Application of cosSOURCE Code for PWR Primary Coolant System Source Term Analysis

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INTRODUCTION

Radioactive nuclide produced during reactor operation can be carried by coolant and flow into the reactor coolant system(RCS), auxiliary system and factory area, which causes radiation exposure to equipment and personnel in the plant. RCS radiative source term analysis can provide the basis for radiation shielding design.

The cosSOURCE code is a member of COSINE (COre and System INtegrated Engine for Design and Analysis) code package. It use mathematical model based on migration law of radioactive nuclide in reactor coolant, fully considered activation, decay, purification, leakage and other factors. The cosSOURCE can calculate the distribution and activities of radionuclides in RCS as well as the secondary coolant system, chemical and volume control system (CVS) or other auxiliary systems, containment building or other facilities of pressurized water reactor (PWR).

This paper focus on introducing the function of cosSOURCE program about reactor coolant system source term calculation, and the radionuclides activities calculation results are provided.

PROGRAM MAIN FUNCTION

#1 RCS fission product source term

The RCS fission product source term calculation module is based on the migration rule of fission products in reactor coolant. It is assumed that small cladding defects are present in fuel rods producing 0.25 percent of the core power output [1]. At the same time, the cosSOURCE fully consider the factors such as the coolant leakage from RCS to the secondary coolant system by reason of steam generator tube defects and the up and letdown of CVS. The program needs to input core source which is time variable. The cosSOURCE can calculate activities over time and maximum activities of fission products in RCS. The program can also calculate gamma ray source strength released by the fission products and their decay products. The calculation model of fission products source term in RCS is as follows.

$$\frac{dN_i^1}{dt} = v_i N_i^0 + P_i N_i^1 - D_i N_i^1 \quad (1)$$

Where, the first item represents fission products production rate because of the damaged fuel rods; the second item represents nuclides production rate due to other generation ways; and the last item represents the sum of nuclide reduction rate.

#2 RCS activation product source term

The RCS activation product source term calculation module can calculate the activated products in reactor coolant as the coolant flow through the core and activated by the neutron irradiation. The cosSOURCE consider decay and purification of activation products in reactor coolant. The program can compute the activation products activities of the reactor coolant flowing through multiple locations in the primary loop.

#3 RCS corrosion product source term

When the radioactive activities of corrosion products are calculated, it can be carried out according to experience value or test determined values of the same type reactor [1]. Thus, the reactor coolant corrosion products source term adopt the realistic source term model. The reactor coolant realistic source term is determined by the assumption in national standard named radioactive source term of PWR nuclear power plant for operational states [2]. If the main design parameters of the considered nuclear power plant are in accordance with the nominal value of the reference nuclear power plant, the radioactive nuclides activities in the main fluid of the considered plant are consistent with the reference plant. Otherwise, it is necessary to adjust the radionuclides activities in the main fluid of the reference nuclear power plant. In the cosSOURCE, the nuclear power plant adjustment factor is calculated based on the main design parameters of the considered nuclear power plant and the reference nuclear power plant. The calculation formula of the adjustment factor is as follows.

$$C = \frac{S}{m \cdot (\lambda + \beta)} \quad (2)$$

Where, C stand for radionuclides special activities; S stand for radionuclides production rate in the system; m stand for the mass of fluid; β stand for total removal rate because of purification, filtration and leakage.

#4 RCS tritium source term

There are many ways to produce tritium in a PWR. The main source include: 1) Fuel ternary fission; 2) Neutron reactions in burnable poison rods and control rods; 3)

Neutron reactions with soluble boron in the reactor coolant as soluble chemical neutron absorber; 4) Neutron reactions with soluble lithium in the reactor coolant for pH adjustment; 5) Neutron reactions with deuterium in the reactor coolant [3].

In this module, a concentration equilibrium equation is established for each tritium production pathway based on its generation and disappearance. Tritium activity in reactor coolant for each production approach during different nuclear power plant operation period can be calculated. The calculation model is as follows.

$$\frac{dN_t}{dt} = \sum_{i=1}^{5} P_i - \beta N_t \qquad (3)$$

Where, P_i denote the tritium production rate in the above approaches; β denote the disappear rate constant.

NUMERICAL RESULTS

The cosSOURCE has ability to calculate the activities of various radionuclides in RCS. The following figures and tables list the relevant calculation results of PWR primary coolant system source term. The parameters involved in the calculations below are from the reference [3]. TABLE I. lists some key parameters used for calculation of RCS source term. TABLE II. lists the reactor coolant flow time at some locations in the primary loop. The parameters that can not be found in the reference [3] are hypothetical.

TABLE I. Parameters used in the calculation of RCS source term

Parameter	Value
Core thermal power (MWt)	3400
Reactor coolant liquid volume (ft^3)	9575
Purification flow rate (gal/min)	91.3
Failed fuel fraction	0.0025
CVS Resin volume (ft^3)	50
Initial boron concentration (ppm)	1400
Operation time	12492

TABLE II. Reactor coolant flow time at various locations in the primary loop

Position in loop	Loop transit time (s)
Leaving core	0.0
Leaving reactor vessel	0.9
Entering steam generator	1.2
Leaving steam generator	6.8
Entering reactor vessel	8.0
Entering core	9.5

#1 Fission products activities

Fig. 1. plots the radionuclides activities over time. As can be seen from the trend of the curve, during the initial operation stage, the amount of radionuclides released from the core to the coolant for the fuel cladding defects is greater than its attenuation amount. As a result, the rate of time related activities is positive. As time goes on, the production rate is gradually equal to the disappearance rate for some radionuclides and so that their activities maintain a state of dynamic balance. With the reactor running, the comprehensive effect of dilution by feed and bleed as well as some other factors will break the balance, and the radionuclides activities begins to decrease.

