importance. It is for this reason that the CEA, in collaboration with EDF and AREVA NP, has launched a R&D program involving a specific experiment in the CIRENE out-of-pile loop. This program is focused on particle behaviour. The goal of this preliminary experiment is to estimate particle deposition kinetics in the primary circuit within controlled particle injections combined with in-line particle concentration measurements. This paper presents the experimental results of this new CIRENE test in terms of the kinetics of particle deposition and compares them with the particle deposition rate calculated by the OSCAR V1.2 contamination simulation code, implementing the Beal model. The test conditions, as the particle injection and in-line monitoring methodologies are presented as well.

The CIRENE out-of-pile loop, dedicated to the study of corrosion product transfers and deposits on core and steam generator tube surface areas, is a 27-liter mock-up of a PWR primary circuit. It is equipped with a Chemical Volume Control System which allows to settle a particle injection device and an in-line particle counting system for this test. The selected particles are zirconium (IV) oxide, iron (II, III) oxide and nickel in powder forms, and they have been chosen with different range of particle sizes from 0 to 5 µm. The Fe<sub>3</sub>O<sub>4</sub> and Ni powders are assumed to be chemically representative of the most relevant corrosion products encountered under solid form in the PWR primary fluid. The ZrO<sub>2</sub> powder has been chosen for its chemically inert behaviour in order to demonstrate the relevance of the injection device and of the particle counting methodology. In this experiment, the thermal-hydraulic parameters and chemical conditions are representative of a French PWR primary circuit operational conditions and series of short duration injections of the relevant fine powders have been carried out under permanent conditions with continuous in-line particle counting.

Experimental results of the CIRENE test have led to the main following conclusions:

- the first experimental results show the consistency and the reproducibility of the overall particle concentration measurements which enables to validate the particle counting methodology and the powder injection process;
- the time constant representative of the particle deposition kinetics deduced from the decrease over time of particle concentrations in the CIRENE primary circuit (an exponential law of the form  $C = C_0 e^{-\lambda t}$ ) is of the same order of magnitude for fine particles as the one obtained from the CIRENE test simulations with the OSCAR V1.2 code.

The particle deposition kinetics modelling implemented in the OSCAR V1.2 code---which is based on Beal model --- proved to be validated by this CIRENE experiment by taking into account adjustments against PWR feedback.



The thermal hydraulic conditions correspond to a single-phase flow regime along the core section and they are kept constant during the test.

The 27-liter primary circuit is equipped with a Chemical Volume Control System (CVCS) which allows to settle both the injection and particle counting system. The powder injection device is placed at the outlet of the CVCS, where the fluid temperature is approximately 20 °C and the pressure is 150 bar. The injection is performed based on a Dirac's pulse type injection of a predefined mass contained in a 300 cm<sup>3</sup> cylinder, the powder being carried by the CVCS flow via a set of valves. The particle counting system is placed at the inlet of the CVCS where the fluid temperature is approximately 20 °C and the pressure is 2 bar.

The total volume of the RCS is around 26 L, the relevant wet surfaces are around 4.8 m<sup>2</sup>.

## 2.2 Test operation

The thermal hydraulic and chemical data of this test are given in Table 1. The thermal hydraulic parameters which remain stable until the shutdown, lead to a  $R_e$  number (Reynolds number) of  $\sim 2E+05$  in the core and the SG tube sections with a relevant 5 200 L/h primary flow rate. The chemical conditioning of the primary water is representative of PWR operation.

Table 1: Thermal hydraulic parameters and chemical conditioning of the CIRENE test

Thermal hydraulic parameters	
Pressure	15 MPa (150 bar)
Primary flow rate	1.46E-03 m <sup>3</sup> /s (5 200 L/h)
Mass flow rate in the core section	2 640 kg/m <sup>2</sup> /s
Core section - inlet / outlet temperature	297°C / 320°C
- Re	1.8E+05
- fluid velocity	3.6 m/s
Primary fluid chemical conditioning	B = 100 mg/kg Li = 0.6 mg/kg pH <sub>300°C</sub> = 7.35 H <sub>2</sub> = 12-28 cm <sup>3</sup> /kg O <sub>2</sub> < 10 µg/kg

Figure 2 below provides the order of magnitude of the residence time in the RCS and CVCS circuits for flow rates set respectively at 5 200 and 6 L/h: note that the residence time of a particle, from the powder injection device up to the connection onto the RCS circuit is 216 s for a 0.3 L-cylinder with a CVCS flow rate set at 6 L/h. The CVCS flow rate may range between 5 and 9 L/h.

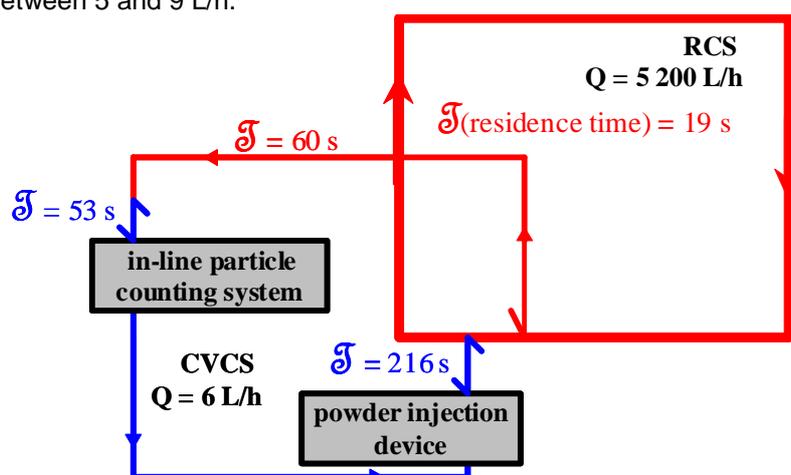


Figure 2: Residence times of a particle ( $\mathcal{T}$ ) expected along the CIRENE loop circuits

## 2.3 Particle injection sequences and particle counting

Particle injections were performed as follows:

- step 1 : injections of zirconia powder with a  $< 5 \mu\text{m}$ -particle size in order to validate the powder injection procedure;

- step 2 : injections of different powders as zirconia with a  $\leq 2 \mu\text{m}$ -particle size,  $\text{Fe}_3\text{O}_4$  with a  $< 1 \mu\text{m}$ -particle size and nickel with a  $< 3 \mu\text{m}$ -particle size.

