Source Term Analysis for Reactor Coolant System with Consideration of Fuel Burnup

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1. Introduction

The radiation source terms in reactor coolant system (RCS) of pressurized water reactor (PWR) are basic design information for ALARA design such as radiation protection and shielding. Usually engineering companies own self-developed computer codes to estimate the source terms in RCS. DAMSAM[1] and FIPCO[2] are the codes developed by engineering companies. KEPCO E&C has developed computer code, RadSTAR, for use in the **Rad**iation **S**ource **T**erm **A**nalysis for **R**eactor coolant system during normal operation. The characteristics of RadSTAR are as follows.

(1) RadSTAR uses fuel inventory data calculated by ORIGEN, such as ORIGEN2[3] or ORIGEN-S[4] to consider effects of the fuel burnup.
(2) RadSTAR estimates fission products by using finite differential method and analytic method to minimize numerical error.
(3) RadSTAR enhances flexibility by adding the function to build the nuclide data library (production pathway library) for user-defined nuclides from ORIGEN data library.
(4) RadSTAR consists of two modules. RadSTAR-BL is to build the nuclide data library. RadSTAR-ST is to perform numerical analysis on source terms.

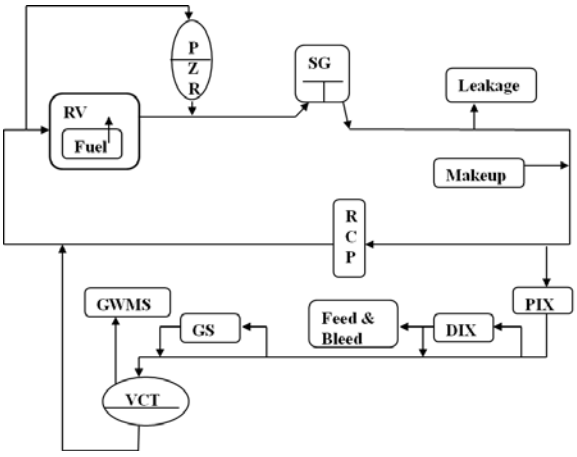
This paper includes descriptions on the numerical model, the buildup of nuclide data library, and the sensitivity analysis and verification of RadSTAR.

2. Numerical Methods

In this section, the modeling of RCS and the finite differential and analytic methods used to solve the radionuclide generation (production) and depletion (removal) in RCS are described.

2.1 Reactor Coolant System

The simplified diagram on RCS is shown in Fig.1. The radiation source terms, especially fission products, are generated in fuel, and are escaped from defected fuel to RCS. The fission products circulate in RCS and parts of them are depleted by neutron capture or radioactive decay, and removed by demineralization processes in purification system. The typical removal processes in purification system are removal by purification ion exchanger, deborating ion exchanger, feed & bleed operation for boron control, gas stripper, and gas purging of volume control tank. Some parts of fission products are removed together with reactor coolant leakage. These fission product generation and depletion mechanisms are included in the numerical model of RadSTAR.



RV : reactor vessel, PZR : pressurizer, SG : steam generator,
RCP : reactor coolant pump, PIX : purification ion exchanger,
DIX : deborating ion exchanger, GS : gas stripper,
VCT : volume control tank,
GWMS : gaseous waste management system

Fig. 1. RCS model for RadSTAR

2.2 Numerical Model

The general equation for generation and depletion of fission products in RCS is as follow;

$$\frac{dN_{c,i}}{dt} = P_i - R_i N_{c,i} \quad (1)$$

where,
N : nuclide inventory in RCS (atom),
P : production rate (atom/sec),
R : removal rate (1/sec), and
subscripts are
i, c : nuclide i and RCS, respectively.

