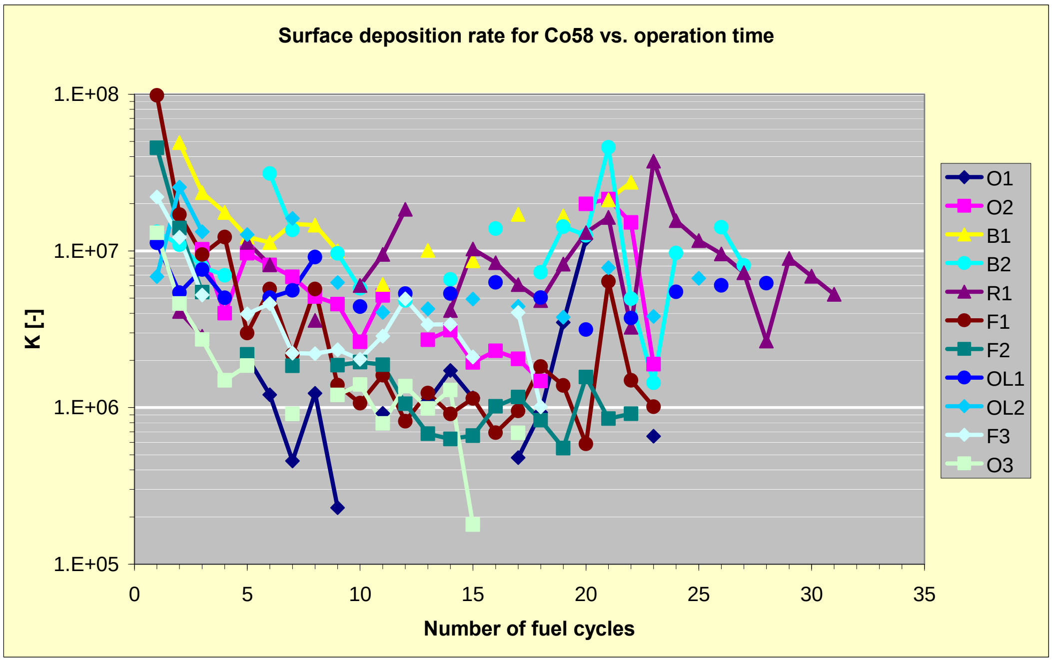

ANTIOXI -
Development of oxide model for activity buildup in LWRs - BWR plant data analysis

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Confidentiality	Public

Report's title

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Summary

The objective of the ANTIOXI projects is to develop a deterministic model for the build-up and properties of the oxide layers formed on LWR out-of-core primary system surfaces. The main focus in the development is to be able to model and predict the radioactivity build-up occurring on these surfaces.

This report presents an evaluation of BWR data. The BWRs specifically reviewed are the 11 Scandinavian BWRs (9 in Sweden and 2 in Finland). These plants are of two different types, with external recirculation loops or with internal recirculation pumps.

All but one of the plants have been power upgraded. Two of the plants have been phased out in 1999 and 2005, respectively. Data are normally covered from the initial start up to the 2006 outage, and represent more than 250 operation years. A data review for each plant is presented. An analysis of the data is provided, discussing the influence of different water chemistry and other factors. The report ends with a summary and conclusions.

The field experience compiled in this report does support the approach that surface chemistry, as studied by surface complexation methods, is an appropriate technique in assessing the real activity build-up mechanism as well as the impact of the water chemistry on the oxide formation mechanism in BWR environments.

Confidentiality: Public

Espoo, 1 June 2007

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Preface

The work discussed in the present report has been carried out as a part of the Work Package 3 of the project FP6036367 A deterministic model for corrosion and activity incorporation in nuclear power plants (ANTIOXI) in 2006 - 2007. The ANTIOXI project is a part of the EURATOM FP6 Programme “Advanced tools for nuclear safety assessment and component design”.

The ANTIOXI project in EURATOM FP6 concentrates on development of modelling tools for activity incorporation and corrosion phenomena into oxide films on construction materials in light water reactor environments.

The main funding source of the work has been the Sixth Framework Programme of the European Commission. The cooperation of the Members of the Advisory Board of the ANTIOXI project is gratefully acknowledged.

Espoo, Finland, 1 June 2007

Author

Contents

1 Introduction

The objective of the LWROXI/ANTIOXI[1] project is to develop a deterministic model for the build-up and properties of the oxide layers formed on LWR out-of-core primary system surfaces. The main focus in the development is to be able to model and predict the radioactivity build-up occurring on these surfaces. Work package 1 (WP-1) of the ANTIOXI project includes refinement and improvement of the earlier developed model for interaction between the oxide on a structural material and the coolant originating species. WP-2 contains quantifications of the surface complexation / deposition constants through high-temperature laboratory measurements. WP-3 includes critical evaluation of BWR, PWR and VVER reactor water and activity build-up data for validation and benchmarking of the developed model.

This report presents the WP-3 evaluation of BWR data. The BWRs specifically reviewed are the 11 Scandinavian BWRs (9 in Sweden and 2 in Finland). These plants are of two different types (start of commercial operation and thermal power level (initial and present) given for each plant):

1. <u>BWRs with external recirculation loops:</u>
    a. Oskarshamn 1 (O1): 1972 - , 1375 MWt
    b. Ringhals 1 (R1): 1976 - , 2270 → 2500 MWt
    c. Oskarshamn 2 (O2): 1975 - , 1700 → 1800 MWt
    d. Barsebäck 1 (B1): 1975 – 1999, 1700 → 1800 MWt
    e. Barsebäck 2 (B2): 1975 – 2005, 1700 → 1800 MWt
2. <u>BWRs with internal recirculation pumps:</u>
    a. Olkiluoto 1 (OL1): 1979 - , 2000 → 2500 MWt
    b. Olkiluoto 2 (OL2): 1982 - , 2000 → 2500 MWt
    c. Forsmark 1 (F1): 1980 - , 2711 → 2928 MWt
    d. Forsmark 2 (F2): 1981 - , 2711 → 2928 MWt
    e. Forsmark 3 (F3): 1985 - , 3020 → 3300 MWt
    f. Oskarshamn 3 (O3): 1985 - , 3020 → 3300 MWt

Note that all but one of the plants (O1) has been power upgraded. Two of the plants, B1 and B2, have been phased out in 1999 and 2005, respectively. Data are normally covered from the initial start up to the 2006 outage, and represent more than 250 operation years.

A data review for each plant is presented in chapter 2. An analysis of the data is provided in chapter 3, discussing the influence of different water chemistry and other factors. The report ends with a summary and conclusions.

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[1] LWROXI was originally a joint Swedish/Finnish project sponsored by utilities and radiation protection authorities. The project has later been converted to the ANTIOXI project with support from the EU.

2 BWR data

Reactor water activity and chemistry data from the plants are based on the ordinary surveillance performed at the plants, and comprise typically weekly measuring campaigns. Reactor water activity and chemistry data covered in the present study are:

- Mn-54, Co-58, Co-60, Zn-65, Cr-51, Fe-59, Sb-124
    - In some plants with online monitoring also the short-lived nuclides Mn-56, Zn-69m and Sb-122
- Fe, Zn, Ni, Cr, Co, Cu and conductivity
    - Plus measured ECP in plants on hydrogen injection, i.e. Hydrogen Water Chemistry (HWC)[2]

Main data for treated activated corrosion products are presented in **Table 1**.

***Table 1**: Half lives, decay constants, way of production and gamma yields for treated activated corrosion product.*

Nuclide	$T_{½}$	λ [s^{-1}]	Production	γ [MeV/diss]
Cr51	27.7 d	2.90E-07	Cr50 (n,γ) Cr51	0.0326
Mn54	312.5 d	2.57E-08	Fe54 (n,p) Mn54	0.836
Mn56	2.58 h	7.46E-05	Mn55 (n,γ) Mn56	1.692
Fe59	45.1 d	1.78E-07	Fe58 (n,γ) Fe59	1.188
Co58	70.78 d	1.13E-07	Ni58 (n,p) Co58	0.977
Co60	5.27 y	4.17E-09	Co59 (n,γ) Co60	2.504
Zn65	244.3 d	3.28E-08	Zn64 (n,γ) Zn65	0.584
Zn69m	13.76 h	1.40E-05	Zn68 (n,γ) Zn69m	0.417
Sb122	2.7 d	2.97E-06	Sb121 (n,γ) Sb122	0.441
Sb124	60.2 d	1.33E-07	Sb123 (n,γ) Sb124	1.857

The activity build-up on primary piping has already from the beginning of operation been followed-up by annual or semi-annual measurements during refuelling outages. Dose rates have been measured on a large number of locations as well as gamma scanning on selected locations to determine the contribution from different radio-nuclides. A standard location selected for both types of measurements are on the RHR[3] piping, that contains hot reactor water upstream of clean-up systems during reactor operation. The selection of the RHR piping instead of the recirculation loops has the advantage, that the internal pump plants can also be included in a comparison. The RHR piping has also locations that are more easily accessible for measurements, especially for the gamma scans where a heavy collimator has to be transported to the location. The RHR piping is made of stainless steel, and the water temperature is typically 270°C[4]. The RHR piping has also been equipped with on-line gamma

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[2] Operation without hydrogen injection is normally designated Normal Water Chemistry (NWC)

[3] Residual Heat Removal system. The RHR piping takes water from one recirculation loop in the external pump plants, and direct from the upper part of the reactor pressure vessel in the internal pump plants. The RHR system feeds the reactor water clean-up (RWCU). The pipe diameter is typically 200 mm, and the flow velocity is typically 2 m/s.

[4] The resulting temperature when reactor water from the core outlet (286°C) is mixed with feedwater (180 - 215°C depending on reactor) in the reactor downcomer. Note that the core flow varies during the cycle, which means that the temperature in the RHR piping is gradually increasing during the cycle. The RHR pipes in the internal pump plants are connected upstream of the feedwater spargers which means a somewhat lower involvement of feedwater. Subcooled conditions are, however, promoted by injecting some

monitoring (On-Line Activity – OLA) in some plants (O1, B2, R1, O2), which makes detection of some of the short-lived activated corrosion products on the piping possible.

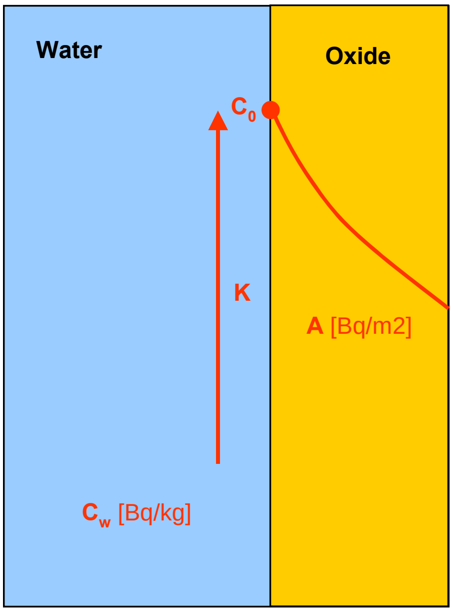

***Figure 1**: Evaluation model for BWR reactor water and system surface activity data*

Plant radioactivity data has been evaluated in a generalised way based on an earlier developed method /1/. RHR system activity levels (A) are recalculated to activity concentrations in the outer oxide layer (C_0) assuming an activity profile based on diffusion in the oxide layer, see **Figure 1**. An enrichment factor (K) has thereafter been determined by comparing this concentration in the outer oxide layer with the measured reactor water concentration of the same radionuclide, see ***Eq. 1***.

Eq. 1 $$C_0 = K \cdot C_w$$

where:
C_0 – *Concentration in outer part of oxide layer [Bq/kg]*
C_w – *Concentration in reactor water [Bq/kg]*
K – *Enrichment factor [-]*

The evaluation of the time dependent enrichment factor K(t) has been performed with a generalised expression from /1/ assuming that equilibrium has been reached between the reactor water conditions and the activity content in the oxide:

Eq. 2 $$K(t) = \frac{A(t) \cdot \sqrt{\lambda}}{C_w(t) \cdot \rho \cdot \sqrt{D}}$$

where:
$A(t)$ – *Activity in oxide film* $[Bq/m^2]$ *at time "t"*
λ – *Decay constant* $[s^{-1}]$
ρ - *Assumed density for oxide layer* $[=3500\ kg\ m^{-3}]$
D – *Assumed average diffusion rate in oxide layer* $[=10^{-18}\ m^2\ s^{-1}]$

The equilibrium conditions are normally true for nuclides with rather short half-life compared to reactor operation of several years, e.g. Co-58, but are a simplification in

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colder water upstream of the RHR pumps. The result is expected to be rather similar operation conditions in the RHR piping in external and internal pump plants.

some cases for long-lived nuclides as e.g. Co-60, especially after a short time of activity build-up. Deviations in such cases are not corrected for but commented in the evaluation. The assumed values for oxide density and diffusion rate are based on earlier assessments /1/. Note that other values of the density and the diffusion rate will of course affect the value of the enrichment factor but only as a scaling factor.

The RHR system activity data, *A(t)*, are basically been determined from performed gamma scan data, but a normalization has been performed against measured dose rate levels:

Co-60:

Eq. 3 $$A(t)_{Co60} = f_{Co60} \cdot DR(t)$$

where:
DR(t) – Measured dose rate [mSv/h] at time "t"
f_{Co60} *– Average ratio between measured Co-60 activity and dose rate for all years* [Bq/m^2 *per mSv/h]*

Other nuclides (XXxx):

Eq. 4 $$A(t)_{XXxx} = \frac{{}^{m}A(t)_{XXxx}}{{}^{m}A(t)_{Co60}} \cdot A(t)_{Co60}$$

where
${}^{m}A(t)_{XXxx}$, ${}^{m}A(t)_{Co60}$ *– Measured activity for the nuclide XX-xx and for Co-60* [Bq/m^2]

The reason for this normalization is to "smooth" the data due to occasionally problems with the calibration of the gamma scans, and to get estimated Co-60 values also for cycles where only dose rate measurements have been performed. All experience shows, that the contribution from Co-60 to the dose rate is very high, typically 80%.

Some additional data has also been included for comparison. Decontamination campaigns of primary piping have been performed in some plants, where both the radioactivity removed, as well as the amount of corrosion products in the oxides have been evaluated. The decontamination is expected to remove only the oxide layer, and not significantly dissolve the base material. Measured data are therefore a good evaluation of the oxide layer composition in the decontaminated systems.

2.1 External loop plants

2.1.1 O1

O1 is the oldest Scandinavian BWR, which started operation already in 1972. The reactor water chemistry as cycle-average data is shown in **Table 2**. The characteristics of O1 from the water chemistry point of view can be summarised in the following way:

- A comprehensive plant modernisation, the FENIX project, was carried out during the period 1992 – 1995, which significantly affected the water chemistry conditions. The pre-FENIX conditions were characterised by:
    - Considerable content of reactor water Cu and Zn due to some feedwater preheater brass tubes.
    - Increased reactor water conductivity due to resin intrusion from a condensate clean-up (CCU) plant operating at a very high temperature. The increased conductivity was therefore mainly due to increased concentrations of sulphate and nitrate.
    - Rather high inflow of Co due to large areas of Stellite in the recirculation loops. Rather low feedwater Fe (≈0.3 ppb).
- The FENIX project included removal of the brass material and rebuilding of the CCU system to lower operation temperature. The turbine plant was changed to a design with forward pumped heater drains resulting in a small increase of feedwater Fe. The post-FENIX reactor water chemistry conditions are characterised by:
    - Reduced Cu and Zn concentrations. The Zn concentration has, however, from cycle 2003-04 been increased by Zn injection of DZO[5] in order to control radiation levels. The resulting Zn levels are close to the pre-FENIX levels.
    - Reduced reactor water conductivity due to much lower levels of reactor water sulphate and nitrate.
    - Some additional feedwater Fe has been injected during recent years due to recommendation from the fuel vendor.
- The plant has stayed on NWC during the whole operation period.

The cycle average values of reactor water activated corrosion products are presented in **Table 3**. The activity data are well explained by the reactor water chemistry conditions:

- A high inflow of Zn results in low levels of Mn-54, see **Figure 2**. The post-FENIX conditions before start of DZO injections means gradually increased reactor water Mn-54, but the start of DZO injection means a return to low reactor water Mn-54.

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[5] DZO – Depleted Zinc Oxide, i.e. Zn where the Zn-64 level of about 50% in natural Zn has been reduced to about 1% in order to avoid a large production of the radioactive nuclide Zn-65.

- The pre-FENIX Zn-65 levels are high, and a considerable post-FENIX reduction is seen.
- The Co-60 levels are high. An increase is seen during the post-FENIX period without DZO injection, and the start of injection seems to result in somewhat reduced levels. On the other hand, Co-58 levels seem to increase after DZO.

Outage gamma scanning data and dose rates on the standard RHR location are presented in **Table 4**. There are rather few post-FENIX gamma scanning data, but the dose rate data have been used to estimate the Co-60 build-up, assuming that Co-60 dominates the radiation fields (older gamma scan data shows that Co-60 contributes with about 80% to the dose rates). Some additional post-FENIX RHR data are, however, available from OLA measurements, which is further treated below. Note that the whole primary system including the RHR pipes were decontaminated during the FENIX project.

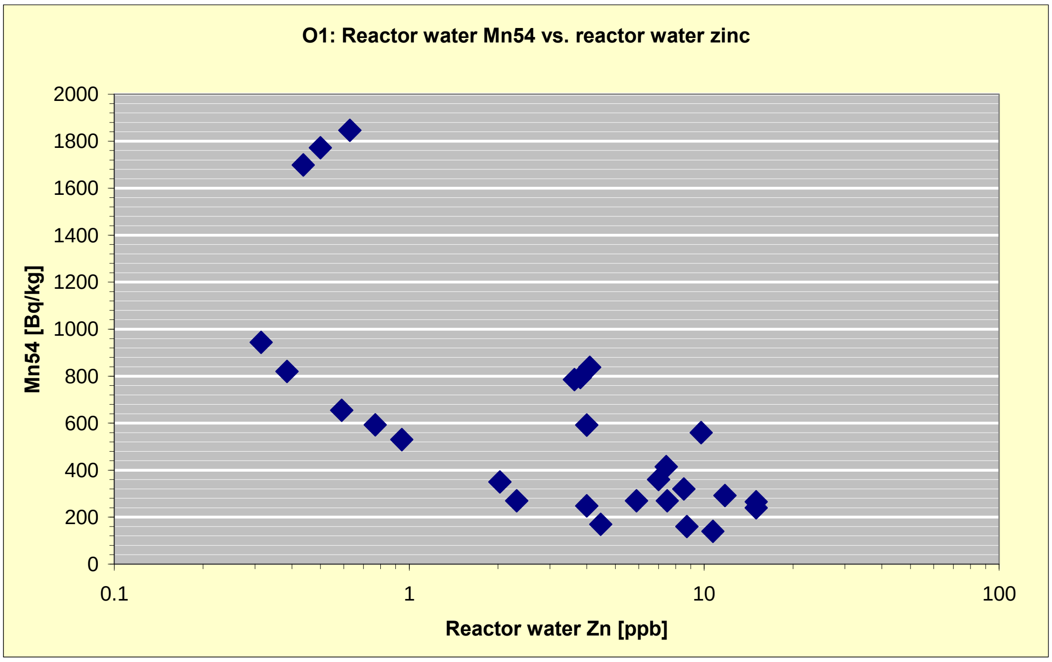

Figure 2: O1: Reactor water Mn-54 vs. reactor water Zn

Table 2: *Oskarshamn 1 – Corrosion product reactor water chemistry data – Annual average data during reactor operation*

		$C_w(t)$								
Cycle	Year	Fe [ppb]	Zn [ppb]	Ni [ppb]	Cr [ppb]	Co [ppb]	Cu [ppb]	Cond. [μS/cm]	N/HWC [0/1]	
1	1973		5.00				30.00		0	Cu + Zn (Brass), κ>0.2 μS/cm
2	1974		5.00				35.00		0	
3	1975	0.80	5.00	0.20			22.00	0.22	0	
4	1976		10.00	0.30			22.00	0.15	0	
5	1977	3.40	4.00	0.30			6.00	0.30	0	
6	1978	2.10	4.00	0.20			9.50	0.21	0	
7	1979	1.90	11.75	0.24	1.50	0.045	30.00	0.18	0	
8	1980	0.99	5.90	0.38	1.94	0.028	20.00	0.15	0	
9	1981		7.00			0.045	15.00		0	
10	1982		15.00				15.00		0	
11	1983	0.40	15.00	0.20			13.00	0.27	0	
12	1984	0.67	9.77	0.27	0.72	0.085	17.00	0.22	0	
13	1985	1.00	7.44	0.23	1.47	0.030	11.00	0.18	0	
14	1986	1.41	8.53	0.23	1.62		10.45	0.20	0	
15	1987	2.46	7.50	0.30	2.49	0.120	11.00	0.22	0	
16	1988	1.45	10.70	0.26	1.95	0.120	22.00	0.18	0	
17	1989	1.72	8.73	0.23	1.47	0.081	19.00	0.16	0	
18	1990	0.98	4.46	0.28	2.55	0.094	9.90	0.17	0	
19	1991	1.62	2.32	0.36	3.82	0.077	5.70	0.22	0	
20	1992	2.52	2.03	0.44	2.57	0.082	3.80	0.24	0	
21	1996	3.75	0.94	0.46	4.17		1.01	0.13	0	
22	1997	2.30	0.77	0.35	3.84		0.81	0.13	0	
23	1998	0.84	0.59	0.24	3.51	0.065	0.61	0.13	0	
24	1999	1.24	0.39	0.28	3.19	0.061	0.53	0.14	0	
25	2000	1.05	0.32	0.23	4.20	0.057	0.54	0.13	0	
26	2001	0.94	0.44	0.22	3.71	0.062	0.60	0.13	0	
27	2002								0	
28	2003	0.90	0.63	0.90	3.07	0.128	0.89	0.16	0	
29	2004	0.38	4.09	0.21	1.81	0.040	0.45	0.11	0	DZO
30	2005	0.60	3.80	0.29	1.93	0.050	0.40	0.11	0	
31	2006	0.86	3.63	0.31	1.84	0.052	0.26	0.11	0	

***Table 3**: Oskarshamn 1 – Activated corrosion products in reactor water – Annual average data during reactor operation*

		$C_w(t)$							
Cycle	Year	Mn54 Bq/kg	Co58 Bq/kg	Co60 Bq/kg	Zn65 Bq/kg	Cr51 Bq/kg	Fe59 Bq/kg	Sb124 Bq/kg	
1	1973	*5.0E+02*	*1.0E+04*	*5.0E+02*	*5.0E+03*	*1.0E+05*	*5.0E+02*		Cu + Zn (Brass), κ>0.2 μS/cm
2	1974	*1.0E+03*	*1.0E+04*	*1.0E+03*	*1.0E+04*	*1.0E+05*	*5.0E+02*		
3	1975	1.7E+03	*1.0E+04*	1.9E+03	1.7E+04	8.0E+04	3.1E+03	3.5E+02	
4	1976	1.9E+03	9.6E+03	4.8E+03	5.9E+04	1.0E+05	2.0E+02	*6.2E+02*	
5	1977	5.9E+02	1.4E+04	8.5E+03	4.4E+04	2.8E+05	2.0E+02	*7.9E+02*	
6	1978	2.5E+02	6.3E+03	6.1E+03	5.2E+04	1.5E+05	2.0E+02	*1.5E+02*	
7	1979	2.9E+02	6.1E+03	5.9E+03	6.3E+04	8.7E+04	7.4E+02	2.7E+02	
8	1980	2.7E+02	5.4E+03	5.6E+03	4.2E+04	6.6E+04	1.0E+02	*7.9E+02*	
9	1981	3.6E+02	7.2E+03	9.1E+03	5.4E+04	3.0E+04	9.9E+01	4.4E+02	
10	1982	2.4E+02	7.2E+03	5.6E+03	3.4E+04	2.8E+04	1.3E+02	5.6E+02	
11	1983	2.7E+02	1.1E+04	6.3E+03	3.0E+04	3.1E+04	8.1E+01	4.1E+02	
12	1984	5.6E+02	1.2E+04	7.4E+03	2.6E+04	4.2E+04	3.8E+01	3.5E+02	
13	1985	4.2E+02	8.9E+03	8.6E+03	2.3E+04	3.8E+04	4.1E+01	3.1E+02	
14	1986	3.2E+02	8.4E+03	9.5E+03	3.4E+04	4.2E+04	4.0E+01	3.8E+02	
15	1987	2.7E+02	7.2E+03	7.8E+03	2.2E+04	4.4E+04	5.0E+01	1.3E+03	
16	1988	1.4E+02	5.6E+03	6.8E+03	3.0E+04	3.5E+04	3.5E+01	9.5E+02	
17	1989	1.6E+02	7.2E+03	6.2E+03	2.5E+04	3.7E+04	9.1E+01	3.1E+02	
18	1990	1.7E+02	9.8E+03	8.3E+03	2.5E+04	5.7E+04	3.6E+01	3.8E+02	
19	1991	2.7E+02	7.3E+03	9.9E+03	2.1E+04	9.1E+04	2.9E+01	3.6E+02	
20	1992	3.5E+02	7.0E+03	1.1E+04	2.0E+04	1.1E+05	5.2E+01	6.0E+01	
21	1996	5.3E+02	4.9E+03	5.1E+03	5.2E+03	1.5E+05	5.1E+01	1.3E+02	
22	1997	5.9E+02	6.2E+03	6.4E+03	6.4E+03	1.5E+05	4.1E+01	1.4E+02	
23	1998	6.6E+02	7.5E+03	7.8E+03	7.6E+03	1.5E+05	3.1E+01	1.4E+02	
24	1999	8.2E+02	8.1E+03	8.2E+03	5.0E+03	1.2E+05	5.4E+01	3.1E+02	
25	2000	9.4E+02	9.7E+03	1.1E+04	7.6E+03	1.9E+05	7.3E+01	1.7E+02	
26	2001	1.7E+03	1.4E+04	2.8E+04	1.1E+04	1.5E+05	2.1E+02	1.2E+02	
27	2002	1.8E+03	1.2E+04	2.1E+04	7.1E+03	1.1E+05	1.6E+02	8.7E+01	
28	2003	1.8E+03	9.8E+03	1.3E+04	3.3E+03	7.4E+04	9.8E+01	9.9E+01	
29	2004	8.4E+02	1.2E+04	6.9E+03	3.2E+03	3.5E+04	7.6E+01	9.7E+01	DZO
30	2005	7.9E+02	1.5E+04	9.5E+03	4.0E+03	7.7E+04	6.6E+01	7.5E+01	
31	2006	7.9E+02	1.6E+04	1.1E+04	4.0E+03	8.3E+04	1.2E+02	2.3E+02	

***Table 4**: Oskarshamn 1 – Gamma scanning data and measured dose rate during outage on RHR piping*

		A(t)								
		Mn54	Co58	Co60	Zn65	Cr51	Fe59	Sb124	DR	
Cycle	Year	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	mSv/h	
1	1973								0.36	Cu + Zn (Brass), $\kappa>0.2$ µS/cm
2	1974								0.45	
3	1975								0.56	
4	1976								1.40	
5	1977	2.2E+07	3.3E+08	6.7E+08	7.8E+08	2.6E+08	1.3E+07	2.3E+07	1.95	
6	1978	3.0E+07	1.0E+08	4.6E+08	3.3E+08		1.2E+07	6.9E+06	1.13	
7	1979	1.2E+07	2.5E+07	4.8E+08	2.3E+08		8.0E+06	8.2E+06	1.73	
8	1980	1.1E+07	6.9E+07	6.7E+08	3.5E+08		2.7E+07	2.6E+07	2.05	
9	1981	1.4E+07	2.7E+07	7.4E+08	1.1E+08			3.4E+07	1.45	
10	1982								1.41	
11	1983	1.2E+07	1.6E+08	9.1E+08	2.2E+08		1.4E+07	2.2E+07	1.80	
12	1984								2.26	
13	1985		6.0E+07	4.3E+08	8.8E+07			8.9E+06	2.28	
14	1986		1.0E+08	8.3E+08	1.4E+08			3.4E+07	3.73	
15	1987	1.9E+07	9.8E+07	1.1E+09	2.1E+08	7.5E+07	1.9E+07	2.5E+07	2.98	
16	1988								3.00	
17	1989	7.7E+06	4.7E+07	9.6E+08	1.8E+08	8.5E+07	9.5E+06	1.4E+07	2.25	
18	1990	4.8E+06	3.0E+07	4.7E+08	5.2E+07	5.0E+07	8.7E+05	4.5E+06	4.60	
19	1991	2.3E+07	1.8E+08	9.7E+08	2.4E+08	1.3E+08	1.4E+07	3.3E+07	4.25	
20	1992	4.2E+07	8.6E+08	2.2E+09	4.5E+08	4.5E+09	6.5E+07		6.73	
		FENIX incl. primary system decontamination								
21	1996			8.1E+07	7.0E+06				0.29	
22	1997								0.40	
23	1998		1.2E+08	5.0E+08	1.1E+08			4.4E+06	0.65	
24	1999								4.50	
25	2000								2.30	
26	2001									
27	2002								1.90	
28	2003								2.60	
29	2004								2.70	DZO
30	2005								2.80	
31	2006								2.80	

The above reactor water activities and gamma scanning data have been recalculated to surface enrichment factors K for the different activated corrosion products according to ***Eq. 1*** and ***Eq. 2***. Note the increase of K factors just prior to the FENIX project, a period that was characterised by a decrease of reactor water Zn. The post-FENIX period is characterised by low K-factors (especially compared to other plants, see below). The introduction of DZO injection seems not to have significantly decreased the K factor for Co-60, but the observed reduction of reactor water Co-60 means a reduced activity build-up.

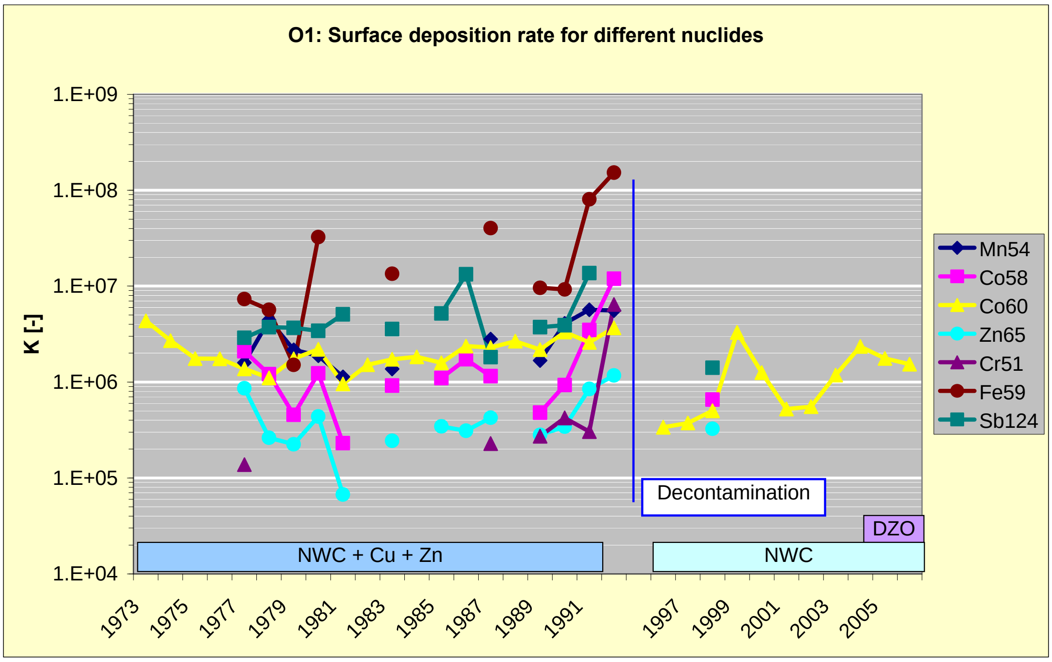

Figure 3*: O1: Surface enrichment factor K based on cycle average reactor water activity and reported gamma scan and dose rate measurements on RHR pipes*

An on-line gamma scan equipment has been in operation on a RHR line after the FENIX project, and some data in form of calculated K factors according to ***Eq. 1*** and ***Eq. 2*** are presented in **Figure 4** - **Figure 7**. The on-line data provide some additional information about the post-FENIX conditions, however recent data after the introduction of DZO are lacking. Of interest is, however, to note that the determination of K factors for pairs of radio-nuclides with same chemistry properties but different half-lives, i.e. Co-58 – Co-60 (**Figure 4**) and Sb-122 – Sb-124 (**Figure 7**) shows large agreement, which supports the evaluation according to ***Eq. 2*** with the assumption of surface adsorption followed by diffusion into the oxide film as base mechanism.

