BJRS
BRAZILIAN JOURNAL OF RADIATION SCIENCES

doi.org/10.15392/2319-0612.2024.2648
2024, 12(4B) | 01-23 | e2648
Submitted: 2024-08-28
Accepted: 2025-02-12

Methodology for evaluating controlled area subdivision during conceptual design phase of nuclear facilities

Murata [a*], H. M.; Baroni [b], D. B.; Ruzzarin [a], A.; Rother [b], F. C.; Borsoi [b], S. S

[a] Fundação para o Desenvolvimento Tecnológico da Engenharia (FDTE), 05508-000, São Paulo, SP, Brazil.
[b] Diretoria de Desenvolvimento Nuclear da Marinha (DDNM), 05508-000, São Paulo, SP, Brazil.

*Correspondence: helio.murata.contratado@marinha.mil.br

Abstract: This work discusses the classification of subdivision of radiologically controlled areas in nuclear facilities, including those in research facilities with particle accelerators, such as CERN and KEK. The classification of radiological areas is a regulatory requirement proposed to assist in managing occupational exposures. The International Atomic Energy Agency (IAEA) recommends that the subdivision of controlled areas be based on similar facilities and dose rates. However, in a facility still in the conceptual design phase, without similar references and with an uncertain source term inventory, a more assertive classification for radioprotection purposes can be challenging. The document explores classification systems in various countries, including Brazil, Japan, South Korea, the United Kingdom, and the United States, highlighting differences in dose rate limits and regulatory frameworks. The presented methodology is suitable for classifying radiological areas in facilities without references during the conceptual phase, such as naval bases supporting nuclear ships. The approach aims to balance safety and operational requirements, in line with the ALARA principle specified in Recommendation 60 of the International Commission on Radiological Protection.

Keywords: Radiological Protection, Occupational Exposure, Nuclear Facilities, Dose Rate Limits.

SBPR

BJRS
BRAZILIAN JOURNAL OF RADIATION SCIENCES

doi.org/10.15392/2319-0612.2024.2648
2024, 12(4B) | 01-23 | e2648
Submitted: 2024-08-28
Accepted: 2025-02-12

Metodologia para avaliação da subdivisão de áreas controladas durante a fase de projeto conceitual de instalações nucleares

Resumo: Este trabalho discute a classificação da subdivisão das áreas controladas radiológicas em instalações nucleares, incluindo aquelas de pesquisa com aceleradores de partículas, como o CERN e KEK. A classificação das áreas radiológicas é um requisito regulatório proposto para auxiliar na gestão das exposições ocupacionais. A Agência Internacional de Energia Atômica (AIEA) recomenda que a subdivisão das áreas controladas seja baseada em instalações similares e nas taxas de dose. No entanto, em uma instalação ainda na fase de projeto conceitual, sem similares e com um inventário do termo fonte incerto, uma classificação mais assertiva para fins de radioproteção pode ser desafiadora. O documento explora os sistemas de classificação em vários países, incluindo Brasil, Japão, Coreia do Sul, Reino Unido e Estados Unidos, destacando as diferenças nos limites de taxa de dose e nos marcos regulatórios. A metodologia apresentada é adequada para classificar áreas radiológicas em instalações sem referências durante a fase de conceitual, como bases navais que apoiam navios nucleares. A abordagem visa equilibrar os requisitos de segurança e operacionais, em conformidade com o princípio ALARA especificado na Recomendação 60 da Comissão Internacional de Proteção Radiológica.

Palavras-chave: Proteção radiológica, Exposição ocupacional, Instalações nucleares, Limites de taxa de dose.

SBPR

1. INTRODUCTION

In a nuclear facility, radiological areas are specific locations where the handling, production, possession, and use of radiation sources can occur, as well as the transport, storage, and disposal of radioactive materials, covering all related activities that involve or may involve exposure to radiation. The classification of radiological areas is a proposed regulatory requirement designed to assist the management of occupational exposures of workers and public through administrative and operational controls. The International Atomic Energy Agency (IAEA) recommends classifying working areas with occupational radiation exposure as part of the radiation protection program. This classification, based on prior radiological evaluation, identifies two types of areas: controlled and supervised. The main differences between these areas are radiation level, access restrictions, protective measures, monitoring and surveillance, and regulatory compliance, with controlled areas being more stringent [1].

In controlled areas, specific safety and security measures are required for: Controlling exposures or preventing the spread of contamination in normal operation; Preventing or limiting the likelihood and magnitude of exposures in anticipated operational occurrences and accident conditions [2].

Subdividing the controlled area in terms of dose rate limits is an alternative to facilitate the management of radiological protection and control of occupational exposure, regarding decision making. The regulations of individual nations utilize distinct requirements based on their own dose rate limits, consistent with the criteria established by the IAEA.

In the context of Nuclear Power Plants (NPPs), the IAEA proposes specific procedures to be adopted for developing zoning based on anticipated dose rates, contamination levels, access requirements, and specific requirements such as the separation

of components performing safety functions. These dose rates may be calculated using either source terms derived from released radioactive material or, alternatively, data from operating experience at similar facilities, assuming insignificant changes in relevant design and operational parameters [3]. However, accurately determining these source terms presents challenges due to the complex modeling required for radioactive material behavior and interactions within the facility. Additionally, relying solely on operating experience data can be problematic due to variations in design and operational conditions. During the conceptual design phase of a nuclear facility, subdividing the controlled area assertively becomes difficult, as many aspects impacting the dose remain undefined.

