Research Article

Parametric Study of Time-Dependent Corrosion Product Activity due to ^{56}Mn , ^{58}Co , and ^{60}Co in the Primary Coolant Circuit of a Typical Pressurized Water Reactor

Muhammad Rafique,^{1,2} Nasir M. Mirza,³ Sikander M. Mirza,³
Kimberlee J. Kearfott,² Shahab A. Abbasi,¹ and Syed F. Naeem²

¹Department of Physics, University of Azad Jammu and Kashmir, Muzaffarabad, Azad Kashmir 13100, Pakistan

²Department of Nuclear Engineering and Radiological Sciences, University of Michigan, 2355 Bonisteel Boulevard, Ann Arbor, MI 48109-2104, USA

³Department of Physics and Applied Mathematics, Pakistan Institute of Engineering and Applied Sciences, Nilore, Islamabad 45650, Pakistan

Correspondence should be addressed to Muhammad Rafique; mrafique@gmail.com

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Results of a detailed study, based on the parametric analysis of activated corrosion products, in primary coolant of a typical pressurized water reactor (PWR) are presented. The parameters influencing time dependent buildup of corrosion product activity (CPA) in primary coolant loop of PWR were identified. The computer program CPAIR was used to accommodate for time dependent corrosion rates. The behaviors of ^{56}Mn , ^{58}Co , and ^{60}Co were studied over the reactor operational time. During the course of normal operation of reactor, the CPA is dominated by ^{56}Mn , while ^{58}Co and ^{60}Co are the predominant radionuclides after reactor shutdown. Parametric study suggests that the total CPA is most sensitive to ion-exchanger removal rates. For a removal rate of $300\text{ cm}^3\text{-s}^{-1}$, the specific activity due to ^{56}Mn has the maximum value of $3.552 \times 10^4\text{ Bq-m}^{-3}$ after 1,000 hours of reactor operation. This value decreases drastically to $8.325 \times 10^3\text{ Bq-m}^{-3}$ at removal rate of $900\text{ cm}^3\text{-s}^{-1}$. Additionally, CPA due to ^{56}Mn , ^{58}Co , and ^{60}Co shows strong dependence on removal rates from the core material surfaces. Variations in the values of radionuclide removal rates from piping surface and radionuclide removal rate from deposition on pipes showed only very small effects on CPA buildup.

1. Introduction

Corrosion products activated by high neutron flux in the reactor core are the dominant contributors to the postshutdown radiation field (PSRF) for all water reactors. Pressurized water reactors (PWRs) have an order of magnitude higher PSRF values compared to gas-cooled reactors. Large PSRF values affect the plant availability factor by prolonging repair and maintenance schedules, entailing annual economic penalties of several billion US dollars [1].

In the past, several authors [2–18] carried out investigations on the formation, transport, and deposition of radioactive corrosion products in various parts of PWRs.

Several models were developed to simulate corrosion product transport and the buildup of activity in the primary coolant systems of PWRs. The PACTOLE program [4] was developed for predicting the time-dependent behavior of the activation of PWR corrosion products. Based upon experimental data, the CORA code was upgraded in 1985 [19] to model the transport of corrosion products in primary coolant loop of PWRs. The MIGA code was developed [20] on a strong understanding of the chemical thermodynamics that determines the most stable oxide phase likely to exist under the chemistry and temperature conditions in each region of the primary circuit. The DISER program [21] simulates corrosion product activity (CPA), assuming that the coolant contains

solute, colloids, and particulate corrosion products. Song and Lee [22] investigated the generation mechanism of crud in the long term fuel cycle, using the COTRAN code, which simulates the behavior of the crud based on double layer concept model and solubility difference. The effects of flow and power transients on CPA were investigated by Mirza et al. and Deeba et al. using the code CPAIR [23, 24]. This was further modified to account for CPA under linearly and nonlinearly rising corrosion rate models by Mirza et al. [13, 14] and Rafique et al. [15].