Table 2 below provides the characteristics of the injected powders and the relevant injected masses, these masses being consistent with the expected saturation level of the particle counters, the characteristics of each injected powder (the density data) and the total RCS volume (25,7 L).

Table 2: Characteristics of the injected powders

Injected powders	Range of particle sizes	Purity	Density	Range of the injected masses
ZrO <sub>2</sub> Zirconia	$< 5 \mu\text{m}$	99,99%	6 g/cm <sup>3</sup>	180-360 mg
ZrO <sub>2</sub> Zirconia	$\leq 2 \mu\text{m}$	99%	6 g/cm <sup>3</sup>	80-190 mg
Fe <sub>3</sub> O <sub>4</sub>	$\leq 1 \mu\text{m}$	98%	4 g/cm <sup>3</sup>	10-40 mg
Nickel	$< 3 \mu\text{m}$	99,7%	9 g/cm <sup>3</sup>	190-380 mg

The primary fluid was subjected to particle counting of a 10 mL volume through laser sensor counters. Two different devices were involved for these continuous in-line measurements of the primary fluid:

- model #1 with a range of particle sizes from 1 to 200  $\mu\text{m}$  and for a maximum concentration which may reach 1 200 000 part/10 mL ;
- model #2 with a range of particle sizes from 0.5 to 20  $\mu\text{m}$  and a maximum particle concentration of 120 000 part/10 mL.

The in-line particle counting was carried out as close as possible to the start of the low temperature section of the CVCS so that any dissolution of particles caused by the decrease in temperature ( $\text{Fe}_3\text{O}_4$  powder for example) is limited by the time factor. The CVCS line maintained at 300°C does not involve any dissolution risk for the particles coming from the RCS reactor primary system, however, deposition may take place on the walls due to the laminar flow ( $R_e \sim 450$ ).

### 3 – EXPERIMENTAL RESULTS

#### 3.1 The in-line particle concentration measurements

A typical histogram given by the particle counter and related to a zirconia injection is presented in Figure 3 below: the histogram provides the number of particles countered in a 10 mL -primary fluid volume over time, for a specific range of particle size.

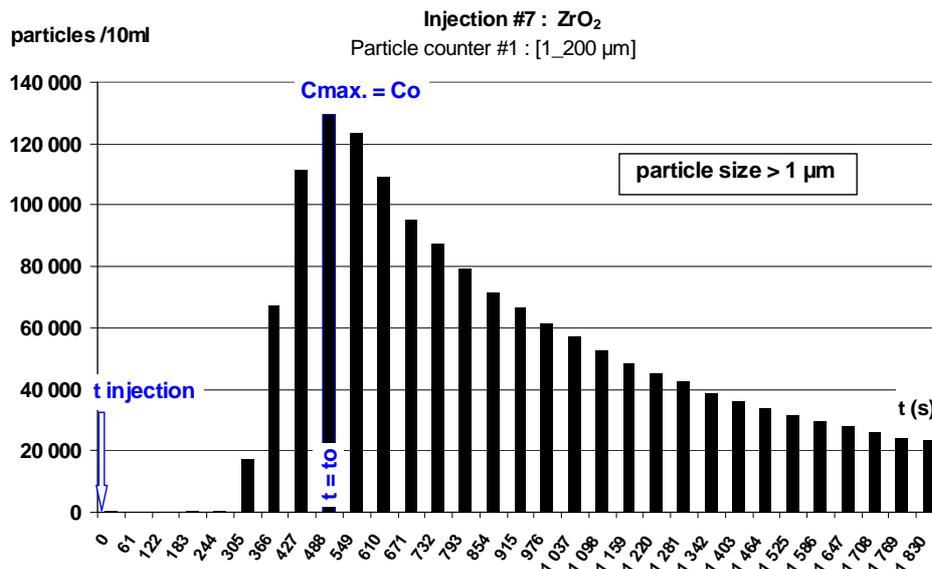


Figure 3: Typical histogram  $C = f(t)$  provided by the particle counter settled on the CIRENE CVCS - Zirconia injection #7

These histograms based on  $C = f(t)$ , provide access to the particle deposition kinetics within the RCS of the CIRENE loop according to the following approach:

- a) the hypothesis is, once the maximum particle concentration  $C_0$  has been reached, that the only flux responsible for the change in particle concentration is the deposition sink term on the wall surfaces of the CIRENE circuits. The erosion flux, which is one of the fluxes taken into account in the global deposition profile measurement, is considered here to be negligible compared to the deposition flux in the time period following the injections;
- b) we then have an equation of type  $C = C_0 \cdot e^{-\lambda t}$ , where  $\lambda$  is the time constant associated with the studied experimental deposition speed ;
- c) we determine the time constant  $\lambda$  as follows:
  - after subtracting the background measurement, the curves are plotted in relation to  $t_0$  ( $t_0$  corresponding to the particle concentration peak  $C_0 = C_{max}$ ) and studied over a time period during which the deposition regime is constant, i.e. globally on  $\Delta t = 800$  s for zirconia injections;
  - each curve is then treated as an “exponential trend curve” from which the term  $\lambda_{CIRENE}$  is identified as  $C = C_0 \cdot e^{-\lambda_{CIRENE} t}$  ( $\lambda$  is expressed as  $s^{-1}$ ).

As an example, Figure 4 hereafter presents exponential trend curves relative to zirconia injection #4 for two specific particle range measurements,  $[0.7\_1 \mu m]$  and  $[1\_2 \mu m]$ .

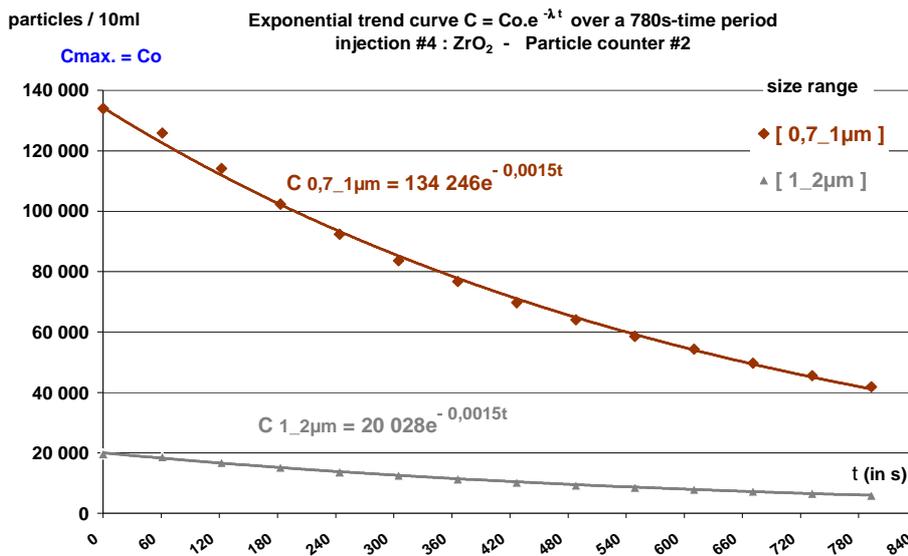


Figure 4: Determination of the time constant  $\lambda_{CIRENE}$  through exponential trend curves  $C = C_0 \cdot e^{-\lambda t}$  for two particle size channels - Zirconia injection #4