This work addresses the possibility of subdividing a controlled area based in facilities at the conceptual design phase, on criteria adopted by several nuclear facilities and predicted dose rates resulting from preliminary accident analysis. It aims to assist in the development of the preliminary radiological protection plan. Considering that optimizing radiation exposure for workers, the public, and the environment is essential (consistent with the ALARA principle specified in Recommendation 103 of the International Commission on Radiological Protection [4]), this approach seeks to balance safety and operational requirements.

2. MATERIALS AND METHODS

Nuclear facilities operate within a complex web of regulations, shaped by the unique sociocultural, technological, and administrative contexts of each nation. The classification of areas as controlled or supervised directly impacts worker safety, public health, and environmental protection. Understanding the relationship between national regulations and radiological protection is essential for maintaining safe and efficient nuclear operations.

The following subsections highlight specific aspects related to dose limits for classifying areas, applicable in distinct locations.

2.1. Radiation area classification

This work focuses on the radiological classification of areas based on the expected dose rates for workers, excluding the specific issues related to young people (16~18 years), women, pregnant women, and contamination. It also assumes a reference value of 2,000 hours per year for the exposure time of workers. The dose limits and criteria adopted by different countries for classifying areas are reviewed in the following subsections.

2.1.1. Brazil

In Brazil, the radiological classification of areas is regulated by the National Nuclear Energy Commission (CNEN) and is structured into three categories: Controlled Area, Supervised Area, and Free Area. According to the CNEN NN 3.01 standard, a Controlled Area is defined as one where the design anticipates annual effective doses for occupationally exposed individuals to be equal to or greater than 6 mSv, whether under normal operating conditions, due to anticipated operational failures, or in accident situations. Workers subject to occupational exposure due to activities performed in supervised or controlled areas must be classified as occupationally exposed individuals, with a maximum annual effective dose limit of 20 mSv, averaged over 5 consecutive years, provided it does not exceed 50 mSv in any single year. Free areas are those where the dose rate and the risk of contamination by radioactive materials are sufficiently low, with an effective dose not exceeding 1 mSv per year. Under normal operating conditions, this ensures that the level of radiological protection and safety required for workers is comparable to that required for the members of public [5].

The Central Nuclear Almirante Álvaro Alberto (CNAAA) – Unit 2 (Angra 2) NPP in Brazil initially classified its radiological areas according to DIN 25440:1982 standard and CNEN NE 3.01:1988 [6], which at the time incorporate some influences from American classification systems due to the design of the first NPP in Brazil, CNAAA – Unit 1 (Angra 1), developed in partnership with Westinghouse Electric Company. This classification system

(**Table 1**) divided controlled areas into different classes (zones) based on maximum dose rates, reflecting the German engineering origins in this initial approach.

Table 1: Preliminary classification and dose rate limits of controlled area of Angra 2 NPP [6].

Description of area subdivision	Dose rate
Radiation area	≥ 7.5 μSv/h
High radiation area	≥ 1.0 mSv/h
Locked high radiation	≥ 10.0 mSv/h
Rooms without limited time of occupancy	≤ 10.0 μSv/h
Rooms and compartments with slightly limited time of occupancy	≤ 0.1 mSv/h
Compartments with limited time of occupancy	≤ 1.0 mSv/h
Rooms and compartments with substantially limited time of occupancy	> 1.0 mSv/h

The first three lines of **Table 1** refer to CNEN NE 3.01:1988, while the other four lines was based on DIN 25440:1982 standard. The expected local dose rate reference for CNEN NE 3.01:1988 considered measurements at 0.3 meters from any radiation source, whereas for DIN 25440:1982, considered measurements at 0.5 meters from the strongest radiation source in the room.

2.1.2. Japan

The regulatory framework in Japan for occupational radiation protection is established through a comprehensive set of regulations and guidelines designed to ensure the safety of workers exposed to radiation. This framework, which includes twelve acts related to the use of atomic energy, is primarily governed by the Industrial Safety and Health Act, under the authority of the Ministry of Health, Labour and Welfare (MHLW), focusing on radiation safety for workers. Additionally, the Act for Regulation of Nuclear Source Material, Nuclear Fuel Material, and Reactors, issued by the Nuclear Regulation Authority (NRA), ensures safety in the use of nuclear energy [7].

In the Regulation on Prevention of Ionizing Radiation Hazards [8], a Controlled Area is defined as an area where the combined effective dose from external radiation and airborne

radioactive materials is likely to exceed 1.3 mSv over every three month, or where the surface density of radioactive materials is likely to exceed one-tenth of the following limits: 4 Bq/cm² for alpha-emitting radioisotopes and 40 Bq/cm² for other radioisotopes. The exposure dose limit for radiation workers shall not exceed 100 mSv over five years or 50 mSv in any single year.

