

2026

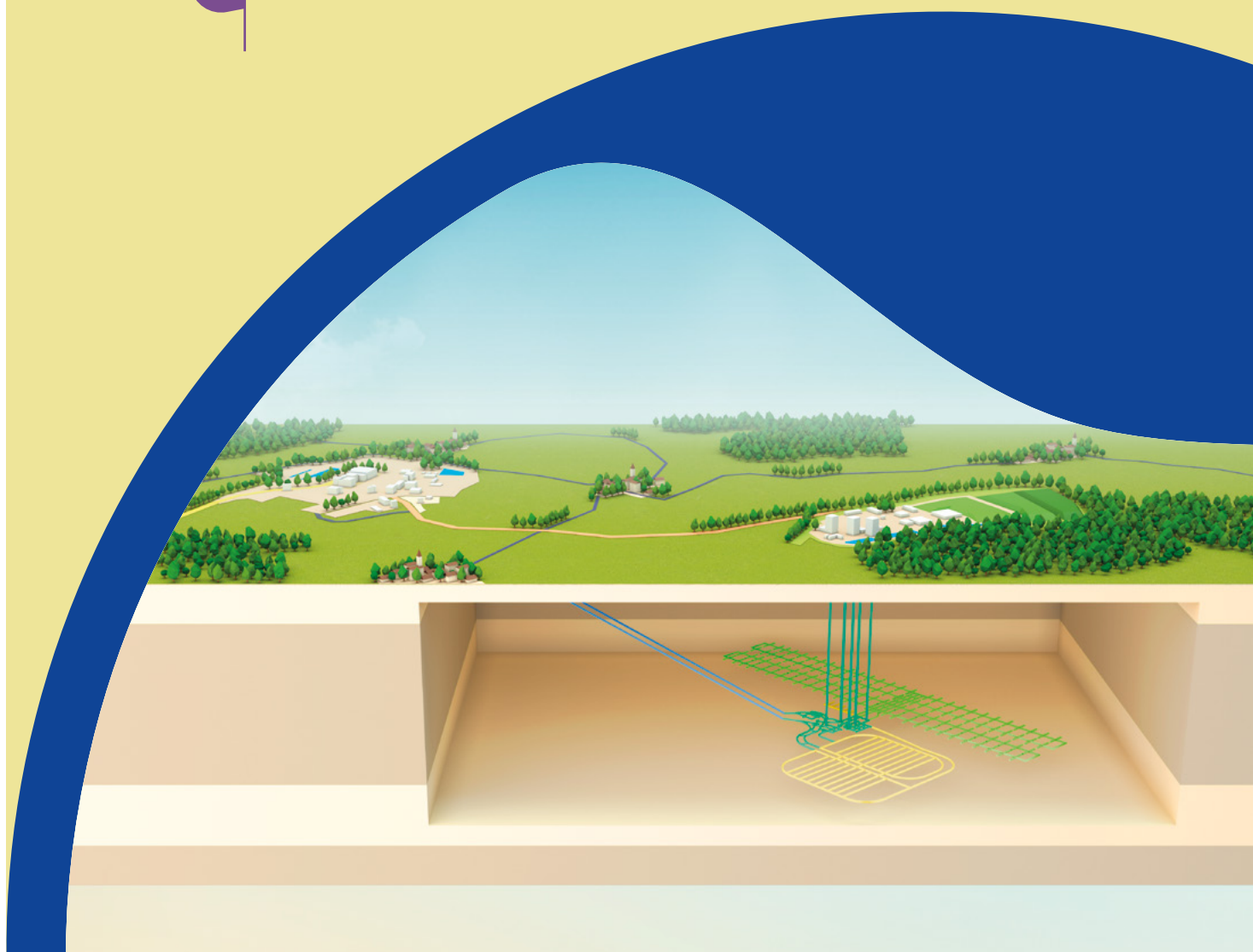
**LICENCE APPLICATION FILE FOR THE CREATION
OF THE CIGÉO BASIC NUCLEAR INSTALLATION (BNI)**



DOCUMENT 8BIS

Risk management study

**NON-TECHNICAL
SUMMARY**



This text is a translation of document No 8bis-RNT of the licence application file for the creation of the Cigéo basic nuclear installation, updated in 2026.

This document has been produced to facilitate access to the creation application file for non-French readers. This translation is for information purposes only; Andra is liable solely on the basis of the original French-language version.

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1

Purpose of the non-technical summary

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1.1 The risk management study: general principles and adaptations to the specific characteristics of Cigéo

The purpose of this non-technical summary is to help the public understand the risk management study, which is one of the documents included in the file joined to the creation licence application (*demande d'autorisation de creation, DAC*) of the basic nuclear installation (BNI, *installation nucléaire de base - INB*) Cigéo, for which Andra is the project owner.

Like any basic nuclear installation, Cigéo involves risks that may arise during its construction and operation, and like any radioactive waste disposal facility, risk management must be ensured after closure, over long periods of time, given the duration of the hazard associated with the radioactive waste for which it is designed.

» A POST-CLOSURE PROTECTION OBJECTIVE

ASN Safety Guide No. 1 (1), on deep geological disposals, defines the objectives that must be met, particularly for the design of such disposal facilities, and its safety demonstration specifies that *"Protecting the health of individuals and the environment is the fundamental safety objective of the deep geological disposal of radioactive waste."*

ASN Guide No. 1 is available on the ASNR's website².

The risk management study aims to demonstrate that the Cigéo BNI presents the lowest possible level of risk, given the knowledge and best techniques available to date. To this end, it sets out the risks identified for Cigéo, presents their analysis and the measures implemented to prevent and control these risks, as well as the measures considered to respond to possible accident situations, with the sole objective of protecting personnel, the public, and the environment. It has been written with a view to making it be accessible to as many people as possible, particularly for local consultations and the forthcoming public inquiry relating to the creation licence application file.

As with any analysis of this type, the risk study carried out by Andra consists of:

- identifying the risks presented by Cigéo,
- preventing and reducing these risks,
- monitoring the facility in order to be able to detect any malfunctions,
- limiting the consequences of any malfunction.

The risks analysed and presented in the risk management study may stem from various sources:

- nuclear: directly related to the presence of waste packages, such as exposure to radiation, dissemination of radioactive substances, etc.;
- internal: directly generated by the presence of components or activities taking place within the facility;
- external, linked to natural events or external human activities.

¹ BNIs are facilities which, by their nature or due to the quantity or activity of the radioactive substances they contain, are subject to specific provisions designed to protect people and the environment.

² <https://regulation-oversight.asnr.fr/regulation/asnr-guides/asn-guide-no.-1>

The risk management study comprises two risk analyses conducted in parallel and in a coordinated manner:

- an analysis known as "post-closure risk management," which is specific to radioactive waste disposal and is intended to ensure long-term safety once the disposal facility has been permanently closed;
- an analysis known as "operational risk management," which is a conventional analysis applied to other basic nuclear installations and which also aims to ensure that the measures taken during operation do not hinder the achievement of post-closure safety objectives.

To assess the impact of radiological risks, Andra establishes various scenarios with a view to evaluating the robustness of disposal during operation and after closure. For example, in relation to the specific nature of Cigéo, Andra is studying the following for the post-closure phase:

- a design-basis evolution scenario, which represents the expected evolution of the repository over time and space, as designed and in line with scientific and technological knowledge;
- scenarios known as "non design-basis evolution" and "*what-if*," which make it possible to study the consequences of component malfunctions, whether unlikely or very unlikely, that cause the repository to deviate from its normal evolution;
- scenarios involving inadvertent human intrusion (e.g., drilling of boreholes) that assume the disposal has been forgotten.

Quantitative assessment of scenarios using a set of indicators makes it possible to evaluate the objectives of protecting people and the environment, the proper performance of safety functions under normal conditions, and the overall robustness of the disposal system in the event of a function failure.

» A SAFETY APPROACH CONSISTENT WITH NATIONAL AND INTERNATIONAL PRACTICES

The safety approach adopted by Andra complies with the safety regulations issued by international organizations (International Atomic Energy Agency - IAEA, Nuclear Energy Agency - NEA, International Commission on Radiological Protection - ICRP). These bodies set principles and establish common references for all those responsible for nuclear activities. In order to have a proven base of knowledge, methods, and analyses, and to share feedback, Andra is involved in international cooperation, particularly with its foreign counterparts.

Andra exchanges information with nuclear operators on standards and their implementation. It also calls on organizations with recognized expertise in a wide range of fields: geosciences (geology, structural sedimentology, geomechanics, geochemistry, tectonics/seismicity, hydrogeology, etc.), radiochemistry, materials science, climate science, underground works, civil engineering, nuclear engineering, applied mathematics, numerical simulation, metrology, radiation protection, fire safety, etc.

Finally, several external reviews, inspections, or equivalent procedures have verified the consistency of Andra's approach with these national and international practices:

- Since 1991, various files related to the development of Cigéo have been submitted to the French Nuclear Safety Authority (ASN), which has issued opinions and recommendations (notably for the "Safety Options Report" (*Dossier d'options de sûreté*, DOS) prepared by Andra in 2016 (2, 3). These ASN opinions are based on assessments carried out by the Institute for Radiological Protection and Safety (IRSN) and submitted to advisory committees. The ASN also conducts monitoring visits, particularly to the Meuse/Haute-Marne Centre, during which it assesses the quality of the work being carried out in the Underground Research Laboratory.

- Established by the Act of December 30, 1991 (4) and then that of 2006 (5), National Assessment Board (*Commission nationale d'évaluation des recherches et études relatives à la gestion des matières et déchets radioactifs* - CNE2) is responsible for evaluating the quality of Andra's scientific work and produces an annual report in which it issues an opinion on this work. Its opinions and recommendations provide input for refining the priorities of the research program and, more generally, the design and safety assessment work. The CNE reports annually to the Parliamentary Office for the Evaluation of Scientific and Technological Choices (*Office parlementaire d'évaluation des choix scientifiques et technologiques* - OPECST).

In order to verify the consistency of Andra's approach with international practices, at the request of Andra's supervisory ministries, two reviews by international experts were organized in 2002 and 2005 by the OECD Nuclear Energy Agency, and in 2016 by the IAEA (the conclusions of these reviews are available online³). Thus, wishing to obtain the opinion of international peers in the context of the review of the safety options report (DOS) for the Cigéo deep geological radioactive waste disposal project, the ASN asked the IAEA to organize an international review of this report by experts from foreign safety authorities. Following this review and the examination of the safety options report by the IRSN, the ASN stated in its opinion of January 11, 2018 that "Andra has *adopted principles that are generally satisfactory in terms of safety during operation and after closure, consistent with the February 2008 ASN safety guide mentioned above and the work of international bodies*" (10).

Furthermore, the risk management study incorporates the principle of reversibility of deep geological disposal and presents the measures planned to ensure this reversibility⁴ as required by Article R. 593-16 III, paragraph 3 pursuant to Article L. 542-10-1 of the French Environment Code.

» THE PRINCIPLE OF REVERSIBILITY

Cigéo is designed to offer future generations choices in terms of waste management and not to lock them into design choices made at the start of the project. The deployment of the disposal facility will therefore be marked by decisions and authorisations of all kinds, technical or political, local or national in scope, which will be submitted to stakeholders as part of Cigéo's governance. Prescribed by Act No. 2016-1015 of July 25, 2016 (11), the principle of reversibility is provided for in Article L. 542-10-1 of the French Environment Code. It is reflected in provisions aimed at ensuring:

- **the gradual nature of construction**, with a cautious sequence of successive construction and commissioning operations;
- **flexibility of operation**, to absorb variations in its industrial program;
- **the adaptability of facilities** and the ability to modify them to take into account new design assumptions;
- **the retrievability of packages**, i.e., the ability to remove packages that have been emplaced in the disposal facility.

ASN Safety Guide No. 1 (1), on deep geological disposals, also specifies that "*deep geological disposal of radioactive waste is the disposal of these substances in an underground facility specially designed for this purpose, complying with the principle of reversibility.*" The reversibility of disposal requires appropriate operating methods and means of monitoring the facility. The measures taken to ensure the reversibility of disposal must not compromise operational safety and safety after closure of the disposal facility. The measures taken in relation to reversibility are presented in Chapter 6 of the risk management study.

³ The reports of the international reviews are available at the following addresses: reviews conducted under the auspices of the OECD/NEA in 2001 (6), in 2005 (7), and in 2016 under the auspices of the IAEA (8, 9).

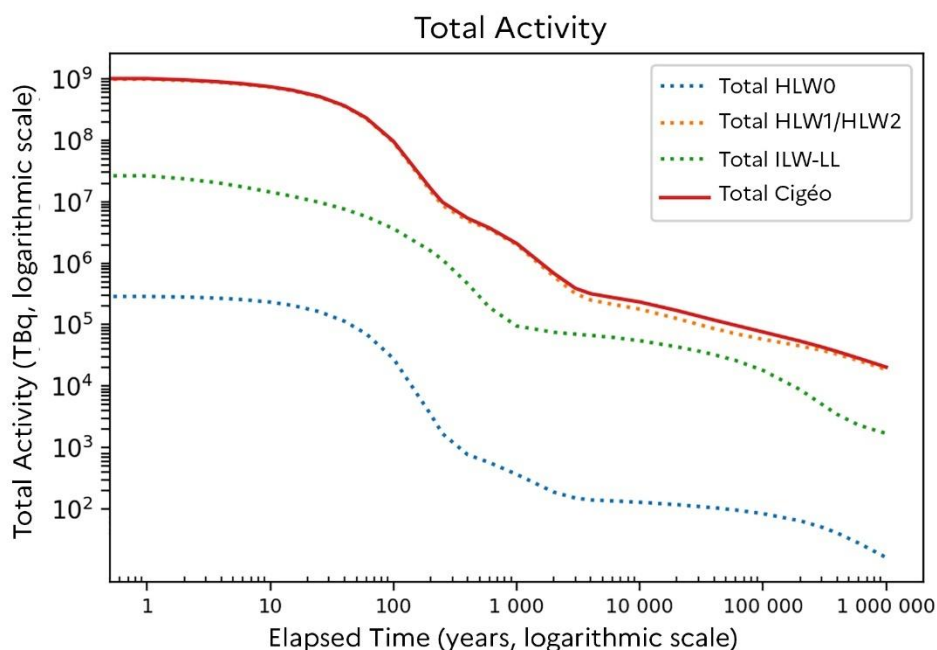
⁴ For deep geological disposal, the four aspects of reversibility in response to III of Article R. 593-16 are gradual nature, flexibility, adaptability, and retrievability.

1.2 Some preliminary concepts

1.2.1 Radioactivity

Radioactivity is a natural phenomenon that has existed since the beginning of the universe when atoms were formed. It is the phenomenon whereby certain unstable atoms—radionuclides—tend to become stable. To do this, they decay and expel energy in the form of radiation and/or particles. Radioactivity can also be created artificially by human activities. This involves creating or recreating radioactive nuclei using a particle accelerator or a nuclear reactor.

The radioactive half-life refers to the time it takes for a quantity of the same radionuclide to fall to half as a result of the disintegrations it has undergone. It varies greatly depending on the radionuclide. For example, a given quantity of tritium decays to half of its original amount in 12.3 years, while carbon-14 takes 5,700 years.



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Figure 1-1 *Illustration of the decay over time of the total radioactivity of waste in the Cigéo reference inventory (red curve) and the radioactivity of the total inventory of HLW0, HLW1/HLW2 (High-Level Waste classified by activity level from low to high : 0, 1, 2), and ILW-LL packages (dotted curves)*

Three units of measurement are frequently used to measure radioactivity:

- the international unit of measurement for radioactivity is the becquerel (Bq). It measures the activity (number of disintegrations per second) of radioactive material;
- the gray (Gy) measures the dose physically "absorbed" by the material. It represents the energy absorbed by one kilogram of material exposed to ionizing radiation providing 1 joule of energy (1 Gy = 1 J.kg⁻¹);
- the sievert is used to assess the biological effects of radiation on a living organism exposed to radioactivity. These effects vary depending on the nature of the radiation and the organs exposed. The most commonly used unit is the millisievert (mSv), which corresponds to one thousandth of a sievert.

