Analysis of Dose Constraint Setting for Multiple Nuclear Facilities and Site Dose Management at Nuclear Sites

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Date: 2025-02-12T00:00:00+00:00

Abstract

Public individual dose constraint is an important indicator for radiation impact assessment and management of nuclear facilities in China. This study addresses the needs of nuclear base construction where multiple types of nuclear facilities coexist, and through systematic investigation and analysis of domestic and international dose constraint management requirements and practices—particularly the recommendations of the IAEA and other organizations regarding generic and specific dose constraints and their applications in major nuclear energy countries—in combination with China' s regulatory realities, proposes a recommended upper limit of 0.25mSv·a-1 for dose constraints at nuclear bases. Simultaneously, a case analysis was conducted based on the development plan of a certain nuclear base, and through screening of effluent discharges from various facilities and critical groups and dose assessments, a methodology for setting dose constraint values for multiple nuclear facilities was proposed, ultimately yielding reasonable and feasible recommendations for dose constraint values for multi-facility nuclear bases.

Full Text

Preamble

Dose Constraint Setting for Multiple Nuclear Facilities at a Nuclear Base

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Abstract

[Background] The public individual dose constraint serves as a crucial indicator in the assessment and management of radiological impacts from nuclear facilities in China. [Purpose] This study addresses the practical needs of newly constructed nuclear bases where various types of nuclear facilities coexist. [Methods] Through systematic investigation and analysis of domestic and international dose constraint management requirements and practices, particularly the recommendations from the IAEA regarding generic and specific dose constraints and their application in major nuclear power countries, and in combination with China' s regulatory practices, we propose an upper limit of 0.25 $mSv \cdot a^{-1}$ for nuclear base dose constraints. [Results] Furthermore, a case analysis of a developing nuclear base was conducted. Based on effluent emissions from each facility and the screening and dose assessment of critical groups, we propose a methodology for setting dose constraint values for multiple nuclear facilities. [Conclusions] Finally, reasonable and feasible recommendations for dose constraints for multiple nuclear facilities are provided.

Keywords: Multiple nuclear facilities, Dose constraint, Dose management, Critical group

1. International and Domestic Dose Constraint Management Requirements for Nuclear Facilities

The International Commission on Radiological Protection (ICRP) introduced the concept of dose constraint in its 1990 recommendations within the framework of optimization of protection, and simultaneously proposed the three principles of radiation protection: justification of practices or interventions, optimization of protection, and individual dose/risk limits. Subsequently, ICRP Publication 103 clarified that dose constraint is a concept for optimization of protection applicable to planned exposure situations, corresponding to reference levels for emergency and existing exposure situations. The ICRP recommends that public dose constraints should be set at 1 $mSv \cdot a^{-1}$ or less, with an ideal target of $0.3mSv \cdot a^{-1}$.

The International Atomic Energy Agency (IAEA) provides detailed provisions on dose constraints in its publication *Radiation Protection of the Public and the Environment*. Key points include: (1) dose constraint is defined as representing a fundamental level of protection that is always below the dose limit, but need not be treated as a target value–optimization of radiation protection should aim to establish dose levels below the dose constraint; (2) it is specified that the dose constraint for a single specific source ensures that the sum of doses from all planned sources to a representative individual remains below the dose limit, with future potential practices considered during the design or planning stage when determining dose constraints; (3) for planned exposure situations, the annual public dose constraint should fall within the range of 0.01 to <1 mSv·a^{-1}. Specifically, the IAEA' s *Regulatory Control of Radioactive Discharges to the Environment* suggests that when establishing generic dose constraints, regulatory bodies may consider the Agency' s previous guidance, which recommends 0.3 mSv·a^{-1} as an appropriate default value based on typical optimized individual radiation levels used in nuclear fuel cycle facilities across various countries. Additionally, the IAEA' s *Disposal of Radioactive Waste* stipulates a dose constraint of 0.3 mSv·a^{-1} to optimize public protection for the design, construction, operation, and closure of disposal facilities.

Based on the two principles of planned exposure situations for sources and optimization of radiation protection, many countries have established corresponding dose constraint values for different types of nuclear facilities, as shown in . Annual dose constraint values for single sources are generally set between 0.05-0.3 mSv·a^{-1}, consistent with recommendations from ICRP, IAEA, and other organizations.

