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Application of Magnetic Filter to Reduce the Crud in PWR Primary Coolant System

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Abstract

In order to develop techniques for reducing personnel exposure rate through the moving alternative magnetic filter, the prediction of crud concentration and activity reduction through the COTRAN code are to be carried out. This implies a new type of magnetic filter and can be used for the separation of crud at high temperature and pressure. The rotational motion of the permanent magnet assembly surrounding the vessel produces the moving alternative magnetic field in the vessel. Then crud can be removed from the coolant by the magnetic force. This study shows that usage of magnetic filter can be reduce the concentration and activities of crud.

1. Introduction

The major sources of the radiation are generated by the neutron activation of the corrosion products at reactor core, and then the radioactive corrosion products are transported to the outside of the core, and accumulated near the steam generator side at PWR. Major radioactive corrosion products, Co^{58} and Co^{60}, are known to contribute approximately more than 70% of the total ORE.

The ICRP 60 for the radiation protection for the public requires more strict reduction of the ORE. The radiation activity levels continue to increase with the circulation of reactor loop water and the associated increase in occupational radiation exposure prevents operational maintenance and inspection activities. It is essential to reduce the build-up of CRUD radioactivity and to increase removal rate of CRUD in the primary coolant system for radiation exposure reduction.

There are several ways to reduce the radiation levels around the primary water system, i.e. improvement of purification system, high pH operation, adoption of low corrosive and low cobalt containing materials in the primary coolant system and periodical decontamination of the primary system.

And there are also suggested new methods for CRUD reduction too. For examples, using of enriched boric acid (EBA) or zinc injection are another new methods for CRUD reduction. The benefits of EBA are related to change in the primary coolant chemistry that reduces the concentration of boric acid required for operation. Use of EBA at enrichment allows the operation at significantly reduced boric acid concentrations. Operation under these conditions could reduce the transport of corrosion products and the corresponding amounts of radio-cobalt deposited on ex-core surfaces, thus eventually reducing the plant dose rates. Also, the addition of zinc to the coolant of Boiling Water Reactors (BWRs) is known as a widespread practice since it has been observed to inhabit the corrosion and the cobalt deposition in the primary circuit and onset of stress corrosion cracking of incore materials. Since the corrosion and activity incorporation mechanisms are similar in BWRs and PWRs, zinc addition or injection might show similar benefits in PWRs [1].

On the other hand, the objective of this study is a more active method to remove radioactive corrosion particles through the moving alternative magnetic filter.

In this study, the theory of magnetic separation and the derivation of separation factor have been introduced to evaluate the performance of moving alternative magnetic filter.

2. Radioactive Corrosion Product

The materials of construction that normally come into contact with the coolant streams of thermal power systems are metal alloys containing the elements iron, nickel, copper, chromium, cobalt, aluminum, zinc, titanium, zirconium, carbon, and manganese as major constituents. All these elements react chemically with water and dissolved oxygen to form oxides (mixture of metal oxide) [2]. Its structure is known as a spinel, which comprise of Fe^{2+}, Fe^{3+}, and $Fe^{3+}O_4$ with partially substituted of Fe^{2+} with Ni^{2+} and Co^{2+} while Fe^{3+} with Cr^{3+} and Co^{3+} cation. The oxides show relatively low solubilities and display quite varied magnetic properties [3]. They are transported by the coolant stream and deposited throughout the systems where they may induce an adverse effect on power plant operation.

