A Study on the Application of CRUDTRAN Code in Primary Systems of PWR & PHWR in Domestic NPPs for the Prediction of Radiation Source Term

Hoon Jo Cho, Kee Nam Choo, Man Soon Cho, Sung Woo Yang, Jong Soon Song*
Neutron Utilization Research Division, Korea Atomic Energy Research Institute
*Department of Nuclear Engineering, Chosun University**
*Corresponding author: jhj1869@kaeri.re.kr

1. Introduction

Water has diverse applications in a nuclear power plant (NPP), e.g., as a moderator of neutrons, a coolant for nuclear reactors, and auxiliary feed water. Corrosion of metals in the primary coolant system of a nuclear reactor generates precipitated particles, which are converted into radioactive materials in the reactor core by neutron activation and then moved by water. Although the inventory of surface contaminants is smaller than that of activated materials, it would play an important role in deciding the method of decommissioning an NPP. In addition, the inventory would provide information required for planning the decommissioning process, thus affecting operational scheduling and manpower requirements. Especially, it would directly influence the exposure of workers in high radiation zones.

In this study, the Pressurized Water Reactor (PWR) and Pressurized Heavy-Water Reactor (PHWR) in domestic NPPs were assessed by using the CRUDTRAN Code, which is an assessment code for activated corrosion products in a PWR. To assess major nuclides not estimated in the CRUDTRAN, the chalk river unidentified deposit (CRUD) was measured in the coolant collected at the reactor coolant system (RCS) of Kori #1, Wolsong #1. By using the nuclide concentration ratios computed according to the data, the average calculated values of major nuclides; that is, ^{58}Co, ^{60}Co, ^{54}Mn, ^{52}Cr; measured currently at Kori #1 and wolsong #1 were compared with the average measured values at the site. The evaluation results showed that the estimated values computed using the code and the nuclide concentration ratios were similar to the measured field data, and the results are assumed to contribute to future studies on the prediction of decommissioning source terms of domestic NPPs.

2. Corrosion Products

In NPPs, water is being used for diverse purposes including moderator of neutron, coolant for nuclear reactors and auxiliary feed water. The water is very chemically activated medium in a high temperature environment such as a nuclear power plant. From the experience of operating NPPs, it has been found that there are many phenomena occurred in normal operating conditions owing to water such as corrosion, erosion and depositions on system surfaces. The continual contacts between water and corroded surfaces in the primary system would mix corrosion products with coolant, which would be circulated in the system. Some of these corrosion products would be existed as a dissolved form, while some materials would become suspended solids made of insoluble metallic oxides to be deposited on the surfaces of pipes and equipment. It is called as CRUD, and the incidence rate of corrosions in NPPs is determined by temperature, systems, materials, environment of radiation field, durable years of materials, and so forth. In general, it is known that in the initial stage of operating a NPP, the corrosion incidence rate is increasing steeply and over time it would be in a constant equilibrium state. Since the coolant system contains fuel, it is the major source of radioactive materials. In a coolant system, any metal contacting with the coolant becomes corroded slowly. Some corrosion products may be dissolved or suspended in the coolant, or passed through neutron fluxes in the reactor core. As corrosion products between coolant and system surfaces have been exchanged continuously, the radioactive materials have been accumulated progressively on the system surfaces ultimately, and radiation fields have been formed. Some radioactive materials have leaked from the coolant system and have become the secondary source of radiation.