The experimental term  $\lambda_{CIRENE}$  will be compared with the time constant  $\lambda_{OSCAR}$  associated with the deposition kinetics modelled in the OSCAR code and calculated in the case of the CIRENE primary circuit for a given particle size distribution. This comparative study is presented in chapter 4.

### 3.2 Experimental results

#### Preliminary test - step 1

The first injections and particles counting have led to the following points:

- the background level in particle concentration of the primary fluid gives a population ranging for the most part between 0.5 and 1  $\mu m$ , with a total value of 24 000 part/10 mL in the  $[0,5\_20 \mu m]$  measurement range. Thus, the measurement ranges  $[0.7\_20\mu m]$  and  $[1\_20\mu m]$  were selected for the following injections to correctly carry out the in-line monitoring during the powder injection sequences;
- the injections conducted with “chemically inert” zirconia powders made it possible to validate the powder injection procedure and to check the consistency of the in-line measurements results by particles counting;

- due to the consistency and the good reproducibility of the step 1 results, injection sequences of powders of various natures and with various particle sizes can be carried out.

### Experimental results – step 1 and step 2

#### ➤ ZrO<sub>2</sub> powder injections

Table 3 below shows the time constant  $\lambda_{\text{CIRENE}}$  relative to injection #7 to injection #12, for the two available zirconia powders (theoretical particle size  $< 5 \mu\text{m}$  and  $\leq 2 \mu\text{m}$ ). The study is conducted for various particle size ranges over the relevant 4 time periods after the maximum particle concentration peak. The size of the measured particles is then within the range [1\_20  $\mu\text{m}$ ].

Table 3: Experimental time constants -  $\lambda_{\text{CIRENE}}$  - deduced from zirconia powder injections

injection # injected powder : ZrO <sub>2</sub>		inj_7 ZrO <sub>2</sub> $< 5 \mu\text{m}$	inj_8 ZrO <sub>2</sub> $< 5 \mu\text{m}$	inj_9 ZrO <sub>2</sub> $\leq 2 \mu\text{m}$	inj_12 ZrO <sub>2</sub> $\leq 2 \mu\text{m}$
$\lambda$ (s-1)	part $> 1\mu\text{m}$	14-15E-04	17E-04	18E-04	16E-04
1rst period (0-800 s)	1 $<$ part $<$ 1.5 $\mu\text{m}$	15E-04	17E-04	19E-04	16E-04
	3 $<$ part $<$ 4 $\mu\text{m}$	12E-04	17E-04	16E-04	15E-04
$\lambda$ (s-1)	part $> 1\mu\text{m}$	11E-04	11E-04	10E-04	9E-04
2d period (800-1 600 s)	1 $\mu\text{m}$ $<$ part $<$ 1.5 $\mu\text{m}$	11E-04	11E-04	10E-04	9E-04
	3 $\mu\text{m}$ $<$ part $<$ 4 $\mu\text{m}$	8E-04	11E-04	10E-04	8E-04
$\lambda$ (s-1)	part $> 1\mu\text{m}$	7E-04	7E-04	7E-04	6E-04
3rd period (1 600-2 400s)	1 $\mu\text{m}$ $<$ part $<$ 1.5 $\mu\text{m}$	7E-04	7E-04	7E-04	6E-04
	3 $\mu\text{m}$ $<$ part $<$ 4 $\mu\text{m}$	6E-04	7E-04	7E-04	7E-04
$\lambda$ (s-1)	part $> 1\mu\text{m}$	4E-04	5E-04	6E-04	5E-04
4th period (2 400-3 200s)	1 $\mu\text{m}$ $<$ part $<$ 1.5 $\mu\text{m}$	5E-04	6E-04	6E-04	4E-04
	3 $\mu\text{m}$ $<$ part $<$ 4 $\mu\text{m}$		6E-04	7E-04	5E-04
in-line particle counter #1 [1_200 $\mu\text{m}$ ] Cmax. = 1 200 000 part/10ml					

The following points can be noted:

- $\lambda_{\text{CIRENE}}$  constant measured close to the concentration peak is in the order of 15 to 19E-04 s<sup>-1</sup> for the finest particles ( $< 1.5 \mu\text{m}$ );
- as the two injected zirconia powders show relatively similar particle size distributions, with an actual averaged particle size around  $\leq 1.5 \mu\text{m}$ , the measurements did not show any discrepancy which may be related to a particle size difference;
- for a same time period, the deposition constant shows very little variation within the studied particle size range;
- the deposition constant decreases to a value close to 4 to 6E-04 s<sup>-1</sup> in the fourth time period of the study (from 2 400 to 3 200 s), we may suppose that the contribution of the erosion flux becomes more significant in such period.

Experimental time constants deduced from similar series of zirconia injections within a [0.7\_20  $\mu\text{m}$ ] particle measurement range have led to similar values of  $\lambda_{\text{CIRENE}}$  close to the concentration peak, with 15 to 18E-04 s<sup>-1</sup> for particles  $< 2 \mu\text{m}$ ; as for the previous zirconia injections, the  $\lambda_{\text{CIRENE}}$  constant does not appear to be sensitive to the particle size in the range of the study.

#### ➤ Fe<sub>3</sub>O<sub>4</sub> injections

Table 4 shows the  $\lambda_{\text{CIRENE}}$  values determined from the injections #21 to #23. The study is carried out over 4 time periods. The size of particles measured is within the range [1\_20  $\mu\text{m}$ ].

