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Research and Application of Airborne Radioactive Source Term Analysis Programs for Nuclear Facility Buildings (Submission to the 27th Annual Conference of the China Association for Science and Technology and the 2nd Youth Nuclear Science and Technology Academic Conference)

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Abstract

In nuclear facility buildings, leaked radionuclides can exist in the form of gas or aerosol, forming airborne radioactive source terms that subsequently cause internal exposure to workers, representing one of the primary sources of occupational exposure dose for nuclear facility personnel. To analyze the distribution of airborne source terms and personnel exposure conditions within nuclear facility buildings, the "Airborne Radioactive Source Term Analysis Program for Nuclear Facility Buildings" was independently developed. This paper introduces the main computational models involved in the program, including generation models, removal models, and airborne source term calculation models. Three buildings (containment, annulus space, and environment) were selected as case studies to compare the numerical and analytical solutions of the computational program, thereby verifying the accuracy of the program's numerical algorithm. The program was further applied to evaluate and analyze the distribution characteristics of source terms within buildings, providing a research basis for worker exposure dose analysis.

Full Text

Research and Application of Airborne Radioactive Source Term Analysis Program for Nuclear Facility Buildings

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Abstract

In nuclear facility buildings, leaked radioactive nuclides exist in the form of gases or aerosols, forming airborne radioactive source terms that cause internal exposure to workers. This represents one of the primary sources of occupational radiation dose for nuclear facility personnel. To analyze the distribution of airborne source terms within nuclear facility buildings and assess personnel exposure conditions, we independently developed the "Airborne Radioactive Source Term Analysis Program for Nuclear Facility Buildings." This paper introduces the main calculation models employed in the program, including generation models, removal models, and airborne source term calculation models. Three compartments (containment, annular space, and environment) were selected as examples to compare the numerical solutions from the program with analytical solutions, thereby verifying the accuracy of the numerical algorithm. The program can be used to evaluate and analyze source term distribution characteristics within buildings and provides a research basis for analyzing worker exposure doses. Finally, based on various influencing factors of the calculation program, measures to reduce airborne radioactive levels in nuclear facility buildings are discussed.

Keywords: Airborne radioactivity; Source term calculation model; Radiation safety

1 Research Background

Airborne radioactive source terms in nuclear facility buildings serve as critical input for calculating radiation doses to workers [1]. During normal operation of nuclear facilities, equipment leakage and seepage, along with evaporation of radioactive liquids from open pools, cause airborne radioactive materials to permeate nuclear island buildings. The portion retained within these buildings leads to internal inhalation exposure during worker operations [2]. In accident scenarios such as a Loss of Coolant Accident (LOCA), large quantities of radioactive nuclides from the reactor core are released into the containment and may subsequently be released to other buildings and the environment through multiple pathways. For radiation protection and safety considerations, it is necessary to analyze and optimize airborne radioactive source term levels in nuclear island buildings.

Traditional analysis methods often employed a "large compartment" model, which assumes uniform distribution of airborne radioactivity within a building. These methods primarily considered generation from leakage and pool evaporation, and removal via decay and ventilation, but did not comprehensively account for all generation and removal mechanisms. Furthermore, due to limitations in equation solving methods, they could not address migration processes involving more than three compartments. In reality, airborne radioactive concentrations vary significantly between different compartments within a building, and existing calculation methods cannot meet the demands of refined analysis. Therefore, it is necessary to develop a widely applicable airborne radioactive source term analysis software for various nuclear facilities throughout their lifecycle stages, based on research into generation, migration, and deposition pathways of airborne radioactive source terms and incorporating operational experience data from existing nuclear facilities.

2 Software Model

Based on research into airborne radioactive source term generation, migration, and deposition pathways in nuclear facilities, this study developed an analysis software using refined models that can be widely applied to various nuclear facilities throughout all lifecycle stages. The software comprehensively considers generation and removal models for airborne radioactive materials in each compartment, while also accounting for migration processes between different compartments, as illustrated in Figure 1 [Figure 1: see original paper].

Figure 1 The Main Generation and Removal Mechanisms Considered in the Multi-Compartment Model

2.1 Calculation Program Assumptions

To ensure broad applicability of the calculation program and its models, the following assumptions were adopted for the airborne radioactive source term analysis program: (1) radioactive nuclides are assumed to be uniformly distributed within each compartment; (2) once released into a compartment, radioactive nuclides are assumed to be sufficiently dispersed to achieve uniform distribution; (3) during specified generation or release phases, the generation rates of each generation model remain constant; and (4) during specified removal phases, the removal rates of each removal model remain constant.

2.2 Generation Models

Based on nuclear facility operational and potential accident conditions, the program comprehensively considers generation terms for airborne radioactivity within compartments, including: instantaneous release models for radioactive liquid leakage, uniform release models for radioactive liquid leakage, pool evaporation generation models, resuspension models, instantaneous release models for radioactive gases and aerosols, and uniform release models for radioactive gases and aerosols. Migration generation terms between compartments include ventilation or leakage generation models and ventilation filtration generation models.

2.3 Removal Models

Removal models are categorized into intra-compartment removal terms and inter-compartment migration removal terms. Intra-compartment removal terms include decay removal models, deposition removal models, filtration removal models, and spray removal models (the latter is not used for reprocessing plant airborne radioactive source term calculations but is applied to other nuclear facility airborne radioactive source term calculations). Inter-compartment migration removal terms include ventilation or leakage removal and ventilation filtration removal.