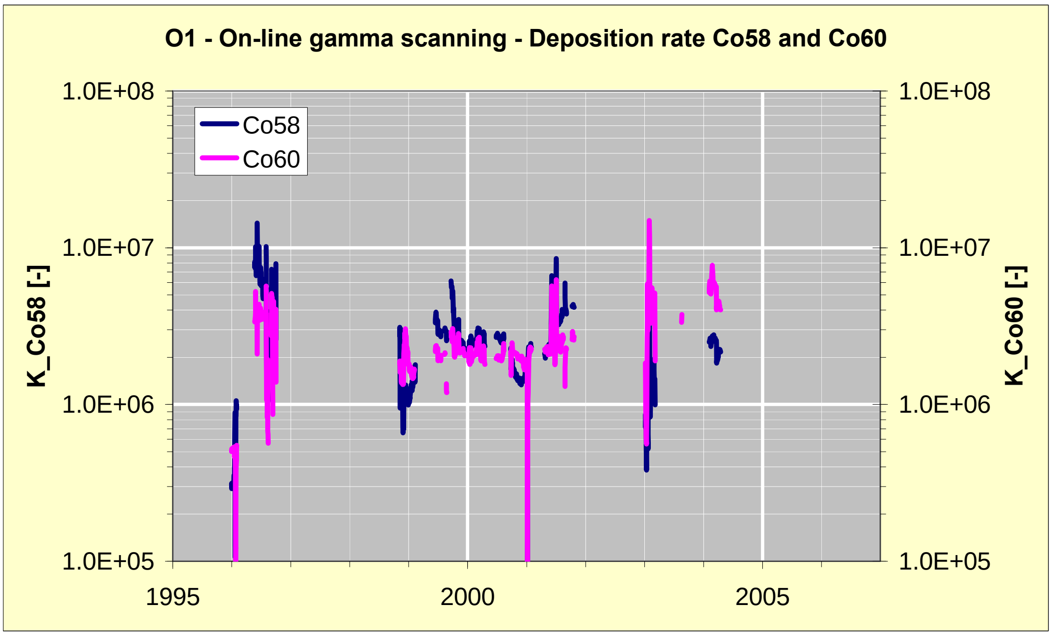

Figure 4: O1: Co-58 and Co-60 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes

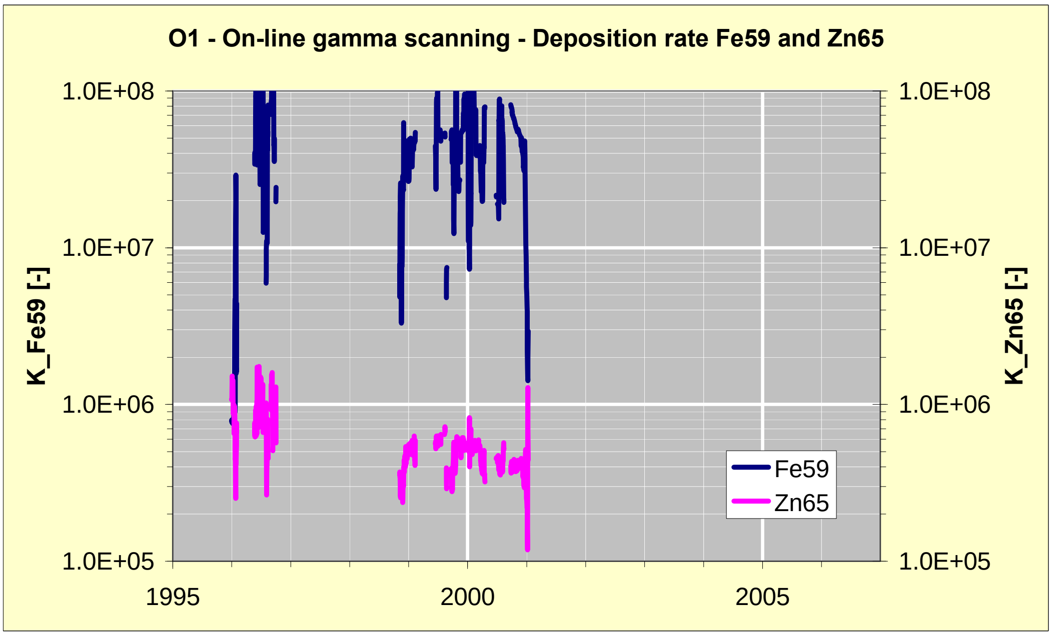

Figure 5: O1: Fe-59 and Zn-65 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes

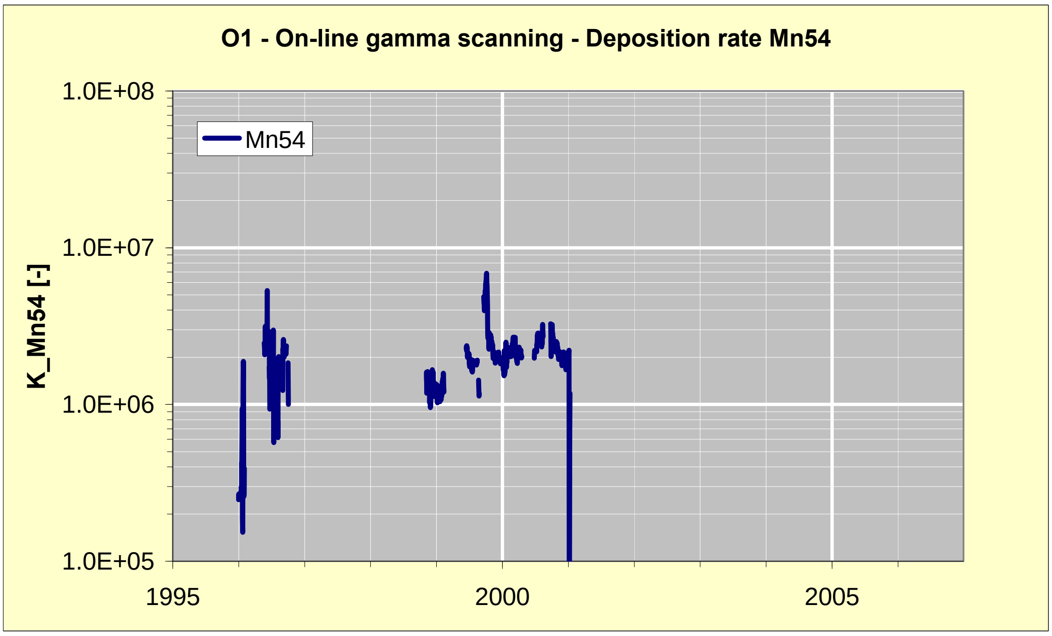

Figure 6: O1: Mn-54 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes

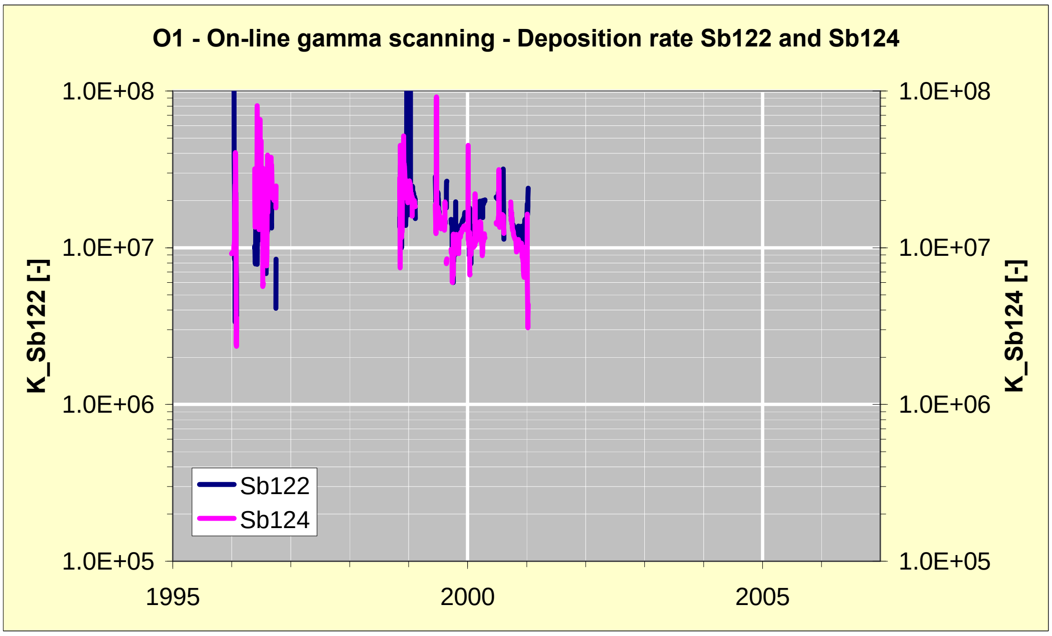

Figure 7: O1: Sb-122 and Sb-124 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes

The FENIX project involved two substantial decontamination campaigns of the primary system, and summaries of removed corrosion products and radio-nuclides are presented in **Table 5** and **Table 6**. The radioactivity is presented both for the date of decontamination, and recalculated to the shutdown date for the FENIX project. The first campaign, in June 1993, involved a mix of systems, i.e. both systems in contact with hot reactor water during operation and other less contaminated systems. The second campaign involved basically 450 m^2 of primary system surfaces (plus some inactive/ already decontaminated surfaces), mainly the lower part of the reactor pressure vessel including internals, and the recirculation loops. All data are presented per m^2.

***Table 5**: O1: Primary system decontamination summary for campaign performed in June 1993 during the FENIX project (Shutdown date Aug. 1992) (Totally 895 m^2, systems 312/ 315/ 321/ 331[6]). Note: The recalculation of Cr51 to Aug. 1992 has been skipped due to an unrealistic high activity level*

	kg	kg/m2
Fe	4.9	5.47E-03
Cr	1.5	1.68E-03
Ni	0.11	1.23E-04
Cu	0.06	6.70E-05
Zn	0.43	4.80E-04
Total		7.82E-03

			jun-93		aug-92
	%	Bq	Bq/m2	%	Bq/m2
Co58	1%	2.00E+09	2.23E+06	8%	4.39E+07
Co60	73%	2.56E+11	2.86E+08	58%	3.19E+08
Fe59	0%			0%	
Mn54	1%	4.00E+09	4.47E+06	2%	8.77E+06
Cr51	1%	4.00E+09	4.47E+06	0%	
Zn65	20%	6.90E+10	7.71E+07	33%	1.83E+08
Total	96%	3.50E+11	3.91E+08	100%	5.54E+08

***Table 6**: O1: Primary system decontamination summary for campaign performed in January 1994 during the FENIX project (Shutdown date Aug. 1992) (450 m^2 plus 900 m^2 inactive surfaces, 211/ 313/ 321/ 354/ 312[7])*

	kg	kg/m2
Fe	16.9	3.76E-02
Cr	5.1	1.13E-02
Ni	3.1	6.89E-03
Cu	0.4	8.89E-04
Zn	1.8	4.00E-03
Total		6.07E-02

			jan-94		aug-92
	%	Bq	Bq/m2	%	Bq/m2
Co58	0%			0%	
Co60	93%	2.14E+12	4.76E+09	83%	5.73E+09
Fe59	0%			0%	
Mn54	0%	1.10E+10	2.44E+07	1%	7.71E+07
Cr51	0%			0%	
Zn65	5%	1.10E+11	2.44E+08	15%	1.06E+09
Total	98%	2.30E+12	5.11E+09	100%	6.87E+09

The measured Co-60 contamination level in the two campaigns can be compared to the 1992 gamma scan result from **Table 4**:

- 1992 Co-60 contamination levels:
  - RHR gamma scanning: 2.2 GBq/m^2
  - Decontamination campaign Jun-93: 0.32 GBq/m^2
  - Decontamination campaign Jan-94: 5.7 GBq/m^2

The lower activity level for the Jun-93 campaign is explained by a large fraction of systems included with lower contamination level than for the RHR. On the other hand, the noticeable higher contamination level for the Jan-94 campaign is realistic considering that in-vessel locations may have somewhat higher contamination than the RHR lines (some sedimented crud may have been accumulated in in-vessel locations).

The decontamination data can be recalculated to oxide thickness. If we assume a composition typical to spinel, e.g. trevorite $NiFe_2O_4$, and that the oxide layer density is typically 3500 kg m^{-3}, the following oxide thicknesses are obtained:

- ***Eq. 5***

$$\delta = \frac{1000000 \cdot m}{frac \cdot dens}$$

where:
d – Oxide thickness [μm]
m – Mass of metals (Fe + Cr + Ni + Cu + Zn) [kg/m^2]

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[6] 312 – Feedwater system, 315 – shutdown cooling system, 321 – RHR system, 331 – RWCU system.

[7] 211 – Pressure vessel (up to bottom of core support), 313 – recirculation system, 321 – RHR, 354 – control rod drive system, 312 – feedwater system.

frac – mass fraction of metals in spinell [=0.7265]
dens – Assumed oxide density [=3500 kg/m^3*]*

- - Decontamination campaign Jun-93: 3.1 µm
  - Decontamination campaign Jan-94: 23.9 µm

The rather thick calculated oxide thickness in the second campaign is an indication that a significant fraction of the removed corrosion products is from sedimented crud.

2.1.2 R1

The R1 plant started operation in 1975. The reactor water chemistry in form of cycle-average data is shown in **Table 7**. The characteristics of R1 from the water chemistry point of view can be summarised in the following way:

- Some Zn and Cu in the reactor water during the first five cycles due to brass condenser tubes. An exchange to titanium tubes has thereafter meant low levels of Zn and Cu. No Zn injection has been applied.

- HWC operation has been applied since 1984, with a short interruption 1992-93 (noticed by significantly increased reactor water level of Cr). The degree of reducing conditions has, however, been varying, i.e. some cycles with HWC has in reality only resulted in a slight reduction of the corrosion potential in the primary piping (will be discussed in more detail in a later section).

- A large modernisation program was carried out during the 1997 outage. Large areas of Stellite were removed from the recirculation lines, which has reduced the input of Co to the primary loop.

The cycle average values of reactor water activated corrosion products are presented in **Table 8**. The activity data are well explained by the reactor water chemistry conditions. The gradually reduced Co-60 activity after 1997 indicates an influence of the Stellite replacement. Recent levels of Mn-54, with typically 4000 Bq/kg, indicate that it exists a surplus of Fe in the primary circuit. Most of the Fe is coming from reactor water systems, especially the CRD system, due to the locally reducing conditions form at HWC operation, and not from the feedwater. The Cr-51 reactor water activity is as expected much reduced when the reactor is on HWC.

Outage gamma scanning data and dose rates on the standard RHR location are presented in **Table 9**. Note that a system decontamination involving the RHR pipes was carried out during the 1997 outage when the large modification work was performed (the 1997 gamma scanning measurements were performed before the decontamination, but the 1997 dose rate measurements after the decontamination).

***Table 7**: Ringhals 1 – Corrosion product reactor water chemistry data – Annual average data during reactor operation*

		$C_w(t)$								
Cycle	Year	Fe [ppb]	Zn [ppb]	Ni [ppb]	Cr [ppb]	Co [ppb]	Cu [ppb]	Cond. [mS/cm]	N/HWC [0/1]	
1	1976	5.00	4.00		2.00		6.00	0.16	0	
2	1977	4.00	2.00				2.00		0	
3	1978	11.00	3.00				3.00		0	
4	1979	2.00	2.50				4.00		0	
5	1980	2.00	3.00				5.00		0	
6	1981	1.11	0.40				0.92		0	
7	1982	1.55	0.40	0.10	1.00		0.40		0	
8	1983	1.06	0.30	0.13	0.78	0.050	0.26		0	
9	1984	0.60	0.30	0.20	1.40	0.100	0.30	0.08	1	HWC
10	1985	0.81	0.20	0.10	1.17	0.040	0.35	0.08	1	
11	1986	0.68	0.23	0.08	0.59	0.030	0.46	0.10	1	
12	1987	0.74	0.22	0.06	0.59	0.020	0.60	0.04	1	
13	1988	0.96	0.09	0.09	0.13	0.025	0.29	0.04	1	
14	1989	1.57	0.15	0.17	0.43	0.030	0.37	0.06	1	
15	1990	1.48	0.06	0.15	0.13	0.030	0.34	0.05	1	
16	1991	0.70	0.21	0.14	0.33	0.060	0.38	0.04	1	
17	1992	0.40	0.10	0.10	1.20	0.100	0.40	0.10	0	
18	1993	0.40	0.10	0.20	1.22	0.080	0.30	0.14	0	
19	1994	0.36	0.03	0.12	0.03	0.040	0.28	0.06	1	HWC
20	1995	0.68	0.04	0.09	0.10	0.020	0.18	0.08	1	
21	1996	1.21	0.01	0.10	0.01	0.006	0.16	0.06	1	
22	1997	1.44	0.01	0.08	0.03	0.008	0.12	0.08	1	
23	1998	1.56	0.01	0.19	0.09	0.012	0.38	0.08	1	
24	1999	1.38	0.04	0.16		0.017	0.34	0.11	1	
25	2000	0.79	0.01	0.08	0.04	0.009	0.38	0.10	1	
26	2001	0.96	0.01	0.12	0.07	0.011	0.29	0.10	1	
27	2002	1.83	0.01	0.10	0.07	0.009	0.27	*0.10*	1	
28	2003	2.00	0.02	0.11	0.11	0.010	0.50	0.10	1	
29	2004	1.85	0.03	0.10	0.07	0.008	0.47	*0.10*	1	
30	2005	0.89	0.09	0.08	0.09	0.007	0.55	*0.10*	1	
31	2006								1	

Table 8: *Ringhals 1 – Activated corrosion products in reactor water – Annual average data during reactor operation*

		$C_w(t)$							
Cycle	Year	Mn54 Bq/kg	Co58 Bq/kg	Co60 Bq/kg	Zn65 Bq/kg	Cr51 Bq/kg	Fe59 Bq/kg	Sb124 Bq/kg	
1	1976	*3.0E+02*	*7.0E+03*	*2.0E+03*	*3.0E+03*	*1.0E+05*	*4.0E+02*	1.3E+03	
2	1977	2.8E+02	7.0E+03	4.6E+03	4.1E+03	1.1E+05	3.8E+02	1.9E+02	
3	1978	2.9E+02	4.3E+03	2.3E+03	3.6E+03	4.8E+04	1.7E+03	1.0E+03	
4	1979	1.1E+03	7.0E+03	3.2E+03	1.5E+04	4.8E+04	1.0E+03	1.6E+03	
5	1980	1.5E+03	3.4E+03	3.9E+03	1.5E+04	4.5E+04	8.6E+02	1.3E+03	
6	1981	8.1E+02	3.4E+03	2.9E+03	7.2E+03	5.0E+04	5.6E+02	7.7E+02	
7	1982	3.4E+03	3.1E+03	4.1E+03	8.3E+03	8.2E+04	4.5E+03	1.0E+03	
8	1983	2.7E+03	4.3E+03	3.6E+03	2.9E+03	7.3E+04	9.3E+02	8.4E+02	
9	1984	2.1E+03	2.7E+03	3.1E+03	4.5E+03	1.2E+05	2.7E+03	3.9E+03	HWC
10	1985	2.1E+03	2.7E+03	3.1E+03	4.5E+03	1.2E+05	2.7E+03	5.3E+02	
11	1986	5.6E+02	2.4E+03	1.7E+03	2.2E+03	4.8E+04	5.0E+02	4.8E+02	
12	1987	4.2E+02	1.2E+03	1.2E+03	2.3E+03	3.7E+04	2.9E+02	4.1E+02	
13	1988	7.1E+02	2.2E+03	2.5E+03	1.1E+03	6.6E+03	1.0E+02	2.3E+02	
14	1989	1.2E+03	4.4E+03	4.4E+03	1.3E+03	2.7E+04	1.7E+02	2.8E+02	
15	1990	1.3E+03	3.8E+03	7.7E+03	6.6E+02	2.0E+03	2.1E+02	1.3E+02	
16	1991	1.2E+03	4.4E+03	5.4E+03	4.0E+02	2.0E+03	4.1E+02	2.2E+02	
17	1992	1.2E+03	5.0E+03	4.0E+03	9.0E+02	9.5E+04	1.2E+02	4.3E+02	
18	1993	6.4E+02	4.2E+03	7.0E+03	8.0E+02	2.0E+05	1.6E+02	3.6E+02	
19	1994	1.2E+03	4.0E+03	8.0E+03	3.6E+02	1.2E+04	3.2E+02	3.2E+02	HWC
20	1995	1.4E+03	2.9E+03	5.2E+03	3.4E+02	7.5E+03	4.2E+02	3.4E+02	
21	1996	3.3E+03	3.3E+03	5.2E+03	2.3E+02	2.8E+03	2.0E+02	9.0E+02	
22	1997	5.2E+03	4.9E+03	5.7E+03	7.0E+02	6.0E+03	6.0E+02	1.1E+03	
23	1998	3.4E+03	3.8E+03	3.2E+03	2.3E+02	5.2E+03	2.4E+02	1.3E+02	
24	1999	2.6E+03	5.1E+03	3.1E+03	1.5E+02	3.5E+05	6.0E+02	1.7E+02	
25	2000	3.9E+03	5.8E+03	3.2E+03	1.7E+02	4.1E+03	1.2E+02	4.3E+02	
26	2001	3.0E+03	4.6E+03	3.2E+03	1.8E+02	5.3E+04	1.9E+02	3.8E+02	
27	2002	3.6E+03	6.1E+03	2.3E+03	1.2E+02	2.0E+04	1.3E+02	6.4E+02	
28	2003	4.9E+03	7.2E+03	2.9E+03	1.2E+02	1.7E+05	7.1E+02	1.3E+03	
29	2004	3.3E+03	4.8E+03	1.4E+03	1.4E+02	4.8E+04	1.4E+03	1.0E+03	
30	2005	4.3E+03	5.8E+03	1.8E+03	5.5E+01	4.2E+04	3.3E+03	1.6E+02	
31	2006	*4.3E+03*	*5.8E+03*	*1.8E+03*	*5.5E+01*	*4.2E+04*	*3.3E+03*	*1.6E+02*	

***Table 9**: Ringhals 1 – Gamma scanning data and measured dose rate during outage on RHR piping*

		A(t)								
		Mn54	Co58	Co60	Zn65	Cr51	Fe59	Sb124	DR	
Cycle	Year	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	mSv/h	
1	1976									
2	1977		3.0E+08	5.2E+08	1.4E+08		1.2E+06	1.3E+06		
3	1978		1.3E+08	5.6E+08	1.1E+08					
4	1979			7.0E+08						
5	1980		2.1E+08	5.6E+08	3.7E+08			2.7E+05	1.00	
6	1981	2.3E+07	2.5E+08	9.2E+08	4.9E+08	2.4E+08	3.4E+07	5.5E+06	1.00	
7	1982								1.50	
8	1983	1.7E+07	1.6E+08	1.2E+09	1.7E+08	1.5E+08	1.4E+07	1.4E+06	1.15	
9	1984								1.45	HWC
10	1985		1.2E+08	1.2E+09	6.2E+07			1.9E+07	1.50	
11	1986	7.8E+07	2.0E+08	1.8E+09	6.3E+07			5.7E+07	2.00	
12	1987	3.1E+07	2.3E+08	1.6E+09	3.6E+07		1.3E+07	2.4E+07	1.45	
13	1988								2.20	
14	1989	1.7E+07	1.0E+08	1.1E+09	1.3E+07		8.4E+06	1.2E+07	1.90	
15	1990	3.1E+07	5.1E+08	2.3E+09			4.0E+07	1.8E+07	1.70	
16	1991	3.9E+07	2.0E+08	1.5E+09				9.0E+06	2.70	
17	1992	4.4E+07	2.2E+08	1.7E+09		1.6E+08		2.4E+07	2.30	
18	1993		1.7E+08	2.3E+09				3.8E+07	2.60	
19	1994		3.3E+08	2.4E+09				3.2E+07	2.36	HWC
20	1995		4.6E+08	3.7E+09					2.90	
21	1996		6.6E+08	4.6E+09					3.60	
22	1997	5.9E+07	7.0E+08	4.1E+09						
		Decontamination								
									0.90	
23	1998	1.4E+08	2.1E+09	5.5E+09		9.2E+08		5.3E+07	3.60	
24	1999	1.1E+08	1.1E+09	5.3E+09				3.1E+07	3.70	
25	2000	1.7E+08	9.3E+08	3.8E+09	2.0E+07	2.2E+08	3.8E+07	4.4E+07	2.68	
26	2001	1.2E+08	5.3E+08	3.2E+09		2.6E+08	2.4E+07	2.9E+07	2.54	
27	2002	9.2E+07	5.3E+08	3.4E+09				1.5E+07	2.72	
28	2003	3.9E+07	1.5E+08	1.8E+09			6.9E+06	7.8E+06	2.27	
29	2004	6.4E+07	5.1E+08	3.1E+09		7.4E+08	2.9E+07	9.2E+06	2.51	
30	2005	2.9E+07	2.5E+08	1.7E+09			1.7E+07	8.0E+06	2.66	
31	2006	5.9E+07	3.5E+08	2.7E+09		2.6E+08	2.5E+07	1.3E+07	2.30	

The above reactor water activities and gamma scanning data have been recalculated to surface enrichment factors K for the different activated corrosion products according to ***Eq. 1*** and ***Eq. 2***. The resulting K factors for different radionuclides are presented in **Figure 8**. A reduction of K factors is seen after 2002, especially for Fe-59 and Sb-124, which coincides with improved HWC operation with reduced corrosion potential (which will be discussed further later).

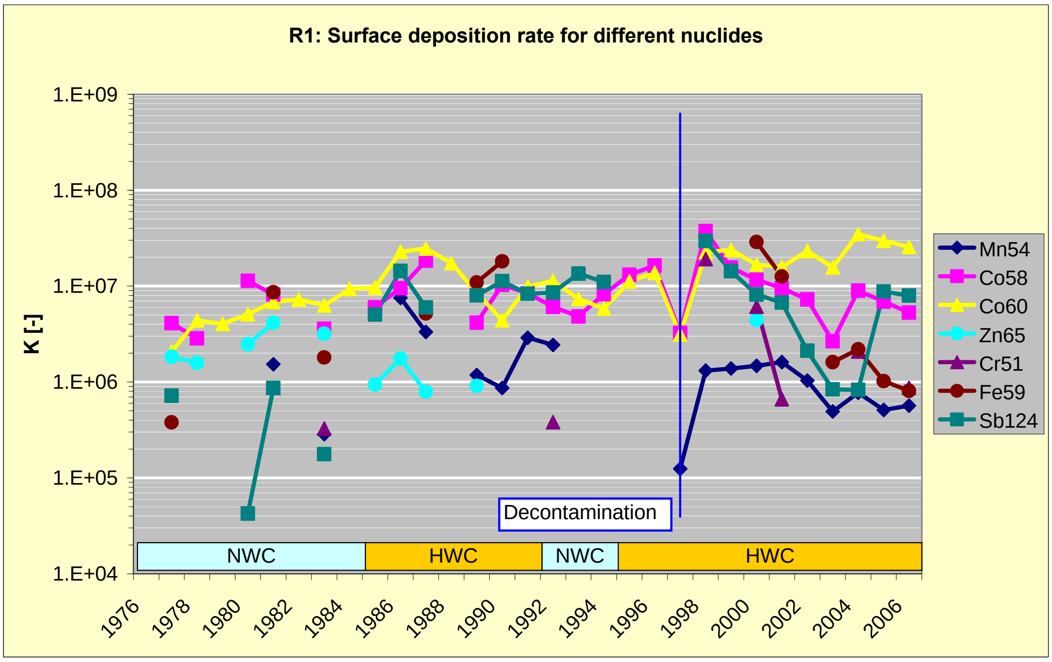

Figure 8*: R1: Surface enrichment factor K based on cycle average reactor water activity and reported gamma scan and dose rate measurements on RHR pipes*

An on-line gamma scan equipment has been in operation on a RHR line after 1995, and some data in form of calculated K factors according to ***Eq. 1*** and ***Eq. 2*** are presented in **Figure 9** - **Figure 12**. The K-factors according to the on-line measurements show large similarities with those in **Figure 8**. The reduction of K-factors for Fe-59 and Sb-122 after the 2002 outage can be correlated to more efficient HWC operation with reduced corrosion potential (ECP), which is demonstrated in **Figure 14** and **Figure 15**. The same influence of ECP on the K-factor for Co-58 is not seen, see **Figure 13**. Note also the difference in K-factors for Mn isotopes, with higher values for the very short-lived Mn-56 nuclide (**Figure 10**). This result is probably a measurement artefact due to reduced reactor water Mn-56 activity due to significant deposition in the sampling lines (which is further discussed in a later section).

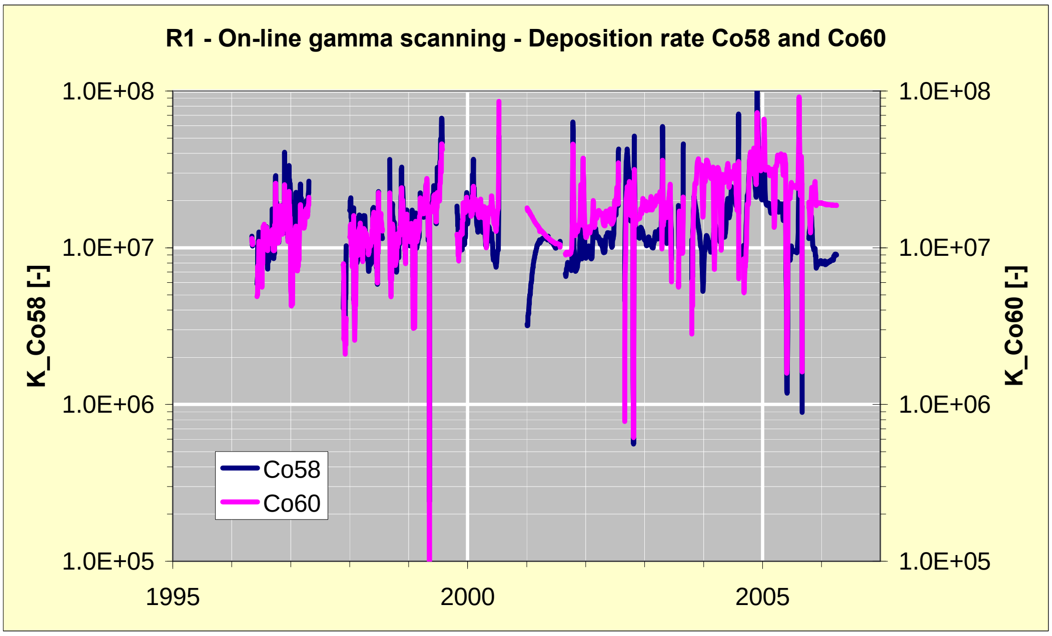

Figure 9: *R1: Co-58 and Co-60 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes*

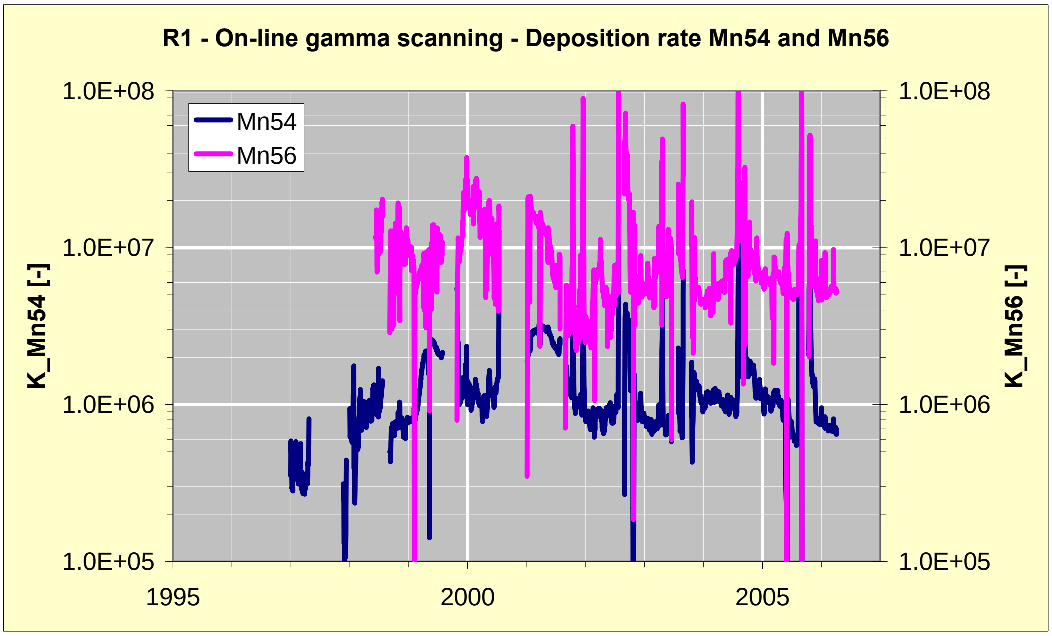

Figure 10: *R1: Mn-54 and Mn-56 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes*

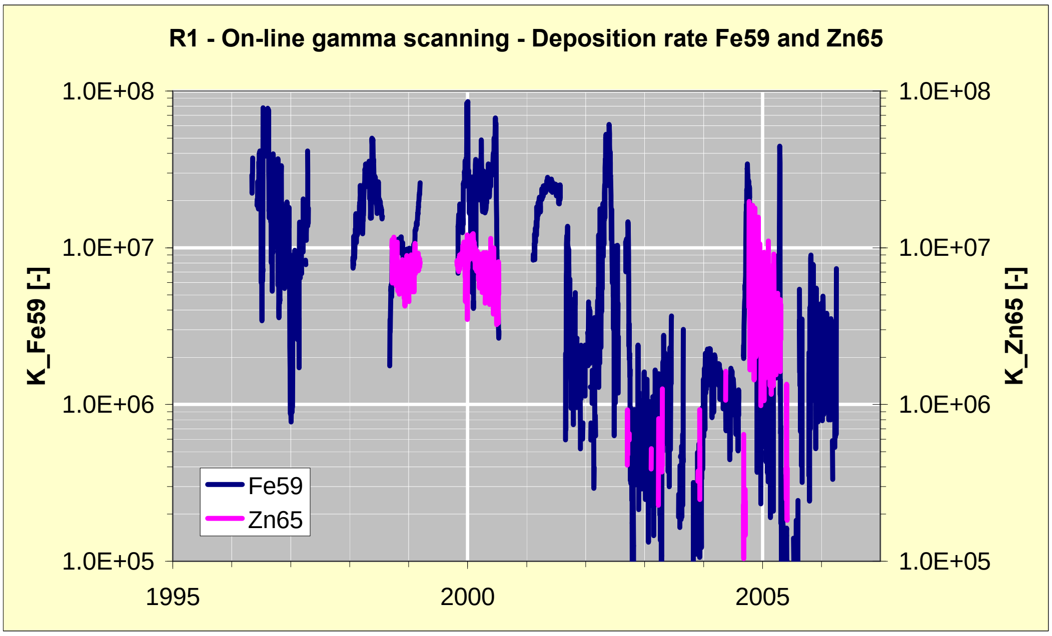

Figure 11: R1: Fe-59 and Zn-65 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes

