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

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Contents

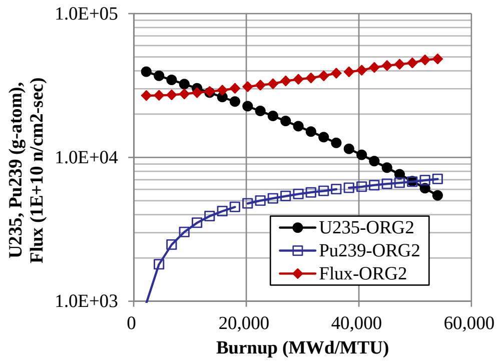
I. Background

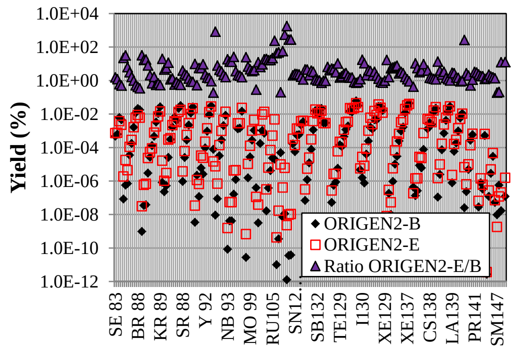
❑ Fission Product Source Terms in RCS

- ❍ FPs in RCS come from defected fuel
- ❍ FP source terms are basic information for ALARA design

❑ Fuel Burnup

- ❍ Neutron flux, Pu 239, and fission yield increase





- ❍ Fuel burnup should be considered in FP source terms

I. Background

❑ RCS Source Term Analysis Codes

Code	DAMSAM (1972) (CE)	FIPCO 3.1 (1999) (WH)
Data Library	• 112 FP nuclides • Fixed Library	• 88 FP nuclides • User input Parent/daughter data
Pros & Cons	• Direct fuel inventory calculation → not use ORIGEN output • Limited and fixed nuclide data library → not consider various FPs and generation paths • Not consider neutron reactions in fuel and RCS (except Cs133, Xe135)	• Direct fuel inventory calculation or use of ORIGEN output • User input of parent/daughter nuclide data → not consider various FPs and generation paths • Not consider neutron reactions in RCS

II. Development of RadSTAR

❑ RadSTAR

- **Radiation Source Term Analysis Code for Reactor Coolant System**

❑ Purposes

- **Self-development of RCS source term analysis code**
- **Satisfy regulatory requirements**
  - Consideration of fuel inventory from ORIGEN (RG 1.206)
- **Enhance flexibility to answer the RAIs**
  - RAI on nuclides for LILW acceptance measurement or on nuclides measured in effluents (SWN 1,2)
    - H 3, C 14, Ar 41, Co 60, *Mn 56, Ni 59, Ni 63,* Sr 90, *Nb 94, Tc 99, Sb 124, Sb 125, I 129,* Cs 137, *α emitter*
  - RAI on nuclides existing in core (NRC-DC)
    - Y 90, Rb 86, *Sr 92, Y 92, Zr 97, Ru 105,* Sb 127, Sb 129, Te 127, Te 127m, *Ba 139,* La 141, *La 142, Rh 105,* Pr 143, *Nd 147, Pu 238, Pu 289, Pu 240, Pu 241, Am 241, Cm 242, Cm 244*.

