eurad 2

European Partnership
on Radioactive Waste Management

4.3.2 Climate change, Domain Insight

EURAD Roadmap

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The **EURAD Roadmap** is a representation of a generic radioactive waste management programme that shall enable users and programmes to access existing knowledge and active work or future plans in EURAD-2 and elsewhere. The content is focused on what knowledge, and competencies (including infrastructure) is considered most critical for implementation of RWM, aligned to the EURAD Vision.

All Roadmap documents can be accessed at the EURAD website: https://www.ejp-eurad.eu/roadmap.

The **Theme Overview Series** is part of the EURAD Roadmap, which is 7 high-level introductions to the EURAD Roadmap providing:

- **Guidance on typical goals and activities for RWM –** Activities (which may be of variable importance and scope depending on the nature of the disposal programme) provide generic guidance on how to achieve key programme goals and how priorities evolve throughout programme phases, from advanced programmes perspectives.
- **Competencies for RWM** – Needed competencies (and accessible infrastructure) for successfully managing a disposal program within the different phases of implementation.

The **Domain Insight Series** is part of the EURAD Roadmap, which in totality provides a high-level checklist of generic and typical activities needed for the full radioactive waste management lifecycle, leading to geological disposal including:

- **Functionality –** Contextual information about how activities and knowledge associated with a domain contribute towards achieving generic safety and implementation goals.
- **Maturity and State-of-Knowledge (SoK)** – Links to available SoK are included, providing an Experts' view of the most relevant knowledge and associated uncertainties (including areas of ongoing scientific and technological enquiry) in a specific domain applied in the context of a radioactive waste management programme.
- **Safety and Implementation Significance** – Contextual information about how activities and knowledge associated with a domain impact long-term safety or practical implementation.

The **Domain Insight Series** of EURAD comprises over 70 short documents, prepared by Europe's leading Subject Matter Experts across Radioactive Waste Management. The documents are aimed at early career professionals or new starters interested in best practice and key knowledge sources.

Overview

Climate domain is an integral part of any safety case needed to demonstrate the safety of radioactive waste disposal, be it surface, near-surface or deep geological disposal. Knowledge of climate and climate change are needed for all the EURAD Roadmap themes of national program management, pre-disposal, engineered barrier system, geoscience, disposal facility design & optimisation, siting & licensing and safety case. Climate change is one of the key issues in the analysis of long-term safety of any surface, near surface, and geological radioactive waste disposal system. It will influence the long-term evolution and performance of the natural environment (surface system and geosphere) and the engineered barrier system of surface and underground facilities. To this end, climate change affects both site selection (e.g. depth of the repository) and design of the engineered barrier system. It is also a key consideration when developing the biosphere models used to estimate possible radiological impacts. Its potential impacts on nuclear waste disposal are analysed in scenarios covering time frames from a few hundred or thousand years (operational and post-closure safety for surface and near-surface disposal) up to one million years (post-closure safety for deep geological disposal).

Keywords

climate, climate change, ice sheets, permafrost, sea-level change, air temperature, precipitation, IPCC, AMOC, safety case scenarios, disposal, barrier performance, anthropogenic greenhouse gas emissions, site selection.

Key Acronyms

AMOC – Atlantic Meridional Overturning Circulation

EBS – Engineered Barrier System

FEP – Features, Events and Processes

IPCC – Intergovernmental Panel on Climate Change

RE – Research Entity

TSO – Technical Safety Organisation

WMO – Waste Management Organisation

1. Typical overall goals and activities in the domain of Climate Change

In the analyses of long-term safety for a radioactive waste disposal system, the climate evolution is one of the key issues. Climate is considered as an overarching external FEP (Features, Events and Processes) subgroup that will influence the long-term evolution, and hence, the performance of the disposal system for radioactive waste. Climate will, of course, influence also other FEPs that affect the evolution of the natural environment (geosphere, surface system (that includes the biosphere), the engineered barrier system (EBS), and in case of radionuclide releases, effective doses to humans and dose rates to non-human biota.

Typical FEPs that belong to the Climate FEP subgroup are: global climate change, regional and local climate change, sea level change, periglacial effects, glacial and ice-sheet effects, warm climate effects, hydro(geo)logical response to climate change, ecological response to climate change, human response to climate change and, finally, geomorphological response to climate change (NEA, 2024).

