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Assessment of Activated Corrosion Products for the DEMO WCLL

Luigi Di Pace[a], Lina Quintieri[b],

ENEA Fusion and Technology for Nuclear Safety and Security Department,
[a]CR Frascati, Via Enrico Fermi 45, 00044 Frascati (Roma), Italy
[b]CR Casaccia, Via Anguillarese 301, 00123 S. Maria di Galeria (Roma), Italy

This paper presents the assessment of the activated corrosion products (ACPs) for the First Wall loop of the DEMO Water Cooled Lithium Lead reactor. The aim was devoted to scan some operating parameters, not yet frozen, which eventually proved to be very important, such as coolant temperatures during plasma dwell, material for the Steam Generator piping, or more in general to demonstrate the need to be adherent in the ACPs assessment to the real operative conditions. The Pulsed Scenario, simulating more closely the operation of the cooling system, has provided lower ACPs inventories in terms of mass and activity. For the pulsed scenario two different dwell temperatures have been considered, 150 °C and 250 °C; the one with the largest dwell temperature has given very low ACP mass inventory. It has been also investigated the influence, in the case of Continuous Scenario, of the Steam Generator piping material; Inconel 600, as the case of PWRs, instead of SS 316 L(N)-IG.

Keywords: DEMO, WCLL, Activated Corrosion Product.

1. Introduction

The objective of this paper is the assessment of ACPs inventories in the First Wall (FW) cooling loop of the DEMO Water Cooled Lithium Lead (WCLL) reactor, by using the code PACTITER v2.1 which was widely used for the ACP inventories assessment of the ITER TCWS providing related data in the ITER Preliminary Safety Report (RPrS) [1]. The choice of PACTITER v2.1 is due to its capability to rapidly perform parametric analyses, allowing determining the impact of the various parameters. The reference design of the DEMO WCLL FW cooling loop was taken from the CEA Technical Note [2], but it cannot be considered the frozen design of the WCLL FW cooling loop as further developments have been carried out since the issue of that document.

2. Preparation of the PACTITER v2.1 input

2.1 Input data required

To prepare an input for PACTITER v2.1, it is necessary to provide a series of data summarized in five main groups.

1. Geometric and thermal-hydraulics (for each region of the geometric model of the loop);
2. Material properties (including oxide);
3. Neutron activation data;
4. Loop main data;
5. Operation mode (scenario).

Details are given in the Technical Report for the EUROfusion Task WP SAE2.19-T01 [3].

2.2 Thermal hydraulics data of DEMO WCLL FW loop

Data per group 1, 2 and 4, above, have been derived from [2] for the zones of the FW cooling loop located in the tokamak vacuum vessel. The other geometric dimensions for the ex-vessel piping were calculated based on engineering judgment or for the Chemical & Volume Control System (CVCS), based on those of the analogous system of the ITER FW-Blanket PHTS. The overall coolant flow rate which is to remove a thermal power, P_{th}, equal to 683 MW is reported to be 3024.7 kg/s [2]. The blanket segmentation resulting in 384 Outboard and 224 Inboard Modules were considered in agreement with the reference document [2] together with the overall dimension of blanket modules to work out the number of piping, taking into account the given internal diameter for the FW piping facing the plasma (d=8 mm). In the next table overall dimension of tokamak piping are given.

Table 1. Tokamak regions piping data

Piping	Wet Surface [m^2]	Volume [m^3]
8-mm FW cooling pipes	2290.1	4.6
Module feed/return pipes	689.2	6.4
Back plate vertical headers	860.9	34.6
Total tokamak piping	3840.2	45.6

A coolant velocity of 2.7-2.8 m/s was assumed for the 8-mm FW cooling pipes In agreement with reference [2], while for the other in-vessel piping (FW feeding pipes, vertical headers and ring manifold) the coolant velocity was assumed ~ 7 m/s. To complete the geometric model of the FW cooling loop, it was assumed for the ex-vessel piping, making a comparison with the lengths of the similar piping for ITER TCWS, a length of 42 m for the hot leg, and for the cold length a value of 55 m. The main data, number of pipes, inner diameter and length, of the Steam Generator (SG) of the DEMO WCLL FW Cooling loop have been worked out based on the total power P_{th} (683 MW) to be removed. The overall geometric values for the FW cooling circuit of the DEMO WCLL reactor are shown in the next Table 2.

