Discharge of radioactive effluents into the environment: use case for the Joint Research Centre of Ispra

LESSONS LEARNED REPORT

KP-JRC-007

20/03/2023

Foreword

In 2021, the European Commission (EC) adopted a new proposal for a Council Regulation[1] establishing a dedicated financial programme for decommissioning nuclear facilities and managing Radioactive Waste (RAW). This instrument covers the co-funding of the decommissioning programmes of Bulgaria, Slovakia, and the decommissioning of the Joint Research Centre (JRC). A separate Council Regulation[2] was adopted for the decommissioning programme of Lithuania.

The EC JRC is mandated to foster the spread of decommissioning knowledge across all the European Union Member States and facilitate knowledge sharing arising from implementing the abovementioned decommissioning programmes, funded by the Nuclear Decommissioning Assistance Programme (NDAP).

The decommissioning operators from the NDAP (NDAP Operators) implemented and tested a knowledge management methodology in 2021 through Project ENER/D2/2020-273. Using this methodology, the NDAP Operators can develop Knowledge Products that are currently available to share with other European stakeholders. In addition, this methodology is under implementation in the JRC Nuclear Decommissioning and Waste Management Directorate (NDWMD), which becomes a knowledge generator extracting the knowledge from the ongoing decommissioning activities at the different sites (Geel, Ispra, Karlsruhe, and Petten).

The JRC NDWMD aims to become a Centre of Excellence in nuclear decommissioning knowledge management and develop a decommissioning knowledge platform which allows exchanging information and building on the best practices in the EU inside the multi-annual financial framework (2021 – 2027) strategy. The operational phase of the project is expected to start in 2024 to develop ties and exchanges among EU stakeholders and document explicit knowledge and make it available through multi-lateral knowledge transfers on decommissioning and waste management governance issues, managerial best practices, technological challenges, and decommissioning processes at both operational and organisational level, to develop potential EU synergies.

This is a Knowledge Product prepared by the Nuclear Decommissioning and Waste Management Directorate (NDWMD) – Directorate J of the Joint Research Centre.

Document code	KP-JRC-007		
Performed by	G. MAGROTTI, G. IURLARO, F. GUELI, M. CECCHINI, G. MERLA, C.TINÈ		
Revised by	Nuclear Decommissioning Knowledge Management Team		
Version	V0	09/12/2023	Initial version
	V1	17/01/2024	Reviewed version
	V2	20/03/2024	Final version
Sent to	Andrea PIAGENTINI		
Approved by	Andrea PIAGENTINI		

[1] Council Regulation (Euratom) 2021/100 of 25 January 2021 establishing a dedicated financial programme for the decommissioning of nuclear facilities and the management of RAW, and repealing Regulation (Euratom) No 1368/2013

[2] Council Regulation (EU) 2021/101 of 25 January 2021 establishing the nuclear decommissioning assistance programme of the Ignalina nuclear power plant in Lithuania and repealing Regulation (EU) No 1369/2013

PRODUCT DESCRIPTION

The present report has been prepared by the Radiation Protection Experts team from Directorate J - Nuclear Decommissioning and Waste Management at the Joint Research Centre site of Ispra (JRC-Ispra) in Italy. The guidance and recommendations of this product are collected from the experience gained during the study and the implementation of the methodology used to revise the radioactive effluent discharge formula for JRC-Ispra nuclear installations considering the regulatory requirements and forthcoming decommissioning activities.

The lessons learned presented in this report aim to assist Operating Organisations and professional staff in defining a proper discharge formula in accordance with regulatory discharge limits.

This product was developed as part of an effort to disseminate and share with all EU State Members the knowledge acquired during the decommissioning and radioactive waste management activities performed with NDAP funding under the Council Regulation (Euratom) 2021/100 of 25 January 2021.

ABSTRACT

The Joint Research Centre (JRC-Ispra) operates nuclear facilities and installations as part of the research and decommissioning activities carried out by the European Commission. The present report provides the methodology applied at the JRC-Ispra to define the new discharge formula for liquid and airborne effluents in accordance with the current Italian legislative framework on radiation protection (i.e., Legislative Decree no. 101/2020 [1]) implementing the Council Directive 2013/59/Euratom.

The methodology used to define the new discharge formula relies on the identification of authorised discharge points, the radionuclides involved, and the pathways of exposure to the representative individual of the population, limiting the effective dose to a value of 10 μSv/year in compliance with the criterion of radiological non-relevance.

Based on the same methodology, preventive assessments of radiological impact and effective dose for workers within the JRC-Ispra area have also been carried out. The result of this study allowed the definition of discharge activity limits for each type of effluent, and each considered radionuclide, depending on the different facilities and installations present on the site. In addition, specific formulas applicable for periods of time shorter than the calendar year have been implemented to monitor the temporal evolution of the discharges recorded during the year, as required by the operating licences of the nuclear installations.

This work presents the comparison between the new discharge formula and the one previously in force, which resulted from a constantly evolving dispersion and exposure model, always aimed at protecting the environment, the population, and the workers.

OBJECTIVE

To establish a systematic approach for determining discharge formulas of airborne and liquid radioactive effluents in the environment, enabling the calculation of dischargeable activity limits at a site housing multiple nuclear plants and installations, including facilities for radioactive waste management and radiometric laboratories.

APPROACH

In the development of this guide, the team of experts incorporated the experiences and lessons learned from the methodology developed for calculating a discharge formula for facilities at the JRC- Ispra site in Italy. They also incorporated the requirements of the Regulator for compliance with the pertinent dose constraints.

RESULTS, FINDINGS, AND INSIGHTS

This document provides guidance for establishing the radioactivity limits of the effluents that can be discharged to air and water for nuclear plants and/or installations on a site. The evaluation protocol of the radioactive effluents discharged into the environment includes objectives of dose constraints to the population, criteria for the investigation of the environment around the site (environmental network) and the release limits. Considerations that should be included in the decision protocol are:

- Source term representative of each nuclear facility and installation.
- Model for estimating the dispersion of radionuclides in the air, in surface water and the transfer in the food chain.
- Exposure pathways for dose assessment to the representative person.
- Identification of the representative person for potential exposure.
- Assessment of the dose to the representative person.
- Comparison of estimated doses with criteria.

TARGET USERS

The objective of this document is to provide governments, regulatory bodies, applicants and operating organisations with a structured approach to controlling radiation exposures of the public resulting from discharges from normal operations of facilities and activities and for the optimisation of protection and safety. Guidance is provided on authorisations for discharges, demonstrating compliance with the authorisation and enforcing the authorisation.

This document is for use by those applying for an authorisation for discharges to the environment and by those reviewing applications and authorising discharges as part of an authorisation process.

It may also be relevant for other interested parties, in particular: Operating Organisations embarking on the decommissioning of their installations that need to review the discharge formula in the transition from operation to decommissioning, Operating Facilities for the management of radioactive effluents; Radiation Protection Experts and/or Engineers tasked with the evaluation of the dose to the population.

KEYWORDS

NUCLEAR DECOMMISSIONING, ENVIRONMENT, DISCHARGE FORMULA, DOSE CALCULATIONS, DOSE CONSTRAINTS, DISMANTLING, WASTE MANAGEMENT.