Malik et al. [25] studied CPA under flow rate transients, having extended burn-up cycles with time-dependent pH-level and boric acid variations. Their finding showed CPA buildup towards saturation following the mixing of boron in primary coolant and a decreasing trend following an increase in pH value. Another study by Malik et al. [26] showed that the use of enriched boric acid as chemical shim actually lowers the primary coolant activity when higher pH values are employed in coolant rather than natural boric acid.

Lewis et al. [27] developed a physical model describing the coolant activity behavior of ^{99}Tc during constant and reactor shutdown operations. Kang and coworkers [19] investigated the inventory of radioactivity in the typical 1,000 MWe Spanish PWR. Analysis was based on DORT models. Henshaw and coworkers [28] proposed a model for simulating thermal hydraulic and chemical conditions within fuel crud deposits. The unique feature of their model is that the chemistry is coupled to the thermohydraulics via the increase in the saturation temperature with the concentration of dissolved species. The model explains several crud scrape observations.

Particulate fouling due to corrosion product sedimentation plays an important role in heat exchanger material integrity and water chemistry. Zebardast et al. [29] proposed a new experimental method for the detection of magnetite particles at temperatures up to 473 K.

In-pile loops were used for the experimental study of possible improvements in the coolant chemistry for reducing the corrosion product dose rates [30, 31]. Those studies indicated that dissolution and crystallization cannot be modeled accurately enough in the absence of the required experimental coefficients for these processes. Those detailed studies revealed that the rate of corrosion in the reactor systems continues increasing as the time of reactor operation at full power increases. Access and frequent maintenance to areas near primary pumps then become very limited due to high radiation doses from primary water and pipe scale.

In this work, parametric studies of CPA under normal reactor operation were carried out. The three radionuclides ^{56}Mn , ^{60}Co , and ^{58}Co were considered. Sensitive parameters are identified from the models, showing their effects on CPA buildup in the primary coolant of typical PWRs.

2. Mathematical Models

The purpose of the parametric analysis of CPA in the primary coolant loop of PWRs is to study the sensitivity of the model simulations to uncertainties in the values of model input data. This work identifies sensitive parameters occurring in

mathematical models used for simulating the behavior of CPA.

The governing time-dependent differential equations for modeling CPA in the primary circuits of PWRs appear in the literature [13–16, 18, 23, 24] and now are summarized. The rate of buildup of target nuclide concentration in coolant water can be written as

$$\frac{dN_w}{dt} = -\left(x_1 N_w + x_2 N_w - x_3 N_p - x_4 N_c\right) A_2 - A_1 + S_w, \quad (1)$$

where

$$A_1 = \sigma \phi_e N_w, \quad A_2 = \frac{g(t)}{V_w}, \quad (2)$$

$$x_1 = \sum_j \varepsilon_j Q_j = \varepsilon_I Q_I + \varepsilon_p Q_p + \varepsilon_c Q_c + \varepsilon_F Q_F$$

and the quantities $\varepsilon_I Q_I$, $\varepsilon_p Q_p$, $\varepsilon_c Q_c$, and $\varepsilon_F Q_F$ are removal rates due to ion-exchanger, deposition on pipes, deposition on core surfaces, and removal by filters, respectively. Similarly, the leakage rate from the k th leak is given by $x_2 = \sum_k l_k$, where the term l_k is the rate at which primary coolant loop loses water from its k th leak ($\text{cm}^3\text{-s}^{-1}$). In addition, $x_3 = K_p$, where K_p is the rate at which isotopes are removed from the scale on piping ($\text{cm}^3\text{-s}^{-1}$), and $x_4 = K_c$, where K_c is the rate at which isotopes are removed from the scale on core material ($\text{cm}^3\text{-s}^{-1}$).

In the above equations x_1 (the radionuclide removal rates due to ion-exchanger, deposition on pipes, deposition on core surfaces, and removal by filters), x_2 (leakage rate from the k th leak), x_3 (radionuclide removal from piping surface), and x_4 (radionuclide removal rate from scales on core materials) are sensitive variables which change the time-dependent CPA in the primary coolant of PWR.