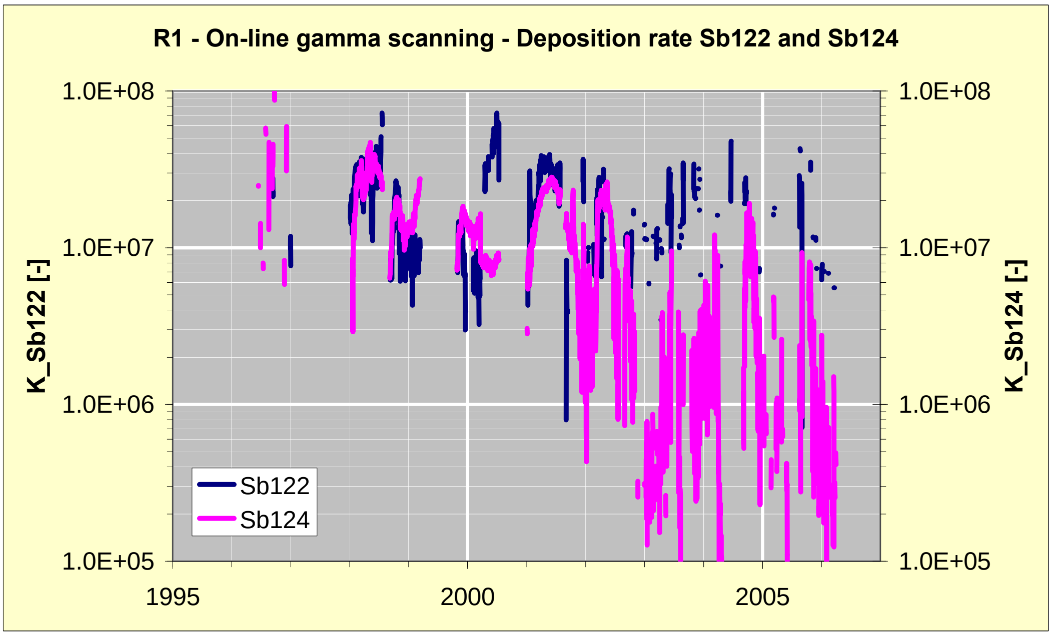

Figure 12: R1: Sb-122 and Sb-124 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes

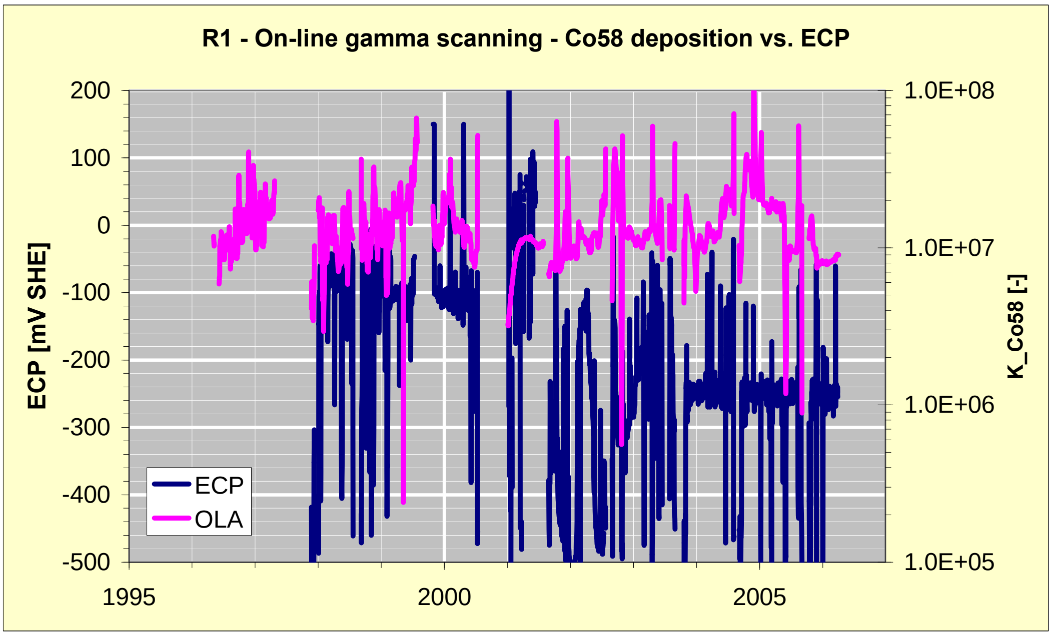

Figure 13: R1: Co-58 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes vs. measured ECP in RHR line

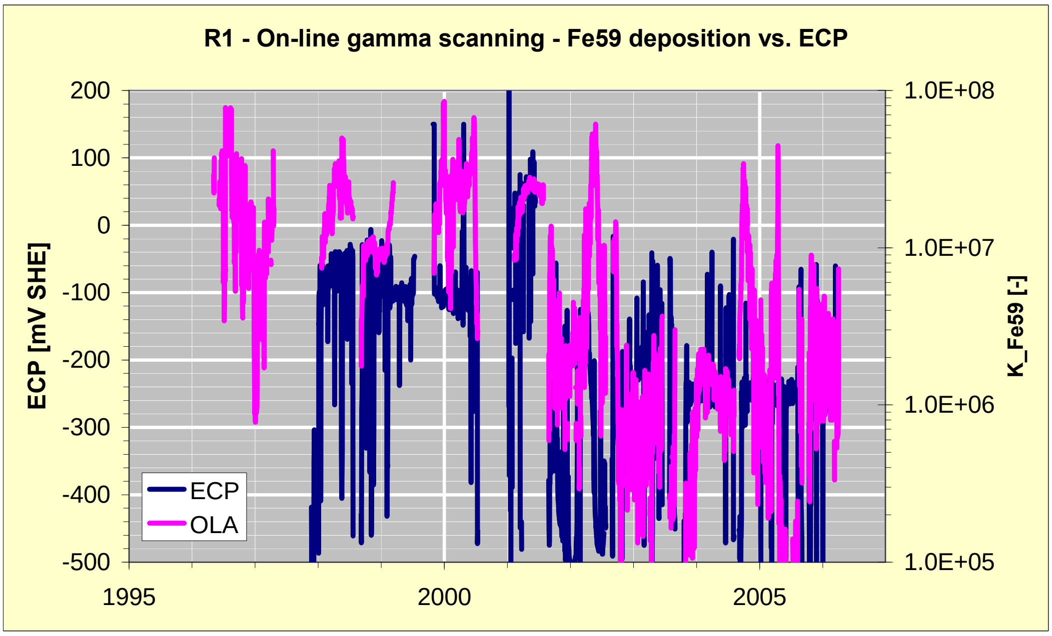

Figure 14: R1: Fe-59 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes vs. measured ECP in RHR line

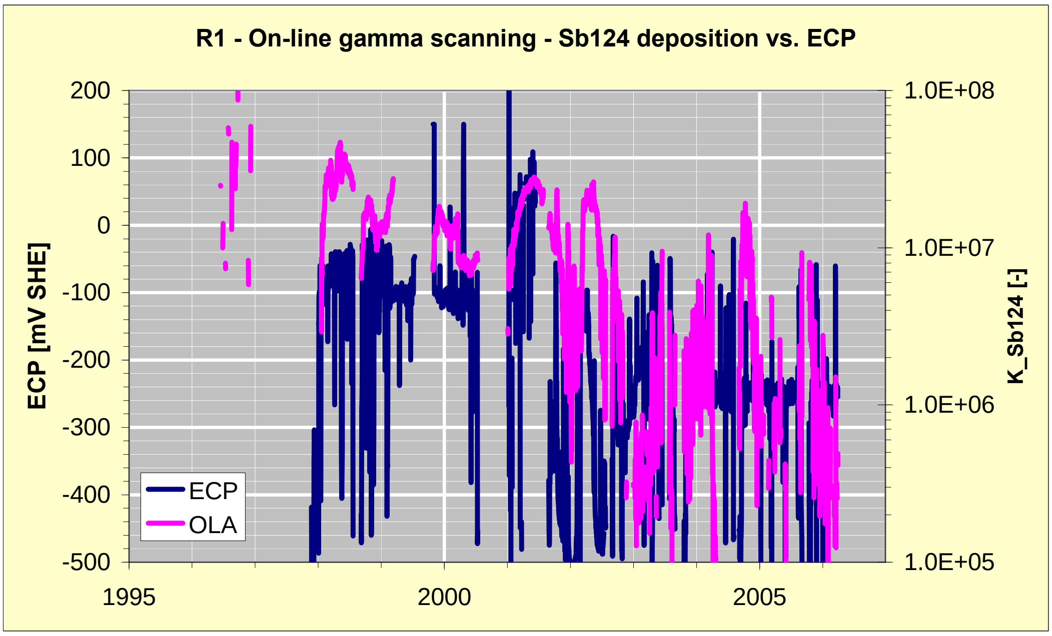

***Figure 15**: R1: Sb-124 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes vs. measured ECP in RHR line*

2.1.3 O2

The O2 plant started operation in 1974. The reactor water chemistry in form of cycle-average data is shown in **Table 10**. The characteristics of O2 from the water chemistry point of view can be summarised in the following way:

- Some Zn and Cu in the reactor water during the first four cycles due to brass condenser tubes[8]. An exchange to titanium tubes has thereafter meant low levels of Cu. Low levels of reactor water Zn was maintained up to the 2003 outage, thereafter DZO injection was started in order to control radiation fields. A major decontamination campaign of primary piping was performed during the 2003 outage, i.e. DZO injection was started with decontaminated pipes.

- HWC operation has been applied since 1993. ECP monitoring has been performed both in the recirculation lines and in the RHR lines, and the hydrogen injection has been determined to control the corrosion potential in the recirculation lines (ECP <-230 mV SHE), which means that the RHR lines show lower potential (ECP ≈-500 mV SHE).

- The feedwater Fe was moderate during the first 10 cycles, but has thereafter been very low (<0.1 ppb)[9]. The introduction of HWC in 1993 has meant an extra inflow of Fe to the primary circuit due to local corrosion in reactor systems obtaining very low corrosion potential, e.g. the CRD[10] system.

The cycle average values of reactor water activated corrosion products are presented in **Table 11**. The variation of reactor water Mn-54 reflects the total inflow of Fe, with the lowest levels the cycles before the introduction of HWC. The introduction of DZO injection also means a reduction of the Mn-54 activity. The Co-58, Co-60 and Sb-124 activity show the opposite influence, with the highest levels during periods with low Fe inflow, and an increase of reactor water activity when DZO injection is started. The Cr-51 reactor water activity is as expected much reduced when the reactor is operating with HWC.

Outage gamma scanning data and dose rates on the standard RHR location are presented in **Table 12**. No gamma scan results have been available during the 9 last cycles, but the Co-60 activity has been estimated based on the dose rate measurements. Note that a system decontamination involving the RHR pipes was carried out during the 2003 outage (the 2003 dose rate measurements reported were performed before the decontamination).

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[8] Note there was a considerable design difference between the O1 and O2 turbine plants resulting in considerable higher feedwater Cu and Zn concentrations in the former.

[9] Note, that the reactor water Fe is not always reflecting the variation in feedwater Fe.

[10] CRD – Control Rod Drives system, i.e. the system providing the control rod drives with a purge flow.

***Table 10**: Oskarshamn 2 – Corrosion product reactor water chemistry data – Annual average data during reactor operation*

		$C_w(t)$								
Cycle	**Year**	**Fe [ppb]**	**Zn [ppb]**	**Ni [ppb]**	**Cr [ppb]**	**Co [ppb]**	**Cu [ppb]**	**Cond. [mS/cm]**	**N/HWC [0/1]**	
1	1975	*1.00*	2.00	*0.20*	2.00	*0.030*	2.00	0.11	0	
2	1976	0.20	1.00	0.13	2.00	0.030	2.00	0.15	0	
3	1977	2.00	0.60	0.40	0.80	0.025	1.00	0.10	0	
4	1978	2.30	0.40	0.20	0.60	0.013	1.00	0.11	0	
5	1979	1.60	0.30	0.20	1.50	0.018	0.20	0.09	0	
6	1980	0.90	0.20	0.30	1.50	0.025	0.10	0.10	0	
7	1981	0.46	0.14	0.20	2.62	*0.020*	*0.10*		0	
8	1982	*0.40*	*0.25*	*0.25*	2.50	0.015	0.08		0	
9	1983	0.20	0.35	0.30	2.35	0.030	0.06	0.08	0	
10	1984	0.37	0.20	0.21	2.00	0.025	0.04	0.07	0	
11	1985	0.54	0.23	0.21	4.60	0.015	0.07	0.08	0	
12	1986	0.41	0.15	0.18	3.34	*0.030*	0.04	0.07	0	
13	1987	0.64	0.21	0.20	4.36	0.080	0.06	0.09	0	
14	1988	0.73	0.17	0.32	3.36	0.040	0.03	0.10	0	
15	1989	1.22	0.10	0.59	3.55	0.028	0.04	0.12	0	
16	1990	0.74	0.15	0.50	2.66	0.030	0.02	0.11	0	
17	1991	0.71	0.17	0.57	4.64	0.039	0.02	0.10	0	
18	1992	0.44	0.09	0.24	2.66	0.034	0.03	0.09	0	
19	1993	1.07	*0.10*	0.33	0.06	0.017	*0.05*	0.05	1	HWC
20	1994	*2.00*	*0.10*	*0.30*	*0.20*	*0.018*	*0.05*	0.05	1	
21	1995	2.89	0.06	0.29	0.21	0.018	0.08	0.05	1	
22	1996	2.47	0.08	0.30	0.45	0.017	0.06	0.05	1	
23	1997	4.47	0.09	0.59	*0.50*	0.012	0.08	0.06	1	
24	1998	1.55	0.03	0.24	0.44	0.008	0.06	0.06	1	
25	1999	1.45	0.08	0.27	0.22	0.012	0.06	0.06	1	
26	2000	1.38	0.04	0.21	0.25	0.009	0.05	0.07	1	
27	2001	1.19	0.15	0.18	0.29	0.005	0.05	0.06	1	
28	2002	2.00	0.36	0.34	0.35	0.017	0.13	0.06	1	
29	2003	1.30	0.42	0.19	0.29	0.012	0.09	0.06	1	
30	2004	1.30	4.82	0.16	0.19	0.016	0.07	0.07	1	+DZO
31	2005	1.10	5.23	0.19	0.23	0.021	0.06	0.07	1	
32	2006	1.64	4.28	0.20	0.25	0.015	0.05	0.07	1	

***Table 11**: Oskarshamn 2 – Activated corrosion products in reactor water – Annual average data during reactor operation*

		$C_w(t)$							
Cycle	Year	Mn54 Bq/kg	Co58 Bq/kg	Co60 Bq/kg	Zn65 Bq/kg	Cr51 Bq/kg	Fe59 Bq/kg	Sb124 Bq/kg	
1	1975	3.7E+02	6.3E+03	2.3E+02	1.1E+03	6.7E+04	7.0E+00	5.8E+02	
2	1976	8.0E+02	1.2E+04	1.7E+03	7.8E+03	1.1E+05	3.0E+02	7.2E+02	
3	1977	5.0E+02	8.5E+03	2.4E+03	1.1E+04	8.1E+04	1.9E+03	2.0E+02	
4	1978	4.1E+02	6.7E+03	1.1E+03	3.2E+03	5.7E+04	3.0E+02	2.4E+02	
5	1979	1.0E+03	6.7E+03	1.3E+03	3.4E+03	1.1E+05	2.4E+02	1.4E+02	
6	1980	1.3E+03	7.3E+03	2.2E+03	3.6E+03	8.3E+04	1.5E+02	1.1E+02	
7	1981	1.7E+03	1.0E+04	1.9E+03	1.7E+03	1.5E+05	4.0E+01	7.3E+01	
8	1982	2.1E+03	1.2E+04	1.8E+03	1.5E+03	2.9E+05	4.0E+01	2.1E+02	
9	1983	3.7E+03	1.5E+04	2.4E+03	1.4E+03	1.4E+05	2.8E+01	1.5E+02	
10	1984	4.0E+03	1.6E+04	2.3E+03	9.5E+02	1.2E+05	4.0E+01	1.9E+02	
11	1985	3.8E+03	1.6E+04	2.7E+03	8.3E+02	1.1E+05	2.9E+01	1.7E+02	
12	1986	5.1E+03	1.8E+04	3.4E+03	8.2E+02	1.0E+05	2.9E+01	6.2E+02	
13	1987	4.0E+03	2.2E+04	3.5E+03	6.2E+02	1.4E+05	2.6E+01	1.7E+03	
14	1988	2.6E+03	2.8E+04	7.1E+03	9.4E+02	2.1E+05	6.1E+01	1.7E+03	
15	1989	1.2E+03	3.7E+04	6.5E+03	9.4E+02	3.7E+05	5.6E+02	1.5E+03	
16	1990	5.4E+02	3.9E+04	6.2E+03	1.3E+03	2.2E+05	3.5E+02	1.3E+03	
17	1991	4.0E+02	4.0E+04	6.6E+03	1.7E+03	2.2E+05	2.1E+02	1.4E+03	
18	1992	5.0E+02	3.1E+04	5.7E+03	1.0E+03	1.7E+05	1.3E+02	2.8E+02	
19	1993	5.8E+02	7.2E+03	3.7E+03	3.5E+02	2.1E+03	1.1E+02	4.4E+02	HWC
20	1994	1.2E+03	7.6E+03	2.9E+03	3.0E+02	4.0E+03	3.4E+02	2.6E+02	
21	1995	2.8E+03	8.2E+03	2.3E+03	2.2E+02	4.3E+03	2.7E+02	1.8E+02	
22	1996	3.3E+03	7.4E+03	1.9E+03	1.5E+02	1.3E+03	1.0E+02	7.6E+02	
23	1997	4.7E+03	1.3E+04	8.6E+03	6.9E+02	2.5E+05	1.5E+03	4.0E+02	
24	1998	2.7E+03	5.2E+03	1.4E+03	1.0E+02	3.4E+04	2.1E+02	2.2E+02	
25	1999	3.3E+03	4.7E+03	2.0E+03	1.2E+02	4.4E+04	3.8E+02	1.6E+02	
26	2000	5.1E+03	6.9E+03	5.9E+03	3.1E+02	5.4E+04	2.2E+03	5.3E+02	
27	2001	2.5E+03	4.3E+03	3.8E+03	2.7E+02	6.6E+03	4.4E+02	1.4E+02	
28	2002	2.3E+03	3.7E+03	2.1E+03	1.6E+02	3.2E+03	2.3E+02	1.7E+02	
29	2003	2.1E+03	2.4E+03	1.5E+03	9.4E+01	2.7E+03	9.8E+01	1.2E+02	
30	2004	1.0E+03	8.6E+03	3.1E+03	4.9E+02	1.8E+03	4.9E+01	7.9E+02	+DZO
31	2005	1.3E+03	1.2E+04	4.2E+03	7.7E+02	4.0E+03	1.5E+02	2.7E+02	
32	2006	1.2E+03	1.9E+04	4.4E+03	1.0E+03	3.5E+03	9.3E+01	4.8E+02	

***Table 12**: Oskarshamn 2 – Gamma scanning data and measured dose rate during outage on RHR piping*

		A(t)								
		Mn54	Co58	Co60	Zn65	Cr51	Fe59	Sb124	DR	
Cycle	Year	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	mSv/h	
1	1975								0.26	
2	1976								1.20	
3	1977	2.9E+07	5.0E+08	3.4E+08	2.4E+08	1.3E+08	1.8E+07	3.8E+07	1.12	
4	1978	2.9E+07	3.1E+08	3.5E+08	2.0E+08	2.2E+08	1.9E+07	1.1E+07	0.55	
5	1979	8.3E+07	5.6E+08	4.6E+08	2.0E+08		4.1E+07	2.5E+07	1.00	
6	1980	1.0E+08	4.3E+08	4.3E+08	9.4E+07		2.9E+07	1.6E+07	1.10	
7	1981	1.5E+08	4.9E+08	5.2E+08	4.3E+07		1.3E+07	2.2E+07	1.35	
8	1982	1.4E+08	6.0E+08	6.3E+08	6.3E+07	1.3E+07	2.0E+07	3.2E+07	1.20	
9	1983	2.3E+08	8.1E+08	8.9E+08	5.0E+07		2.8E+07	4.0E+07	1.45	
10	1984	5.0E+07	4.2E+08	7.7E+08				2.5E+07	1.45	
11	1985	2.3E+08	9.0E+08	1.0E+09			4.0E+07	6.7E+07	1.80	
12	1986								1.60	
13	1987	2.3E+08	9.6E+08	1.4E+09	4.1E+07		4.1E+07	2.0E+08	1.55	
14	1988	9.9E+07	7.0E+08	1.2E+09	3.3E+06	1.2E+08	4.3E+07	2.7E+08	2.70	
15	1989	1.0E+08	9.1E+08	1.7E+09	2.7E+07		1.2E+07	2.2E+07	2.50	
16	1990	6.2E+07	1.2E+09	2.0E+09	2.8E+07	1.1E+08	8.6E+06	4.3E+07	2.80	
17	1991	3.5E+07	8.5E+08	1.8E+09	3.9E+07		8.7E+06	5.3E+07	3.30	
18	1992	1.9E+07	4.8E+08	1.7E+09	2.2E+07	7.3E+07	1.1E+07	3.5E+07	2.98	
19	1993								3.10	HWC
20	1994	2.1E+07	1.2E+09	1.5E+09	7.5E+07	5.7E+08			3.70	
21	1995	4.8E+07	1.3E+09	1.9E+09	9.2E+07	7.5E+08			4.80	
22	1996	6.9E+07	1.4E+09	3.4E+09	1.5E+08	4.1E+08			4.90	
23	1997	2.5E+08	4.6E+08	2.3E+09	2.1E+08	1.5E+09		1.3E+07	2.30	
24	1998								5.90	
25	1999								3.45	
26	2000								4.20	
27	2001								4.67	
28	2002								5.13	
29	2003								6.41	
30	2004	Decontamination							0.97	+DZO
31	2005								0.97	
32	2006								1.13	

The above reactor water activities and gamma scanning data have been recalculated to surface enrichment factors K for the different activated corrosion products according to ***Eq. 1*** and ***Eq. 2***. The resulting K factors for different radionuclides are presented in **Figure 16**. Some comments to the results:

- The reduction of total inflow of Fe at the end of the 1980s results in a reduction of K factors, especially for Fe-59 and Sb-124.
- The introduction of HWC in 1993 results in increased K-factors for many nuclides (most dramatic for Cr-51) but not for Mn-54. Note that no Fe-59 RHR activity is measured after the introduction of HWC, indicating a low Fe-59 activity below the detection limit, i.e. the K-factor for Fe-59 is significantly reduced.
- The introduction of DZO injection after 2003 results in a reduction of the Co-60 K-factor back to the pre-HWC level.

A special on-line dose rate measurement technique on the RHR pipes have been introduced in the O2 plant, where the background level from N-16 in the water is discriminated. Four such locations on the RHR line is monitored, and the measured dose rates from crud in the pipe together with reactor water Zn concentration are shown in **Figure 17**. The radiation build-up without Zn prior to the 2003 outage was fast, but the build-up after decontamination and introduction of DZO has been slow, at least during the two first cycles.

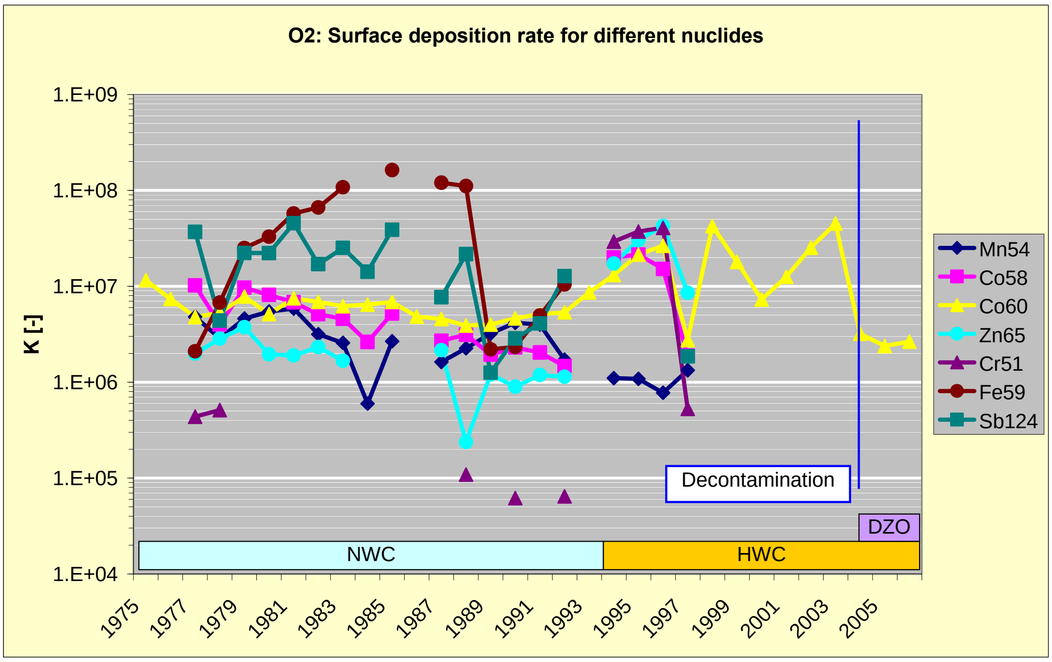

Figure 16: *O2: Surface enrichment factor K based on cycle average reactor water activity and reported gamma scan and dose rate measurements on RHR pipes*

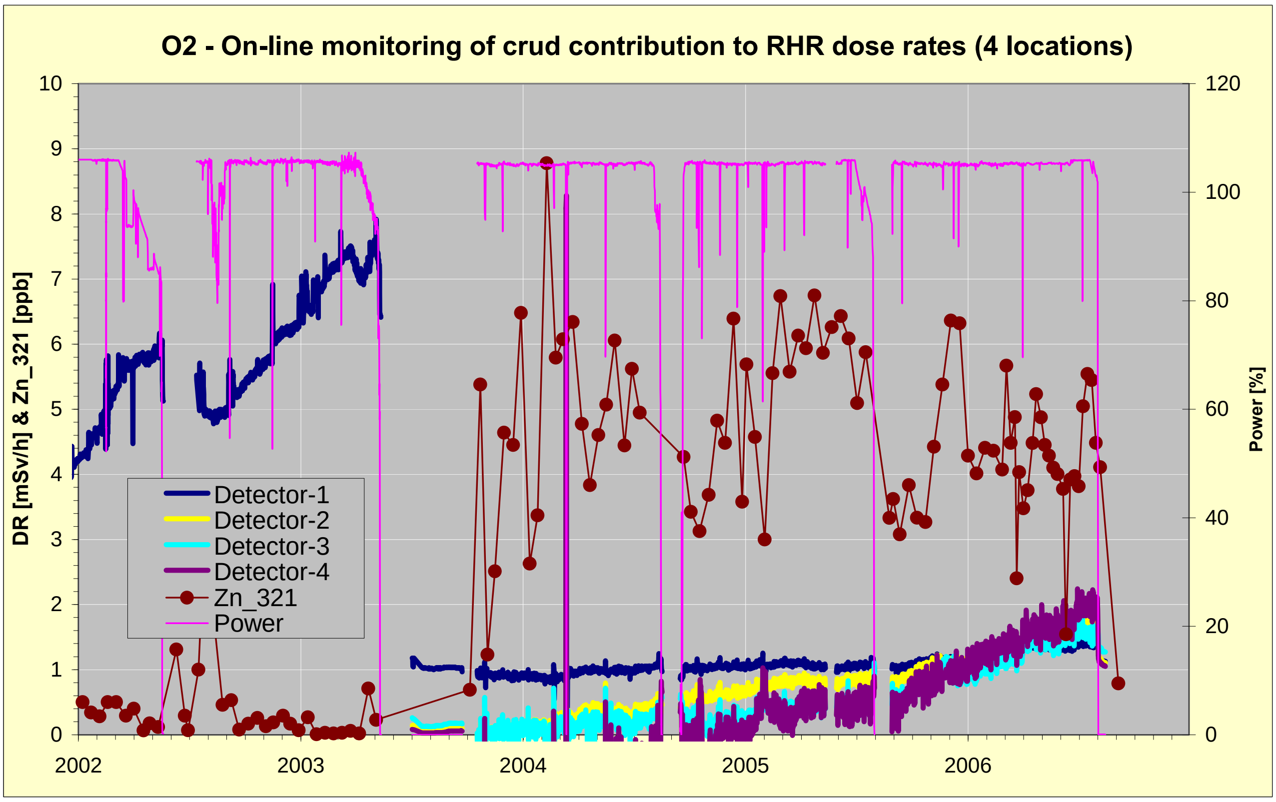

***Figure 17**: O2 – On-line monitoring of crud contribution to RHR dose rates (4 locations) compared to reactor water Zn*

Decontamination of part of the recirculation lines was performed during the 1991 outage, i.e. prior to the introduction of HWC (**Table 13**). A corresponding decontamination of part of the RHR system was performed in 1995, i.e. after two cycles of HWC operation (**Table 14**). The decontamination summaries show large similarities, the main difference being one order of magnitude higher Cr-51 activity in the oxide film formed under HWC conditions. Note that the amount of Cr in both films is comparable.

***Table 13**: O2: Recirculation loop decontamination summary for campaign performed in Aug-1991, i.e. prior to HWC operation (Totally 15 m^2, system 313 (recirculation lines)*

	kg	kg/m2
Fe	0.33	2.20E-02
Cr	0.03	2.00E-03
Ni	0.07	4.67E-03
Cu		0.00E+00
Zn		0.00E+00
Total		2.87E-02

			Aug-91
	%	Bq	Bq/m2
Co58	42%	4.70E+10	3.13E+09
Co60	51%	5.80E+10	3.87E+09
Fe59	0%		
Mn54	2%	1.80E+09	1.20E+08
Cr51	3%	3.30E+09	2.20E+08
Zn65	2%	1.90E+09	1.27E+08
Total	99%	1.13E+11	7.53E+09

***Table 14**: O2: RHR lines decontamination summary for campaign performed in Aug-1995, i.e. after 2 cycles of HWC operation (Totally 30 m^2, system 321 (RHR lines)*

	kg	kg/m2
Fe	0.65	2.17E-02
Cr	0.08	2.67E-03
Ni	0.1	3.33E-03
Cu		0.00E+00
Zn		0.00E+00
Total		2.77E-02

			Aug-95
	%	Bq	Bq/m2
Co58	22%	6.90E+10	2.30E+09
Co60	36%	1.11E+11	3.70E+09
Fe59	0%		
Mn54	1%	4.00E+09	1.33E+08
Cr51	35%	1.09E+11	3.63E+09
Zn65	0%		0.00E+00
Total	95%	3.09E+11	1.03E+10

The measured Co-60 contamination level in the two campaigns can be compared to the 1991 and 1995 gamma scan result from **Table 12**:

- 1991 Co-60 contamination levels:

- RHR gamma scanning:	1.8 $\mathrm{GBq/m^2}$
- Decontamination campaign Aug-91:	3.9 $\mathrm{GBq/m^2}$

- 1995 Co-60 contamination levels:

- RHR gamma scanning:	1.9 $\mathrm{GBq/m^2}$
- Decontamination campaign Aug-95:	3.7 $\mathrm{GBq/m^2}$

The somewhat lower gamma scan results compared to the decontamination results are probably due to that some sedimentary crud is included in the decontamination results.

The decontamination data are recalculated to oxide thickness using ***Eq. 5***. If we assume a composition typical to spinell, e.g. trevorite $NiFe_2O_4$, and that the oxide layer density is typically 3500 kg m^{-3}, the following oxide thicknesses are obtained:

-

- Decontamination campaign Aug-91:	11.3 μm
- Decontamination campaign Aug-95:	10.9 μm

I.e. the film thicknesses are quite similar.

2.1.4 B1

The B1 plant started operation in 1975, and was finally phased-out at the end of 1999. The plant has a similar design as the O2 and B2 plants. The reactor water chemistry in form of cycle-average data is shown in **Table 15**. The characteristics of B1 from the water chemistry point of view can be summarised in the following way:

- Some Zn and Cu in the reactor water during the first four cycles due to brass condenser tubes. An exchange to titanium tubes has thereafter meant low levels of Zn and Cu.

- HWC operation has been applied since 1992. ECP monitoring has been performed both in the recirculation lines and in the RHR lines, and the hydrogen injection has been applied, at least during later cycles, to control the corrosion potential in the recirculation lines (ECP <-230 mV SHE), which means that the RHR lines show lower potential (ECP ≈-500 mV SHE). The initial HWC operation was less well controlled and the average corrosion potential was probably somewhat higher than during the later cycles.

- The feedwater Fe has been moderate to low. The introduction of HWC in 1992 has meant an extra inflow of Fe to the primary circuit due to local corrosion in reactor systems obtaining very low corrosion potential, e.g. the CRD system (cfr. O2).

The cycle average values of reactor water activated corrosion products are presented in **Table 16**. The Mn-54 activity was surprisingly low during the first 10 cycles in spite of not so low inflow of Fe.

Outage gamma scanning data and dose rates on the standard RHR location are presented in **Table 17**.

