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Current status of SIRIUS code development

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1. Introduction

CINEMA code is a C++ based, integral code that combines individual codes, each capable of independently analyzing severe accident phenomena occurring during a severe accident [1]. Developed and maintained in Republic of Korea since 2011, this code has been validated through analyses of severe accident experiments, including PHEBUS and LOFT, as well as through comparison with MAAP code for operating nuclear power plant [2]. Recently, it has also been used for severe accident analysis for i-SMR licensing [3]. CINEMA code consists of three independent phenomena analysis codes and a MASTER module that links their data, as shown in Fig. 1. The scope of three analysis codes is as follows:

- CSPACE: System thermal hydraulics and in-vessel phenomena
- SACAP: System thermal hydraulics and ex-vessel phenomena
- SIRIUS: Fission product behavior

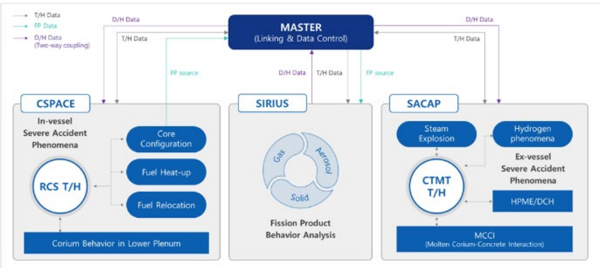

Fig. 1. Structure of CINEMA code [1]

CSPACE and SACAP codes each analyze in-vessel and ex-vessel phenomena based on separate thermal-hydraulic analyses. These two codes interlink their thermal-hydraulic data at each time step through MASTER module, which collects and shares the data to facilitate integrated analysis. In contrast, SIRIUS code does not directly simulate phenomena such as fuel melting or movement of gases but instead utilizes the thermal-hydraulic data provided by MASTER module to model fission product behavior.

SIRIUS code predicts the amount of fission product gases released from reactor core during severe accident that are transported within the RCS, converted into aerosols, and deposited on RCS piping, the pressurizer, and the steam generator, or released into the containment as they are carried by steam and non-condensable gas mixtures.

This paper presents the current development status of SIRIUS code, based on version 2.1.0.393.

2. Fission product group

In a light water reactor core, more than 1,000 fission product nuclides exist when considering isotopes. However, integral codes based on the lumped parameter method, such as MELCOR and MAAP codes, as well as CINEMA code, typically classify highly volatile nuclides according to their chemical properties (generally by periodic table group) to minimize computational costs.

SIRIUS code allows the analysis of major volatile fission products by grouping them based on the NUREG-1465 report [4] and has recently been improved to enable grouping based on the SAND2011-0128 report [5] as well. As shown in Table I, the NUREG-1465 report categorizes 17 fission products into 8 groups. The bolded nuclides are used as the representative molecular weights for each group. It is assumed that **I** (Iodine) and **Cs** (Cesium) in Group 2 and Group 3 exist as **CsI** (Cesium iodide) and **CsOH** (Cesium hydroxide) upon release, respectively.

Table I. Fission product group based on the NUREG-1465 report [4]

No.	Group name	Components
1	Noble gases	**Xe**, Kr
2	Alkali metal iodides	**CsI** (infuel: I)
3	Alkali metal hydroxides	**CsOH** (infuel: Cs)
4	Chalcogens	**Te**, Sb, Se
5	Alkaline earths	**Ba**, Sr
6	Platinoids	**Ru**, Mo
7	Rare earths	**La**, Zr(fission product)
8	Structural materials	**Zr**, Fe, Cr, Ni, Mn

The SAND2011-0128 report, as shown in Table II, classifies 41 fission products into 14 groups. The bolded nuclides are used as the representative molecular weights for each group.

Table II. Fission product group based on the SAND2011-0128 report [5]

No.	Group name	Components
1	Noble gases	**Xe**, Kr
2	Alkali metals	**Cs**, Rb
3	Cesium iodide	**CsI** (infuel: I)
4	Halogens	**I_2**, Br_2
5	More volatile main group	**Cd**, Sb, As
6	Less volatile main group	**Sn**, Ag, In
7	Alkaline earths	**Ba**, Sr
8	Chalcogens	**Te**, Se
9	Early transition elements	**Mo**, Nb, Tc
10	Platinoids	**Ru**, Rh, Pd

11	Trivalents	**La**, Y, Pr, Nd, Pm, Sm, Eu, Gd, Am, Cm
12	Uranium	**U**
13	Tetravalent	**Ce**, Zr(fission product), Np, Pu
14	Structural materials	**Fe**, Zr, Cr, Ni, Mn

In the NUREG-1465-based grouping, it is assumed that all $\mathbf{I_2}$ gas released from the core combines with **Cs** to form **CsI**. In the SAND2011-0128-based grouping, the combination ratio between $\mathbf{I_2}$ and **Cs** can be adjusted depending on the analysis, allowing the independent evaluation of both **CsI** formation and the behavior of $\mathbf{I_2}$ gas.

3. Numerical method

To support uncertainty analysis using SIRIUS code [6], computational performance (calculation speed) has been improved. Previously, SIRIUS code performed calculations based on the same *dt* as CSPACE or SACAP code, with the smaller *dt* of the two being used as the CINEMA code *dt*. However, the *dt* used in CINEMA code for computational stability is generally less than 0.1s. This value is too small for SIRIUS code, which must simultaneously compute all thermal-hydraulic nodes and multiple fission product groups at each time step, leading to a slowdown in CINEMA code when SIRIUS code is included.