The production of fission products in RCS consists of production by escape from fuel, decay of parent nuclide, and neutron capture of predecessor. The removal

consists of removal by decay, ion exchangers, neutron capture, and leakage. The detailed composition of production term and removal term in Eq.(1) are as follows;

$$P_i = Dv_i N_{p,i} + \sum(\lambda_{j\to i} N_{c,j}) + F_c \varphi \sum(\sigma_{k\to i} N_{c,k}) \quad (2)$$

$$R_i = \lambda_i + \frac{Q}{W_c}\{1 - (1 - \varepsilon_{pix,i})(1 - f_{dix}\varepsilon_{dix,i}) \quad (3)$$

$$(1 - f_{gs}\varepsilon_{gs,i})(1 - \varepsilon_{vct,i})\} + \sigma_i \varphi F_c + \frac{L}{W_c}$$

where,

λ : decay constant with branching (1/sec),
σ : neutron reaction cross section (cm^2),
φ : neutron flux (n/cm^2-sec),
ν : escape rate from defected fuel (1/sec),
ε : removal efficiency (fraction),
f : flow rate of feed & bleed or deborating (fraction of reactor coolant purification flow rate),
D : fraction of defected fuel (fraction),
F_c : volume ratio of coolant in core to RCS (fraction),
Q : reactor coolant purification flow rate (kg/sec),
L : reactor coolant leak rate (kg/sec),
W : mass of coolant (kg), and
subscripts are
i, j, k: nuclide i, parent j to produce nuclide i by decay, and predecessor k to produce nuclide i by neutron capture,
p, c : fuel and RCS, respectively, and
pix, dix, gs, vct : purification ion exchanger, deborating ion exchanger, gas stripper, volume control tank.

The design variables, such as fraction of defected fuel(D), volume of coolant in core to RCS(F_c), purification flow rate(Q), leak rate(L), and mass of coolant(W), are constant during operation. The neutron flux(φ) and flow rate for boron control(f) are functions of burnup and assumed as constants during a few tens days of interim burnup period in fuel cycle. On the while the nuclide inventories in fuel(N_p) and RCS(N_c) are assumed as functions of time. The US NRC Regulatory Guide(RG) 1.206[5] requires that the source terms in RCS should be provided at design-basis fuel defect level and the source terms in core(fuel) should be determined based on time-dependent core inventories that are calculated by the ORIGEN.

The types of reactions to transmute nuclides come from ORIGEN nuclide data library files. In this case, the decay library in SCALE 6.1 based on ENDF/B-VII and the cross section libraries of ORIGEN2 or ORIGEN-S in SCALE 6.1 are used. The 7 types of decay reactions in decay library and major 6 types of neutron capture reactions in cross section libraries are considered to solve Eq.(1). Therefore the production of specific nuclide can be related with 13 types of reactions of parent or predecessor nuclides and the parent nuclide can be produced from another 13 reactions. The production pathways are very complex and this is the reason of difficulty to solve Eq.(1) analytically.

Eq.(1) is expanded by finite differential method as follow:

$$N_{c,i}(t + \Delta t) = P_i(t) \cdot \Delta t + (1 - R_i(t) \cdot \Delta t) N_{c,i}(t) \quad (4)$$

To solve Eq.(4), iteration calculation with user-defined time increment(Δt) should be implemented. In Eq.(4), if the production rate(P) is zero(0), the inventory should not be less than zero(0) and not be builtup either. Therefore the range of Δt is limited by the following condition to have effective solution.

$$0 < (1 - R_i(t) \cdot \Delta t) < 1 \quad (5)$$

The accuracy of solution is improved with decrease of Δt and the Δt is limited by the condition of ($0<\Delta t<1/R$) from Eq.(5). The removal rate(R) includes variables such as λ, Q/W_c, $\sigma\varphi F_c$, and L/W_c. For APR1400, the numerical ranges of the removal terms are shown in Table I as typical values.