II. Development of RadSTAR

❑ Tool of Development

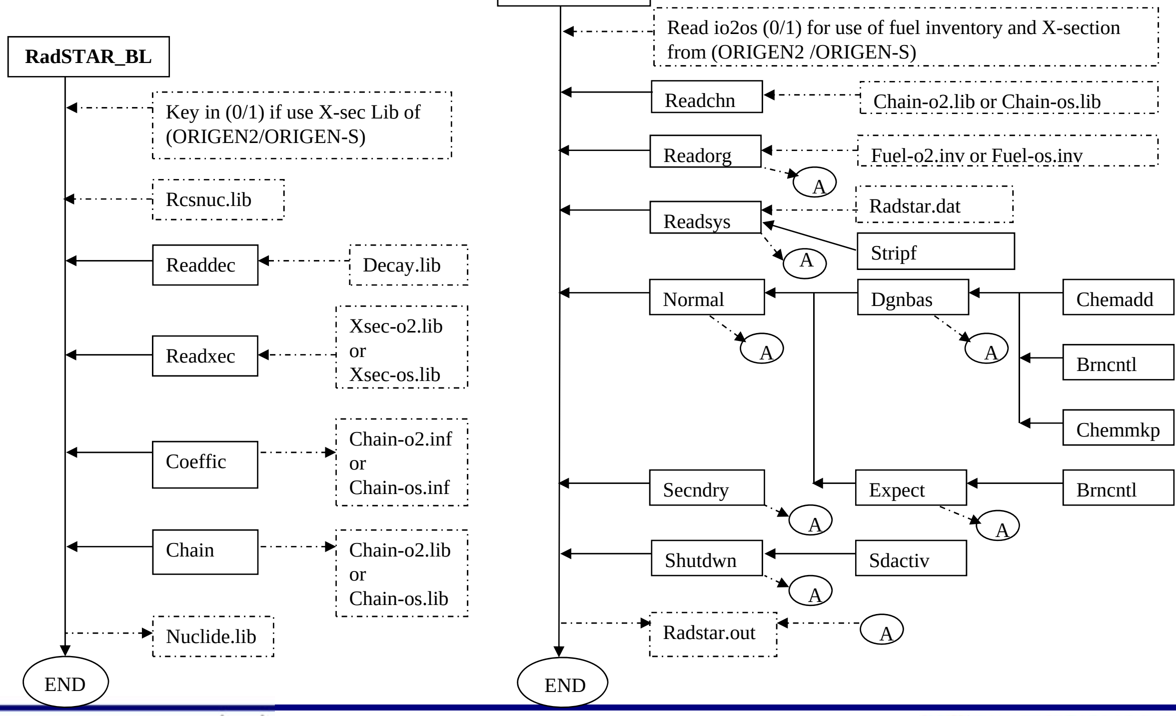
- **Language : FORTRAN**
- **Compiler : Intel® Visual Fortran Composer XE 2011**

❑ Modules and Functions

- **RadSTAR-BL**
  - Build nuclide data library for user-defined nuclides using ORIGEN library
  - Consider generation pathways of 7 decay and 6 neutron reactions
  - Enhance flexibility of nuclide to calculate
  - Exclude repetitive running if design/operation data are changed
- **RadSTAR-ST**
  - Use fuel inventory from ORIGEN2/ORIGEN-S
  - Solve nuclide balance equation with finite differential method and analytic method to minimize numerical error
  - Calculate FP source terms in RCS of PWR or similar type reactor

II. Development of RadSTAR

❑ Structure



III. RadSTAR-BL

❑ Verification

❍ Method

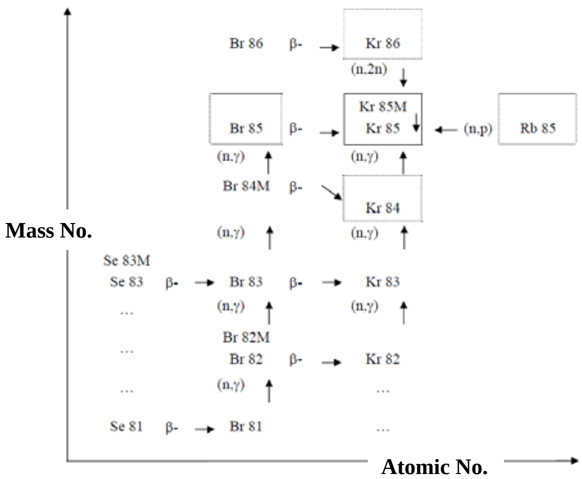
- Test to build nuclide data library for example
  - 115 reference nuclides
  - 1675 ORIGEN nuclides (iterate 8 time to build library)
- Confirm whether the nuclide data library is built successfully