TABLE OF CONTENTS

LIST OF ACRONYMS AND DEFINITIONS

ATM	Airborne Tritium Monitor
ESSOR	Essay Orgel nuclear research reactor
FRAMES	Framework for Risk Analysis in Multimedia Environmental Systems – U.S. EPA
GENII	Generalized Environmental Radiation Dosimetry Software System - Hanford Dosimetry System (Generation II) (designated toolbox software)
IAEA	International Atomic Energy Agency
INE	Isola Nucleare ESSOR, ESSOR Site
ISIN	National Inspectorate for Nuclear Safety and Radiation Protection (Italy)
JRC-Ispra	Joint Research Centre, European Commission, Site of Ispra (Italy)
NGM	Noble Gas Monitor
RAM	Radioactive Airborne particulate Monitor
STEL	Liquid effluents treatment station, authorised liquid release point

LIST OF FIGURES

LIST OF TABLES

1. BACKGROUND

Nuclear installations play a pivotal role in providing energy and various applications in fields such as medicine, research, and industry. However, as these facilities reach the end of their operational lifespan, the process of decommissioning becomes necessary. Decommissioning involves the safe and systematic dismantling of nuclear installations, which includes addressing the release of radioactive effluents. The establishment of a discharge formula is crucial in ensuring the responsible management of these effluents, protecting both human health and the environment. This product aims to explore the definition and significance of a discharge formula for nuclear installations in operation, under decommissioning or in the transition from operation to decommissioning.

A nuclear discharge formula refers to a set of guidelines, limits, and calculations used to regulate and control the release of radioactive effluents from nuclear facilities into the environment. It is a systematic approach that determines the allowed quantities and concentrations of radioactive materials that can be discharged, ensuring that the releases are within safe and acceptable limits. A nuclear discharge formula typically takes into account various factors, including the type of effluent (liquid or airborne), the radionuclides involved, the pathways of exposure (such as ingestion, inhalation, or external exposure), and the potential impact on human health and the environment.

The formula sets specific limits on the activity or concentration of radionuclides that can be discharged, typically expressed in terms of becquerels (Bq). These limits are established based on scientific knowledge, risk assessments, and regulatory requirements to ensure that the exposure to radiation from the discharged effluents remains within acceptable levels.

The formula may also include provisions for monitoring and reporting the effluent releases, establishing a framework for regular assessment and documentation of the discharged quantities and characteristics. This helps ensure transparency, accountability, and regulatory compliance. Having a nuclear discharge formula for a site is crucial for several reasons:

- **Protection of the environment:** nuclear facilities generate various types of effluents, such as liquid and airborne, which may contain radioactive substances. A discharge formula sets limits on the amount and concentration of these effluents that can be released into the environment. By defining these limits, the formula ensures that the discharge remains within safe levels and minimises the potential impact on ecosystems and natural resources.
- **Health and safety of the population:** the discharge formula takes into account the pathways of exposure to radiation for the representative person of the population. By setting the dose limit to a safe value, typically 10 μSv/year, the formula ensures that the radiation exposure to the public remains within acceptable levels. This helps protect the health and well-being of the nearby communities.
- **Compliance with regulations:** nuclear facilities are subject to strict regulations and legislative frameworks regarding radiation protection. A discharge formula ensures that the facility operates in compliance with these regulations. It provides a standardised approach for evaluating and controlling the release of radioactive effluents, helping the facility demonstrate its commitment to safety and regulatory compliance.
- **Monitoring and accountability:** the discharge formula is not just a set of limits but also includes a monitoring system. This system ensures that the discharge remains within the defined limits and facilitates regular monitoring and reporting of the effluents. It helps maintain transparency and accountability and provides an early warning system to detect any deviations from the established limits.

1.1. Description of the Challenge

The transition from operational to decommissioning nuclear discharge formula poses several challenges that need to be addressed. At the JRC-Ispra, in light of the forthcoming decommissioning activities, the Regulator (ISIN) asked for a revision of the previously authorised formula, thus entailing the following challenges:

- **Changing regulatory requirements:** the regulatory requirements for nuclear facilities may differ between the operational phase and the decommissioning phase. The discharge formula needs to be updated to align with the new regulatory framework specific to decommissioning activities. This may involve revising the limits, parameters, and monitoring requirements to ensure compliance with the evolving regulations.

- **Managing the evolution of the activities and the effluent composition:** during the operational phase, the focus of the discharge formula is primarily on managing and controlling the release of liquid and airborne effluents. The discharge formula needs to be expanded or re-evaluated in the decommissioning stage, taking into consideration the evolution of the dismantling activities, the radiological inventory or variation in the release point. These factors have to be addressed periodically together with the work progress.

- **Changing radionuclide inventory:** the radionuclide inventory in a nuclear facility can change during the decommissioning phase as different processes are carried out. Some radionuclides may decay over time, while others may be more relevant through the decommissioning activities. The discharge formula needs to account for these changes in the radionuclide inventory to ensure accurate assessments and control of effluent releases.

- **Long-term monitoring and surveillance:** decommissioning activities can span several years or even decades, requiring long-term monitoring and surveillance of effluent releases. The discharge formula needs to incorporate provisions for continuous monitoring, periodic evaluations, and reporting to ensure ongoing compliance with the established limits throughout the decommissioning process.

Addressing these challenges requires careful planning, collaboration between regulatory authorities and facility operators, and adherence to best practices and guidelines for decommissioning. It is crucial to ensure that the discharge formula remains robust, adaptable, and aligned with the changing requirements and conditions during the transition from operational to decommissioning phases.

1.2. Constraints

The main challenge related to the reformulation of the discharge formula concerned the requirement to comply with **Legislative Decree 101/2020 [1], which means respecting the limit of 10 μSv/year to the population**. This value is to be considered as a trivial dose within the Italian legal framework; it is worth noting that this constraint may vary in accordance with the regulatory requests and the applicable national legislation.

2. SCOPE

The primary objective of establishing a discharge formula is to safeguard human health and the environment from the potential hazards associated with radioactive effluents. By setting strict limits on the release of radionuclides, the formula ensures that exposure to radiation remains within acceptable levels, minimising the risk of adverse health effects for both the public and the personnel involved in the decommissioning process.

The development and implementation of a discharge formula involves a comprehensive evaluation of potential impacts and risks associated with radioactive effluents. This process encourages transparency and facilitates stakeholder engagement, allowing affected communities, local authorities, and relevant organisations to actively participate in the decision-making process. By considering different perspectives and concerns, the discharge formula can be optimised to strike a balance between the decommissioning activities and the well-being of the surrounding environment and communities.

By employing a well-defined methodology, the formula ensures that all relevant factors are considered and accounted for uniformly across different decommissioning projects. This consistency enables effective comparison and benchmarking of decommissioning activities, allowing for the development of best practices and continuous improvement in the industry.

3. USE CASE AT THE JRC-ISPRA

3.1. Authorisation Status of the Discharge Formula

The European Atomic Energy Community (EURATOM) was established with the signing of the EURATOM Treaty in Rome on March 25, 1957. One of the provisions of the treaty was the establishment of a Joint Research Centre (JRC) with various locations in member states to conduct high-level research and share its results.

The Ispra Centre was initially established by the National Committee for Nuclear Energy (CNEN) to house the first Italian research reactor, "Ispra-1," which became operational in March 1959 and was transferred to the European Community on March 1, 1961. In the following years, new experimental facilities and laboratories were built. The construction of the ESSOR experimental reactor began in 1962, and it became operational in 1968. During the same period, additional research laboratories (such as the Radiochemistry Laboratory and Hot Cells Laboratory) and installations for the management of radioactive waste were constructed. These facilities and installations, as part of their safe operational and storage activities, discharge radioactive effluents within the limits imposed by authorisation measures. These limits, known as discharge formulas, have been updated multiple times based on the operational conditions of the facilities and changes in regulatory guidelines.