If σ is the group constant for the production of isotope from target nuclide, then ϕ_e , the effective group flux (neutrons- $\text{cm}^{-2}\text{-s}^{-1}$), is defined by the equation

$$\phi_e = \left\{ \frac{1 - \exp(-\lambda T_c)}{1 - \exp(-\lambda T_L)} \right\} \phi_0. \quad (3)$$

The values of decay constant (λ) for ^{56}Mn , ^{60}Co , and ^{58}Co are provided in Table 1. The group flux ϕ_0 is averaged over the geometry of the core and has been estimated using LEOPARD [32] and ODMUG [33] programs in the CPAIR. The times T_c and T_L are the core residence and loop times, respectively.

The core residence time is given by

$$T_c = \frac{H\rho A}{w(t)}, \quad (4)$$

where H is the core height, A is the flow cross-sectional area in (cm^2), ρ is the coolant density at operating temperatures, and $w(t)$ is the time-dependent flow rate (g-s^{-1}).

The loop time is approximated as $L_p T_c / H$ for the complete loop length L_p . N_w , N_p , and N_c stand for the target nuclide concentration in water, on piping surfaces, and on

TABLE 1: Activated corrosion products and their reaction properties [13].

Corrosion products	Reaction and neutron energy	Activation cross section and half-life	ϕ_0
^{56}Mn	$^{55}\text{Mn}(n, \gamma) ^{56}\text{Mn}$ (En is thermal)	13.4 b (2.58 h)	9.2×10^{13}
^{58}Co	$^{58}\text{Ni}(n, p) ^{58}\text{Co}$ (fast neutrons)	0.146 b (70.88 d)	9.02×10^{13}
^{60}Co	$^{59}\text{Co}(n, \gamma) ^{60}\text{Co}$	20 b (5.3 y)	9.02×10^{13}

core surfaces (atoms-cm⁻³); $g(t)$ is flow rate perturbation parameter, defined as $g(t) = w(t)/w_0$, where $w(t)$ is the time-dependent flow rate and w_0 is the steady state flow rate under normal operations. Because in this study transient conditions are avoided, in our subsequent study we will take value of $g(t)$ equal to unity; that is, $w(t) = w_0$. V_w is primary coolant volume.

The corrosion source term appearing in the above equation is given by

$$S_w = \frac{C(t)S}{V_w} \frac{N_0}{A} f_n f_s, \quad (5)$$

where $C(t)$ is the time-dependent corrosion rate (gram cm⁻² s⁻¹), S is the area of system exposed to coolant for corrosion, N_0 is Avogadro's number (6.023×10^{23} atoms g-mole⁻¹), and A is the atomic weight of the target nuclide (g). Here, f_n and f_s are abundances of target nuclides and chemical elements in the system, respectively.

The rate of change of active material concentration in primary coolants for each radionuclide is given by

$$\frac{dn_w}{dt} = A_1 - A_2(x_1 + x_2)n_w - A_3n_w + A_2x_3n_p + A_2x_3n_c, \quad (6)$$

where n_w , n_p , and n_c are the concentrations of the activated radionuclides in the primary coolant water, on the piping, and on the core surfaces, respectively, in atoms-cm⁻³.

The rate of activity buildup on core scale is given by

$$\frac{dn_c}{dt} = B_1 + B_2y_1n_w - B_2x_4n_c - A_3n_c, \quad (7)$$

where $B_1 = \sigma\phi_0N_c$ and $B_2 = g(t)/V_c$.

Here V_c is volume of the scale on the core (cm³). And $y_1 = \epsilon_c Q_c$, where $\epsilon_c Q_c$ is removal rate from scales on core surfaces. Consider $A_3 = \lambda$.

The rate of buildup of target nuclide concentration on the core scale, N_c , is given by

$$\frac{dN_c}{dt} = y_1B_2N_w - x_4B_2N_c - B_1. \quad (8)$$

It then follows that the rate of change of target nuclide on piping walls, N_p , is

$$\frac{dN_p}{dt} = z_1C_1N_w - x_3C_1N_p. \quad (9)$$

The rate of deposition of active materials on the pipes is expressed as

$$\frac{dn_p}{dt} = C_1z_1n_w - C_1x_3n_p - A_3n_p, \quad (10)$$

where $C_1 = g(t)/V_p$, with V_p equal to volume of scale on the piping (cm³). $z_1 = \epsilon_p Q_p$, $\epsilon_p Q_p$ is removal rate from piping surface (cm³).