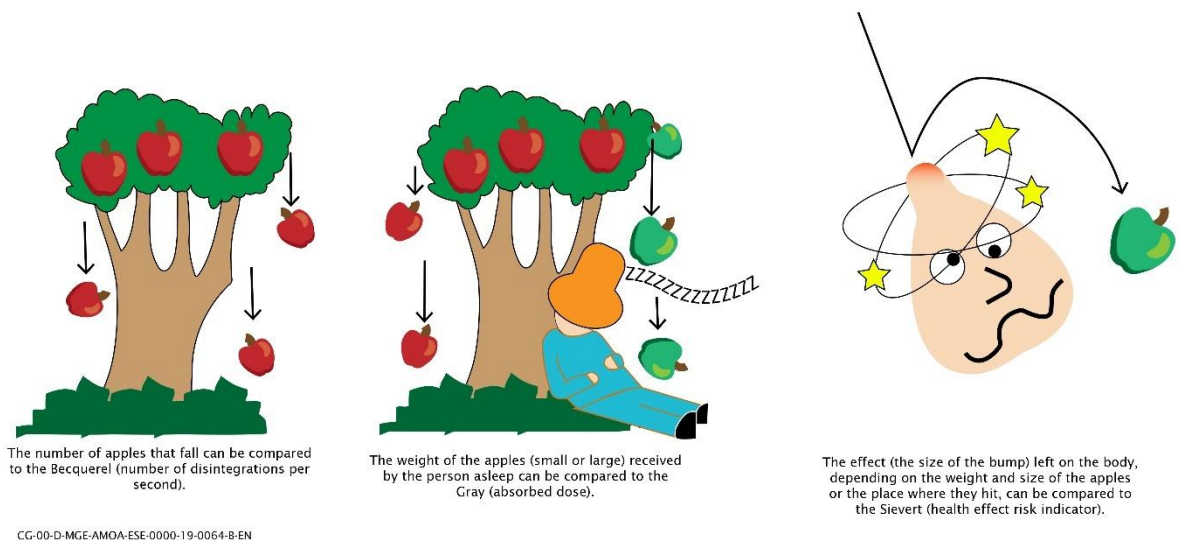
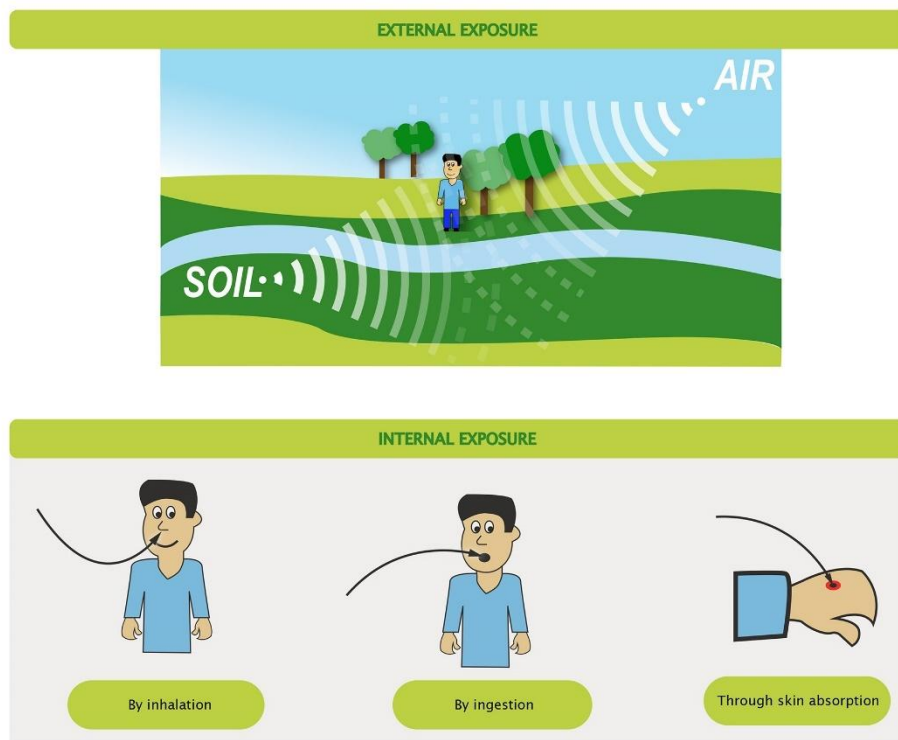


Figure 1-2 *Illustration of the effect of radioactivity, from becquerel (Bq) to sievert (Sv)*

There are two types of exposure to ionizing radiation:

- irradiation, or external exposure, which occurs when a person is exposed from outside to ionizing radiation emitted by a radioactive source located in their vicinity. In this case, exposure ceases as soon as the source of radioactivity is removed from the person or if a screen (e.g., shielding) is placed between the person and the source;
- contamination, or internal exposure, i.e. when radioactive elements have entered the body. This can occur through inhalation of radioactive particles in the air, ingestion of food contaminated with radioactive particles, or direct contact with the skin or a wound (in this case, it is referred to as "external contamination"). During contamination, exposure to radioactive particles continues as long as the source is inside or in contact with the body.



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Figure 1-3 Illustration of types of exposure to radioactivity

1.2.2 Concepts of risk and danger

According to the definition proposed by the French National Institute for Industrial Environment and Risks (*Ineris*) (12), the concepts of risk and danger are understood as follows:

- risk: "A potential danger, more or less predictable, inherent in a situation or activity," "The possibility of a future event, uncertain or of indefinite duration, not depending exclusively on the will of the parties and capable of causing the loss of an object or any other damage." The technical concept of risk is therefore based on two main components: the hazard and its potential impact on exposed targets or assets;
- danger: property intrinsic to a substance, technical system or living organism which can lead to the damage of a vulnerable constituent.

2

The Cigéo BNI

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2.1 The principle of deep geological disposal

Deep geological disposal meets the objective of sustainable management of high-level (HLW) and long-lived intermediate-level (ILW-LL) radioactive waste, as defined in the French Environment Code:

- to gradually avoid burdening future generations with the management of this waste, which will remain radioactive for a very long time, thanks to the passive nature of the protective measures;
- to protect people and the environment in the long term from the risks posed by this most dangerous radioactive waste, by isolating it and limiting the transfer of radionuclides to the surface.

To meet these two challenges, the principle of deep geological disposal is therefore to place radioactive waste in a geological layer at a sufficient depth (at least 200 meters) within a layer whose properties (thickness, permeability, etc.) greatly reduce the migration of radioactive substances over time (through retention, low solubility, limited displacement in water due to advection by water circulation or diffusion in water, etc.), while also taking advantage of radioactive decay.

To ensure the long-term protection of people and the environment, Andra draws on more than 20 years of research and development, which have led to:

- the acquisition of scientific and technological knowledge to understand physical and chemical phenomena and their evolution over very long periods of time. This knowledge has made it possible to reduce residual uncertainties as much as necessary throughout the development of the Cigéo project;
- the design of the repository, in line with the state of scientific and technological knowledge. This design takes advantage of the favourable properties of the Callovo-Oxfordian clay host formation and helps to control the behaviour of the repository, in particular by limiting its complexity and the weight of residual uncertainties about its behaviour;
- the description and understanding of the behaviour of the repository and its geological environment over time, particularly in the long term after the final closure of the repository;
- the assessment of safety during operation and after closure, carried out on the basis of iterations between knowledge, design and safety.

2.2 The phases of Cigéo

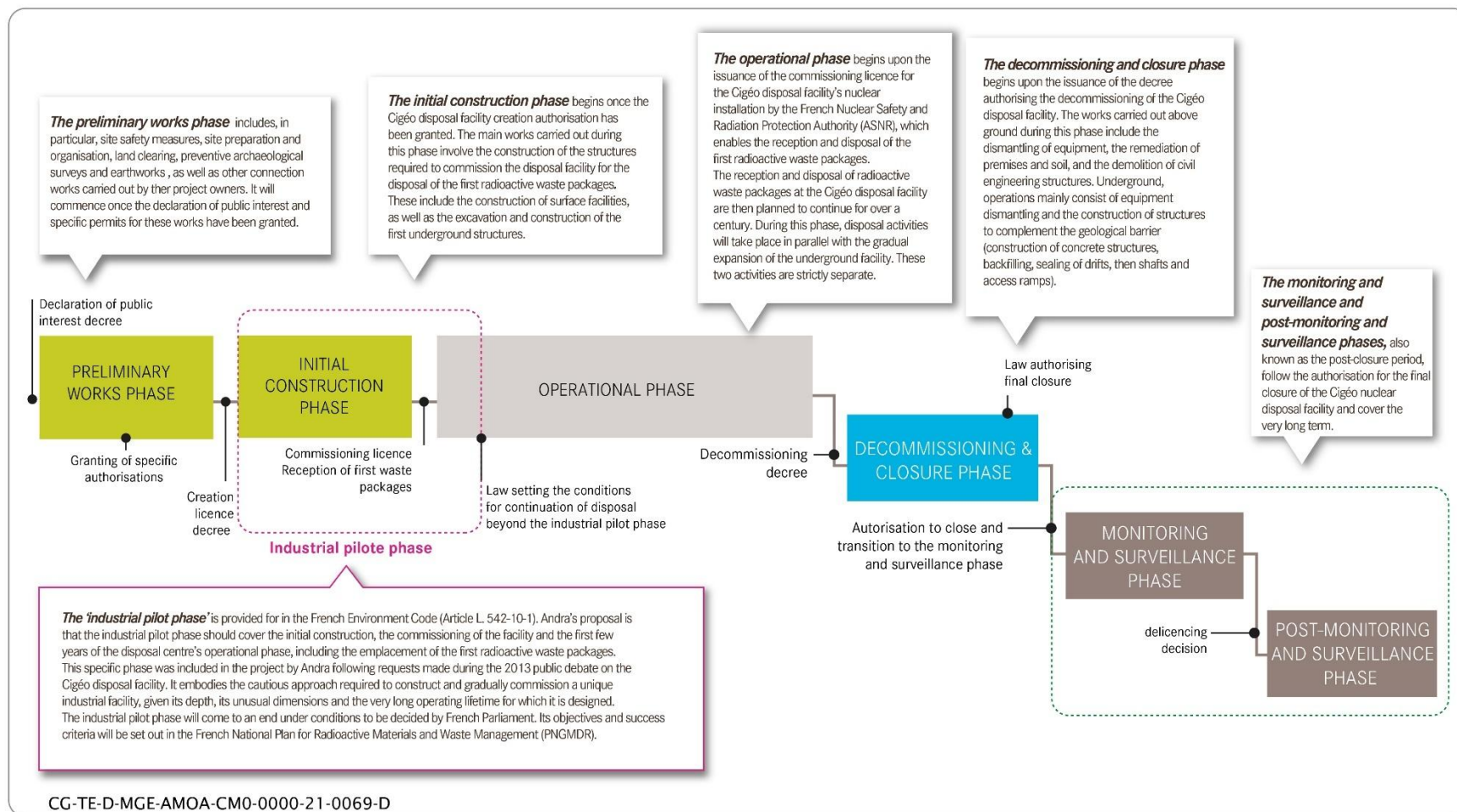


Figure 2-1 Cigéo time phases

2.3 Waste intended for disposal in Cigéo

The radioactive waste intended for disposal in Cigéo is high-level (HLW) and long-lived intermediate-level (ILW-LL) waste, mainly from the nuclear power industry, but also from research and national defence:

- HLW consists mainly of residues extracted from spent nuclear fuel during reprocessing (fission products and minor actinides), which are then incorporated into a glass matrix (vitrification process);
- ILW-LL consists mainly of waste from the metal structures surrounding the fuel (shells and ends), resulting from the reprocessing of spent fuel and, to a lesser extent, technological waste related to operation and maintenance of nuclear facilities, waste from the treatment of liquid effluents, and activated waste related to nuclear reactors.

The reference inventory for which Cigéo is designed includes HLW and ILW-LL that has already been produced and waste that will be produced in the future by existing nuclear facilities as well as those authorised for construction at the end of 2016 (Flamanville EPR, ITER fusion reactor, Jules Horowitz experimental reactor), until the foreseeable end of their operation and subsequent decommissioning. Today, approximately 50% of HLW and ILW-LL has already been produced.

The volume of radioactive waste in the reference inventory is around 83,000 m³. This corresponds to around 225,000 packages to be disposed of.

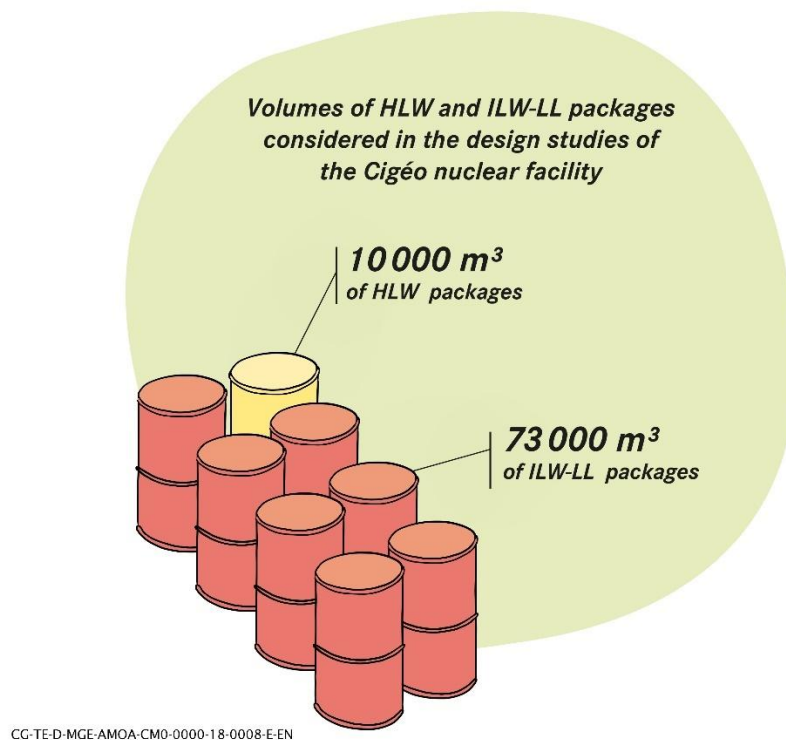


Figure 2-2

Volumes of HLW and ILW-LL packages taken into account in the Cigéo design studies

Andra is designing Cigéo so that it can evolve thanks to its successive phases of construction to take into account possible changes in the inventory of waste to be disposed of, particularly in relation to national energy strategies or the implementation of new waste management methods. At this stage, these changes are being studied through a reserve inventory and adaptability studies.

The level of radioactivity of HLW and ILW-LL makes it highly dangerous from a radiological point of view and poses the following associated risks:

- risks of external irradiation (or external exposure):
 - ✓ an individual standing in the immediate vicinity of high-level radioactive waste without protection would have a life expectancy of a few minutes due to its radiation;
 - ✓ due to its nature and significantly lower concentrations of radionuclides, IL-LL radioactive waste is generally less irradiating.
- risks of contamination (or internal exposure), for example in the event of inhalation of contaminated dust emitted in the vicinity of the packages if an accident resulted in a loss of containment. Ingestion or inhalation of HLW and ILW-LL particles could lead to internal contamination and irradiation of the body, which could be very serious for health.

Given this high level of danger and the very long period during which it persists, HLW and ILW-LL packages cannot be disposed of safely, sustainably, and without human intervention on the surface or near the ground surface.

►► PRIMARY RADIOACTIVE WASTE PACKAGES

- All radioactive waste received at Cigéo comes in the form of packaged waste: HLW and ILW-LL packaging is carried out by the waste producers. The finished product at the end of each packaging operation constitutes the "primary package";
- Primary packages are solid objects that confine radionuclides and toxic chemicals within them;
- Primary packages must comply with the package acceptance specifications mentioned in Article L. 542-12 4° of the French Environment Code, a preliminary version of which is presented in "Document 19 – Preliminary package acceptance specifications" referenced at (13).

►► PACKAGE ACCEPTANCE SPECIFICATIONS

The package acceptance specifications mentioned in Article L. 542-12 of the French Environment Code define the criteria that a radioactive waste package must meet in order to be accepted at Cigéo (13). They cover the radiological, physical, mechanical, and chemical characteristics and properties of the packages. They were established as a result of an approach that combines knowledge of radioactive waste packages with the design and safety demonstration of the Cigéo basic nuclear installation during its operation and after its closure.

►► MONITORING OF PACKAGES BY ANDRA

The monitoring of packages contributes to the quality control of the packages that will be received at Cigéo. Its objectives are to verify that the producer has implemented the provisions described in its packaging and storage standards and to verify that the packages comply with the criteria set out in the package acceptance specifications.

2.4 The Cigéo site, its facilities, the disposal process, and the post-closure disposal system

2.4.1 The Cigéo site

Cigéo is located in the Grand Est region, on the border between the departments of Meuse and Haute-Marne. Its facilities are located in the municipalities of Bonnet, Bure, Cirfontaines-en-Ornois, Gillaumé, Gondrecourt-le-Château, Houdelaincourt, Horville-en-Ornois, Mandres-en-Barrois, Ribeaucourt, Saint-Joire and Saudron.

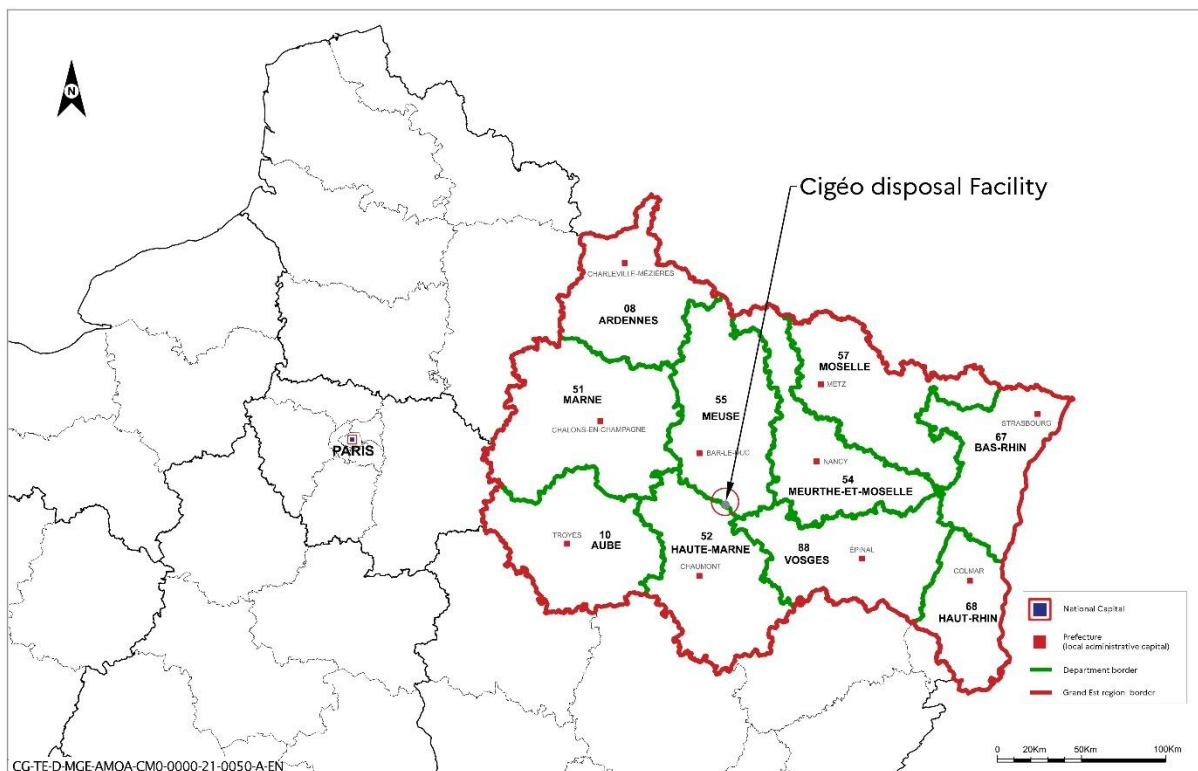


Figure 2-3 Location of Cigéo in eastern France

2.4.2 Cigéo's main facilities

The Cigéo disposal facility comprises both surface and underground facilities:

- a surface ramp zone (ZD), primarily dedicated to the reception of radioactive waste packages sent by the producers, their inspection and preparation for disposal prior to their transfer to the underground facility;
- a surface shaft zone (ZP), dedicated to support facilities for the activities carried out in the underground facility, in particular excavation works;
- an underground structures zone (ZIOS), comprising disposal areas for radioactive waste packages, logistics support zones (ZSL) and their access routes from the surface.