High Energy Accelerator Research Organization (KEK) is a research institution in Japan dedicated to high-energy physics, accelerator science, and related fields. Within KEK, the controlled areas are referred to as Radiation-Controlled Areas, which are typically enclosed by fences. Numerous monitors are installed inside these areas to measure radiation and radioactivity, ensuring that radiation levels do not exceed the established criteria for each controlled area [9], according to the **Table 2**.

Table 2: Dose rate limits criteria for Radiation-Controlled Areas in KEK, Japan [9].

Area	Description of area subdivision	External dose rate
Non-designated Area	---	≤ 0.2 μSv/h
Warning Area	---	≤ 1.5 μSv/h
Radiation-Controlled Area	General radiation area	≤ 20 μSv/h
Radiation-Controlled Area	Restricted area	≤ 100 mSv/h
Radiation-Controlled Area	Forbidden area	> 100 mSv/h

The access protocols in Radiation-Controlled Area in KEK [9] is:

- Forbidden Area: Entry is strictly prohibited except in emergencies, as determined by the Directors-General.
- Restricted Area: Access is allowed only for radiation workers who have obtained prior permission from the regional radiation safety officers.
- General Radiation Area: Radiation workers may enter freely due to low radiation levels; however, only those registered to work in this area are permitted for safety reasons.

- Warning Area: This area is fenced with locked entrances to exclude the members of public and non-radiation workers. Radiation workers can enter by borrowing a key, while members of public or non-radiation workers must report to the regional radiation safety office to gain access.

2.1.3. Republic of Korea

In Republic of Korea, nuclear safety is regulated by the Nuclear Safety and Security Commission (NSSC), with technical support provided by the Korea Institute of Nuclear Safety (KINS) [10]. Currently, in Korea, there are nuclear facilities, including 25 nuclear power plants (NPPs) in operation, 3 under construction, and 2 permanently shut down. Additionally, there are research and education reactors, nuclear fuel cycle facilities (such as fuel fabrication and spent fuel processing), radioactive waste management facilities for intermediate and low-level waste, and other radiation-using facilities [11, 12].

In Korean regulation, a Controlled Area is defined as a zone where radiation levels, airborne radioactive material concentration, or surface contamination may exceed limits of 400 μSv/week. Public access is restricted, and protective measures are required to prevent radiation exposure [13]. According to "Regulations on Technical Standards for Nuclear Reactor Facilities, Etc." [14], the dose limit is the maximum radiation exposure permitted, including both external and internal exposures. Radiation workers are limited to a maximum exposure of 100 mSv over five years or 50 mSv in any single year. A "year" refers to the radiation dose received between January 1 and December 31 of a given year, while "five years" denotes each five-year period beginning on January 1, 1998 [15].

Initially, the Controlled Area of NPPs in Korea was divided into a few subdivisions, with no designated supervised areas, and one general area (not part of the Controlled Area). Today, the dose rate limit for the general area used in NPPs in Korea is set at 1 μSv/h. However, as newer plants are brought online, additional subdivisions have been introduced to enhance safety and more effectively manage radiation exposure [16].

Given that two NPPs in Korea are about to be decommissioned and the current criteria for controlled areas in decommissioning are the same as those during normal operation, a subdivision of the controlled area has been proposed using a new methodology to address the specific exposure risks faced by workers involved in decommissioning activities. This ensures that occupational exposure is kept as low as achievable while considering potential exposure routes [17]. One example of a draft of decommissioning radiation-controlled areas proposed in the final decommissioning plan for Kori Unit 1 NPP in Korea as shown in Table 3.

Table 3: Draft of decommissioning radiation-controlled areas proposed in the final decommissioning plan for Kori Unit 1 NPP in Korea [17].

Description of area subdivision	Dose rate limits
Unlimited access	< 5 μSv/year
General access	< 25 μSv/year
Controlled access (4h/week)	< 0.25 mSv/year
Controlled access (1h/week)	< 1 mSv/year
Limited access	> 1 mSv/year

2.1.4. United Kingdom

In the United Kingdom, "The Ionising Radiations Regulations 2017" (IRR17) [18] establishes classifications for radiological areas based on potential radiation dose levels to ensure the protection of workers and the public from ionizing radiation. These classifications determine the control measures required to limit radiation exposure within distinct parts of a workplace where ionizing radiation is present. Compliance with IRR17 is enforced by the Health and Safety Executive (HSE) [19]. Employers must ensure that they meet all regulatory requirements, including the proper classification of radiological areas, to avoid penalties and ensure the safety of workers and the public.

According to IRR17 and HSE, an area is classified as a Controlled Area if any individual working in the area could receive a radiation dose exceeding 6 mSv per year, which

is three-tenths of the annual dose limit for radiation workers (20 mSv/year). It is also classified as controlled if the dose rate in the area exceeds 7.5 μSv per hour, which could lead to significant exposure over time. An area is classified as a Supervised Area if the potential dose could exceed 1 mSv per year but is unlikely to exceed 6 mSv per year, which is below the threshold for Controlled Areas but still requires oversight. Supervised Areas are also identified if the dose rate is above 2.5 μSv per hour but does not exceed 7.5 μSv per hour, as shown in **Table 4**.