In China, the public individual dose constraint constitutes one of four levels in the operational radiological impact management system for nuclear facilities. The *Basic Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources* clarifies that dose constraints are source-related and serve as constraints for optimization of protection and safety for the source under consideration. It also requires that the dose constraint for any particular source in practice should not exceed the value specified by the regulatory authority and should not exceed the principle that could lead to exceeding the dose limit. Specific dose constraint value requirements for relevant nuclear facilities are provided in specialized standards: 0.25 mSv·a^{-1} for nuclear power plants and 0.2 mSv·a^{-1} for uranium processing and fuel fabrication facilities. These provisions are generally consistent with international standards and can guide radiological protection design and optimization for relevant nuclear facilities.

2. Recommendations for Dose Constraint Setting at Multi-Facility Nuclear Bases

As new types of nuclear facilities are being planned or deployed within existing nuclear bases in China, current dose constraint requirements for single-type facilities can no longer meet nuclear safety regulatory needs. It has become necessary to propose site-specific dose constraint management requirements that consider the coexistence of different facility types. This section discusses the necessity and feasibility of such requirements based on relevant domestic and international requirements and practices, and provides corresponding recommendations.

First, the IAEA' s *Regulatory Control of Radioactive Discharges to the Environment* proposes that when multiple facilities or activities exist at the same location, simply apportioning the generic dose constraint by the number of facilities may not be reasonable. Instead, a specific dose constraint should be established for each facility or activity based on its specific contribution to the dose received by the representative individual, ensuring optimal protection for each radiation source while keeping the combined dose below the dose limit. For specific dose constraints, the IAEA's *Prospective Radiological Environmental Impact Assessment for Facilities and Activities* recommends that "the regulatory body should set specific dose constraints for a single facility or activity, taking into account dose contributions to the representative individual from other nearby or co-located facilities or activities" and that "in the early regulatory stage, comparison of generic dose constraint values with initial radiation dose assessment results may be used, with facility-specific dose constraints considered subsequently." Therefore, establishing specific dose constraints for different nuclear facilities and activities based on site characteristics is reasonable beyond generic dose constraints.

For setting specific dose constraints for multiple facilities or activities, it should be clear that the sum of effective doses to critical groups (or representative individuals) from all sources under consideration must remain below the dose limit (1 $mSv \cdot a^{-1}$). According to IAEA recommendations, the estimated maximum future dose from global, regional, and exempted sources is approximately 200 Sv per person per year, leaving about 800 Sv per year as the remaining committed dose that can be considered the upper limit for dose constraints. In practice, countries impose stricter limits on site dose constraints (generally regarded as the upper limit for site dose constraints) than the IAEA recommended value of 0.8 $mSv \cdot a^{-1}$. For example, the UK specifies a source dose constraint of 0.3 $mSv \cdot a^{-1}$ as the upper limit for planned operational future discharges and direct radiation from a single source, and a site dose constraint of 0.5 $mSv \cdot a^{-1}$ to limit future discharges from multiple adjacent sources at the same site (excluding direct radiation). Spain sets dose constraints of 0.3 $mSv \cdot a^{-1}$ for nuclear power plants and fuel cycle facilities, and 0.1 $mSv \cdot a^{-1}$ discharge control requirements for gaseous and liquid effluents from single nuclear facility operation and decommissioning. The US and South Korea have established 0.25 $mSv \cdot a^{-1}$ dose control requirements for nuclear fuel cycle facility sites containing multiple reactors (in practice, this value is controlled as site radiological environmental capacity), while also setting whole-body dose design objectives for gaseous and liquid pathways for single-type reactors. Additionally, the US Department of Energy (USDOE) stipulates a total effective dose (TED) limit of 1 $mSv \cdot a^{-1}$ for the public residing outside DOE sites and controlled areas, but also requires assessment of public dose impacts from DOE-related sources using a representative individual dose not exceeding 0.25 $mSv \cdot a^{-1}$, with combined exposure from DOE-related and major non-DOE-related sources considered when the DOE source dose exceeds 0.25 $mSv \cdot a^{-1}$.

