7.2.2 Information, Data and Knowledge Management, Domain Insight

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Overview

Radioactive waste management (RWM) activities are knowledge-intensive and often challenging undertakings. The information, data and knowledge that is essential for the safety of a radioactive waste repository should be managed in line with national regulations and international good practices. Managing these organisational resources requires the proper and timely adoption of relevant strategies, policies, processes and practices. The information, data and knowledge management (IDKM) domain assists in applying these instruments in the field of RWM activities.

Keywords

Information, knowledge, data, organisation, repository, knowledge management, radioactive waste, safety case, radioactive waste management, future generations, records, awareness, preservation

Key Acronyms

DGR	Deep Geological Repository
IAEA	International Atomic Energy Agency
IDKM	Information, Data & Knowledge Management
KIF	Key Information File
KM	Knowledge Management
KMS	Knowledge Management System
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
RD&D	Research, Development and Demonstration
RepMet	Repository Metadata Initiative
RK&M	Records, Knowledge and Memory
RK&M Initiative	Initiative on the Preservation of RK&M across Generations
RWMO	Radioactive Waste Management Organisation
RMS	Requirements Management System
RWM	Radioactive Waste Management
SER	Set of Essential Records
WP-IDKM	Working Party on Information, Data and Knowledge Management

1. Typical overall goals and activities in the domain of information, data and knowledge management

The primary goal of IDKM in the case of deep geological repository (DGR) activities is to establish a system for organising and preserving the information, data and knowledge generated and needed throughout the DGR lifetime to increase repository safety. IDKM is particularly important and demanding for RWM due to:

- the volume and multidisciplinary nature of the specialist information, data and knowledge produced;
- the extended duration of national programmes, with DGRs often planned to operate for more than one hundred years; and
- the need to preserve records and awareness of the DGR for future generations over even much longer periods of time.

Several generations of workers will be part of the RWM programme, and the information, data and knowledge that previous generations created must remain accessible and understandable to contribute to continued safety. Ownership of the associated records may also pass between different organisations during this period. After the closure of a repository, future generations are anticipated to require sufficient information to reduce the risk of inadvertent human intrusion and to be able to make informed decisions (NEA, 2014). Preserving the awareness of radioactive waste repositories requires consideration of not only the technical features, but also the social and human aspects.

The table below outlines IDKM Domain Activities that should take place during various DGR phases. Some IDKM techniques and methods mentioned below are a part of everyday operations while others serve to ensure that IDKM is preserved for the longer term. The focus of IDKM will change as the programme progresses through different phases, although these phases are not always sequential e.g. DGR construction can be viewed as a continuous expansion of underground storage chambers with the construction phase reaching well into the operations phase.

Domain Goal	
7.2.2 Establish a system and adopt international good practice for information, data and knowledge management, modelling, transfer and preservation (IDKM)	
IDKM Domain Activities*	
Phase 1: Programme Initiation	Initial IDKM activities for Phase 1 include establishing and applying an organisational framework for IDKM, this includes compliance to existing statutory framework and establishing a strategy, policies, processes, knowledge management systems (KMS) and tools for IDKM activities. IDKM can contribute more to the success of the DGR programme if these systems and frameworks are established early.
Phase 2: DGR** Site Identification	It is timely to establish selection criteria for data and records and to assign ownership of data and records in the site identification phase, IDKM activities include instituting metadata policies for data and records. These metadata policies should provide clear instructions on how to capture crucial information relevant for regulatory compliance, essential records, and long-term preservation and archiving.