Table 4: Experimental time constant  $\lambda_{\text{CIRENE}}$  deduced from  $\text{Fe}_3\text{O}_4$  powder injections

injection # (injected mass) injected powder : $\text{Fe}_3\text{O}_4 < 1\mu\text{m}$		inj_21 (m)	inj_22 (m)	inj_23 (m x 4)
$\lambda$ (s-1) 1 <sup>st</sup> period (0-800 s)	part > $1\mu\text{m}$	18E-04	18E-04	33-34E-04
	1 < part < $1.5\mu\text{m}$	19E-04	21E-04	34E-04
	$1.5\mu\text{m}$ < part < $2\mu\text{m}$	11E-04	13E-04	27E-04
	2 < part < $3\mu\text{m}$	10E-04	11E-04	21E-04
	3 < part < $4\mu\text{m}$	9E-04	12E-04	19E-04
$\lambda$ (s-1) 2 <sup>d</sup> period (800-1 600 s)	part > $1\mu\text{m}$	7E-04	8E-04	8-9E-04
	$1\mu\text{m}$ < part < $2\mu\text{m}$	7E-04		10E-04
	$2\mu\text{m}$ < part < $3\mu\text{m}$	7E-04		9E-04
	$3\mu\text{m}$ < part < $4\mu\text{m}$	8E-04		9E-04
$\lambda$ (s-1) 3 <sup>rd</sup> period (1 600-2 400 s)	part > $1\mu\text{m}$	6E-04	2E-04	6E-04
	$1\mu\text{m}$ < part < $2\mu\text{m}$	6-7E-04		5-6E-04
	$2\mu\text{m}$ < part < $3\mu\text{m}$	6E-04		7E-04
	$3\mu\text{m}$ < part < $4\mu\text{m}$	7E-04		5E-04
$\lambda$ (s-1) 4 <sup>th</sup> period (2 400-4 200s)	part > $1\mu\text{m}$	2E-04	3E-04	3E-04
	$1\mu\text{m}$ < part < $2\mu\text{m}$	2E-04		
	$2\mu\text{m}$ < part < $3\mu\text{m}$	1E-04		
	$3\mu\text{m}$ < part < $4\mu\text{m}$	1E-04		
in-line particle counter #1 [1_200 $\mu\text{m}$ ] Cmax. = 1 200 000 part/10ml				

The following points can be noted:

- we obtained a certain reproducibility for the injections #21 and #22 carried out in the same conditions, with a constant  $\lambda_{\text{CIRENE}}$  measured close to the concentration peak in the order of 18 to 21E-04 s<sup>-1</sup> for the finest particles (<1.5  $\mu\text{m}$ ). Particles with a size > 1.5  $\mu\text{m}$  follow slower deposition kinetics, with a  $\lambda_{\text{CIRENE}}$  of approximately 9 to 13E-04 s<sup>-1</sup>. We observe deposition kinetics similar to the kinetics of the zirconia powders in the 3<sup>rd</sup> time period;
- the deposition constant given by the injection # 23 (injected mass x 4) is much higher, with a value of 34E-04 s<sup>-1</sup> measured close to the concentration peak for the finest particles (< 1.5  $\mu\text{m}$ ). We observe slower deposition kinetics for larger particles, with for example  $\lambda_{\text{CIRENE}} = 19\text{E-}04 \text{ s}^{-1}$  for the particle size range from 3 to 4  $\mu\text{m}$ . We again find deposition kinetics comparable to the kinetics of injections #21 and #22 from the 2<sup>nd</sup> time period.

#### ➤ Ni injections

Table 5 shows the values of  $\lambda_{\text{CIRENE}}$  determined from injections #25 and #26 of Ni powder. The study is carried out over 4 time periods of ~ 800 s each. The measured particle size is within the range [1\_20  $\mu\text{m}$ ].

The following points can be noted:

- the  $\lambda_{\text{CIRENE}}$  constant measured close to the concentration peak reaches 16E-04 s<sup>-1</sup> for particles with a size < 2  $\mu\text{m}$ . These particles account for ~ 92% of the total nickel powder population;
- for the first 2 time periods, the constant  $\lambda_{\text{CIRENE}}$  seems to increase with the particle size, a trend contrary to the one observed for the  $\text{Fe}_3\text{O}_4$  powder: we obtain a higher deposition constant  $\lambda_{\text{CIRENE}}$  for particles of a size between 3 and 4  $\mu\text{m}$ , with for example,  $\lambda_{\text{CIRENE}} = 32.5\text{E-}04 \text{ s}^{-1}$  in the 2<sup>nd</sup> time period of the injection #26;
- from the 3<sup>rd</sup> time period, the deposition kinetics greatly decreases.

Table 5: Experimental time constant  $\lambda_{\text{CIRENE}}$  deduced from Ni powder injections

injection # (injected mass) injected powder : Ni < 3 $\mu\text{m}$		inj_25 (m)	inj_26 (m x 2)
$\lambda$ (s-1)	part>1 $\mu\text{m}$	15.5E-04	16.5E-04
1rst period (0-800 s)	1 $\mu\text{m}$ <par <1.5 $\mu\text{m}$	16.5E-04	
	1 $\mu\text{m}$ <part<2 $\mu\text{m}$	15.5E-04	16.5E-04
	2 $\mu\text{m}$ <part<3 $\mu\text{m}$	15.5E-04	20E-04
	3 $\mu\text{m}$ <part<4 $\mu\text{m}$	17.5E-04	23E-04
$\lambda$ (s-1)	part>1 $\mu\text{m}$	12.5E-04	12.5E-04
	1 $\mu\text{m}$ <part<1.5 $\mu\text{m}$	11.5E-04	
	1 $\mu\text{m}$ <part<2 $\mu\text{m}$	14.5E-04	11.5E-04
	2 $\mu\text{m}$ <part<3 $\mu\text{m}$	18E-04	22.5E-04
	3 $\mu\text{m}$ <part<4 $\mu\text{m}$	24.5E-04	32.5E-04
$\lambda$ (s-1)	part>1 $\mu\text{m}$	3.5E-04	10E-04
	3rd period (1 600-2 400 s) 1 $\mu\text{m}$ <part<1.5 $\mu\text{m}$	2.5E-04	
in-line particle counter #1 [1_200 $\mu\text{m}$ ] Cmax. = 1 200 000 part/10ml			

### 3.3 Summary status

The injections of the various powders led to similar deposition constant values for particle size ranging from 0.7 to 2  $\mu\text{m}$ , with  $\lambda_{\text{CIRENE}} = 15$  to  $18\text{E-}04 \text{ s}^{-1}$  measured after the concentration peak. This status allows to define a reference experimental constant  $\lambda_{\text{CIRENE reference}}$  for the following study with numerical simulations.