3. Behavior Mechanism of Corrosion Products in PWR & PHWR

3.1 PWR

The primary coolant system of the PWR can be largely divided into Core, Coolant and S/G. The major driving force of behavior of the corrosion products in the primary coolant system is the change of solubility according to the change of coolant temperature. Figure 1 shows behaviors of corrosion products and radioactive materials in the primary coolant system. CRUD type metallic impurities are discharged into the condensate water or feed water from the surfaces of parts or pipes in the system. These impurities would be circulated and entered into the reactor coolant system. Metallic ions are discharged into the coolant from corroded surfaces in the primary system. The oxides that exceed the saturation level of the coolant would then form particle materials such as colloids, oxides, or non-oxides. Owing to the interactions between soluble ions and CRUD particles, ionic materials are absorbed onto the surfaces of CRUD particles suspended in the coolant. These CRUD and soluble materials precipitate on the fuel surface by diverse mechanisms; some of these materials do not leak

into the system, and are fixed over the fuel surface and radio-activated through neutron irradiation from precipitates on the fuel surfaces and structure materials in the reactor core. Owing to dissolution and friction, radioactive materials are discharged from the structural material in the reactor core, whereas they are dissolved into the coolant because of erosion and exfoliation of precipitates on the fuel surface owing to water pressure. The radioactive materials are precipitated on the outer surface of the reactor core because of various interactions. Two layers are formed on the outer shell of the core because of the corrosion of base metal and CRUD precipitates containing water. Owing to oxidation on the surface, some corrosion products leak into the coolant from the oxidized layer on the outer surface of the reactor core.
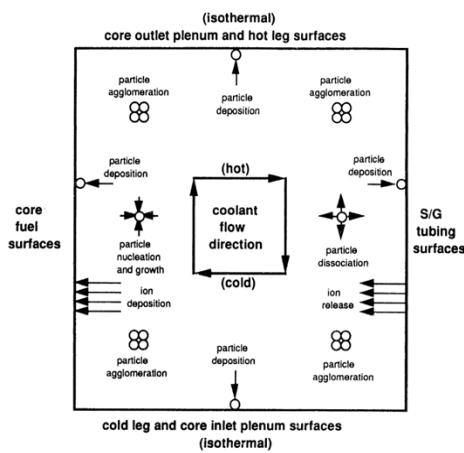

Fig 1. Processes involved in PWR corrosion products transport

3.2 PHWR

Fig. 2 shows the behaviors of corrosion products and radio-activated materials in the primary coolant system of a PHWR. FAC at the outlet of the feeder pipe made of carbon steel causes dissolved iron to be discharged into the coolant of the primary coolant system and the iron dissolved into the coolant is precipitated on the low-temperature tube of the steam generator. At this point, if the temperature of the coolant is reduced in the low-temperature tube, the solubility of magnetite (Fe_3O_4), an iron oxide, decreases, and the rate of FAC is reduced. As the same phenomenon occurs at the inlet of the feeder pipe and that of the nuclear fuel loading tube, oxides are precipitated. Among these materials, some corrosion products are precipitated and others are dissolved in the coolant passing through the reactor core and then precipitated on its surface. The precipitated materials are activated by high temperatures and neutron fluxes, yielding radioactive materials. The generated radioactive materials are dissolved again into the coolant owing to the erosion and exfoliation caused by the difference in the solubility depending on the coolant temperature and pressure. These dissolved materials are circulated and contaminate the entire primary coolant system.
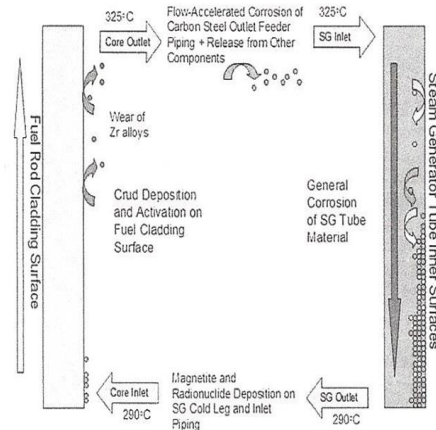