Table 4: U.K. regulation for classified area [18, 19].

Area	Effective dose	Dose rate
Non designated	< 1mSv/year	< 2.5 μSv/h (working day)
Supervised	< 6 mSv/year	< 7.5 μSv/h (working day)
Controlled	< 20 mSv/year (1)	> 7.5 μSv/h (working day)

(1) Arithmetic mean over 5 consecutive years, if it does not exceed 50 mSv in any year.

Beyond the compliance with IRR17, The Office for Nuclear Regulation (ONR), Environment Agency and Natural Resources Wales (NRW) regulate any new NPPs built in Great Britain through a process called Generic Design Assessment (GDA). The GDA is an assessment designed to evaluate the safety, security, and environmental aspects of a NPP design before it is constructed. In the GDA process, dose rate limits can be set more conservatively depending on the specific design and safety considerations of the nuclear plant under assessment.

For the classification of radiological areas at the UK HPR1000 GDA, international recommendations, EURATOM directives [20], and relevant national legislation were adhered to. This classification includes 13 subdivisions within the controlled area, categorized according to dose rate [21], as shown in Table 5.

Table 5: Classification of radiation area for UK HPR1000 GDA [21].

Area	Description of area subdivision	Zoning	Classification	Dose rate
Undesignated	---	---	---	≤ 0.5 μSv/h
Supervised	---	White zone	---	≤ 2.5 μSv/h
Controlled	Conventional working area	Green zone	A	≤ 10.0 μSv/h
Controlled	Intermittent working area	Yellow zone	2.5A	≤ 25.0 μSv/h
Controlled	Intermittent working area	Yellow zone	B	≤ 0.1mSv/h
Controlled	Intermittent working area	Yellow zone	2B	≤ 0.2mSv/h
Controlled	Intermittent working area	Yellow zone	C	≤ 1.0 mSv/h
Controlled	High radiation area	Orange zone	2C	≤ 2.0 mSv/h
Controlled	High radiation area	Orange zone	D	≤ 10.0 mSv/h
Controlled	High radiation area	Orange zone	3D	≤ 30.0 mSv/h
Controlled	High radiation area	Orange zone	E	≤ 100.0 mSv/h
Controlled	Extremely high radiation area	Red zone	3E	≤ 300.0 mSv/h
Controlled	Extremely high radiation area	Red zone	F	≤ 1.0 Sv/h
Controlled	Extremely high radiation area	Red zone	3F	≤ 3.0 Gy/h
Controlled	Extremely high radiation area	Red zone	G	> 3.0 Gy/h

In the Undesignated Area, the annual dose of workers does not exceed 1 mSv and the effective dose rate is lower than 0.5 μSv/h. In the Supervised Area, individuals may receive an effective dose exceeding 1 mSv a year, but not exceeding 5 mSv a year, and the effective dose rate is lower than 2.5 μSv/h. Instead of special protection measures or safety measures, periodic supervision and evaluation of occupational radiation exposure conditions are needed. In the Controlled Area, individuals are likely to receive an effective dose greater than 5 mSv a year and the effective dose rate is higher than 2.5 μSv/h. Special protection measures or safety measures are needed in this area. This area requires special protective measures to manage exposure, prevent radioactive contamination, and minimize radiation doses to workers from both external sources and inhaled or ingested materials.

The limitation of quarterly working time in the White Zone is 500 hours. During the operational phase, the operator will conduct periodic monitoring within the supervised area to ensure that radiation levels remain below 2.5 μSv/h. In the Green Zone, the limitation of

weekly working time is 40 hours while in the Yellow Zone, the limitation of working time is less than 4 hours a week. Localized protection measures such as signage and local barriers or temporary shielding around dose rate hotspots on pipes or equipment will be used within yellow zones to minimize dose uptake. The access and stay time in the Orange Zone will be strictly controlled. Appropriate assessment and work control procedures will be used to authorize entry and control time spent by workers in these areas. Access to the Red Zone is usually forbidden, however, in special case, exclusive access permission and license by the personnel in charge of units must be needed to authorize entry into the Red Zone. The access and the stay provisions for the orange zone are also applied to Red Zone, but with much less exposure time and more careful preparations for each operation [21].

Radiation classification of compartments is carried out to enhance radiation protection design and is more detailed than general radiation zoning. This method provides guidelines and operational schemes for various compartments, covering a wide range of dose rates. It also facilitates communication among different organizations involved in project design.

The compartment classification uses a letter-digit coding system. The letter indicates the order of magnitude of the dose rate, with each letter representing a dose rate ten times higher than the previous one. For instance, 'A' corresponds to dose rates not exceeding 10 μSv/h. The digit preceding the letter denotes the dose rate multiplier for that magnitude; for example, '2B' indicates a dose rate limit of 0.2 mSv/h. Areas with dose rates exceeding 3 Gy/h are designated with the letter 'G.' Designers can further specify classifications as needed [21].