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author's email: luigi.dipace@enea.it

Table 2. Main geometric data of DEMO WCLL FW loop.

	Under Flux Wet Surf. (m^2)	Out-of Flux Wet Surf. (m^2)	Under Flux Vol. (m^3)	Out-of Flux Vol. (m^3)
Tokamak regions	3840.2	-	45.6	-
Steam Generator	-	5488.8	-	31.8
Hot & Cold Legs + Ring Manifolds	-	890.1	-	135.6
CVCS	-	850.6		19.3
Total	3840.2	7229.5	45.6	186.7

Other main thermal-hydraulics data of DEMO WCLL FW loop were defined as it follows:

- By-pass circuits structure is shown in Figure 1
- Efficiency of CVCS resin and filter = 98%
- Mass flow rate distribution, Inboard side 35.8%; Outboard side 64.2%
- Fraction of the main flow rate to CVCS = 0.5%
- Coolant temperature at zero power TPNUL = 250 °C (dwell temperature).

The 54-region PACTITER geometric model of DEMO WCLL FW loop is shown in Figure 1.

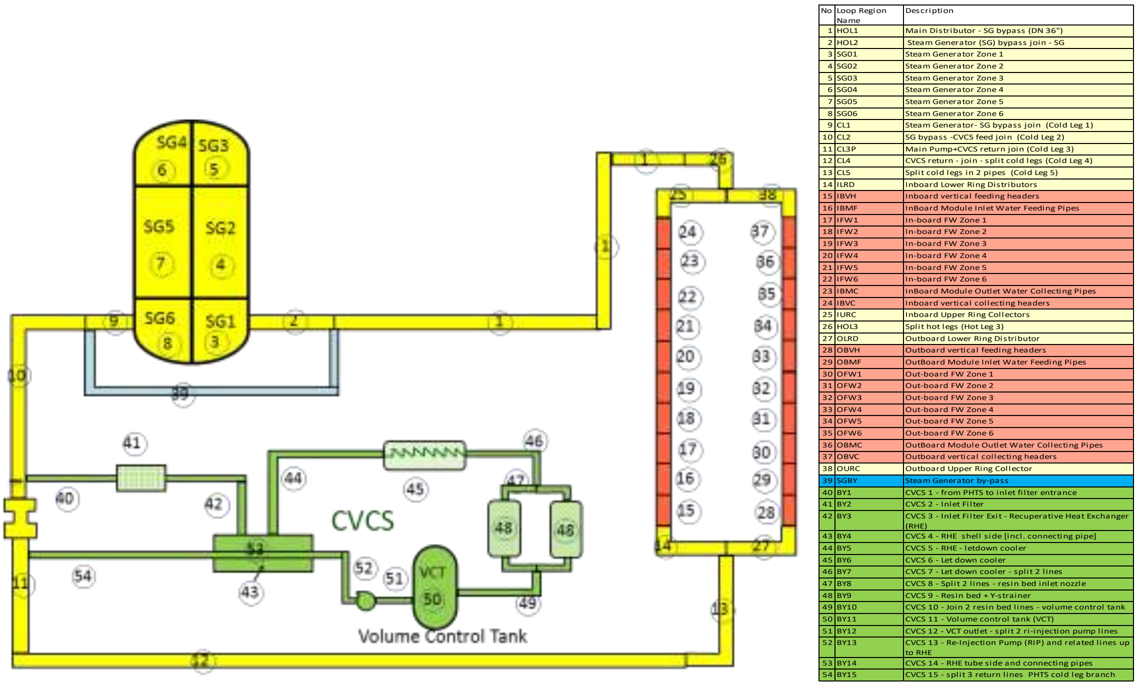
2.2 Material properties of DEMO WCLL FW loop

The DEMO WCLL FW cooling loop materials are listed in Table 3 (with the main element Wt.%).

Table 3. DEMO WCLL FW loop materials composition.