The rate of activity buildup in ion-exchanger is expressed mathematically as

$$\frac{dn_I}{dt} = D_1y_2n_w - A_3n_I, \quad (11)$$

where $D_1 = g(t)/V_I$, where V_I is volume of ion-exchanger. $y_2 = \epsilon_I Q_I$ is removal rate by ion-exchanger.

The rate of activity buildup in filters becomes

$$\frac{dn_f}{dt} = D_2y_3n_w - A_3n_f, \quad (12)$$

where $D_2 = g(t)/V_f$, V_f is volume of filter, and $y_3 = \epsilon_f Q_f$ is removal rate of filters.

Using the above set of coupled differential equations ((1) through (12)), the computer program CPAIR (corrosion product activity in reactors) [15], using fourth-order Runge-Kutta method to find the activity values due to corrosion, was modified for this work.

3. Methods and Assumptions

The computer code CPAIR, utilizing specifications of a typical PWR with power of 1,000 MWe, was considered [13–15, 34]. Initial impurity concentrations were assumed to be zero. The numerical values of experimental fractional exchange rates ($\epsilon_j Q_j/V_q$) and resolution rates (K_j/V_q) assumed for this work are summarized in Table 2.

The design data values for a typical PWR under consideration are given in Table 3 [13–15, 34]. The core averaged group fluxes have been computed using LEOPARD and ODMUG computer codes. The LEOPARD program is a zero-dimensional unit cell computer code with 54 fast and 172 thermal energy groups. Evaluated Nuclear Data (ENDF-IV) set has been used in the cross section library. In this work, equivalent cells of a typical PWR [34] have been employed to generate group constants for fuel cells and water holes. These cell-averaged group constants are then used in the one-dimensional multigroup diffusion theory based ODMUG code [33]. It calculates the group fluxes as a function of position in the reactor. These group fluxes are subsequently averaged over the core. Both LEOPARD and ODMUG are treated as subroutines of the CPAIR program.

The plant surface area of $\sim 10^8$ cm² is exposed to the primary coolant for corrosion. In the presence of corrosion inhibitors, an equilibrium corrosion rate of 2.4×10^{-13} g-cm⁻²-s⁻¹ [13–15, 33–35] exists after 1 y operation of a reactor with a primary coolant volume of 1.3×10^7 cm³. The corrosion rate of $25 \mu\text{g-s}^{-1}$ has been used as normal equilibrium rate in subsequent studies.

TABLE 2: Experimental values of exchange rates in a typical PWR [13–15, 34].

Rate type	Value
Deposition on core ($\epsilon_c Q_c$)	$80.0 \text{ cm}^3 \cdot \text{s}^{-1}$
Deposition on piping ($\epsilon_p Q_p$)	$13.7 \text{ cm}^3 \cdot \text{s}^{-1}$
Ion-exchanger removal ($\epsilon_I Q_I$)	$500\text{--}781 \text{ cm}^3 \cdot \text{s}^{-1}$
Resolution ratio for core (K_c)	$40.0 \text{ cm}^3 \cdot \text{s}^{-1}$
Resolution ratio for piping (K_p)	$6.9 \text{ cm}^3 \cdot \text{s}^{-1}$
Volume of primary coolant (V_w)	$1.37 \times 10^7 \text{ cm}^3$
Volume of scale on core (V_c)	$9.08 \times 10^6 \text{ cm}^3$
Volume of scale on piping (V_p)	$1.37 \times 10^6 \text{ cm}^3$
Total corrosion surface (S)	$1.01 \times 10^8 \text{ cm}^2$

TABLE 3: Typical design specifications of a PWR [13–15, 34].

