Comprehensive Study for Methodology Development of Effluent Evaluation in i-SMR

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1. Introduction

In nuclear power plant operations, evaluating effluents is crucial for regulatory compliance and public safety. While existing large PWR have relied on the GALE code for these assessments, the emergence of Small Modular Reactors (SMRs) introduces unique challenges that require adapted methodologies.

Given SMRs' potential for increased safety and efficiency, this study seeks to develop a unique effluent evaluation method by referencing NUREG-0017 to suit SMR-specific requirements. By focusing on various PWR designs, this research aims to establish a robust theoretical foundation for effective and compliant effluent management in future SMR applications.

2. Methods and Results

2.1 Review of Regulatory Requirements for Radioactive Effluent Evaluation

When constructing a new nuclear power plant, an operating license must be obtained in accordance with the Korea Nuclear Safety Act chapter 3. Among the required documents, results of radioactive effluent evaluations must be included. The Nuclear power plant design must ensure that radioactive waste is discharged in compliance with the standards for controlling radioactive substances in liquid and gaseous effluents.

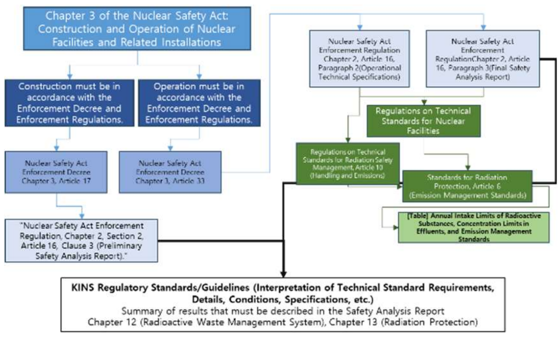

Fig. 1. Legal framework related to radioactive effluent

Figure 1 illustrates the legal framework governing radioactive effluent as stipulated in the Nuclear Safety Act. The KINS Regulatory Guide, particularly Chapter 12 on radioactive waste systems, specifies the concentrations of radioactive substances in liquid and gaseous effluents. It also mandates verifying that the discharge quantities during normal operation comply with the emission control standards set forth in the Nuclear Safety Act.

Furthermore, the regulatory guidelines from the NSSC recommend referencing ANSI/ANS-18.1-1999, PWR-GALE(86) codes, and industry standards such as Radiation Protection and Radiation Protection Design when calculating the types and concentrations of radioactive nuclides in the coolant. If alternative methods are used, the basis for such calculations must be clearly documented[1]

2.2 Existing Methods for Evaluating Radioactive Effluents in Large Nuclear Power Plants

The effluent evaluation methodology used in large nuclear power plants was analyzed by referring to the Final Safety Analysis Report (FSAR).[2] The flow of radioactive effluents was depicted in Figures 2 and 3.

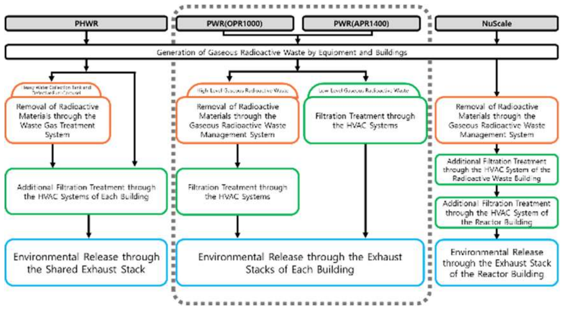

Fig. 2. Flow diagram of gaseous radioactive waste

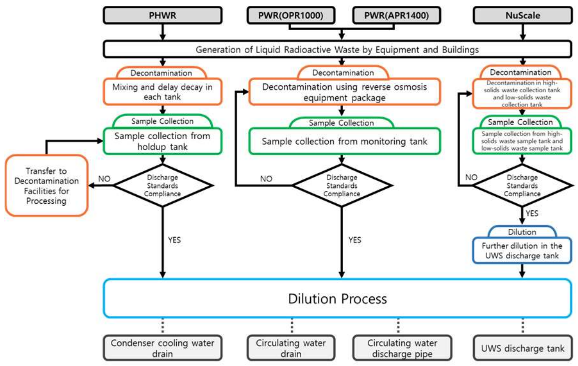

Fig. 3. Flow diagram of liquid radioactive waste

Following these flow diagrams, 43 parameters were derived, and the GALE code was utilized to calculate the discharge concentrations of liquid and gaseous radioactive waste. The results calculated using the GALE code can be used to derive the annual average concentrations of liquid and gaseous effluents at the restricted area boundary. Equation (1) presents the calculation formula for determining the concentration of gaseous effluents, while Equation (2) presents the formula for liquid effluents.