The last defined discharge formula was included in the Technical Specifications attached to the ESSOR reactor's operating license in 1987, which encompassed the discharges from all the installations on the site. It outlined limits for airborne effluents containing specific radionuclides present in the operational facilities at that time, such as radioactive gases (I-131, H-3, Ar-41, and other gases) and gamma-emitting aerosols (excluding alpha emitters and beta emitters like Sr-90, Pb-210, etc.). It also included limits for the release of liquid effluents containing Ra-226, Ra-228, alpha emitters, Sr-90, P-32, beta-gamma emitters, and H-3 into the environment. The limits were defined for a one-year period (Bq/year), as well as for intermediate quarterly periods (Bq/quarter) and consecutive 24-hour periods (Bq/day).

Since the 1980s, the mission of the JRC has progressively expanded into new sectors, reducing its commitment to nuclear research and development. Many of the nuclear installations at the Ispra site have been gradually shut down and placed under safe storage (Ispra-1 in 1973 and ESSOR in 1983). In 1999, the European Commission initiated a Decommissioning & Waste Management Program (D&WM) for nuclear installations and waste management. According to this program, JRC-Ispra is required to submit decommissioning proposals for various installations on the site and manage the radioactive waste and nuclear materials resulting from past research activities and decommissioning.

In this context, in November 2020, JRC-Ispra received authorisation for a modification of the ESSOR Nuclear Installation (INE) to establish a temporary storage area for special fissile materials and irradiated fuel, known as the Transit Safe Area (TSA). This authorisation included the requirement to submit a new discharge formula proposal within three months, ensuring compliance with the current regulatory provisions (D. Lgs. 101/2020 [1]) by guaranteeing the limitation of the effective dose of 10 μSv/year to individuals of the population.

In February 2021, JRC-Ispra presented a "Proposal for the Modification of the ESSOR Nuclear Installation's Discharge Formula". The basis of the proposal was an in-depth study conducted in the early 2000s to characterise the climate, hydrology, and population surrounding the site. The conclusions of this study were reaffirmed in 2021 with the collection of recent meteorological and anthropic data.

According to this study, receptor points were defined at or near inhabited settlements within a radius of 6 km from JRC-Ispra. Larger urban centres and smaller locations of particular radiological relevance were included in the assessments through multiple points (Figure 1).

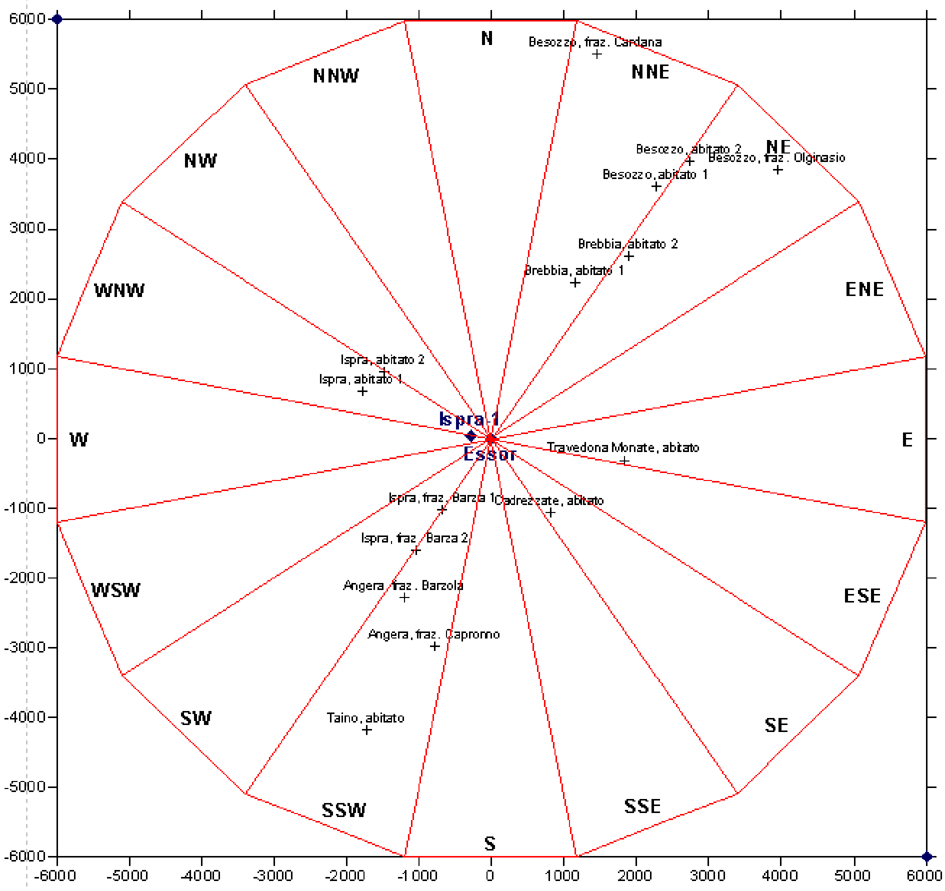

Figure 1 – Main settlements within 6000 m from the JRC-Ispra.

Although it is always possible to simulate the correlation between radioactivity in the environment, the food chain, and the dose to the population, it obviously loses its meaning if the population does not live in the environment under consideration, or if the population itself is not the endpoint of the food chain. The lifestyle and dietary habits of the representative person of the population have been conservatively treated as if the consumption of local products in the area around JRC-Ispra still persists today, even though this has drastically decreased with the massive increase in the distribution of food products. The radionuclides considered are those identified as being most present in the JRC-Ispra installations as a result of radiometric characterisation campaigns and which could be released in liquid or airborne form during decommissioning and waste management operations.

Following the examination of the proposal for a new discharge formula, the ISIN Inspectorate, while confirming the validity of the calculation model, has highlighted the **need to consider the non-exposed workers of JRC-Ispra as a group equivalent to the population**. These workers are present on the site only during working hours and are not exposed to all the pathways of exposure of the resident population, but they may be located at distances closer to the authorised discharge points. It has also requested an assessment of the radiological impact at the **points of maximum projected dose** from liquid and gaseous effluent discharges, regardless of the presence of population. This is to take into account that urban development and productive activities could result in the settlement of population groups in currently unoccupied areas during the time required to complete the JRC-Ispra decommissioning and waste management program.

Taking into account these observations, a revision of the "Proposal for the Modification of the ESSOR Nuclear Installation's Discharge Formula" was submitted in November 2021 to ensure compliance with the individual dose constraints at the receptor points identified with the FRAMES-GENII calculation code [2] and [3]. This proposal was approved with an ISIN opinion on April 20, 2022, and led to the definitive modification of the ESSOR discharge formula, including the other installations at the Ispra site, including the Ispra-1 reactor, whose license is under the competence of a different Operators. according to article 1, paragraph 538, of Law no. 205 of December 27, 2017, [4]. Compliance with the limits for discharges is ensured through the monitoring system established under the JRC-Ispra Environmental Surveillance Program.

3.2. General Setting of the Discharge Formula

In order to assess the impact of a given discharge to the environment, it is necessary to assess the dispersion and accumulation of the radionuclides in environmental materials. Given that authorisations are based on a prospective assessment, an environmental modelling approach is essential. Dispersion models allow the activity concentration of a radionuclide in the air or water medium, into which it is discharged, to be assessed as a function of time and distance from the source. Environmental transfer information may then be used to assess activity concentrations in other environmental media (e.g., sediment or food products) based on time-varying or equilibrium assumptions. The bioaccumulation characteristics will depend on the chemical and physical properties of the radioactive material discharged. As outlined in [5], the first stage in assessing the potential impact of a radioactive discharge to the environment is the characterization of the nature of that discharge, in terms of:

- Industrial process or activity and supporting assumptions.
- Radionuclide composition.
- Chemical and physical form of the radionuclides (related to behaviour in the environment).
- Routes of discharge and discharge points, including discharge characteristics such as stack height, exit velocity, exit temperature, maximum and average discharge rates.
- Total amount of various radionuclides expected to be discharged in one year.
- Expected time pattern of discharge, including the need for and likelihood of enhanced short-term discharges.