***Table 15**: Barsebäck 1 – Corrosion product reactor water chemistry data – Annual average data during reactor operation*

		$C_w(t)$								
Cycle	Year	Fe [ppb]	Zn [ppb]	Ni [ppb]	Cr [ppb]	Co [ppb]	Cu [ppb]	Cond. [mS/cm]	N/HWC [0/1]	
1	1976	2.00	3.00	*0.30*	4.10	0.050	2.00	0.11	0	
2	1977	1.30	0.80	*0.30*	2.60	0.041	0.60	0.14	0	
3	1978	1.60	*0.80*	*0.30*	3.70	0.012	0.60	0.12	0	
4	1979	1.55	0.80	*0.30*	*2.50*	*0.013*	1.00	0.20	0	
5	1980	0.50	0.12	0.23	1.89	0.013	0.51	0.10	0	
6	1981	0.33	0.10	0.28	1.96	0.018	0.24	0.10	0	
7	1982	0.46	0.07	0.08	1.67	0.026	0.11	0.12	0	
8	1983	0.22	0.07	0.64	1.50	0.087	0.10	0.10	0	
9	1984	0.36	0.06	0.51	1.36	0.041	0.06	0.09	0	
10	1985	0.23	0.07	0.22	1.71	0.026	0.05	0.09	0	
11	1986	0.22	0.05	*0.20*	1.85	*0.027*	0.05	0.10	0	
12	1987	0.22	0.07	0.19	2.49	0.028	0.05	0.15	0	
13	1988	0.17	0.10	0.51	2.70	0.015	0.05	0.17	0	
14	1989	*0.20*	*0.07*	*0.20*	*2.50*	*0.030*	*0.06*		1	II
15	1990	0.24	0.07	0.17	2.03	0.040	0.07	0.15	0	
16	1991	0.39	*0.07*	0.14	0.15	0.040	0.10	0.14	0	
17	1992	0.74	0.06	0.18	0.27	0.043	0.09	0.07	1	HWC
18	1993	1.44	0.05	0.17	0.19	0.047	0.08	0.08	1	
19	1994	0.29	0.06	0.16	0.11	0.052	0.09	0.07	1	
20	1995	0.57	0.05	0.11	0.08	0.023	0.12	0.07	1	
21	1996	0.56	0.02	0.11	0.05	0.023	0.13	0.07	1	
22	1997	0.74	0.02	0.11	0.06	0.022	0.06	0.07	1	
23	1998	1.09	0.08	0.13	0.14	0.018	0.09	0.07	1	
24	1999	0.86	0.01	0.10	0.08	0.013	0.06	0.07	1	

***Table 16**: Barsebäck 1 – Activated corrosion products in reactor water – Annual average data during reactor operation*

		$C_w(t)$							
Cycle	Year	Mn54 Bq/kg	Co58 Bq/kg	Co60 Bq/kg	Zn65 Bq/kg	Cr51 Bq/kg	Fe59 Bq/kg	Sb124 Bq/kg	
1	1976	4.8E+02	7.6E+03	8.1E+02	1.0E+03	1.1E+05	1.5E+03	5.8E+02	
2	1977	3.6E+02	3.1E+03	1.2E+03	1.1E+03	1.1E+05	2.7E+02	4.4E+02	
3	1978	1.8E+02	3.3E+03	1.0E+03	1.0E+03	9.6E+04	5.2E+02	1.6E+02	
4	1979	3.4E+02	5.2E+03	1.0E+03	9.3E+02	1.4E+05	3.3E+02	6.7E+02	
5	1980	4.5E+02	5.0E+03	1.1E+03	1.1E+03	9.7E+04	2.6E+02	2.2E+02	
6	1981	5.0E+02	4.7E+03	1.2E+03	8.7E+02	9.0E+04	1.7E+02	3.9E+02	
7	1982	4.2E+02	3.9E+03	1.2E+03	7.4E+02	5.5E+04	2.2E+02	5.5E+02	
8	1983	4.3E+02	2.8E+03	1.1E+03	3.6E+02	4.3E+04	1.8E+02	1.0E+03	
9	1984	4.7E+02	6.1E+03	1.2E+03	2.7E+02	6.4E+04	6.2E+02	4.6E+02	
10	1985	6.5E+02	9.0E+03	1.3E+03	1.2E+02	1.1E+05	3.0E+02	8.2E+02	
11	1986	1.2E+03	9.6E+03	1.6E+03	1.3E+02	1.4E+05	3.3E+02	5.4E+02	
12	1987	1.5E+03	1.1E+04	1.7E+03	2.5E+02	1.6E+05	1.4E+02	1.1E+03	
13	1988	8.3E+02	1.2E+04	2.0E+03	2.7E+02	1.5E+05	2.8E+02	4.5E+02	
14	1989	1.4E+03	7.5E+03	2.1E+03	1.8E+02	2.1E+03	1.4E+02	6.4E+02	II
15	1990	1.2E+03	8.4E+03	3.0E+03	2.7E+02	8.0E+04	1.3E+02	2.6E+02	
16	1991	1.7E+03	6.8E+03	2.5E+03	2.9E+02	7.6E+04	1.3E+02	4.3E+02	
17	1992	2.4E+03	5.0E+03	3.1E+03	3.4E+02	1.6E+04	2.9E+02	2.5E+02	HWC
18	1993	2.0E+03	3.2E+03	3.3E+03	2.4E+02	2.1E+03	2.4E+02	3.8E+02	
19	1994	2.2E+03	4.1E+03	3.0E+03	2.5E+02	1.8E+03	1.8E+02	4.5E+02	
20	1995	2.7E+03	4.0E+03	2.8E+03	9.7E+01	1.4E+03	1.4E+02	3.3E+02	
21	1996	3.8E+03	3.3E+03	2.5E+03	8.6E+01	1.7E+03	8.7E+01	5.0E+02	
22	1997	3.0E+03	3.2E+03	2.0E+03	1.0E+02	3.0E+03	1.3E+02	1.0E+03	
23	1998	3.4E+03	7.2E+03	5.8E+03	2.2E+02	5.4E+04	1.5E+03	1.5E+03	
24	1999	2.3E+03	4.6E+03	2.1E+03	4.3E+01	3.4E+04	2.1E+02	6.1E+02	

Table 17: *Barsebäck 1 – Gamma scanning data and measured dose rate during outage on RHR piping*

		A(t)								
		Mn54	Co58	Co60	Zn65	Cr51	Fe59	Sb124	DR	
Cycle	Year	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	mSv/h	
1	1976								0.95	
2	1977	1.6E+07	7.0E+08	4.8E+08	4.8E+07		1.3E+07		1.46	
3	1978		8.2E+08	7.4E+08			3.5E+07	1.4E+07	1.00	
4	1979	1.0E+08	5.9E+08	5.6E+08				1.4E+07	1.19	
5	1980	4.4E+07	1.0E+09	1.3E+09				5.9E+07	1.07	
6	1981		4.1E+08	7.0E+08					1.26	
7	1982	3.0E+07	4.4E+08	6.7E+08	2.2E+07		1.2E+07	2.0E+07	1.23	
8	1983	3.8E+07	4.6E+08	1.0E+09	2.7E+07		2.0E+07	2.5E+07	1.24	
9	1984		4.2E+08	8.1E+08				3.8E+07	1.64	
10	1985								1.40	
11	1986		7.3E+08	1.3E+09					1.43	
12	1987								1.59	
13	1988	5.9E+07	1.3E+09	1.2E+09	2.2E+07		1.5E+07	5.2E+07	1.55	
14	1989								1.70	=
15	1990	8.5E+07	9.6E+08	1.8E+09	9.1E+06	5.4E+07	2.3E+07	1.0E+08	1.85	
16	1991								1.78	
17	1992	6.6E+07	9.4E+08	2.2E+09	2.3E+07	1.6E+08	3.0E+07	4.9E+07	2.80	HWC
18	1993								2.13	
19	1994	2.6E+07	5.8E+08	1.2E+09				1.1E+07	1.94	
20	1995								1.91	
21	1996	5.9E+07	1.1E+09	1.9E+09		2.7E+08	1.0E+07	9.0E+06	1.78	
22	1997	1.4E+07	2.5E+08	6.6E+08				1.1E+07	3.23	
23	1998								6.11	
24	1999								4.85	

The above reactor water activities and gamma scanning data have been recalculated to surface enrichment factors K for the different activated corrosion products according to ***Eq. 1*** and ***Eq. 2***. The resulting K factors for different radionuclides are presented in **Figure 16**. Some comments to the results:

- The K-factors show a rather low variation, especially for Co-60. There is an indication of an increase for Co-60 during the last 3 cycles, which coincides with the period with improved control of HWC with reduced corrosion potential.

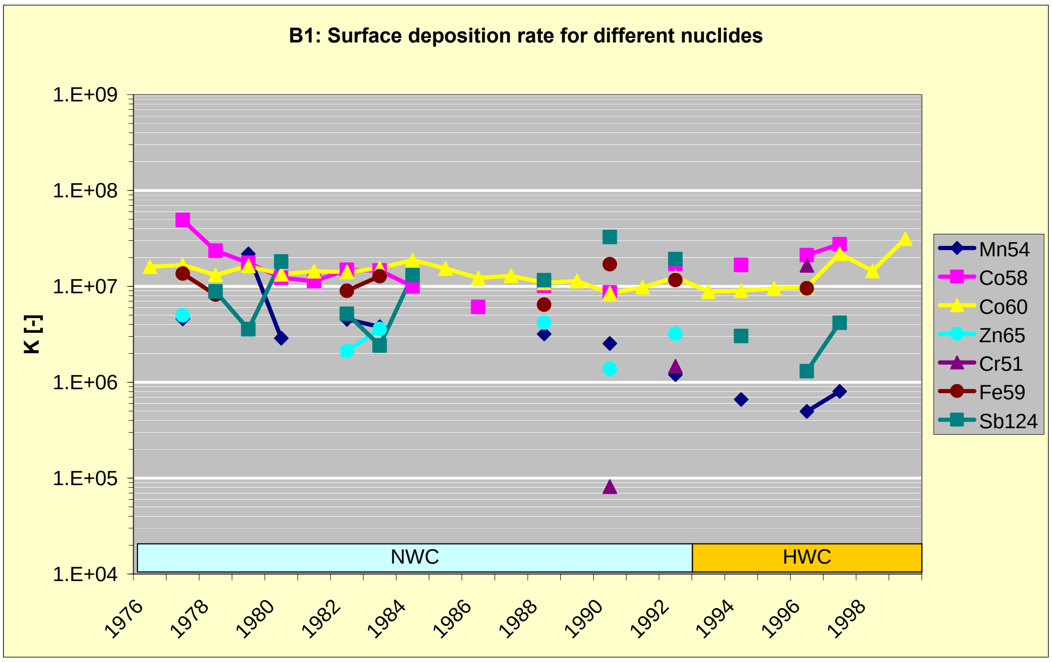

***Figure 18**: B1: Surface enrichment factor K based on cycle average reactor water activity and reported gamma scan and dose rate measurements on RHR pipes*

2.1.5 B2

The B2 plant started operation in 1977, and was finally phased-out during 2005. The plant has a similar design as the O2 and B1 plants. The reactor water chemistry in form of cycle-average data is shown in **Table 18**. The characteristics of B2 from the water chemistry point of view can be summarised in the following way:

- Some Zn and Cu in the reactor water during the first two cycles due to brass condenser tubes. An exchange to titanium tubes has thereafter meant low levels of Cu, and also Zn up to the 1998 outage. DZO was, however, started in the beginning of 1999 and maintained the rest of operation. The Zn reactor water concentration during the DZO injection has, however, been kept somewhat lower than in the O2 plant, cf. **Table 10**.

- HWC operation has been applied since 1992. ECP monitoring has been performed both in the recirculation lines and in the RHR lines, and the hydrogen injection has been applied, at least during later cycles, to control the corrosion potential in the recirculation lines (ECP <-230 mV SHE), which means that the RHR lines show lower potential (ECP ≈-500 mV SHE). The initial HWC operation was less well controlled and the average corrosion potential was probably somewhat higher than during the later cycles.

- The feedwater Fe has been moderate to low. The introduction of HWC in 1992 has meant an extra inflow of Fe to the primary circuit due to local corrosion in reactor systems obtaining very low corrosion potential, e.g. the CRD system (cf. O2 and B1).

The cycle average values of reactor water activated corrosion products are presented in **Table 19**. The Mn-54 activity was surprisingly low during the first 6 cycles in spite of not so low inflow of Fe, cf. B1 (**Table 16**).

Outage gamma scanning data and dose rates on the standard RHR location are presented in **Table 20**. Note that system decontamination was performed during the 2002 outage, but the dose rate measurement reported in the table was performed before the decontamination.

***Table 18**: Barsebäck 2 – Corrosion product reactor water chemistry data – Annual average data during reactor operation*

		$C_w(t)$								
Cycle	**Year**	**Fe [ppb]**	**Zn [ppb]**	**Ni [ppb]**	**Cr [ppb]**	**Co [ppb]**	**Cu [ppb]**	**Cond. [mS/cm]**	**N/HWC [0/1]**	
1	1978	1.65			5.25	0.020	1.70	0.09	0	
2	1979	1.80	1.10				0.65	0.10	0	
3	1980	0.70	0.10	0.32	1.54	0.016	0.46	0.10	0	
4	1981	0.54	0.14	0.43	1.67	0.041	0.42	0.11	0	
5	1982	0.63	0.05	0.14	1.21	0.017	0.20	0.10	0	
6	1983	0.56	0.07	0.34	1.40	0.044	0.14	0.09	0	
7	1984	0.55	0.06	0.74	1.46	0.045	0.06	0.09	0	
8	1985	0.46	0.04	0.27	3.15	0.017	0.05	0.13	0	
9	1986	0.28	0.05	0.30	3.24	0.021	0.05	0.15	0	
10	1987	0.28	0.09	0.38	3.01	0.026	0.04	0.15	0	
11	1988	0.31	0.13		3.08		0.05	0.17	0	
12	1989								0	
13	1990	0.42	0.09	0.41	1.88	0.048	0.07	0.12	0	
14	1991	1.34	0.47	0.29	1.89	0.046	0.12	0.15	0	
15	1992	1.59	0.09	0.17	0.19	0.051	0.07	0.10	1	HWC
16	1993	2.20	0.07	0.16	0.20	0.045	0.04	0.08	1	
17	1994	0.65	0.06	0.13	0.10	0.049	0.04	0.06	1	
18	1995	0.50	0.06	0.14	0.06	0.027	0.05	0.07	1	
19	1996	2.99	0.03	0.15	0.06	0.027	0.07	0.07	1	
20	1997	3.29	0.13	0.16	0.06	0.032	0.07	0.07	1	
21	1998	2.69	0.02	0.17	0.04	0.018	0.07	0.06	1	
22	1999	1.01	1.68	0.11	0.05	0.022	0.05	0.06	1	DZO+HWC
23	2000	0.66	3.98	0.10	0.02	0.023	0.04	0.06	1	
24	2001	0.70	2.65	0.11	0.05	0.019	0.07	0.06	1	
25	2002	0.92	1.76	0.09	0.05	0.015	0.05	0.06	1	
26	2003	3.06	2.49	0.36	0.34	0.016	0.10	0.06	1	
27	2004	1.94	2.34	0.28	0.46	0.018	0.10	0.06	1	
28	2005	0.70	2.57	0.13	0.11	0.015	0.05	0.06	1	

***Table 19**: Barsebäck 2 – Activated corrosion products in reactor water – Annual average data during reactor operation*

		$C_w(t)$							
Cycle	**Year**	**Mn54 Bq/kg**	**Co58 Bq/kg**	**Co60 Bq/kg**	**Zn65 Bq/kg**	**Cr51 Bq/kg**	**Fe59 Bq/kg**	**Sb124 Bq/kg**	
1	1978	4.3E+02	4.1E+03	7.0E+02	7.8E+02	9.3E+04	5.4E+02	2.5E+03	
2	1979	2.9E+02	4.2E+03	8.5E+02	8.7E+02	1.2E+05	6.8E+02	3.0E+02	
3	1980	4.2E+02	4.8E+03	1.1E+03	1.0E+03	1.1E+05	5.3E+02	2.1E+02	
4	1981	4.4E+02	4.2E+03	9.1E+02	9.4E+02	1.2E+05	6.0E+02	7.3E+02	
5	1982	5.0E+02	1.8E+03	5.9E+02	1.0E+03	9.1E+04	7.0E+02	1.5E+03	
6	1983	6.5E+02	1.2E+03	7.1E+02	8.3E+02	1.6E+05	2.9E+02	1.4E+02	
7	1984	1.1E+03	2.4E+03	1.1E+03	7.1E+02	1.4E+05	1.6E+03	2.6E+03	
8	1985	1.3E+03	3.5E+03	8.0E+02	6.1E+02	1.6E+05	1.2E+03	4.8E+02	
9	1986	3.2E+03	5.9E+03	1.9E+03	5.2E+02	2.2E+05	1.2E+03	3.0E+02	
10	1987	3.5E+03	1.4E+04	2.2E+03	5.1E+02	1.2E+05	2.2E+02	8.9E+02	
11	1988	2.7E+03	1.6E+04	2.5E+03	4.9E+02	1.0E+05	3.1E+03	9.9E+02	
12	1989	2.1E+03	1.5E+04	2.8E+03	5.5E+02	9.2E+04	1.2E+03	2.5E+02	
13	1990	1.6E+03	1.6E+04	3.0E+03	4.9E+02	8.3E+04	1.2E+02	3.0E+02	
14	1991	2.5E+03	1.9E+04	2.7E+03	4.3E+02	9.8E+04	6.2E+02	2.4E+02	
15	1992	3.3E+03	1.2E+04	3.2E+03	3.9E+02	4.5E+03	6.4E+02	2.3E+02	HWC
16	1993	3.1E+03	1.0E+04	2.9E+03	3.3E+02	4.1E+03	2.6E+02	3.1E+02	
17	1994	3.6E+03	1.1E+04	3.8E+03	2.8E+02	4.1E+03	3.3E+02	3.8E+02	
18	1995	3.2E+03	8.6E+03	2.7E+03	1.8E+02	1.5E+03	1.3E+02	1.9E+02	
19	1996	3.6E+03	6.2E+03	2.3E+03	1.2E+02	1.2E+03	1.6E+02	3.9E+02	
20	1997	3.4E+03	5.8E+03	2.0E+03	9.6E+01	1.6E+03	1.2E+02	2.1E+02	
21	1998	3.2E+03	4.2E+03	1.4E+03	6.6E+01	8.7E+02	7.5E+01	1.6E+02	
22	1999	2.1E+03	9.9E+03	2.0E+03	1.4E+02	3.5E+02	3.1E+01	7.8E+01	DZO+HWC
23	2000	1.0E+03	1.4E+04	2.2E+03	3.3E+02	4.1E+02	2.4E+01	1.4E+02	
24	2001	1.6E+03	1.3E+04	2.6E+03	3.6E+02	3.3E+03	6.5E+01	1.3E+02	
25	2002	2.1E+03	1.4E+04	3.7E+03	4.3E+02	9.3E+03	1.4E+02	3.4E+02	
26	2003	1.8E+03	1.2E+04	3.4E+03	4.2E+02	1.3E+04	1.9E+02	1.6E+02	
27	2004	1.8E+03	1.4E+04	6.2E+03	5.5E+02	1.6E+04	2.7E+02	3.4E+02	
28	2005	2.4E+03	1.8E+04	4.3E+03	7.0E+02	6.4E+03	1.2E+02		

***Table 20**: Barsebäck 2 – Gamma scanning data and measured dose rate during outage on RHR piping*

		A(t)								
		Mn54	Co58	Co60	Zn65	Cr51	Fe59	Sb124	DR	
Cycle	Year	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	mSv/h	
1	1978		2.5E+08	1.3E+08	2.2E+07			1.2E+06	0.55	
2	1979	1.1E+07	5.6E+08	3.7E+08	6.3E+07			3.3E+06	0.63	
3	1980	2.4E+07	3.7E+08	3.7E+08	3.6E+07	1.9E+08	1.7E+07	5.9E+06	0.78	
4	1981		1.1E+09	1.1E+09					0.60	
5	1982								0.84	
6	1983	1.1E+08	6.2E+08	8.7E+08	9.5E+07		3.9E+07	1.0E+07	1.08	
7	1984	9.7E+07	3.3E+08	6.3E+08					1.25	
8	1985								1.66	
9	1986	1.0E+08	4.0E+08	7.2E+08				4.0E+07	2.08	
10	1987	2.5E+08	1.3E+09	1.5E+09	2.7E+07	1.6E+08	4.3E+07	6.4E+07	1.94	
11	1988								1.95	
12	1989	6.9E+07	7.6E+08	1.2E+09	2.0E+07	5.5E+07	1.5E+07	3.6E+07	2.30	
13	1990								1.80	
14	1991	4.4E+07	9.0E+08	9.5E+08	2.9E+07	8.6E+07	9.1E+06	8.0E+06	2.70	
15	1992								2.60	HWC
16	1993	6.7E+07	1.1E+09	1.7E+09	4.2E+07		1.4E+07	1.4E+07	4.30	
17	1994								2.60	
18	1995	4.6E+07	7.5E+08	1.3E+09	1.4E+07	4.5E+08	1.3E+07	1.3E+07	2.20	
19	1996	3.9E+07	1.0E+09	1.5E+09	3.0E+07	2.4E+08	2.3E+07		2.69	
20	1997	7.7E+07	1.3E+09	1.4E+09	5.6E+07	5.7E+08			1.55	
21	1998	8.5E+07	1.9E+09	1.7E+09	7.2E+07	3.0E+08			3.48	
22	1999		1.6E+08	5.6E+08					3.42	DZO+HWC
23	2000	2.9E+07	2.7E+08	1.5E+09	4.2E+07	1.8E+08			2.30	
24	2001	3.1E+07	1.7E+09	2.1E+09	6.5E+07	8.8E+08	9.7E+06	1.4E+06	3.20	
25	2002								3.90	
		Decontamination								
26	2003	4.6E+07	1.2E+09	5.5E+08	5.2E+07	1.4E+09	6.7E+06	2.2E+06	1.50	
27	2004	3.3E+07	8.5E+08	8.0E+08	4.8E+07	1.4E+09	3.9E+06	3.3E+06	2.15	
28	2005									

The above reactor water activities and gamma scanning data have been recalculated to surface enrichment factors K for the different activated corrosion products according to ***Eq. 1*** and ***Eq. 2***. The resulting K factors for different radionuclides are presented in **Figure 19**. Some comments to the results:

- The K-factors show a rather low variation for the Co isotopes, especially for Co-60. The HWC operation after some years means an increase of the K-factors, especially for Cr-51, while the introduction of DZO injection means a reduction of K-factors, especially for Sb-124.

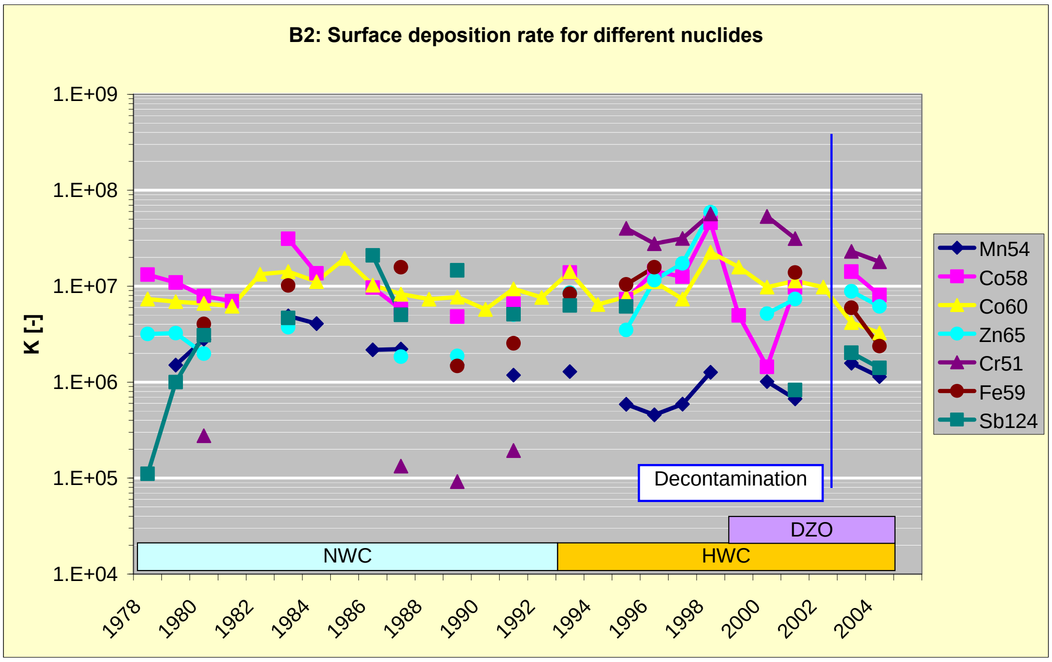

***Figure 19**: B2: Surface enrichment factor K based on cycle average reactor water activity and reported gamma scan and dose rate measurements on RHR pipes*

An on-line gamma scan equipment has been in operation on a RHR line from the end of 1998, i.e. just prior to the start of DZO injection, and some data in form of calculated K factors according to ***Eq. 1*** and ***Eq. 2*** are presented in **Figure 20** - **Figure 22**. The K-factors according to the on-line measurements show large similarities with those in **Figure 19**. The reduction of K-factors with the introduction of DZO injection is seen. The effect of varying Zn level in the reactor water is especially studied in **Figure 23**, where the evaluated variation of K-factor for the short-lived nuclide Zn-69m is compared to measured reactor water Zn concentration. The data show some scattering, but the general trend is that increased reactor water Zn means reduced Zn-69m K-factor, and vice versa. Not also again the difference between K-factors for the Mn isotopes with different half-lives, Mn-54 and Mn-56 (**Figure 21**), as well as for the Zn isotopes Zn-65 and Zn-69m (**Figure 22**). This difference is probably as mentioned earlier a measuring artefact due to a significant consumption of the short-lived nuclides Mn-56 and Zn-69m in the sampling lines, i.e. the reactor water activity of these nuclides is underestimated.

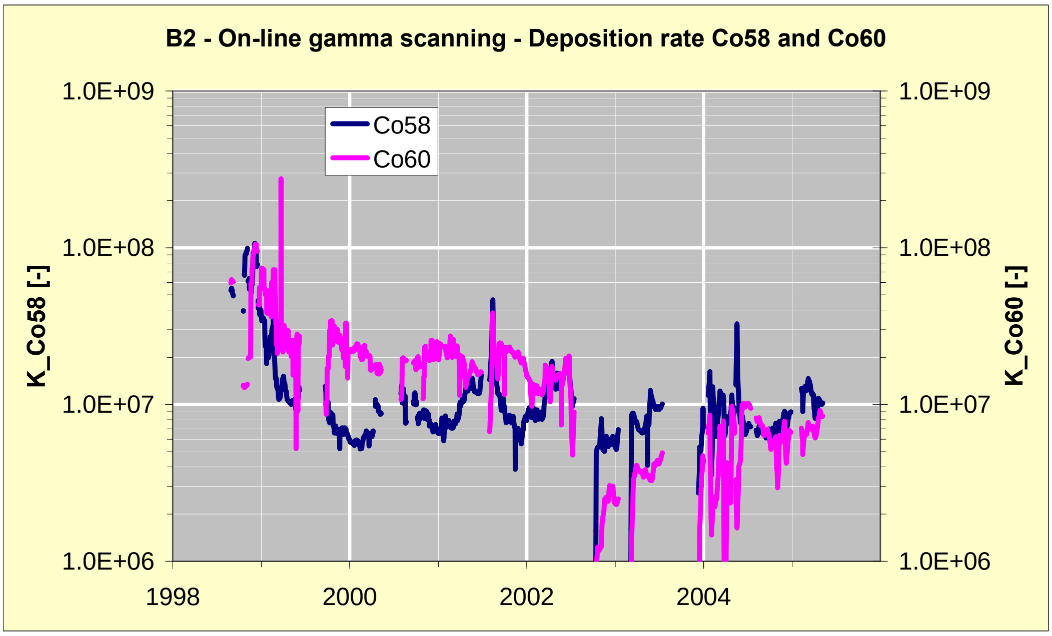

***Figure 20**: B2: Co-58 and Co-60 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes*

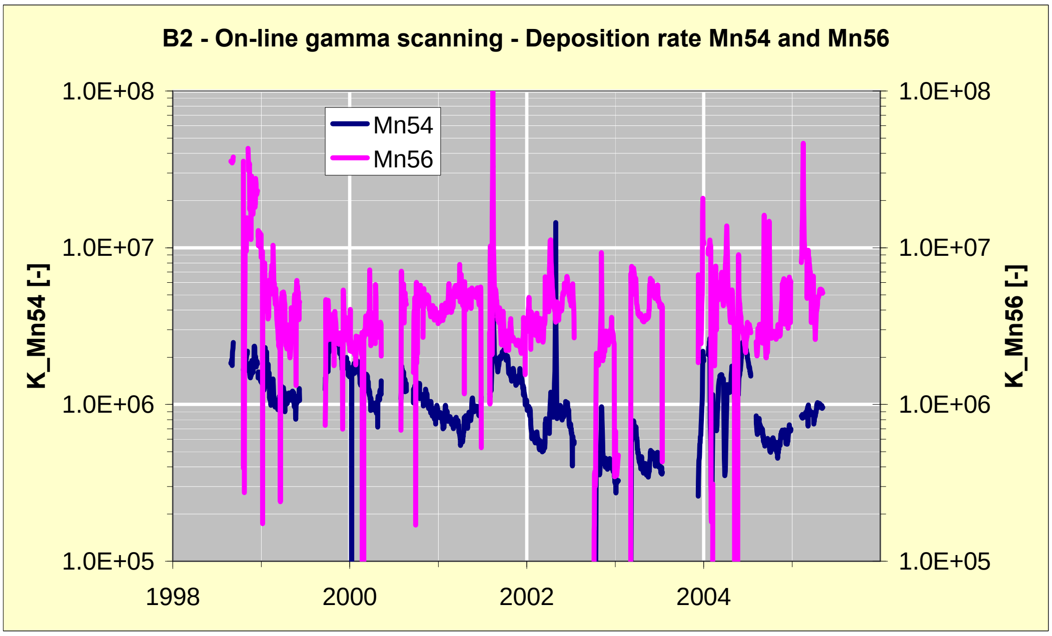

***Figure 21**: B2: Mn-54 and Mn-56 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes*

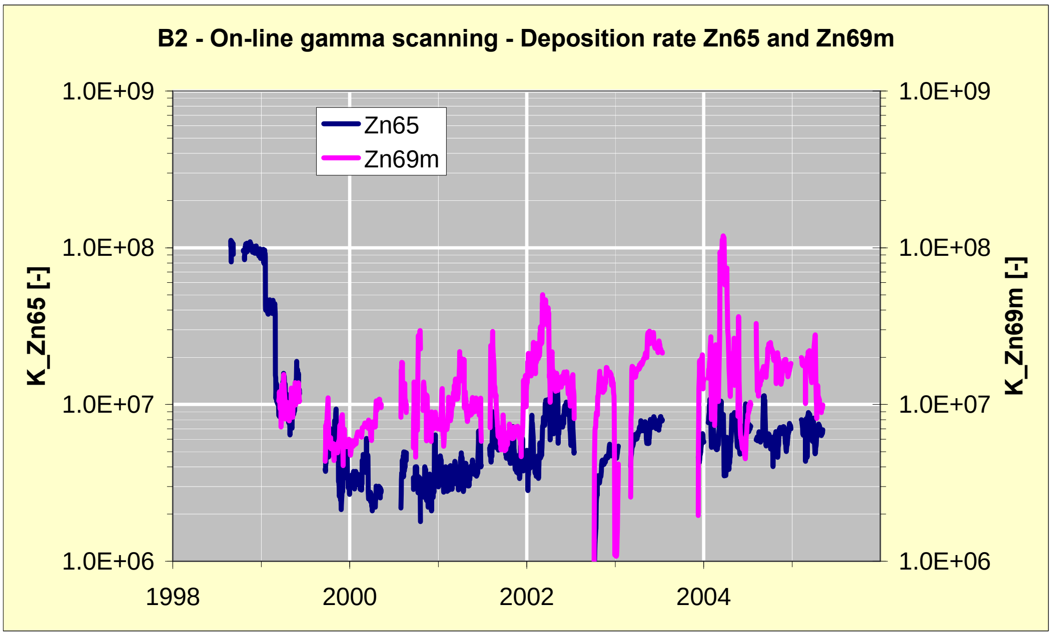

Figure 22: B2: Zn-65 and Zn-69m surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes

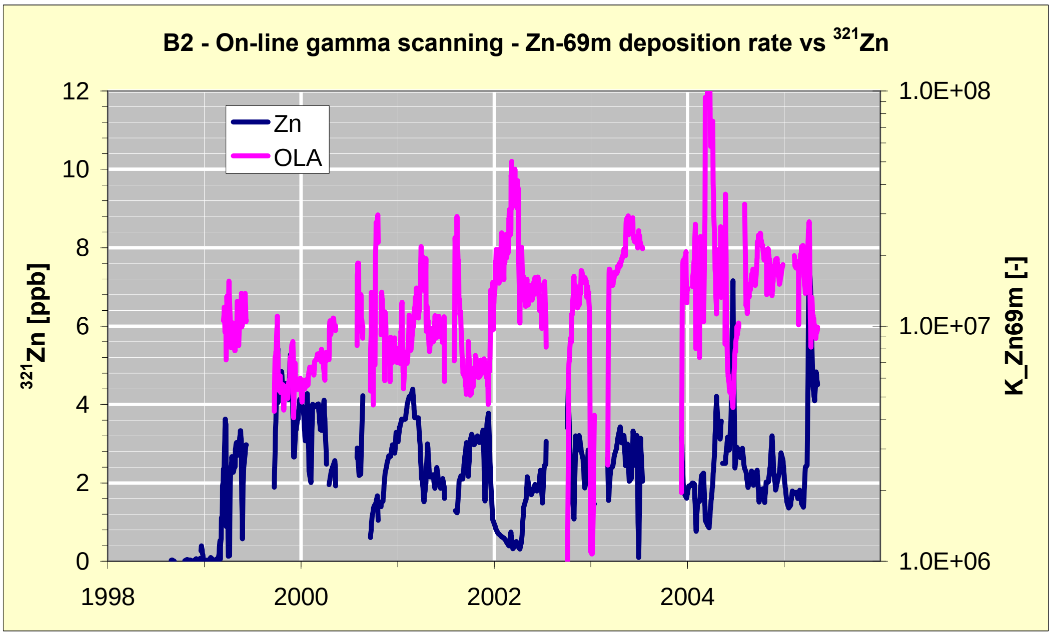

Figure 23: B2: Zn-69m surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes vs. measured reactor water Zn

Decontamination of a large fraction of the primary system was performed during the 2002 outage, i.e. after 3 cycles of DZO injection (**Table 21**). Note that the amount of Zn, not only the amount of radioactive Zn-65, incorporated in the oxide film was measured. The measured radioactivity is quite comparable to the earlier performed gamma scans, see **Table 19**. Note especially the rather large activity of Cr-51 in the oxide, which seems to be typical for films formed under HWC conditions (cf. O2, **Table 14**).