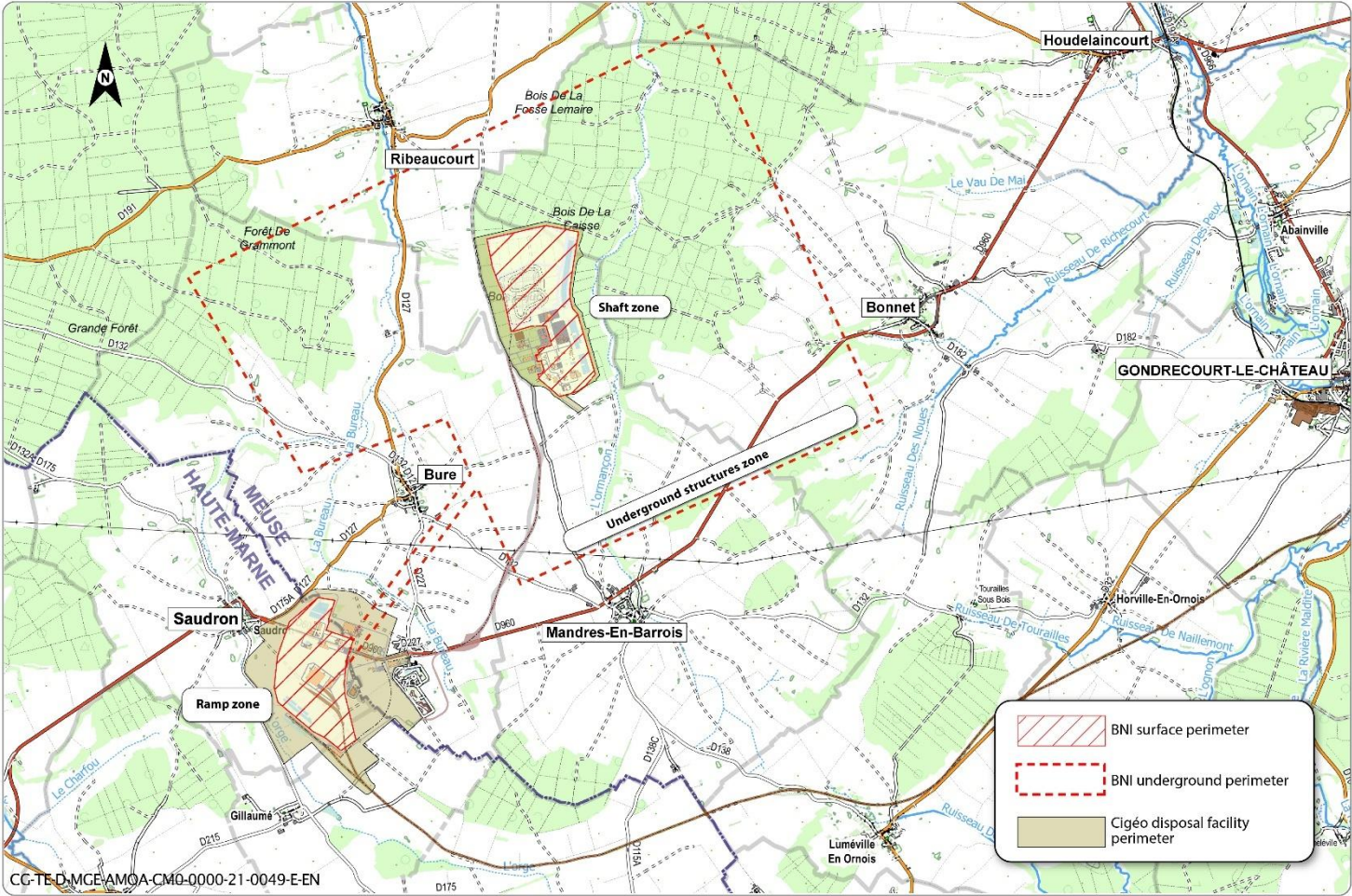


Figure 2-4 Location of Cigéo's surface facilities

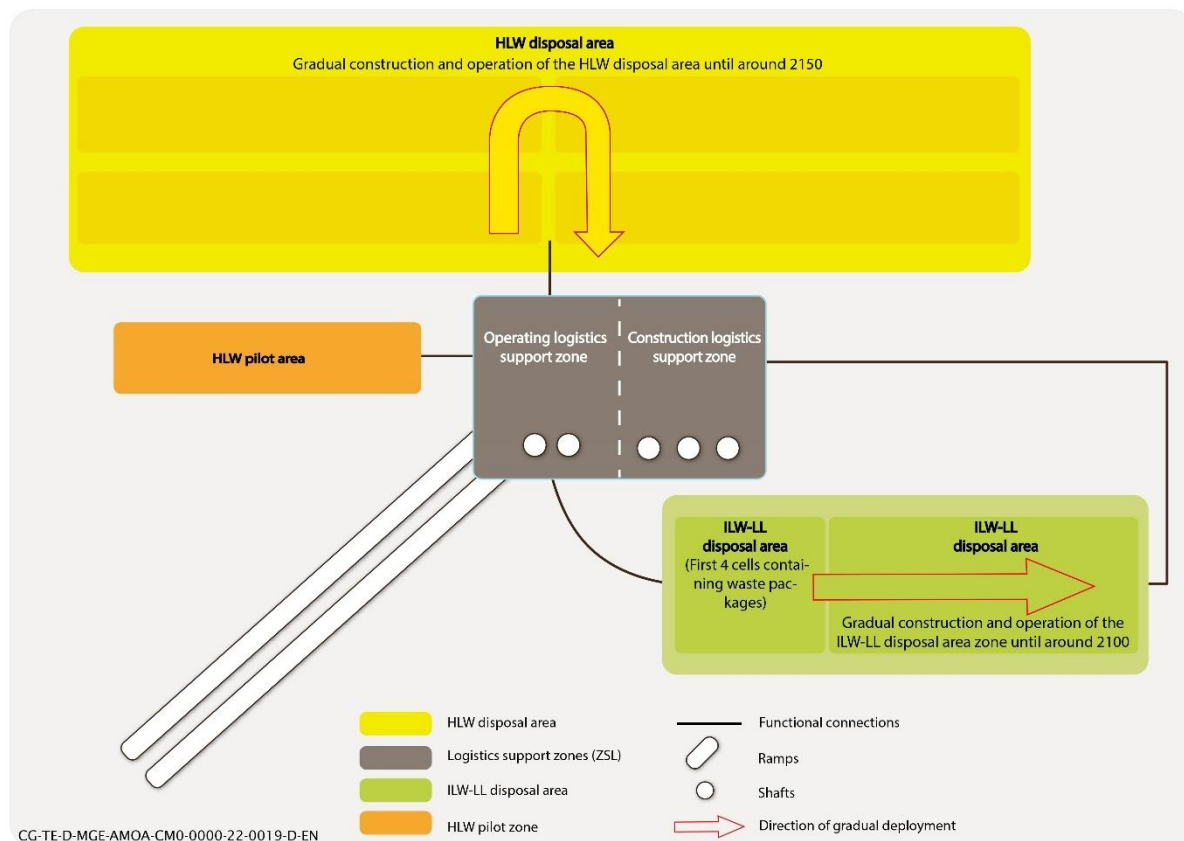


Figure 2-5 Schematic representation of the Cigéo underground facilities and their deployment over time

2.4.3 The Cigéo BNI perimeter

The perimeter of the basic nuclear installation proposed in this creation licence application is shown schematically in the figure below. In accordance with Article R. 593-16 of the French Environment Code, "Document 4 - Site plans at a scale of 1:10,000 indicating the proposed perimeter" (14) presents the plan of the facility at a scale of at least 1:2,500.

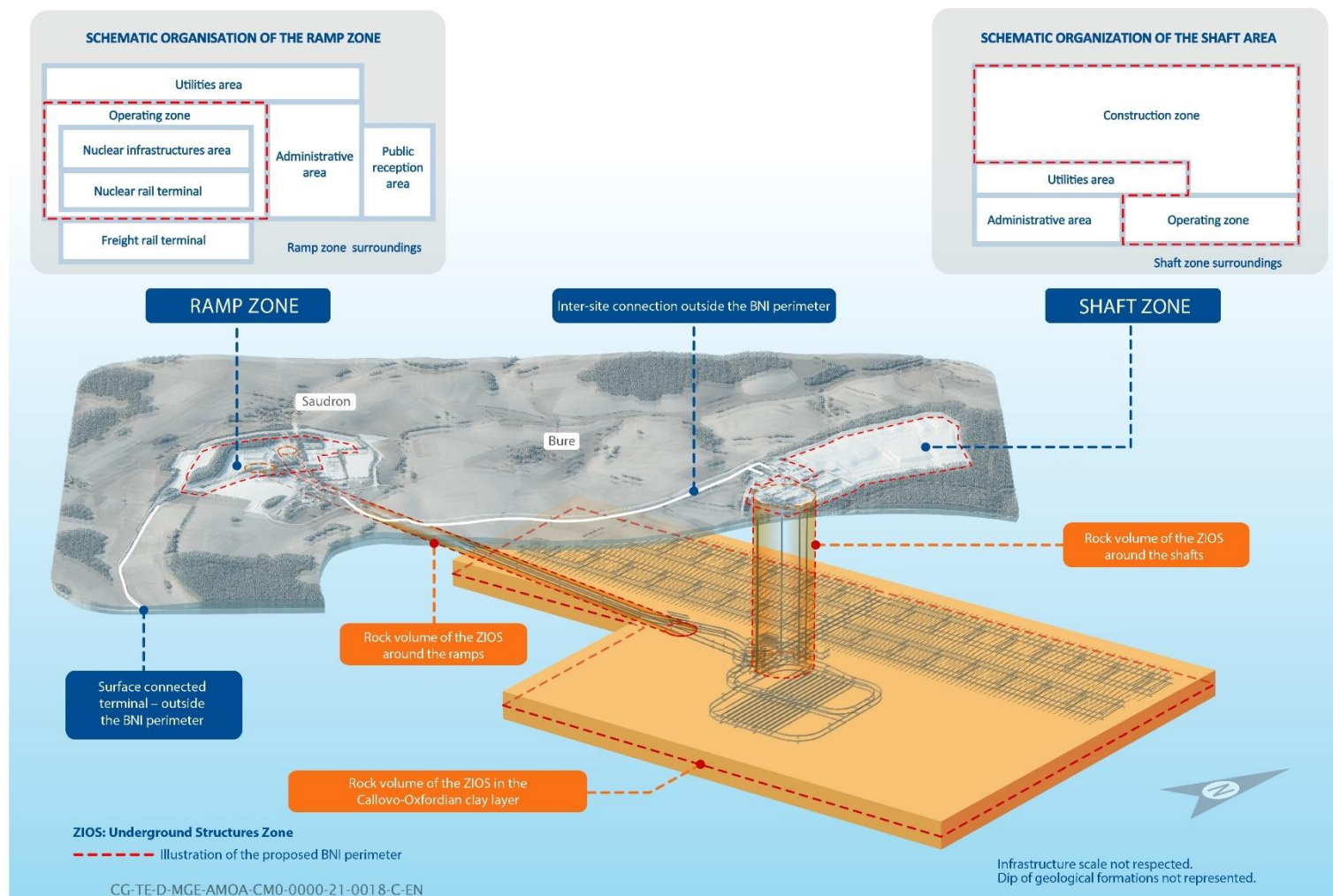


Figure 2-6

Schematic representation of the Cigéo BNI perimeter

2.4.4 The process of managing radioactive waste packages in Cigéo

The various operations planned for the waste packages include reception in the surface ramp zone, preparation of the waste packages, placement of the packages in transfer casks in transfer casks prior to their transfer underground, and placement of the packages in their designated disposal cells.

The sequence of these operations as a continuous process is summarized below:



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Figure 2-7

Path taken by waste packages from their arrival at Cigéo to their disposal location

2.4.5 The post-closure disposal system

The fundamental objective of deep geological disposal of radioactive waste is to protect people and the environment. At the end of its operational lifespan, Cigéo will have to be closed. After closure, safety will be ensured passively: that is, people and the environment will be protected from the radionuclides and toxic chemicals contained in the radioactive waste without the need for intervention.

The closure of Cigéo can only be authorised by an Act passed by Parliament. The surface facilities in the ramps and shafts zones will be dismantled, and the entire underground facility will be backfilled and sealed using seals installed in the drifts and in the connections between the surface and the disposal areas (see "Decommissioning, Closure and Monitoring & Surveillance Plan" (15).

The principle of post-closure disposal is to isolate the waste from surface phenomena and human activity over the long term and to limit the migration of radionuclides and toxic substances contained in the waste to the surface. It comprises three main categories of components:

- the Callovo-Oxfordian layer, a geological formation in which the disposal areas are located, and a central component in terms of post-closure safety;
- the closure structures of the underground facility, which are of two types:
 - ✓ "seals," which are low-permeability structures installed in drifts and surface-underground connections. These seals are designed to prevent water from circulating in the repository, thereby preventing it from altering the waste and contributing to migration of radionuclides;
 - ✓ backfill, which is designed to limit long-term deformation of the Callovo-Oxfordian layer near the structures thereby preserving its favourable characteristics.
- The backfilled and sealed underground facility, which is designed to take advantage of the favourable properties of the Callovo-Oxfordian layer and help preserve them.

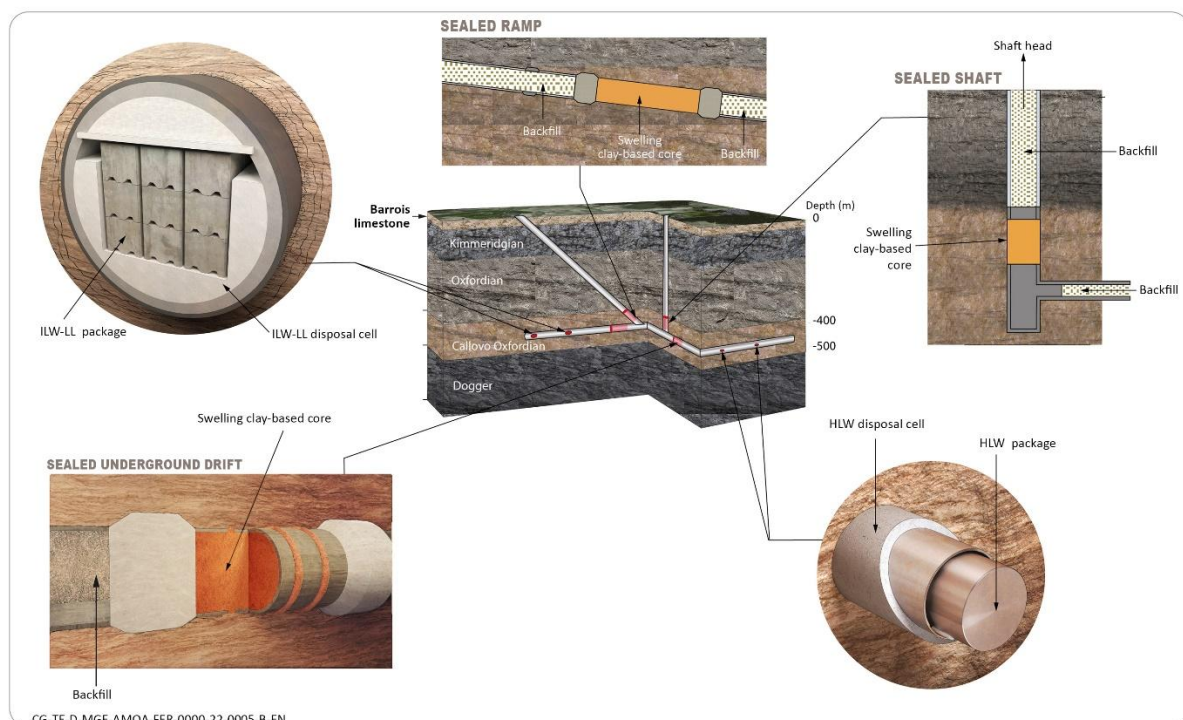


Figure 2-8

Illustration of the Cigéo underground facility after closure (i.e., once backfilled and sealed, subject to authorisation of its closure by law)

3

The risk management approach adopted for the study

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In line with the fundamental objective of protecting people and the environment from the dangers posed by the most radioactive and long-lived waste, Cigéo is a special nuclear facility that, once created, is designed to endure beyond its operational lifespan. The study of the risks associated with it is therefore also unique, as it seeks to identify and analyse both operational risks and long-term post-closure risks.