Parameter	Value
Specific power (MW(th)-kg ⁻¹ U)	33
Power density (MW(th)-m ⁻³)	102
Core height (m)	4.17
Core diameter (m)	3.37
Number of assemblies	194
Number of rods per assembly	264
Fuel type	UO ₂
Clad type	Zircoloy
Lattice pitch (mm)	12.6
Fuel rod outer diameter (mm)	9.5
Average enrichment (w%)	3.0
Flow rate (Mg-s ⁻¹)	18.3
Linear heat rate (kW-m ⁻²)	17.5
Coolant pressure (MPa)	15.5
Inlet coolant temperature (°C)	293
Outlet coolant temperature (°C)	329

The purification rate due to an ion-exchanger $\epsilon_I Q_I$ was considered to be large enough to regard deposition, resolution, and leakage as second-order effects. Three radionuclides, ⁵⁶Mn (soluble corrosion products, coming from impurities in the steel), ⁶⁰Co, and ⁵⁸Co (insoluble corrosion products), were considered.

4. Results and Discussion

During normal reactor operation at full power, the major contributor towards activity comes from the radionuclide ⁵⁶Mn. The ⁵⁶Mn activity saturates at about 150 h after start of the reactor. The saturation of ⁵⁶Mn activity was due to the fact that we assumed abundances of target nuclides (f_n) and chemical elements (f_s) in the system equal to 1 and 0.5, respectively. Its saturation value is $8.325 \times 10^{-3} \text{ Bq} \cdot \text{cm}^{-3}$ and it makes the primary coolant as a $2.453 \times 10^7 \text{ Bq}$ source (including coactivity) within 150–230 h of reactor operation at full power.

FIGURE 1: Variation of specific activity in primary coolant of PWR with different values of ion-exchanger removal rates.

4.1. Effect of Ion-Exchanger Removal Rates ($\epsilon_I Q_I$) on CPA Buildup in Primary Coolant Loop. Specific activity due to each of the radionuclides (⁵⁶Mn, ⁵⁸Co, and ⁶⁰Co) changes significantly, in the primary coolant loop, with the assumed removal rates for the ion-exchanger.

At removal rate of $300 \text{ cm}^3 \cdot \text{s}^{-1}$, the specific activity due to ⁵⁶Mn reaches a maximum value (saturation value) of $3.552 \times 10^4 \text{ Bq} \cdot \text{cm}^{-3}$ after 1,000 h of reactor operation as shown in Figure 1. Specific activities at removal rates of 400, 500, 600, 700, 800, and $900 \text{ cm}^3 \cdot \text{s}^{-1}$ result in CPA values of $(2.49, 1.868, 1.465, 1.188, 0.984, 0.832) \times 10^4 \text{ Bq} \cdot \text{cm}^{-3}$, respectively.

These values indicate the fact that ion-exchanger removal rates play an important role in controlling the specific activity in PWR primary coolant. So removal rates of $800 \text{ cm}^3 \cdot \text{s}^{-1}$ and greater are optimal values of ion-exchanger removal rate. The parameter $\epsilon_I Q_I$ is the most sensitive parameter for the mathematical models above. By changing values of $\epsilon_I Q_I$ there will be considerable change in the coolant activity.

The normalized specific activity due to ⁵⁶Mn was evaluated using a conventional removal rate of $600 \text{ cm}^3 \cdot \text{s}^{-1}$. Specific activity due to ⁵⁶Mn at removal rates of 300, 400, 500, 700, 800, and $900 \text{ cm}^3 \cdot \text{s}^{-1}$ was 2.42, 1.7, 1.27, 0.81, 0.67, and 0.57 times the conventional removal rate, respectively. Normalized specific activity as a function of different removal rates is shown in Figure 2.

4.2. Effect of Radionuclide Removal Rate from Core Surface Scale (K_c) on CPA Buildup in Primary Coolant Loop. Variations in the value of K_c change the value of CPA in primary circuit of PWR. At $K_c = 25 \text{ cm}^3 \cdot \text{s}^{-1}$ the specific activity due to ⁵⁶Mn in primary coolant becomes $1.21 \times 10^4 \text{ Bq} \cdot \text{cm}^{-3}$, which decreases at higher values of K_c and becomes $1.16 \times 10^4 \text{ Bq} \cdot \text{cm}^{-3}$ at $K_c = 55 \text{ cm}^3 \cdot \text{s}^{-1}$. The variation of ⁵⁶Mn specific

FIGURE 2: Normalized specific activity due to ^{56}Mn as a function of different removal rates.