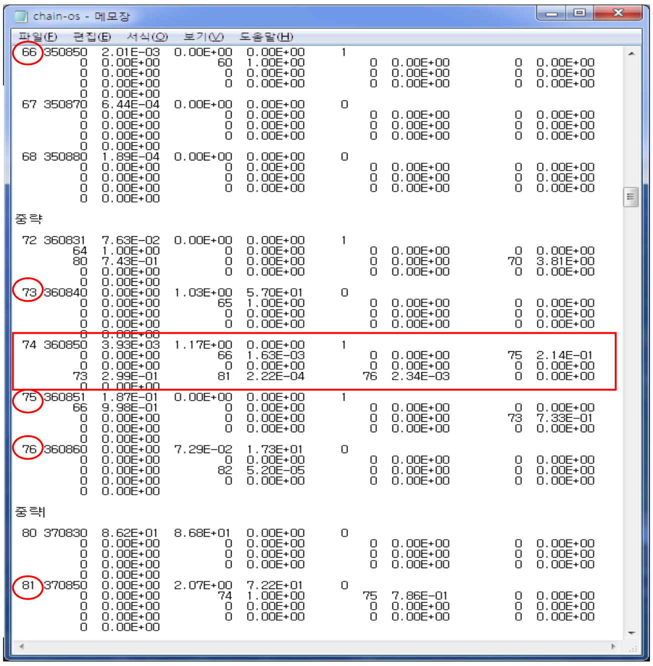
❍ Result

- The nuclide data libraries are built successfully including 7 decay and 6 neutron reactions

III. RadSTAR-BL

❑ Ex. Generation Pathways of Kr 85 (36850)





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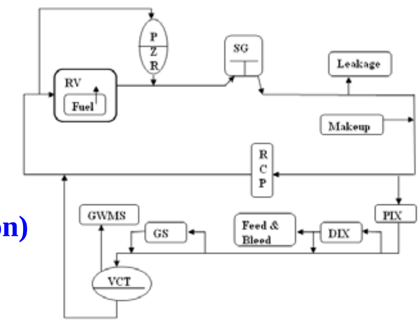
IV. RadSTAR-ST

❑ Balance Equation of FPs in RCS



$$\frac{dN_{c,i}}{dt} = P_i - R_i N_{c,i}$$

$$P_i = Dv_i N_{pi} + \sum_j \lambda_{j\to i} N_{cj} + F_c \varphi \sum_k \sigma_{k\to i} N_{ck} + qN_{mi}$$ **(Generation)**

Fuel Escape | Decay in | Neutron Capture | Makeup (Feed)

$$R_i = \lambda_i + \frac{Q}{W_c}(1-(1-\varepsilon_{pix,i})(1-f_{dix}\varepsilon_{dix,i})(1-f_{gs}\varepsilon_{gs})(1-\varepsilon_{vct})) + \sigma_i \varphi \cdot F_c + \frac{L}{W_c}$$ **(Depletion)**

Decay out | Removal by PIX, DIX, GS, VCT | Neutron Capture | Leakage

❍ **Difficult to solve analytically because of complex reaction-chains**

IV. RadSTAR-ST

❑ Finite Differential Equation

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

❍ Limitation to have effective solution

$$0 < (1 - R_i(t)\cdot\Delta t) \le 1 \qquad 0 \le \Delta t < 1/R_i(t)$$

❍ Δt is determined by 1/λ

- If Δt is fixed → Short-lived nuclide (λ > 1/Δt) should be solved by analytic solution

❑ Analytic Solution within Δt

❍ For short-lived nuclide (λ > 1/Δt)

$$N_{ci}(t+\Delta t) = \frac{P_i(t)}{R_i(t)}(1.0 - exp(-R_i(t)\Delta t) + N_{ci}(t)\, exp(-R_i(t)\Delta t)$$

IV. RadSTAR-ST

❑ Verification

❍ Method

- Verification of accuracy
  - Comparison of results with DAMSAM/BORAME or hand calculation
  - Analyze the differences by reasonable engineering judgment
- Sensitivity analysis
  - Assessment of maximum Δt to give acceptable results
  - Confirmation whether the change of major variables is reflected in the result
    - Single core/average core
    - Deborating/gas stripping/purification flow rate