The processes involved in setting discharge limits and authorisation conditions are illustrated in Figure 2. The processes are presented as discrete steps for ease of presentation, but it is recognised that, in reality, they represent an iterative procedure. Furthermore, the level of detail involved in each part of the process may vary among types of sources and different Member States. Quality assurance of all parts of the process is an important consideration, although this term is not explicitly referred to in this diagram. It is worth noting that the level of realism required in estimating the transfer of material from one environmental compartment to another will depend upon the type of facility under consideration, the nature of the discharge and the availability of information.

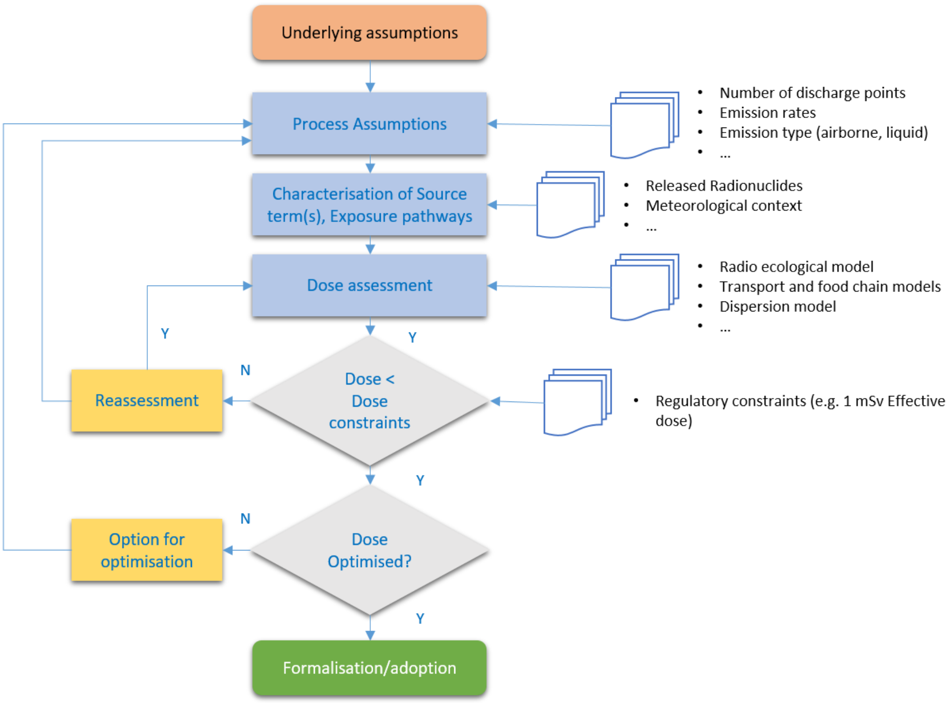

Figure 2 – General flow chart for the determination of a generic discharge formula

Once the concentration of discharged radionuclides in environmental materials has been estimated, the routes by which ‘receptors’, such as representative members of the public, may come into contact with the discharged material may be identified. The critical group is generally the focus for assessments for authorisation purposes, and a schematic diagram of exposure pathways is given in Figure 3.

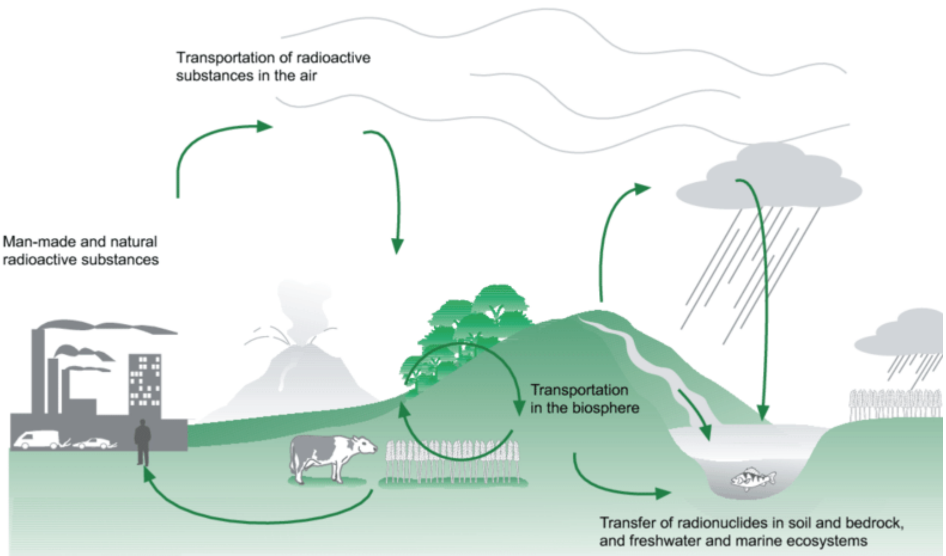

Figure 3 – Main potential exposure pathways for discharges in the environment

There are two main categories of exposure:

- External exposure from radionuclides present in the air or in material incorporated in for example soils or sediment.
- Internal exposure from the inhalation or ingestion of radionuclides present in air or incorporated in water or foods, respectively.

An example of typical radionuclides involved with the nuclear facilities and their associated most relevant exposure pathways is given in Table 1.

Table 1 – Example of exposure pathways for key radionuclides discharged into the environment

Radionuclide	Important exposure pathway
	Airborne discharge
H-3	Ingestion of food and inhalation of plume
C-14	Ingestion of foodstuffs
P-32	Ingestion of foodstuffs
Ar-41	External irradiation from plume
Co-60	External irradiation from deposited activity and ingestion of food
Kr-85	External irradiation from plume
I-131	Ingestion of foodstuffs (milk)
Cs-137	Ingestion of foodstuffs and external irradiation from deposited activity
U-238/235	Inhalation of plume
Pu-238/241	Inhalation of plume
Th-228	Inhalation of plume
Ra-228	Inhalation of plume and ingestion of foodstuffs
Ra-226	Inhalation of plume and external irradiation
Pb-210	Ingestion of foodstuffs
Po-210	Inhalation of plume and ingestion of foodstuffs
	Discharges to aquatic environment
H-3	Ingestion
C-14	Ingestion
P-32	Ingestion
Co-60	Ingestion and external irradiation from deposited activity
Sr-90	Ingestion
Ru-106	Ingestion and external irradiation from deposited activity
I-131	Ingestion
Cs-137	Ingestion and external irradiation from deposited activity
Pu-239	Ingestion
U-238/235	Ingestion of water
Th-228	External irradiation
Ra-228	Ingestion of water and fish
Ra-226	Ingestion of water and fish
Pb-210	Ingestion of fish
Po-210	Ingestion of water and fish

The relative importance of different exposure pathways will be dependent upon the magnitude of the discharge, the route of discharge, the physical and chemical characteristics of the radionuclides discharged and the characteristics of the radioactive decay.

This process may also involve an assessment of the probability of occurrence of each discharge and exposure scenario. The scenarios of relevance to this report are those that may be reasonably predicted to occur as part of normal operation; accident scenarios are outside the scope of authorization considerations. In practice, this process will involve consideration of the relative frequency and consequences associated with different operational conditions that might lead to elevated levels of discharge. Reasonably foreseeable conditions of relatively low consequence would be considered in allowing for operational flexibility in setting the regulatory discharge level.

In order to ensure compliance with the obligations arising from current legislation [1] for the release into the environment of airborne and liquid radioactive effluents, a calculation model has been developed to pre-evaluate the radiological impact and effective dose to the representative person of the population outside JRC-Ispra, as well as to the workers within the JRC area as mentioned in the previous section.