FIGURE 3: Specific activity of ^{56}Mn as a function of reactor operation time in primary coolant of PWR with different values of K_c .

activity with K_c is depicted in Figure 3 and saturation values are listed in Table 4.

Normalized values of specific activities due to ^{56}Mn as a function of different resolutions rates from core surfaces are shown in Figure 4. A conventional value of $K_c = 40 \text{ cm}^3\text{-s}^{-1}$ was chosen and specific activity due to ^{56}Mn at resolution rates of 25, 30, 35, 45, 50, and $55 \text{ cm}^3\text{-s}^{-1}$ was found as a factor of 1.019, 1.012, 1.006, 0.99, 0.987, and 0.981 with the conventional chosen resolution rate activity.

TABLE 4: Specific activities of ^{56}Mn , ^{58}Co , and ^{60}Co in primary coolant of PWR with different values of K_c .

$K_c \text{ (cm}^2\text{/s)}$	Specific activity (Bq/cm ³) after 1000 hours of reactor operation		
	^{56}Mn	^{58}Co	^{60}Co
25	12118	21088	432
30	12042	17753	362
35	11965	15321	311
40 ^a	11889	13476	273
45	11813	12026	243
50	11739	10858	219
55	11666	9899	199

^a Actual experimental value of resolution value for core in a typical PWR.

FIGURE 4: Normalized specific activity of ^{56}Mn as a function of K_c .

Variation in the value of K_c also changes the amount of radioactivity due to ^{58}Co in primary coolant. The specific activity due to ^{58}Co decreases with increasing the values of K_c . For $K_c = 25 \text{ cm}^3\text{-s}^{-1}$ the specific activity due to ^{58}Co has the value $2.11 \times 10^4 \text{ Bq-cm}^{-3}$ after 1,000 hours of reactor operation, and this value decreases to $0.989 \times 10^4 \text{ Bq-cm}^{-3}$ at $K_c = 55 \text{ cm}^3\text{-s}^{-1}$ as shown in Figure 5 and Table 4. The resolution rates must also be considered a sensitive parameter.

Normalized values of specific activities due to ^{58}Co as a function of different resolutions rates from core surfaces are shown in Figure 6. A conventional value of $K_c = 40 \text{ cm}^3\text{-s}^{-1}$ was chosen and specific activity due to ^{58}Co at resolution rates of 25, 30, 35, 45, 50, and $55 \text{ cm}^3\text{-s}^{-1}$ was found as a factor of 1.56, 1.31, 1.14, 0.89, 0.81, and 0.73 with the conventional chosen resolution rate activity.

Similarly specific activity due to ^{60}Co in primary coolant decreases with increasing values of K_c . For $K_c = 25 \text{ cm}^3\text{-s}^{-1}$

FIGURE 5: Variation in specific activity of ^{58}Co in primary coolant of PWR with different values of K_c .

FIGURE 7: Specific activity of ^{60}Co in primary coolant of PWR with different values of K_c .

FIGURE 6: Normalized specific activity of ^{58}Co as a function of K_c .

FIGURE 8: Specific activity of ^{58}Co on primary coolant piping surfaces of PWR with different values of K_c .

the specific activity has the value $432 \text{ Bq}\cdot\text{cm}^{-3}$ after 1,000 h of reactor operation. This value decreases to $199 \text{ Bq}\cdot\text{cm}^{-3}$ at $K_c = 55 \text{ cm}^3\cdot\text{s}^{-1}$ as shown in Figure 7 and Table 4.