The overall goal is to identify and quantify uncertainties in climate and climate-related processes that may affect operational and post-closure safety of the disposal system. Post-closure safety is often evaluated on timescales up to one million years in the case of geological disposal. The activities needed to achieve this goal are summarised in the table below.

Domain Goal	
4.3.2 Assess the nature of future climate change and landscape evolution and its potential impacts on THMC conditions in the repository host rock (including the repository) and surrounding formations (Climate change)	
Domain Activities	
Phase 1: Programme Initiation	Literature studies of current and past climate(s) in a broad range of latitudes and geographical regions (e.g. coastal sites, inland sites). Make a list of potential climate-related risks (e.g., heavy rainfall, freezing) for the desired facility (surface, underground).
Phase 2: Site Identification	From a climate-related risks point of view evaluate geographical regions or candidate sites to identify those most likely to be suitable.
Phase 3: Site Characterisation	Select a latitude-longitude interval around the selected site and develop a range of possible climate scenarios for both in the short-term (construction, operation) and long-term (post-closure). Assess potential risks and define appropriate design requirements and specifications for engineered barriers (e.g. depth, thickness, materials, …). The potential consequences are analysed in a safety assessment included in a safety case.
Phase 4: Construction	Review and, if needed, update climate scenarios based on the most recent scientific knowledge and lessons learned from previous phases, focusing on factors most relevant to repository performance. This might lead to an update of the safety case including of the safety assessment.
Phase 5: Operation and Closure	Same as phase 4.

2. Contribution to generic safety functions and implementation goals

Climate change is not a physical barrier to which safety functions are attributed. However, climate change and associated risks are relevant to the selection of a suitable site and the design of the EBS. For example, a range of future climate change scenarios have been accounted for in the implementation of the disposal programme for both surface facilities (e.g., Dessel in Belgium, El Cabril in Spain and Centre de stockage de l'Aube in France) and underground facilities (Forsmark in Sweden, Olkiluoto in Finland and Terradura in Switzerland).

Climate change also affects the development of the surface systems (e.g. landscape evolution and ecosystems). These systems and surface/underground disposal systems are interconnected, through especially, aquifers, surface water bodies and infiltration through the soil, overburden or multi-layer cover.

Potential impacts on the safety functions of disposal system components and on migration processes are analysed in the safety assessment. Because future climate conditions, particularly atmospheric CO_2 levels, are uncertain, it is necessary to define several climate scenarios, analyse their potential impacts in the safety assessment and ensure that the disposal system is sufficiently robust in the face of these uncertainties.

3. Impact of climate change on storage safety and long-term safety of the disposal system

Climate change is an EXTERNAL feature that must be considered to ensure STABILITY (that is, robustness) of the disposal system. Taking climate change into account is also essential to ensure ISOLATION (the waste is isolated from the human environment in a stable environment that is unlikely to be disturbed by human activities) because it may affect the barriers and the depth of the repository. Considering future climate change is also relevant for OPERATIONAL SAFETY.

Climate change is not a physical barrier and, by itself, does not contribute to storage safety or the long-term safety of a disposal system. However, it can influence engineered barriers and their surrounding natural environment (the surface systems and geosphere) to such an extent that long-term safety could be compromised if climate-related parameters (precipitation, temperature) and their impacts (e.g. floods, sea-level rise, ice-sheet development, permafrost) are not considered during design and site selection. For this reason, a repository (surface or underground) must be designed and located where its performance will not be significantly affected by future climate changes.

The long-term isolation of radioactive waste in deep geological repositories (DGRs) – often up to one million years – requires consideration of potential climate change during that period, including the possibility of future glaciations across northern high- and potentially even mid-latitude land masses. Under such conditions, permafrost may develop across large parts of the European continent, leading to frozen conditions in the geosphere. To account for this, DGRs should either be placed deep enough to avoid frozen conditions or use engineered and/or natural barriers capable of withstanding low temperatures. Sites that could experience future ice-sheet coverage, primarily the Nordic region and northernmost parts of mainland Europe (e.g. Posiva 2021, Liakka & Näslund 2025, Chapter 4), must also consider these changes in their design. This includes selecting barrier systems that can withstand increased isostatic pressure from ice loads and cope with higher groundwater flow rates during ice-sheet advances and retreats. Furthermore, the depth of the repository must also account for increased erosion rates due to these ice sheets. The robustness of any repository, surface or underground, under a wide range of future climate conditions is demonstrated through scenario analyses in the post-closure safety assessment.