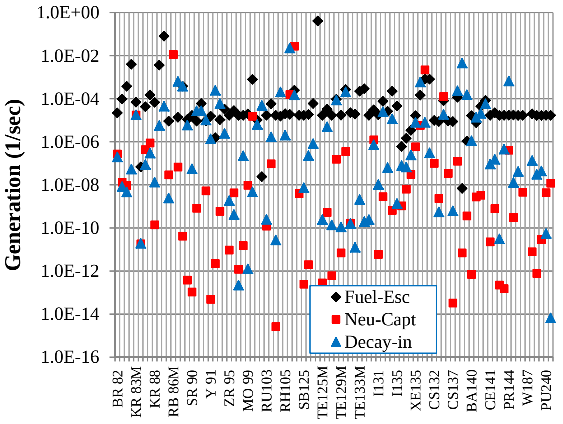
❍ Results

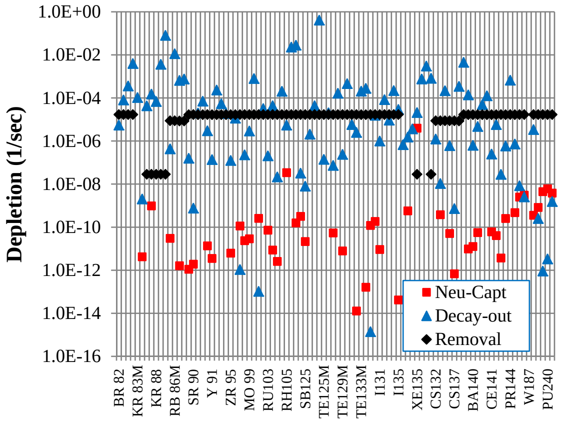
- RadSTAR is verified in accuracy and stability and gives reasonable outputs with change of major variables

IV. RadSTAR-ST

❑ Contribution of Generation/Depletion

- ❍ **At Maximum or Saturation Condition**
  - ■ Generation Rate = Depletion Rate
- ❍ **Generation : Fuel escape > Decay-in > Neutron capture**
- ❍ **Depletion : Decay-out, Removal > Neutron capture**

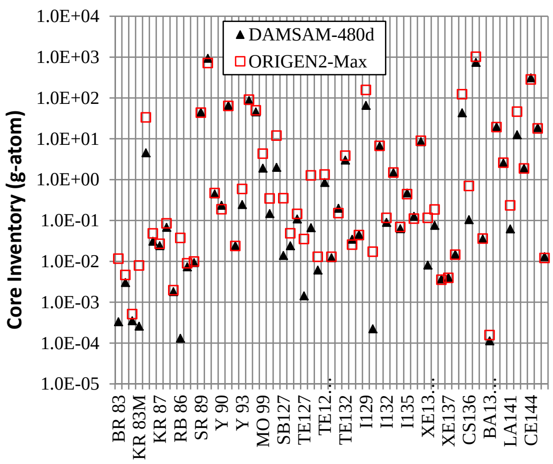


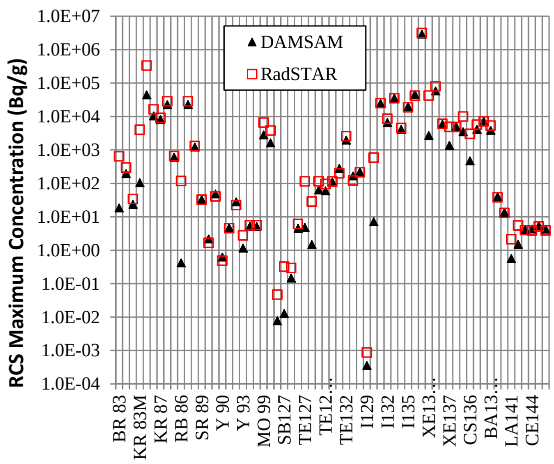


IV. RadSTAR-ST

❑ Comparison of Core Inventory and RCS Concentration

- ❍ **Core inventory : DAMSAM ≤ ORIGEN2**
- ❍ **RCS concentration : DAMSAM ≤ RadSTAR**