In-vessel piping EUROFER 97 *		Ex-vessel piping SS316L(N)-IG **		Steam Generator SS304L **	
Element	Wt.%	Element	Wt.%	Element	Wt.%
Fe	88.82	Fe	68.7	Fe	64.8
Ni	0.01	Ni	9.00	Ni	12.3
Co	0.005	Co	0.005	Co	0.05
Cr	9.00	Cr	19.0	Cr	17.5
Mn	0.55	Mn	2.00	Mn	1.80
Cu	0.003	Cu	0.10	Cu	0.30
W	1.10				

* Reference [4] ** reference [5]



No	Loop Region Name	Description
1	HOL1	Main Distributor - SG bypass (DN 36")
2	HOL2	Steam Generator (SG) bypass join - SG
3	SG01	Steam Generator Zone 1
4	SG02	Steam Generator Zone 2
5	SG03	Steam Generator Zone 3
6	SG04	Steam Generator Zone 4
7	SG05	Steam Generator Zone 5
8	SG06	Steam Generator Zone 6
9	CL1	Steam Generator- SG bypass join (Cold Leg 1)
10	CL2	SG bypass -CVCS feed join (Cold Leg 2)
11	CL3P	Main Pump+CVCS return join (Cold Leg 3)
12	CL4	CVCS return - join - split cold legs (Cold Leg 4)
13	CL5	Split cold legs in 2 pipes (Cold Leg 5)
14	ILRD	Inboard Lower Ring Distributors
15	IBVH	Inboard vertical feeding headers
16	IBMF	InBoard Module Inlet Water Feeding Pipes
17	IFW1	In-board FW Zone 1
18	IFW2	In-board FW Zone 2
19	IFW3	In-board FW Zone 3
20	IFW4	In-board FW Zone 4
21	IFW5	In-board FW Zone 5
22	IFW6	In-board FW Zone 6
23	IBMC	InBoard Module Outlet Water Collecting Pipes
24	IBVC	Inboard vertical collecting headers
25	IURC	Inboard Upper Ring Collectors
26	HOL3	Split hot legs (Hot Leg 3)
27	OLRD	Outboard Lower Ring Distributor
28	OBVH	Outboard vertical feeding headers
29	OBMF	OutBoard Module Inlet Water Feeding Pipes
30	OFW1	Out-board FW Zone 1
31	OFW2	Out-board FW Zone 2
32	OFW3	Out-board FW Zone 3
33	OFW4	Out-board FW Zone 4
34	OFW5	Out-board FW Zone 5
35	OFW6	Out-board FW Zone 6
36	OBMC	OutBoard Module Outlet Water Collecting Pipes
37	OBVC	Outboard vertical collecting headers
38	OURC	Outboard Upper Ring Collector
39	SGBY	Steam Generator by-pass
40	BY1	CVCS 1 - from PHTS to inlet filter entrance
41	BY2	CVCS 2 - Inlet Filter
42	BY3	CVCS 3 - Inlet Filter Exit - Recuperative Heat Exchanger (RHE)
43	BY4	CVCS 4 - RHE shell side [incl. connecting pipe]
44	BY5	CVCS 5 - RHE - letdown cooler
45	BY6	CVCS 6 - Let down cooler
46	BY7	CVCS 7 - Let down cooler - split 2 lines
47	BY8	CVCS 8 - Split 2 lines - resin bed inlet nozzle
48	BY9	CVCS 9 - Resin bed + Y-strainer
49	BY10	CVCS 10 - Join 2 resin bed lines - volume control tank
50	BY11	CVCS 11 - Volume control tank (VCT)
51	BY12	CVCS 12 - VCT outlet - split 2 ri-injection pump lines
52	BY13	CVCS 13 - Re-Injection Pump (RIP) and related lines up to RHE
53	BY14	CVCS 14 - RHE tube side and connecting pipes
54	BY15	CVCS 15 - split 3 return lines PHTS cold leg branch

Fig. 1. 54-region PACTITER geometric model of DEMO WCLL FW loop.

The parameter defined as oxide open porosity rate was assumed larger for EUROFER 97 (40 %), while for the AISI steels was 4%. This parameter “ν" enters in the following equation (1) used by PACTITER to calculate the release rate R from a material in contact with water:

$$R = \frac{h \cdot D \cdot \nu \cdot z}{D \cdot z + h \cdot \sqrt{2 \cdot x}} \cdot (C_{sat} - C) \qquad (1)$$

Where:

- h: ion transfer coefficient from oxide surface to bulk coolant;
- D : ion diffusion coefficient in the coolant;
- ν: oxide open porosity rate;
- z: element content in base metal;
- x: deposit thickness;
- C_{Sat}: element concentration at wall pipe, assumed to be the element solubility;
- C: element concentration in bulk coolant.