An important class of oxides is known as the ferrites, in which iron is the major metallic constituent. It was based on the assumption that the corrosion product was magnetite (Fe_3O_4). However, recent research reveals that corrosion product is mainly composed of nickel-ferrite ($Ni_xFe_{3-x}O_4$). The ferrites show strong magnetic properties in contrast to the other corrosion products that have very much weaker magnetic properties. The stable form of Fe_2O_3 at low temperatures is the well-known hematite, α-Fe_2O_3 [4]. This oxide, or its hydrated form, is the usual iron corrosion product found in the condensate or feedwater systems of fossil and nuclear power plants during startup, when the exposure to the atmospheric oxygen and temperatures are low. At high temperatures in the presence of oxygen, another valence-3 oxide known as maghemite or γ-Fe_2O_3 may form. The γ-form is quite different in crystal structure and, as we shall later see, in its magnetic properties. Both valence-3 oxides of iron are very insoluble in water [5,6,7].

A comparison of magnetic property of the components at the important corrosion products is presented in Table I.

Table I. Magnetic properties of metals and metal oxides

Ferromagnetic	Ferrimagnetic	Paramagnetic	Diamagnetic
ANSI 52100 chrome steel	Magnetite (Fe_3O_4) Cobalt ferrite ($CoFe_2O_4$) Maghemite (γ-Fe_2O_3) Nickel ferrite ($NiFe_2O_4$) Copper ferrite ($CuFe_2O_4$) Hematite (α-Fe_2O_3)	Ferrous oxide (FeO) Cobaltous oxide (CoO) Chromic oxide (Cr_2O_3) Nickelous oxide (NiO) Cupric oxide (CuO)	Copper (Cu) Cuprous oxide (Cu_2O) Zinc oxide (ZnO)

3. Design of Magnetic Filter

This is a new type of magnet filter and can be used for high temperature and high pressure. The separator, which has been tried to develop, consists of a cylindrical and annular vessel and permanent magnet assembly. Rotation of permanent magnet assembly surrounding the vessel produces moving alternative magnetic field in the vessel. CRUD such as magnetite in the magnetic field is magnetized. Thus magnetized CRUD may be transferred to the shifting direction of moving alternating magnetic field. CRUD divided from the coolant is deposited in sludge at the vessel wall. And then, CRUD can be easily separated from the coolant by moving alternative magnetic force. Therefore it is very important to analysis of magnetic properties of corrosion products and magnetic separation theory and to evaluate of the advanced CRUD separator. The effectiveness of a magnetic filter in separating particles from a fluid stream depends on the relative magnitudes of the magnetic attractive force. In general, the competing forces are those due to hydrodynamic drag, to the gravitational field and to the inertial effects on the particle. Experimental device of moving alternative magnetic filter is shown in Figure 1.