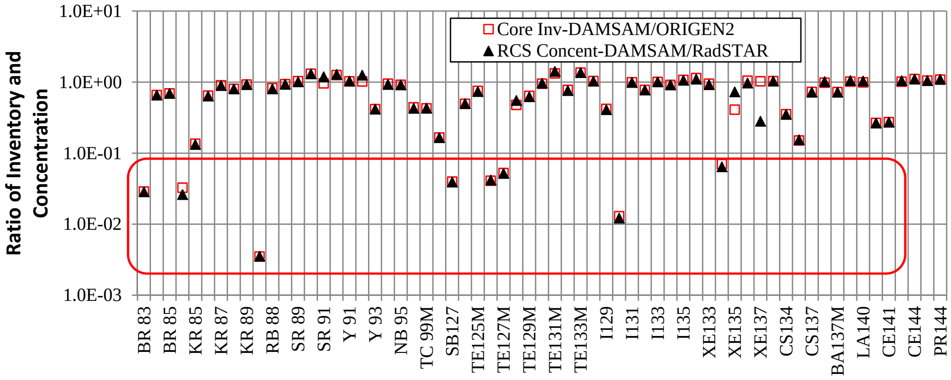




IV. RadSTAR-ST

❑ Comparison of Core Inventory and RCS Concentration

- ❍ Ratio of core inventory ≈ Ratio of RCS concentration
- ❍ Differences in core inventory are transmitted to RCS concentration

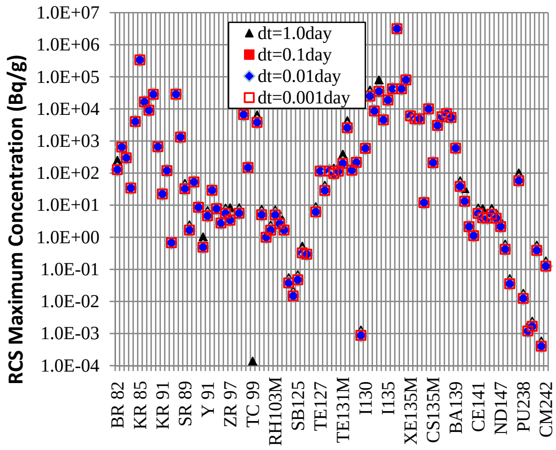


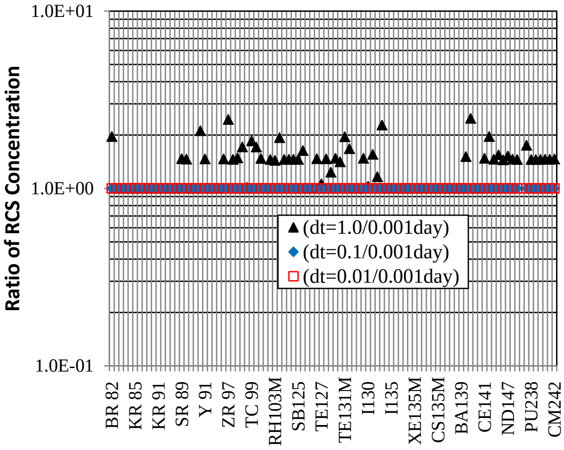
- ❍ **The low core inventory of DAMSAM comes from omission of generation paths**
  - ▪ Br 83, Kr 83m, Rb 86, Sb 127, Te 127, Te 127m, I 130, Xe 133m

IV. RadSTAR-ST

❑ Sensitivity Analysis for Iteration Time (Δt)

- ❍ Δt = 1.0, 0.1, 0.01, 0.001 day





- ❍ **Δt of 0.1 day is enough short period to keep stability**

V. Conclusion and Plan

❑ Conclusion

- **KEPCO E&C developed RadSTAR to calculate RCS source terms**
- **RadSTAR was verified in accuracy and stability**
- **RadSTAR gives information on**
  - Generation pathway (parent/predecessor nuclide)
  - Maximum source terms in RCS with fuel burnup
  - Contribution per generation/depletion pathway (fuel escape, decay, neutron capture, removal)

❑ Plan

- **RadSTAR will replace DAMSAM to calculate RCS design basis source terms**
- **RadSTAR will be expanded to calculate activation product**