***Table 21**: B2: Primary system decontamination summary for campaign performed in Aug-2002, i.e. after 3 cycles of DZO injection (Totally 685 m^2, system 313 (recirculation lines), 326 (Reactor head flange cooling), 321 (RHR system), 331 (RWCU system)*

	kg	kg/m2
Fe	10.247	1.50E-02
Cr	3.796	5.54E-03
Ni	1.57	2.29E-03
Mn	10.447	
Zn	0.60	8.76E-04
Total		2.37E-02

			Aug-02
	%	Bq	Bq/m2
Co58	17%	7.31E+11	1.07E+09
Co60	35%	1.51E+12	2.20E+09
Fe59	1%	2.58E+10	3.77E+07
Mn54	1%	5.59E+10	8.16E+07
Cr51	44%	1.89E+12	2.76E+09
Zn65	2%	7.74E+10	1.13E+08
	100%	4.30E+12	6.28E+09

The decontamination data can be recalculated to oxide thickness using ***Eq. 5***. If we assume a composition typical to spinell, e.g. trevorite $NiFe_2O_4$, and that the oxide layer density is typically 3500 kg m^{-3}, the following oxide thicknesses are obtained:

- \- Decontamination campaign Aug-02: 9.3 µm

The film thickness is quite similar as was found in earlier decontamination campaigns in O2.

2.2 Internal pump plants

2.2.1 OL1

The OL1 plant started operation in 1978. The reactor water chemistry in form of cycle-average data is shown in **Table 22**. The characteristics of OL1 from the water chemistry point of view can be summarised in the following way:

- The plant has in principle always been operating with low levels of Cu and Zn.
- The plant started with a rather high inflow of feedwater Fe, but this inflow has been gradually reduced to presently rather, but not extremely, low levels (i.e. >0.1 ppb).
- The plant has always operated with NWC.

The cycle average values of reactor water activated corrosion products are presented in **Table 23**. The decrease in Fe inflow is seen as reduced reactor water concentrations of Mn-54 and Fe-59.

Outage gamma scanning data and dose rates on the standard RHR location are presented in **Table 24**.

Table 22: *Olkiluoto 1 – Corrosion product reactor water chemistry data – Annual average data during reactor operation*
*(*Data in *italics* has been estimated*)*

		$C_w(t)$							
Cycle	**Year**	**Fe [ppb]**	**Zn [ppb]**	**Ni [ppb]**	**Cr [ppb]**	**Co [ppb]**	**Cu [ppb]**	**Cond. [mS/cm]**	**N/HWC [0/1]**
1	1979	*0.30*	*0.20*	*0.30*	*0.50*	*0.020*	*0.50*	0.24	0
2	1980	*0.30*	*0.20*	*0.30*	*0.50*	*0.020*	*0.50*	0.07	0
3	1981	*0.30*	*0.20*	*0.30*	*0.50*	*0.020*	*0.50*	0.06	0
4	1982	*0.30*	*0.20*	*0.30*	*0.50*	*0.020*	*0.50*		0
5	1983	*0.30*	*0.20*	*0.30*	*0.50*	*0.020*	*0.50*		0
6	1984	0.30	0.10	0.30	0.50	*0.020*	0.40		0
7	1985	0.40	0.10	0.30	0.50	*0.020*	0.70		0
8	1986	0.20	0.20	0.20	0.50	0.017	0.50	0.07	0
9	1987	0.28	0.10	0.35	1.00	0.020	0.18	0.08	0
10	1988	0.45	0.10	0.30	3.25	0.020	0.12	0.13	0
11	1989	0.45	0.10	0.25	2.50	0.015	0.07	0.12	0
12	1990	0.55	0.05	0.25	2.00	0.020	0.06	0.13	0
13	1991	0.83	0.05	0.30	1.50	0.030	0.04	0.12	0
14	1992	0.68	0.10	0.25	1.50	0.025	0.04	0.10	0
15	1993	0.30	0.10	0.20	1.50	0.025	0.03	0.09	0
16	1994	0.35	0.05	0.25	1.50	0.025	0.03	0.10	0
17	1995	0.30	0.05	0.20	1.50	0.025	0.01	0.13	0
18	1996	0.18	0.05	0.20	1.50	0.030	0.02	0.08	0
19	1997	0.20	0.10	0.20	1.00	0.027	0.02	0.12	0
20	1998	0.20	*0.10*	0.25	1.00	0.023	0.02	0.13	0
21	1999	0.27	0.13	0.28	1.42	0.029	0.02	0.13	0
22	2000	0.29	0.05	0.24	1.50	0.028	0.01	0.11	0
23	2001	0.26	0.04	0.16	1.29	0.027	0.01	0.10	0
24	2002	0.21	0.05	0.14	1.11	0.027	0.01	0.09	0
25	2003	0.18	0.09	0.16	1.11	0.026	0.02	0.08	0
26	2004	0.17	0.10	0.15	1.06	0.027	0.02	0.08	0
27	2005	0.14	0.04	0.13	0.97	0.023	0.02	0.08	0
28	2006	0.16	0.34	0.16	1.07	0.022	0.02	0.08	0

***Table 23**: Olkiluoto 1 – Activated corrosion products in reactor water – Annual average data during reactor operation*
*(*Data in *italics* has been estimated*)*

		$C_w(t)$						
Cycle	**Year**	**Mn54 Bq/kg**	**Co58 Bq/kg**	**Co60 Bq/kg**	**Zn65 Bq/kg**	**Cr51 Bq/kg**	**Fe59 Bq/kg**	**Sb124 Bq/kg**
1	1979	*2.0E+03*	*1.0E+04*	*1.0E+03*	*7.0E+02*	*1.0E+05*	*2.0E+03*	
2	1980	4.4E+03	1.5E+04	1.4E+03	8.9E+02	1.8E+05	2.6E+03	
3	1981	*3.5E+03*	*7.0E+03*	*1.3E+03*	*1.0E+03*	*1.0E+05*	*2.0E+03*	
4	1982	*3.5E+03*	*7.0E+03*	*1.3E+03*	*1.0E+03*	*1.0E+05*	*2.0E+03*	
5	1983	*3.5E+03*	*7.0E+03*	*1.3E+03*	*1.0E+03*	*1.0E+05*	*2.0E+03*	
6	1984	*3.5E+03*	*7.0E+03*	*1.3E+03*	*1.0E+03*	*1.0E+05*	*2.0E+03*	
7	1985	*3.5E+03*	*7.0E+03*	*1.3E+03*	*1.0E+03*	*1.0E+05*	*2.0E+03*	
8	1986	3.1E+03	6.2E+03	1.3E+03	1.5E+03	5.8E+04	7.7E+03	6.7E+03
9	1987	2.9E+03	5.1E+03	1.3E+03	1.8E+03	8.7E+04	1.2E+03	1.9E+04
10	1988	4.9E+03	8.0E+03	2.5E+03	1.1E+03	3.2E+05	1.2E+03	2.6E+02
11	1989	6.9E+03	8.7E+03	3.3E+03	9.5E+02	2.2E+05	3.3E+02	1.2E+03
12	1990	8.1E+03	8.5E+03	4.2E+03	3.5E+02	1.3E+05	2.7E+02	1.5E+02
13	1991	9.2E+03	8.1E+03	4.1E+03	1.6E+02	8.4E+04	2.3E+02	1.2E+02
14	1992	8.0E+03	7.2E+03	4.7E+03	2.3E+02	1.1E+05	1.5E+02	1.7E+02
15	1993	7.6E+03	7.1E+03	5.2E+03	2.3E+02	9.3E+04	1.1E+02	1.8E+02
16	1994	7.7E+03	6.9E+03	5.2E+03	2.1E+02	6.5E+04	1.3E+02	4.0E+02
17	1995	5.6E+03	7.1E+03	5.1E+03	1.6E+02	4.7E+04	7.9E+01	2.7E+02
18	1996	4.2E+03	6.8E+03	3.4E+03	9.0E+01	4.6E+04	2.7E+01	6.0E+02
19	1997	2.7E+03	6.8E+03	3.3E+03	1.2E+02	5.6E+04	3.1E+01	3.8E+02
20	1998	2.7E+03	6.2E+03	3.2E+03	8.9E+01	4.2E+04	2.4E+01	1.0E+03
21	1999	1.8E+03	7.1E+03	3.7E+03	1.4E+02	4.3E+04	4.6E+01	1.5E+03
22	2000	1.0E+03	7.1E+03	4.5E+03	1.4E+02	5.4E+04	4.2E+01	1.5E+03
23	2001	7.0E+02	6.1E+03	4.4E+03	9.0E+01	4.2E+04	2.7E+01	7.2E+02
24	2002	1.2E+03	5.8E+03	4.0E+03	6.4E+01	3.9E+04	2.0E+02	5.7E+02
25	2003	2.3E+03	5.3E+03	3.4E+03	9.8E+01	3.5E+04	1.8E+01	1.2E+03
26	2004	2.0E+03	5.7E+03	3.9E+03	8.0E+01	3.8E+04	8.5E+01	6.4E+02
27	2005	2.3E+03	5.2E+03	3.1E+03	7.5E+01	4.3E+04	2.1E+01	1.1E+03
28	2006	2.6E+03	5.1E+03	3.4E+03	5.7E+01	3.7E+04	2.5E+01	4.9E+02

***Table 24**: Olkiluoto 1 – Gamma scanning data and measured dose rate during outage on RHR piping*

		A(t)							
		Mn54	Co58	Co60	Zn65	Cr51	Fe59	Sb124	DR
Cycle	Year	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	mSv/h
1	1979	3.2E+07	2.6E+08	4.3E+07	9.6E+06		1.5E+07	6.1E+06	0.25
2	1980	1.0E+08	4.2E+08	1.8E+08	4.4E+07	6.7E+08	2.9E+07	6.4E+06	0.45
3	1981	1.5E+08	3.7E+08	3.1E+08			1.6E+07	5.4E+06	0.60
4	1982	1.2E+07	2.2E+08	2.7E+08	7.6E+05				0.57
5	1983								1.10
6	1984	5.3E+07	3.0E+08	4.2E+08					0.65
7	1985	6.6E+07	2.1E+08	3.2E+08	1.7E+07	1.5E+08	2.8E+07	3.7E+06	0.80
8	1986	9.6E+07	2.4E+08	3.4E+08	1.3E+07	2.5E+08	2.7E+07	4.2E+06	1.05
9	1987								0.80
10	1988	3.0E+08	4.0E+08	9.0E+08	3.5E+07	2.4E+08	6.5E+07	1.7E+07	1.06
11	1989								1.38
12	1990	4.2E+08	3.5E+08	9.8E+08	1.7E+07	4.6E+07	5.7E+07	2.1E+07	1.70
13	1991								1.25
14	1992	5.4E+08	4.0E+08	1.4E+09	2.0E+07	1.6E+08	7.7E+07	4.5E+07	1.78
15	1993								2.05
16	1994	8.4E+08	5.7E+08	2.3E+09	1.1E+07		9.2E+07	8.5E+07	2.35
17	1995								2.40
18	1996	3.7E+08	4.4E+08	2.2E+09			4.4E+07	1.0E+08	2.30
19	1997								2.08
20	1998	1.5E+08	3.4E+08	1.8E+09			3.0E+07	1.0E+08	1.41
21	1999								1.17
22	2000	1.6E+08	4.6E+08	2.0E+09			2.5E+07	2.2E+08	1.50
23	2001								1.04
24	2002	1.7E+08	5.3E+08	1.8E+09			4.0E+07	1.5E+08	1.44
25	2003								1.25
26	2004	2.2E+08	4.5E+08	1.7E+09			2.8E+07	1.8E+08	1.73
27	2005								1.46
28	2006	2.6E+08	4.6E+08	1.7E+09		4.0E+07		2.5E+08	1.59

The above reactor water activities and gamma scanning data have been recalculated to surface enrichment factors K for the different activated corrosion products according to ***Eq. 1*** and ***Eq. 2***. The resulting K factors for different radionuclides are presented in **Figure 24**. Some comments to the results:

- The K-factors show a rather low variation for the Co isotopes, and very similar values for Co-58 and Co-60.
- K-factors for Fe-59 and Sb-124 are higher than the Co factors, while the Cr-51 factors are much lower, which is typical for oxides formed under NWC conditions.

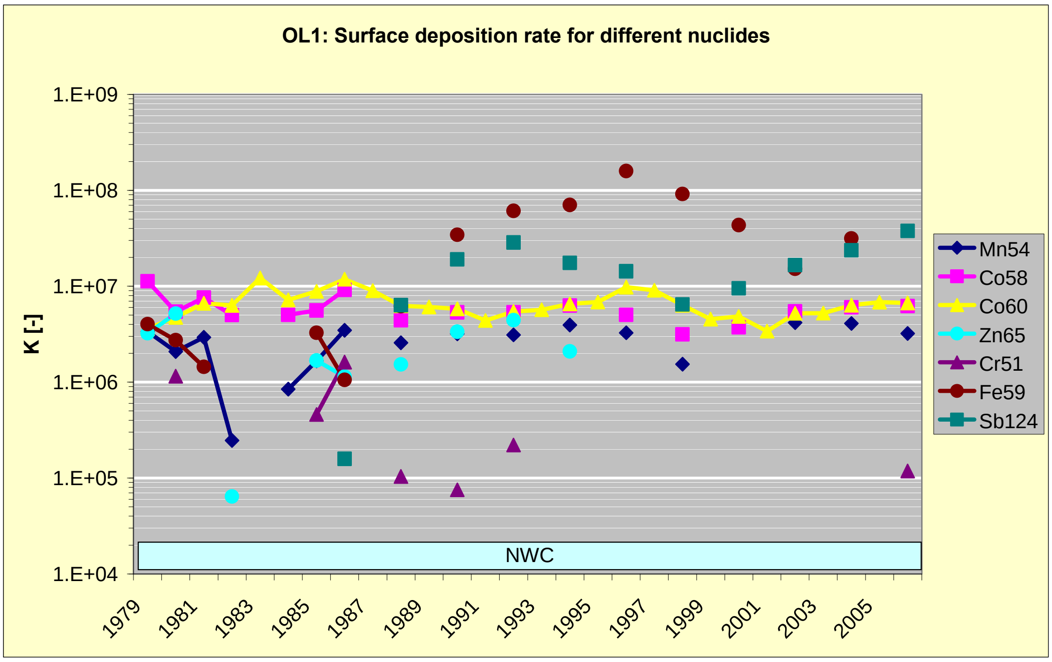

Figure 24*: OL1: Surface enrichment factor K based on cycle average reactor water activity and reported gamma scan and dose rate measurements on RHR pipes*

2.2.2 OL2

The OL2 plant started operation in 1980, and is a sister plant to OL1 with very similar operation conditions. The reactor water chemistry in form of cycle-average data is shown in **Table 25**. The characteristics of OL2 from the water chemistry point of view can be summarised in the following way:

- The plant has in principle always been operating with low levels of Cu and Zn.
- The plant started with a rather high inflow of feed water Fe, but this inflow has been gradually reduced to presently rather, but not extremely, low levels (i.e. >0.1 ppb).
- The plant has always operated with NWC.

i.e. very similar conditions as in OL1.

The cycle average values of reactor water activated corrosion products are presented in **Table 26**. The decrease in Fe inflow is seen as reduced reactor water concentrations of Mn-54 and Fe-59, c.f. OL1. One main difference between OL1 and OL2 is higher Co-58 reactor water activity in OL2 due to considerable contribution from fuel spacers of Inconel.

Outage gamma scanning data and dose rates on the standard RHR location are presented in **Table 27**.

Table 25: Olkiluoto 2 – Corrosion product reactor water chemistry data – Annual average data during reactor operation

		$C_w(t)$							
Cycle	**Year**	**Fe [ppb]**	**Zn [ppb]**	**Ni [ppb]**	**Cr [ppb]**	**Co [ppb]**	**Cu [ppb]**	**Cond. [mS/cm]**	**N/HWC [0/1]**
1	1981							0.10	0
2	1982								0
3	1983								0
4	1984	0.40	0.20	0.30	0.70		0.80		0
5	1985	0.50	0.10	0.30	1.00		0.80		0
6	1986	0.45	0.10	0.20	1.50	0.020	0.08	0.06	0
7	1987	0.30	0.10	0.20	1.00	0.020	0.07	0.07	0
8	1988	0.30	0.10	0.20	1.50	0.020	0.04	0.08	0
9	1989	0.35	0.10	0.25	3.25	0.015	0.03	0.11	0
10	1990	0.68	0.10	0.20	2.00	0.015	0.02	0.10	0
11	1991	1.00	0.08	0.28	1.75	0.015	0.03	0.09	0
12	1992	1.50	0.08	0.25	2.50	0.015	0.03	0.10	0
13	1993	0.60	0.05	0.20	2.00	0.015	0.01	0.09	0
14	1994	0.50	0.05	0.25	2.00	0.015	0.02	0.10	0
15	1995	0.30	0.05	0.25	2.00	0.019	0.01	0.12	0
16	1996	0.25	0.10	0.20	1.50	0.025	0.01	0.11	0
17	1997	0.20	0.05	0.20	1.75	0.027	0.02	0.12	0
18	1998	0.30	0.05	0.25	1.50	0.032	0.03	0.14	0
19	1999	0.20	0.05	0.25	1.50	0.031	0.01	0.12	0
20	2000	0.18	0.03	0.26	1.19	0.034	0.01	0.10	0
21	2001	0.27	0.04	0.24	1.24	0.036	0.01	0.10	0
22	2002	0.16	0.08	0.18	1.03	0.034	0.01	0.09	0
23	2003	0.19	0.09	0.18	0.99	0.031	0.02	0.09	0
24	2004	0.20	0.07	0.14	1.15	0.023	0.02	0.08	0
25	2005	0.17	0.04	0.16	1.31	0.022	0.02	0.08	0
26	2006	0.25	0.03	0.14	2.20	0.028	0.03	0.09	0

***Table 26**: Olkiluoto 2 – Activated corrosion products in reactor water –*
Annual average data during reactor operation
*(*Data in *italics* has been estimated*)*

		$C_w(t)$						
		Mn54	Co58	Co60	Zn65	Cr51	Fe59	Sb124
Cycle	Year	Bq/kg	Bq/kg	Bq/kg	Bq/kg	Bq/kg	Bq/kg	Bq/kg
1	1981	*3.0E+03*	*1.0E+04*	*1.0E+03*	*5.0E+02*	*1.0E+05*	*5.0E+02*	
2	1982	*3.0E+03*	*1.0E+04*	*1.0E+03*	*5.0E+02*	*1.0E+05*	*5.0E+02*	
3	1983	*3.0E+03*	*1.0E+04*	*1.0E+03*	*5.0E+02*	*1.0E+05*	*5.0E+02*	
4	1984	*3.0E+03*	*1.0E+04*	*1.0E+03*	*5.0E+02*	*1.0E+05*	*5.0E+02*	
5	1985	*3.0E+03*	*1.0E+04*	*1.0E+03*	*5.0E+02*	*1.0E+05*	*5.0E+02*	
6	1986	6.9E+03	9.7E+03	1.4E+03	2.7E+02	6.2E+04	6.2E+02	3.8E+03
7	1987	7.6E+03	9.3E+03	1.4E+03	*3.0E+02*	1.2E+05	1.7E+03	1.7E+04
8	1988	6.0E+03	9.4E+03	1.7E+03	5.5E+02	1.4E+05	7.2E+02	3.2E+03
9	1989	7.7E+03	1.6E+04	2.2E+03	1.7E+02	2.1E+05	2.3E+03	1.1E+02
10	1990	7.4E+03	1.9E+04	2.1E+03	1.3E+02	1.4E+05	1.6E+02	3.6E+02
11	1991	9.8E+03	1.9E+04	2.4E+03	1.3E+02	2.0E+05	2.8E+02	1.2E+03
12	1992	7.4E+03	1.7E+04	3.4E+03	9.9E+02	2.1E+05	6.5E+03	2.3E+04
13	1993	4.8E+03	1.5E+04	4.6E+03	1.5E+03	1.9E+05	1.5E+04	1.6E+03
14	1994	4.8E+03	1.4E+04	4.7E+03	2.1E+02	1.2E+05	9.2E+03	4.0E+02
15	1995	3.5E+03	1.4E+04	4.7E+03	*2.5E+02*	1.1E+05	3.0E+03	4.2E+02
16	1996	2.5E+03	1.3E+04	4.7E+03	2.8E+02	7.8E+04	7.4E+02	1.1E+03
17	1997	2.2E+03	1.5E+04	5.3E+03	2.0E+02	6.7E+04	1.9E+02	3.2E+02
18	1998	2.4E+03	1.2E+04	3.5E+03	1.2E+02	4.3E+04	5.9E+01	1.7E+03
19	1999	1.2E+03	1.4E+04	4.0E+03	9.7E+01	4.2E+04	5.5E+01	1.5E+03
20	2000	7.1E+02	1.1E+04	3.4E+03	8.1E+01	2.8E+04	3.7E+01	1.2E+03
21	2001	1.1E+03	8.8E+03	3.2E+03	6.1E+01	2.9E+04	6.6E+01	8.2E+02
22	2002	8.9E+02	7.2E+03	2.8E+03	7.3E+01	2.5E+04	2.7E+01	5.9E+02
23	2003	2.3E+03	7.4E+03	3.1E+03	7.3E+01	2.7E+04	9.7E+02	1.1E+02
24	2004	2.1E+03	1.3E+04	2.8E+03	1.2E+02	5.9E+04	3.4E+02	3.9E+02
25	2005	2.8E+03	1.7E+04	2.9E+03	1.1E+02	6.5E+04	3.5E+01	2.9E+02
26	2006	3.2E+03	2.2E+04	4.5E+03	1.8E+02	8.8E+04	8.3E+01	1.3E+02

***Table 27**: Olkiluoto 2 – Gamma scanning data and*
measured dose rate during outage on RHR piping

		A(t)						
		Mn54	Co58	Co60	Zn65	Cr51	Fe59	Sb124	DR
Cycle	Year	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	mSv/h
1	1981	5.5E+07	7.1E+08	7.7E+07	2.7E+07	5.5E+08	2.9E+07	1.5E+07	
2	1982	1.4E+08	8.9E+08	3.7E+08	2.4E+08	4.0E+08	4.0E+07	1.8E+07	1.35
3	1983	1.4E+08	1.1E+09	6.9E+08	4.2E+07	3.7E+07	5.5E+07	7.5E+06	1.10
4	1984								1.25
5	1985	1.8E+08	1.4E+09	1.2E+09	3.6E+07		6.3E+07	2.9E+07	1.35
6	1986								1.35
7	1987	4.8E+08	1.6E+09	1.3E+09	2.1E+07	4.5E+08	1.0E+08	8.7E+06	1.50
8	1988								2.00
9	1989	3.6E+08	8.0E+08	9.8E+08		2.3E+08	7.1E+07	1.8E+07	1.60
10	1990								2.00
11	1991	3.3E+08	7.3E+08	1.0E+09	8.8E+06	1.7E+08	6.8E+07	1.4E+07	1.36
12	1992								1.46
13	1993	4.7E+08	5.8E+08	1.2E+09		1.1E+08	8.8E+07	1.5E+07	1.70
14	1994								1.05
15	1995	3.9E+08	9.4E+08	1.6E+09	1.8E+07	1.7E+08	4.6E+07	4.9E+07	1.45
16	1996								1.89
17	1997	1.7E+08	8.6E+08	2.2E+09	1.2E+07		2.2E+07	7.6E+07	2.10
18	1998								1.64
19	1999	1.6E+08	1.0E+09	2.1E+09			4.4E+07	2.8E+08	1.40
20	2000								1.85
21	2001	6.8E+07	4.1E+08	1.3E+09			2.0E+07	1.7E+08	2.67
22	2002								1.35
23	2003	1.2E+08	5.0E+08	1.6E+09			3.6E+07	9.6E+07	1.14
24	2004								1.63
25	2005	2.5E+08	1.2E+09	1.5E+09			3.6E+07	7.2E+07	1.83
26	2006								1.85

The above reactor water activities and gamma scanning data have been recalculated to surface enrichment factors K for the different activated corrosion products according to ***Eq. 1*** and ***Eq. 2***. The resulting K factors for different radionuclides are presented in **Figure 25**. Some comments to the results:

- The K-factors show a rather low variation for the Co isotopes, and very similar values for Co-58 and Co-60.

- K-factors for Fe-59 and Sb-124 are higher than the Co factors, while the Cr-51 factors are much lower, which is typical for oxides formed under NWC conditions.

i.e. the same comments as for the sister plant OL1.

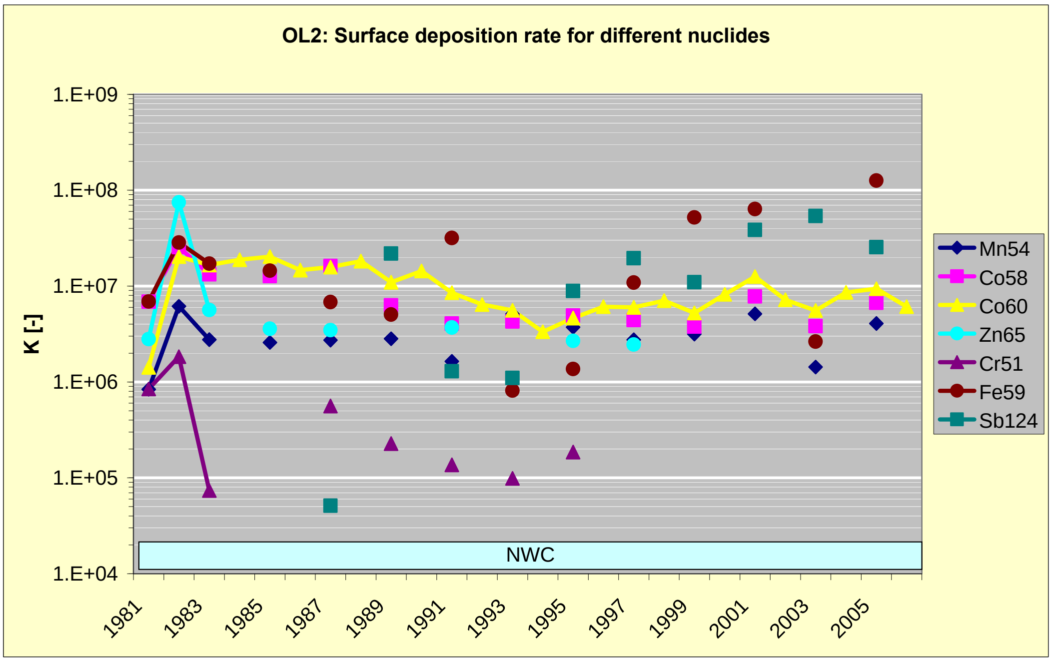

***Figure 25**: OL2: Surface enrichment factor K based on cycle average reactor water activity and reported gamma scan and dose rate measurements on RHR pipes*

2.2.3 F1

The F1 plant started operation in 1980. The reactor water chemistry in form of cycle-average data is shown in **Table 28**. The characteristics of F1 from the water chemistry point of view can be summarised in the following way:

- The plant has never injected Zn, but has occasionally have some Zn in the reactor water. Initially some Zn and Cu was obtained from the brass condenser tubes, which were later replaced with Ti tubes. During the period 1992 – 2001 some increased levels of reactor water Zn were observed due to Zn-containing coatings used in the turbine plant to reduce erosion-corrosion.

- The feedwater Fe has during most cycles been very low, <0.1 ppb.

- The plant operated with HWC during the period 1986-1991 with the objective to obtain low corrosion potential in the bottom of the pressure vessel. Note that the RHR pipes are connected to the upper part of pressure vessel, i.e. upstream of the downcomer. The RHR lines therefore maintained on oxidising conditions also during the period with HWC operation.

- The plant operated during the 1990s with rather high reactor water conductivity. The main impurity responsible for this increase was nitrate originating from CCU ion exchange resins[11].

The cycle average values of reactor water activated corrosion products are presented in **Table 29**. The HWC operation resulted in some decrease of reactor water Cr-51, but no other significant changes.

Outage gamma scanning data and dose rates on the standard RHR location are presented in **Table 30**. Data for most recent cycles are lacking.

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[11] Low-sulphur resin (LSR) was used in order to reduce reactor water levels of sulphate. The thermal stability of the LSR is, however, rather low, which results in increased reactor water nitrate concentrations.

***Table 28**: Forsmark 1 – Corrosion product reactor water chemistry data – Annual average data during reactor operation*

		$C_w(t)$								
Cycle	Year	Fe [ppb]	Zn [ppb]	Ni [ppb]	Cr [ppb]	Co [ppb]	Cu [ppb]	Cond. [mS/cm]	N/HWC [0/1]	
1	1981	1.00						0.14	0	
2	1982	0.50	0.20		0.50	0.030	0.30	0.17	0	
3	1983	0.33	0.22	0.55	1.90	0.025	0.35	0.20	0	
4	1984	0.17	0.10	0.44	1.40	0.030	0.41	0.16	0	
5	1985	0.11	0.05	0.56	1.56	0.020	0.28	0.17	0	
6	1986	0.14	0.05	0.51	0.92	0.020	0.16	0.10	1	HWC
7	1987	0.16	0.04	0.43	0.56	0.020	0.11	0.09	1	
8	1988	0.14	0.04	0.43	0.24	0.020	0.11		1	
9	1989	0.14	0.03	0.32	0.27	0.020	0.08		1	
10	1990	0.13	0.06	0.42	0.24	0.020	0.04	0.08	1	
11	1991	0.18	0.06	0.39	0.30	0.010	0.04	0.09	1	
12	1992	0.12	0.64	0.50	0.89	0.027	0.06	0.20	0	$\kappa \geq 0.2$, ^{nat}Zn
13	1993	0.14	0.82	0.50	0.67	0.032	0.04	0.18	0	
14	1994	0.16	0.90	0.54	0.63	0.017	0.05	0.25	0	
15	1995	0.15	0.55	0.49	0.75	0.029	0.04	0.18	0	
16	1996	0.15	0.38	0.60	1.10	0.033	0.02	0.25	0	
17	1997	0.09	0.23	0.44	2.14	0.030	0.01		0	
18	1998	0.25	0.16	0.43	2.86	0.035	0.02		0	
19	1999	0.18	0.14	0.41	1.46	0.040	0.01		0	
20	2000	0.15	0.13	0.52	1.25	0.043	0.01	0.09	0	
21	2001	2.59	0.35	0.93	4.11	0.028	0.21	0.10	0	
22	2002	0.33	0.08	0.37	1.37	0.025	0.02	0.10	0	
23	2003	0.18	0.06	0.39	1.35	0.027	0.01	0.07	0	
24	2004	0.21	0.05	0.18	1.09	0.031	0.01	0.07	0	
25	2005	0.13	0.06	0.14	0.99	0.035	0.01	0.09	0	
26	2006								0	

***Table 29**: Forsmark 1 – Activated corrosion products in reactor water – Annual average data during reactor operation*

		$C_w(t)$							
Cycle	Year	Mn54 Bq/kg	Co58 Bq/kg	Co60 Bq/kg	Zn65 Bq/kg	Cr51 Bq/kg	Fe59 Bq/kg	Sb124 Bq/kg	
1	1981	4.4E+02	3.2E+03	3.9E+02	1.5E+03	1.3E+05	3.0E+02	1.3E+03	
2	1982	4.7E+02	8.3E+03	7.3E+02	9.0E+02	1.0E+05	5.0E+02	7.3E+02	
3	1983	4.3E+02	1.2E+04	1.0E+03	1.2E+03	1.2E+05	5.6E+01	4.7E+02	
4	1984	3.9E+02	1.1E+04	9.1E+02	1.7E+03	1.5E+05	6.1E+01	7.1E+02	
5	1985	3.9E+02	1.3E+04	1.2E+03	6.1E+02	1.5E+05	4.4E+01	1.0E+03	
6	1986	4.2E+02	9.2E+03	9.5E+02	4.7E+02	5.5E+04	2.8E+01	1.6E+03	HWC
7	1987	4.3E+02	7.6E+03	8.9E+02	2.8E+02	2.1E+04	4.3E+01	9.9E+02	
8	1988	4.5E+02	6.4E+03	1.2E+03	2.4E+02	6.8E+03	2.3E+01	1.1E+03	
9	1989	6.0E+02	4.8E+03	1.4E+03	2.2E+02	2.8E+03	2.2E+01	1.1E+03	
10	1990	6.6E+02	9.8E+03	1.2E+03	1.8E+02	4.3E+03	1.9E+01	1.3E+03	
11	1991	7.6E+02	9.2E+03	9.3E+02	1.1E+02	3.7E+03	1.4E+01	2.1E+03	
12	1992	1.6E+03	2.4E+04	2.7E+03	1.3E+03	5.3E+04	2.0E+01	1.4E+03	$\kappa \geq 0.2$, ^{nat}Zn
13	1993	1.4E+03	2.3E+04	4.1E+03	2.2E+03	5.4E+04	2.2E+01	1.2E+03	
14	1994	1.4E+03	2.1E+04	6.7E+03	4.7E+03	4.7E+04	1.7E+01	1.0E+03	
15	1995	1.1E+03	1.0E+04	5.2E+03	4.6E+03	5.6E+04	2.1E+01	8.2E+02	
16	1996	9.9E+02	7.8E+03	6.0E+03	4.4E+03	5.9E+04	2.4E+01	9.9E+02	
17	1997	7.6E+02	5.7E+03	5.0E+03	3.3E+03	7.5E+04	2.3E+01	9.6E+02	
18	1998	4.0E+02	4.6E+03	4.3E+03	2.1E+03	8.1E+04		1.5E+03	
19	1999	3.9E+02	5.3E+03	4.6E+03	2.3E+03	6.7E+04	1.9E+02	2.6E+03	
20	2000	3.8E+02	7.5E+03	4.2E+03	1.2E+03	4.0E+04	4.7E+01	2.2E+03	
21	2001	2.8E+03	1.1E+04	4.1E+03	5.5E+02	1.9E+05	7.1E+02	3.4E+03	
22	2002	2.2E+03	1.6E+04	7.8E+03	6.8E+02	8.2E+04	5.8E+02	4.7E+03	
23	2003	1.2E+03	1.6E+04	1.1E+04	8.9E+02	4.5E+04		5.8E+03	
24	2004	9.6E+02	1.3E+04	9.6E+03	6.6E+02	5.1E+04		5.7E+03	
25	2005	7.5E+02	1.2E+04	7.6E+03	4.7E+02	5.7E+04		7.7E+03	
26	2006							2.2E+03	

***Table 30**: Forsmark 1 – Gamma scanning data and measured dose rate during outage on RHR piping*

		A(t)								
		Mn54	Co58	Co60	Zn65	Cr51	Fe59	Sb124	DR	
Cycle	Year	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	mSv/h	
1	1981	1.3E+07	5.9E+08	7.3E+07	4.8E+07		8.7E+06	6.6E+06	0.43	
2	1982	1.8E+07	5.9E+08	1.4E+08	5.4E+07		1.3E+07	9.6E+06	0.38	
3	1983	2.8E+07	6.9E+08	3.0E+08	7.3E+07	9.6E+07	1.8E+07	5.1E+06	0.55	
4	1984	3.5E+07	8.9E+08	3.8E+08	1.4E+08	1.4E+08	2.0E+07		0.64	
5	1985	8.8E+06	2.6E+08	3.7E+08	2.4E+07		7.6E+06	4.5E+06	0.60	
6	1986	1.5E+07	5.8E+08	5.2E+08	7.1E+07				0.53	HWC
7	1987	7.2E+06	1.2E+08	3.7E+08	6.6E+06		4.8E+06	4.2E+06	0.59	
8	1988	1.9E+07	3.2E+08	4.6E+08	3.2E+07		6.9E+06		0.59	
9	1989	1.1E+07	8.8E+07	6.1E+08	7.4E+06	2.0E+08	8.3E+06	1.7E+07	0.51	
10	1990	1.2E+07	1.2E+08	6.3E+08	1.0E+07	2.1E+08	7.7E+06		0.60	
11	1991	9.6E+06	2.0E+08	7.1E+08		4.2E+08	8.2E+06	1.4E+07	0.59	
12	1992	1.1E+07	2.3E+08	6.9E+08	1.2E+07	1.9E+08	5.9E+06	4.6E+06	0.64	$\kappa \geq 0.2$, ^{nat}Zn
13	1993	7.2E+06	3.0E+08	6.7E+08	1.9E+07	4.6E+07	1.3E+07	5.3E+06	0.72	
14	1994	1.3E+07	1.7E+08	8.5E+08	2.8E+07		8.1E+06	4.4E+07	1.05	
15	1995	1.0E+07	1.5E+08	9.5E+08	3.7E+07	4.5E+07	5.9E+06	4.5E+06	0.83	
16	1996	5.5E+06	6.1E+07	1.0E+09	3.7E+07		6.7E+06	1.4E+07	1.01	
17	1997	1.1E+07	6.2E+07	1.2E+09	3.7E+07		9.7E+06	8.9E+06	1.14	
18	1998	5.3E+06	1.0E+08	1.4E+09	4.0E+07	9.7E+07	6.1E+06	2.6E+06	1.29	
19	1999	3.4E+06	7.0E+07	1.1E+09	2.4E+07			6.1E+06	1.24	
20	2000	1.4E+06	4.6E+07	1.4E+09	1.9E+07					
21	2001	1.1E+08	7.1E+08	2.1E+09	3.8E+07	1.9E+09	1.5E+08	4.9E+07		
22	2002	3.5E+07	2.5E+08	1.8E+09			2.2E+07	1.5E+07		
23	2003	2.1E+07	1.7E+08	2.1E+09	3.7E+07		1.5E+07			
24	2004									
25	2005									
26	2006									

The above reactor water activities and gamma scanning data have been recalculated to surface enrichment factors K for the different activated corrosion products according to ***Eq. 1*** and ***Eq. 2***. The resulting K factors for different radionuclides are presented in **Figure 26**. Some comments to the results:

- The K-factors for most nuclides (Mn-54, Co-58, Co-60, Zn-65, Sb-124) are at low levels compared to most other reactors. The lowest levels are obtained during the 1990s when the reactor chemistry was characterised by:
  - Very low Fe-inflow
  - Some Zn in the water
  - Increased conductivity due to reactor water nitrate.