2.4 Compartment Source Term Calculation Equation

Based on the generation and removal models, the temporal variation of radionuclide i in compartment k during time stage j is described by Equation (1). The equation employs the Gear numerical method for solution, forming the basis of the airborne radioactive source term analysis program for nuclear facility buildings.

The terms are defined as follows: Q_k^{nT} represents the total quantity of radionuclide i in compartment k during time stage j; $\frac{dQ_k^{nT}}{dt}$ represents its rate of change over time; R_k^{nT} represents generation terms for radionuclide i in compartment k during time stage j, including leakage generation terms, evaporation generation terms, and uniform release terms. L_k^{nT} represents removal terms for radionuclide i in compartment k during time stage j, including decay removal, deposition removal, filtration removal, spray removal (not applied to reprocessing plant calculations), ventilation or leakage removal, and ventilation filtration removal. L_{mk}^{nT} represents migration generation terms for radionuclide i from compartment m to compartment k during time stage j, including ventilation or leakage migration and ventilation filtration migration; and Q_m^{nT} represents the total quantity of radionuclide i in compartment m during time stage j.

3 Model Validation and Application

3.1 Model Validation Analysis

To verify the accuracy of the analysis models and algorithms, three compartments that permit analytical solution were selected as examples [3]. The three compartments were assumed to be containment, annular space, and environment, with their connections illustrated in Figure 2 [Figure 2: see original paper]. The program calculated airborne radioactive source term concentrations in the three compartments from 0 to 2 hours. The results demonstrate excellent agreement between the numerical solutions from the program and the analytical solutions, with deviations below 0.05%, thereby verifying the accuracy of the program models and algorithms.

Figure 2 Schematic Diagram of the Three-Compartment Connection

Table 1 Comparison of Airborne Radioactive Source Terms in Three Compartments from 0 to 2 Hours

Nuclide	Containment Activity Concentration (GBq/m^3)	Annulus Activity Concentration (GBq/m^3)	Environment Activity Concentration (GBq/m^3)
	Numerical	Analytical	Deviation %
85mKr	1.46E+8	1.46E+8	0.00
131mXe	1.05E+7	1.05E+7	0.00
133mXe	1.79E+6	1.79E+6	0.00
135Xe	3.94E+9	3.94E+9	0.00
138Xe	2.69E+8	2.69E+8	0.00
134Cs	4.54E+7	4.54E+7	0.00
	8.26E+9	8.26E+9	0.00
	5.79E+8	5.79E+8	0.00
	9.81E+7	9.81E+7	0.00
	1.14E+9	1.14E+9	0.00
	1.12E+8	1.12E+8	0.00
	1.99E+7	1.99E+7	0.00
	1.73E+9	1.73E+9	0.00
	1.17E+8	1.17E+8	0.00
	2.01E+7	2.01E+7	0.00
	9.98E+7	9.98E+7	0.00
	1.28E+7	1.27E+7	0.79

3.2 Complex Building Model Application

A five-compartment model was designed with flow between all compartments, as illustrated in Figure 3 [Figure 3: see original paper]. The airborne radioactivity in Compartment 1 originates from pool evaporation, while radioactivity in the remaining compartments results from ventilation leakage between compartments.

Figure 3 Schematic Diagram of the Five-Compartment Model Connection

The airborne radioactive source term analysis program was used to calculate the airborne radioactivity concentrations in each compartment at various times. Figures 4 [Figure 4: see original paper] and 5 [Figure 5: see original paper] illustrate the temporal variation of airborne source terms in Compartment 1 and Compartment 5, respectively. Since Compartment 1 receives radioactive material from pool evaporation, it exhibits the highest initial radioactivity concentration at time zero. As gas flows in from other compartments, the decay rate of airborne radioactivity in Compartment 1 decreases and approaches equilibrium, with iodine and alkali metal nuclides showing the most pronounced behavior.

Examining Compartment 5 as an example to observe the variation patterns in other compartments, the airborne radioactivity concentrations of iodine, alkali metals, and inert gases initially increase, reach peak values at 3-4 hours, and then decrease. These calculation results can provide recommendations regarding the timing of worker entry and appropriate protective measures.

Figure 4 Airborne Radioactivity Concentrations of Inert Gases, Iodine, and Alkali Metals in Compartment 1

Figure 5 [**Figure 5: see original paper**] Airborne Radioactivity Concentrations of Inert Gases, Iodine, and Alkali Metals in Compartment 5

Conclusion

This study independently developed an airborne radioactive source term analysis program for nuclear facility buildings, detailing the main calculation models involved, including generation models, removal models, and airborne source term calculation models. The program can calculate airborne source term distributions within nuclear facility buildings. Example cases were selected to compare numerical solutions with analytical solutions, verifying the accuracy of the program' s numerical algorithms. The program can be used to evaluate and analyze source term distribution characteristics within buildings, providing a reference basis for analyzing radiation doses to personnel in nuclear facility buildings. Additionally, it provides analytical support for normal operation, decontamination and maintenance, accident prevention, accident management, and environmental protection of nuclear facilities. Combined with actual radiation monitoring data, the program ensures that workplace dose levels meet design requirements, enables timely identification of radiation safety issues and potential hazards, and supports the ALARA (As Low As Reasonable Achievable) principle by providing data for worker dose calculations, thereby ensuring personnel safety.

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