To this end, two risk analyses are conducted in parallel and in a coordinated manner:

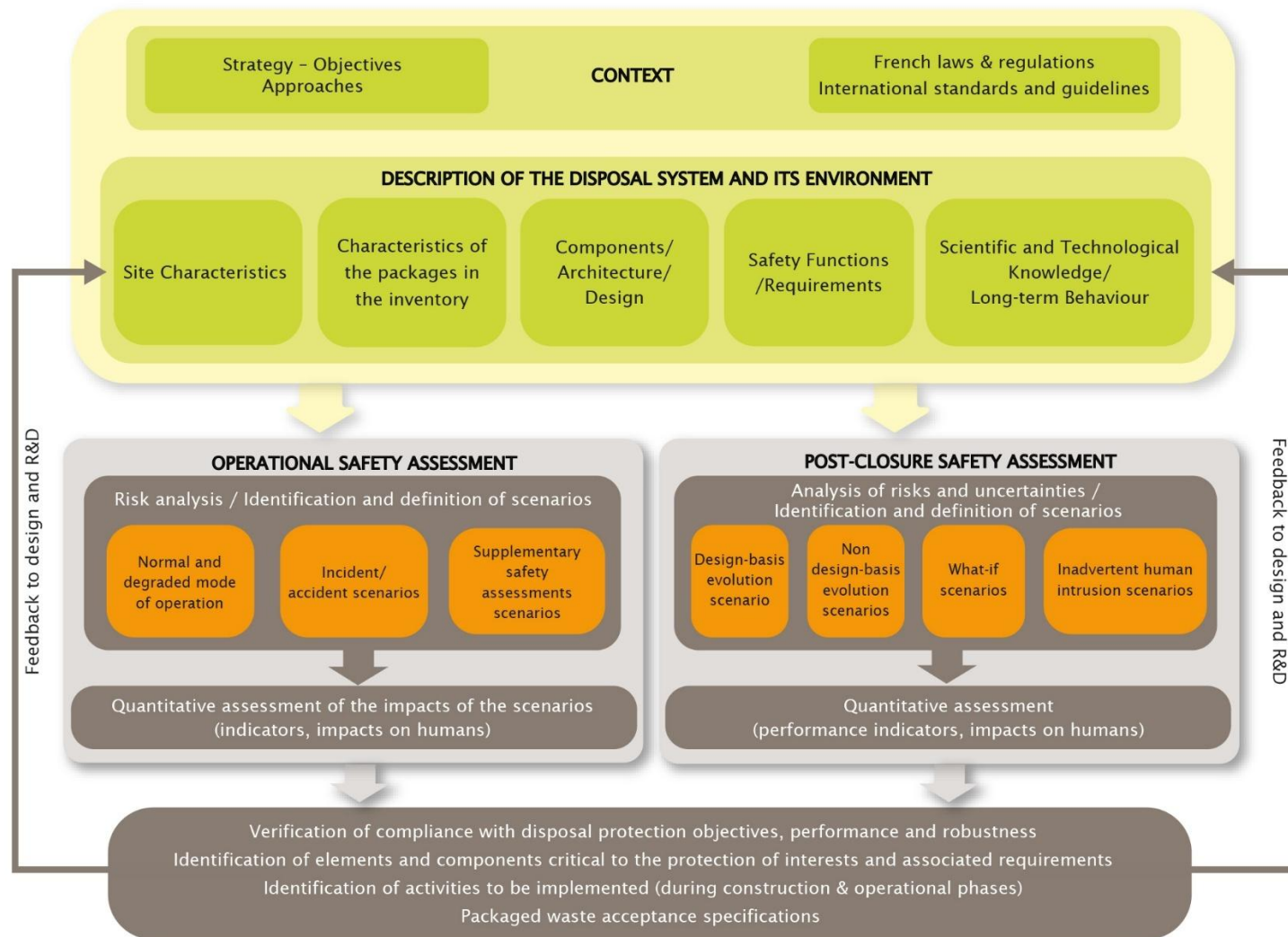
- **an analysis known as "post-closure risk management,"** which is specific to radioactive waste disposal and designed to ensure long-term safety once the disposal facility is permanently closed;
- **an analysis known as "operational risk management,"** a conventional analysis applied to other nuclear facilities, which also aims to ensure that the measures taken during operation do not hinder the achievement of post-closure safety objectives.

This integrated approach makes it possible to assess the robustness of Cigéo at each stage, related to the disposal components taken as a whole or separately, and the safety functions they perform.

» WHAT IS ROBUSTNESS?

Robustness is the ability of an equipment, a component, or a system to function in a wide range of environmental conditions (heat, cold, liquid water, humidity, dryness, vibration, geometric deformations, contamination, ageing, after an impact, etc.) or to be tolerant to component failure or external aggressions.

The figure below summarizes the various stages of the approach applied to Cigéo for the risk management study.



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Figure 3-1

Diagram illustrating the general safety approach applied to Cigéo

The analysis of the risks associated with Cigéo is based on a significant knowledge base that includes:

- **knowledge of the radioactive waste packages to be disposed of.** Provided by waste producers and analysed by Andra, this knowledge contributes to the safety of the disposal facility during operation and, as necessary, to the safety of disposal after closure: origin, packaging processes, packaging assumptions when packaging is yet to be defined, physical, chemical and radiological properties;
- **knowledge of the site and geological layer selected for the disposal facility.** All the investigations carried out to characterise the site and the layer (drilling, 2D/3D seismic campaigns, Meuse/Haute-Marne Underground Research Laboratory) enabled Andra to ensure that the geological environment has the expected properties, particularly with regard to the site selection criteria defined in ASN Safety Guide No. 1 (depth of the host formation, stability, hydrogeology, etc.);
- **knowledge of how the disposal system will evolve after closure.** Demonstrating the safety of disposal after closure requires an understanding of how the natural and engineered components that make up the disposal system will evolve after closure, as well as their possible interactions, and how the system as a whole will evolve after closure. The purpose of describing the evolution of the repository is to provide as robust an understanding as possible of the "future history" of the repository, without claiming to make predictions, particularly regarding its thermal, hydraulic, mechanical and chemical evolution.

» THE FAVOURABLE CHARACTERISTICS OF THE CALLOVO-OXFORDIAN LAYER FOR DEEP GEOLOGICAL DISPOSAL

Data acquired over more than 20 years of studies and research conducted on and in the Callovo-Oxfordian clay layer show that it has favourable characteristics that guarantee the long-term protection of people and the environment.

Located in the Paris Basin, this layer is situated in an area that has been recognised as stable for around 160 million years and virtually free of seismic activity. It is located at a depth of around 500 meters, which is well deeper than the level of erosion possible over several hundred thousand years (estimated at less than 200 meters): it therefore protects the disposal system from geodynamic phenomena (tectonics, climate, erosion) over the next million years and limits their potential effects on the disposal system.

The geometry of the Callovo-Oxfordian layer (low dip, approximately 1.5 degrees), its considerable thickness (approximately 140 to 160 meters at the disposal site) and the very low variability of its properties over at least several dozen square kilometers make it suitable for disposal facilities and allow for significant thicknesses of the Callovo-Oxfordian layer (at least 50 meters) above and below the disposal cells.

All of the properties of the Callovo-Oxfordian layer are very favourable: its hydraulic characteristics (in particular its very low permeability) limit water circulation; its physicochemical characteristics promote the retention and low solubility of most radionuclides and toxic chemicals, and generally their very low migration over time.

Combined with these properties, the thickness of the Callovo-Oxfordian layer helps to delay, limit, and mitigate the amount of radionuclides and toxic chemicals released by waste packages, which could potentially migrate from the disposal in the Callovo-Oxfordian layer and then out of it into the environment.

3.1 Post-closure safety functions

The primary post-closure safety function is to isolate the waste from surface phenomena and human activities. This function is reflected in the following design elements:

- locating the drifts and disposal facilities far underground, in the Callovo-Oxfordian layer, sufficiently far away from natural surface phenomena (in particular erosion) and away from areas with exceptional or specific underground resources (in particular to avoid intrusion by drilling of boreholes);
- maintain memory keeping measures of the existence of the repository for as long as possible after closure (at least 500 years).

The second post-closure safety function is to limit the transfer of radionuclides and toxic chemicals contained in the waste to people and the environment by constraining and slowing down as much as possible the migration of some of these elements to the surface so as to benefit from the radioactive decay of radionuclides. This function is reflected in the following design features:

- preventing water circulation: locating facilities in the Callovo-Oxfordian layer, where water flow is low due to its low permeability; designing facilities with "dead-end" cells in the disposal areas; installing seals in access shafts/ramps to limit water flow in underground facilities, etc.;
- limiting the release of radionuclides and toxic chemicals and immobilizing them in the cell: materials used in the design of disposal containers (e.g., steel disposal containers for high-level waste packages, whose impermeability over a given period prevents water from reaching the high-level waste packages), physical and chemical conditions in the cells, etc.;
- delay and mitigate the migration of radionuclides and toxic chemicals: location of disposal areas in the Callovo-Oxfordian layer to take advantage of its thickness (planar architecture, length of disposal cells and underground drifts, etc.);
- preserving the favourable characteristics of the Callovo-Oxfordian layer and the engineered components involved in performing safety functions after closure: choice of materials compatible with the characteristics of the Callovo-Oxfordian layer, thermal, thermo-hydraulic and mechanical design of disposal areas, orientation of disposal cells, limitation of voids in disposal cells, etc.

► EFFECTS OF THE DECAY AND MIGRATION OF RADIONUCLIDES IN THE CALLOVO-OXFORDIAN LAYER

The diffusion process results in a flow of radionuclides (*i.e.*, quantity per unit of time) at a given distance that increases over time, reaches a maximum, and then decreases. The time taken to reach the maximum and the value of the maximum flux depend on the distance from the source and the behaviour of the radionuclide in the environment: the greater the distance from the source, or the greater the radionuclide retention capacity of the porous medium, or the lower the diffusion capacity of the porous medium, the longer the time taken to reach the maximum and the lower the value of the maximum flux. Depending on the time taken to reach the maximum flux in relation to the radionuclide's half-life, radioactive decay can further contribute to reducing the maximum flux value.

The figure below illustrates the effects of decay and retention in the migration of a radionuclide by diffusion in a given porous medium, for example the Callovo-Oxfordian layer, at a given distance from a radionuclide source.

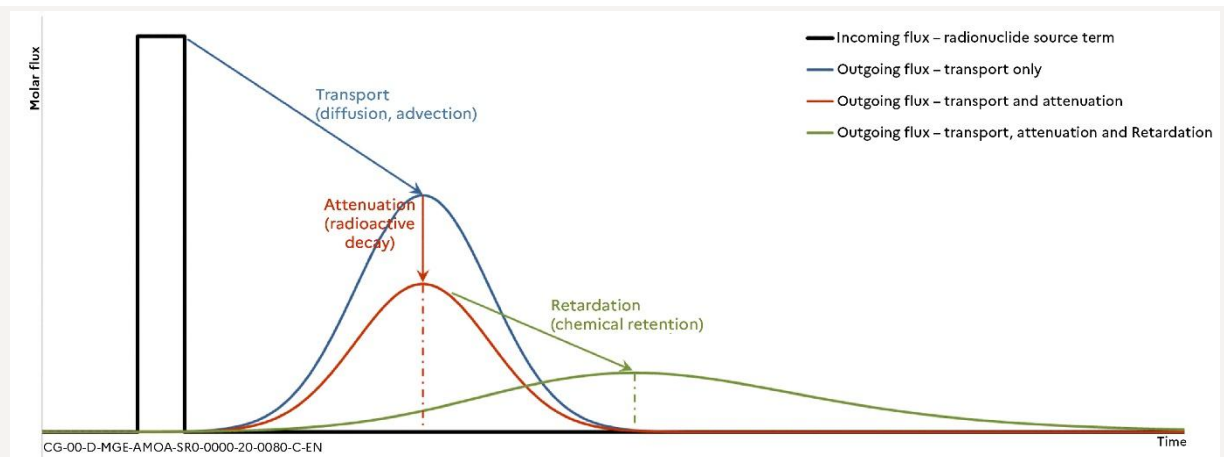


Figure 3-2 *Diagram illustrating the processes of decay, attenuation and delay of a radionuclide put into action in its migration by diffusion over time at a given distance from a source (radionuclide flux arriving at a given distance from a radionuclide source represented here by a quantity released at a constant rate over a given time interval)*

This is what happens in the Callovo-Oxfordian layer and is the basis for its capacity to satisfy radioactive-waste disposal requirements: the potential source of radionuclides is the disposal facility and the porous medium is the Callovo-Oxfordian layer. The latter has a high retention capacity for most of the radionuclides contained in radioactive waste, its diffusion capacity is very low, and it is very thick (between approximately 140 m and 160 m, that is to say at least 50 m to 60 m on either side of the disposal facility), so that most radionuclides migrate very little by diffusion inside the Callovo-Oxfordian layer and remain confined in the disposal cells or in the Callovo-Oxfordian layer in the immediate vicinity of the cells. The few mobile (non-retained) long-lived radionuclides that can migrate by diffusion, such as chlorine-36 or iodine-129, do so very slowly in the Callovo-Oxfordian layer, resulting in total flux at the boundaries of the Callovo-Oxfordian layer taking several hundred thousand years to reach maximum values and very low total radionuclide fluxes.

3.2 Operational safety functions

For Cigéo, as for any nuclear facility in France, regulations specify the following four safety functions to be taken into consideration:

- control of nuclear chain reactions, commonly referred to as "criticality risk";
- the removal of thermal power generated by radioactive substances and nuclear reactions;
- the containment of radioactive substances;
- protection of people and the environment against ionizing radiation.

In addition to these functions, Andra adds an additional function related to the specific characteristics of Cigéo: the evacuation of gases formed by radiolysis⁵ and corrosion.

⁵ Radiolysis is the decomposition of matter (solid, liquid, or gaseous) by ionizing radiation. Water can be radiolysed, as can gases, mineral salts and many organic molecules. It can potentially generate gases such as hydrogen (H₂), carbon dioxide (CO₂) or carbon monoxide (CO).

3.3 The guiding principles for managing the risks associated with Cigéo

3.3.1 Defence in depth

The principle of defence in depth for basic nuclear installations involves the implementation of successive lines of defence, each of which can intervene after the failure of the previous one. These lines of defence are designed to prevent the occurrence of, or, if necessary, limit the consequences of technical, human or organizational failures that could lead to accidents affecting human health or the environment.

After closure, the safety of geological disposal relies on passive systems that do not require human intervention. The principle of defence in depth means that the safety of disposal relies on the complementarity and diversity of components and on the redundancy of safety functions, so that plausible component failures do not compromise the safety of the facility. The application of the defence-in-depth principle results in:

- the assignment of safety functions to natural components (the site and in particular the host rock) and engineered components (preservation of the characteristics of the host rock);
- the implementation of monitoring activities from the construction of the repository onwards, and then during the operation of the BNI, to monitor the natural and engineered components that perform safety functions after closure;
- the definition of scenarios to ensure the robustness of the disposal system as a whole in the event of a failure or deviation from the expected evolution of the disposal system and the contribution of each component to this robustness, and to enable an assessment of whether the objectives of protecting people and the environment are being achieved.

During the operational phase, the principle of defence in depth aims to protect against failures by implementing successive lines of defence (or barriers). It consists of interposing between the source of danger and workers, the public, or the environment, enough technical and organizational measures to eliminate or limit the risk to an acceptable level. These measures are proportionate to the significance of the risks or disadvantages presented by the facility. The levels of defence in depth are organized into four levels:

- prevention, aimed at avoiding the occurrence of failures;
- monitoring, to detect malfunctions;
- control of accidents that could not be prevented, in order to restore and keep the facility in a safe condition;
- management of accidents that could not be controlled, in order to limit the consequences for people and the environment.

3.3.2 Design choices

Design choices also play a role in controlling the safety of the facility in the short and long term. These choices are guided by:

3.3.2.1 **Controlling the risks associated with the presence of radioactive waste packages and their handling**

Waste packages confine radioactivity and must be protected. Technological solutions for their handling (transfer operations, disposal) are chosen accordingly (e.g., limiting the height at which packages are handled and therefore the height from which they can fall). Once disposed of, the packages are kept in conditions that ensure the confinement of radioactivity.

3.3.2.2 **Controlling the risks of radionuclides and toxic chemicals being released from radioactive waste packages and potentially migrating to the surface**

The safety of post-closure disposal relies on the Callovo-Oxfordian layer and the complementary closure structures of surface-underground connections. The design of the underground structures and seals aims to limit both water circulation within these structures and the migration of radionuclides and toxic chemicals to the surface. Given the central role of the Callovo-Oxfordian layer, the design of the architecture of the underground structures and seals also aims to preserve its highly favourable characteristics by limiting the disturbances caused by the packages (radioactivity, heat, etc.) and by the structures (for example, by orienting the disposal cells in a direction that favours the preservation of a mechanically undamaged layer of Callovo-Oxfordian on both sides).

In addition, the technological solutions chosen for the design are as standard as possible and have been proven, in particular through technological tests conducted in underground laboratories or in fields other than disposal (e.g., underground work for the excavation of shafts, access ramps, drifts, and disposal cells).

4

Post-closure risk management

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The post-closure analysis is organized according to the following key stages:

- analysis of risks and residual uncertainties, based on an examination of potential disturbances to the behaviour of the Callovo-Oxfordian layer linked to the presence of radioactive waste disposal (thermal, hydraulic, mechanical, chemical), natural events and human activities (in the event of disposal being forgotten) that could occur, and on the state of scientific and technological knowledge;
- identification and definition of "post-closure safety scenarios" to represent how radionuclides contained in waste are likely to reach humans, in order to verify the disposal system's ability to ensure the long-term protection of people and the environment, and to ensure the robustness of this ability in the event of malfunctions or deviations from the expected evolution of the disposal system;
- quantitative assessment of these scenarios (quantification of indicators of the disposal system's ability to ensure the long-term protection of people and the environment, e.g., radionuclide inventory assessments at a given time between the different components of the disposal system compared to the initial radionuclide inventories in the emplaced waste packages, or human doses at exits);
- lessons learned from these assessments for subsequent iterations of knowledge/design/safety.

4.1 Analysis of risks and residual uncertainties

4.1.1 Overview of internal risks to the disposal system

After the disposal facility is closed, risks may arise from disturbances originating within the disposal system and their possible interactions. Design choices have been made to limit these internal risks.

4.1.1.1 Thermal disturbances

HLW packages are characterized by heat release that can alter the behaviour of disposal components, particularly the Callovo-Oxfordian layer.

The disturbances caused by this heat release are managed by limiting the temperature in the Callovo-Oxfordian layer through design measures (e.g., distance between HLW disposal cells, separation of HLW disposal areas from ILW-LL disposal areas to limit any thermal interaction between cells/areas).

4.1.1.2 Chemical disturbances

Due to their chemical composition and gradual degradation over time, waste packages, and in particular certain ILW-LL packages, can cause chemical disturbances in the environment in which they are emplaced.

Controlling these disturbances requires design provisions and rules for co-disposal of ILW-LL packages during operation (for example, to prevent chemical degradation products from one family of ILW-LL packages from disturbing the behaviour of radionuclides in another family of ILW-LL packages after closure). This is particularly the case for waste families containing organic components whose degradation products over time can complex radionuclides, and which are therefore not emplaced in cells with waste package families that do not contain organic components), and by physically separating the HLW and ILW-LL disposal areas.

4.1.1.3 Mechanical disturbances

In order to limit damage to the Callovo-Oxfordian layer caused by the excavation of structures within it, the voids left after closure in the underground facility are limited (drifts, shafts, and access ramps are backfilled, and disposal cells are designed and operated to minimize these voids as well). Disposal represents less than 1 % of the total volume of the surrounding Callovo-Oxfordian layer, helping to limit its mechanical effects on the geological environment in general.