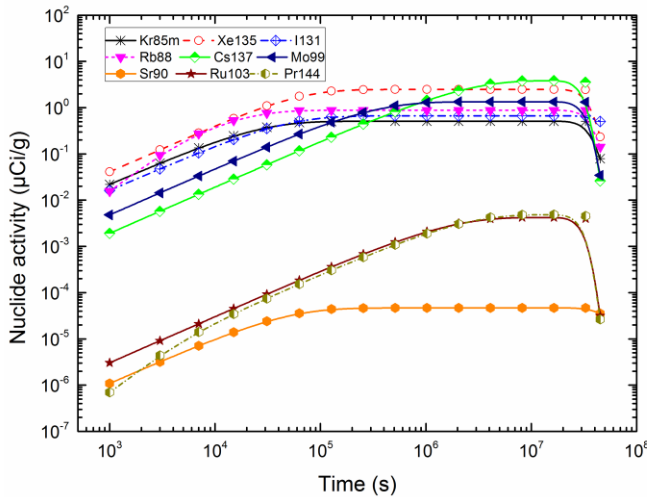

Fig. 1. The activities of fission products variation with time

#2 Corrosion products activities

TABLE III lists the corrosion products activities in the reference [3], cosSOURCE calculation results and their comparison offset. The offset can be calculated as the ratio of cosSOURCE minus reference to reference, and then multiply the results by one hundred percent.

TABLE III. Corrosion products calculation results

Nuclide	Activity (μCi/g)		Offset
	Reference	cosSOURCE	
Cr51	2.6E-03	2.67E-03	2.7%
Mn54	1.3E-03	1.37E-03	5.4%
Fe55	1.0E-03	1.03E-03	3.0%
Fe59	2.5E-04	2.58E-04	3.2%
Co58	3.9E-03	3.96E-03	1.5%
Co60	4.4E-04	4.55E-04	3.4%

As shown in TABLE III, cosSOURCE calculation results is deviated from the reference values. The main reason is radionuclides decay constant is not exactly the same, and the calculation results retain a different number of valid digits.

#3 Nitrogen16 activity

Because of the Nitrogen16 half-life is fairly short (about 7.1 seconds), the change of activity at different positions in the primary circuit is obvious. Therefore, in this section, the activity of N-16 at several key locations for the coolant flowing through the primary circuit is calculated.

Fig. 2. plot the activity of nitrogen16 at some locations in the primary loop

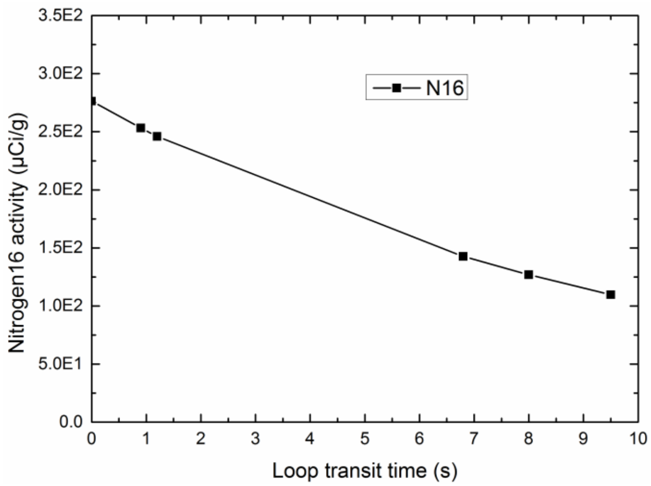

Fig. 2. Nitrogen16 activity in the primary loop

As can be seen from Fig. 2, the core exit has the maximum nitrogen16 activity. As coolant flows, the activity of nitrogen16 in the reactor coolant gradually decreases. This is because when the coolant flow through the core, it can be irradiated by neutrons and produce nitrogen16. When the coolant leave the core and flowing through the primary loop, there is no way to produce nitrogen16, only through decay and purification and other factors to reduce. Therefore, the nitrogen16 activity in the reactor coolant at the core exit reaches the maximum value.

#4 Tritium activity

TABLE IV. lists tritium activity in the reactor coolant produced from each pathway.

TABLE IV. Calculation results of tritium source term

Tritium source	Release to coolant (Ci)
Ternary fission	1.34591E+02
Burnable absorbers	1.80216E+01
Soluble boron	2.02266E+02
Soluble lithium	4.84370E+01
Deuterium	1.22583E+00
Total	4.04541E+02

The data from TABLE IV. shows that fuel ternary fission and neutron reaction with soluble boron in the coolant is the two tritium production routes that contribute the most to tritium activity in the coolant.

CONCLUSION

This paper describes the calculation model of radiation source program cosSOURCE in COSINE code package for the fission products, activation products, corrosion products and tritium source term in the PWR primary coolant system.

The code is able to perform the time-dependent and maximum fission products activities, as well as activation products activities at different locations in the primary circuit, corrosion products activities in the reactor coolant, and tritium activity in RCS during normal operation and refueling period of nuclear power plant. The relevant results shown in this paper indicate that both the computational model and the code implementation of cosSOURCE code for RCS source term analysis are reasonable.

This paper only describes the calculation model of RCS source term, and carries out preliminary calculation. In the future study, the systematic test for all functions of the cosSOURCE will be conducted.

ACKNOWLEDGMENT

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