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Technical Note

A Study on the Application of CRUDTRAN Code in Primary Systems of Domestic Pressurized Heavy-Water Reactors for Prediction of Radiation Source Term

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ABSTRACT

The importance of developing a source-term assessment technology has been emphasized owing to the decommissioning of Kori nuclear power plant (NPP) Unit 1 and the increase of deteriorated NPPs. We analyzed the behavioral mechanism of corrosion products in the primary system of a pressurized heavy-water reactor-type NPP. In addition, to check the possibility of applying the CRUDTRAN code to a Canadian Deuterium Uranium Reactor (CANDU)-type NPP, the type was assessed using collected domestic onsite data. With the assessment results, it was possible to predict trends according to operating cycles. Values estimated using the code were similar to the measured values. The results of this study are expected to be used to manage the radiation exposures of operators in high-radiation areas and to predict decommissioning processes in the primary system.

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. These precipitated radioactive particles are deposited on the surfaces of the reactor core of the system. Although the inventory of surface contaminants is smaller than that of activated materials, it plays an important role in deciding the decommissioning method for an NPP. It also provides information required to plan decommissioning processes, and exerts a direct influence on operational scheduling, manpower requirements, and exposure of operators in high-radiation zones.

A previous study involved the selection and analysis of a code for the assessment of corrosion products generated in a pressurized water reactor (PWR)-type NPP. The present study involved researching a computing code that could be used to assess the behaviors of radioactive corrosion products

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generated in a pressurized heavy-water reactor (PHWR)-type NPP. In addition, the applicability of the CRUDTRAN code, an assessment code for corrosion products from PWR-type NPPs, was assessed. The assessment results were compared with data measured onsite, revealing a similarity. These results contribute to research for predicting the decommissioning source terms of PHWR-type NPPs.

2. Deposition and radioactivation of corrosion products in PHWR-type NPPs

The coolant system in a PHWR-type NPP comprises coolant pumps, header pipes, and feeder pipes connected to each fuel channel, the primary side of the steam generator, and pressurizers. A coolant system is composed of two independent loops, each taking charge of a half function; both of these are commonly connected to pressurizers, the emergency reactor core system, and the purification system. A coolant pump is a centrifugal pump with a multistage sealed shaft, driven by an electric motor. A steam generator has a vertical U-shaped tube with a complete suite for preheating. The tube is made of Alloy 800.

Both the coolant system and the moderator system are primary sources of radioactive materials. Major causes of the generation of radioactive materials include nuclear fission of fuel, activation of equipment in the primary system, and radioactivation of corrosion products, heavy water, and additives that accumulate in the system. Some radioactive materials are transported or leaked into other systems, such as steam generators, water-feeder systems, and spent fuel pools, and become secondary radiation sources of radioactive materials. Concentrations of radioactive materials change according to the performance of the fuel and the purification flux. In the case of a PHWR-type NPP, there are frequent fluctuations in the concentrations of radioactive materials owing to the daily changing of the nuclear fuel.

Metals contacting the coolant in the coolant system corrode slowly. Some corrosion products may be dissolved or suspended in the coolant, or may pass through the neutron flux in the reactor core. Therefore, neutron activation of corrosion products is limited to the period during which the coolant passes though the reactor core. As the corrosion products are continually exchanged between the coolant and the surfaces of the system, radioactive materials accumulate on the surfaces, ultimately forming a radiation field. Some radioactive materials may leak from the coolant system and become secondary radiation sources [1].

Major sources of radioactive materials in the primary system of a PHWR-type NPP are the corrosion of the heat transfer pipe in the steam generator and the flow-accelerated corrosion (FAC) in feeder pipes. Heat transfer pipes of steam generators in domestic PHWR-type NPPs in operation are made of Alloy 800. Unlike Alloy 600 and Alloy 690, the chemical composition of Alloy 800 is 30–35.0% Ni, 19–23% Cr, and 39.5% Fe. Such a chemical composition can cause corrosion reactions in the steam generator and generate a chalk river unidentified deposit (CRUD) such as Ni, Cr, or Fe. In addition, the CRUD may be converted into radioactivated products such as Co-58, Co-60, Mn-54, Cr-51, and Fe-59 owing to a high temperature and reactions, as shown in Table 1.

Unlike those of a PWR-type NPP, feeder pipes of a PHWR-type NPP are connected to nuclear fuel channels. Thus, the feeder pipes are another major source of radioactive materials. The material used to make the feeder pipes is low carbon steel (SA 106 Gr. B) made of iron and carbon containing under 0.3 weight% (wt%) C, 0.29–1.06 wt% Mn, and less than 0.4 wt% Cr. The composition can be a cause of generation of CRUD, such as Fe, Mn, and Cr, owing to the FAC reaction in the feeder pipes [2].

2.1. *Deposition of corrosion products*

Even though the CRUD concentration in nuclear reactor coolants is low, because the nuclear reactor coolant flows at a high speed, a considerable quantity of CRUD may move into the core in a relatively short period of time. The CRUD is unstable at all times and tends to be deposited on any part of the coolant system while moving. Such a CRUD has the following characteristics:

- Deposited at parts with high heat flux
- Increased deposition in radiation flux
- Increased deposition at parts with low fluid velocity
- Heavily deposited on the surface of Zircaloy rather than on stainless-steel surface
- Less deposition in high pH operating conditions than in neutral pH conditions

The quantity of CRUD generated increases following the operations in NPPs. If it is deposited on nuclear fuel cladding, it may curtail the capacity of heat transfer. Moreover, as it contains a considerable quantity of boron, it may unbalance the output. If CRUD occurs in tubes of a steam generator, it will reduce the capacity of heat transfer and increase the radiation level in the steam generator, thus complicating the maintenance. In addition, if CRUD occurs in some low-fluid-velocity parts of mechanical components such as control rod actuators or valves, it may cause mechanical damage [3].

2.2. *Radioactivation of corrosion products*

A considerable quantity of CRUD in the coolant of a primary system occurs on the reactor core surface through continuous circulation. When such materials are activated, they are converted into materials with high radioactivity. Through sequential substitution of these materials with CRUD in the coolant, the CRUD becomes highly radioactive. Such

Table 1 – Corrosion product and generation source in pressurized heavy-water reactor.

Nuclide	Half-life	Generation unit	Source
^{51}Cr	27.8 d	$^{50}Cr(n,\gamma)^{51}Cr$	System material
^{54}Mn	312 d	$^{54}Fe(n,p)^{54}Mn$	System material
^{59}Fe	45 d	$^{59}Fe(n,\gamma)^{59}Fe$	System material
^{58}Co	71 d	$^{58}Ni(n,p)^{58}Co$	Steam generator tube
^{60}Co	5.24 yr	$^{59}Co(n,\gamma)^{60}Co$	Stellite and nickel alloy

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