## 4. OSCAR V1.2 SIMULATIONS OF THE CIRENE TEST

### 4.1 Modelling of the CIRENE loop [5]

The schematization describes the RCS with 22 relevant control volumes and the CVCS with low temperature ( $T = 20^\circ\text{C}$ ) and low pressure ( $P = 2 \text{ bar}$ ) with 2 control volumes simulating the powder injection sequences as follows: creation of two control volumes (0.3 L each) corresponding respectively to an iron and a nickel external injection source in particle form.

Injections in the primary coolant occur at the control volume located just upstream from the core section. In this schematization, the volume of the RCS is 25.7 L and the total volume of the CVCS is 1.3 L.

### 4.2 Input data files

The reference input data file --- reference IDF --- integrates the thermo-hydraulic and chemical conditions of the CIRENE test with one iron injection and one nickel injection in particle forms. The zirconia injections are not simulated. The particle injections correspond exactly to the conditions of the injection #22 of  $\text{Fe}_3\text{O}_4$  powder and of the injection #25 of Ni powder, with the relevant injected masses of 10 and 190 mg.

The other data taken into account concern the particle size distribution data: the deposition speed given by the OSCAR calculation depends, inter alia, on the particle size distribution. Such distribution is represented according to a normal log law, with

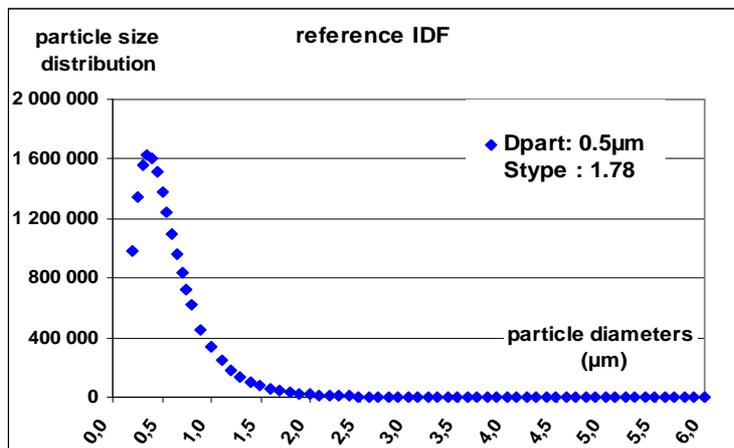
- "Stype": geometric standard deviation of the particle size distribution
- "NZone": number of particle size ranges describing the normal log law distribution
- "ZonePitch": pitch of the particle size ranges
- "Dpart": mean geometric diameter.

The specifications of the reference IDF CIRENE test are summarized in Table 6 hereafter, with "DensPart" corresponding to particle density. The calculation stops at  $t = 14.75$  day-operation and does not include any shutdown phase. The particle size distribution profile corresponding to this reference IDF is presented as well.

Table 6: Reference OSCAR IDF of the CIRENE test with the relevant particle size distribution data

IDF CIRENE test simulations	
at 14.75 operation days B = 100 mg/kg Li = 0.6 m g/kg H <sub>2</sub> = 26 cm <sup>3</sup> /kg	
Fe <sub>part</sub> source at 12.75 days : 4.23E-05 g/s during 260 s (inj#22)	
Ni <sub>part</sub> source at 13.75 days : 0.73E-03 g/s during 260 s (inj#25)	

reference IDF	Dpart = 0.5 μm
particle	Nzone = 100
size	ZonePitch = 600 Å
distribution	Stype = 1.78
data	DensPart = 4 000 kg/m <sup>3</sup>



**4.3 Simulation results studies**

The interpretation of the simulation results concerns the following data:

- the time constant of the deposition kinetics  $\lambda_{BEAL}$  (in s<sup>-1</sup>), based on BEAL model [3] and calculated for the CIRENE primary circuit for a given particle size distribution. The deposition model implemented in OSCAR is the Beal model with a correction factor ---coef\_Deposition Speed---applied to the deposition speed which was calibrated against the PWR feedback at 10<sup>-1</sup> to reproduce, at best, the particle concentration levels observed in the primary fluid in operation [6]. The time constant of OSCAR deposition kinetics  $\lambda_{OSCAR}$  is also regarded and  $\lambda_{OSCAR} = \lambda_{BEAL} \times 10^{-1}$ . These two calculated time constants can be compared with the experimental time constant  $\lambda_{CIRENE}$ , over a time period following the injection.
- the fluxes of the various mechanisms involved and competing in the global deposition process, these fluxes being calculated over the complete CIRENE primary circuit. The characteristics of the OSCAR calculated decrease in iron or nickel masses in particulate form in the CIRENE primary circuit after the powder injection, are also studied.

**5. COMPARISON BETWEEN EXPERIMENTAL RESULTS AND OSCAR V1.2 SIMULATIONS**

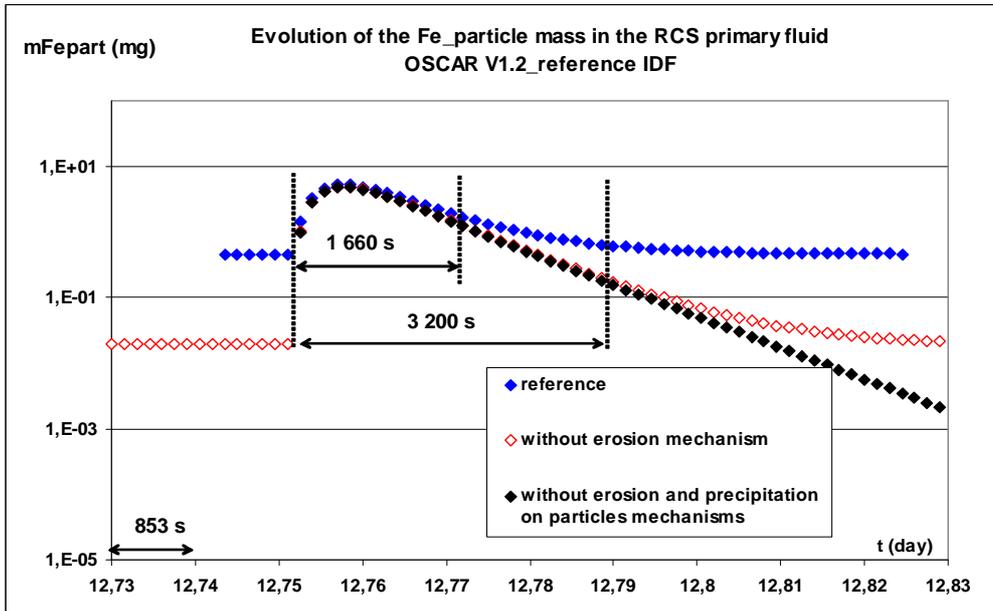
**5.1 OSCAR simulation with reference IDF**