4.1.2 Overview of external risks

External risks are linked to natural events (climatic and geodynamic events, earthquakes, etc.) or human events (given the very nature of disposal, particularly its depth, human activities known as "inadvertent human intrusion" mainly involve drilling of deep boreholes, assuming that the disposal facility has been forgotten).

The potential effects of these risks are also limited by design provisions:

- **Climate and geodynamic change**

The location of the disposal facility at a depth of 500 meters protects it for the next million years from geodynamic phenomena linked to climate change and surface erosion.

- **Earthquakes**

The seismic hazard is examined in terms of its potential effects on the characteristics of the Callovo-Oxfordian layer and on the closure structures, mainly the seals.

The influence of the presence of the disposal facility on the Callovo-Oxfordian layer in the event of an earthquake is considered negligible and does not call into question its favourable properties. Any seismic stresses on the seals and their effects are negligible regardless of the level of seismic hazard.

- **Inadvertent human intrusion**

Given the timescale considered (one million years), and although measures are taken to maintain the memory of the existence of the repository, it is postulated that the existence of the repository will be forgotten 500 years after its final closure.

If the repository is forgotten, the depth of the layer in which it is located will isolate the waste from human activities on the surface or at shallow depths. Furthermore, the repository site and the repository itself do not contain any exceptional natural resources that would encourage intrusion *via* deep drilling.

4.1.3 Overview of residual uncertainties

In order to assess whether the disposal system is functioning as expected, and whether the fundamental objective of protecting people and the environment is being achieved, the focus after closure is on integrating scientific and technological knowledge and controlling the residual uncertainties that have been identified.

The management of residual uncertainties is therefore an integral part of the safety demonstration. To this end, an analysis of the state of available scientific and technological knowledge is carried out regarding the safety functions that the components (natural and engineered) of the post-closure disposal system must perform.

Following the analysis of the disposal system's behaviour as it can be described based on the state of scientific and technological knowledge and the associated residual uncertainties, post-closure safety scenarios are identified. These are then quantitatively evaluated in terms of appropriate indicators (e.g., water flow in underground structures, radionuclide molar flow rates over time at the surface of the packages, cells, and Callovo-Oxfordian layer). These indicators make it possible to verify the functioning of the disposal system as a whole and to ensure its robustness. Assessments of the impact on human health expressed in terms of dose also make it possible to verify compliance with protection objectives.

» A SOLID AND ROBUST KNOWLEDGE BASE ACQUIRED OVER MORE THAN TWENTY YEARS

More than twenty years of research and development have led to the acquisition of a solid and robust knowledge base on the Callovo-Oxfordian layer and the geological site in general, the waste, the engineered components, and the interactions between the repository and the Callovo-Oxfordian layer in terms of characteristics and behaviour over time, particularly after closure.

This knowledge base has been enriched as Cigéo has progressed through key stages of development (2005 file, 2009 file, Safety Options Report in 2016, etc.), feeding into the design and safety assessment work following an iterative approach that can lead, for the objectives of a key stage in the development of Cigéo, to the adoption of design provisions that reduce knowledge uncertainties or minimize their consequences on safety, or to increasing knowledge in order to reduce uncertainties.

4.1.3.1 Residual uncertainties in input data

Residual uncertainties regarding knowledge of HLW and ILW-LL packages

The knowledge base on waste package families held by Andra enables the establishment of the radiological inventory to be disposed of. As a precautionary measure, Andra applies a multiplier factor to all 144 radionuclides in the radiological inventory; this factor can be as high as ten for some waste package families.

Residual uncertainties regarding knowledge of the Callovo-Oxfordian layer

Given the extensive work and studies conducted over more than 20 years on the site and the Callovo-Oxfordian layer, the level of residual uncertainty regarding the characteristics of the Callovo-Oxfordian layer with respect to the migration of radionuclides and toxic chemicals is limited.

4.1.3.2 Residual "technological" uncertainties

HA disposal containers

The technical solution chosen for the HLW disposal container has been studied for over twenty years. Based on a cautious approach, given the tests carried out, the checks during handling operations and their emplacement conditions, it is postulated that containers will lose their integrity prematurely as soon as the disposal facility is closed.

Seals

Based on positive feedback, particularly from experiments conducted at Andra's Underground Research Laboratory, those conducted by its foreign counterparts, and from surface demonstrators, a malfunction of a seal related to the construction operations is considered highly unlikely.

Taking a cautious approach, it is postulated that there may be interface defects between the seals and the Callovo-Oxfordian layer or defects in the intrinsic materials of the seal.

4.1.4 Overview of potential disturbances related to the presence of the disposal facility in the Callovo-Oxfordian layer

Mechanical disturbances

The acquired knowledge provides a good representation of the mechanical damage to the Callovo-Oxfordian layer in the immediate vicinity of underground structures. As a precaution, unfavourable developments in this damage are considered (e.g., at the level of the seals, which could lead to a deterioration in their hydraulic performance).

Thermal disturbances

The acquired scientific knowledge, particularly that relating to HLW cells, allows us to assess that the intensity and spatio-temporal extent of thermal disturbances due to the disposal facility on the Callovo-Oxfordian layer are limited.

Disturbances related to gas production

After closure, the disposal facility enters a phase known as "hydraulic-gas transient " due to the gradual return of water from the Callovo-Oxfordian layer into the disposal structures (resaturation phenomenon) and the production of hydrogen mainly from the corrosion of metal components present in the structures.

The design provisions aim to limit as much as possible the use of steel in the components left in place after closure. In addition, the design and construction of "permeable-to-gas" closure structures⁶ make it possible to limit gas pressure in the disposal facility during the hydraulic-gas transient and thus preserve the favourable characteristics of the Callovo-Oxfordian layer.

The evaluation of this phase has been the subject of experimental studies, particularly *in situ*, and numerical simulations, which demonstrate the robustness of the knowledge and carried out simulations, and draw attention to any residual uncertainties.

⁶ For seals, the concept of " permeable to gas" should be understood as allowing sufficient gas to pass through. The two functions of seals, "gas permeability" and "limitation of water flow within the disposal facility," are achieved through the remarkable characteristics of the swelling clays that form the basis of the cores, the choice of mixture of swelling clay and other components (e.g., sand), and the density of the mixture.

Chemical disturbances from ILW-LL

After the closure of the disposal facility, the gradual return of water from the Callovo-Oxfordian layer may cause chemical disturbances related to the presence of ILW-LL packages (saline or organic disturbances), concrete components (alkaline disturbance) or corrosion of metal elements. While these disturbances are limited, technical provisions are defined for the physico-chemical co-disposal of ILW-LL packages in order to limit this disturbance between waste packages in the cells and, ultimately, in the Callovo-Oxfordian layer.

» MONITORING MEASURES SPECIFIC TO THE POST-CLOSURE PHASE

Monitoring provisions are implemented from the initial construction phase onwards, then during the operating phase, and are intended in particular to ensure the proper behaviour of the various natural and engineered components.

Post-closure monitoring, the minimum duration of which will be set by the BNI dismantling and closure decree, will include measures already in place before final closure and maintained after closure if necessary. These measures will be chosen in such a way as to preserve the Callovo-Oxfordian layer so that it can play its role fully without intervention in the long-term protection of people and the environment.

Following publication of the decree on the dismantling and closure of the BNI and completion of the operations prior to the facility's definitive closure, the ASN will be responsible for authorising its transition to the monitoring phase. This authorisation will be issued on the basis of additional information provided by Andra, which will focus on demonstrating the effectiveness of the monitoring measures. This authorisation will also specify the procedures considered for preserving and transmitting the facility's memory during and after the monitoring phase.

4.1.5 Long-term evolution of the surrounding geological formations and hydrogeology

The Callovo-Oxfordian layer is surrounded by geological layers known as surrounding geological formations. These surrounding geological formations consist of limestone and marl layers. They have no safety functions, but they are nevertheless a pathway, known as a transfer pathway, for some radionuclides and toxic chemicals that may escape from the top and bottom of the Callovo-Oxfordian layer. The evolution of water flows in the aquifer levels or zones of the surrounding geological formations over the next million years has been assessed using simulations based on potential climate change scenarios (natural evolution, evolution disrupted by greenhouse gases) in order to cover the possible range of water flow evolution (*i.e.* Evolution of hydrogeology) over the long term. These simulations thus incorporated the effects of climate change on the erosion of outcropping geological formations and hydrography.

Thickness (m)	Formation	Lithology
0 to 4 m	Upper Jurassic and Cretaceous (undifferentiated)	
20 to 140 m	Barrois limestone	
≈ 110 m	Kimmeridgian marls	
≈ 280 m	Oxfordian limestones	
140 to 160 m	Callovo-Oxfordian (COX)	
> to 200 m	Dogger	

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Figure 4-1

Simplified geological cross-section

4.2 Post-closure safety assessment scenarios

The quantitative assessment of post-closure safety scenarios is based on the use of numerical simulation tools capable of modelling and quantifying the release and migration of radionuclides and toxic chemicals specific to each scenario.

The assessment of the potential impact on human health is based on an approach that draws on ASN Safety Guide No. 1 and international practices.

This approach, implemented by Andra, consists of several stages:

- selection of standard biospheres to be used for the assessment;
- selection of the location of water sampling points (outlets) for the hypothetical reference groups;
- selection of hypothetical reference groups to be used for the assessments. In accordance with the usual precautionary approach for this type of study over long time scales, several hypothetical groups are assumed to be potentially exposed, with behaviours representative of the habits and resources of the biosphere in its regional context;
- definition of human exposure pathways and potential transfer pathways between the outlets and humans.

» **BIOSPHERE:** all ecosystems, encompassing all living organisms and the environment in which they live.

To carry out quantitative assessments of post-closure scenarios, three standard biospheres are selected: a temperate biosphere, a warm biosphere (humid subtropical type), and a cold biosphere (boreal type). The analysis is based on simulations that consider two climate and geomorphological changes over the next million years: natural changes (climate not altered by human activity) and changes from anthropic effects (climate altered by greenhouse gases).

4.2.1 The "hypothetical reference groups"

The health impact assessment is based on mathematical modelling: a group of humans, known as the reference group, is imagined. This is a theoretical group that would live near the outlets and for which a variety of dietary behaviours are considered. This diversity aims to ensure that consuming, for example, much more meat or fruit than average, or fishing in rivers, would not lead to an unacceptable impact on an individual's health. For each selected outlet, various possible activities that make use of water are also examined: drinking water, watering animals, irrigation.

The different hypothetical reference groups selected for quantitative assessments are:

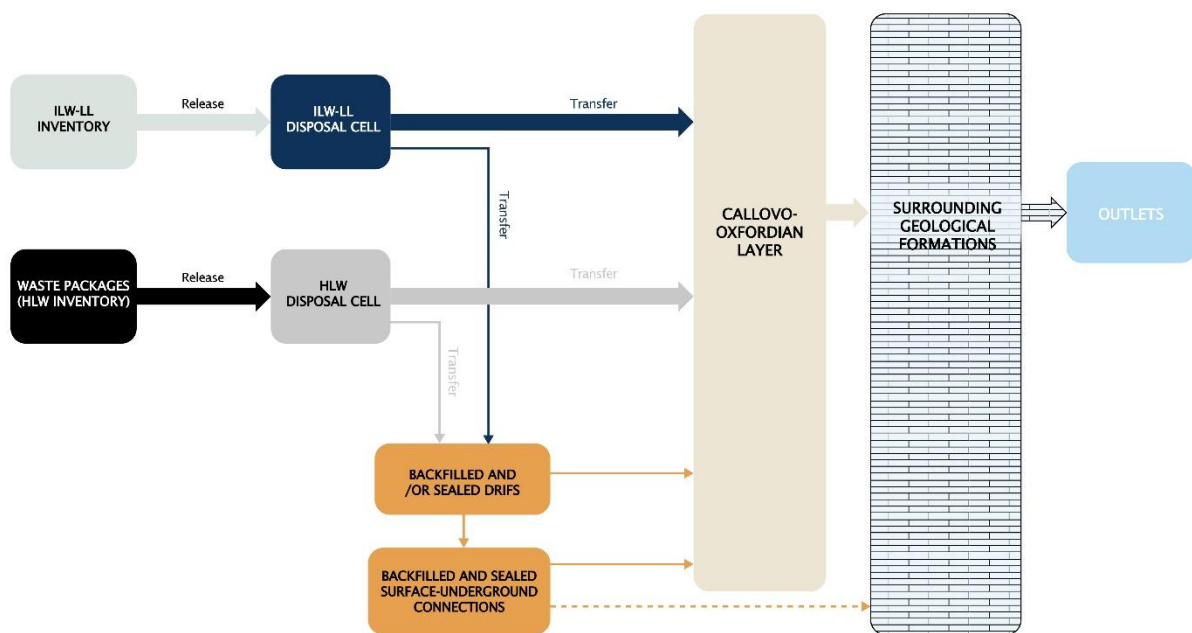
- a multi-activity group;
- a "cattle farmer" group (multi-activity) with higher consumption of beef and dairy products;
- a "gardener" group (multi-activity) with higher consumption of products from orchards and vegetable gardens;
- a "fisher-hunter" group (multi-activity) consuming products from river fishing and game hunting.

» **OUTLET:** a place (in the surface, subsurface, or deep layers of the ground) where water, possibly contaminated with radioactive substances, can enter the biosphere.

4.2.2 The different scenarios

The post-closure scenarios aim to cover all possibilities, even those that are highly unlikely, for changes over the next million years in the disposal facility and its geological environment after closure. They are classified into four main categories:

- **a design-basis evolution scenario**, which aims to represent the disposal system as designed, in which all post-closure safety functions are considered to be fulfilled. It includes two situations:
 - ✓ a reference situation, which is based on a set of assumptions and data selected on the basis of the best scientific and technical knowledge available and represent the expected evolution of the repository;
 - ✓ a "conservative" situation, which is a conservative estimate of individual exposures in order to cover knowledge related residual uncertainties.
- **a set of scenarios that cover different deviations from this design-basis evolution**. These scenarios consider malfunctions of components that contribute to the performance of safety functions: sealing, HLW packages, undetected discontinuity in the Callovo-Oxfordian layer. Depending on the situation, these scenarios are divided into:
 - ✓ "non design-basis evolution" scenarios representing events or processes considered unlikely based on current scientific and technological knowledge;
 - ✓ "What-if" scenarios based on the highly unlikely nature of the considered events, or based on postulated events to consider, for example, the loss of one or more safety functions. These hypothetical scenarios make it possible to "push" certain malfunctions to the extreme in order to demonstrate the robustness of the disposal system as a whole;
 - ✓ scenarios involving inadvertent human intrusion into the disposal facility site due to ignorance of its existence.



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Figure 4-2 *Illustrative diagram of components and transfer routes for the design-basis evolution scenario*

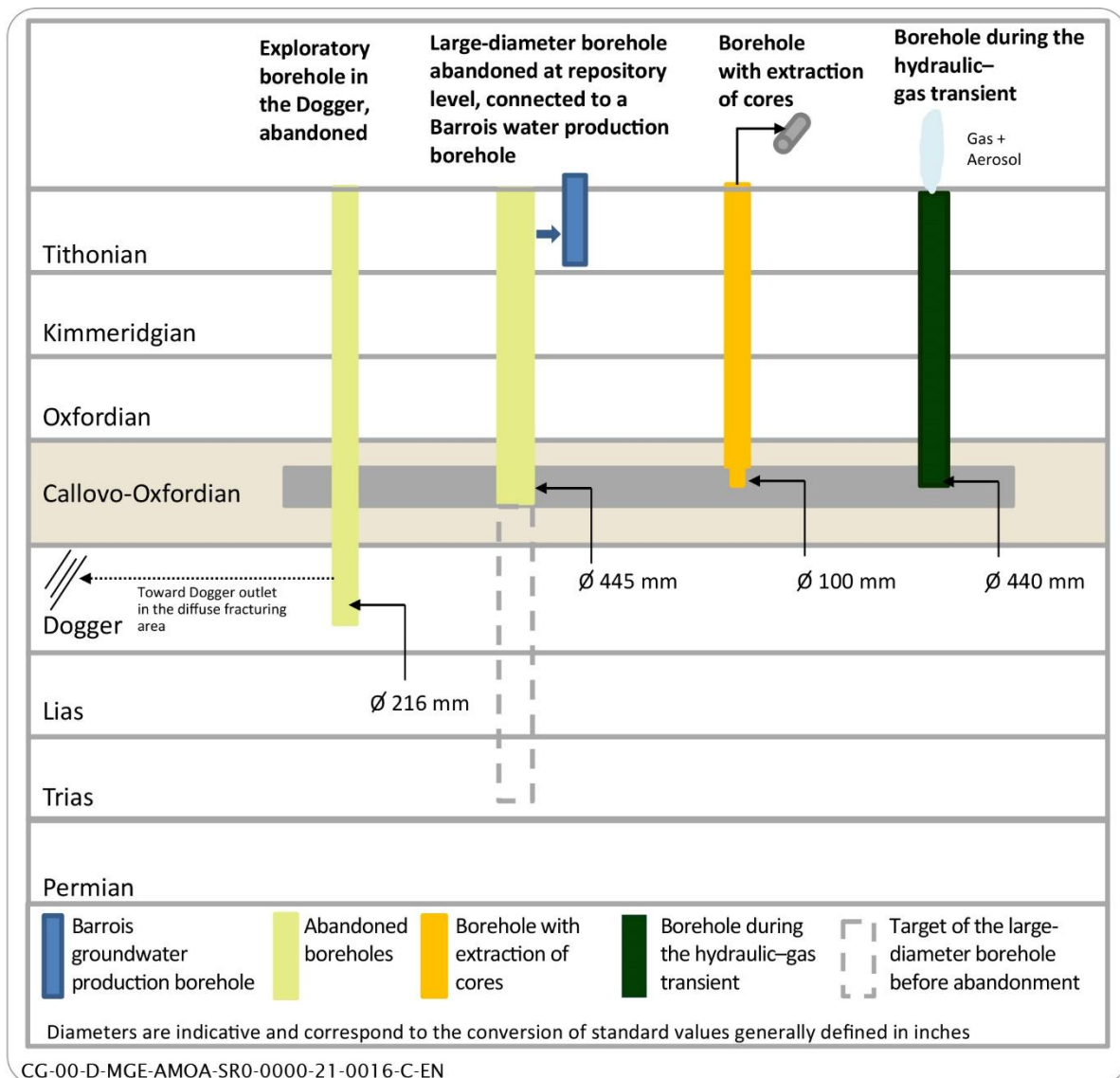


Figure 4-3

Diagram illustrating the different drilling scenarios postulated in the scenarios of inadvertent human intrusion

4.3 Quantitative assessment of post-closure safety scenarios

4.3.1 Assessment of the reference situation for the design-basis evolution scenario

The results of the assessments of the reference situation for the design-basis evolution of the disposal facility highlight the central role of the Callovo-Oxfordian layer and the very low health impacts on humans. They show that:

- most of the 144 radionuclides contained in the waste packages remain in the disposal cells or in the Callovo-Oxfordian layer in the immediate vicinity of the disposal facility. Only a few long-lived mobile radionuclides (selenium-79, iodine-129 and chlorine-36) can migrate over a very long period of time out of the disposal facility inside the Callovo-Oxfordian layer;
- The disposal system as a whole fulfils post-closure protection objectives.
- Regarding toxic chemicals, only mobile substances, mainly selenium and boron, reach the outlets, but their maximum concentrations at the outlets are well below regulatory quality standards and the hazard quotients and high individual risk values remain below the reference values.