4.3. Effect of Radionuclide Removal Rate from Core Surface Scale (K_c) on CPA Buildup on Piping Surface. Activated corrosion products once produced may get deposited on piping surfaces of primary coolant loop over the period of reactor operation, thereby becoming the potential source of radiation field. On piping surfaces of primary coolant

loop the value of specific activity due to ^{58}Co for $K_c = 25 \text{ cm}^3\cdot\text{s}^{-1}$ has the value $5.81 \times 10^4 \text{ Bq}\cdot\text{cm}^{-3}$ after 1,000 h of reactor operation, and this value decreases radically to $2.838 \times 10^4 \text{ Bq}\cdot\text{cm}^{-3}$ at $K_c = 55 \text{ cm}^3\cdot\text{s}^{-1}$ as shown in Figure 8.

On piping surfaces of primary coolant loop the value of specific activity due to ^{60}Co for $K_c = 25 \text{ cm}^3\cdot\text{s}^{-1}$ has the value $4847 \text{ Bq}\cdot\text{cm}^{-3}$ after 1,000 h of reactor operation, and this value decreases radically to $2331 \text{ Bq}\cdot\text{cm}^{-3}$ at $K_c = 55 \text{ cm}^3\cdot\text{s}^{-1}$, as illustrated in Figure 9.

FIGURE 9: Specific activity of ^{60}Co on primary coolant piping surfaces of PWR with different values of K_c .

FIGURE 10: Specific activity of ^{58}Co in primary coolant of PWR with different values of K_p .

4.4. Effects of Radionuclide Removal Rate from Piping Scales (K_p) on CPA Buildup in Primary Coolant Loop. While changing the value K_p , change in CPA in primary coolant has been observed. For the CPA due to ^{58}Co has value $3626 \text{ Bq}\cdot\text{cm}^{-3}$, which decreases to $3589 \text{ Bq}\cdot\text{cm}^{-3}$ at $K_p = 8.0$ as shown in Figure 10. Similarly for ^{60}Co specific activity has the value $270 \text{ Bq}\cdot\text{cm}^{-3}$ at $K_p = 6.0$, and this value decreases to the value $266 \text{ Bq}\cdot\text{cm}^{-3}$ at $K_p = 8.0$ as shown in Figure 11 and Table 5.

FIGURE 11: Specific activity of ^{60}Co in primary coolant of PWR with different values of K_p .

TABLE 5: Specific activity of ^{58}Co and ^{60}Co with various K_p values.

K_p (cm^2/s)	Specific activity (Bq/cm^3) after 1000 hours of reactor operation	
	^{58}Co	^{60}Co
6.0	3595	268
6.5	3605	269
7.0 ^b	3612	270
7.5	3621	271
8.0	3629	271

^b Actual experimental value of resolution rate for piping in a typical PWR.

4.5. Effects of Removal Rate from Deposition on Piping Surfaces ($E_p Q_p$) on CPA Buildup in Primary Coolant Loop. Effect of $E_p Q_p$ on CPA due to ^{58}Co and ^{60}Co in primary coolant has also been studied. For ^{58}Co the specific activity has the value $3697 \text{ Bq}\cdot\text{cm}^{-3}$, and this value decreases to $3589 \text{ Bq}\cdot\text{cm}^{-3}$ for $E_p Q_p = 10.7$ after 1,000 h of reactor operation, as shown in Figure 12 and Table 6. For ^{60}Co the specific activity has the value $277 \text{ Bq}\cdot\text{cm}^{-3}$, and this value decreases to $268 \text{ Bq}\cdot\text{cm}^{-3}$ for $E_p Q_p = 10.7$ after 1,000 h of reactor operation, as shown in Figure 13.

Some of the results of CPAIR have been compared with the code CRUDSIM/MIT [31]. The same data were used to simulate the CPA using CPAIR program, resulting in $2.02 \times 10^4 \text{ Bq}\cdot\text{cm}^{-3}$ estimated for the stainless steel letdown filters, whose function is to retain corrosion products ^{58}Co , ^{60}Co , and ^{56}Mn . Because solubility is a function of temperature and the temperature of the filters is less than that of the bulk coolant, the filter activity concentrations are not necessary representatives of actual coolant activity concentrations. The filter results, however, are very similar to the value of $1.85 \times 10^4 \text{ Bq}\cdot\text{cm}^{-3}$ reported elsewhere [31].

TABLE 6: Specific activity of ^{58}Co and ^{60}Co in primary coolant of PWR with different values of $E_p Q_p$.