  A small increase is seen in the beginning of 2000 when reactor water Zn and conductivity are decreased.

- Note also, that there is a slight difference between the Co isotopes, with somewhat higher K-factors for Co-60 compared to Co-58. This difference is not typical for most of the other plants.

- The effect of HWC operation is seen as an increase of the K-factors for Cr-51, but not in the form of decrease of the Fe-59 K-factors which is seen in other plants, e.g. in the R1 plant, see **Figure 14**. Note, that the RHR lines in internal pump plants a high corrosion potential remains also at HWC conditions.

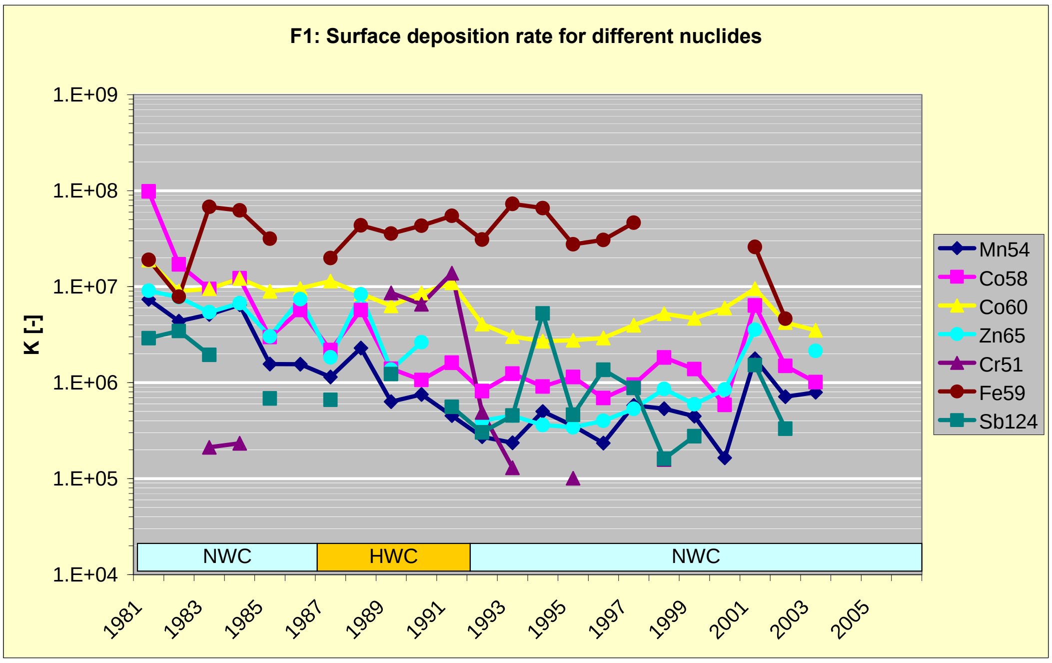

Figure 26*: F1: Surface enrichment factor K based on cycle average reactor water activity and reported gamma scan and dose rate measurements on RHR pipes*

2.2.4 F2

The F2 plant started operation in 1981, and is a sister plant to F1 with very similar operation conditions. The reactor water chemistry in form of cycle-average data is shown in **Table 31**. The characteristics of F2 from the water chemistry point of view can be summarised in the following way:

- The Zn history is very similar to F1, i.e. the plant has never injected Zn, but has occasionally have some Zn in the reactor water. Initially some Zn and Cu was obtained from the brass condenser tubes, which were later replaced with Ti tubes. During the period 1992 – 2001 some increased levels of reactor water Zn were observed due to Zn-containing coatings used in the turbine plant to reduce erosion-corrosion. The Zn levels in F2 during that period were somewhat higher than the corresponding levels in F1.

- The feedwater Fe has during most cycles been very low, <0.1 ppb. The feedwater Fe has, however, been increased during some recent cycles due to Fe injection (iron oxalate) in order to reduce fuel corrosion.

- The plant operated with HWC during the period 1986-1991 with the objective to obtain low corrosion potential in the bottom of the pressure vessel. Note that the RHR pipes are connected to the upper part of pressure vessel, i.e. upstream of the downcomer. The RHR lines therefore had oxidising conditions also during the period with HWC operation.

- The plant operated during the 1990s with rather high reactor water conductivity. The main impurity responsible for this increase was nitrate originating from CCU ion exchange resins.

The cycle average values of reactor water activated corrosion products are presented in **Table 32**. The HWC operation resulted in some decrease of reactor water Cr-51, but no other significant changes, c.f. F1.

Outage gamma scanning data and dose rates on the standard RHR location are presented in **Table 33**. Data for most recent cycles are lacking.

Table 31: *Forsmark 2 – Corrosion product reactor water chemistry data – Annual average data during reactor operation*

		$C_w(t)$								
Cycle	**Year**	**Fe [ppb]**	**Zn [ppb]**	**Ni [ppb]**	**Cr [ppb]**	**Co [ppb]**	**Cu [ppb]**	**Cond. [mS/cm]**	**N/HWC [0/1]**	
1	1982	0.50	0.40	0.70	0.50	0.010	0.40	0.16	0	
2	1983	0.35	0.26	0.34	1.21	0.020	0.38	0.21	0	
3	1984	0.13	0.10	0.21	1.20	0.010	0.26	0.15	0	
4	1985	0.16	0.06	0.59	1.54	0.020	0.08	0.18	0	
5	1986	0.13	0.06	0.59	1.10	0.020	0.05	0.14	1	HWC
6	1987	0.16	0.05	0.72	0.83	0.020	0.04	0.12	1	
7	1988	0.19	0.03	0.49	0.60	0.020	0.04		1	
8	1989	0.26	0.04	1.23	1.25	0.020	0.03		1	
9	1990	0.35	0.18	1.69	0.51	0.020	0.04	0.08	1	
10	1991	0.42	0.25	0.39	0.31	0.010	0.05	0.08	1	
11	1992	0.48	1.30	0.38	1.28	0.023	0.07	0.22	0	$\kappa \geq 0.2$, ^{nat}Zn
12	1993	0.20	1.49	0.59	0.49	0.018	0.06	0.20	0	
13	1994	0.23	1.40	0.43	0.63	0.012	0.06	0.22	0	
14	1995	0.14	1.21	0.61	0.62	0.029	0.03	0.17	0	
15	1996	0.17	0.90	0.69	1.13	0.036	0.03	0.26	0	
16	1997	0.11	0.62	0.75	2.01	0.038	0.02		0	
17	1998	0.19	0.54	0.57	2.13	0.037	0.02		0	
18	1999	0.49	0.44	0.45	1.30	0.031	0.02		0	
19	2000	1.05	0.39	0.12	1.40	0.031	0.02	0.10	0	
20	2001	0.81	0.28	0.43	1.52	0.029	0.02	0.14	0	
21	2002	0.39	0.25	0.44	1.25	0.029	0.02	0.09	0	
22	2003	1.19	0.30	0.40	1.28	0.028	0.02	0.09	0	
23	2004	0.42	0.20	0.20	1.03	0.033	0.02	0.09	0	
24	2005	0.15	0.20	0.12	1.03	0.041	0.02	0.10	0	
25	2006								0	

Table 32: *Forsmark 2 – Activated corrosion products in reactor water – Annual average data during reactor operation*

		$C_w(t)$							
Cycle	**Year**	**Mn54 Bq/kg**	**Co58 Bq/kg**	**Co60 Bq/kg**	**Zn65 Bq/kg**	**Cr51 Bq/kg**	**Fe59 Bq/kg**	**Sb124 Bq/kg**	
1	1982	6.2E+02	6.4E+03	6.2E+02	9.0E+02	7.5E+04	3.5E+02	2.8E+02	
2	1983	5.1E+02	1.1E+04	1.3E+03	1.2E+03	3.0E+05	4.0E+01	1.2E+02	
3	1984	3.8E+02	1.1E+04	1.5E+03	1.2E+03	1.9E+05	3.2E+01	7.9E+02	
4	1985	5.8E+02	1.4E+04	2.5E+03	1.3E+03	2.3E+05	1.7E+01	3.6E+02	
5	1986	5.4E+02	9.6E+03	1.4E+03	7.0E+02	4.2E+04	3.4E+01	1.2E+03	HWC
6	1987	7.0E+02	7.0E+03	8.9E+02	3.3E+02	2.8E+04	3.6E+01	1.1E+03	
7	1988	1.0E+03	2.0E+04	1.2E+03	1.6E+02	1.3E+04	8.9E+01	7.4E+02	
8	1989	6.3E+02	4.5E+04	4.4E+03	6.1E+02	2.3E+04	3.0E+02	6.0E+02	
9	1990	6.0E+02	6.1E+04	4.9E+03	9.9E+02	2.6E+04	8.0E+01	3.8E+02	
10	1991	1.6E+03	1.8E+04	1.8E+03	8.6E+02	7.4E+03	4.1E+01	8.3E+02	
11	1992	3.7E+03	2.6E+04	5.2E+03	6.5E+03	1.4E+05	6.9E+01	1.1E+03	$\kappa \geq 0.2$, ^{nat}Zn
12	1993	4.1E+03	2.7E+04	6.4E+03	9.7E+03	5.6E+04	6.6E+01	1.7E+03	
13	1994	3.9E+03	2.5E+04	6.1E+03	8.8E+03	4.0E+04	3.3E+01	1.9E+03	
14	1995	2.5E+03	2.5E+04	6.3E+03	9.0E+03	4.6E+04	2.6E+01	1.0E+03	
15	1996	1.6E+03	1.6E+04	6.3E+03	8.2E+03	5.7E+04	3.0E+01	1.3E+03	
16	1997	1.5E+03	1.4E+04	4.6E+03	5.6E+03	7.3E+04	4.7E+01	1.1E+03	
17	1998	1.4E+03	1.2E+04	4.8E+03	5.4E+03	8.5E+04	2.2E+01	7.7E+02	
18	1999	2.3E+03	1.1E+04	5.5E+03	6.5E+03	5.8E+04	1.1E+02	8.4E+02	
19	2000	5.5E+03	1.3E+04	5.6E+03	5.5E+03	5.3E+04	3.6E+02	1.4E+03	
20	2001	5.9E+03	1.3E+04	5.9E+03	4.7E+03	5.4E+04	1.3E+03	2.4E+03	
21	2002	3.4E+03	2.2E+04	6.0E+03	3.4E+03	6.3E+04		3.2E+03	
22	2003	2.1E+03	2.6E+04	6.6E+03	2.2E+03	8.1E+04	4.3E+01	4.7E+03	
23	2004	1.4E+03	2.6E+04	4.7E+03	1.6E+03	6.5E+04	3.1E+01	3.6E+03	
24	2005	8.0E+02	2.2E+04	5.3E+03	1.5E+03	6.2E+04	8.4E+01	4.2E+03	
25	2006							3.0E+03	

Table 33: *Forsmark 2 – Gamma scanning data and measured dose rate during outage on RHR piping*

		A(t)								
		Mn54	Co58	Co60	Zn65	Cr51	Fe59	Sb124	DR	
Cycle	Year	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	mSv/h	
1	1982	3.5E+07	9.9E+08	1.7E+08	8.4E+07		2.3E+07	9.9E+06	0.58	
2	1983	3.5E+07	1.2E+09	4.0E+08	1.1E+08	4.7E+08	1.5E+07	6.3E+06	0.63	
3	1984	1.7E+07	7.0E+08	6.9E+08	7.0E+07				0.70	
4	1985								0.70	
5	1986		1.6E+08	5.5E+08	3.4E+07			1.0E+07	0.85	HWC
6	1987								0.83	
7	1988	1.4E+07	2.8E+08	5.5E+08	6.7E+06	1.6E+08	7.1E+06	6.4E+06	0.85	
8	1989									
9	1990	3.6E+07	1.2E+09	1.2E+09	1.9E+07	1.5E+08	1.4E+07	3.2E+07		
10	1991	4.0E+07	4.5E+08	1.6E+09	2.7E+07	9.7E+08	9.7E+06	9.5E+06	1.50	
11	1992	5.4E+07	4.6E+08	1.4E+09	1.2E+08	1.1E+08	2.5E+07	1.9E+07	1.80	$\kappa \geq 0.2$, ^{nat}Zn
12	1993	7.3E+07	3.2E+08	1.5E+09	1.2E+08	5.5E+07	2.2E+07	2.8E+07	1.62	
13	1994	4.8E+07	1.8E+08	1.4E+09	8.1E+07	3.7E+07	2.0E+07	2.1E+07	1.60	
14	1995	2.9E+07	1.5E+08	1.5E+09	7.4E+07		1.6E+07	1.8E+07	1.75	
15	1996	1.6E+07	1.2E+08	1.5E+09	6.6E+07		1.1E+07	2.6E+07	1.53	
16	1997	1.9E+07	1.5E+08	1.4E+09	6.0E+07	5.8E+07		1.8E+07	1.65	
17	1998	1.5E+07	1.5E+08	1.6E+09	4.7E+07			8.8E+06	1.77	
18	1999	6.3E+07	1.3E+08	1.7E+09	4.8E+07	8.6E+07	4.7E+07	3.0E+07	1.53	
19	2000	3.5E+07	7.3E+07	1.3E+09	2.8E+07		4.4E+06	7.2E+06		
20	2001	1.3E+08	2.1E+08	1.5E+09	3.4E+07		2.6E+07	2.2E+07		
21	2002	6.6E+07	1.9E+08	1.8E+09	3.4E+07		2.0E+07	3.4E+07		
22	2003	4.8E+07	2.5E+08	1.6E+09	3.3E+07		8.5E+06			
23	2004									
24	2005									
25	2006									

The above reactor water activities and gamma scanning data have been recalculated to surface enrichment factors K for the different activated corrosion products according to ***Eq. 1*** and ***Eq. 2***. The resulting K factors for different radionuclides are presented in **Figure 27**. Some comments to the results:

- The K-factors for most nuclides (Mn-54, Co-58, Co-60, Zn-65, Sb-124) have low levels compared to most other reactors, c.f. F1. The lowest levels are obtained during the 1990s when the reactor chemistry was characterised by:
  - Very low Fe-inflow
  - Some Zn in the water
  - Increased conductivity due to reactor water nitrate.

- Note, that as for F1 there is a slight difference between the Co isotopes, with somewhat higher K-factors for Co-60 compared to Co-58.

- The effect of HWC operation is seen as an increase of the K-factors for Cr-51, but not in the form of decrease of the Fe-59 K-factors which is seen in other plants, c.f. F1.

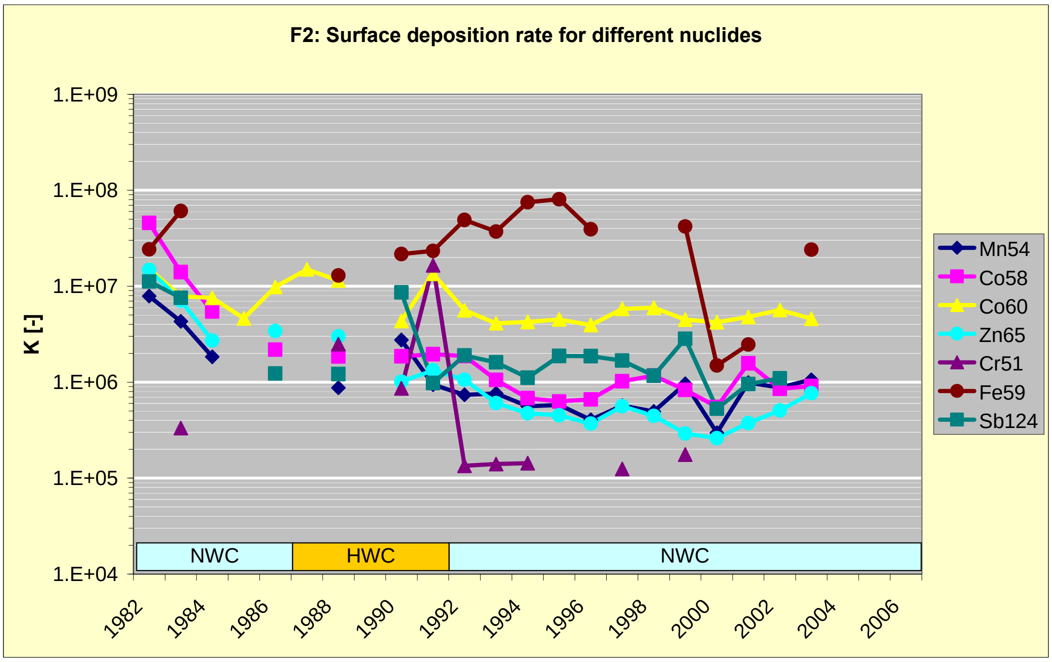

Figure 27*: F2: Surface enrichment factor K based on cycle average reactor water activity and reported gamma scan and dose rate measurements on RHR pipes*

2.2.5 F3

The F3 plant started operation in 1985. The reactor water chemistry in form of cycle-average data is shown in **Table 34**. The characteristics of F3 from the water chemistry point of view can be summarised in the following way:

- The plant was already from the beginning equipped with condenser tubes of titanium, and has displayed low Zn and Cu reactor water levels the whole operation period.
- The turbine plant design is of the forward pumped heater drain (FPHD) design, which means that part of the turbine drains is not passing the CCU plant. This fact has very much determined the Fe history of the plant:
    - The initial cycle was characterised by a very high inflow of Fe.
    - A turbine plant modification introduced at the first outage, with redirection of some of the low pressure drain flows to be cleaned in the CCU, resulted in a considerable reduction of iron, with resulting feedwater Fe <0.1 ppb.
    - A slight increase of feedwater Fe has been achieved during recent cycles by again pumping forward some of the low pressure drains.
- The plant has stayed on NWC.

The cycle average values of reactor water activated corrosion products are presented in **Table 35**. The Fe history is seen in the variation of Mn-54 and Fe-59 reactor water activities.

Outage gamma scanning data and dose rates on the standard RHR location are presented in **Table 36**. Data for most recent cycles are lacking.

Table 34: *Forsmark 3 – Corrosion product reactor water chemistry data – Annual average data during reactor operation*

		$C_w(t)$							
Cycle	Year	Fe [ppb]	Zn [ppb]	Ni [ppb]	Cr [ppb]	Co [ppb]	Cu [ppb]	Cond. [mS/cm]	N/HWC [0/1]
1	1986	7.20	0.23	0.41	4.60	0.020	0.16	0.16	0
2	1987	0.63	0.05	0.27	4.10	0.040	0.07	0.20	0
3	1988	0.60	0.10	0.33	4.70	0.040	0.06		0
4	1989	0.77	0.03	0.80	2.38	0.060	0.05	0.13	0
5	1990	0.37	*0.05*	0.45	2.35	0.050	0.04	0.12	0
6	1991	0.26	0.08	0.41	2.00	0.060	0.04	0.11	0
7	1992	0.59	0.45	0.58	2.40	0.043	0.03	0.11	0
8	1993	0.33	0.15	0.52	1.35	0.046	0.04	0.09	0
9	1994	0.35	0.04	0.48	1.10	0.038	0.04	0.09	0
10	1995	0.60	0.04	0.41	1.50	0.041	0.04	0.09	0
11	1996	0.68	0.03	0.29	1.20	0.037	0.04	0.10	0
12	1997	0.31	0.01	0.21	1.07	0.038	0.03		0
13	1998	0.40	0.03	0.23	1.07	0.041	0.04		0
14	1999	0.92	0.06	0.22	1.40	0.048	0.05		0
15	2000	0.94	0.03	0.18	1.45	0.046	0.05		0
16	2001	0.82	0.02	0.25	1.53	0.050	0.06		0
17	2002	1.93	0.02	0.59	1.79	0.075	0.06		0
18	2003	0.34	0.02	0.18	1.62	0.062	0.05		0
19	2004	1.83	0.03	0.33	1.79	0.069	0.06		0
20	2005	6.43	0.04	0.36	1.99	0.063	0.07		0
21	2006								0

Table 35: *Forsmark 3 – Activated corrosion products in reactor water – Annual average data during reactor operation*

		$C_w(t)$						
Cycle	Year	Mn54 Bq/kg	Co58 Bq/kg	Co60 Bq/kg	Zn65 Bq/kg	Cr51 Bq/kg	Fe59 Bq/kg	Sb124 Bq/kg
1	1986	3.8E+03	6.9E+03	7.0E+02	2.9E+02	1.4E+05	8.3E+02	3.5E+02
2	1987	7.2E+03	1.3E+04	6.9E+03	1.0E+03	1.9E+05	1.8E+02	2.4E+03
3	1988	5.8E+03	2.3E+04	1.1E+04	9.5E+02	2.4E+05	1.1E+02	3.8E+03
4	1989	4.0E+03	3.3E+04	1.1E+04	6.4E+02	3.5E+05	1.7E+02	1.3E+03
5	1990	1.5E+03	2.6E+04	7.4E+03	3.3E+02	1.9E+05	7.7E+01	1.6E+03
6	1991	8.8E+02	3.4E+04	9.6E+03	2.0E+02	1.9E+05	5.6E+01	1.2E+03
7	1992	6.6E+02	3.3E+04	1.2E+04	*2.0E+02*	2.5E+05	6.7E+01	1.8E+03
8	1993	4.2E+02	2.8E+04	1.2E+04	3.7E+02	1.3E+05	5.8E+01	1.6E+03
9	1994	3.7E+02	2.5E+04	1.2E+04	4.7E+01	1.1E+05	6.9E+01	2.4E+03
10	1995	7.4E+02	1.9E+04	8.5E+03	2.6E+01	1.2E+05	6.8E+01	2.1E+03
11	1996	6.7E+02	1.5E+04	7.6E+03	3.7E+01	8.5E+04	1.1E+02	3.2E+03
12	1997	8.8E+02	1.4E+04	6.8E+03	4.4E+01	6.4E+04	7.8E+01	2.0E+03
13	1998	9.7E+02	1.5E+04	6.0E+03	5.7E+01	5.5E+04	5.4E+01	3.9E+02
14	1999	3.7E+03	1.4E+04	6.8E+03	4.7E+01	4.9E+04	6.5E+01	3.5E+02
15	2000	4.4E+03	1.3E+04	6.2E+03		4.8E+04	1.2E+02	2.3E+02
16	2001	5.2E+03	1.3E+04	6.5E+03		5.0E+04	1.8E+02	1.5E+03
17	2002	5.3E+03	1.4E+04	8.0E+03		5.3E+04	*1.5E+02*	2.9E+03
18	2003	4.0E+03	1.3E+04	8.5E+03		5.8E+04	1.2E+02	3.0E+03
19	2004	1.7E+03	1.0E+04	7.9E+03	2.3E+02	6.3E+04	7.7E+01	2.3E+03
20	2005	2.5E+03	9.2E+03	8.3E+03	2.6E+01	6.4E+04	1.6E+02	2.0E+03
21	2006							2.4E+03

***Table 36**: Forsmark 3 – Gamma scanning data and measured dose rate during outage on RHR piping*

		A(t)							
		Mn54	Co58	Co60	Zn65	Cr51	Fe59	Sb124	DR
Cycle	Year	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	mSv/h
1	1986	2.6E+08	1.7E+09	1.3E+09	1.5E+08		8.0E+07	2.1E+07	1.85
2	1987	6.6E+08	1.9E+09	3.4E+09	2.0E+08	1.6E+08	7.2E+07	8.4E+07	4.50
3	1988	2.2E+08	8.9E+08	2.1E+09	6.0E+07		2.5E+07	6.5E+07	4.70
4	1989								4.25
5	1990	1.3E+08	1.3E+09	3.1E+09	2.8E+07	4.7E+07	1.2E+07	1.5E+07	4.00
6	1991	7.3E+07	1.4E+09	3.4E+09			1.4E+07	1.8E+07	6.15
7	1992	4.0E+07	9.2E+08	3.4E+09				1.3E+07	4.50
8	1993	1.3E+07	6.1E+08	3.2E+09	8.6E+06		2.4E+06	1.2E+07	5.30
9	1994	1.3E+07	6.1E+08	3.3E+09			1.5E+07	3.4E+07	5.20
10	1995	1.1E+07	4.3E+08	3.2E+09			1.2E+07	3.5E+07	4.60
11	1996	2.5E+07	4.9E+08	3.1E+09			1.4E+07	2.7E+07	4.50
12	1997	8.8E+07	7.1E+08	3.3E+09			2.4E+07	3.7E+07	5.15
13	1998	7.5E+07	5.1E+08	3.1E+09				2.1E+07	5.05
14	1999	1.1E+08	3.4E+08	2.4E+09	3.5E+07		6.7E+06	9.3E+06	5.46
15	2000	1.8E+08	2.9E+08	2.6E+09				2.3E+06	
16	2001								
17	2002	1.7E+08	5.9E+08	1.7E+09			1.9E+07	4.4E+07	
18	2003	5.9E+07	1.3E+08	2.0E+09		1.4E+06			
19	2004								
20	2005								
21	2006								

The above reactor water activities and gamma scanning data have been recalculated to surface enrichment factors K for the different activated corrosion products according to ***Eq. 1*** and ***Eq. 2***. The resulting K factors for different radionuclides are presented in **Figure 28**. Some comments to the results:

- Most K-factors are somewhat reduced after the initial operation with high inflow of Fe. The slightly increased Fe inflow during recent cycles has not increased the K-factors.

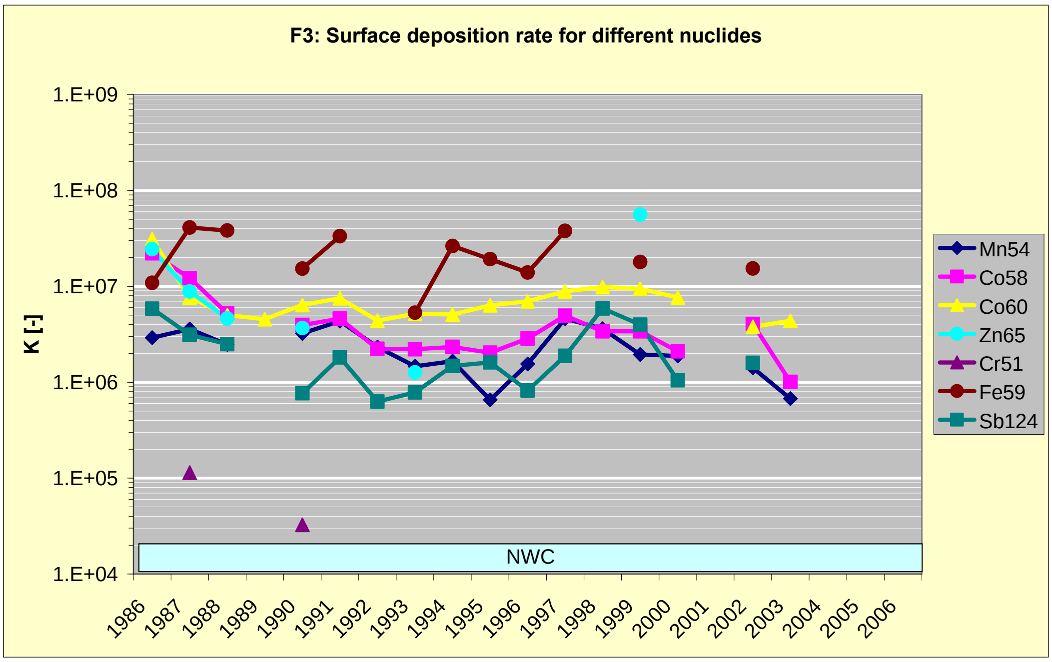

***Figure 28**: F3: Surface enrichment factor K based on cycle average reactor water activity and reported gamma scan and dose rate measurements on RHR pipes*

2.2.6 O3

The O3 plant started operation in 1985, and is a sister plant to F3 with rather similar operation conditions. The reactor water chemistry in form of cycle-average data is shown in **Table 37**. The characteristics of O3 from the water chemistry point of view can be summarised in the following way:

- The plant was already from the beginning equipped with condenser tubes of titanium, and has the whole operation period displayed low Zn and Cu reactor water levels.
- The turbine plant design is of the forward pumped heater drain (FPHD) design, which means that part of the turbine drain flows are not passing the CCU plant. This fact has very much determined the Fe history of the plant:
    - The feedwater Fe was already initially low, contrary to the F3 situation. O3 was at the start-up equipped with a possibility to clean low pressure drain flows in the CCU, a design feature that was later introduced in the F3 plant.
    - A slight increase of feedwater Fe has been achieved from 2000 by pumping forward some of the low pressure drains.
    - In general, the O3 plant has had a much more stable inflow of Fe compared to F3 where larger variations have been experienced.
- The plant has stayed on NWC.

The cycle average values of reactor water activated corrosion products are presented in **Table 38**. The more constant Fe history is seen in a rather small variation of Mn-54 and Fe-59 reactor water activities, c.f. F3.

Outage gamma scanning data and dose rates on the standard RHR location are presented in **Table 39**. Data for most recent cycles are lacking. Note that a decontamination campaign involving the RHR pipes was carried out at the 2000 outage.