In terms of human dose indicators, the maximum dose is reached after more than 600,000 years. It is low, approximately 0.0015 mSv/year, which is well below the reference value of 0.25 mSv/year mentioned in ASN Safety Guide No. 1.

4.3.2 Assessment of the other situations and scenarios

The design-basis-evolution "conservative" situation, which is a conservative estimate of the impacts in a normal evolution situation of the disposal facility, confirms the robustness of the disposal system regardless of residual uncertainties in knowledge.

It shows that the vast majority of radionuclides remain confined within the disposal areas or in the Callovo-Oxfordian layer near the facilities built in the layer. The few radionuclides that migrate from the disposal facility into the Callovo-Oxfordian layer are on the whole identical to those in the reference situation (iodine-129, chlorine-36 and selenium-79). However, the transfer times to the boundaries of the Callovo-Oxfordian layer are shorter than in the reference situation (in the range of 100,000 to 200,000 years).

Regarding toxic chemicals, only mobile substances, mainly selenium and boron, reach the outlets, but their maximum concentrations at the outlets are well below regulatory quality standards and the hazard quotients and high individual risk values remain below the reference values.

The robustness of the disposal system is further demonstrated by the results of the deviation scenarios of the design-basis evolution. For example, these deviations could be due to:

- premature loss of integrity of HLW disposal containers;
- a malfunction of seals;
- a possible discontinuity that has not been detected in the Callovo-Oxfordian layer;
- inadvertent human intrusion (deep drilling).

The results of the assessments of these scenarios further highlight the central role of the Callovo-Oxfordian layer, even with conservative characteristics, reinforced by the aforementioned design of the disposal system (in particular the modularity of the disposal or the lengths of the drifts from the cells to the surface-underground connections structures). These results are essentially similar to those of the design-basis evolution scenario in terms of containment performance. The maximum impact on human health in terms of annual dose remains in most cases of the same order of magnitude as that of the design-basis evolution scenario.

In all cases for the non design-basis evolution, *What-if*, and inadvertent human intrusion scenarios, the maximum dose levels remain below the levels likely to induce deterministic effects and, in most cases, below the reference value used for the design-basis evolution scenario (0.25 mSv/year).

4.4 Lessons learned from the assessment of scenarios

The assessment of the various scenarios, even taking into account penalizing values, highlights the central role of the Callovo-Oxfordian layer in long-term safety thanks to its characteristics: significant thickness, low permeability, low hydraulic gradient, high retention, and low diffusion of solutes over very long time scales (several hundred thousand to millions of years).

The robustness of the disposal system relies heavily on the low water circulation within the Callovo-Oxfordian layer. For example, even assuming the existence of an undetected fracture in the Callovo-Oxfordian layer, this fracture does not constitute a preferred transfer route for radionuclides: only a very small fraction of the total radionuclide inventory is mobilized by the fracture. This behaviour is due to the fact that the fracture cannot circulate more water than the Callovo-Oxfordian layer is capable of providing, i.e., a small amount of water, even when the fracture connects the two formations above and below the Callovo-Oxfordian layer, the Dogger and the Carbonated Oxfordian.

All of the assessment results that were obtained are consistent with observations made on the Callovo-Oxfordian layer, but also on deep clay formations, in terms of their ability over very long time scales (several hundred million to millions of years) to limit water and solute flows (measurements of natural tracers or observations of fractures show, in particular, very low water circulation or transparent hydraulic behaviour, except in extreme cases of tectonic context, which has not been the case in the Paris Basin for several million years and will not be for thousands of years to come), but also their physicochemical buffering capacity in response to physicochemical stresses, such as those, even limited and controlled, of caused by the disposal facility in the Callovo-Oxfordian layer.

The design of the underground architecture takes advantage of these characteristics to limit water flow in the disposal facility and constrain the migration of radionuclides and toxic chemicals within the Callovo-Oxfordian layer, thus making this migration very low and slow.

In addition, prudent design choices have been made, such as limiting the maximum temperature in the Callovo-Oxfordian layer, separating the HLW and ILW-LL disposal areas, and adding a disposal container for HLW primary packages, which aim to simplify the behaviour of the disposal facility and the Callovo-Oxfordian layer over time, thus ensuring its control and limiting residual uncertainties.

This combination makes the disposal facility highly robust in response to residual uncertainties and possible or postulated failures of disposal system components, such as a failure of all HLW disposal containers or all seals. Nevertheless, these sophisticated components play a complementary role to the Callovo-Oxfordian layer by helping to ensure the containment of radionuclides or toxic chemicals in the repository and in the Callovo-Oxfordian layer in the near field of the repository, or by limiting their migration into the Callovo-Oxfordian layer.

5

Operational risk management

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5.1 Principles and methodology

The safety demonstration approach applies to all basic nuclear installations. It aims to demonstrate that the technical provisions and organizational measures implemented in the facilities guarantee the protection of interests, i.e., public safety, health, and welfare, as well as the protection of nature and the environment.

These provisions are designed to prevent accidents and limit their consequences in all situations encountered (normal and degraded, incidents and accidents, aggravated accidents). The approach is based on:

- **the principle of "defence in depth,"** i.e., the implementation of several protective barriers to prevent and limit risks;
- **the ALARA** (as low as reasonably achievable) **principle:** this approach consists of keeping the dose received by operating personnel and the public as low as reasonably achievable, considering the available techniques and economic and social factors. In all cases, this dose must be below the regulatory limits defined in the French Public Health Code;
- **radiation protection objectives**, which encompass all measures aimed at preventing or reducing the harmful effects of ionizing radiation on people or the environment. These objectives are defined by the French Public Health Code, and Andra also relies on the recommendations issued by the International Commission on Radiological Protection (ICRP).

Andra's demonstration of operational safety is based on several stages:

- risk analysis, i.e., the methodical study of all internal and external physical phenomena that could affect the facility;
- analysis by operating situations, i.e. the methodical study of events likely to affect the facility;
- assessment of the radiological and non-radiological impacts of different operating situations, to verify compliance with protection objectives and the ability to manage accident and post-accident situations, with the aim of assessing the acceptability of these situations.

The demonstration of operational safety covers the entire facility and relates to construction and operating activities.

5.2 Taking feedback into account

The demonstration of operational safety is also based on an analysis and consideration of feedback from the construction and operation of other facilities. For example, for underground facilities, the following were examined:

- **WIPP (United States)**

The WIPP is a deep geological repository operated in the United States for long-lived radioactive waste of military origin. It is located in a salt formation at a depth of approximately 700 meters and began operating in 1999.

In 2014, two events, a fire and an exothermic reaction inside a waste package, occurred in quick succession, affecting the facilities and leading to a shutdown until January 2017, after corrective measures were implemented and approved by the authorities.

The feedback from WIPP highlights several points that have been considered for Cigéo:

- ✓ the importance of controlling the contents of waste packages;
- ✓ the need for a rapid monitoring and detection system;
- ✓ the physical separation of the work area from the nuclear area in the Cigéo underground facility;
- ✓ the organization of Cigéo, which promotes rapid and effective management of accident situations.

- **The Asse mine (Germany)**

Asse is a former German salt mine that has been converted into a radioactive waste disposal facility using various salt mining cavities in their current state. Contaminated brine from the dissolution of salt by water was detected as early as 1994, highlighting the risk of water ingress and the possible risk of cavities collapsing due to salt dissolution. This led to the permanent shutdown of radioactive waste disposal at the Asse mine. Since the accident, Germany has studied several options for managing the Asse site and has resumed the search for a site for the disposal of its waste.

The lessons learned from the Asse mine highlight several points that have been taken into account for Cigéo:

- ✓ a facility designed and dedicated from the outset solely for the disposal of radioactive waste;
- ✓ making provisions in advance to enable the retrievability of waste packages;
- ✓ a design that limits the risk of water infiltration into the underground facility;
- ✓ providing for conservative sizing of the linings/supports of underground facilities;
- ✓ implementing a total separation between the nuclear operating area and the area where excavation work is carried out in order to avoid the risks associated with coactivity.

- **Stocamine, France**

Stocamine is a former salt mine that has been converted into a disposal facility for industrial chemical waste received in bags ("big bags") or metal drums, sometimes emplaced on wooden pallets. Stocamine experienced a fire in September 2002, caused by internal heating within the chemical waste.

The lessons learned from Stocamine highlight several points that have been considered for Cigéo:

- ✓ the importance of the process for accepting packages for disposal;
- ✓ the implementation of fire monitoring, prevention, and control measures, as well as the separation of the work area from the nuclear area in the underground facility;
- ✓ the consideration of human factors in risk analysis and accident management.

- **Andra's Underground Research Laboratory**

The Meuse/Haute-Marne Underground Research Laboratory has experienced two serious accidents, each resulting in the death of an operator: one in 2002 during the excavation of the laboratory's main shaft (falling steel plate) and the other in 2016 during an operation to shape a gallery lining, an operation that had been carried out without any particular problems dozens of times before (falling rock block).

Feedback from the Andra's Underground Research Laboratory highlights several points that have been considered for Cigéo:

- ✓ the preferred use of full-face tunnel boring machines for digging access shafts and galleries, thus eliminating the need for human presence at the working face;
- ✓ the separation of excavation activities from operational activities (disposal of packages);
- ✓ the implementation of systems to monitor the construction and maintenance of underground structures;
- ✓ taking human factors into account in risk assessments relating to underground work and the management of related accident situations.

5.3 Inventory of operational risks and measures considered to control them

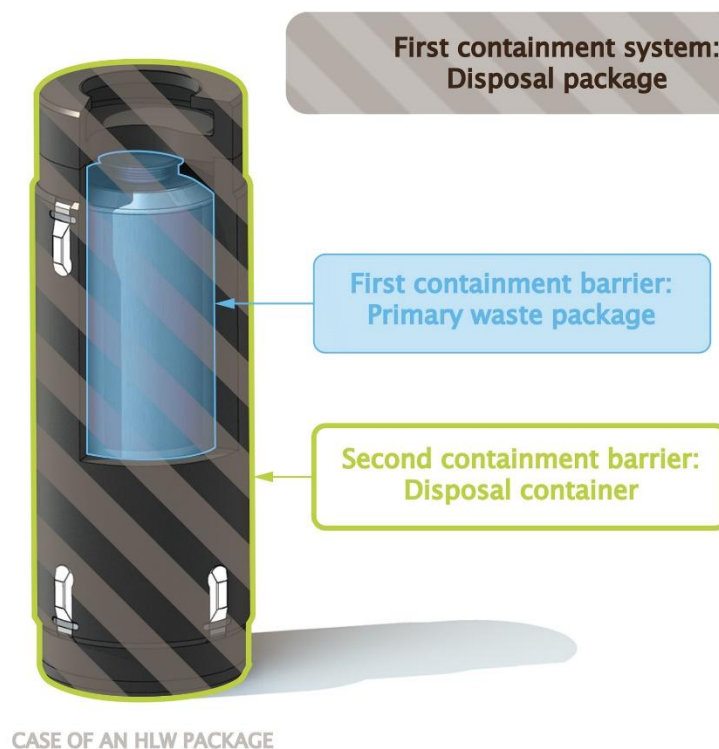
5.3.1 Internal nuclear risks

'Internal nuclear risks' are risks associated with the presence of radioactive elements within waste packages.

5.3.1.1 Risk of radioactive substance release

The risk of release is linked to the presence of radioactive substances inside or on the surface of waste packages. It concerns all areas through which waste packages pass. The measures taken to address the risks of radioactive substance release, depending on operating conditions, are as follows:

- presence of two independent containment barriers in normal operation and in degraded mode;
- maintenance of at least one containment barrier at all times for incident and accident situations.



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Figure 5-1 *Illustration of the first containment system associated with HLW in disposal packages consisting of two barriers*

Ventilation may be used to supplement a containment barrier as needed. Containment systems are monitored through checks on packages and radiological monitoring of premises, as well as checks on static containment barriers.

5.3.1.2 Risks of exposure to ionizing radiation

The risk of exposure to ionizing radiation mainly concerns workers who may be in the vicinity of HLW and ILW-LL packages. It may be of the following types:

- internal: suspension and transfer through contact with contamination present on the surface of waste packages or through breach of waste package containment;
- or external: proximity to radiological sources.

As a preventive measure, the risk of exposure to ionizing radiation is controlled primarily by favouring remote-controlled operations and organizing the facility into radiation zones in accordance with regulations on radiation protection for workers.

Monitoring covers the premises and relevant personnel. Sensors for monitoring contamination or external exposure are coupled with alarms to alert personnel of any abnormal situation.

The main measures to limit the consequences in terms of external and internal exposure are based on ensuring that premises and equipment used for radiation protection purposes are sufficiently sized and that appropriate intervention procedures are in place.

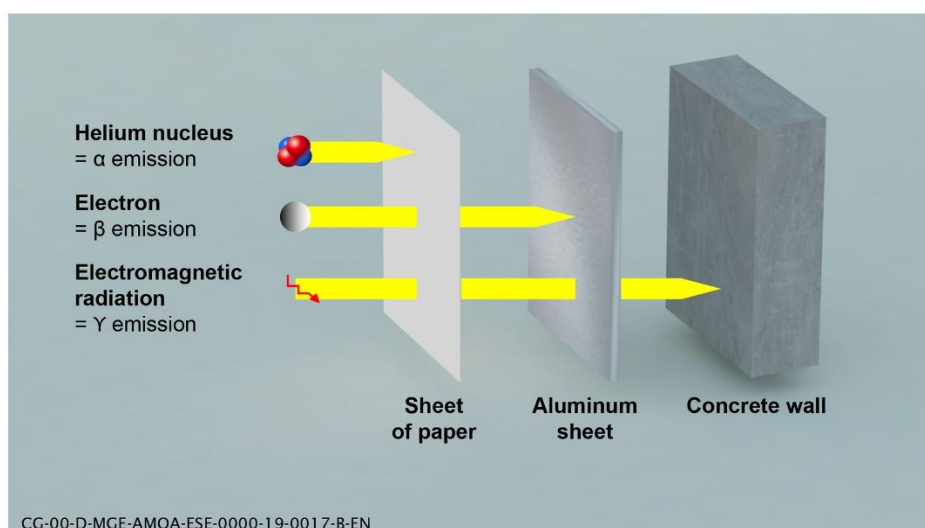


Figure 5-2 *Illustration of the penetrating power of different types of ionizing radiation*

5.3.1.3 Risks related to criticality

The criticality risk is the risk of an untimely and uncontrolled nuclear chain reaction, unlike what happens in a nuclear reactor where the reaction is initiated and controlled. This risk is linked to the presence of fissile materials in certain types of waste and is accompanied by a considerable release of radiation, heat, and gaseous fission products and aerosols.

The criticality risk is prevented by imposing a limit on the mass of fissile materials contained in packages and by implementing a control method in each part of the facility (storage and disposal).

5.3.1.4 Risks related to package thermal characteristics

The heat release from HLW packages and, to a lesser extent, from certain ILW-LL packages is linked to the presence of radionuclides. It can degrade the properties of materials, cause thermosensitive equipment to malfunction, and/or create hazardous working conditions for personnel.

Risks related to package heat generation mainly concern areas where there are large numbers of packages (buffer zones in the surface nuclear building and disposal cells) as well as unventilated and/or small-volume spaces (e.g., transfer casks).

Preventive measures to control the risk associated with package thermal conditions are based on knowledge and limitation of the thermal power of the packages received (which is why they must first be stored for a long period before being accepted into Cigéo), and compliance with the design of the disposal packages and the premises containing the waste packages and their equipment. A monitoring system is provided to detect any rise in temperature.

5.3.1.5 Risks associated with gases produced by radiolysis and corrosion (which may lead to a risk of explosion)

Risks associated with gases produced by radiolysis and corrosion, mainly hydrogen, are analysed regarding explosion prevention in the BNI.

For an explosion to occur, the following conditions must be met simultaneously:

- the presence of a gas, the concentration of which is such that it is within its explosive range;
- the presence of an oxidizer (usually oxygen in the air);
- the presence of an ignition source (spark, friction, ambient or wall temperature above the auto-ignition temperature of the gas in question).

The phenomenon of radiolysis results from the presence of materials containing hydrogen in waste packages, particularly certain ILW-LL packages. In the case of HLW packages, the production of radiolysis gas is negligible compared to the quantities produced by steel corrosion. Ionizing radiation can cause radiolysis gases (mainly hydrogen) to be produced.

The areas associated with risks related to radiolysis and corrosion gases are those in which there is a concentration of packages emitting radiolysis gases. In the case of corrosion gases, these are areas where hydrogen is released as a result of the corrosion of metallic materials.