In China, it must first be clarified that facilities within the same nuclear base (typically defined within a 5 km radius) are generally considered to be at the same site, meeting IAEA requirements for both specific and generic dose constraints. On the other hand, China has not yet established requirements for reactor dose design objectives. Currently, effluent discharge design source terms for nuclear power plants, as representative examples, are primarily based on the primary loop activity spectrum of 5 GBq/t I-131 equivalent. Although this reflects accumulated experience from Chinese PWR nuclear power plants and research on the normal operation source term framework system, it cannot represent all operational states of nuclear power plants including anticipated operational occurrences. Therefore, dose constraints derived forward from discharge source terms are very low, failing to meet the requirement of >10 $\mathrm{Sv \cdot a^{-1}}$ and providing insufficient consideration for facility operational margins. Consequently, facility-specific dose constraints should be included within the scope of site generic dose constraints. Drawing on relevant foreign experience and considering China' s current nuclear base management practices, this paper recommends setting the upper limit of dose constraints for nuclear base sites at 0.25 $\mathrm{mSv \cdot a^{-1}}$.

3. Case Analysis of Dose Constraint Setting for a Nuclear Base

3.1 Overview of Nuclear Facilities at the Base

According to GB6249-2011 requirements, sites with reactor spacing less than 5 km should be treated as multi-reactor nuclear power plant sites. The nuclear base described in this section is located on the coast of the South China Sea and currently operates a commercial nuclear power plant with six million-kilowatt units. Approximately 3 km from the nuclear power plant operates a nuclear fuel research and experimental platform (classified as a Category III nuclear fuel cycle facility). Additionally, two nuclear facilities are under construction near the nuclear power plant, two are in the pre-application stage, and three more are planned for subsequent construction. The overview of each nuclear facility is presented in , all located within the 5 km radius planning restriction zone established for the nuclear power plant (see [Figure 1: see original paper]).

lists the effluent discharge methods for each facility. All facilities use chimneys for gaseous effluent discharge. From the perspective of integrated marine outfall arrangement, each facility plans to discharge liquid effluents through a unified base outfall (i.e., the nuclear power plant' s circulating cooling water outlet). To meet transfer requirements for liquid effluents between facilities, radioactivity will be treated to meet the requirements of GB8978-1996 or GB5759-2022 before being transported via appropriate means to the base outfall for controlled discharge.

3.2 Selection of Critical Groups

The ICRP has long used the concept of "critical group"to characterize individuals in the representative population receiving higher radiation exposure. In its new recommendations, the ICRP has equivalently replaced this with the concept of "representative person," referring to the average individual in the critical resident group. In practice, however, both concepts are essentially the same for dose assessment purposes, and doses can be calculated using similar methods. The representative person proposed by the ICRP is typically a hypothetical concept at the site boundary rather than an actual resident, but in Chinese practice, actual resident groups are generally used as the basis for screening critical groups.

In this study, the screening range for critical groups is the planning restriction zone of Nuclear Power Plant A. Based on environmental impact assessment conclusions for each project, six residential locations were selected from within the planning restriction zone as candidate critical groups for dose constraint setting according to the following principles: (1) DA Village, GX Village, and X Village are the critical groups identified in the environmental impact reports for Nuclear Power Plant A, Facility C, and Facility F, respectively; (2) NA Village was an early critical resident group for Nuclear Power Plant A, adjacent to the plant' s living area; (3) RA Village and PD Village are important residential locations with larger populations in the western and northeastern directions of the base, respectively.

provides location information for the critical groups of interest, with the distribution of each residential location also shown in [Figure 1: see original paper].

3.3 Dose Constraint Setting Methodology and Results

3.3.1 Public Exposure Pathways and Dose Calculation Parameters This study employs the IAEA-recommended model for public exposure dose calculations. Following atmospheric dispersion of gaseous effluent discharges from each facility, radiation impacts on the public around the site occur through external exposure from air immersion, ground deposition, inhalation of air, and ingestion of terrestrial foods (including grain crops, vegetables, meat, and milk). Liquid radioactive effluents entering the receiving water body (the nearby South China Sea) are diluted and dispersed, causing radiation impacts through external exposure from water immersion, water activities, shoreline deposition, and ingestion of marine products (including fish, crustaceans, mollusks, and algae). Using meteorological observation data from Nuclear Power Plant A for two complete consecutive years from January 2021 to December 2022, annual average atmospheric dispersion factors were calculated based on design parameters such as stack height and discharge flow rates for each facility, as shown in . Nuclide transfer parameters and dose conversion factors used in dose calculations were obtained from relevant literature, while food consumption and lifestyle data for critical groups were derived from site survey results.