Fig 2. Processes involved in PHWR activity transport

4. CRUDTRAN

4.1 Selection of Code and Its Background

The CRUDTRAN code was developed by the Korea Atomic Energy Research Institute by revising the CRUDSIM code developed by the Electric Power Research Institute and the CRUDMIT code improved by the Massachusetts Institute of Technology to predict the behaviors of corrosion products and activated materials in the primary system of PWR-type NPPs. The CRUDTRAN code is capable of assessing three parts (reactor core, coolant and steam generator) in the primary system. The major driving force of the behaviors of the corrosion products is changes of solubility caused by the temperature change of the coolant. The CRUDTRAN code is a model that can predict the change in the radioactivity of [58]Co and ^{60}Co over time, and can be used to predict the behaviors of corrosion products based on differences of solubility, locomotive force, and other experimental variables, as well as to assess behaviors of corrosion products caused by chemical changes in the coolant. This study would contribute to future studies conducted for predicting the decommissioning of source terms by comparing the modeling results on PWR (Kori #1) and PHWR (Wolsong #1) with the CRUDTRAN code and the data actually measured at Kori #1, Wolsong #1 and check their similarities to obtain the level of confidence.

4.2 Driving Factor of the CRUDTRAN Code

The driving factor for the execution of the CRUDTRAN code is divided into 11 groups. And it can be divided into factors that can be obtained from the field and factors that can be obtained experimentally and numerically. The main factors in the code are shown in Table 1.

Table 1. The main factor in the CRUDTRAN Code

Input	contents
Calculation Parameter	Evaluation cycle, time interval, Code output display method, etc.
Plant Operating Condition	Concentration of boron, LiOH, and hydrogen as power plant operating conditions, Flow rate and density of coolant, core temperature, purification efficiency, etc.
Plant Geometry	Hydraulic diameter and surface area of core and S/G, surface area of contact with the coolant in the primary system depending on the geometry of the plant
Diffusion Coefficients	Diffusion coefficient of soluble and particulate in the primary system
Radioactivity Parameter	Production rate of ^{58}Co and ^{60}Co evaluated in Code
Crystal Growth and Dissolution	Growth rate and Dissolution rate of corrosion products in the primary system
Corrosion Rate	Corrosion rate in S/G tube

The number of factors required for the CRUDTRAN code is approximately 50. These were collected from various reports including the actual measurement data of Kori #1, Wolsong #1 offered by the Korea Hydro & Nuclear Power Co., Ltd. (KHNP). Otherwise, the input factors were obtained through the CRUAS NPP's data, which is similar to the PWR.

5. Application of CRUDTRAN to domestic PWR & PHWR NPPs and assessment

5.1 Selection of Cycle

This study selected a specific cycle based on data of water chemistry and the primary system of the Kori #1, Wolsong #1 modelled by using the CRUDTRAN Code, and then compared and analyzed the behavior of the corrosion products and radioactive materials generated in the primary system. In here, the specific cycle is from the data of starting commercial operations of the Kori #1 (1978), wolsong #1 (1983) through the entire life cycle and the activity of radioactive materials over time has been assessed.

To verify the similarity by using the CRUDTRAN Code, the level of confidence was assessed by comparing and verifying the average measured values of ^{58}Co and ^{60}Co during the operational duration (Kori #1; between 2006 and 2015, Wolsong #1; between 1998 and 2004) presented in the field data of the KHNP and the average estimated values computed with the CRUDTRAN Code.

5.2 Assessment Results

Fig 3 ~ 4 show the analysis results of radioactive nuclide in each zone during the entire cycle of Kori #1, Wolsong #1 including the behavioral changes of ^{58}Co &