$E_p Q_p$ (cm^2/s)	Specific activity (Bq/cm^3) after 1000 hours of reactor operation	
	^{58}Co	^{60}Co
10.7	3589	268
11.7	3606	269
12.7	3624	271
13.7 ^c	3642	273
14.7	3660	274
15.7	3678	276
16.7	3697	277

^c Actual experimental value of resolution rate from deposition on piping.

FIGURE 12: Variation in specific activity of ^{58}Co in primary coolant of PWR with different values of $E_p Q_p$.

5. Conclusions

Corrosion products are strong contributors to radiation levels produced in personnel working environment of PWR, and thus the estimation of corrosion product activity (CPA) is important. Higher burn-up, longer-lived reactor cores make the problem more critical. In this work, a parametric study of CPA in primary coolant of a typical PWR was carried out using the CPAIR computer code. Conclusions based upon those numerical simulations include the following.

- During normal operation ^{56}Mn dominates the CPA, while ^{58}Co and ^{60}Co are the main contributors after shutdown.
- The CPA shows a strong sensitive dependence on K_c .
- The variation in other parameters, including K_p , l_k , and $\varepsilon_p Q_p$, only weakly affects the CPA.

FIGURE 13: Specific activity of ^{60}Co in primary coolant of PWR with different values of $E_p Q_p$.

- Excellent agreement was found between predictions of CPA using a modified version of CPAIR and CRUDSIM/MIT findings.

Nomenclature

- N_w : Target nuclide concentration in primary coolant water, $\text{atoms}\cdot\text{cm}^{-3}$ ((1), (8), and (9))
- N_p : Target nuclide concentration on inner walls of the piping, $\text{atoms}\cdot\text{cm}^{-3}$ ((1) and (9))
- N_c : Target nuclide concentration on core surfaces, $\text{atoms}\cdot\text{cm}^{-3}$ ((1) and (8))
- n_w : Radionuclide concentration primary water, $\text{atoms}\cdot\text{cm}^{-3}$ ((6), (7), (10), (11), and (12))
- n_p : Radionuclide concentration on the piping, $\text{atoms}\cdot\text{cm}^{-3}$ ((6) and (10))
- n_c : Radionuclide concentration on the core surface, $\text{atoms}\cdot\text{cm}^{-3}$ ((6) and (7))
- $\varepsilon_I Q_I$: Removal rate due to ion-exchanger (1)
- $\varepsilon_p Q_p$: Removal rate from deposition on pipes (1)
- $\varepsilon_c Q_c$: Removal rate from deposition on core surfaces (1)
- $\varepsilon_F Q_F$: Removal rate by filters (1)
- l_k : Primary coolant loop water loss rate from the k th leak, $\text{cm}^3\cdot\text{s}^{-1}$ (1)
- K_p : Radionuclide removal rate from pipe scale, $\text{cm}^3\cdot\text{s}^{-1}$ (1)
- K_c : Radionuclide removal rate from core surface scale, $\text{cm}^3\cdot\text{s}^{-1}$ (1)
- S_w : Corrosion source term (5)
- $C(t)$: Time-dependent corrosion rate, $\text{g}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ (5)
- S : Area of system exposed to coolant for corrosion, 10^8 cm^2 (5)

- N_0 : Avogadro's number, 6.023×10^{23} atoms-g⁻¹-mole⁻¹ (5)
 A : Target nuclide atomic weight (5)
 f_n : Target nuclide abundance of target nuclide in system (5)
 f_s : Chemical element abundance of chemical element in system (5)
 V_c : Volume of the scale on the core, cm³
 V_p : Volume of scale in the piping, cm³
 V_w : Coolant water volume, cm³ ((1) and (5))
 ϕ_0 : Thermal neutron flux averaged over the core geometry, neutrons-cm⁻²-s⁻¹ (3)
 σ : The group constant for radionuclide production from target nuclides
 ϕ_e : The effective group flux, neutrons-cm⁻²-s⁻¹
 w_0 : Steady state flow rate under normal operations (4)
 $w(t)$: Time-dependent flow rate (4).

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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