$$(1) \quad \mathrm{C(i)} = \mathrm{R(i)} \times \mathrm{MF(i)} \times \frac{\mathrm{X}}{\mathrm{Q}} \times \mathrm{CF}$$

Where:
$C(i)$= *Radiological concentration in the effluent at the controlled boundary* (Bq/ml)
$R(i)$= *Release rate of the isotope ii in* Bq/yr
$MF(i)$= $(RCS(i)\ of\ DAMSAM)/(RCS(i)\ of\ GALE)$
CF = *Unit conversion factor, which is given* 3.17×10^{-14} $Bq/ml\times sec/m^3\times yr/m^3\times ml$

$$(2) \quad \mathrm{C(t)} = \mathrm{Fdil} \times \mathrm{CFR(i)} \times \mathrm{MF(i)}$$

Where:
$C(t)$= *Concentration of the isotope in the effluent at the restricted boundary* (Bq/ml)
$R(i)$= *Release rate of isotope ii in* Bq/yr
$MF(i)$= $(RCS(i)\ of\ DAMSAM)/(RCS(i)\ of\ GALE)$
F_{dil}= *Flow rate* (cfs)
CF = *Unit conversion factor, which is given as* $1.0^6(cm^3\ sec - Bq/ft^3\ cfs\ yr - Bq)$

2.3 Modifications to the GALE Code Source for SMRs

When using the GALE code to evaluate radioactive effluents for SMRs, three factors need to be considered: thermal output, Capacity Factor, and boron-free operation. These factors all affect the release of tritium, and specific variable modifications were suggested by PNNL.[3]

table 1. changes in key parameters related to the effluent evaluation

Parameter	Original Value	Updated Value	Change Description
Capacity Factor	80%	90%	Increased
Tritium Release Rate	0.4 Ci/yr/MWth	0.27 Ci/yr/MWth	Decreased
Ar-41 Release Rate	34 Ci/yr	6 Ci/yr	Decreased
C-14 Release Rate	7.3 Ci/yr	5.9 Ci/yr	Decreased
Unexpected Release Rate	0.16 Ci/yr	1.6×10^{-4} Ci/yr	Decreased
Decontamination Factor of PWR Condensate Decontaminator	50	10	Decreased

2.4 Effluent Evaluation Methodology of NuScale

Given NuScale's leading position in the SMR field and its recognition by the NRC, this study investigated NuScale's effluent evaluation methodology. The effluent evaluation for the NuScale SMR is conducted using the GALE code, similar to the approach used in large nuclear power plants.[4] However, when unique design characteristics of SMRs need to be considered, new values were used in addition to those specified in NUREG-0017.

Specifically, in the evaluation of gaseous effluents, NuScale accounted for the potential release of gases due to unintended core cooling system operations, as well as additional sources of TGB gas effluents. The exhaust gas release rate was set at 125 Ci/year/NPM, a value derived by linearly adjusting the NUREG-0017 release rate of 1700 Ci/year per µCi/g of primary coolant according to the reactor's thermal output.

For the evaluation of liquid effluents, NuScale considered that all effluents would be treated by the Liquid Radwaste System (LRWS) before being discharged at a common discharge point. Similar to the gaseous effluents, input volumes and various parameters were adjusted linearly based on the values from NUREG-0017, in proportion to the thermal output.

These considerations are crucial for ensuring that the NuScale SMR meets regulatory standards and accurately assesses the environmental impact of its effluents.

3. Conclusions

In this study, the methodology for evaluating radioactive effluents during normal operation from innovative SMRs was developed by reviewing regulatory frameworks and analyzing effluent evaluation methods used in large nuclear power plants. The analysis identified key parameters necessary for accurate effluent evaluation across various reactor types, including both large conventional reactors and SMRs, ensuring a comprehensive approach that accounts for the unique characteristics of each. The findings revealed that specific considerations, such as thermal output, Capacity Factor, and boron-free operation, are crucial for adapting the GALE code to effectively evaluate effluents in SMRs.

Future work will involve the application of the adapted GALE code to real-world SMR scenarios to validate the effectiveness and compliance of the effluent evaluation process. This will ensure that the unique characteristics of SMRs are appropriately addressed, contributing to the safe and efficient management of radioactive effluents in advanced nuclear systems.

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