Table I: Limitation of time increment (Δt)

Removal Rate	Value (1/sec)	Maximum Δt (day)
λ_i	$\leq 1.16\times10^{-2}$ (half-life : 1.0 min)	0.001
Q/W_c	$\approx 1.67\times10^{-5}$	0.693
$\sigma\varphi F_c$	$\approx 1.0\times10^{-11}$	1.16×10^{6}
L/W_c	$\approx 2.1\times10^{-7}$	55.12

Consequently, the limitation of Δt is determined by decay constant of nuclides as $\Delta t<1/\lambda$, and inversely, if Δt is defined, the short-lived nuclides ($\lambda\geq1/\Delta t$) require another method to overcome this limitation. Instead of the finite differential method, the analytic method is used for short-lived nuclides. The variables, except the inventories of short-lived nuclide, are assumed as constant values during Δt and the nuclide inventories are calculated by analytic method. The analytic solution of Eq.(1) during Δt is as follow:

$$N_{c,i}(t + \Delta t) = \frac{P_i(t)}{R_i(t)}(1.0 - e^{(-R_i(t)\Delta t)}) + N_{c,i}(t) e^{(-R_i(t)\Delta t)} \quad (6)$$

Therefore one of Eq.(4) and Eq.(6) is selectively used for each nuclide in numerical calculation with its decay constant and Δt. From Eq.(4) and Eq.(6), nuclide inventory increases or decreases in linear shape with time in finite differential method and in exponential form in analytic method, respectively.

3. Nuclide Data Library

About 100 nuclides are considered as major nuclides existing in RCS and important to radiation protection and shielding design. The number of nuclides included

in ORIGEN data library is more than 1,600 nuclides. RadSTAR uses its own data library instead of ORIGEN data library. RadSTAR finds production pathway (pair of parent nuclide and reaction constant) of user-defined product nuclide and builds RadSTAR data library for the nuclide by using ORIGEN data library. Therefore the flexibility is established in selection of nuclide to be estimated.

The RadSTAR data library includes, as shown in Table II, decay constants and branching fractions for 7 types of decay reactions and cross sections for 6 types of neutron capture reactions.

Table II: Nuclide data included in RadSTAR data library

Product nuclide
- Decay constant(λ), (n,γ) X-section(σ), natural abundance
Production pathway
- Pairs of parent nuclides and decay branching fractions for 7 decay reactions; β^-(-,*), β^-(-,-), β^-(*,-), γ (*,-), β^+(-,*), β^+(-,-), and α(-,-).
- Pairs of predecessor nuclides and X-sections for 6 neutron reactions; (n,γ*), (n,γ), (n,p), (n,2n), (n,3n), and (n,α).

[Note] In decay reaction a(b,c), a means decay mode, b and c means isomeric state of parent and product nuclide, respectively (isomeric state, * : excited, - : ground).

The RadSTAR data library depends on the data library of ORIGEN2 or ORIGEN-S. For sample runs, user defined 115 product nuclides existing in RCS and executed RadSTAR-BL, the RadSTAR data library was built which included production pathway data of 281 or 299 parent and product nuclides with the data library of ORIGEN2 or ORIGEN-S, respectively.

4. Sensitivity Analysis and Verifications

Reference input data for RadSTAR was constructed to be used for sensitivity analysis and accuracy verification based on APR1400 design data. The reference input data are shown in Table III.

Table III: Reference input data based on APR1400

Description	Unit	Design data
Thermal power for design basis	MWt	4063.0
Duration of power operation	day	480.0
Time to start deborating	day	400.0
Time increment for iteration	day	0.01
Defective fuel rods	fraction	0.0025
Mass of reactor coolant	kg	2.92E+05
Density of reactor coolant	kg/m^3	711.2
Volume ratio of coolant in core to RCS	-	0.0732
Leak rate of reactor coolant	kg/sec	0.0
Purification flow rate	kg/sec	5.02
Gas stripping (fraction of purification flow rate)	fraction	0.0
Boron concentration at BOC and EOC	ppm	1110, 30

4.1 Sensitivity Analysis

RadSTAR uses finite differential method and analytic method to solve the generation and depletion of nuclide in RCS. The value of Δt is major variable to affect the stability and number of iterations in RadSTAR calculation.