Another important climate-related factor for the site selection is proximity to the coast. Sea levels are currently rising and are expected to continue increasing for several centuries to millennia (Fox-Kemper et al. 2021). The extent of this rise depends on the level of anthropogenic warming, as higher temperatures lead to greater melting of glaciers and ice sheets, as well as thermal expansion of the oceans. For repositories located near the coast – such as the planned high-level nuclear waste facilities in Sweden and Finland, or the existing low-level waste repositories in Sweden and Finland – sea-level rise must be considered for both operational and post-closure safety. During construction and operation, protective measures should be implemented to prevent seawater intrusion into critical infrastructure. These measures must address both gradual increases in average sea level and short-term fluctuations caused by storms (Liakka & Näslund 2025, Chapter 5). Facilities located further inland but near potential future estuaries may also be affected by sea level rise (Leterme & Jacques 2018).

After closure, higher sea levels may enhance safety if the repository becomes submerged. This is particularly relevant for designs that rely on retardation rather than full containment as the primary safety function to avoid or limit the release of radionuclides. Submerged conditions lead to a decrease in hydraulic gradients compared to terrestrial conditions, slowing the transport of radioactive substances from the repository. Furthermore, any radionuclides that escape through the seabed would be diluted in a large body of water, resulting in minimal annual effective doses to humans and dose rates to non-human biota (see e.g. SKB 2023a).

Climate change needs also to be accounted for in the design of multi-layer covers of surface and near-surface disposal systems limiting water ingress towards the waste and protecting underlying engineered barriers from external disturbances. Climate change can indeed affect the rate at which these covers erode, thereby shortening their lifespan. In particularly dry conditions, it may also cause the clay layer to desiccate, reducing its capacity to reduce water inflows.

Finally, climate change also influences both the magnitude and distribution of precipitation and evapotranspiration. These changes must be considered by hydrogeological and biosphere models used in post-closure safety assessments, as they affect key factors such as groundwater recharge, flow rates, and the water demand for future human settlements. In addition, climate-driven ecosystem changes (e.g., transitions from forest to tundra) should be considered in biosphere models because they alter exposure pathways, including agricultural practices and fishing.

4. International examples

An early project that considered climate change in the context of the long-term safety of radioactive waste disposal was the BIOCLIM project. Specifically, it provided a scientific basis and practical methodology for assessing the potential impacts of long-term climate change on biosphere characteristics in the context of radioactive waste repositories. The project brought together twelve different European organisations with responsibilities for either the safe disposal of radioactive waste or the development of climate models. BIOCLIM was one of the first initiatives to provide climate change projections over the next one million years under different anthropogenic CO_2 forcings (See BIOCLIM deliverable D10-12: Development and application of a methodology for taking climate-driven environmental change into account in performance assessments).

The IAEA Environmental Modelling for Radiation Safety programme (EMRAS II) already mentions the use of analogues for climate change (IAEA 2016). This programme was followed by MODARIA (MOdelling and DAta for Radiological Impact Assessments), which aimed at achieving a consensus on the global climate future(s) and developing a common approach on how to use that future in a regional or site-specific context. MODARIA focused on the development of common assumptions for global climate change and updated downscaling methods, and on potential impacts on effective dose.

A methodology for handling climate change in assessments of long-term repository safety was proposed by Näslund et al. (2013). This approach has served as the basis for handling climate and climate-related questions in several safety assessments conducted by the Swedish waste management organisation (WMO), SKB. The handling of climate change in these assessments has been documented in dedicated climate reports. This includes for example, the climate reports supporting the application for the construction license for the high-level and (the extension of) the low-level radioactive waste repositories in Sweden (SKB 2020 and SKB 2023b, respectively). Since the publication of these reports, SKB has split the documentation of climate and its impact of post-closure safety into (i) a scientific report, which describes the latest scientific developments, and (ii) a “handling” report where the climate scenarios are presented for each safety assessment and repository. The updated scientific knowledge report was recently published and can be found in Liakka & Näslund (2025).