- $\lambda_{OSCAR}$  via calculated “Deposition Speed” and coef\_Depo Speed =10<sup>-1</sup>:
  - related to the CIRENE primary circuit (22 control volumes), the calculated deposition constant  $\lambda_{OSCAR}$  equals 18E-04 s<sup>-1</sup>;
  - $\lambda_{OSCAR}$  is of the same order of magnitude as the experimental time constants  $\lambda_{CIRENE}$  resulting from the first time period for smaller particles  $\leq 1.5\mu\text{m}$ . This result is consistent regarding the mean geometric diameter of the particles of the reference IDF, i.e. 0.5 μm.
- particle masses in the RCS fluid

The decrease in iron or nickel particle masses in the primary circuit given for the reference IDF is compared with a calculation done, firstly, by disabling the erosion mechanism, and secondly, by disabling the erosion and precipitation on particles mechanisms (the calculated particle concentration refers among others to these fluxes):

- Figure 5 below shows that the deposition process of the iron particles is only disturbed by the erosion flux and the precipitation on particles flux after 1 660 s after the concentration peak and after 3 200 s if we only take into account, as other fluxes, the precipitation flux on particles;
- the deposition process of the nickel particles is only disturbed by the erosion and precipitation on particles fluxes after a much longer time, i.e. 4 260 s after the concentration peak.

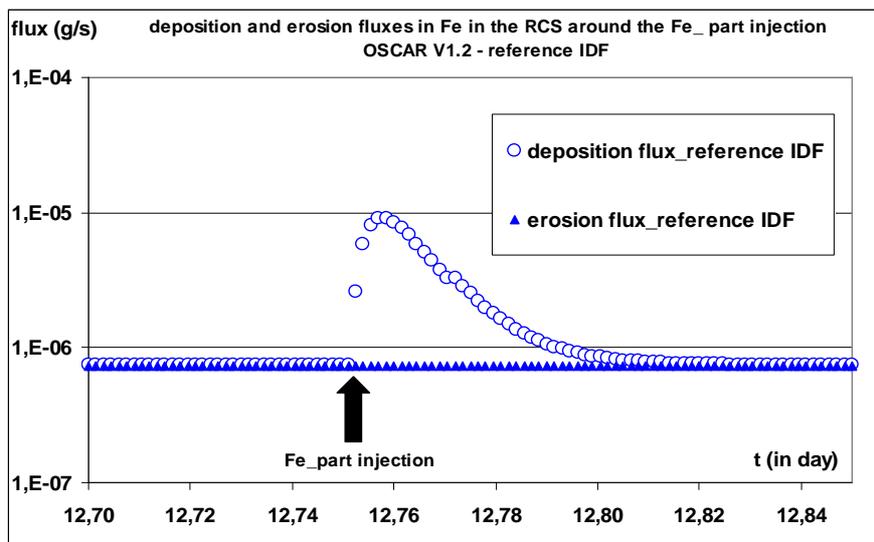
Figure 5: Fe mass in the RCS fluid calculated around the Fe particle injection with different disabled mechanisms (erosion mechanism and precipitation on particles mechanism)



Flux studies :

Figure 6 below relates to the deposition and erosion fluxes given by the calculation for the complete primary circuit around the Fe particle injection sequence: this figure shows that the particle counting methodology proposed in § 3.1 that “once the maximum particle concentration  $C_0$  has been reached, the only flux responsible for the change in particle concentration is the deposition sink term on the surfaces of the reactor primary system” is verified around the concentration peak for the reference calculation. This is also true for the nickel element, for which the calculation gives a deposition/erosion fluxes ratio close to 1 000 at the particle concentration peak.

Figure 6: erosion and deposition Fe fluxes intensities calculated around the injection at 12.75 days



All these first simulation results justify directly comparing the theoretical deposition constant  $\lambda_{OSCAR}$  with the experimental constant  $\lambda_{CIRENE}$  in the period following the particle concentration peak.

5.2 OSCAR simulations with various “Dpart” and “Denspart”

For the following simulations, the input data “DensPart” and “Dpart” of the reference IDF were modified to identify their impact on the  $\lambda_{OSCAR}$  value given by the calculation. The values selected for “DensPart” are representative of the density of the different powders (see Table 2). The standard deviation “Stype” remains set at 1.78.

Table 7 can be used to compare the results obtained for all these calculations and shows the following points:

- the mean diameter of particles "Dpart" has a strong impact on the value of  $\lambda_{OSCAR}$ : for a density of 4 g/cm<sup>3</sup> the deposition constant  $\lambda_{OSCAR}$  increases fivefold when "Dpart" changes from 0.5 to 2  $\mu\text{m}$ ;
- for particles with a mean diameter  $\leq 1\mu\text{m}$ , the deposition constant  $\lambda_{OSCAR}$  noticeably increases with the increase from 4 to 9 g/cm<sup>3</sup> in particle density, which is no longer the case for a population of particles with a mean diameter  $\geq 1.5\mu\text{m}$ .