The result of this assessment has allowed the definition of a discharge formula with the corresponding limits of dischargeable activity for each isotope "i", for each type of effluent (airborne or liquid), and for each installation at JRC-Ispra.

In accordance with current legislative guidelines, it was necessary to redefine the discharge formula according to an approach that allows establishing the maximum dischargeable activity into the environment for each radionuclide, within a specific time interval, to meet the predetermined dose objectives for the individual representative of the population. In line with this approach, the discharge formula can be expressed according to the following general formulation:

$$\sum_{i=1}^{n} \frac{A_i}{L_i} < 1 \; (per\ calendar\ year)$$

Where:

A_i Activity (Bq) of the i-th radionuclide present in the mixture discharged into the environment as airborne or liquid effluent;

L_i Limit (Bq) of activity for an airborne or liquid discharge corresponding to an effective dose of 10 μSv/year to the representative person of the population for the i-th radionuclide.

n Number of radionuclides in the mixture discharged into the environment as airborne or liquid effluent.

The expression above for the discharge formula, referring to releases occurring over the course of a calendar year, has been complemented with similar formulas for intermediate time periods (daily and quarterly) in order to monitor the trend of discharges continuously throughout the year.

The radionuclides explicitly considered as representative are those predominant in the radiological inventories or those most relevant for radiological impact purposes of JRC-Ispra installations, as indicated by the results of pre-characterisation or characterisation activities conducted to date. To account for the possible presence of other radionuclides, two additional categories have been considered: "Other alpha emitters" and "Other beta-gamma emitters," to which the most cautious limits L_i calculated for the same type of emitters have been associated.

3.3. Calculation Methodology

For the implementation of the discharge formula, the GENII code was utilised within the FRAMES software platform [2] and [3], allowing for the modelling of the transport and diffusion of radioactive effluents in the environment and the calculation of the radiological impact on the population and non-classified workers at JRC-Ispra.

The GENII code enables the construction of a conceptual model of the area surrounding the JRC-Ispra installations through modules connected by lines indicating the hypothetical flow of the contaminant, representing environmental systems. For all used modules, site-specific parameterisation was carried out where possible, while default values were maintained for the remaining parameters.

To estimate contaminants in the premises and surrounding environment of the JRC-Ispra site, the sectors of the radial grid used by the air transport model were considered. This grid is centred on the release source and divided into 16 sectors (each with an angle of 22.5°) and 10 rings (with increasing radius and variable steps). For dose assessments, effective dose coefficients and types of lung absorption for inhaled particulate radionuclides were considered in accordance with legislative requirements [1]. The release scenario was defined, both for airborne and liquid effluents, through the sequence of modules listed below:

- **Radionuclides:** In the first module, radionuclides composing the release inventory were selected from the database.
- **Release:** This module included the released activity for the selected radionuclides, and the release source was modelled.
- **Transport Model:** This module modelled the transport and dispersion of airborne and liquid radioactive effluents in the environment.
- **Exposure Pathways:** In this module, exposure pathways were selected.
- **Population:** Lifestyle and dietary habits were defined for individuals in the population or workers at JRC-Ispra (the latter for airborne releases only).
- **Radiological Impact:** In this module, ICRP dose coefficients [6] and types of lung absorption were chosen for dose calculations for different individuals' representative of the population or workers (the latter for airborne releases only).

3.4. Airborne Releases

The main site-specific parameters used in GENII [2] and [3] for assessing the radiological impact of airborne effluent releases are described for each module below. Figure 4 represents the scenario set up with the anticipated modules and their connections.

The values of the limits L_i were derived in relation to the airborne releases from INE. From these, in order to obtain a generalised discharge formula for the site, equivalence coefficients ($f_{1,i}$, $f_{2,i}$) were derived for other installations that take into account the different release sources foreseen at JRC-Ispra: Ispra-1 ($f_{1,i}$), Other installations: SGRR, LCSR, STRRL, Cyclotron, etc. ($f_{2,i}$).

Radionuclides Module

For airborne effluents, the representative radionuclides for the JRC-Ispra site during decommissioning and operation activities included in the release scenario are H-3, Co-60, Sr-90, Cs-137, U-235, U-238, Pu-239, Am-241, Ni-59, Ni-63, Fe-55, and Kr-85.

Airborne Effluent Release Module

A specific scenario was envisaged for each installation by creating a file for each release source ("file.gid," typical of the GENII code) to assess the radiological impact for each individual installation.

The sources were modelled with a release from a point source at:

- A height of 80 m for the INE chimney and 40 m for the Ispra-1 chimney.
- Ground level for other installations (SGRR, LCSR, STRRL, Cyclotron, etc.).

To conservatively neglect the rise of the plume, equal values were set for the flue gas temperature and ambient temperature (assumption of cold flue gas). For each dischargeable radionuclide, a release of 1 Bq/year was considered to assess the normalised radiological impact at various distances within 6000 m from the release source (specifically, 160 calculation points were defined, intersections of the 16 considered sectors, each with an angle of 22.5°, with the 10 rings within 6 km).

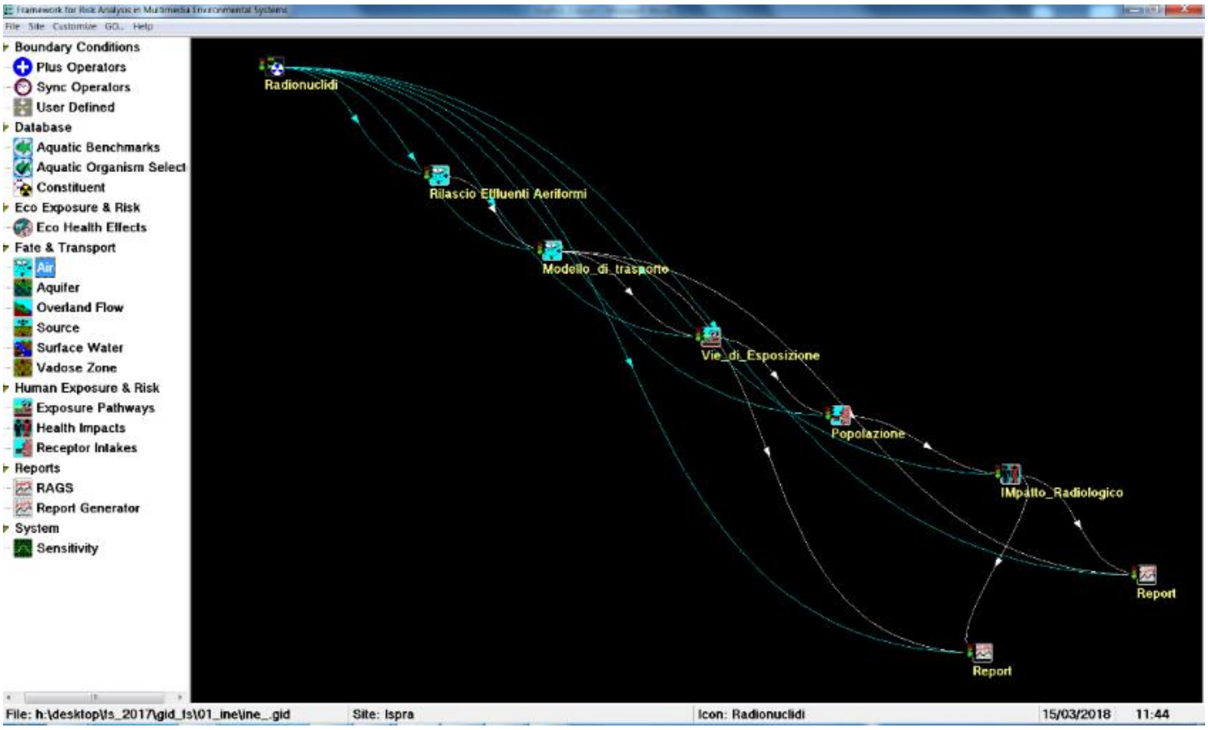

Figure 4 – Screenshot of the FRAMES module

Transport Model Module

In this module, a Gaussian plume dispersion model suitable for chronic releases was used, assuming a Gaussian distribution characterised by standard deviations (or atmospheric diffusion coefficients) σ_y and σ_z, respectively in the horizontal and vertical directions. Pasquill-Gifford relationships [2] were chosen for these coefficients.