The ten activation reactions taken into account were:

^{54}Fe (n, p) ^{54}Mn
^{55}Mn (n, γ) ^{56}Mn
^{58}Ni (n, p) ^{58}Co
^{59}Co (n, γ) ^{60}Co
^{52}Cr (n, 2n) ^{51}Cr
^{58}Ni (n, np) ^{57}Co
^{63}Cu (n, α) ^{60}Co
^{65}Cu (n, 2n) ^{64}Cu
^{63}Cu (n, γ) ^{64}Cu
^{58}Fe (n, γ) ^{59}Fe

The reaction rates [s^{-1}] used and the other neutron activation data are given in reference [3].

2.3 Operative scenarios for the ACP assessment

Two operative scenarios for ACP assessment were selected. One defined as Continuous Scenario which just replicates the DEMO WCLL materials activation scenario based on the continuous pulse method [6] which was also adopted for activation calculations [7] by FISPACT. The second, defined as Pulsed Scenario, should better represent better the operations of the cooling loop, in terms of coolant temperature, rather than representing the activation of the base metal EUROFER.

The scenarios are summarized in the next Tables 4 and 5.

Table 4. Continuous Scenario power distribution

Neutron Wall load [MW/cm^2]	No. of pulses	Time interval [h]	Total duration [h]	Total duration [days]
0.3	1	45312	45312	1888
1.0	10	19.2	192	8
0.0	10	4.8	48	2

Table 5. Pulsed Scenario power distribution

Neutron Wall load [MW/cm^2]	No. of pulses	Time interval [h]	Total duration [h]	Total duration [days]
1.0	188	72	13536	564
0.0	188	168	31584	1316
1.0	1	57.6	57.6	2.4
0.0	1	134.4	134.4	5.6
1.0	10	19.2	192	8
0.0	10	4.8	48	2

The major difference is the way how the long continuous pulse period of 45312 hours (1888 days) at 0.3 MW/cm^2 was simulated by 188 periods (3 days at 1 MW/cm^2 + 7 days at zero power, for a total of 1880 days) plus 1 period (2.4 days at 1 MW/cm^2 + at zero power) (for a total of 8 days). The last 10 days were simulated the same way for both scenarios: 10 pulses UP of 0.8 days each and 10 pulses DOWN of 0.2 days.

3. ACP assessment results

In the next graphs, it is shown the main outputs calculated by PACTITER v2.1 code. The ACP deposit mass is depicted in Figure 2 for the two scenarios, while the total material release from the FW loop is presented in Figure 3. Pulsed Scenario presents a much lower ACP deposit mass inventory (factor ~50) and a lower mass release (-12%). That is due to different coolant temperature distribution profile between continuous scenario and pulsed scenario when the coolant temperature falls down to 250 °C in all loop during dwell periods; that occurs for a number of 1324 days which is 70% of the overall duration of the scenario.

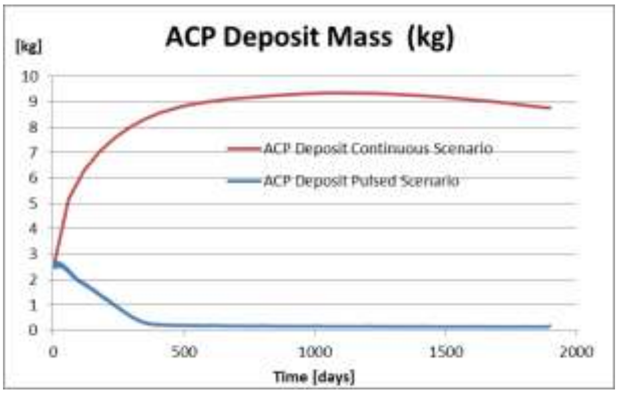


Fig. 2. ACP deposit mass; Continuous vs. Pulsed Scenario

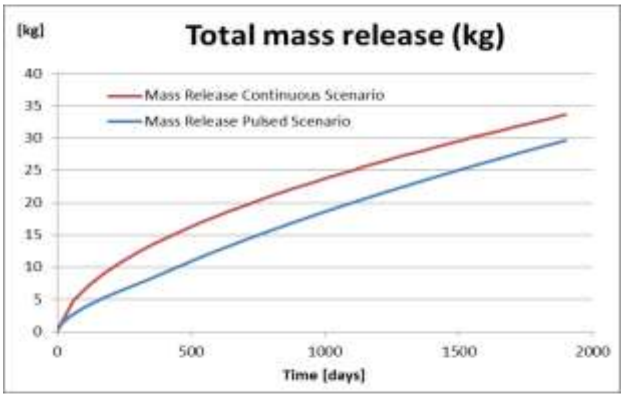


Fig. 3. Mass release; Continuous vs. Pulsed Scenario

For the remaining 574 days of burn periods, the coolant temperature profile in the loop is between 285 and 325 °C, with the exception of the CVCS regions. The burn periods for the Continuous Scenario (at 0.3 or 1 MW/cm^2) last 1896 days (99.9% of the scenario time). That makes a real difference in the element solubility conditions in the coolant, which in turn influences the ACP deposition rate and the material release. Figure 4 shows the ACP mass inventory in the coolant for both.