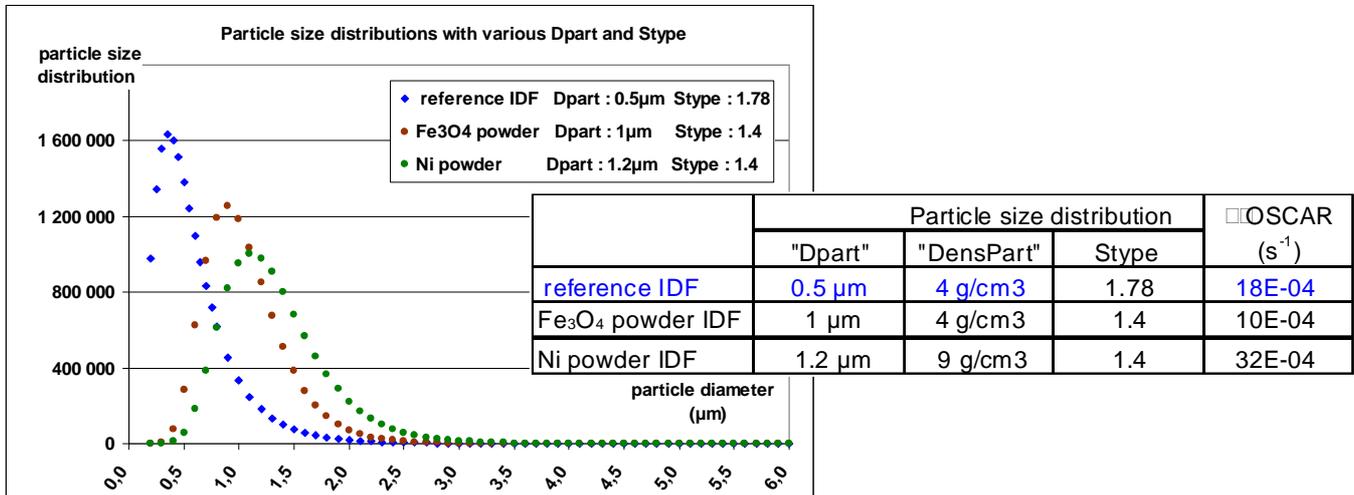
Table 7: Density and Mean geometric diameter impacts on the  $\lambda_{OSCAR}$  value - OSCAR V1.2 simulations

Particle characteristics		calculated deposition time constant $\lambda_{OSCAR}$ (s <sup>-1</sup> )			
		Mean geometric diameter "Dpart"			
reference IDF		0.5 $\mu\text{m}$	1 $\mu\text{m}$	1.5 $\mu\text{m}$	2 $\mu\text{m}$
Density	4 g/cm <sup>3</sup>	18E-04	56E-04	83E-04	100E-04
"DensPart"	6 g/cm <sup>3</sup>	22E-04	62E-04	85E-04	
	9 g/cm <sup>3</sup>	27E-04	65E-04	79E-04	74E-04

### 5.3 OSCAR simulations with the relevant powder characteristics

The density "DensPart" and the particle size distribution via the parameters "Dpart" and "Stype" of the relevant nickel and Fe<sub>3</sub>O<sub>4</sub> powders injected were taken into account for the next calculations. Both parameters, "Dpart" and "Stype", were deduced from the study of the particle size histograms obtained by the in-line counting during injection # 25 of nickel powder and injections #21 and #23 of Fe<sub>3</sub>O<sub>4</sub> powder. The time constants  $\lambda_{OSCAR}$  obtained according to these new IDF are presented in Table 8. The particle distribution profiles thus defined are plotted and compared to the reference profile as well.

Table 8: OSCAR V1.2 simulations with injected powder-IDF and relevant particle size distributions



The following points may be noted:

- $\lambda_{Ni} > \lambda_{CIRENE\ reference}$  : the time constant calculated for the nickel powder is the highest, with 32E-04 s<sup>-1</sup>, which corresponds among others to the increasing in the particle mean diameter and in the particle density in the IDF. The experimental measurement gives a similar constant for a range of larger particles, between 3 and 4  $\mu\text{m}$  (see Table 5);
- $\lambda_{Fe3O4} < \lambda_{CIRENE\ reference}$  : the time constant calculated for the Fe<sub>3</sub>O<sub>4</sub> powder, i.e. 10E-04 s<sup>-1</sup>, is similar to the experimental constant obtained with larger particles, at least equal to 1.5  $\mu\text{m}$  (see Table 4);

### 5.4 OSCAR simulations with various ranges of particle sizes

The following study concerns the variation of the  $\lambda_{OSCAR}$  time constant with specific particle size ranges which are defined reducing "Stype" and considering different "Dpart" of the particle size distributions. Figure 7 below provides

the various size distributions thus defined: size range [1\_1.5  $\mu\text{m}$ ] for the study of the  $\text{Fe}_3\text{O}_4$  powder, [1\_2  $\mu\text{m}$ ] for the study of the Ni powder, [2\_3  $\mu\text{m}$ ] and [3\_4  $\mu\text{m}$ ] for all the powders. The experimental study undertaken for a 0-800 s time-period covers these same size ranges. The  $\lambda_{\text{CIRENE}} / \lambda_{\text{OSCAR}}$  comparisons are reported in Table 9 hereafter.

Figure 7: particle size distributions of OSCAR IDF for the particle size range study

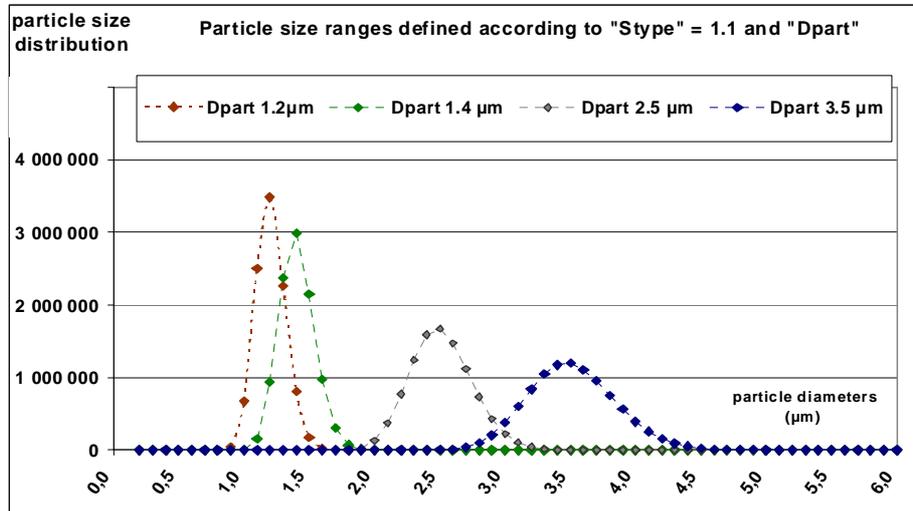


Table 9: calculated  $\lambda_{\text{OSCAR}}$  and experimental  $\lambda_{\text{CIRENE}}$  time constants according to particle size ranges