The meteorological file was set for the entire year on an hourly basis (required input for the GENII code's meteorological processor), reflecting the expected trends in the conducted studies on climatic and hydrological characterisation of the surrounding territory. Data were taken from the meteorological station of the JRC-Ispra, which collects several parameters such as wind speed and direction, temperature, inversion height, and rainfalls.

Exposure Pathways Module

In this module, all exposure pathways specified by the code for airborne effluents were considered (detailed representation in Figure 5). In particular, for the assessment of the representative person of the population, exposure pathways of ingestion, inhalation, and external exposure were considered (selected as shown in Figure 5). For the representative worker of JRC-Ispra, exposure pathways for inhalation and external exposure were considered (selected as in the right part of Figure 5), excluding the ingestion pathway (left part of Figure 5 not selected).

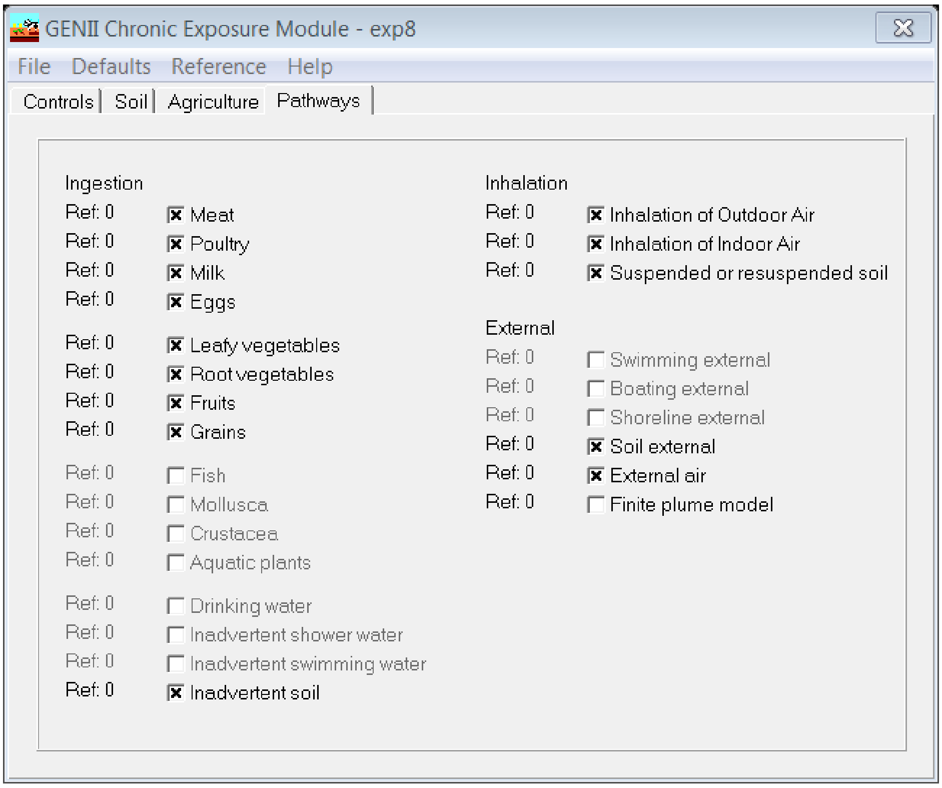

Figure 5 – Exposure pathways determined in GENII for the airborne releases

Population and Workers Module

The population was divided into three representative individuals: infant (≤ 1 year), child (7 - 12 years), and adult (17 – 70 years). Dietary habits for each individual were taken from "L'indagine nazionale sui consumi alimentari in Italia INRAN-SCAI 2005-06. Parte B: I risultati dei consumi alimentari" [9]. For fish ingestion, it is conservatively assumed that the local population consumes fish and tap water coming totally from Novellino stream, where the liquids are discharged.

For representative individuals of the population, respiratory rates were also included (2.88 m^3/day for infants, 15.36 m^3/day for children, 22.32 m^3/day for adults) taken from ICRP 89 [7] and validated in ICRP 119 [6]. The non-exposed worker representative of JRC-Ispra was assimilated to the adult population with the characteristics mentioned above, except being exposed for a total of 2000 hours per year and excluding the ingestion pathway.

Radiological Impact Module

For the assessment of effective dose from inhalation for each representative age class of the population (infant, child, and adult) and for the non-exposed worker representative of JRC-Ispra, dose coefficients and types of lung absorption were chosen (as per Annex XXIV of Legislative Decree No. 101/2020 [1] and reported in ICRP 119 Appendix G of [6]), following the recommendations of ICRP 72 (Table 2 of [8]).

For the assessment of effective dose from ingestion for each representative individual of the population, dose coefficients were chosen as per Annex XXIV of Legislative Decree No. 101/2020 [1] and reported in ICRP 119 (Appendix F of [6]).

3.5. Liquid Releases

Below are described the main aspects concerning the modelling conducted with the GENII code [2] and [3] to define the limits L_i for liquid releases into the environment (Figure 6).