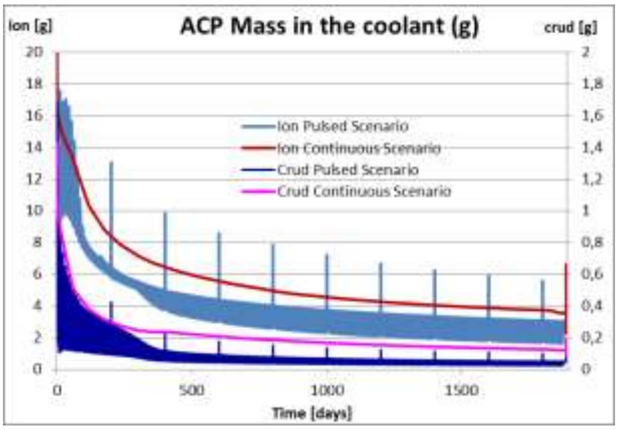


Fig. 4. ACP mass in the coolant; Continuous vs. Pulsed Scenario.

One can note the pulsed trend of the ACP in solution during the Pulsed Scenario due to the change of the elements solubility which depends from the loop coolant temperature profile changing during the burn and dwell periods. The ACP cruds (elements in suspension) mass is very low for both scenarios (< 0.2 g for most of the time). The highest peaks in the previous Fig. 4 are only of computational nature, as that scenario has been simulated by several code restarts (one every 200 days of operation scenario). Those peaks are displayed at the beginning of each new restart. Calculations have also provided the activity inventory, deposited onto the piping and components wall of the cooling loop and in solution and dispersed in the coolant (ion and crud). Figure 5 shows the total activity (ions and cruds) in the coolant for both scenarios.

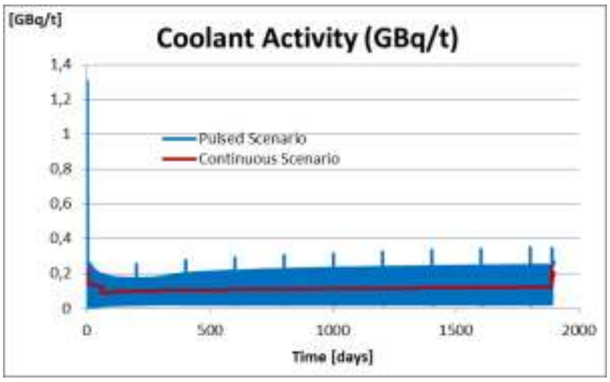


Fig. 5. Coolant specific activity; Continuous vs. Pulsed Scenario

The differences between the peak values of the coolant specific activity of the Pulsed Scenario versus the constant value of the Continuous Scenario can be explained by the differences in the neutron wall load (0.3 MW/cm^2 vs. 1.0 MW/cm^2) during most of the scenario.

Considering the deposit (mobilisable) inventory Figure 6 shows the different values for the two scenarios.