Since SIRIUS code simulates fission product generation based on corium temperature and transport between thermal-hydraulic nodes due to gas flow, its results are affected only by significant changes in thermal-hydraulic conditions. Taking this into account, SIRIUS code has been enhanced to use a larger *dt* than CINEMA code. As shown in Fig. 2, increasing the *dt* of SIRIUS code reduces the number of calculations.

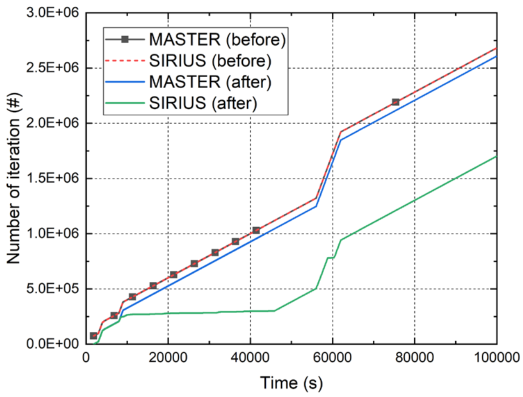

Fig. 2. Effect of increasing *dt* on SIRIUS code calculation frequency

However, this approach does not utilize thermal-hydraulic data at every time step, which may lead to distorted results. To account for this, SIRIUS code monitors all time steps for the following four key thermal-hydraulic variables and checks for changes from the last calculated data:

- Corium temperature
- Thermal-hydraulic node gas temperature
- Thermal-hydraulic node pressure
- Gas flow rate between thermal-hydraulic nodes

If the change exceeds the predefined criteria, SIRIUS code performs calculations not only at the time step *t* but also at the previous time step $t-dt$ (CINEMA code *dt*). This prevents excessive *dt* from being applied when transient noise occurs in the thermal-hydraulic data, which could otherwise distort the results.

For uncertainty analysis using SIRIUS code, an implicit solver is recommended to ensure the stability of massive calculations. The implicit solver in SIRIUS code solves a matrix $i \times k$, considering all thermal-hydraulic nodes *i* from CSPACE and SACAP codes along with fission product groups *k*. To optimize computational performance, the matrix was restructured to include only nodes directly connected to the core, reducing *i*. As shown in Fig. 3, optimizing the implicit solver matrix and adjusting the SIRIUS code *dt* enhance the computational performance of CINEMA code by approximately 20% (The green and blue lines show the post-optimization results). The calculation time of SIRIUS code has been reduced by more than half.

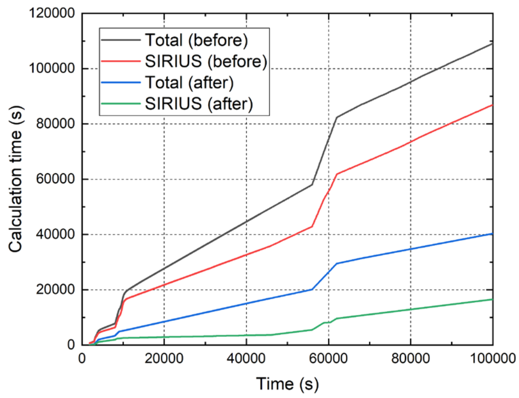

Fig. 3. Optimization of implicit solver matrix and time step adjustment

Since SIRIUS code calculates the release of fission products from corium, it receives the transport rates of unreleased fission products between core nodes from CSPACE code, considering accident progression phenomena such as candling and slumping. If SIRIUS code does not use the same *dt* as CSPACE code, unreleased fission products may experience discrepancies in their mass. Therefore, the transport of unreleased fission products and their gaseous release from corium are calculated based on thermal-hydraulic data at all time steps. Fig. 4 confirms that these optimizations improved computational performance without altering key results, as the before and after optimization results perfectly overlap.

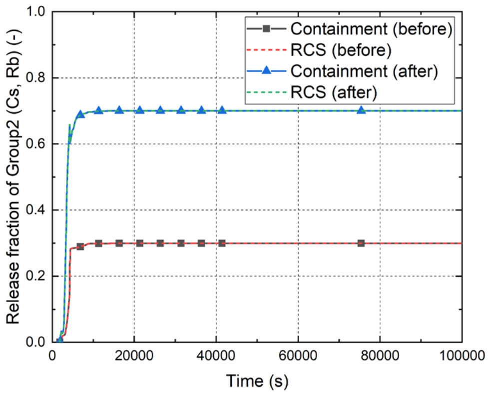

Fig. 4. Comparison of key results before and after optimization

4. Conclusion

This paper presents the current status of SIRIUS code development, focusing on improving the fission product group methodology and optimizing computational performance while maintaining result accuracy. In addition, several key enhancements have been implemented:

- Initial inventories and decay heat of fission products can be specified by nuclide and burnup level using ORIGEN or OpenMC calculation results.
- Gap release can now occur simultaneously in core nodes connected in the axial direction.
- Both default and user-defined fission product groups can be used simultaneously for analysis, enabling more flexible simulations.
- Selective analysis of specific default fission product groups is now possible.

Computational performance can be improved not only by the size of the matrix but also by optimizing its structure, which will be addressed in future studies. Future development plans focus on utilizing the improved computational performance to enable more detailed fission product group analysis and ensure the efficient implementation of the multi-component sectional method.

Acknowledgement

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