The corresponding climate report(s) by Posiva supporting the operational license application are found in Posiva (2020, 2021). Posiva (2021) has been applied in the scenario formulation (Posiva 2021a) for the safety assessments of both, the deep geological repository and the low- and intermediate level waste repository at Olkiluoto (see Posiva 2021b,c). The report by Leterme & Jacques (2018) deals also with climate and has been used to support the license application for a surface disposal repository in Belgium. Recently, also Nagra published a climate report supporting their license application (Nagra 2024).

Currenty climate change is being deal with within the EU EURAD-2 programme in a strategic study.

5. Critical background information

The type and amount of climate-related background information required depends on the implementation phase (see Section 1).

Programme Initiation

During this phase, literature reviews are most relevant for gaining a broad overview of climate-related risks across different timescales.

Site Identification

In this phase, understanding past climates becomes important to assess how climate and related processes have shaped candidate sites. Extensive background information on past climate can be obtained from scientific literature. Also, greater emphasis should be placed on future climate projections over short and long timescales to construct climate change scenarios. Numerous projections up to the year 2100, and to some extent up to 2300, are available in scientific literature, with the Intergovernmental Panel on Climate Change (IPCC) assessment reports serving as a key starting point. For timescales up to 100,000 years or longer, projections of major climate shifts between colder and warmer conditions can be found in the literature.

Site Characterisation

Here, knowledge of past climates should be deepened, as it may be critical for interpreting site data (e.g., water chemistry at DGR depth). This phase also requires a stronger focus on site-specific climate risks due to anthropogenic warming, such as extreme precipitation, landslides, and sea-level rise, to plan protective measures. Future climate scenarios may be refined by conducting long-term modelling projections with greater focus on site-specific implications.

Construction, Operation, and Closure

These phases involve continuous monitoring of scientific developments to determine whether long-term climate scenarios need to be updated or not. However, regular updates of short-term climate projections, based on new information from sources such as the IPCC, are essential for re-evaluating climate-related risks during construction, operation, and closure.

6. Maturity of knowledge and technology

Climate-related features, events, and processes (FEPs) that affect the post-closure safety of a radioactive waste repository, such as natural and anthropogenic climate change, sea-level rise, permafrost and ice-sheet development, have been recognized for decades. The impact of these FEPs on post-closure safety is evaluated through different scenarios in safety assessments. In WMOs that have conducted multiple safety assessments as part of a stepwise licensing process, such as SKB in Sweden and Posiva in Finland, these scenarios have remained broadly consistent over time. Refinements of the scenarios typically include updated projections related to anthropogenic climate change, including sea-level rise, and air temperature and precipitation changes over the coming millennia. These projections are primarily based on scientific literature; especially the assessment reports by the IPCC are valuable in this context.

Information on climate FEPs, such as the timing and extent of future glaciations and permafrost, is obtained from the scientific literature (e.g. timing of future glaciations) or from site-specific modelling (e.g. permafrost depth). Although the underlying physics of these processes is fairly well understood, their timing and magnitude are subject to both scenario uncertainties (e.g. climate change caused by current and future anthropogenic CO_2 emissions) and modelling uncertainties (errors in model parameterizations and representation of boundary conditions). Both types of uncertainty can be identified through modelling and/or the scientific literature. Once established, these uncertainty ranges tend to remain valid for a long time, indicating a relatively mature understanding of the key factors that control them.

Overall, climate change is considered a relatively mature scientific discipline. One potential exception from this conclusion concerns the possibility of climate tipping points, i.e. critical thresholds where a small change in the Earth's climate can cause a large and abrupt shift of the entire system (e.g. Wang et al. 2023). One such tipping point of relevance for the European climate is the potential collapse or dramatic slowdown of the Atlantic Meridional Overturning Circulation (AMOC) due to increased freshwater input to the North Atlantic surface waters. This uncertainty is further discussed in the next section.