2.1.5. United States of America

The Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) are the two main federal agencies in the United States that regulate radiation protection and area classifications at nuclear facilities. While both agencies share similar goals in ensuring safety and radiation protection, their area classifications and associated dose limits differ based on the types of facilities under their jurisdiction and their specific

regulatory frameworks. The NRC regulates civilian use of radioactive materials, including commercial NPPs, medical applications, and industrial uses, with area classifications defined in 10 CFR Part 20 [22], additional NRC directives and guidance documents. The DOE oversees government-owned facilities, including national laboratories, nuclear weapons production sites and non-reactor nuclear facilities, with its own classification system detailed in 10 CFR Part 835 [23], DOE O 458.1 [24], and other directives.

Both NRC and DOE regulations set the maximum permissible effective dose for occupational exposure at 50 mSv/year (5 rem/year) to protect radiation workers and 1 mSv/year (100 mrem/year) to member of public from potential health risks associated with radiation exposure. According to NRC [23], "radiological area" (or "restricted area" in a similar context according to the DOE [24]) refers to any area within a Controlled Area that is classified as a "radiation area", "high radiation area", "very high radiation area", "contamination area", "high contamination area", or "airborne radioactivity area" as shown in Table 6.

Table 6: US regulation for classified area [23, 24] [(1)].

Area	Area subdivision (zones)	Dose rate
Controlled	Radiation area	> 50 μSv/h at 30 cm
Controlled	High radiation area	> 1 mSv/h at 30 cm
Controlled	Very high radiation area	> 5 Gy/h at 100 cm

[(1)] Is not included areas related to surface and airborne contamination.

While both the NRC and DOE provide general regulations regarding radiation protection and area classifications, specific definitions such as "Locked High Radiation Area" and "Locked Very High Radiation Area" are often detailed in the plant's Technical Specifications [25]. These specifications provide more context on the classifications and the procedures associated with access control in high radiation areas and very high radiation areas, respectively. The NRC acknowledges that the requirement to lock all "High Radiation Areas" can be excessively challenging. Therefore, the NRC has provided provisions for licensees to

seek "alternative methods" for controlling "High Radiation Areas" (according to 10 CFR 20.1601(c) [22]. Most United States power reactor licensees have integrated this provision into their Technical Specifications, which are comprehensive licensing documents detailing the necessary conditions for operation, administrative controls, and surveillance requirements [26].

2.1.6. Other facilities

CERN (European Organization for Nuclear Research) operates as an intergovernmental institution situated on the border of France and Switzerland. It is renowned for its state-of-the-art research in particle physics and plays a crucial role in advancing our understanding of the universe. To ensure the safety of its workers, researchers, visitors, and the environment, CERN has established a comprehensive framework for radiological protection, which is guided by a tripartite agreement among France, Switzerland, and the European Union.

The policies of the radiological protection of CERN are built upon European and international standards, as well as directives from both countries. The organization has developed its own internal regulations to effectively address the unique challenges posed by its complex scientific facilities, such as the Large Hadron Collider (LHC) [27].

In addition to regulatory considerations, CERN faces the complexity of its facilities and the need for a certain degree of freedom to conduct its experimental programs and research activities. This implies an area classification, whose conceptual approach meets the needs of activities in a safe and environmentally correct way. The classification of controlled areas is defined based on permanent workplaces (assuming a 2,000-hour working year) and low-occupancy areas (locations where individuals spend less than 20% of their working time) [28]. The Controlled Area is subdivided into 4 areas: "Simple Controlled Radiation Area", "Limited-stay Controlled Radiation Area", "High Radiation Controlled Radiation Area" and "Prohibited Controlled Radiation Area", where dose rates can exceed 100 mSv/h, with no admission allowed into this area, as shown in **Table 7**. In practice, the dose rate limit for

each area is defined depending on the level of occupancy, ensuring that exposure remains within safe limits according to the specific conditions of each area.

Table 7: Area classification of CERN (external exposition) [29, 30] [(1)].

Area	Area subdivision (zones)	Effective dose [(2)]	Dose rate (permanent workplaces)	Dose rate (low-occupancy areas)
Non-designated	---	< 1 mSv/year	< 0.5 μSv/h	< 2.5 μSv/h
Supervised	---	< 6 mSv/year	< 3 μSv/h	< 15 μSv/h
Controlled	Simple Controlled Radiation Area	< 20 mSv/year	< 10 μSv/h	< 50 μSv/h
Controlled	Limited-stay Controlled Radiation Area	< 20 mSv/year	---	< 2 mSv/h
Controlled	High Radiation Controlled Radiation Area	< 20 mSv/year	---	< 100 mSv/h
Controlled	Prohibited Controlled Radiation Area	< 20 mSv/year	---	> 100 mSv/h

[(1)] Is not included areas related to surface and airborne contamination.
[(2)] Consecutive 12 months period.

3. RESULTS AND DISCUSSIONS

Based on the prior radiological evaluation, it has been determined that facility workplaces involving radiation exposure should be classified as at least a supervised or controlled area, as appropriate. This classification aligns with the standard practice of ensuring radiological safety and optimizing occupational exposure to radiation hazards. The establishment of these areas necessitates a comprehensive approach that incorporates expected operational judgment and the cumulative experience from similar facilities.