The sensitivity analyses are performed with various Δt to find optimized Δt in RadSTAR running. RadSTAR is executed with Δt of 1.0, 0.1, 0.01, and 0.001 day, respectively. The results of calculation and relative error with Δt are shown in Fig. 2 and Fig. 3, respectively. As shown in the Fig. 2 and Fig. 3, the case that Δt is 0.1 day gives zero(0.0) of relative error in comparison with the case that Δt is 0.001day. So, the Δt of 0.1 day is an appropriate time increment to keep stability and to reduce number of iteration in RadSTAR calculation.

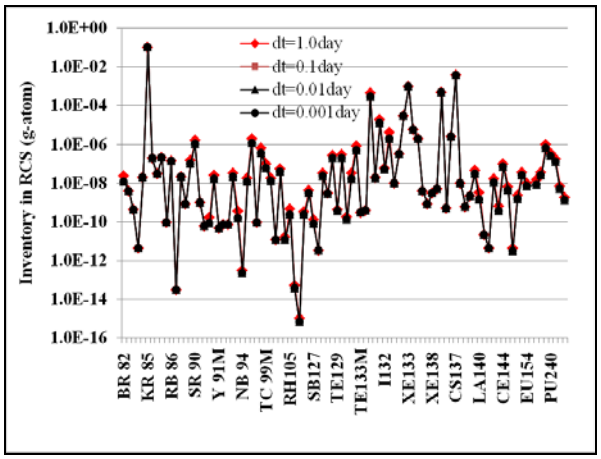


Fig. 2. Nuclide inventories in RCS with Δt

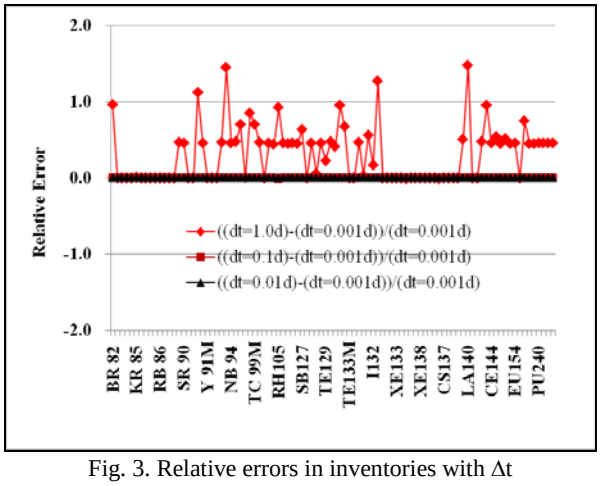


Fig. 3. Relative errors in inventories with Δt

4.2 Accuracy Verification

Accuracy verification is to confirm that RadSTAR gives values acceptable to design of nuclear power plant. The result of RadSTAR calculation is compared with

the result of DAMSAM which has been used to calculate source terms in RCS in Korea for about 30 years. Even though RadSTAR uses ORIGEN output as nuclide inventories in fuel, DAMSAM uses the fixed fission yield data and estimate directly the inventories. DAMSAM uses the fixed production pathway library without considering most of neutron reactions to calculate source terms in RCS. Therefore, it is expected that there are significant differences between two calculation results.

The reference input data in Table III is used for accuracy verification. The results of inventory calculations in fuel and in RCS are compared in Fig. 4 and Fig. 5. The difference between two calculations is not small and the difference in fuel inventories tends to be transmitted to the difference in source terms in RCS.

Instead of direct calculation, RadSTAR uses the inventories from ORIGEN output, which means consideration of burnup-dependent yield data. The difference in fuel inventories comes from the difference in yield data between fixed and burnup-dependent. Therefore, it needs to verify the accuracy only in RCS source term by excluding differences in fuel inventories.