***Table 37**: Oskarshamn 3 – Corrosion product reactor water chemistry data – Annual average data during reactor operation*

		$C_w(t)$							
Cycle	Year	Fe [ppb]	Zn [ppb]	Ni [ppb]	Cr [ppb]	Co [ppb]	Cu [ppb]	Cond. [mS/cm]	N/HWC [0/1]
1	1986	*0.50*	*0.05*	*0.50*	*9.00*	*0.040*	*0.05*	0.14	0
2	1987	0.30	0.07	0.47	8.00	0.034	0.05	0.12	0
3	1988	0.45	0.05	0.43	7.80	0.042	0.08	0.12	0
4	1989	1.80	0.04	0.51	6.60	0.033	0.06	0.24	0
5	1990	0.63	0.07	0.34	4.08	0.049	0.07	0.11	0
6	1991	0.54	0.04	0.29	4.23	0.040	0.09	0.10	0
7	1992	0.58	0.02	0.22	3.10	0.046	0.05	0.10	0
8	1993	0.42	0.01	0.24	1.86	0.042	0.05	0.10	0
9	1994	0.45	0.01	0.23	1.66	0.051	0.05	0.10	0
10	1995	0.73	0.02	0.30	1.31	0.060	0.06	0.09	0
11	1996	1.12	0.02	0.29	1.26	0.067	0.08	0.09	0
12	1997	0.88	0.01	0.28	1.42	0.058	0.08	0.09	0
13	1998	1.36	0.01	0.30	1.71	0.060	0.07	*0.10*	0
14	1999	1.21	0.06	0.29	1.86	0.071	0.06	*0.10*	0
15	2000	0.90	0.03	0.28	1.72	0.055	0.05	*0.10*	0
16	2001	0.93	0.03	0.28	1.60	0.037	0.06	*0.10*	0
17	2002	2.63	0.02	0.30	1.80	0.040	0.07	*0.10*	0
18	2003	3.21	0.01	0.27	1.55	0.033	0.07	*0.10*	0
19	2004	3.64	0.02	0.34	2.09	0.050	0.09	*0.10*	0
20	2005	2.12	0.02	0.24	1.65	0.032	0.06	*0.10*	0
21	2006	1.51	0.02	0.32	2.20	0.027	0.04	*0.10*	0

***Table 38**: Oskarshamn 3 – Activated corrosion products in reactor water – Annual average data during reactor operation*

		$C_w(t)$						
Cycle	Year	Mn54 Bq/kg	Co58 Bq/kg	Co60 Bq/kg	Zn65 Bq/kg	Cr51 Bq/kg	Fe59 Bq/kg	Sb124 Bq/kg
1	1986	1.3E+03	1.3E+04	6.5E+02	1.0E+02	1.6E+05	1.4E+02	3.0E+02
2	1987	2.0E+03	2.2E+04	7.8E+03	6.3E+02	8.8E+04	1.0E+02	9.2E+02
3	1988	1.4E+03	2.5E+04	8.6E+03	3.4E+02	1.2E+05	9.0E+01	7.2E+02
4	1989	6.7E+02	4.0E+04	1.2E+04	4.2E+02	2.3E+05	3.6E+02	2.6E+03
5	1990	9.8E+02	2.2E+04	7.7E+03	2.0E+02	1.3E+05	1.5E+02	2.9E+03
6	1991	1.4E+03	1.9E+04	5.4E+03	1.1E+02	1.0E+05	8.0E+01	2.2E+03
7	1992	1.6E+03	1.8E+04	5.7E+03	9.9E+01	9.8E+04	8.3E+01	2.0E+03
8	1993	1.5E+03	1.8E+04	5.2E+03	9.1E+01	9.0E+04	7.6E+01	1.2E+03
9	1994	1.8E+03	1.5E+04	5.4E+03	8.2E+01	6.0E+04	7.4E+01	2.1E+03
10	1995	1.5E+03	1.4E+04	6.3E+03	8.1E+01	6.7E+04	1.2E+02	1.9E+03
11	1996	1.7E+03	1.5E+04	5.8E+03	8.4E+01	5.5E+04	9.7E+01	1.6E+03
12	1997	2.0E+03	1.5E+04	5.7E+03	8.3E+01	5.3E+04	1.0E+02	1.8E+03
13	1998	3.5E+03	2.4E+04	9.3E+03	9.5E+01	6.1E+04	1.7E+02	1.2E+03
14	1999	1.3E+03	1.6E+04	5.9E+03	7.1E+01	5.3E+04	8.6E+01	1.6E+03
15	2000	1.2E+03	2.0E+04	6.5E+03	7.3E+01	6.2E+04	1.8E+02	9.2E+02
16	2001	1.2E+03	2.0E+04	5.0E+03	6.2E+01	6.7E+04	1.5E+02	7.0E+02
17	2002	2.1E+03	1.9E+04	4.3E+03	5.5E+01	6.8E+04	4.0E+02	1.1E+03
18	2003	3.6E+03	2.0E+04	3.8E+03	5.9E+01	7.4E+04	1.7E+02	1.8E+03
19	2004	3.4E+03	2.0E+04	5.2E+03	7.3E+01	7.4E+04	1.3E+02	1.6E+03
20	2005	4.3E+03	2.8E+04	4.6E+03	7.5E+01	9.8E+04	4.2E+02	2.0E+03
21	2006	2.3E+03	3.3E+04	5.9E+03	9.4E+01	1.9E+05	3.7E+02	1.5E+03

***Table 39**: Oskarshamn 3 – Gamma scanning data and measured dose rate during outage on RHR piping*

		A(t)							
		Mn54	Co58	Co60	Zn65	Cr51	Fe59	Sb124	DR
Cycle	Year	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	Bq/m2	mSv/h
1	1986	1.2E+07	5.6E+08	2.4E+08	9.4E+06		1.2E+07	3.6E+07	1.35
2	1987	3.8E+07	7.3E+08	9.7E+08	2.0E+07		9.8E+06	2.8E+07	2.50
3	1988	1.8E+07	3.8E+08	9.7E+08	1.4E+07		6.5E+06	2.0E+07	3.20
4	1989	1.5E+07	3.9E+08	1.2E+09	1.2E+07		7.0E+06	1.3E+07	3.50
5	1990	7.8E+06	2.7E+08	1.6E+09				1.8E+07	4.50
6	1991								2.45
7	1992	2.4E+07	2.5E+08	1.7E+09			1.7E+07	3.5E+07	2.12
8	1993								2.40
9	1994	2.5E+07	2.0E+08	1.7E+09	6.3E+07		5.7E+07	2.1E+07	2.80
10	1995	2.6E+07	2.2E+08	1.5E+09	6.2E+07		3.5E+07	2.5E+07	2.60
11	1996	2.3E+07	1.2E+08	1.4E+09	9.2E+06			1.1E+07	2.76
12	1997	7.6E+07	4.3E+08	2.8E+09			2.0E+07	3.2E+07	2.54
13	1998	2.4E+07	1.8E+08	1.0E+09					2.51
14	1999	5.4E+07	4.1E+08	2.8E+09					2.66
15	2000		9.0E+07	6.4E+08					0.48
16	2001	Decontamination							0.44
17	2002	1.1E+08	6.4E+08	1.3E+09			3.2E+07	2.9E+07	0.49
18	2003								0.49
19	2004								0.55
20	2005								
21	2006								

The above reactor water activities and gamma scanning data have been recalculated to surface enrichment factors K for the different activated corrosion products according to ***Eq. 1*** and ***Eq. 2***. The resulting K factors for different radionuclides are presented in **Figure 29**. Some comments to the results:

- Most K-factors are somewhat reduced during the initial cycles.
- The recontamination rate seems to be very low after decontamination performed at the 2000 outage.
- The K-factors are somewhat lower than in the sister plant F3, especially after the decontamination.

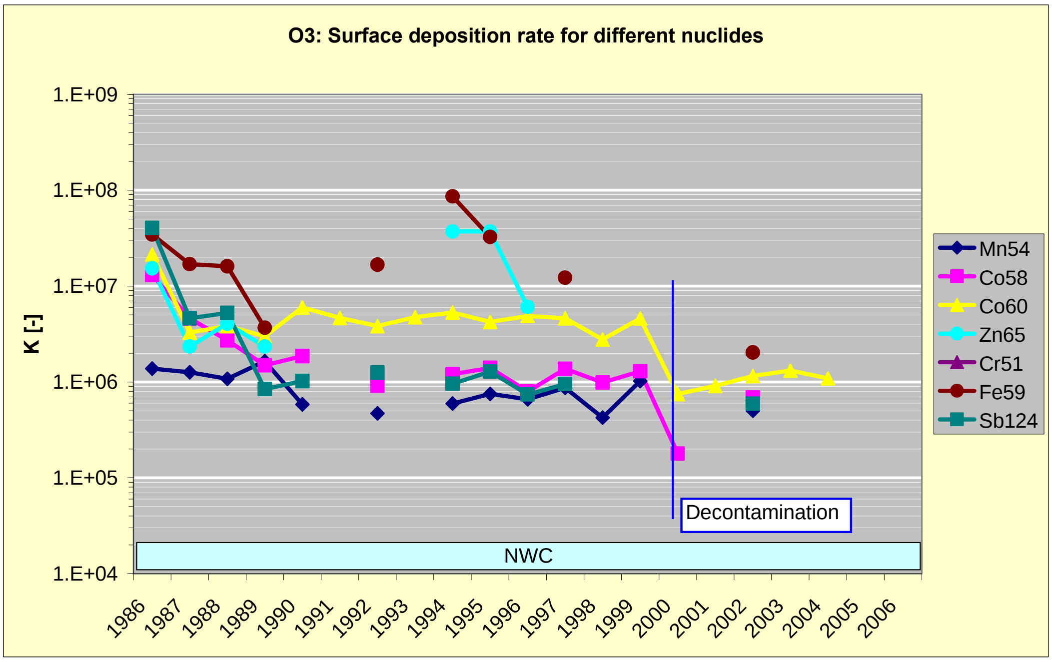

Figure 29*: O3: Surface enrichment factor K based on cycle average reactor water activity and reported gamma scan and dose rate measurements on RHR pipes*

3 Analysis

3.1 Influence of half-life

The influence of the half-life for the nuclide can be studied by comparing pair of radioisotopes, with different half-lives but assumingly same chemistry properties:

- $\frac{T_{½}(Co60)}{T_{½}(Co58)} \approx 27\,;$ $\sqrt{\frac{T_{½}(Co60)}{T_{½}(Co58)}} \approx 5.2$
- $\frac{T_{½}(Mn54)}{T_{½}(Mn56)} \approx 2900\,;$ $\sqrt{\frac{T_{½}(Mn54)}{T_{½}(Mn56)}} \approx 54$
- $\frac{T_{½}(Zn65)}{T_{½}(Zn69m)} \approx 426\,;$ $\sqrt{\frac{T_{½}(Zn65)}{T_{½}(Zn69m)}} \approx 21$
- $\frac{T_{½}(Sb124)}{T_{½}(Sb122)} \approx 22\,;$ $\sqrt{\frac{T_{½}(Sb124)}{T_{½}(Sb122)}} \approx 4.7$

The square root of the half-life ratio is based on what is expected according to the used model, see ***Eq. 2***.

The general impression of the evaluation according to ***Eq. 2*** is that it provides a surprisingly good description of the dependence of half-lives, as shown by the correlation between K-factors for Co-58 and Co-60 is shown in **Figure 30**. Most K-factors are close to the correlation line, especially when considering the involved uncertainties in the evaluation. There is, however a tendency that some of the plants, F1, F2, F3 and O3, show somewhat higher K-factor for Co-60 than for Co-58 in cases with old passive oxides with low relative activity build-up. All these cases represent NWC conditions with very low feedwater Fe. The OL1/2 plants, also NWC but with somewhat higher inflow of Fe, show a better agreement between the Co K-factors.

The difference between K-factors for Co-58 and Co-60 in some of the plants may be explained by a somewhat higher fraction of reactor water Co-60 in the insoluble form. As an example, measurements in O3 shows, that about 15% of the reactor water Co-60 activity is in the insoluble form, while practically no Co-58 is in the insoluble form. The main reason for this difference is different sources for the nuclides, with Co-60 mainly coming from the fuel crud and Co-58 mainly coming from corrosion of Inconel fuel spacers. The following interpretation can be made base on the O3 data:

• K-factor for insoluble Co-60, based on Fe-59:	ca $3{\cdot}10^7$
• K-factor for soluble Co-60, based on Co-58:	ca $1{\cdot}10^6$
• → K-factor for 85% soluble and 15% insoluble Co-60:	ca $5{\cdot}10^6$

i.e. close to the observed K-factor for Co-60. The reason that this effect is especially evident in some plants are conditions with very low K-factor for the soluble fraction, and that there is a difference between the insoluble fractions for the Co isotopes.

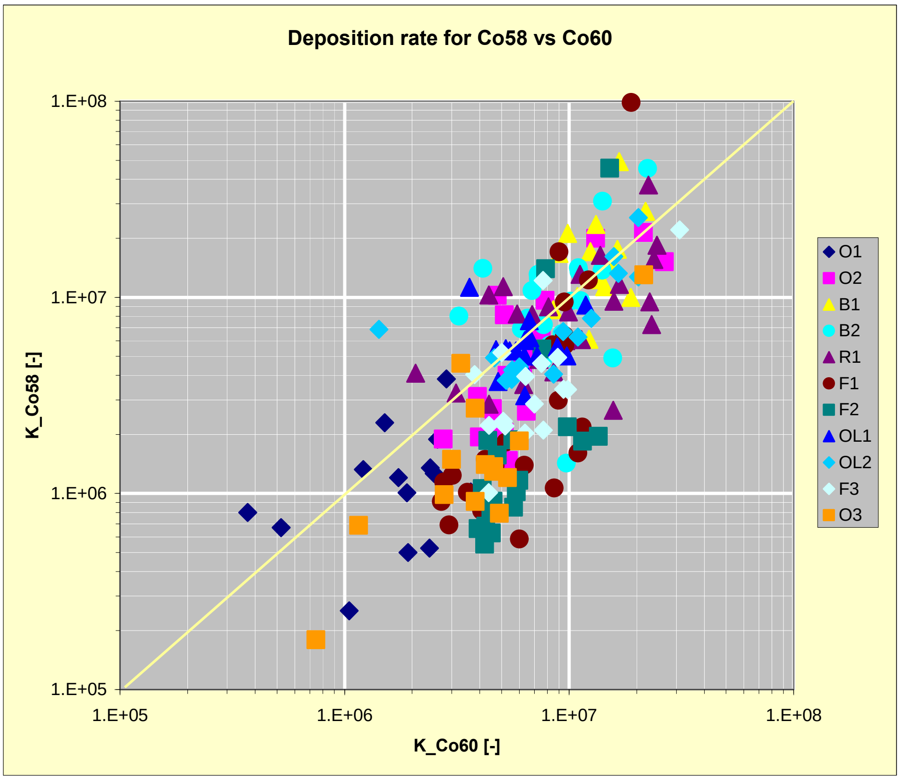

__Figure 30__: Correlation between evaluated K-factors for Co-58 and Co-60

It should also be remembered, that the evaluation according to ***Eq. 2*** assumes equilibrium for the activity between the water and the system oxide, which in case of nuclides with long half-lives, e.g. Co-60, in many cases possibly is not true. Co-58 in this respect reaches equilibrium faster than Co-60, which is well illustrated in the example below from the on-line RHR following up in B2, see **Figure 31**. The variations observed in B2 are explained as follows:

- End of 1998, before start of Zn injection: Equilibrium conditions with $K_{Co58} \approx K_{Co60}$.
- 1999 – 2002: at the beginning of Zn injection: $K_{Co58} < K_{Co60} \rightarrow K_{Co58} \approx K_{Co60}$. The decreasing effect of Zn on the enrichment factor is delayed in the case of Co-60.
- 2002 – 2005: after the decontamination: $K_{Co58} > K_{Co60} \rightarrow K_{Co58} \approx K_{Co60}$, i.e. Co-58 reaches the new equilibrium after the decontamination faster.

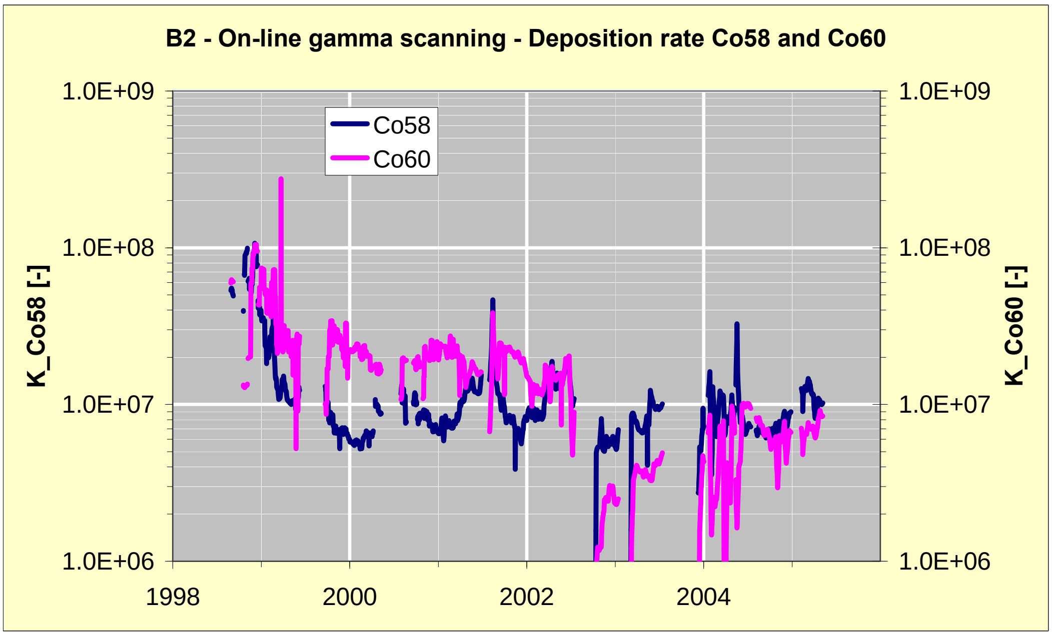

***Figure 31**: B2: Co-58 and Co-60 surface enrichment factor K based on reactor water activity and reported on-line gamma scan (OLA) data on RHR pipes*

It is concluded earlier in the report, that the K-factor determined for a very short-lived nuclide, e.g. Mn-56, Zn-69m and Sb-122, probably is somewhat higher than for the isotope with longer half-life. Typical values for that relation according to the earlier description are:

- K_{Mn56}/K_{Mn54}:	B2:	≈5
	R1:	≈7
- K_{Zn69m}/K_{Zn65}:	B2:	≈2.5
- K_{Sb122}/K_{Sb124}:	O1:	≈1.5
	R1:	≈2

It is suggested that the main reason for the above relation is due to that the reactor water measurements are biased by significant consumption of the short-lived nuclides in the sampling lines. This is illustrated with calculations for four different nuclides and four different K-factors for typical conditions for reactor water sampling lines[12] by using ***Eq. 2***. The results are presented in **Figure 32**, which clearly identifies that an effect as observed is very likely. On the other hand, for more long-lived nuclides, e.g. Co-58, the influence of sampling lines is small. This is, however, only partly true. Fast variations of the reactor water concentrations, or the water chemistry conditions affecting the K-factors will be buffered by the sampling system, i.e. a somewhat delayed response is foreseen.

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[12] Note, that a constant temperature along the sampling line is assumed. Sampling lines are normally not insulated, which means a decrease of temperature along the sampling line, which to some degree reduces the consumption of activity in the line.

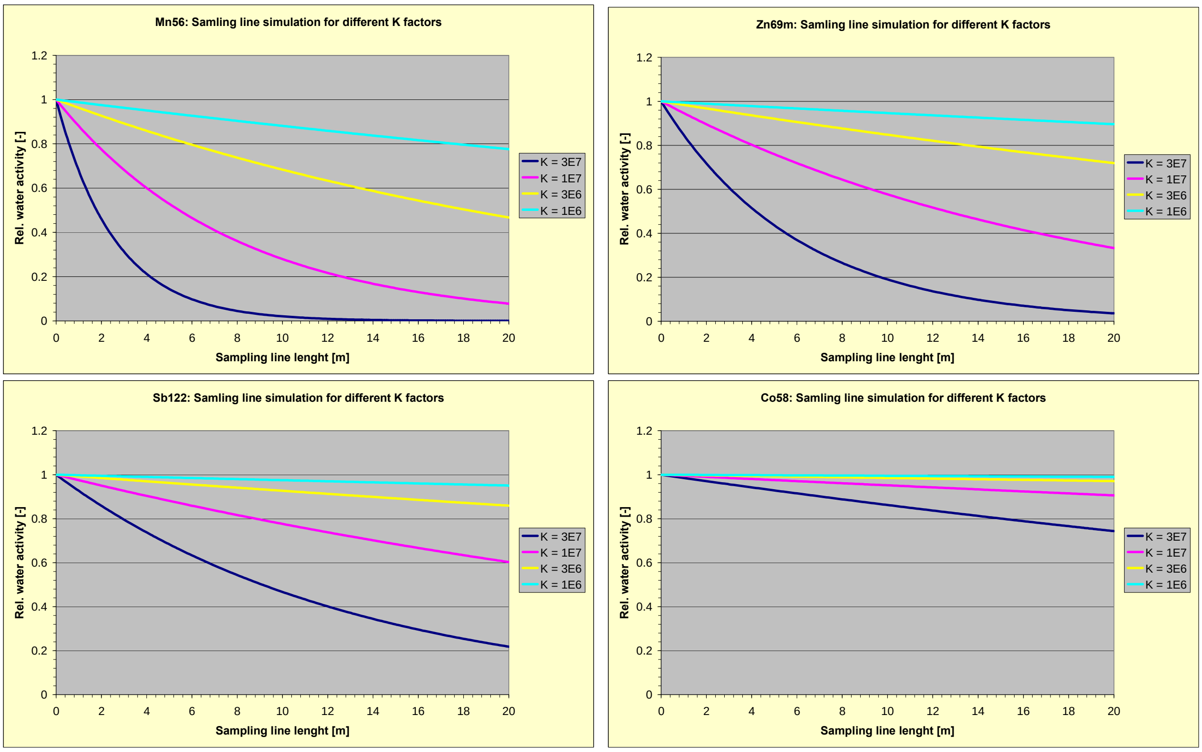

Figure 32: *Sampling line simulation for Mn-56, Zn-69m, Sb-122 and Co-58 for 4 different K-factors (d = 4 mm, F = 30 g/s, T = 270 ℃,* $\rho = 3500\ kg/m^3$*,* $D = 10^{-18}\ m^2/s$*)*

3.2 Influence of operation time

It is expected that the incorporation rate of activity initially is rather high due to a high initial corrosion rate, and thereafter is gradually reduced. The variation of K-factor for Co-60 versus operation time for the different plants is shown in **Figure 33**, and the corresponding information for Co-58 in **Figure 34**. The K-factor for Co-60 does not show any significant variation with time. Initial data for Co-60 have, however, probably not reached equilibrium, i.e. are underestimating the actual incorporation rate. The K-factors for Co-58, on the other hand, have probably already during the first cycle reached equilibrium, and the data in **Figure 34** actually show a decreasing trend up to about 5 cycles. A levelling off is seen thereafter, and the difference between plants is explained by other factors than operation time. Note that the initial operation is not only characterised by high initial corrosion, but also by water chemistry with in general a higher inflow of feedwater Fe than later cycles.

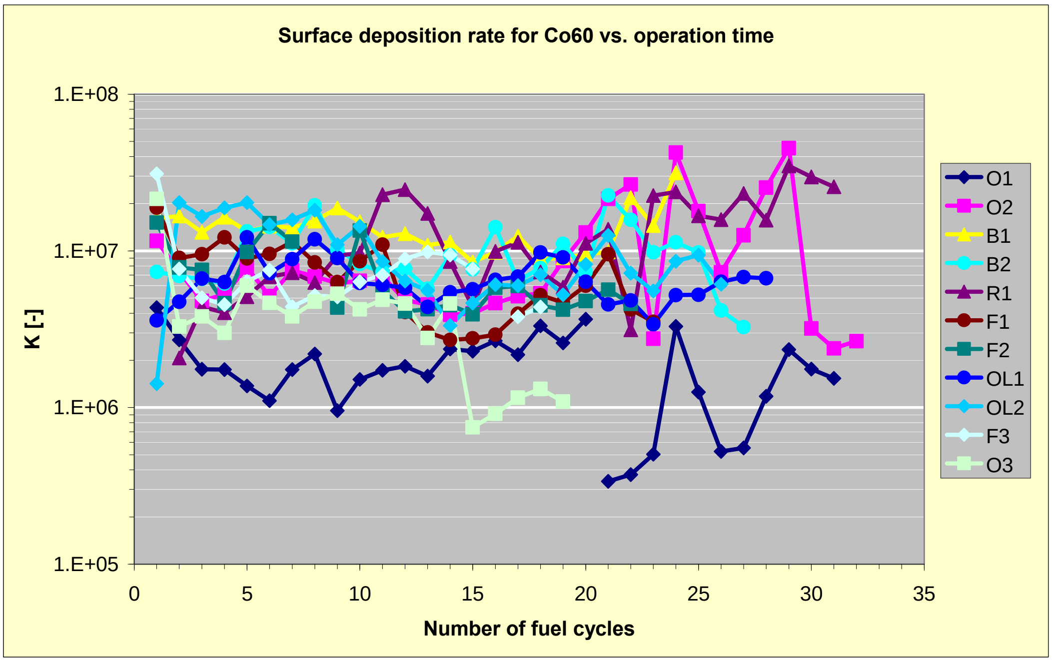

***Figure 33**: K-factor for Co-60 vs. number of fuel cycles*

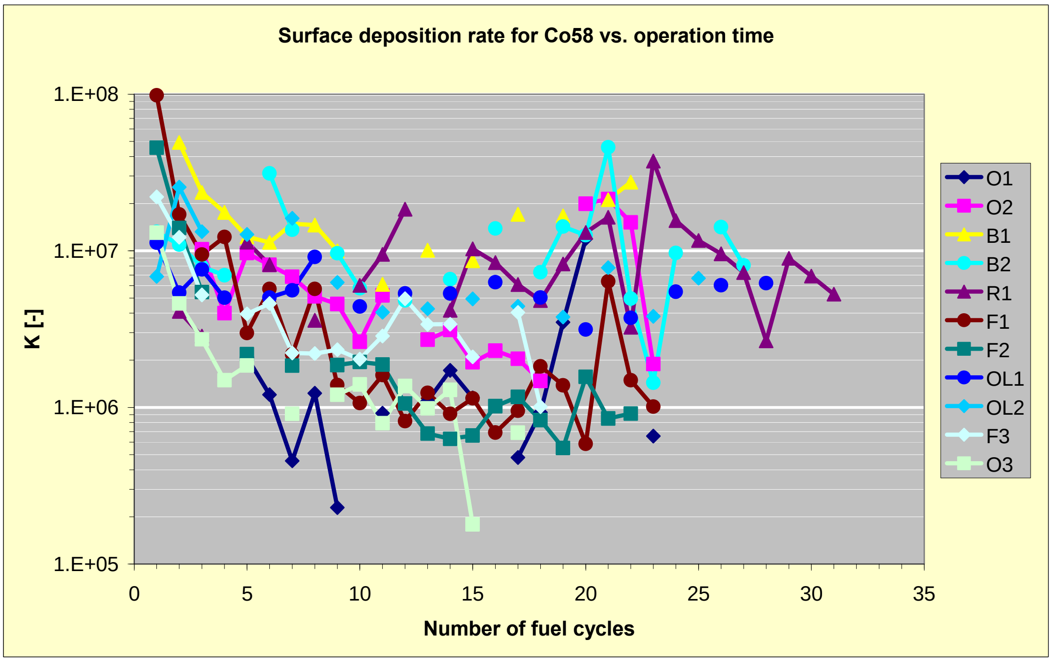

***Figure 34**: K-factor for Co-58 vs. number of fuel cycles*

3.3 Influence of iron

The inflow of Fe to the primary circuit is recognised to have a large impact on the oxide forms in the primary circuit, and thereby affects the activity build-up. That was observed already during the 1990s e.g. in the Forsmark plants /2/. Going from a normal to a very low level of feedwater Fe (<0.1 ppb) was experienced to result in increased reactor water activity, which however was counteracted by a reduced activity uptake on the system surfaces. The net result on dose rates seemed to be rather marginal.

The introduction of HWC meant that extra sources of Fe to the primary circuit were introduced. The solubility of Fe increased in locations achieving low corrosion potential, and significant amounts of Fe in the soluble form was reaching the primary circuit from reactor systems. This extra Fe seemed to increase the activity build-up in the plants.

The influence of Fe inflow on the K-factor for Co-60 is illustrated in **Figure 35**. The K-factors versus operation time are illustrated for three types of reactor cycles:

1. NWC plants with normal inflow of feedwater Fe (>0.1 ppb).
2. NWC plants with low inflow of feedwater Fe (<0.1 ppb)
3. HWC plants

In all cases, reactor cycles with significant Zn in the reactor water (>1 ppb) have been omitted in order to avoid an extra parameter to consider.

The data show that the plants on HWC have in average the highest K-factors and the NWC plants with low feedwater Fe the lowest. The difference between the highest and lowest values is about an order of magnitude.

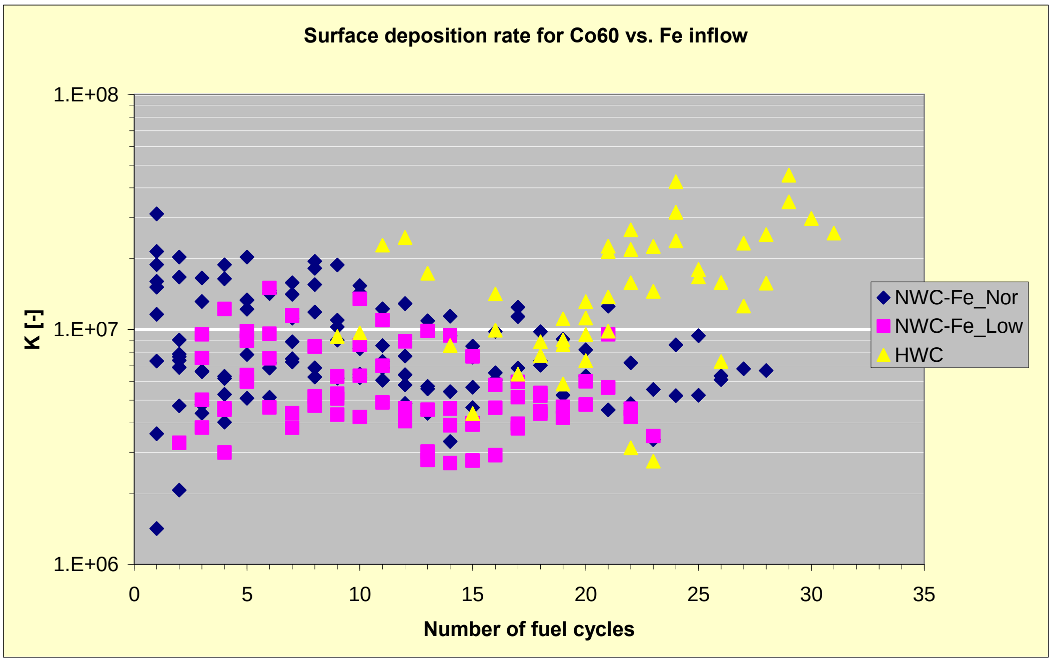

***Figure 35**: K-factor for Co-60 for three different plant categories:*
NWC-Fe_Nor: NWC, normal feedwater Fe (>0.1 ppb)
NWC-Fe_Low: NWC, low feedwater Fe (<0.1 ppb)
HWC: HWC operation (i.e. significant Fe from reactor system)
(Plants and cycles with reactor water Zn >1 ppb skipped)

3.4 Influence of HWC

The method employed to establish reducing conditions in parts of the BWR primary circuit is to inject hydrogen into the feedwater. This technique was first demonstrated in 1979 in the Swedish Oskarshamn 2 plant, and was introduced in several plants during the 1980s. More than 50% of all BWRs are today on HWC to a various degree.

The HWC technique relies on suppressing the radiolytic production of O_2 and H_2O_2, the oxidants responsible for promoting high ECP values on BWR components, from values of several hundred ppb to ppb or sub-ppb levels. Because of the complexity of the interaction between radiolysis production, removal of radiolysis products by boiling and decomposition, the concentration of oxidizing species (O_2 and H_2O_2) is not uniform around the circuit. The net result is that different components reach the -230 mV (SHE) specification at different hydrogen injection rates. In addition, the hydrogen demand to maintain a given location below -230 mV (SHE) can change considerably between different plants and during the cycle.

The variation in the circuit and during the cycle is illustrated with computer models, e.g. the LwrChem code, Lundgren et al., 2004 /3/. As an example, the calculation results for a Swedish external pump BWR, B2, is shown in **Figure 36**. The variation of ECP in the primary circuit for four different H_2 injection rates to the feedwater, 0, 0.5, 1.0 and 1.5 ppm, is presented. The ECP level at NWC conditions, i.e. without H_2 injection, is rather constant at a level of about +200 mV (SHE). The ECP variation in the circuit, when H_2 is injected, is, however, considerable. The potential varies typically between -500 mV to +150 mV (SHE) at an injection rate of about 1 ppm, which is typically needed to achieve the <-230 mV (SHE) protection level in the recirculation loops (“PLR lines”). Locations that are not reaching the -230 mV (SHE) level at this injection rate are inside the core, downstream of the core and in the top of the downcomer. Locations with very low ECP are the bottom of the pressure vessel and external piping far from the pressure vessel, e.g. the RHR and RWCU lines.