^{60}Co in the core, S/G, coolant. The modeling results show that the activity of radioactive nuclides fluctuated periodically according to the cycle of preventive maintenance period. Fig 5 ~ 6 show the graph of the similarity obtained by comparing and verifying the average estimated values computed using the CRUDTRAN code with the average measured values of ^{58}Co & ^{60}Co in the primary system each year, as presented in the field data of the KHNP (Kori #1; between 2006 and 2015, Wolsong #1; between 1998 and 2004). The modeling shows that when comparing the measured values and the estimated values, they are encompassed in the range of allowable errors and reveal a similar trend. In addition, to assess major nuclides not computed in the CRUDTRAN code, the nuclide concentration ratio was utilized according to the measured values of no-site samples. To obtain the nuclide concentration ratio, a nuclide concentration ratio based on the measurement of CRUD in the coolant collected at the RCS Kori #1, Wolsong #1 were used. Figure 7 ~ 8 show the graph of the comparison between the average estimated values of ^{54}Mn & ^{51}Cr and the average on-site measurements based on the earlier results. The comparisons facilitated in determining that the values were encompassed within the allowable error range, and the similarity between the measured and estimated values was verified.
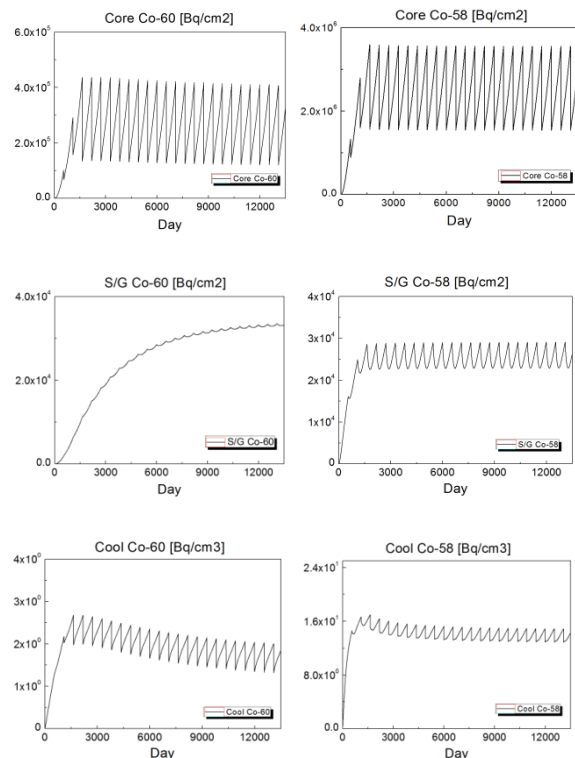

Fig 3. Variation of ^{58}Co and ^{60}Co concentration in the primary system during a life-cycle (Kori #1)
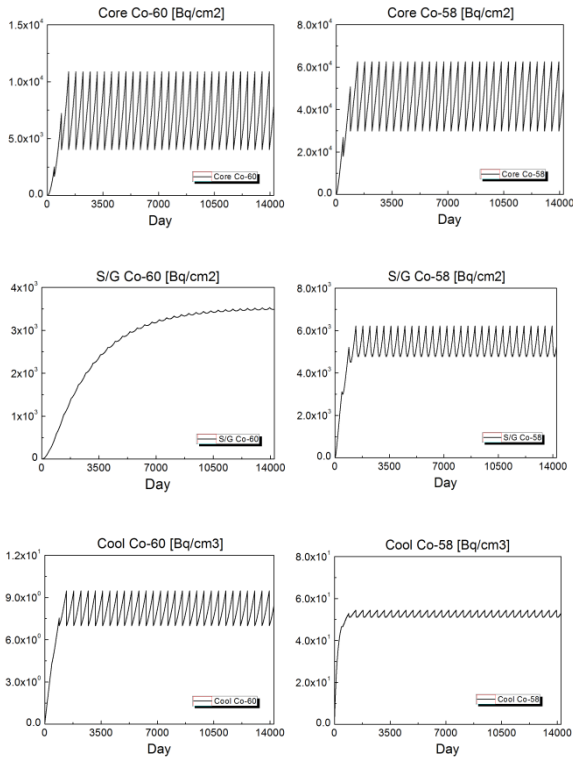
Fig 4. Variation of ^{58}Co and ^{60}Co concentration in the primary system during a life-cycle (Wolsong #1)
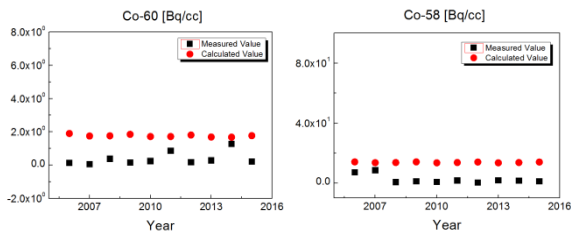