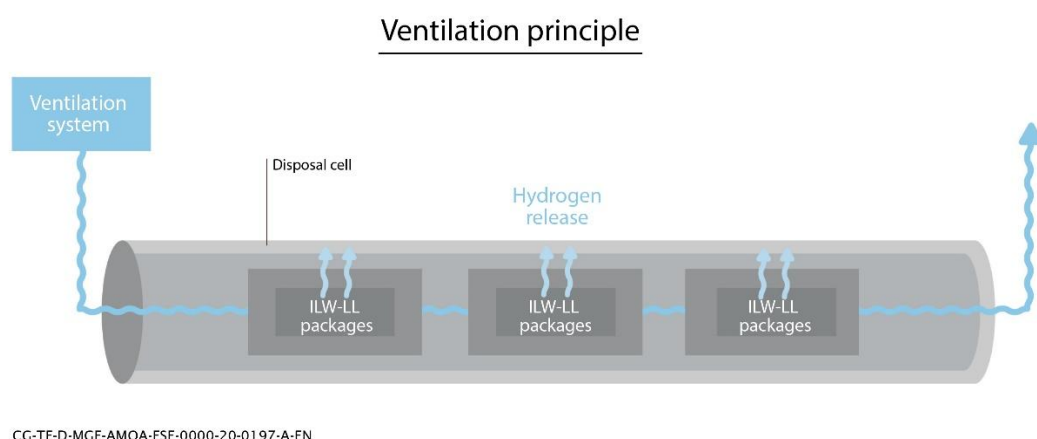


Figure 5-3 Illustration of the ventilation principle of an ILW-LL disposal cell

As a preventive measure, the risks associated with radiolysis and corrosion gases are controlled by two main provisions:

- limitation at source *via* package acceptance specifications, and therefore possible storage prior to shipment and handling at Cigéo;
- maintaining, during normal operation, a concentration well below the explosion limit, through design and/or organizational measures depending on the area concerned.

Monitoring is based on sensors measuring the concentration of hydrogen and/or oxygen in the ambient air, installed in exposed areas, with various alarms triggered when thresholds are reached.

Depending on the area, various measures are implemented to limit the consequences. Examples include: degassing devices, the ability to restart ventilation before the explosion limit is reached within the required timeframe (within 90 days).

5.3.2 Risks related to internal hazards

Risks of so-called "internal" hazards are non-nuclear risks related to the construction and operation of equipment and facilities.

5.3.2.1 Risks related to handling operations

Handling operations are carried out using various types of equipment, the main ones being:

- lifting equipment: handling cranes and lifting tables;
- rail-guided transfer equipment: surface and underground transfer trolleys, transfer carriages, primary package transfer system, surface shuttles, ramp transfer system, docking tables, loading and receiving tables;
- specific disposal equipment: stacking crane/transfer trolleys, pusher or puller robots.

During such operations, if a package were to drop, this could result in the release of radioactive substances, exposure of personnel, or the loss of equipment that protects the facility.

The design of the handling equipment used is based on conventional and proven technological solutions (best available techniques). Preventive measures are designed to control and limit transfer speeds and to secure movements and lifting chains in order to ensure that the load being handled is held securely in the event of a failure or an internal hazard.

For example, particular attention has been paid to the transfer of waste packages from the surface to the disposal areas by means of an inclined transfer in the nuclear facility's package access shaft by funicular, followed by horizontal transfer to the disposal areas once the funicular has reached the bottom.

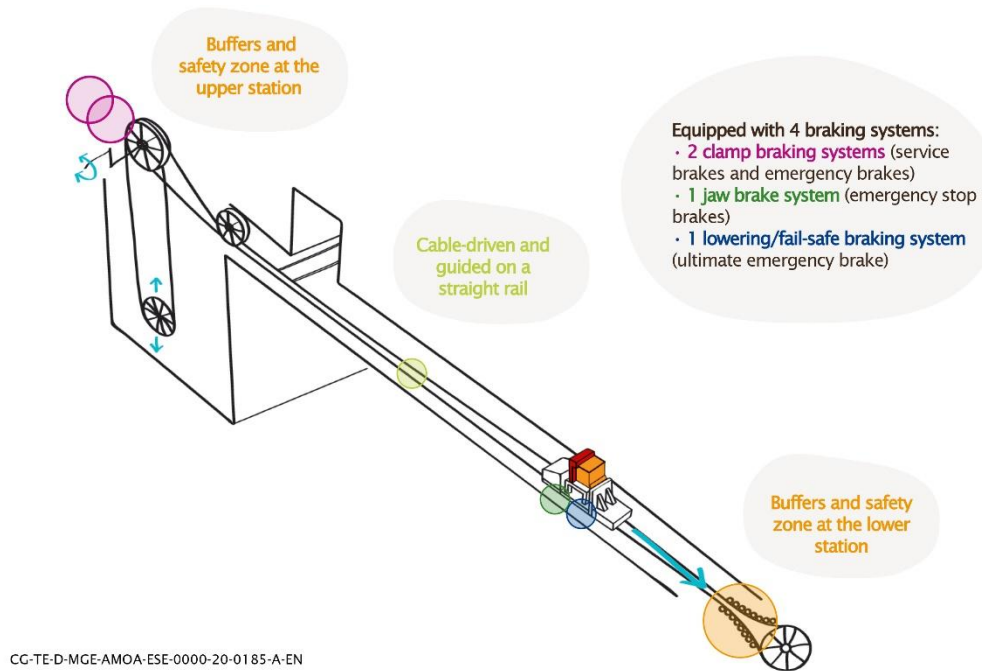


Figure 5-4 Illustration of safety devices for inclined transfer by the ramp transfer system in the access ramp

Measures to ensure the reliability of handling operations, limit lifting heights, and guarantee the inherent quality of primary and disposal packages ensure that the integrity of the packages' containment is maintained, even in the event of accidental drops, overturning, or collisions.



Figure 5-5 Illustration of the handling of ILW-LL disposal packages at low height

Operations are supervised by operators both nearby and remotely thanks to the instrumentation of the handling equipment. In the event of an accident, the equipment's movements are automatically stopped.

5.3.2.2 Fire risks

Fire risk management is primarily based on measures to prevent fires from starting, *including*:

- limiting combustible materials in the facility;
- the use of materials, equipment, and cables that are difficult to ignite or even non-combustible;
- limiting or even prohibiting the use of products that ignite quickly (such as gasoline);
- physically separating materials that could fuel a fire;
- designing handling equipment that limits the use of technologies that pose a fire risk.

Monitoring allows for the early detection of a fire, which can be controlled:

- by dividing the premises into sectors: the facility is designed so that, in the event of a fire, it remains confined to a specific area without affecting adjacent premises;
- by means of intervention and firefighting, in particular the permanent presence of intervention teams on site, combined with the installation of automatic detection and extinguishing devices.

The specific case of risks associated with fires involving packages of bituminous waste

Waste packaged in a bituminous matrix is subject to particular attention due to its sensitivity to temperature increases.

As a precautionary measure, Andra does not plan to emplace bituminous packages in the first cells to be commissioned. The associated design and safety studies currently consider two disposal methods, regardless of the method(s) ultimately selected:

- a method of disposal of bituminous waste packages as they are, in fire-resistant concrete containers, before they are transferred and emplaced in dedicated cells, the design of which is also fire-resistant;
- a method of disposal of waste packages resulting from prior treatment aimed at neutralising bituminous waste.

5.3.2.3 Explosion risks

The explosion risks identified are related to the presence of batteries that may release hydrogen during charging, chemicals that may generate flammable vapours, and flammable gas cylinders.

Controlling the risk of explosion relies on eliminating at least one of the three conditions necessary for an explosion: fuel, oxidizer, and ignition source (such as a spark). Hydrogen and ozone concentrations in the air are continuously monitored and ventilation is used to disperse these gases. Chemical containment systems are frequently visually inspected. Batteries are charged in rooms located away from high-risk areas. Gas-generating equipment is automatically shut down in the event of a loss of ventilation.

5.3.2.4 Risks associated with loss of power supply

Loss of power supply can cause the shutdown of equipment necessary for controlling other risks, such as the containment of radioactive substances, ventilation to prevent the accumulation of hydrogen, or even the monitoring devices for the installation or the air conditioning of electrical technical rooms.

The electrical system is designed around a robust electrical architecture with redundancies and electrical protections that comply with current standards and allow for different levels of reliability depending on the function to be performed. It is continuously monitored to identify any faults and reconfigure the network if necessary.

In the event of a power supply failure, numerous redundant systems take over the most important functions. In addition, a backup power supply provides power to the most sensitive equipment, such as the ventilation system, the monitoring system, the automatic fire detection and extinguishing system, the emergency lighting, and the main handling systems. If the power supply, including the backup power supply, is completely cut off, the equipment automatically switches to safety mode.

5.3.2.5 Risks associated with fluid loss

The risk of fluid loss concerns cooling fluids, heating fluids, compressed air, water-based fire extinguishing systems, and the nitrogen production and distribution network.

Continuous monitoring is carried out. The active equipment in the networks transporting these fluids, and even some of the networks themselves, are redundant. Emergency reserves are provided. In the event of a failure, the installation is brought to a safe condition.

5.3.2.6 Risks associated with loss of ventilation

Ventilation ensures the dynamic containment of certain premises, the maintenance of suitable atmospheric conditions, the evacuation of gases, and smoke extraction in the event of a fire.

The ventilation system is designed to compensate for numerous malfunctions: redundancy of certain equipment such as extraction fans and high-efficiency filters, redundancy of the power supply, and fire protection for certain equipment. The equipment is also designed to withstand external aggressions such as earthquakes or extreme weather events such as tornadoes. The ventilation system is subject to regular visual inspection of equipment, preventive maintenance, and automatic monitoring of equipment by sensors.

In the event of a loss of ventilation, operations are halted until the problem is corrected. A ventilation shutdown does not have any immediate consequences for safety (ventilation must be restored within an estimated 90 days).

5.3.2.7 Risks associated with loss of radiological and gaseous releases monitoring

Radiological monitoring helps control the risk of exposure to ionizing radiation. Prevention is based on compliance with current standards for monitoring equipment, redundancy of this equipment and information networks, a dedicated power supply and installation out of reach of fires. Any faults are reported to the automated control room.

As soon as a loss of radiological monitoring is identified, personnel evacuation and physical lockdown of the affected premises are implemented as a precautionary measure while the necessary checks and corrective measures are carried out.

5.3.2.8 Risks associated with loss of the control system

The control system refers to all systems that automatically perform measurements and provide regulation or protection functions. Its failure can lead to other failures, such as ventilation malfunction or radiological monitoring failure.

The design of the control system is based on proven systems and complies with current standards. It is subject to continuous monitoring. In the event of a malfunction, the control equipment is safely shut down by additional automatic systems, or the equipment itself switches to a safe state.

5.3.2.9 Risks related to internal flooding

The risk of internal flooding stems from the presence of water supply networks, liquid effluent collection networks, and hydraulic fluids. Flooding may be localised or widespread.

The networks are designed in accordance with current standards and a maintenance program is in place. The networks are located as far as possible from sensitive areas (e.g., electrical rooms) and some equipment is raised above ground level. Any leaks are identified by sensors and valves can shut down all or part of the networks.

5.3.2.10 Risks related to non-radioactive hazardous substances

Operations involving hazardous substances are carried out in the absence of any waste packages. However, in the BNI, hazardous substances such as acetone are used for maintenance operations and could damage equipment such as the seals between the package transfer casks and the docking facades of the disposal cells. Operators are therefore trained in the use of this product and in monitoring the seals. If acetone comes into contact with the seals, maintenance operations are carried out to restore containment.

5.3.2.11 Risks related to the emission of projectiles

Risks related to projectile emission concern moving parts that, in the event of failure, could strike a safety target or equipment involved in performing a safety function. This mainly concerns the blades of air supply and extraction fans.

Prevention of this risk is based on the design and maintenance of the fans. Any failure is detected by sensors and, if necessary, the faulty fan is shut down. The redundancy of equipment, the separation of ventilation networks according to buildings and functions to be performed, and the installation of specific ventilation networks to meet specific and local needs make it possible to limit the consequences of projectile emission.

5.3.2.12 Risks related to the ageing of equipment and structures

Ageing is the transformation or modification that a structure or piece of equipment undergoes simply as a result of time or of the environmental conditions to which it is subjected. It is a normal and inevitable phenomenon, which can result in increasingly frequent malfunctions or failures of equipment, or even a breakdown that prevents it from functioning.

Controlling this risk relies on design provisions (in particular, resistant materials and equipment, or equipment redundancy), a maintenance and monitoring program for materials and equipment, and the maintenance of stable environmental conditions during the operational phase.

5.3.3 Risks related to external attacks

Risks of so-called "external" attacks are non-nuclear, natural or man-made risks occurring outside the equipment and facilities.

5.3.3.1 Risks related to aircraft crashes (airplanes or helicopters)

The consequences of an aircraft crash (airplane or helicopter) are mainly likely to affect surface facilities and the exits of the underground facility. In addition to the impact on structures, which could cause more or less localised destruction of civil engineering works, the risk of kerosene spillage and ignition leading to a fire is also considered. Given their location 500 meters underground, the underground structures are not likely to be directly affected by an aircraft crash.

Cigéo is located far from regional airports and air corridors. Risk management is based primarily on the design of the civil engineering structures of the buildings so that they can withstand such a crash. The storage of packages in surface facilities is limited and prohibited outside the surface nuclear building. Sensitive equipment such as fire water tanks are located far apart from each other to prevent them all from becoming inoperable in the event of an aircraft crash.

5.3.3.2 Risks related to the industrial environment and transportation routes

The facilities located in the industrial environment surrounding Cigéo and the transport routes that may pose a risk to the BNI are limited. These risks are mainly related to the presence or transport of hydrocarbons. The consequences are limited due to the sufficient distance between the sources of danger and the structures and equipment located in the BNI and due to the appropriate design of the structures and equipment likely to be impacted.

5.3.3.3 Risks related to earthquakes

The Cigéo site is located within the Paris Basin. The host geological formation is very stable and seismic activity in the area is extremely low.

In addition to damage to buildings and structures, an earthquake can cause damage to or loss of equipment that is important for safety, either through direct destruction of this equipment or through induced damage.

Controlling earthquake-related risks depends on the design of structures and equipment in terms of their stability, integrity, and functional performance. The greater the potential consequences of a component failure, the more robust the design of that component.

5.3.3.4 Risks related to external flooding

The risk of external flooding concerns surface facilities (rain, floods, storms, rupture of external pipes, etc.) and underground structures (water infiltration from aquifers crossed by surface-underground connections). External flooding can lead to risks of radioactive substance dispersion, loss of power supply, or even fire due to short circuits.

The following preventive measures are in place:

- rainwater collection systems and basins designed to absorb exceptional rainfall;
- the surface nuclear building has watertight walls and a watertight foundation slab, with a system for collecting water from rising groundwater;
- surface-underground connections are equipped with a waterproof coating over all or part of their height. Underground, water is collected and then brought back to the surface. Additional measures are provided for access shafts (waterproof walls, drainage systems).

All these systems are regularly monitored through inspections and sensors and this monitoring is stepped up during periods of heavy rainfall. The experience gained from operating the Underground Research Laboratory for more than 20 years provides Andra with a wealth of feedback.

5.3.3.5 Risks associated with extreme temperatures

Extreme temperatures, i.e., very hot or very cold temperatures, can cause equipment failure, particularly ventilation systems. For example, equipment that is sensitive to high temperatures, such as electrical systems, is located in ventilated technical rooms. If very high outdoor temperatures are recorded, certain operations, such as package handling, may be halted to prevent equipment failure due to overheating.

5.3.3.6 Risks related to extreme winds and tornadoes

Sensitive facilities are designed to withstand tornadoes or violent wind gusts of up to 230 km/h. The main risk is that elements may become dislodged and turn into projectiles. This risk particularly affects ventilation systems, which are therefore protected.

5.3.3.7 Risks associated with extreme snowfall

Sensitive installations are designed to withstand heavy snow accumulation on roofs. In addition, ventilation air intakes are all located high up to avoid the risk of obstruction. When Météo-France (French national weather broadcasting service) issues a weather alert, installations can be secured and access routes cleared of snow.

5.3.3.8 Risks related to lightning and electromagnetic interference

Lightning can cause power supply disruptions, damage electrical and electronic equipment, and even start fires. Conventional devices (lightning arresters, grounding) protect conductive equipment and electrical installations. They limit the risk of fire caused by high-current flow.

5.3.3.9 Risks related to external fire

The risk of external fire concerns the surface areas of the nuclear facility, due to their natural environment, which consists of forests and green spaces, or their industrial environment, linked in particular to the presence of fuel stations.

Preventive measures are mainly based on measures aimed at controlling the occurrence of a fire in the vicinity of surface facilities in the shaft and descent zones, by limiting nearby sources of danger. The materials used for facades, roofs, and doors of buildings are selected for their fire resistance properties, which are adapted to the identified risks. The equipment and emergency response organization put in place within the BNI to control fire risks, particularly internal ones, enable effective action to be taken against this risk.

5.3.4 Other risks

5.3.4.1 Risks related to construction operations

Construction operations generate specific risks related to:

- the use of explosives for digging shafts (the use of explosives ceases once digging is complete): prevention of this risk is based on the usual technical and organizational measures: reduction of the quantity of explosives on site, physical separation of detonators and explosives, distance from sources of heat and sparks, exclusive use of specialised personnel. All personnel are warned by audible and even visual signals when explosives are being used. Blasting areas are marked and access to them is monitored when they are in use. Firefighting equipment is located nearby.
- Presence of fuel on site: regulations relating to the transport of hazardous materials on public roads are applied, particularly for unloading operations (vehicles at a standstill). Sites are designed (canopies, enclosed premises) to protect unloading operations; tanks, equipment and pipes are monitored to detect any malfunctions. Limiting the consequences relies on the implementation of firefighting measures and the creation of a closed waiting area.

5.3.4.2 Risks associated with simultaneous activities

In the BNI, the simultaneous performance of nuclear operations and underground construction activities, in particular the excavation of new disposal cells, presents risks known as coactivity risks. Two principles are applied to avoid these risks:

- a robust barrier between the nuclear operating area and the construction area in the underground facility. This barrier consists of physical separations that are resistant to damage and impervious to fumes;
- total independence between the nuclear operation area and the construction area. Each area has its own utility networks (power supply, ventilation, etc.), monitoring systems, emergency systems, and evacuation systems. The excavation, construction, and equipping of new disposal cells are therefore carried out within a site that is "closed and independent" from the nuclear facility.

Regulatory inspections, periodic tests, and preventive maintenance are planned in advance, which limits the risk of simultaneous operations between these activities and those related to plant operation. If necessary, the latter can be interrupted.