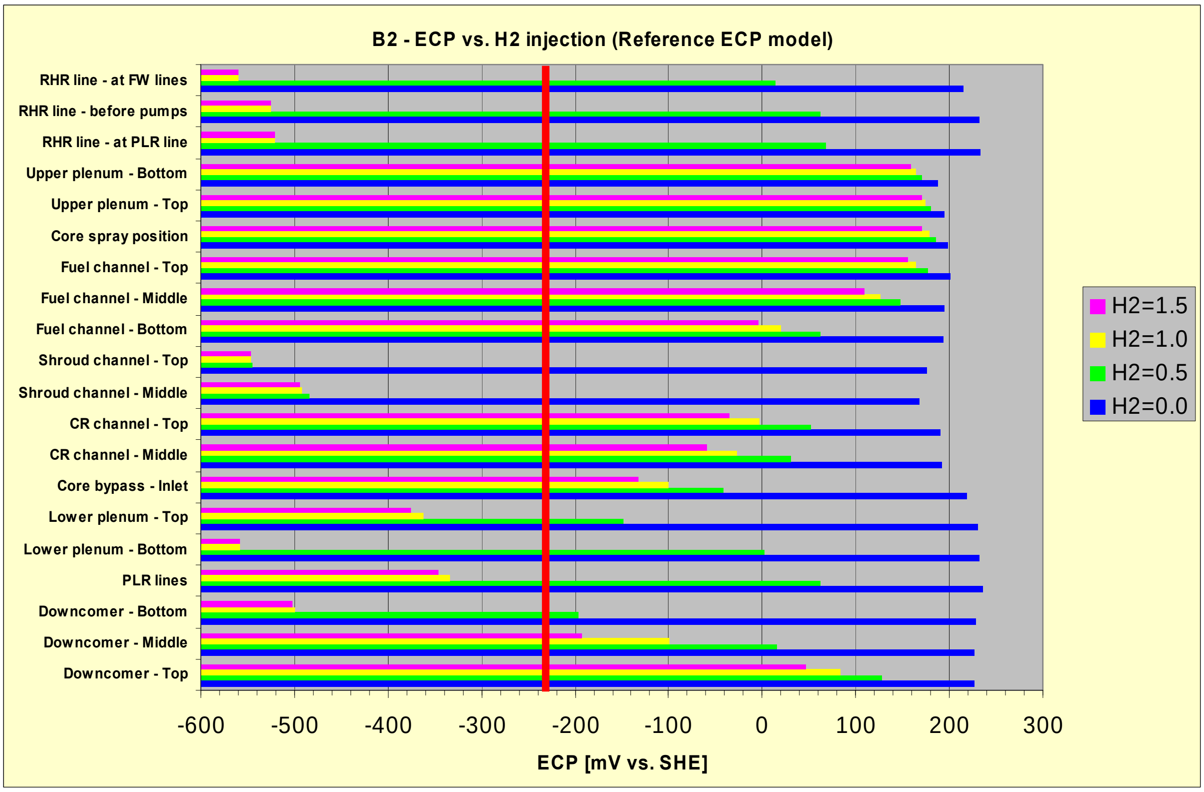

__Figure 36__: Calculated variation of ECP in various position of the primary circuit in a Swedish external pump BWR for four different H_2 injection rates (0, 0.5, 1.0 and 1.5 ppm in the feedwater), Lundgren et al., 2004

The different BWR designs imply some differences in water chemistry conditions, especially the response to hydrogen injection:

- External recirculation loops: Similar conditions are achieved in the recirculation loops and the pressure vessel bottom plenum. The amount of hydrogen needed to obtain protection is moderate.

- Jet-pump design: The different irradiation in the downcomer of the water to the recirculation loops and the driven flow down to the bottom plenum means different need of hydrogen to obtain protection. The corrosion potential in the recirculation lines is reduced with a rather low injection rate, but the bottom plenum needs about a factor of three higher injection rate.

- The internal pump plants: Hydrogen injection has a similar impact on the corrosion potential in the downcomer and the bottom plenum as in the external pump plants. The external piping, e.g. the RHR and RWCU piping, is, however connected to the pressure vessel above the core, i.e. upstream of the downcomer. The connection upstream of the downcomer means that these pipes demand very large amounts of hydrogen injection to be protected.

It has already been shown that the change from NWC to HWC in the external pump plants in general means an increase in the K-factor for the Co isotopes, se e.g. **Figure 35**. The maximum Co-60 K-factor experienced with HWC, but without Zn injection, is about $3{\cdot}10^7$.

The difference of NWC and HWC conditions on K-factors for some other nuclides is shown in **Figure 37**. A considerable increase when going from NWC to HWC is seen for Cr-51. This behavior is expected considering a much reduced solubility of Cr when going from oxidizing to reducing conditions. For Fe-59 a slight tendency in the opposite direction is seen, i.e. a reduction when going from NWC to HWC. The relation between ECP and K-factor for Fe-59 has earlier been discussed, see e.g. **Figure 14**. The influence on Sb-124 is not easily seen in **Figure 37**, but a reduction when going to low ECP is indicated in **Figure 15**. The influence on K-factor for Mn-54 seems to be marginal.

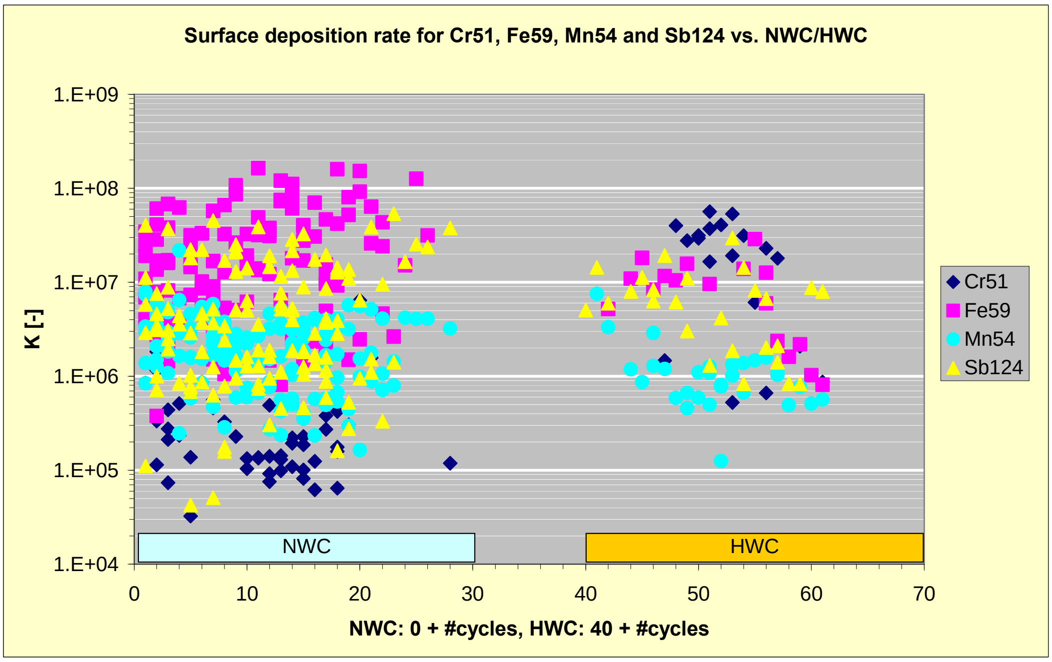

***Figure 37**: K-factor for Cr-51, Fe-59, Mn-54 and Sb-124 separated on NWC and HWC plants (X-axis: NWC = 0 + number of fuel cycles, HWC = 40 + number of fuel cycles)*

3.5 Influence of conductivity

Plants with somewhat high reactor water conductivity have normally enhanced levels of sulphate and nitrate in the water due to intrusion of ion exchange resins or decomposition products of such resins. These impurities result in slightly acidic reactor water conditions. Clean NWC conditions means somewhat higher conductivity levels than clean HWC conditions due to some amount of soluble chromate in the water. Sufficient levels of reactor water Zn and Cu may occasionally result in slightly reduced conductivity by changing the reactor water from slightly acidic to neutral conditions.

The variation of K-factor for Co-60 with reactor water conductivity is shown in **Figure 38**. The data show a large scatter, but there is a trend of reduced K-factors for increased conductivities. Increased conductivity corresponds normally to slightly acidic conditions according to the above discussion.

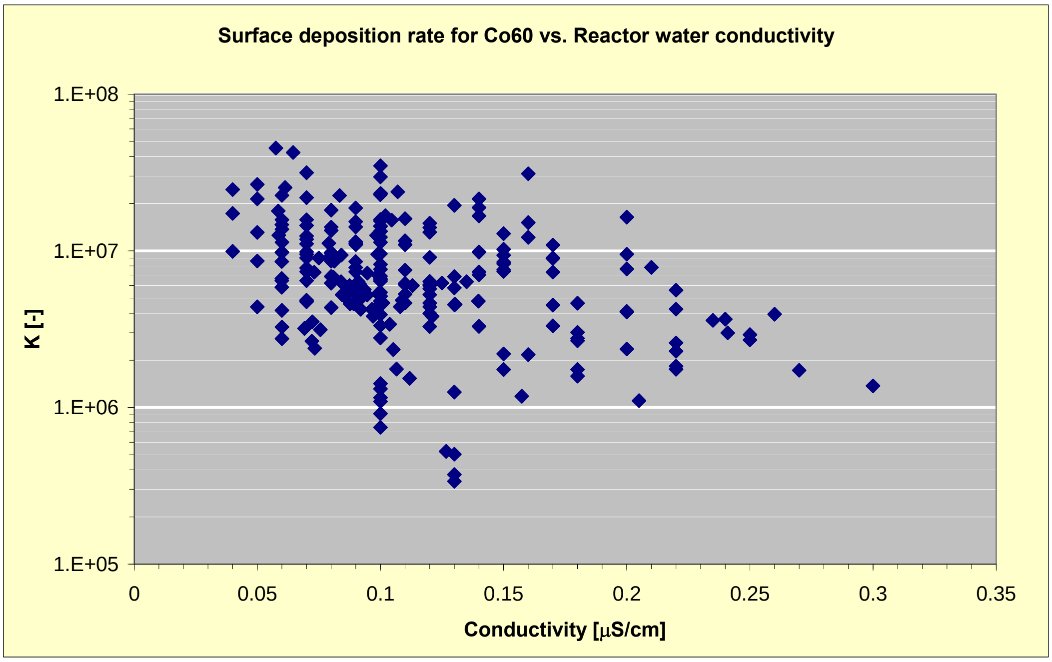

***Figure 38**: K-factor for Co-60 vs. reactor water conductivity*

3.6 Influence of zinc

The earlier description has indicated that the introduction of Zn of the order 3-5 ppb in the reactor water reduces the K-factors, especially if the reactor has HWC operation. A very illustrative example of this is the O2 experience with a very low activity build-up after the combination of HWC, decontamination and introduction of DZO injection, see **Figure 17**.

The correlation between Co-60 K-factors and reactor water Zn is shown in **Figure 39**. The compilation supports the observation, that reactor water Zn of at least 3 ppb seems to result in low K-factors for Co isotopes.

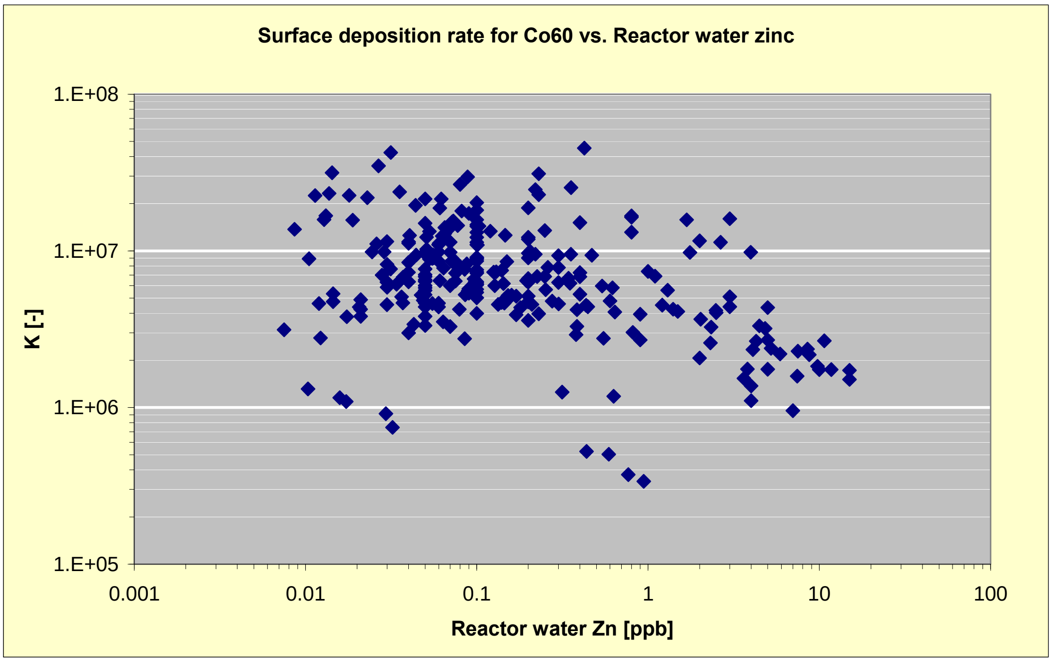

***Figure 39**: K-factor for Co-60 vs. reactor water zinc*

The primary system decontamination data from O1 1992 (**Table 6**) and B2 2002 (**Table 21**) provide a possibility to compare the ratio Zn-65:Zn in the oxide compared to what is expected based on the theory. The following expression for this ratio compared to the ratio in reactor water is derived from /1/:

Eq. 6 $$Q = \frac{1}{1+\sqrt{2\lambda t}}$$

where:

Q – Zn-65/Zn in the oxide relative the ratio in the reactor water [-]

λ - Decay constant for Zn-65 [s^{-1}]

t – Operation time for the oxide with relatively constant reactor water conditions [s]

The calculated relation according to ***Eq. 6*** is compared to the measured data from the two decontamination campaigns in **Figure 40**. The agreement is reasonably good considering the variation in reactor water data (i.e. constant reactor water conditions are not actually fulfilled).

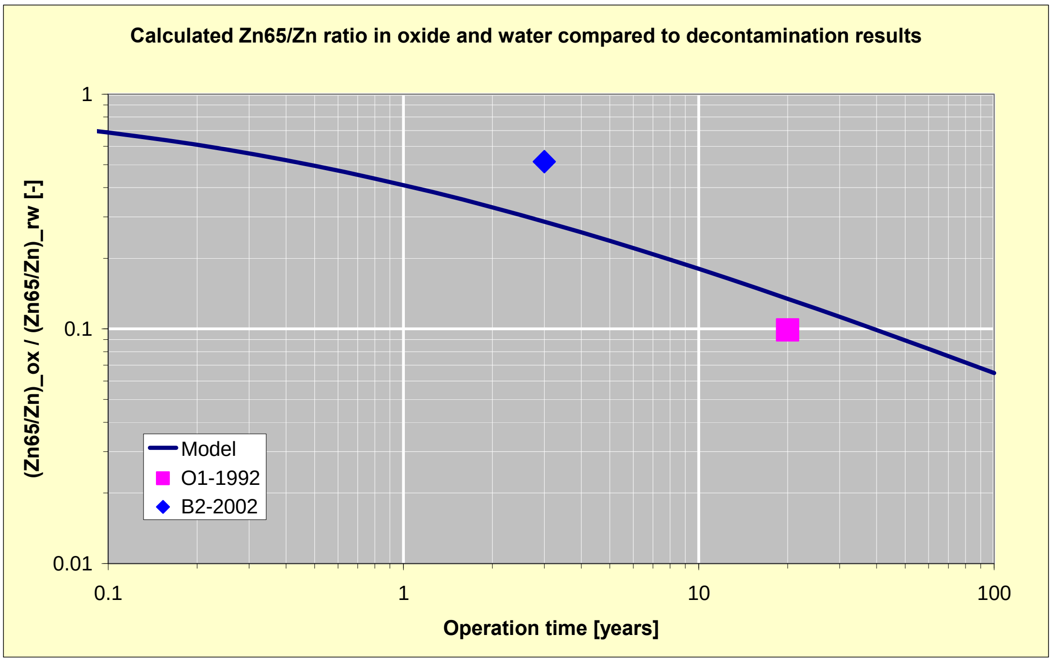

***Figure 40**: Calculated ration Zn-65/Zn relative ratio in reactor water compared to decontamination experience*

3.7 Influence of decontamination

Data before and after five major decontamination campaigns are included in the review of activity build-up:

1. O1 1992: Decontamination campaign in connection to the FENIX modernisation project. Note that modernisation resulted in rather significant change of water chemistry conditions, with reduced Zn, Cu and conductivity.

2. O2 2003: Decontamination of the primary piping. Note that DZO injection was introduced after the decontamination.

3. B2 2002: Decontamination of the primary piping. Similar operation conditions (HWC, DZO) before and after the decontamination.

4. R1 1997: Decontamination of the primary piping. Similar operation conditions (HWC, no Zn) before and after the decontamination.

5. O3 1999: Decontamination of the RHR piping. Similar operation conditions (NWC, no Zn, low feedwater Fe) before and after the decontamination.

The evaluated Co-60 K-factors for the cycles before and after these decontamination campaigns are presented in **Figure 41**. All cases shows reduced K-factors after the decontamination, with R1 as an exception with a slight increase. Note that an initial decrease should be expected for Co-60 due to equilibrium not being reached because of the long half-life. The corresponding data for the more short-lived Co-58 are unfortunately sparse, but gives a somewhat different picture, see **Figure 42**. The Co-58 data indicate rather unaffected conditions in four of the cases, and post-decontamination Co-58 data are not available for the O2 plant.

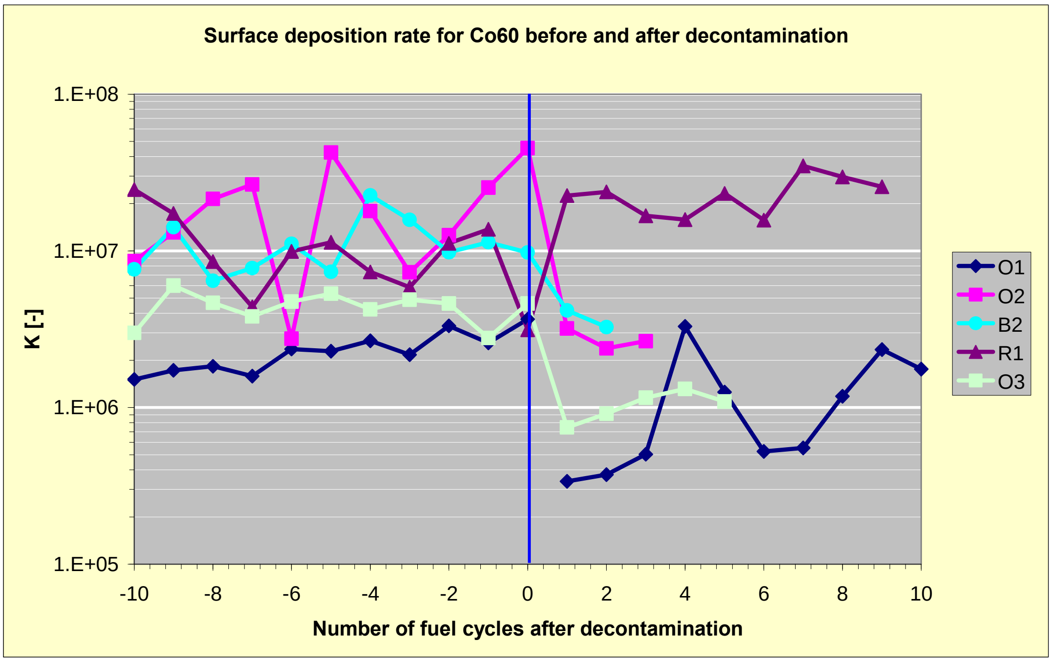

***Figure 41**: K-factor for Co-60 before and after decontamination*

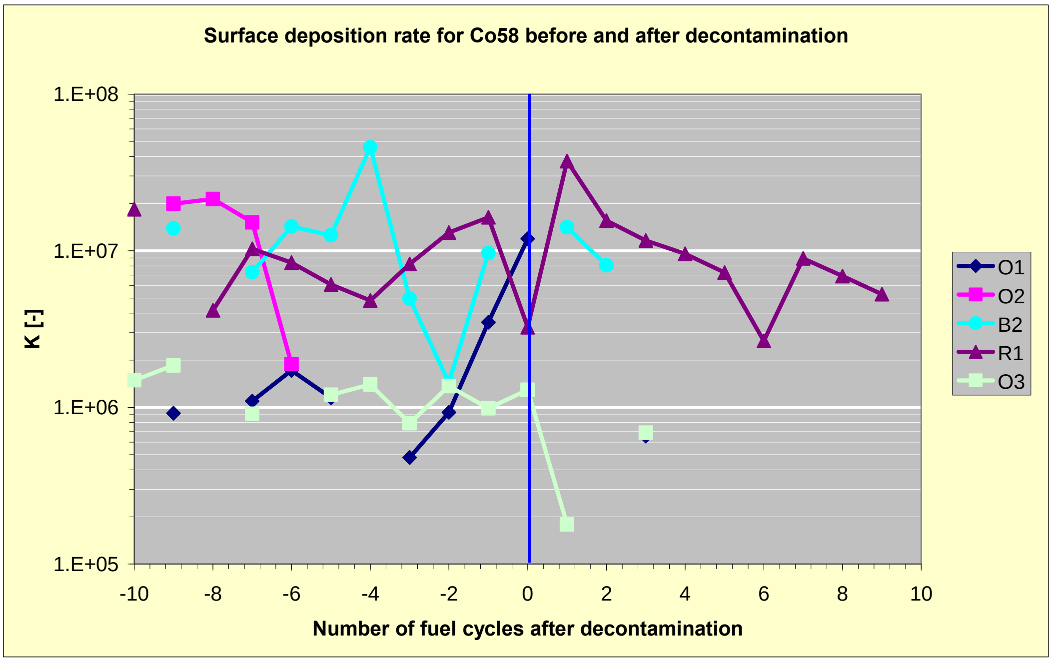

***Figure 42**: K-factor for Co-58 before and after decontamination*

4 Summary and conclusions

4.1 Variation in activity and K values

The variation in the behaviour between different plants implies that most activity build-up effects are generally not simple, one-factor dependencies. This should, however, not be surprising. The main oxide forms are the spinels (see below) and they can have a varied composition, encompassing all the important corrosion product ions (Fe, Ni, Cr, Mn, Co, Zn,...). The fact that there are normal spinels and inverse spinels, and even "depleted" spinels (with vacancies instead of A in the general spinel structure AB_2O_4) as in γ-Fe_2O_3 (maghemite), and the fact that Ni^{2+}, Zn^{2+}, Mn^{2+}, Co^{2+} and even Fe^{2+} all could be the A^{2+} ion, suggests a variation in the activity levels caused by memory effects from previous environmental conditions can be significant in the oxide films. The variation in the water chemistry conditions within the cycles, between the cycles, and between the plants will all affect the actual levels of activity (and of course the level of the corresponding non-active ions, although it is not as straight-forward to study them in the real BWR system) in the oxide films mainly (see below) due to the in-diffusion of the activity into the oxide film. A change in the water chemistry conditions can hence not immediately establish a new steady-state level. Instead, the actual activity level, especially for more long-lived nuclides, will be an integral result of possibly many effects of water chemistry or other environmental changes.

4.2 Incorporation of metal ions into the film

The K values for the different metal ions Ni, Cr, Zn, Co, and even Sb are surprisingly similar, considering that we consider an oxide film on the structural materials surfaces comprising of an inner chromium rich iron or nickel chromite and an outer layer of nickel-iron spinel, i.e. basically trevorite. The compound directly in contact with the coolant is hence normally the trevorite. If the exchange reactions at the surface were directly related to incorporation into the trevorite spinel structure we would expect a much more varied K value, as a result of different formation energies for the corresponding spinels. It is hence tentatively implied that the trevorite structure has a rather large surface area with many sites allowing adsorption of ions from the reactor water. Note that we even have sites allowing chromium to adsorb, although it seems that the K value for chromium on structural material in NWC environment is rather around 10^5 rather than around 10^7 as for most other ions. The chromium is understood to be in the form of negatively charged chromate or dichromate ions in oxidising BWR environment as opposed to the positively charged ions Ni^{2+}, Zn^{2+}, Co^{2+}, and Cu^{2+} generally considered for the other corrosion products. Iron is mainly in colloidal or particulate form at NWC conditions. At very reducing conditions, i.e. locations outside of the core at more extreme HWC conditions, the iron will mainly be available as soluble Fe^{2+}. It is hence postulated that the activity products, but also inferred for the non-activated corrosion products, are adsorbed on the surface of the trevorite phase at the outer surface of the oxide films. This is then the starting point, both from a transport and a thermodynamic point of view, for any diffusion into the oxide film to form new oxide or substitute any metal ions present in the oxide.

The aspect of the sites of ion in the oxide layer is further shown by the basically RW concentration independent surface concentration of the active nuclide, illustrated by the behaviour for zinc in **Figure 43** and cobalt in **Figure 44**. The conditions for these two metals are shown since they are two of the most important ions to control with regard to activity build-up in BWRs.

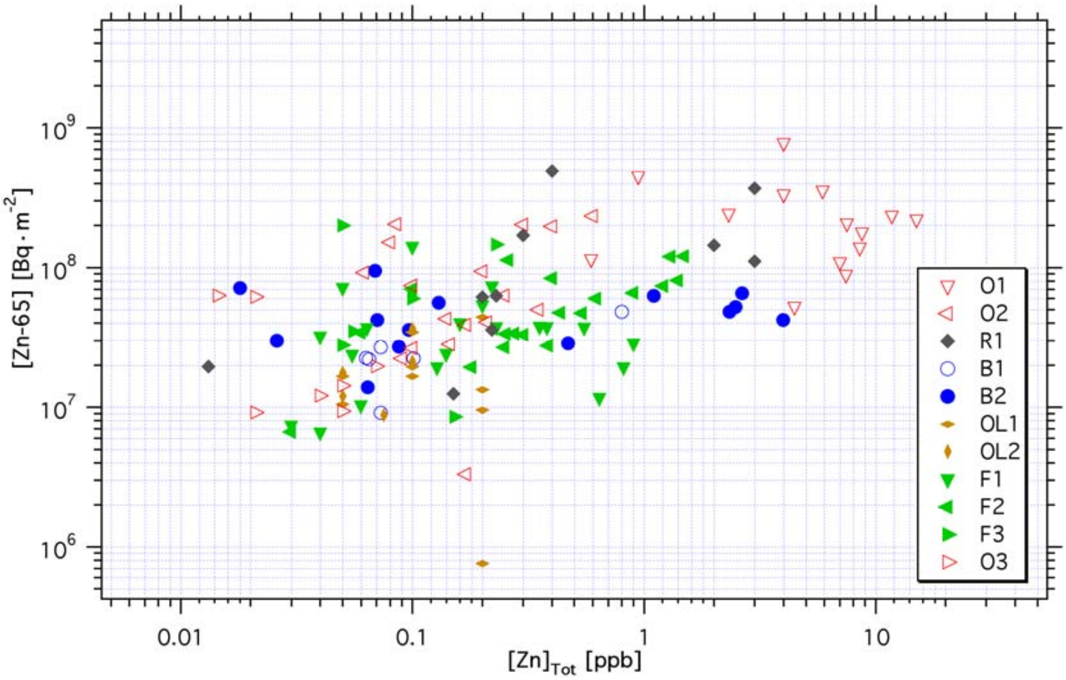

***Figure 43**: Dependence of the surface concentration of Zn-65 as function of the RW zinc (Zn^{2+}) concentration*

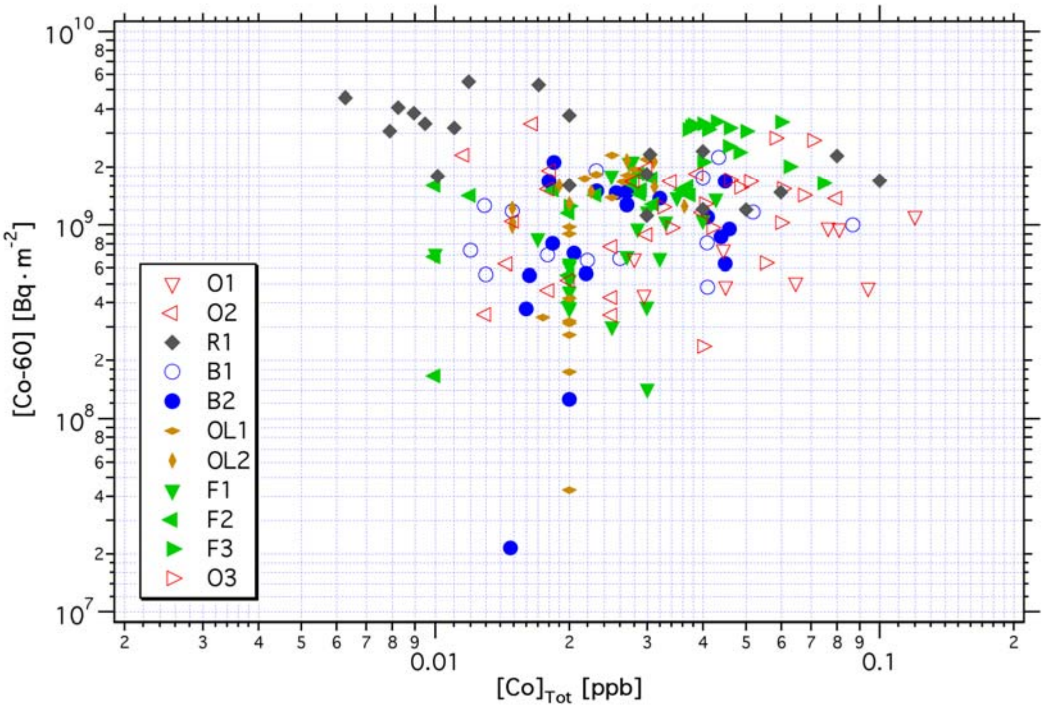

***Figure 44**: Dependence of the surface concentration of Co-60 as function of the RW cobalt (mainly in the form of Co^{2+}) concentration*

The number of sites does not seem to be limited since we can see a constant or even slightly increasing trend with increasing RW concentration of the non-active nuclide, which has to compete for the same absorption sites in the film as the radioactive nuclides of the same chemical form.

The field experience compiled in this report does hence support the approach that surface chemistry, as studied by surface complexation methods, is an appropriate technique in assessing the real activity build-up mechanism as well as the impact of the water chemistry on the oxide formation mechanism in BWR environments.

4.3 Zn for Co-60 removal

A case of special interest is the impact RW zinc on Co-60 in the corrosion film. It is generally considered that zinc in RW at elevated concentration would replace Co-60 in the oxide film. The current data allows us to study that aspect also, as illustrated in **Figure 45**.

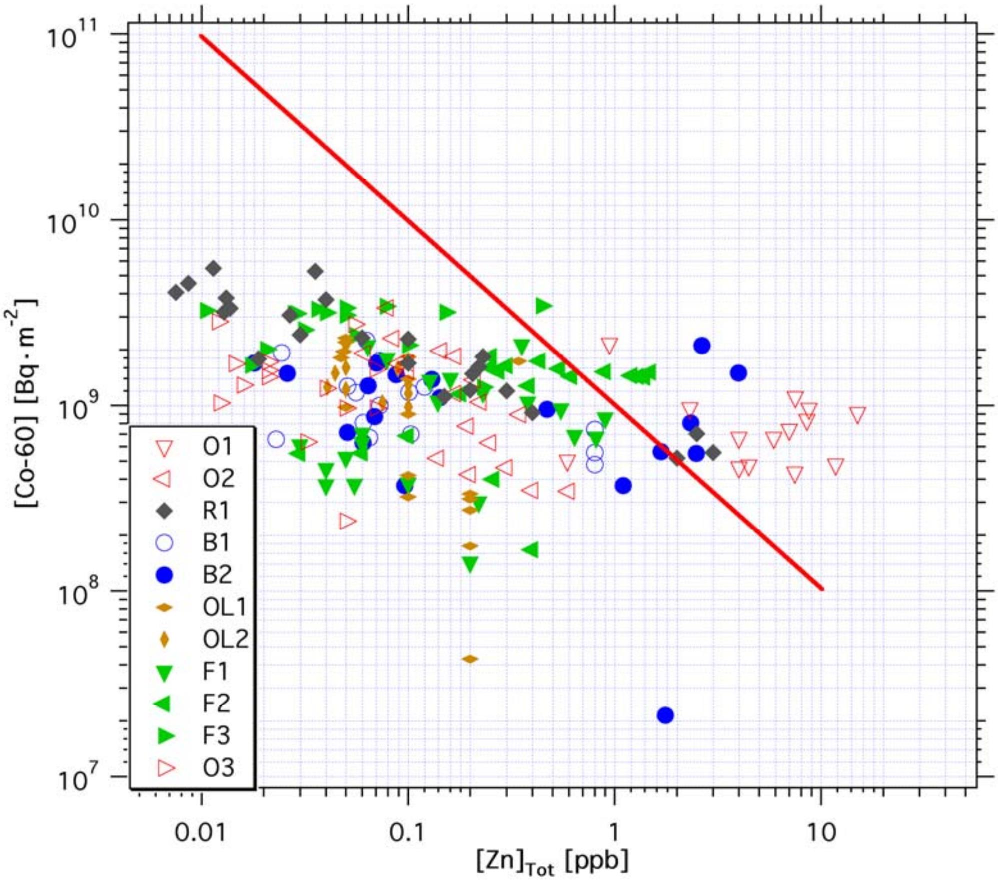

***Figure 45**: Dependence of the surface concentration of Co-60 as function of the RW zinc (mainly in the form of Zn^{2+}) concentration. The solid red line illustrates an inverse relation between the Co-60 surface and the Zn RW concentrations*

As opposed to the figures above, it is seen in **Figure 45** that the there is a trend to have less Co-60 activity in the oxide film at higher Zn concentrations. It is, however, also clear that zinc is not very efficient in general. One reason is probably that Co-60 has been embedded deeper into the oxide film. The effect is consequently present but not very strong.

References

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