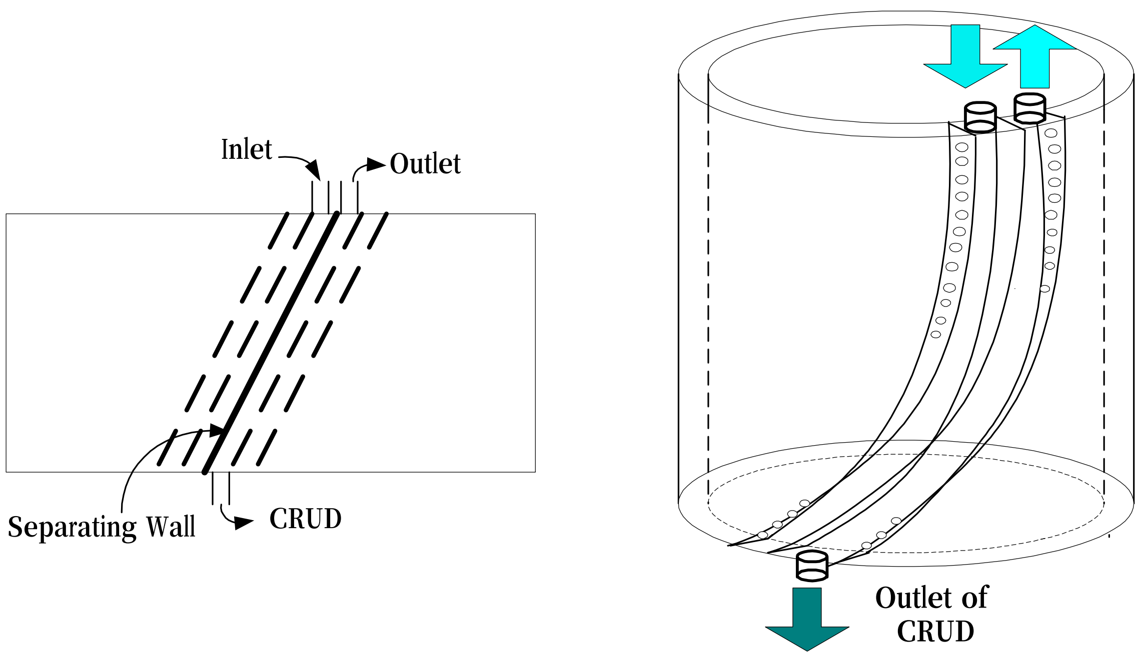


Figure 1. Schematic diagram of magnetic filter

4. Prediction of Crud Concentration & Activity Reduction

COTRAN code was developed at KAIST in 1993 based on the simplicity of CRUDSIM and nodalization of PACTOLE. It considered double layer concept, soluble and particulate CRUD. The COTRAN code was verified by applying PCCL of MIT during one cycle that is short period in previous study. In this study, COTRAN code was used through some modification for prediction of CRUD concentration and activity reduction by magnetic filter.

It is possible only particles to remove by magnetic filter. And then mathematical model is given by the following equations.

$$\frac{dC_p}{dt} = \sum_y f_v \frac{P}{A} a m_{y/o} - \sum_y f_v \frac{P}{A} h_p C_p - t C_p + \sum_{C_y > C_e} f_v \frac{3C_p h_{dif}(C_y - C_e)}{r_p r_p} - h \frac{u_{bypass}}{V_{total}} C_p \qquad (1)$$

$$\frac{dA_{i,p}}{dt} = \sum_y f_v a A_{i,y/o} - \sum_y f_v \frac{P}{A} h_p A_{i,p} - t A_{i,p} - h \frac{u_{bypass}}{V_{total}} A_{i,p} \qquad (2)$$

V	volume [m^3]
r_p	density of particle [kg/m^3]
h	separation factor [-]
C_o	outlet concentration [ppm]
C_i	inlet concentration [ppm]
K	characteristic constant [-]
C_p	particle concentration[g/cm^3]
f_v	volume fraction at y-node [-]
P	perimeter of pipe [cm]
A	cross section area of pipe[cm^3]
a	erosion coefficient [sec^{-1}]
$m_{y/o}$	accumulation of y-node at outer1 [g]
h_p	mass transfer coefficient of particle [cm/sec]
h_{dif}	diffusion coefficient from ion to particle [cm/sec]
t	purification coefficient [sec^{-1}]
r_p	particle radius [cm]
C_y	y-node concentration [g/cm^3]
C_e	equilibrium concentration[g/cm^3]
u_{bypass}	bypass flow rate [%]
V_{total}	total volume of primary coolant [cm^3]
$A_{i,p}$	activity of particle of I-nuclide [nCi/cm^3]
$A_{i,y/o}$	activity of outer oxide layer [nCi/cm^2]

This code will be able to predict CRUD concentration and activity reduction with various conditions.