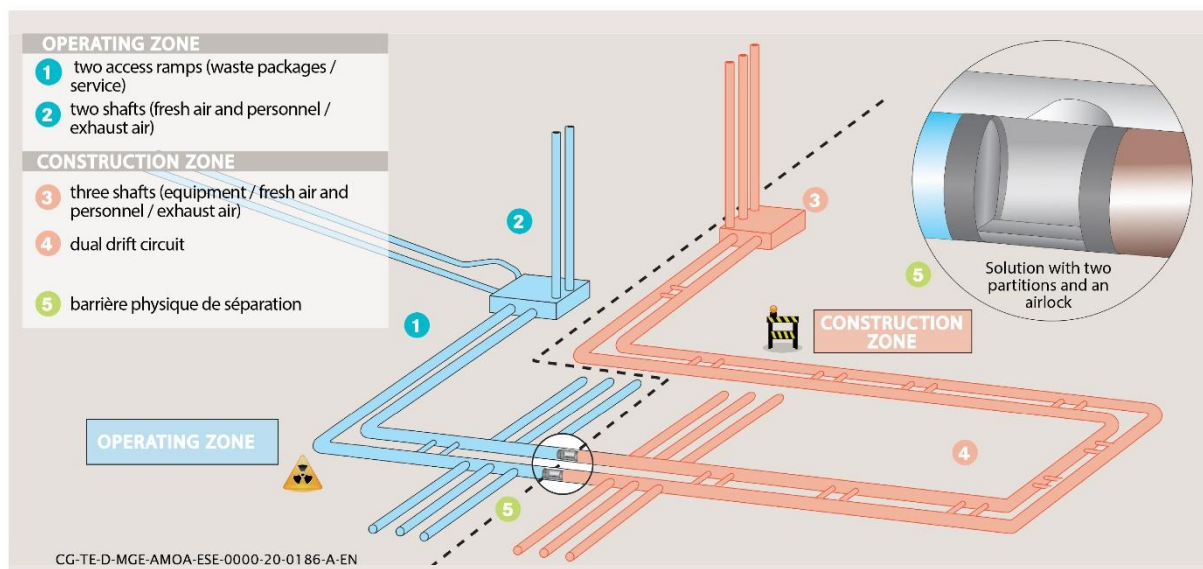


Figure 5-6 Illustration of the principles of coactivity management in the facility

5.3.4.3 Risks related to organisational and human factors

Controlling this risk involves general requirements that are not specific to Cigéo and can be classified into the following four categories:

- technical systems: documentation, equipment, tools used, human/machine control interfaces, means of monitoring and supervising the facility;
- the working environment: layout of premises, physical working conditions;
- work organisation: appropriateness of objectives and tasks, compatibility of roles and distribution;
- team management: management of staff, skills, training, necessary qualifications and certifications, operator experience, etc.

5.4 Analysis of the consequences of potential accidents for people and the environment

The study of accident situations aims to analyse the robustness of the safety demonstration regarding situations that are considered unlikely given the safety measures put in place in terms of prevention, monitoring, and consequence limitation.

The accident situations identified in the safety demonstration are mainly of the type involving falling packages or fire. Among all these situations, the following are developed:

- accident situations deemed plausible but which do not have a significant radiological impact on peoples and the environment;
- accident situations that are less plausible but would be more serious in terms of maximum dose to people and the environment.

In the event of an accident at Cigéo, analysis of even the most severe accident scenarios shows that the protection objectives are not exceeded and that there is no need to consider protective measures for the public, either in terms of time or space (such as sheltering).

5.4.1 Assessment of the impact on humans of accident situations

» THE RADIOLOGICAL IMPACT OF CIGÉO DURING NORMAL OPERATION

The radiological impact of Cigéo during operation is assessed in "Document 6 – Environmental Impact Assessment of the Cigéo overall project"(16), and more specifically in volume 6 "Impact on human health."

This assessment shows that the radiological impact of Cigéo during normal operation on local populations is very low: it is in the order of microsieverts, i.e., 1,000 times lower than 1 millisievert (mSv), which is the limit set by regulations for artificial uses of radioactivity and doses received in medicine. By way of comparison, this impact is imperceptible compared to the annual exposure of the French population to natural radioactivity (2.9 mSv per year on average).

The consequences of accidental situations are analysed by imagining people located in different places in a way that penalises the assessment of impacts: people located outside and in the immediate vicinity of the disposal centre fence, people living in villages located near the shaft and ramp zones who would be affected by atmospheric releases.

Three exposure durations are studied for the assessment of radiological risk to populations in the event of an accident:

- for the short term, the exposure period is 24 hours;
- for the medium term, the exposure period is one year;
- for the long term, the exposure period is 50 years for adults and 70 years for children who were youngest at the time of the accident.

To assess the consequences associated with radionuclide releases, different exposure pathways for humans are considered:

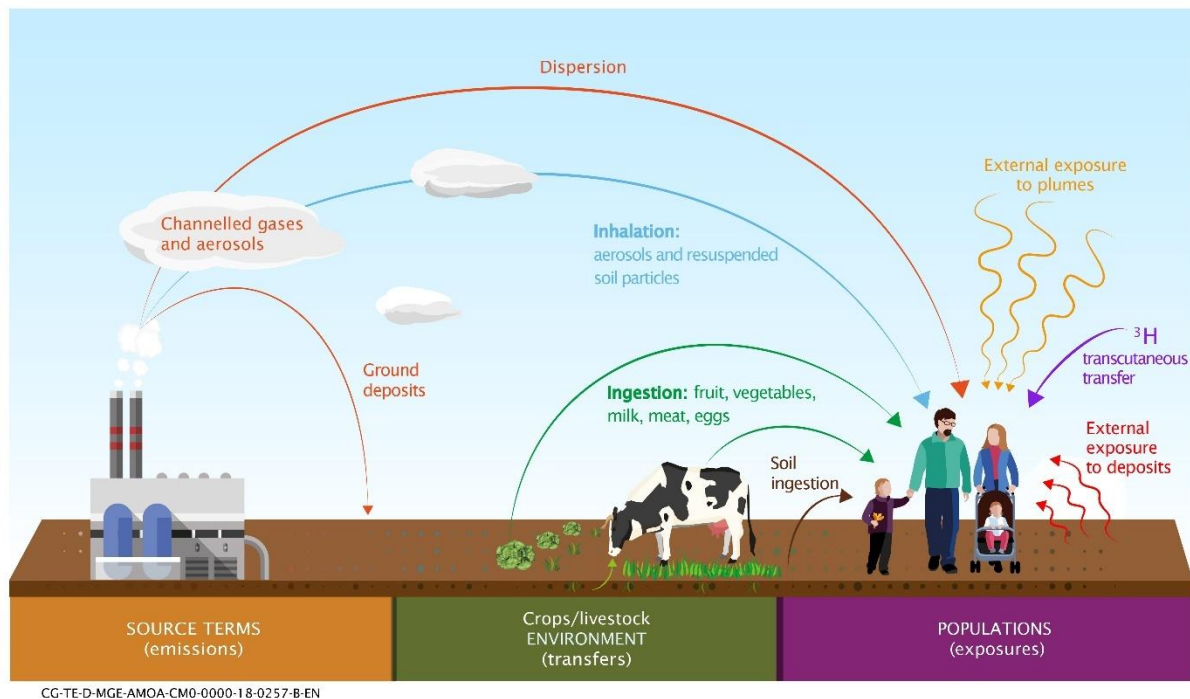


Figure 5-7 Schematic representation of the transfer and exposure pathways of atmospheric emissions

5.4.2 Illustrations of accident scenarios during operation with their potential impacts

The examples cited below are situations considered plausible, but which would not have a significant radiological impact on humans or the environment.

- **Fall of a primary package following the failure of a crane**, compounded by a malfunction of the first level of filtration.

The consequences of such a situation are a loss of containment of the waste package being handled and, if there is one, of the package located directly below. This event would result in the release of radioactive substances into the environment. However, it does not pose a risk of internal exposure to personnel, as no workers are present in the cell during operation of the facility.

The main safety measures taken to prevent this situation are: a robust design of the nuclearised crane lifting chain, limiting the speed and height of handling to what is strictly necessary, real-time atmospheric contamination sensors, and the presence of a second containment system that maintains its integrity in the event of a fall.

The maximum radiological impacts on the public living in the immediate vicinity of Cigéo are assessed over a maximum exposure period of 70 years. Depending on the nature of the waste packages, these impacts are very low, ranging from 0.001 mSv to 0.050 mSv. The maximum concentrations of toxic chemicals to which the public would be exposed are around 1,000,000 times lower than the chemical risk indicators.

- **Fire in a package transfer trolley in the surface nuclear building**, combined with a failure of the extinguishing system.

The consequences of this type of accident would result from the resuspension of labile contamination from the package on the pallet being transferred and from packages potentially located nearby. This event would result in the release of radioactive substances into the environment and a risk of internal exposure for workers who may be present nearby.

The main safety measures taken to prevent this situation are: limiting heat loads, choosing fire-resistant materials, installing an automatic fire detection and extinguishing system, creating a buffer zone classified as a fire zone and equipped with a containment area, and ensuring that primary packages are resistant to heat.

The maximum radiological impacts on the public are less than 0.001 mSv for any member of the public over a cumulative exposure period of 70 years.

5.4.3 Illustration of severe accident situations and their potential impacts during operation

The examples cited below are accident situations that are highly unlikely, but which would be the most severe in terms of maximum dose to people and the environment.

The radiological impacts on the public are estimated to assess the need for short-term protective measures. Under these conditions, estimates are made based on an exposure period of 24 hours. The assessments are compared with the target set by the authorities for accident situations, which is less than 10 mSv for the public.

- **fall of an open ILW-LL transport package during unloading in the surface nuclear building**, compounded by a failure of the shock-absorbing mat.

This situation corresponds to the worst-case accident leading to the highest absorbed doses around the ramp zone. It would result in the release of radioactive and toxic chemicals into the environment due to the loss of containment of the transport package and the ILW-LL primary packages.

The main safety measures designed to prevent this severe accident situation are: robust design of the secure crane lifting chain; sizing of shock-absorbing mattresses for transport package load drops in order to maintain their containment; presence of workers capable of detecting the event; detection of errors or anomalies in the execution of process sequences and evacuation of workers.

Once the drop of the transport packaging leading to the release of the primary packages it contains has been detected, the measures available to the operator to limit the consequences and manage the accident situation are based on:

- ✓ stopping the process: the packaging is immobilised on the floor;
- ✓ restoring the integrity of the packaging's containment (checks for contamination, sealing of joints where necessary, etc.);
- ✓ carrying out repairs to the handling crane, if necessary to evacuate the packaging to a dedicated area;
- ✓ decontamination of the transport containers' unloading hall.

The maximum radiological impacts are assessed based on the assumption that people would remain within 500 meters of the release point for 24 hours. The impacts range from 1 mSv to 9 mSv depending on the nature of the waste packages. The maximum concentrations of toxic chemicals to which the public would be exposed are around 1,000 times lower than the chemical risk indicators. According to current standards, the marketing of agri-food products would not be restricted and the establishment of public utility easements is not necessary.

- **Ignition of a package of bituminous waste in a disposal package**

This situation, assuming that bituminous waste packages are disposed as is (without treatment), corresponds to the worst-case accident scenario leading to the highest absorbed doses around the shaft zone. It would result in a loss of containment and the release of radioactive substances and toxic chemicals into the facility and then into the environment *via* the exhaust vent of the operational shaft.

Upon detection of the fire, the supply ventilation in the cell is stopped by closing the fire dampers on the cell's supply ventilation network. The exhaust ventilation is maintained as much as possible in order to continue filtering any radionuclides that may be resuspended. However, exhaust ventilation is stopped when it is no longer possible to maintain good filtration conditions. Then, despite the static containment provided by the walls of the disposal cell, it is assumed that radionuclides can pass through this wall, spread *via* the ventilation of the connecting galleries at the exit of the cell, and be released by the ventilation outlet of the underground facility in the shaft zone without being filtered.

The maximum 24-hour dose received by the public remains below 0.75 mSv around the shaft zone. This accident does not require protective measures (sheltering) for the public in terms of time or space. According to current standards, the marketing of agri-food products would not be restricted and the establishment of public utility easements is not necessary.

5.4.4 **Accidental situations related to the initial construction phase**

During the construction phase, there are no radioactive substances present within the BNI. Accident situations that could have chemical, thermal, and/or overpressure effects on the public are therefore analysed.

For example, during the construction phase of Cigéo, explosives are used to dig the shafts. The scenario analysed involves an explosion in the warehouse where the explosives are stored. In the event of an explosion, only the warehouse would be affected. The explosion would not have a domino effect on buildings or equipment located in the immediate vicinity. The location of the explosives warehouses will be determined at a later stage. The distances of the effects, assessed using very conservative assumptions and depending on the quantity of explosives used, will be taken into account in order to define the final location of the warehouses, so that they do not compromise the safety of the BNI, *through* the implementation of measures to limit the consequences of an explosion, which may be based on:

- the size of the warehouse in relation to the effects of the explosion;
- the establishment of security perimeters around the warehouse.

5.5 Monitoring systems, emergency response and accident management

5.5.1 Monitoring systems

The monitoring system set up at Cigéo helps protect people (workers and the public) and the environment from the risks posed by radioactive waste.

5.5.1.1 Radiological monitoring

Radiological monitoring of the premises (measurement and control of atmospheric contamination and radiation levels) is carried out using equipment installed throughout the facility. This equipment provides real-time monitoring of the radiological situation. This monitoring is supplemented by mobile atmospheric sampling devices installed as needed.

5.5.1.2 Atmospheric contamination monitoring

Devices enable real-time or delayed monitoring of atmospheric contamination levels. These devices are adapted to the different premises, the substances they contain, and the operations carried out (filtration on filters or cartridges). This monitoring is accompanied by periodic checks to ensure that the devices are in good physical condition, that there is no contamination, and that they are functioning properly, with sensors to signal any malfunction.

5.5.1.3 Radiological monitoring of gaseous effluents

Low gas and particle emissions linked to the presence of radioactive waste packages are the source of releases into the atmosphere. These atmospheric releases are made *via* two outlets, one at the surface nuclear buildings and the other at the stale air shaft in the operating area of the underground facility, allowing them to be channelled and partially filtered. They are monitored at each outlet by flow measurements and periodic and/or continuous measurements of the activities of the channelled releases from the nuclear ventilation system.

5.5.1.4 Radiological monitoring of liquid effluents

Radiological monitoring of liquid effluents is carried out as follows:

- Periodic checks analysed in real time for effluents related to routine operating activities, such as water extracted from access ramps and production shafts;
- Regular checks by sampling and by deferred laboratory analysis for effluents linked to specific operations such as condensate water, any effluents linked to operations in surface nuclear buildings, water drained from HLW disposal cells, and firefighting water.

All of these potentially radioactive effluents are collected, then radiologically monitored and transferred to an external facility for treatment. They are not discharged into the local environment.

5.5.2 Emergency and accident management resources

The nuclear facility has a dedicated emergency system with resources appropriate to the nature of the risks to which the facility is exposed.

The facility also has internal response teams consisting of *at least*:

- a security team corresponding to the internal emergency services, present 24 hours a day;
- a radiation protection team;
- an environmental team.

These teams can be reinforced by technical teams or even external emergency services.

When human intervention in the accident zone is still possible, the response teams have specialised equipment adapted to the situation, such as: firefighting vehicles and equipment, surface contamination measurement equipment, and decontamination equipment.

In the event of an accident where the radiation environment does not allow personnel to intervene *on site*, reconnaissance and analysis of the situation, recovery of the damaged package(s), and evacuation of any source material from the accident zone must be carried out using remote equipment or remotely operated robots. These areas are equipped with atmospheric contamination monitoring sensors, which allow the situation within the cells to be analysed before intervention.

Crisis management measures are defined in the internal emergency plan (IEP, *plan d'urgence interne*) to deploy appropriate emergency resources (technical, organizational, and human) in a timely manner to manage the crisis and limit its consequences. The activation of the IEP involves the establishment of various command posts (central command post, forward command post, central security post, etc.), which are organised with the aim of preventing the accident from becoming more serious in real time and limiting its consequences. IEP implementation exercises are carried out with the participation of the relevant public authorities and the ASNR.

Table 5-1 Objectives of an Internal Emergency Plan (IEP)

1	Control the emergency situation to prevent and/or limit its consequences
2	Alert, inform, and cooperate with public authorities and relevant external services to prevent and/or limit the consequences of the emergency situation
3	Alert and protect staff, provide assistance to victims
4	If necessary, characterise the radiological status of the site and characterise the radiological status of the environment outside the site
5	Inform local stakeholders and the media in liaison with the public authorities

TABLE SHOWING THE MAIN DEVELOPMENTS

The following table specifies the paragraphs that have undergone changes and their origin, which may be of various kinds:

- regulatory change: brought into line with regulatory changes following the initial submission of the DAC application;
- technical review with the ASNR: incorporation of clarifications provided to the ASNR during the technical review in relation to the content of the DAC file;
- file consistency: consistency between documents in the DAC file;
- DR0 consistency: consistency with the DR0 file submitted after the initial submission of the DAC file;
- consistency of the costing file: consistency with the costing file submitted after the initial submission of the DAC file;
- PNGMDR file consistency: consistency with the files submitted in response to the PNGMDR after the initial submission of the DAC file;
- energy policy consistency: updating of the reserve inventory and associated safety studies to take account of changes in energy policy. These elements were communicated to the ASNR as part of the technical review;
- Planning consistency: integration of the update to the commissioning date announced after the initial submission of the DAC file;
- Packaging consistency: brought into line with changes to primary package packaging announced by producers after the initial submission of the DAC application.

Updated paragraph		Update related to								
		Regulatory changes	Technical instruction with the ASNR	File consistency	DR0 consistency	Consistency of costing file	Consistency of PNGMDR files	Energy policy consistency	Planning consistency	Consistency of packaging
2.2	The phases of Cigéo								X	
2.	Waste intended for disposal in Cigéo			X						
3.1	Post-closure safety functions			X						

Updated paragraph		Update related to								
		Regulatory changes	Technical instruction with the ASNR	File consistency	DRO consistency	Consistency of costing file	Consistency of PNGMDR files	Energy policy consistency	Planning consistency	Consistency of packaging
4.3	Quantitative assessment of post-closure safety scenarios		X							

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