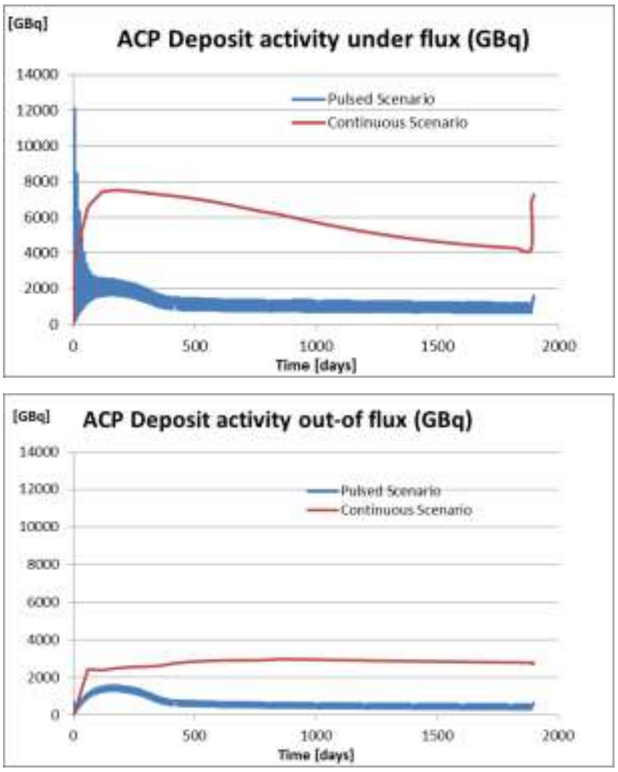


Fig. 6. ACP deposit activity; Continuous vs. Pulsed Scenario

The ACP deposit activity shows lower values for the Pulsed Scenario, as the deposit activity is linked to the ACP mass inventory. For the under flux deposit activity the ratio is in the range ~4-6, while it is between ~3-5 if one considers out-of flux deposit activity.

3.1 Influence of coolant temperature during dwell

It has been assumed that during pulsed operation the coolant temperature would fell down to 150 °C. That might happen during long shut downs. The ACP deposit mass and material release is shown for the two cases, respectively in Figure 7 and Figure 8. The reduced deposit mass is explained by the existence of two conditions: different solubility values for the main material elements and persistence of the coolant temperature at the dwell values for about 70% of the scenario duration.

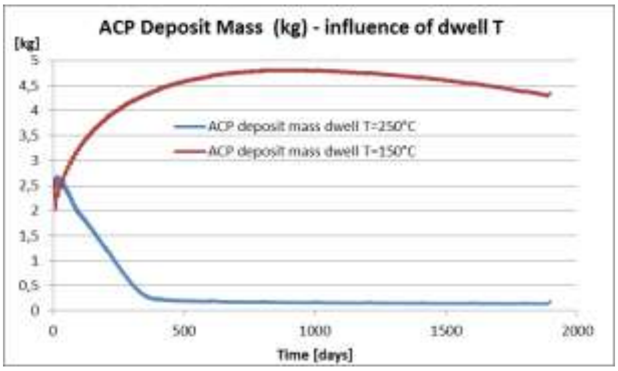


Fig.7. ACP deposit mass for Pulsed Scenario with different dwell coolant temperature

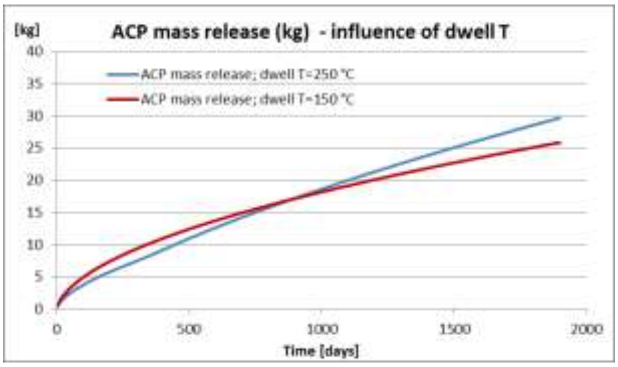


Fig. 8. Mass release from base metals for Pulsed Scenario with different dwell coolant temperature

That also influences the radioactive inventory (coolant and deposit). Next Figures 9 and 10 show the coolant and the deposit activity for the two dwell coolant temperatures.

3.2 Influence of Steam Generator piping material

One possible design choice might be using Inconel 600 for the Steam Generator (SG) piping as the case of PWRs, instead of SS316L(N)-IG. The comparison was made for the Continuous Scenario. Next Figures 10 and

11 show the ACP deposit mass and activity comparing the two options for SG piping material.