Phase 3: DGR Site Characterisation	The foundation for IDKM will have been laid in previous phases, as appropriate. Apply a PDCA (Plan-Do-Check-Act) cycle to improve the IDKM of the DGR. Extend knowledge management (KM) activities, e.g. knowledge transfer, communities of practice, and others as applicable. After the decision is made to establish a site, select record(s) that will be included in the Set of Essential Records (SER) for the DGR, and develop a strategy for long-term awareness preservation that includes site-specific processes.
Phase 4: DGR Construction	Repeat and extend activities of Phase 3 as appropriate. Consider implementing measures for the awareness preservation strategy as early as practicable. Many awareness preservation mechanisms (see the toolbox in NEA, 2019c) do not rely on the construction of the repository and could in principle be instituted as early as Phase 1 or as late as Phase 7. For example, an information centre in the vicinity of the site could be operational as early as Phase 4. During construction, activities usually spread into a wide supply chain and establishing cross-party IDKM becomes more important.
Phase 5: DGR Operation	Repeat and extend activities from Phase 4 as appropriate. If not already in place, processes for creating/updating the Key Information File (KIF) and the SER for the DGR should be in place. Most of the data and records generated during this phase describe the as-built state of the repository and are used to populate the KIF and parsed for inclusion in the SER. This is the phase where most of the data and information need to be captured using systems and processes put in place in earlier phases.
Phase 6: Closure	DGR site closure likely encompasses transfer of responsibility implying significant changes that affect IDKM such as changes in the ownership of the associated records and data. Need for substantial knowledge transfer, preservation and archiving activities. Any sub-surface marking, on-site surface architecture and/or landscape development that is part of the awareness preservation strategy could be considered part of closure activities and completed before “post-closure” starts. At the end of this phase, there should be an integrated information, data, knowledge and awareness preservation strategy.
Phase 7: Post-Closure	As a measure of post-closure/indirect oversight, the ongoing preservation strategy should be examined and adapted if needed at determined regular time intervals. This examination includes an inspection of the review process itself, so that it is perpetuated in an efficient and resource-sensitive manner. The dedicated archive/information centre would facilitate the findability, accessibility, interoperability and reusability of its records, data, objects and artefacts according to current and anticipated future user needs.

*In order to provide a comprehensive illustration of the 7.2.2 IDKM Domain, the DGR activity phases of closure and post-closure have been elaborated in this domain insight. This depiction of the DGR activity phases may differ from those of other EURAD Domain Insights, but does not represent any significant change in understanding of the DGR lifecycle.

**Many of the concepts discussed in this document, while referring to DGR, can also be applied to other forms of radioactive waste disposal sites.

2. Contribution to generic safety functions and implementation goals

A safety case (see, EURAD Domain 7.1.1 Safety Requirements) provides the scientific arguments for a facility's safe operation, in accordance with legislation, and typically expressed via safety functions such as containment and isolation. This generally relies on multiple lines of reasoning, bringing together experimental work, numerical modelling and analysis. While IDKM does not directly contribute to a safety function in the way that a physical barrier does, it is important in ensuring that the information underpinning the safety case is both correct and demonstrable. In other words, an organisation that is unable to appropriately manage its data and information is unlikely to be able to make a case for progressing implementation to a competent authority. The difficulties associated with the safe decommissioning legacy power, disposal or research facilities where initial records were inadequate or even lost over time, are well known and provide evidence for the previous statement.

2.1 Features, characteristics, or properties of information, data and knowledge management that contribute to achieving storage safety as well as long-term safety of the disposal system

IDKM contributes to DGR safety through the following:

2.1.1 Provide a sound, reliable, consistent, and well-structured information and knowledge basis for all steps during the repository programme

National repository programmes tend to run for very long periods of time. Several hundred years can pass between the production of nuclear waste and its final disposal in a geological repository, with many activities and decisions taking place during this period. Multiple generations of workers will participate in the lifecycle of a repository, characterising a site and then safely constructing, operating and closing the repository. There must be a long-term strategy to manage (i.e., create, disseminate and preserve) the knowledge and information of these activities for future generations of scientists, engineers and workers involved in the repository process. Records must be well-structured and contain metadata to justify decisions made and demonstrate that processes were followed correctly. Detailed knowledge must be passed on to future generations of workers to ensure continued safety.

2.1.2 Create a transparent, traceable and living safety case as a basis for construction and operation of a safe repository

A safety case is typically drafted and updated by the implementer of a repository, capturing argumentation and evidence for the key decisions throughout the repository programme. A proper safety case is a crucial element in ensuring and demonstrating regulatory compliance, i.e. operational safety and post-closure safety. Throughout the phases before closure, as designs are developed and geological investigations progress, the information available will increase in type, detail and volume. This includes information on the disposal system itself, including inventory, engineered barriers and geology, how these work together to ensure safety (safety concept), and on the decisions taken throughout the development process, whose rationale must be captured and set into context.