7. Uncertainties

As noted in the previous section, climate science is a relatively mature discipline. Most processes and their interactions are well understood, which allows for reliable quantification of uncertainties in future climate change. An important caveat to this conclusion concerns the possibility and consequences of an AMOC collapse. The risk of an AMOC collapse arises from current and near-future anthropogenic warming, and thus its consequences could coincide with the operational and early post-closure phases of several repositories across Europe. The amount of freshwater required to induce a sudden AMOC collapse is highly uncertain and, consequently, so is the exact timing of such an event. While the latest (sixth) IPCC assessment report concludes that a collapse is unlikely before 2100 (Fox-Kemper et al. 2021), even under very high anthropogenic emissions, subsequent studies have raised concerns that a collapse may be triggered by smaller freshwater inputs than previously anticipated, increasing the risk for a collapse within this century (e.g. Lohmann and Ditlevsen 2021, Ditlevsen and Ditlevsen 2023).

A complete collapse would lead to lower air temperatures and reduced precipitation across much of Europe, with the most severe impacts in northwestern regions. For example, for the Swedish disposal site at Forsmark, a literature review (Liakka & Näslund 2025, Appendix A1) estimated that an AMOC collapse could cause annual cooling of 2–6 °C compared to present temperatures. This range reflects variability among the projections examined.

Another source of uncertainty, particularly for organisations in the early stages of implementation, concerns the impacts of climate change on repository barriers and their surrounding environment. These impacts are typically assessed using climate scenarios tailored to each site, facility, and timescale. For organisations in more advanced stages (e.g. SKB and Posiva), climate-change effects are well understood thanks to decades of research and experience from multiple safety assessments. However, given the diversity of sites and facilities planned for radioactive waste disposal across Europe, it remains uncertain how much of this knowledge can be effectively transferred to organisations that are still in the early phases of development. The identification of safety-significant uncertainties and their management in a disposal programme are indeed very much dependent on the type of facility, site, safety concept and waste inventory, which determines the relevant timeframe for safety assessment.

Worth mentioning is the work performed in the framework of the UMAN WP (EURAD-1) where this topic was specifically addressed and discussed, especially about how future glaciations could be manage in a disposal programme (Kaempfer et al. 2024). The treatment of glaciations and permafrost in the post-closure safety was specifically discussed between the different types of actors involved in the project (WMO, TSO, REs and civil society) (Diaconu et al. 2023, Haverkate et al. 2024, Section 3.2.5, Rocher 2024, Sections 3.1.3 and 3.3.2).

Diaconu et al. (2023) proposed further work in the improvement of coupled models of glaciations, climate evolution, permafrost and groundwater flow. They also proposed a strategic study on climate change that could provide additional insight on how to deal with glacial periods in safety case and safety assessment,

8. Guidance, Training, Communities of Practice and Capabilities

This section provides links to resources, organisations and networks that can help connect people with people, focussed on the domain of Climate change.

Training
Training offered in Eurad-2
Active communities of practice and networks
Bioprota Modaria Studying climate change with nuclear and isotopic techniques | IAEA The Climate, Land, Energy and Water Framework | IAEA Lessons in managing the risk of floods and droughts | News | CORDIS | European Commission A comprehensive toolkit to support the natural mitigation of water risks | NAIAD Project | Results in Brief | H2020 | CORDIS | European Commission

9. Further reading, external Links and references

9.1 Further Reading

EURAD-D10.7-Views-of-actors-on-identification-and-significance-of-uncertainties-on-site-and-geosphere.pdf

EURAD-2 Deliverable 11.1 – White Paper on climate change impacts on nuclear waste management facilities (to be delivered by March 2026).

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896. Climate Change 2021: The Physical Science Basis | Climate Change 2021: The Physical Science Basis

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9.2 External Links

- https://www.skb.com/publications/
- https://www.posiva.fi/en/index/media/reports.html
- BIOCLIM - https://www.andra.fr/mini-sites/bioclim/
- MODARIA - https://www.iaea.org/publications/13642/development-of-a-common-framework-for-addressing-climate-and-environmental-change-in-post-closure-radiological-assessment-of-solid-radioactive-waste-disposal
- EMRASII
- Cordex – Coordinated Regional Climate Downscaling Experiment - https://cordex.org
- https://www.iaea.org/topics/climate-change
- IAEA 2024. The Climate, Land, Energy and Water Framework. A methodology handbook. IAEA-TECDOC-2065. 41 pages. https://doi.org/10.61092/iaea.uiu5-lz0j.
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