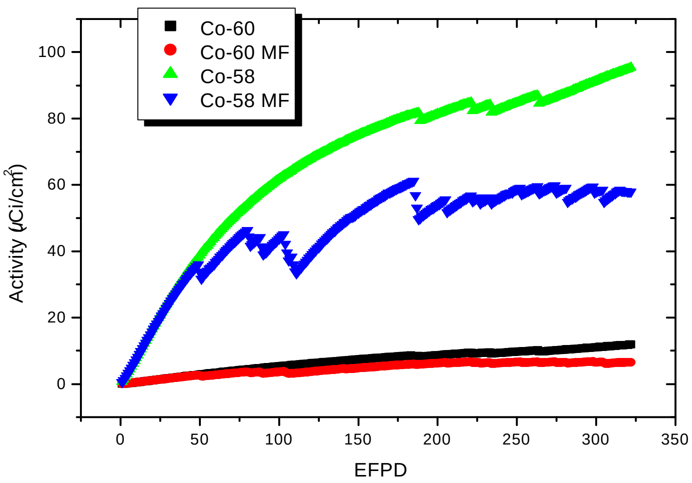
5. Results and Discussion

The input data to be applied these condition is shown on Table II. At Figure 2, Co-58 and Co-60 activity of one cycle is plotted for 322 EFPD at core and steam generator. Reduction of concentration of CRUD is shown on Figure 3. Activity decreases as using the magnetic filter. As the operation time is increasing, the ratio of Co^{58}/Co^{60} becomes small in Figure 4.

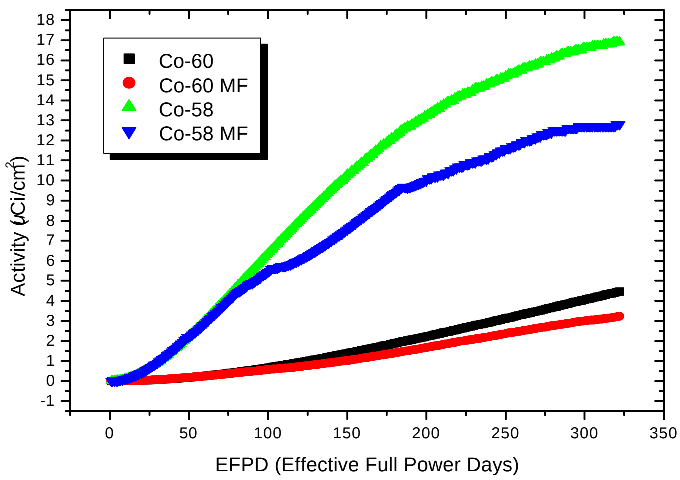
It is 0.01 percent that effective bypass flow rate percentage relative to the primary coolant to reduce CRUD concentration and activity is shown in Figure 5 and 6.

Table II. Input data of COTRAN code

Chemical data	KNU1's Cycle 10 data
Total operation days	322 days
Primary coolant flow rate	1.4E+05 gallon/sec
Bypass flow rate	1%
Efficiency of magnetic filter	90%