The classification of radiological areas within nuclear facilities should be based on a comprehensive evaluation of relevant legislative and regulatory requirements. This involves a detailed review of national and international standards that govern radiological protection, as well as the specific design criteria necessary to meet these standards. The evaluation

extends to all aspects of facility design, including civil engineering, architecture, mechanical systems, and electrical infrastructure, all of which play critical roles in ensuring adequate shielding and containment of radiation sources. Additionally, operational and occupational aspects related to dose rates, as well as the criteria used in different types of nuclear facilities, should also be considered.

During the conceptual design phase of a nuclear facility, to minimize the impact of controlled area subdivision due to uncertainties, it can be advantageous to analyze the feasibility of applying criteria already established in similar nuclear facilities. This approach allows for leveraging existing knowledge and practices to reduce risks and ensure that the design meets safety standards effectively. However, the use of the facility similarity criterion may not be plausible when there are no analogous facilities to reference. An example is a military base for nuclear ships, where project information is not publicly available due to the sensitive and classified nature of the work. Therefore, in a nuclear facility project with no similar ones in the conceptual phase, it becomes challenging to apply standard criteria, requiring the development of customized approaches to ensure radiological safety and compliance with regulatory standards.

In the conceptual phase of a nuclear facility, regarding predicted dose calculations, it is possible to estimate the dose by evaluating the modeling of an unmitigated accident scenario defined as a bounding accident with the assumption of the worst-case dose consequence. For nonreactor nuclear facilities, DOE-STD-3009-2014 [31] provides guidance for assessing such accidents, while NUREG-1935 [32] offers similar guidance for reactor facilities.

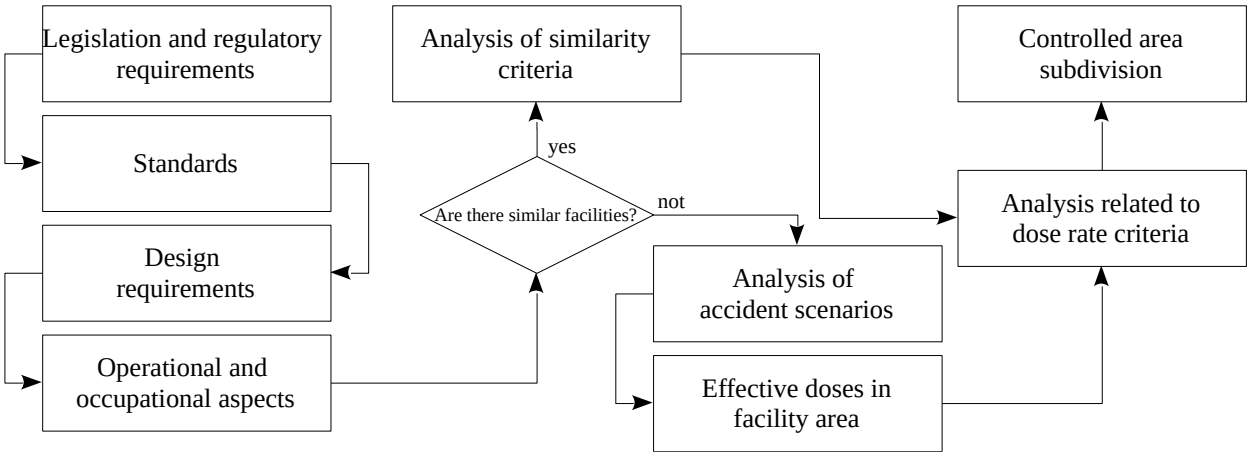
Since accident analysis is performed after hazard analysis, the modeling of the unmitigated accident scenario and the calculation of consequences are conducted according to the following summarized steps:

1. Initial conditions: Details of the parameters preceding the accident.

2. Initiating events: Premises regarding the event that triggers the accident.
3. Inventory of fission products (source term): Identification and quantification of the radioactive materials involved.
4. Radioactive materials release: Estimation of the release rate of each radionuclide into the environment during the accident.
5. Consequences for workers and the public: Assessment of dose values to quantify the impact on both workers and the public.

Based on the total dose, the result of this unmitigated accident analysis, and the outcomes of other accident scenarios from preliminary hazard analyses, it will be possible to map the areas of the facility in terms of potential doses. With all predicted dose ranges, the controlled areas can be subdivided according to the need for appropriate controls based on predicted exposure time. In view of this, the methodology encompassing all the items addressed are shown in **Figure 1**.

Figure 1: Flowchart of the methodology adopted for the subdivision of the controlled area.



Source: Authors.

The design characteristics considered relevant for radiological protection shall be systematically evaluated during the design, construction, and operation phases of the facility. Such characteristics include the sizing of the physical space of work areas, access controls,

radiation shielding, equipment arrangements, radiation alarm systems, monitoring and control of effluents and location of pipes, penetrations and radiation area [33].

It was verified that much of the legislation, regulations, and standards concerning nuclear facilities are primarily based on those for power plants, where the operational environment and radiological risks are well understood and extensively documented. As a result, public information regarding the classification of radiological areas within nuclear facilities is derived from these types of facilities.