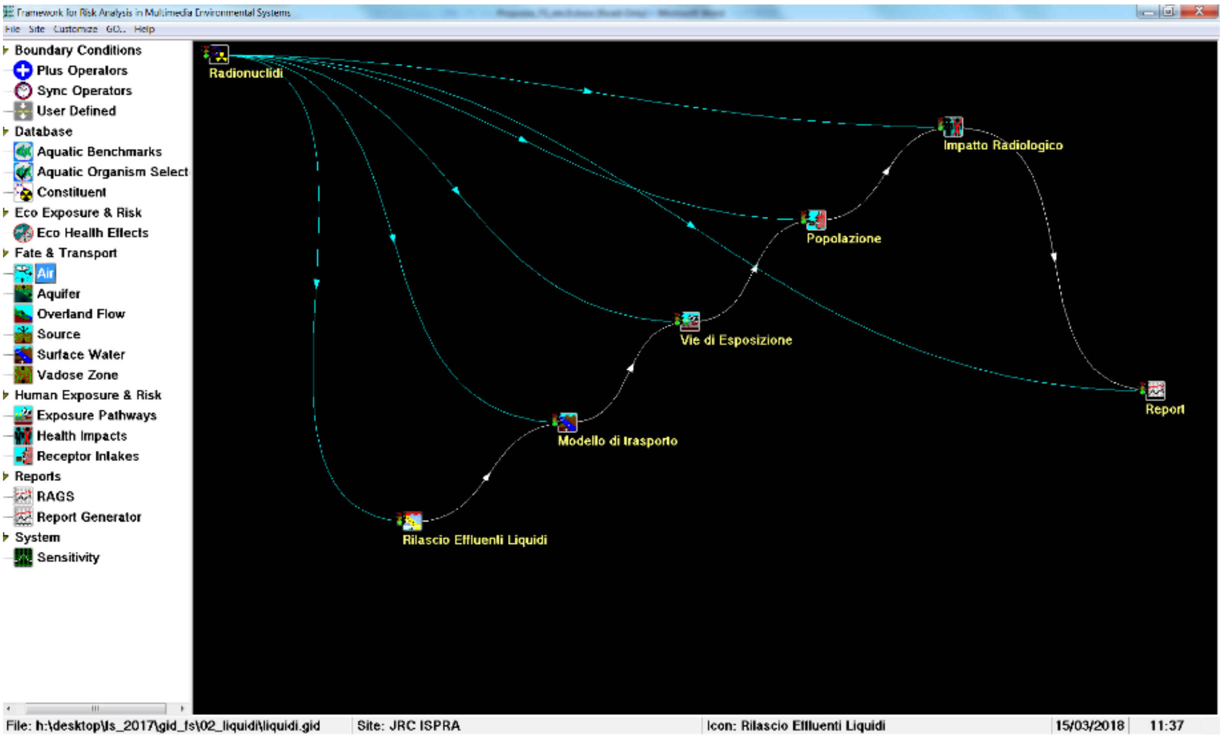

Figure 6 – Schematics of the GENII module for liquid release

<u>Radionuclides Module</u>

For liquid effluents, the representative radionuclides for JRC-Ispra included in the release scenario are H-3, Co-60, Sr-90, Cs-137, Pu-239, Am-241, Ni-59, Ni-63, and Fe-55.

<u>Release Module</u>

As in the case of airborne releases, for evaluation with the GENII code, a release of 1 Bq/year was considered for each radionuclide in this module. Regarding the modelling of the source, for liquid releases, a single point located only in the authorised release facility was considered: the Radioactive Liquid Effluent Treatment Station (STEL) in Area 40.

<u>Transport Model Module</u>

The receiving body identified for liquid effluent releases is the Novellino stream. In the GENII code module used to model the transport of radionuclides, the following parameterisation of Novellino was used:

- Width: 2.5 m.
- Average depth: 0.5 m.
- Flow velocity: 0.11 m/s.
- Annual flow rate: 4,361,000 m^3/year.
- Distance of a hypothetical representative individual: 1500 m from the discharge point.

Exposure Pathways Module

In this module, various exposure pathways provided by the code for liquid effluents were included (similar to what is reported for airborne releases in Figure 5, excluding the inhalation pathway).

Population Module

For liquid releases, the population was also divided into three representative individuals (infant, child, and adult). The values used for the most significant exposure pathways are the same as those reported in "L'indagine nazionale sui consumi alimentari in Italia INRAN-SCAI 2005-06. Parte B: I risultati dei consumi alimentari" [9]. Since liquid effluents can impact the hypothetical representative individual of the population located outside the site, there is no impact of liquid effluents on the non-exposed worker representative of JRC-Ispra.

Radiological Impact Module

For the assessment of effective dose from ingestion for each representative individual of the population, dose coefficients were chosen as per Annex XXIV of Legislative Decree No. 101/2020 [1] and reported in ICRP 119 (Appendix F of [6]).

3.6. Discharge Formula

The atmospheric release of radioactive airborne effluents from any installation on the site and the discharge of liquid effluents from the STEL facility, after prior filtration and radiometric control, must occur in overall compliance with the limitations expressed by the following discharge formula for JRC-Ispra:

$$\sum_{i=1}^{n}\left(\frac{A_{i,INE}}{L_{i,aer}}+\frac{A_{i,Ispra\ 1}}{f_{1,i}\ L_{i,aer}}+\frac{A_{i,Altre\ Installazioni}}{f_{2,i}L_{i,aer}}+\frac{A_{i,liq}}{L_{i,liq}}\right)<\begin{cases}1\ in\ a\ calendar\ year\\ 0{,}25\ in\ 13\ weeks\\ 0{,}05\ in\ 24\ hours\end{cases}$$

Where:

$\mathbf{A_{i,INE}}$	Activity (Bq) of the i-th radionuclide present in the mixture discharged into the environment as airborne from the INE reactor.
$\mathbf{A_{i,Ispra1}}$	Activity (Bq) of the i-th radionuclide present in the mixture discharged into the environment as airborne from the Ispra 1 reactor.
$\mathbf{A_{i,Altre\ installazioni}}$	Activity (Bq) of the i-th radionuclide present in the mixture discharged into the environment as airborne from other installations.
$\mathbf{A_{i,liq}}$	Activity (Bq) of the i-th radionuclide present in liquid effluents.
$\mathbf{L_{i,aer}}$	Annual limit (Bq) of the activity released into the atmosphere corresponding to an effective dose of 10 μSv/year to any member of the public related to the i-th radionuclide individually released by INE, as reported in Table 2.
$\mathbf{f_{1,i}, f_{2,i}}$	Coefficients, for each i-th radionuclide, concerning INE, the Ispra-1 reactor, and the other installations of JRC-Ispra, as reported in Table 2.
$\mathbf{L_{i,liq}}$	Limit (Bq) of the activity for a liquid discharge corresponding to an effective dose of 10 μSv/year to any member of the public related to the i-th radionuclide individually released, as reported in Table 3.
n	Number of radionuclides in the mixture discharged into the environment as airborne or liquid effluent.

Table 2 – $L_{i,aer}$ Limits and coefficients $f_{1,i}$ e $f_{2,i}$ for airborne effluents

Radionuclide	$L_{i,aer}$ (Bq)	$f_{1,i}$ – Ispra-1	$f_{2,i}$ – Other installations
Am-241	5.49E+08	0.3	0.004
Co-60	1.03E+10	0.4	0.024
Cs-137	8.55E+09	0.4	0.024
H-3	8.65E+14	0.1	0.002
Ni-59	3.24E+11	0.4	0.023
Ni-63	1.33E+11	0.4	0.022
Pu-239	4.90E+08	0.3	0.004
Sr-90	2.24E+09	0.4	0.023
U-235	4.45E+09	0.3	0.007
U-238	4.43E+09	0.3	0.007
Fe-55	9.71E+10	0.4	0.024
Kr-85	1.11E+17	0.1	0.001
Other alpha emitters	4.90E+08	0.3	0.004
Other beta-gamma emitters	2.24E+09	0.4	0.022

Table 3 – $L_{i,liq}$ Limits for liquid effluents

Radionuclide	Li, Liq (Bq)
Am-241	2.48E+08
Co-60	1.38E+08
Cs-137	4.07E+08
H-3	1.54E+13
Ni-59	3.29E+11
Ni-63	1.35E+11
Pu-239	2.25E+08
Sr-90	1.22E+09
Fe-55	5.26E+10
Other Alpha emitters	2.25E+08
Other beta-gamma emitters	1.38E+08

3.7. Monitoring System

Adherence to the aforementioned discharge formula is verified through the measurement and subsequent quantification of airborne effluents for the specified values over 13 weeks (quarterly) and a calendar year, while monitoring the limits defined over 24 hours is entrusted to the fixed plant instrumentation.

Verification and quantification for liquid effluents are performed for each batch of liquid destined for discharge through laboratory radiometric measurements on liquid samples prior to discharge.

Verification of the limits for airborne effluents over 13 weeks and a calendar year is achieved by measuring weekly:

- Tritium activity in the water of the bubblers installed at the release point of the plants where this radionuclide can be detected (INE, Ispra-1, Area 40).
- Activity of beta/gamma emitters and alpha emitters through non-destructive measurements of particulate matter on filters positioned at the authorised discharge point of each plant.