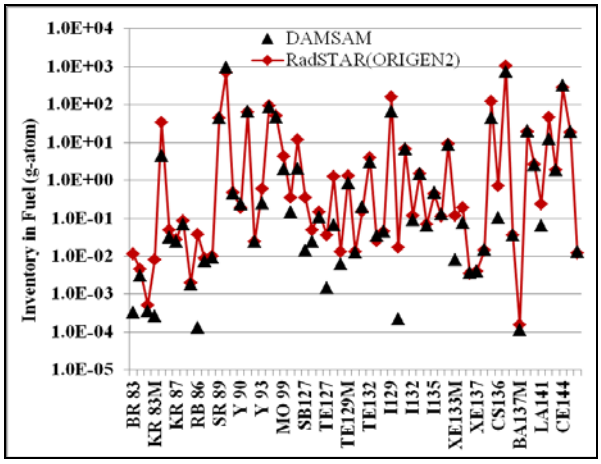


Fig. 4. Comparison of inventories in fuel

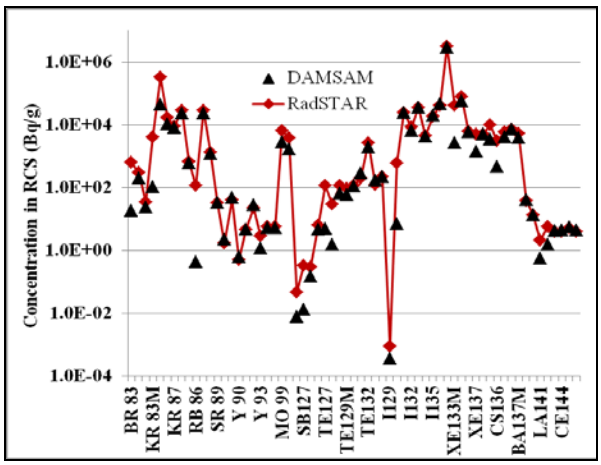


Fig. 5. Comparison of source terms in RCS

The ratios of source terms calculated by DAMSAM and RadSTAR in fuel and in RCS are compared in Fig. 6. The ratios of source terms in fuel and in RCS nearly coincide with each other. This means that the differences in fuel inventory are transmitted directly into the differences in RCS source terms without offset or amplification. For Kr 83M, Xe 135, and Xe 137, the differences come from differences in production pathway and nuclide data library.

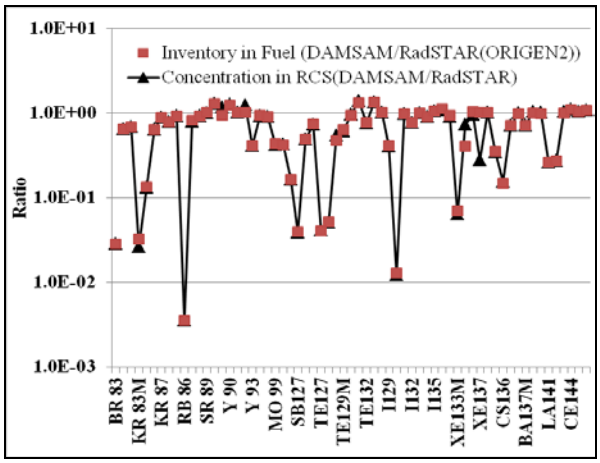


Fig. 6. Comparison of the source term ratios in fuel and RCS

5. Conclusions

KEPCO E&C developed RadSTAR to calculate source terms in RCS during normal operation. Sensitivity analysis and accuracy verification showed that RadSTAR keeps stability at Δt of 0.1 day and gives more accurate results in comparison with DAMSAM. After development, RadSTAR will replace DAMSAM. The areas, necessary to further development of RadSTAR, are addition of source term calculations for activation products and for shutdown operation.

REFERENCES

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