3.3.2 Dose Constraint Setting Based on the previously determined upper limit of 0.25 $mSv \cdot a^{-1}$ for the entire nuclear base dose constraint, this study establishes facility dose constraints by fully considering each facility' s dose contribution to the surrounding public. Dose contributions are calculated using each facility' s designed effluent discharge source terms, consistent with the principle that dose constraints are source-related. For six potential critical groups located in different sub-areas of each facility, the comprehensive weighted impact of each facility' s maximum individual dose is emphasized, from which the weight values for each facility' s dose impact contribution are derived as the initial proportional setting for dose constraints, as shown in Equation (1):

$$w_i = \frac{D_{i,j}}{\sum_{i=1}^{n} D_{i,j}}$$

where w_i is the dose contribution weight value for the i-th nuclear facility, $D_{i,j}$ is the maximum individual effective dose to the j-th critical group from the i-th nuclear facility, m is the total number of critical groups, and n is the total number of nuclear facilities in the multi-facility base.

presents the dose share to critical groups from each facility. Based on the dose contribution weight values for each facility shown in , the 0.25 $\mathrm{mSv \cdot a^{-1}}$ site-wide dose constraint value is proportionally allocated. Considering the current status of nuclear facilities at the base, priority is given to setting dose constraints for facilities that are operational, under construction, and in the application stage. The theoretically calculated values are then optimized and adjusted according to three principles: (1) not exceeding the theoretically calculated proportional allocation; (2) not exceeding existing environmental assessment approvals or application values; and (3) ensuring that the dose constraint set for each nuclear facility is not less than 0.01 $\mathrm{mSv \cdot a^{-1}}$. Accordingly, the proposed dose constraint values for each facility are presented in .

For Facility B, which is under construction and has no effluent discharge during operation, this study tentatively recommends a dose constraint value of 0.01 $\mathrm{mSv \cdot a^{-1}}$ as an independent nuclear facility. However, in actual practice, its dose constraint may also be incorporated with surrounding facilities (such as Nuclear Power Plant A) according to regulatory requirements. Additionally, for the three nuclear facilities planned for construction within the base, considering their significant design uncertainties, it is recommended that dose constraint values be combined and reserved at this stage.

3.3.3 Feasibility Analysis of Dose Constraint Setting Since approved discharge limits for nuclear facilities typically do not cause source-related doses to exceed the dose constraint itself, sufficient margin is reserved for facility operation. Based on the recommendations in , this study further analyzes the proportion of maximum individual effective doses to critical groups from each operational and under-construction nuclear facility relative to their specific dose constraint values. The results show that the dose contribution from each facility to critical groups ranges from a maximum of 23.5% (Facility D) to a minimum of 1.87% (Facility F). Therefore, the proposed dose constraint setting can provide a basis for each facility to optimize effluent discharge design, establish dose management objectives, and apply for annual effluent discharge quantities, while also reserving sufficient operational margin to meet the requirements for implementing the multi-facility base plan.

This study systematically investigates domestic and international dose constraint management requirements and practices, proposes dose constraint value settings for multiple nuclear facilities in a nuclear base based on theoretical analysis, and confirms the reasonableness and feasibility of the recommended dose constraint values through assessment of public radiation impacts after facility operation. The results can serve as a reference for setting dose constraints for different nuclear facilities in domestic nuclear bases and can guide optimization of dose objectives and effluent discharge management for each facility.

It should be noted that dose constraint is only one component of unified environmental protection management for multi-facility nuclear bases. Nuclear bases should also fully consider the design and operational characteristics of each facility, and coordinate the implementation of various management matters within the base—including application for annual effluent discharge quantities, effluent discharge management, radiation monitoring, radioactive waste treatment, and emergency response—to meet nuclear safety and environmental regulatory requirements.

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