(a) at Core



(b) at Steam Generator

Figure 2. Predicted activity of Co-58 & Co-60

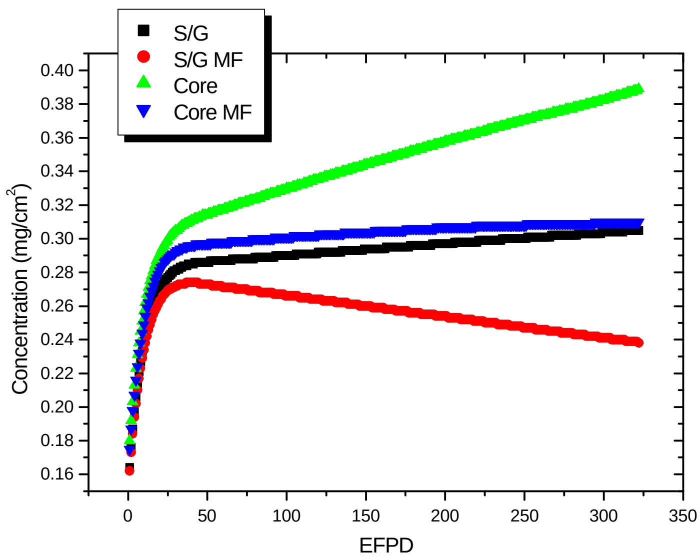


Figure 3. Predicted concentration of CRUD

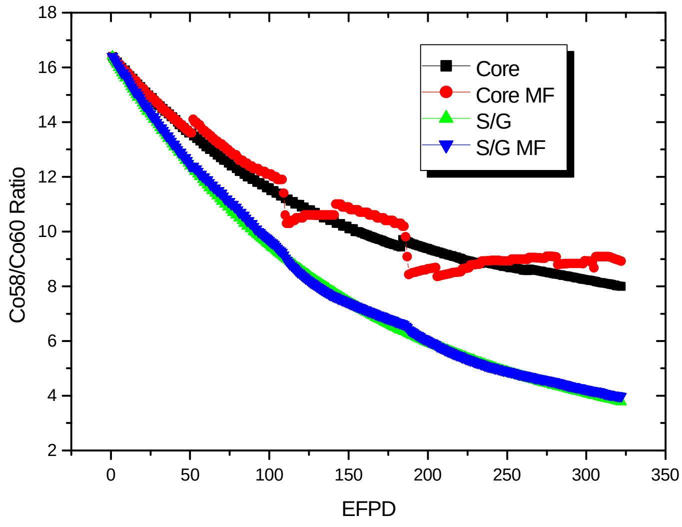


Figure 4. Co-58/Co-60 Ratio

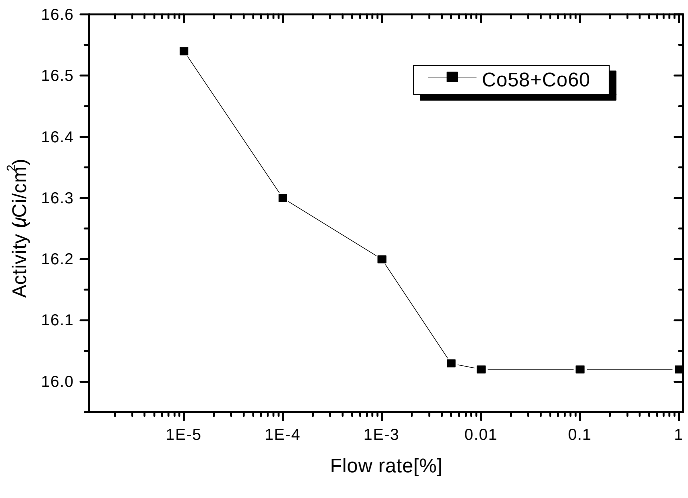


Figure 5. Reduction of CRUD activity at S/G as bypass flow rate

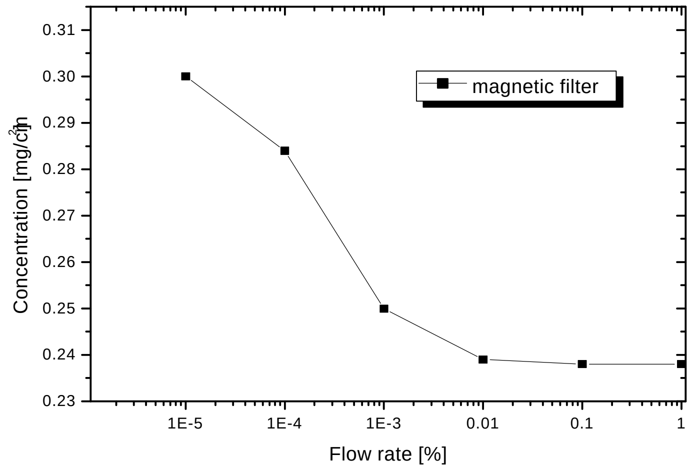


Figure 6. Reduction of CRUD concentration at S/G as bypass flow rate

6. Recommendation

This study shows that the application of magnetic filter can reduce PWR primary coolant system dose rate and hence the moving alternative magnetic filter can be recommended as an effective method for the reduction of radiation build-up. Further improvements of the experimental test are recommended as future works.

Acknowledgement

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