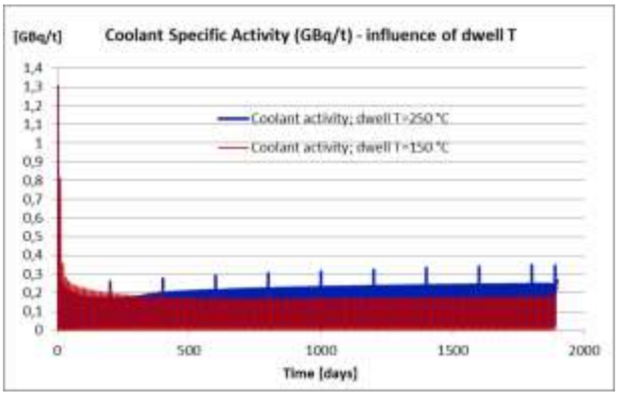


Fig. 9. Coolant activity for Pulsed Scenario with different dwell coolant temperature

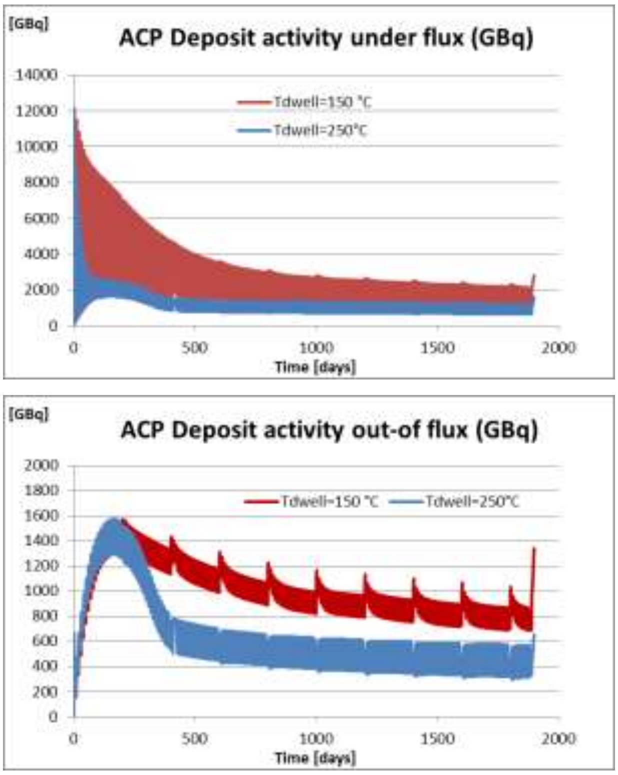


Fig. 10. ACP deposit activity for Pulsed Scenario with different dwell coolant temperature

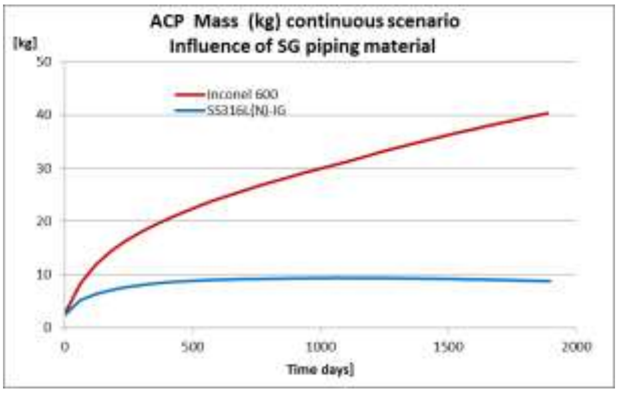


Fig. 11. ACP deposit mass comparison with different SG piping material (SS316L(N)-IG vs. Inconel 600)

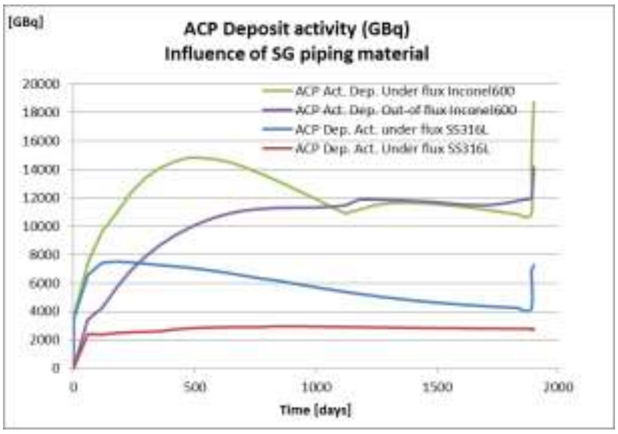


Fig. 12. ACP deposit activity comparison with different SG piping material (SS316L(N)-IG vs. Inconel 600)

The difference is clear, with Inconel 600 as SG piping material there is a larger ACP deposit mass inventory (factor ~ 4.6 at the end of the scenario) and a larger ACP deposit activity (average factors: 2.2 for under flux and 3.8 for out-of flux regions).

Acknowledgments

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