The subdivision of controlled areas by similarity becomes particularly challenging when there are no comparable facilities to reference. In these cases, it is essential to adopt a flexible yet rigorous approach, where the classification is determined based on the predicted radiological consequences, particularly the dose consequences arising from the source term. This ensures that even in the absence of direct analogs, the facility design can still achieve a high standard of radiological safety. The methodology presented in figure 1 provides a structured approach for this classification, enabling a tailored application that reflects the safety operational and environmental conditions of the facility during the conceptual design phase.

4. CONCLUSIONS

The methodology presented is well-suited for classifying radiological zones in nuclear facilities that lack direct references during the conceptual design phase, such as naval bases supporting nuclear ships. By focusing on the consequences of potential doses arising from the source term, this approach provides a systematic and adaptable framework for ensuring radiological safety. It allows for the effective design and subdivision of controlled areas even in the absence of analogous facilities, ensuring that safety standards are met and that appropriate controls are implemented to protect both workers and the public.

ACKNOWLEDGMENT

Authors would like to acknowledge the Diretoria de Desenvolvimento Nuclear da Marinha (DDNM), Coordenadoria-Geral do Programa de Desenvolvimento de Submarino com Propulsão Nuclear (COGESN), Amazônia Azul Tecnologias de Defesa S.A. (AMAZUL), and the Fundação para o Desenvolvimento Tecnológico da Engenharia (FDTE).

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY. **Occupational radiation protection.** Vienna: International Atomic Energy Agency, 2018. (IAEA Safety Standards Series, ISSN 1020–525X, no. GSG-7). ISBN 978–92–0–102917–1.

[2] INTERNATIONAL ATOMIC ENERGY AGENCY. **Radiation protection and safety of radiation sources: international basic safety standards.** Vienna: International Atomic Energy Agency, 2014. (IAEA Safety Standards Series, ISSN 1020–525X, no. GSR Part 3). ISBN 978–92–0–135310–8.

[3] INTERNATIONAL ATOMIC ENERGY AGENCY. **Radiation protection aspects of design for nuclear power plants.** Vienna: International Atomic Energy Agency, 2005. (IAEA Safety Standards Series, ISSN 1020–525X, no. NS-G-1.13). ISBN 92–0–107905–2.

[4] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. **The 2007 Recommendations of the International Commission on Radiological Protection.** Annals of the ICRP (ICRP publication 103). Elsevier Ltd., 2007. ISBN 978-0-7020-3048-2.

[5] COMISSÃO NACIONAL DE ENERGIA NUCLEAR. **CNEN NN 3.01**: Requisitos básicos de radioproteção e segurança radiológica de fontes de radiação. Rio de Janeiro: CNEN, 2024.

[6] ELETRONUCLEAR - Eletrobrás Termonuclear S.A. **Final Safety Report - Central Nuclear Almirante Álvaro Alberto - Unit 2.** Rev. 8. MA/2-0809.2/120000. Rio de Janeiro: ELETRONUCLEAR, 2004.

[7] WAKABAYASHI, G.; YAMADA, T.; ENDO, T.; PYEON C. H. **Introduction to Nuclear Reactor Experiments.** Singapore: Springer, 2023. ISBN 978-981-19-6588-3. DOI 10.1007/978-981-19-6589-0.

[8] JAPAN. Ministry of Labour. **Order No. 41 of September 30, 1972.** Regulation on Prevention of Ionizing Radiation Hazards. Tokyo: Ministry of Labour. Available at: https://www.japaneselawtranslation.go.jp/en/laws/view/2865/en. Access in: July, 2024.

[9] HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION (KEK). **Study Guide for Radiation Safety.** 2nd edition. Ibaraki, Japan: Radiation Science Center, 2022.

[10] REPUBLIC OF KOREA. Nuclear Safety and Security Commission. **Act No. 10917 of Jul. 25, 2011.** Korea Institute of Nuclear Safety Act. Daejeon: NSSC, 2011. Available at: https://www.nssc.go.kr/attach/namo/files/000001/20191206163855453_AJ1BR70Z.pdf. Access in: July 2024.

[11] INTERNATIONAL ATOMIC ENERGY AGENCY. **Country Nuclear Power Profiles.** Non-serial Publications. Vienna: INTERNATIONAL ATOMIC ENERGY AGENCY, 2014. Available at: https://www-pub.iaea.org/MTCD/Publications/PDF/cnpp2022/countryprofiles/KoreaRepublicof/KoreaRepublicof.htm. Access in: July, 2024.

[12] SONG, C.; KONG, T. Y.; KIM, S.; SON, J.; KIM, H.; KIM, J.; KIM, H. G. Classification of Radiation Work in Korean Nuclear Power Plants. **Journal of Radiation Industry**. v. 17, n. 3, p. 239-256, 2023. DOI: https://doi.org/10.23042/ radin.2023.17.3.239.

[13] REPUBLIC OF KOREA. Nuclear Safety and Security Commission. **Act No. 13078 of Jan. 20, 2015.** Nuclear Safety Act. Seoul: NSSC, 2015. Available at: https://www.nssc.go.kr/attach/namo/files/000001/20191206162603834_RZ5ZOK9L.pdf. Access in: July, 2024.