Knowing the volumes of air discharged weekly, it is possible to verify the compliance of the discharge formula using linear projections. The values of the formula parameters are then consolidated quarterly (13 weeks) and annually, considering the sum of the specific contributions of liquid discharges, tritium measured by bubblers for airborne discharges, and other radionuclides for airborne discharges through non-destructive and destructive measurements on filters accumulated over the 13-week period. In the case of limits imposed on 24-hour discharges, for the airborne component, they are verified through alarm thresholds (L_1, L_2, and L_3) defined for monitors installed at the discharge points of airborne effluents from various installations and plants at JRC-Ispra.

Continuous air monitoring instrumentation includes detectors capable of monitoring alpha and beta emitters in aerosol and particulate form (RAM), tritium (ATM), and radioactive noble gases (NGM). The alarm level is calculated based on guide radionuclides among those in Table 2. The maximum activity dischargeable in 24 hours was defined, and then the maximum concentration of activity was calculated, taking into account the flow rate Γ [m^3/h] of the plant, using the following formula:

$$C_{max} = \frac{A_{i,max}[Bq]}{\Gamma\left[{}^{m^3}/_{h}\right] * 24[h]}$$

The thresholds, L_1 and L_2, are associated with longer measurement integration times and are set at 50% and 100%, respectively, of the calculated maximum concentrations. Threshold L_3 is linked to a "Quick Alarm" with very short integration times and is set at 10 times the calculated maximum concentration.

The results obtained for the monitoring instrumentation at INE are reported in Table 4. Similar assessments have also been conducted for other plants and installations.

Table 4 – Monitors setting threshold for the INE area

Monitor	L_1 Threshold [Bq/m^3]	L_2 Threshold [Bq/m^3]	Quick alarm L_3 Threshold [Bq/m^3]
RAM γ/β	1.7E+01	3.4E+01	3.4E+02
RAM α	3.7E+00	7.5E+00	7.5E+01
ATM	6.5E+06	1.3E+07	1.3E+08
NGM	8.5E+08	1.7E+09	1.7E+10

4. CONCLUSIONS

Based on the methodology presented in this work, and the lessons learned in its implementation, it can be affirmed that defining a nuclear discharge formula with a constraint of 10 µSv/year presents several challenges. Some of these include:

- **Management of uncertainty**: determining the potential radiological impact of effluent releases on the population requires accurate and reliable scientific data. However, there can be uncertainties associated with the measurement and assessment of radiation doses.
- **Variability in exposure pathways:** the pathways through which individuals may be exposed to radiation can vary. For example, some individuals may be exposed through inhalation, while others may be exposed through ingestion or external exposure. The discharge formula needs to consider these different exposure pathways and ensure that the cumulative dose from all pathways remains below the 10 µSv/year constraint.
- **Monitoring and enforcement:** monitoring and enforcing compliance with the discharge formula's constraint of 10 µSv/year can be complex. It requires robust monitoring systems, regular inspections, and effective enforcement mechanisms to detect and address any deviations from the established limits.
- **Public perception and acceptance:** the public's perception of radiation risks and their acceptance of the discharge formula's constraint can vary. Communicating the scientific basis and rationale behind the constraint of 10 µSv/year, as well as addressing public concerns and ensuring transparency, are important challenges in gaining public trust and acceptance.

Addressing these challenges required collaboration between regulatory authorities, scientific experts, facility operators, and stakeholders. It involves continuous monitoring, evaluation, and refinement of the discharge formula to ensure that the dose constraint is effectively implemented while protecting public health and the environment.

More specifically, a crucial lesson learned during the development of the discharge formula, was the constant **interaction and collaboration with the regulatory authorities**. This resulted, in fact, essential during several steps of the process, such as:

- Defining the representative person of the population and allocating the radiation dose "budget" accordingly: in the case of JRC-Ispra, it was assumed that a dose limit of 10 µSv/year encompassed both liquid and airborne discharges. However, an alternative approach could be established in coordination with regulatory authorities. For instance, if the representative person for the liquid discharges is distinct from the one for airborne discharges — meaning one is not exposed to the other type — separate constraints of 10 µSv/year for liquid discharges and 10 µSv/year for airborne discharges might be adopted, thus effectively doubling the available radiation "budget".
- Establishing the "location" of the representative person at the outset of the process. Initially proposed by JRC-Ispra, the discharge formula was assessed based on the existing locations of inhabited areas surrounding the site. Regulatory Authorities anticipated future urban expansion and consequently demanded a re-evaluation considering the maximum potential impact of the discharges, even in currently uninhabited zones (it is to be remarked how some of these maximum impact points were identified within the fenced perimeter of the site itself).
- The utilisation of the latest version of the calculation code: through simulations conducted with the GENNI code [2] and [3] to formulate the discharge equation, it was observed that in comparison to significantly older versions (from a few years prior), there exists a variance of up to 30% in the obtained results.

It's crucial to **engage in comparisons with colleagues from other facilities** who have encountered or are currently facing similar challenges regarding the discharge formula. For instance:

- When confronted with parameters for which precise data is unavailable to input into the code, examining the decisions made by others and the feedback received from regulatory authorities can offer valuable insights. At JRC-Ispra, such a comparison was conducted with Sogin (Italian state-owned enterprise responsible for nuclear decommissioning and management and disposal of radioactive waste) regarding certain parameters related to the food chain used to define the representative person's diet for their respective plants. Notably, both institutions adopted the same national reference [9].
- A collaboration agreement was established with Sogin, which operates the Ispra-1 reactor situated within the JRC-Ispra site. This agreement permits the integration of effluents discharged from the Ispra-1 reactor with those from all other plants on the site, ensuring that the total calculation complies with the limit of 10 µSv/year.

Additionally, it is imperative to ensure that once discharge limits are established, they are communicated to both plant operators and technical managers. This facilitates feedback on the feasibility of these limits in light of ongoing activities, as well as future endeavours including those related to operational plants and facilities undergoing decommissioning. Finally, it's essential to assess whether these limits can be realistically adhered to without imposing excessive economic burdens or causing delays. At JRC-Ispra, this sharing process was diligently undertaken, and a thorough comparison was conducted with the previous discharge formula to ensure acceptance of the values by all stakeholders involved.

5. REFERENCES

[1] D. Lgs. 101/2020 e ss.mm.ii. Attuazione della direttiva 2013/59/Euratom, che stabilisce norme fondamentali di sicurezza relative alla protezione contro i pericoli derivanti dall'esposizione alle radiazioni ionizzanti, e che abroga le direttive 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom e 2003/122/Euratom e riordino della normativa di settore in attuazione dell'articolo 20, comma 1, lettera a), della legge 4 ottobre 2019, n. 117.

[2] GENII Version 2 - B. A. Napier. User's Guide. October 2004.

[3] FRAMES - Framework for Risk Analysis in Multimedia Environmental Systems – U.S. EPA.

[4] Legge 27 dicembre 2017, n. 205 – "Bilancio di previsione dello Stato per l'anno finanziario 2018 e bilancio pluriennale per il triennio 2018-2020".

[5] IAEA TECDOC 1638 - Setting Authorized Limits for Radioactive Discharges: Practical Issues to Consider.

[6] ICRP 119 – Compendium of dose coefficients based on ICRP 60.

[7] ICRP 89 - Basic Anatomical Physiological Data for Use in Radiological Protection: Reference Values.

[8] ICRP 72 – Age-dependent doses to members of the public from intake of radionuclides: Part 5 Compilation of ingestion and inhalation dose coefficients.

[9] Piccinelli R., Arcella D., Buonocore P., Capriotti M., D'Addezio L., Le Donne C., Mistura L., Pettinelli A., Sette ., Turrini A., Leclercq C. - L'indagine nazionale sui consumi alimentari in Italia INRAN-SCAI 2005-06. Parte B: I risultati dei consumi alimentari. Osservatorio Consumi Alimentari, INRAN. Roma, 2011.