	"Dpart" OSCAR simulations (Style : 1.1)					"Dpart" OSCAR simulations (Style : 1.1)			
<b>Ni powder</b>	0.5 $\mu\text{m}^*$	1.4 $\mu\text{m}$	2.5 $\mu\text{m}$	3.5 $\mu\text{m}$	<b><math>\text{Fe}_3\text{O}_4</math> powder</b>	0.5 $\mu\text{m}^*$	1.2 $\mu\text{m}$	2.5 $\mu\text{m}$	3.5 $\mu\text{m}$
$\lambda_{\text{OSCAR}}$ (s-1)	18E-04	9E-04	94E-04	120E-04	$\lambda_{\text{OSCAR}}$ (s-1)	18E-04	5E-04	37E-04	110E-04
0 - 800 s	particle size range experimental measurements				0 - 800 s	particle size range experimental measurements			
	> 1 $\mu\text{m}$	1_2 $\mu\text{m}$	2_3 $\mu\text{m}$	3_4 $\mu\text{m}$		> 1 $\mu\text{m}$	1_1.5 $\mu\text{m}$	2_3 $\mu\text{m}$	3_4 $\mu\text{m}$
$\lambda_{\text{CIRENE}}$ inj_26	17E-04	17E-04	20E-04	23E-04	$\lambda_{\text{CIRENE}}$ inj_21	18E-04	19E-04	10E-04	9E-04
(s-1) inj_25	16E-04	16E-04	16E-04	18E-04	(s-1) inj_22	20E-04	21E-04	11E-04	12E-04
					inj_23	34E-04	34E-04	21E-04	19E-04
*reference IDF : Style = 1.78									

Concerning the Ni powder,  $\lambda_{\text{CIRENE}}$  follows the increase observed for  $\lambda_{\text{OSCAR}}$  but to a much lesser extent since  $\lambda_{\text{CIRENE}}$  increases at the most by a factor 1.4 while  $\lambda_{\text{OSCAR}}$  increases by a factor 13 within the enhance of the particle size range.

Out of the three  $\text{Fe}_3\text{O}_4$  powder injections studied,  $\lambda_{\text{CIRENE}}$  does not follow the evolution given by the calculation:  $\lambda_{\text{CIRENE}}$  remains quite stable and even decreases with the increase in the particle size range, while  $\lambda_{\text{OSCAR}}$  increases by a factor 22.

## 6. CONCLUSIONS

A new experiment concerning particle deposition kinetics in a PWR primary circuit has been undertaken in the CIRENE out-of-pile loop. This test involved controlled particle injections combined with in-line particle concentration measurements. This paper presents the experimental results in terms of global particle deposition kinetics and compares them with the particle deposition rate calculated by the OSCAR V1.2 contamination simulation code, implementing the Beal model and an adjustment against PWR feedback.

The CIRENE out-of pile loop is a 27-liter mock-up of a PWR primary circuit. It is equipped with a Chemical Volume Control System through which a particle injection device and an in-line particle counting system have been implemented for this test. The injected particles are zirconium (IV) oxide, iron (II, III) oxide and nickel in powder forms, and they have been chosen with different range of particle sizes from 0 to 5  $\mu\text{m}$ .

### Deposition time constant measurements

- $\text{ZrO}_2$  powder injections: these series of injections lead to reproducible results giving a  $\lambda_{\text{CIRENE}}$  constant close to the concentration peak in the order of 15 to 18E-04  $\text{s}^{-1}$  for particle sizes ranging from 0.7 and 2  $\mu\text{m}$ . For a same time period, the deposition constants do not change with the particle size ranges.
- $\text{Fe}_3\text{O}_4$  and Ni powder injections:

- a series of Fe<sub>3</sub>O<sub>4</sub> powder injections leads to reproducible results giving a constant  $\lambda_{\text{CIRENE}}$  close to the concentration peak in the order of 18 to 21E-04 s<sup>-1</sup> for the finest particles with a size ranging from 1 and 1.5  $\mu\text{m}$ ;
- the Ni powder injections give a relevant  $\lambda_{\text{CIRENE}}$  value in the order of 16E-04 s<sup>-1</sup> for particles size ranging from 1 and 2  $\mu\text{m}$ ;
- some dependency of the  $\lambda_{\text{CIRENE}}$  deposition constant on the size of particles is observed in the 1<sup>st</sup> time period, but with opposite trends for the two powders : thus, we observe an upward trend in  $\lambda_{\text{CIRENE\_Ni}}$  and on the contrary a downward trend in  $\lambda_{\text{CIRENE\_Fe3O4}}$  when the particle size increases.

### Comparison between experimental results and OSCAR V1.2 simulations

- Simulations with the reference-Input data file (IDF): a good agreement between the OSCAR calculated deposition kinetics and the experimental kinetics  $\lambda_{\text{CIRENE\_reference}}$  is obtained considering a population of fine particles (0.7-1.5  $\mu\text{m}$ ) in a 0-800 s time period following the concentration peak. Furthermore this first simulation points out that, as for the PWR simulations, the kinetics constant  $\lambda_{\text{BEAL}}$  (in s<sup>-1</sup>) deduced from the calculated "Deposition Speed" values must be lowered applying a 10<sup>-1</sup> correction factor.
- Simulations with the relevant powder characteristics-IDF: the deposition constants given by the calculation remain on the whole in the same order of magnitude as the constants given by the experiment. However, we note a better agreement between calculations and experiment results for the larger experimental particle size ranges;
- Simulations with various ranges of particle sizes-IDF: OSCAR simulations point out that  $\lambda_{\text{OSCAR}}$  increases from a factor 13 for Ni powder, to a factor 22 for Fe<sub>3</sub>O<sub>4</sub> powder while the particle size range enhances. No experimental dependency of the deposition kinetics with the particle size range emerges as strong as in the calculation. The best correspondence between calculations and experiment results is obtained for the [1-1.5  $\mu\text{m}$ ] range for the nickel injection and for the [1-2  $\mu\text{m}$ ] range for the iron injection;
- The calculated fluxes study indicates that the deposition process of the injected particles is only disturbed by the erosion and precipitation fluxes on particles after 1 660 s after the concentration peak for iron particles, and after a relevant much longer time of 4 260 s for the nickel particles. All these results justify studying the experimental time constant  $\lambda_{\text{CIRENE}}$  in the time period following the particle concentration peak.

The particle deposition kinetics modelling implemented in the OSCAR V1.2 code--which is based on Beal model --proved to be validated by this CIRENE experiment by taking into account adjustments against PWR feedback.

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