[14] REPUBLIC OF KOREA. Nuclear Safety and Security Commission. **Regulation of the Nuclear Safety and Security Commission No.4 of Nov. 11, 2011.** Regulations on

Technical Standards for Radiation Safety Control, Etc. Daejeon: NSSC, 2011. Available at: https://www.nssc.go.kr/attach/namo/files/000001/20200131180700377_KZTENAAJ.pdf. Access in: July, 2024.

[15] REPUBLIC OF KOREA. Nuclear Safety and Security Commission. **Enforcement Decree of the Nuclear Safety Act. Presidential Decree No. 33658 of Aug. 01, 2023.** (in Korean) Nuclear Safety Act. Seoul: NSSC, 2023.

[16] KIM, Y. Review on radiation area zoning of NPPs in Korea. *In:* 2018 ISOE International Symposium, 2018, Tokyo, Japan. Tokyo: Korea Institute of Nuclear Safety (KINS), 2018.

[17] KIM, S.; KONG, T. Y.; CHOI, W. S.; SON, J.; KIM, H.; SONG, C.; KIM, J.; YANG, K. T.; SONG, J. S.; KIM, H. G. A methodology to designate radiation-controlled areas in decommissioning nuclear power plants. Energy Science & Engineering. v. 11, p. 3204-3214, 2023. DOI: https://doi.org/10.1002/ese3.1514.

[18] UNITED KINGDOM. United Kingdom Legislation. **UK Statutory Instruments 2017 No. 1075 of Nov. 27, 2017.** Health and Safety – The ionising radiations regulations 2017. London: United Kingdom Parliament, 2017. Available at: https://www.legislation.gov.uk/uksi/2017/1075/pdfs/uksi_20171075_en.pdf. Access in: July, 2024.

[19] HEALTH AND SAFETY EXECUTIVE. **Working with ionising radiation, Approved Code of Practice and guidance.** L121, 2nd Edition, Norwich: TSO, 2018. ISBN 978–0–7176-6662–1.

[20] EUROPEAN AGENCY FOR SAFETY AND HEALTH AT WORK. **Directive 2013/59/Euratom.** Protection against ionising radiation. Luxembourg: Official Journal of the European Union, 2019.

[21] GENERAL NUCLEAR SYSTEM LTD. **UK HPR1000 GDA Project.** Radiological Protection. Preliminary Safety Report, Chapter 22, Rev. 0. UK: General Nuclear System Ltd., 2017.

[22] UNITED STATES OF AMERICA. U.S. Federal Register. **Code of Federal Regulations (CFR), Title 10, Chapter I, Part 20, Subpart A.** Standards for protection against radiation. Washington D.C.: U.S. Federal Register, 1991. Available at: https://www.ecfr.gov/current/title-10/chapter-I/part-20. Access in: July 2024.

[23] UNITED STATES OF AMERICA. U.S. Federal Register. **Code of Federal Regulations (CFR), Title 10, Chapter III, Part 835, Subpart A.** Standards for

protection against radiation. Washington D.C.: U.S. Federal Register, 1993. Available at: https://www.ecfr.gov/current/title-10/chapter-III/part-835/subpart-A. Access in: July 2024.

[24] U.S. DEPARTMENT OF ENERGY. **DOE O 458.1, Chg 4.** Radiation protection of the public and the environment. Washington D.C.: DOE, 2020.

[25] PRINCE, R. **Radiation Protection at Light Water Reactors.** Heidelberg: Springer, 2012. e-ISBN: 978-3-642-28388-8. DOI: 10.1007/978-3-642-28388-8.

[26] SILLS, J. M. U.S. Lessons Learned Initiative for Locked High Radiation Areas. *In:* 2006 ISOE International ALARA Symposium, 2006, Essen, Germany. Essen: San Onofre NPP, 2006.

[27] FORKEL-WIRTH, D.; CARBONEZ, P.; GOEHRING-CRINON, A.; PERRIN, D.; ROESLER, S.; VINCKE, L.; ULRICI, L. Radiation protection aspects. *In:* Proceedings of Chamonix 2014 Workshop on LHC Performance, 2. Geneva: CERN, 2014. p. 276-280.

[28] BRUGGER, M.; FORKEL-WIRTH, D.; MENZEL, H. G.; ROESLER, S. Radiation protection constraints during the first stages of the LHC, *In:* 3rd LHC Project Workshop: 15th Chamonix Workshop, Geneva: CERN, 2006. p. 66-73.

[29] CERN. **Safety Code**. rev. F, Geneva: CERN, 2006.

[30] CERN. **Safety Signs**. Safety Guideline SG-SH-0-0-2, EDMS 2492550, Ver. 1.2, Geneva: CERN, 2021.

[31] U.S. DEPARTMENT OF ENERGY. D**OE-STD-3009-2014.** Preparation of Nonreactor Nuclear Facility Documented Safety Analysis. Washington D.C.: DOE, 2014.

[32] U.S. NUCLEAR REGULATORY RESEARCH. **NUREG-1935**. State-of-the-Art Reactor Consequence Analyses (SOARCA) Report. Washington D.C.: NRC, 2012.

[33] U.S. DEPARTMENT OF ENERGY. **DOE-HDBK-1132-99.** Design Considerations. Washington D.C.: DOE, 2014.

LICENSE