Fig 5. The comparison of measured and calculated values at Kori #1 during 10 years
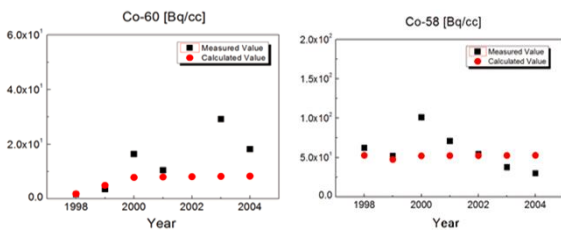

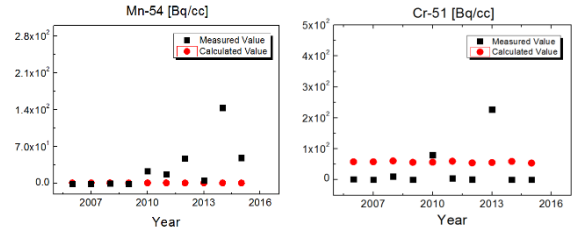Fig 6. The comparison of measured and calculated values at Wolsong #1 during 7 years

Fig 7. The comparison of ^{54}Mn & ^{51}Cr in RCS at Kori #1 by using the radionuclide concentration ratio
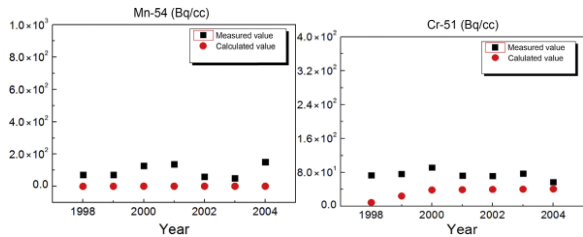

Fig 8. The comparison of ^{54}Mn & ^{51}Cr in RCS at Wolsong #1 by using the radionuclide concentration ratio

6. Conclusions

This study analyzed the properties and behavior mechanisms of radioactive corrosion products in the PWR & PHWR type NPP. It was found out that the major driving force of behavior of corrosion products in the primary coolant system of the NPPs is the change of solubility owing to the temperature change of the primary coolant. To predict and assess the radioactive nuclide inventory in the primary system, the CRUDTRAN code was applied. From the interpretation of the results, a fluctuation trend of radiation source term caused by the operating cycle was confirmed, and the level of confidence of the code was verified as both the on-site measured values and the estimated value from the code were determined to be within the error range, although there were some differences. The results of prediction of the radioactive nuclide inventory in the primary system performed in this study would be used as baseline data for the estimation of the volume of radioactive wastes when decommissioning NPPs in the future.

REFERENCES

[1] C.B. Lee, "Evaluation of CRUDTRAN Code to Predict Transport of Corrosion Products and Radioactivity in the PWR Primary Coolant System", International Conference on Water Chemistry of Nuclear Reactors System, 22-26, INIS-FR-1546 (2002).
[2] International Atomic Energy Agency, Modeling of Transport of Radioactive Substance in the Primary Circuit of Water-Cooled Reactors, IAEA, IAEA-TECDOC-1672, Vienna (2012).
[3] S.H. Lee, "A Study on the Application of CRUDTRAN code in Primary Systems of Domestic Pressurized Heavy-Water Reactors for Prediction of Radiation Source Term", Nuclear Engineering and Technology, (2017)