2.1.3 Achieve acceptance of the repository by all stakeholders and maintain it throughout the lifecycle of the repository

In order to achieve public acceptance of the repository, it is necessary to provide comprehensive and understandable information for stakeholders, and to ensure this information remains accessible to a changing group of stakeholders over the significant period of time during which the repository serves its purpose. Precautionary measures must be taken to prevent loss of information. Failure to capture and preserve information introduces the risk of the loss of confidence of regulators, the public or other stakeholders. The loss of knowledge and information is also costly when it causes work to be redone or the laborious retrieval of knowledge and information. Records must be preserved for very long periods of time to ensure an adequate understanding of the repository system and its performance. After the closure of a repository, future generations will require sufficient information to retain confidence in the safety of the facility and to be able to make their own informed decisions. Therefore, it is important to develop strategies that can help to preserve knowledge and awareness over long timescales when societies and their institutions may have significantly changed or no longer exist.

2.1.4 Ensure that information is available to support the long-term safety of the disposal system

Data and information needs to be captured before or at the latest during closure so that the links between different pieces of information are unambiguous and can be understood in the future. Reconstructing information after the operational phase is extremely resource intensive and some information is inevitably lost. A sufficient amount of quality information needs to be appropriately accessible and well preserved, enabling future generations to make informed decisions regarding the repository.

3. International examples of information, data and knowledge management in national programmes

There are numerous IDKM programmes being carried out at an international level (Abbasova *et.al,.* 2021). The goal of the following list is to provide a snapshot of various ongoing IDKM programmes at national and organisational levels.

<u>Example programmes for IDKM at the French Radioactive Waste Management Agency (ANDRA)</u>

- Critical knowledge review: ANDRA is implementing a periodic review of critical knowledge to tackle the risk of knowledge loss for the most strategic activities of the organisation. This review is based on a knowledge mapping and the assessment of criteria to determine key factors such as the stakes involved in the activities, their implementation's complexity, their impact on the overall activities, their temporality, and their relation to the core business of the organisation. The vulnerability of the knowledge associated with critical areas is then considered through its originality, the usual forms of its documentation, sharing and transfer within the organisation as well as its availability within its ecosystem of actors. Control measures are thus defined and may include knowledge capitalisation and/or transfer actions adapted to the risk intensity, the nature of the knowledge considered, the existing processes, etc. (Arrignon, Maugis and Bauer, 2023).
- Fostering communities of practice: ANDRA supports knowledge sharing communities as well as developing the network of such communities. Criteria are used for characterising existing, developing, and emerging communities, and the various community support projects are organised according to knowledge areas, that are critical for the organisation. Communities and their stakeholders are provided with frames of reference, adapted support modalities and dedicated training for ensuring their sound functioning and for developing efficient and sustainable ways of sharing and capitalising knowledge in a cross-functional fashion. Steering the interconnection of the communities is envisaged towards a continuous knowledge network for activities and projects over time (Arrignon and Maugis, 2023).
- Memory (awareness) for future generations: ANDRA develops a programme aimed at avoiding the risk of involuntary human intrusion in radioactive waste repositories for as long as possible, facilitating the decisions of future generations, and passing on a cultural heritage. These complementary purposes imply the transmission of different types of information in different timescales and to different groups of people, and necessitate a multimodal and multidisciplinary approach that relies on frequent interactions with various stakeholders. The programme is thus structured in four pillars: archives and regulatory provisions, societal interactions, studies and research and international cooperation. The first two pillars aim to build a robust system for transmitting memory (awareness) and knowledge, while the third pillar aims to understand how memory (awareness) and knowledge can be transmitted along different timescales and how the system can be improved. International cooperation contributes to all other pillars.
- Long-term documentation of nuclear waste disposal in Germany by the Federal Office for the Safety of Nuclear Waste Management (BASE)

- The topic of information and knowledge retention for repositories has been addressed in Germany through various directives and laws since the 1980s. The need for documentation of significant, safety-related data on the final repository was formalised for the first time in 1983, as part of the safety criteria for the abandoned rock salt and potash mine converted to a low- and intermediate-level radioactive waste repository. With the planning approval for the construction and operation of the Konrad repository for low- and intermediate-level radioactive waste in 2002, the term "long-term documentation" was established and describes the preservation of information and knowledge beyond the closure of the repository.
- In 2016, the Commission on the Storage of High-Level Radioactive Waste recommended establishing a central government agency responsible for the permanent preservation of relevant documents and data. Documentation of this information was seen as a key safety measure for the entire chain of nuclear waste disposal and, in particular for a repository. The central government agency would be responsible for ensuring institutional awareness of the safety significance of the documented information. The Site Selection Act (StandAG), which came into force in 2017, legally delegated this task to BASE (paragraph 38) as the supervisory and regulatory authority. A dedicated department for long-term documentation was created to address analogue and digital preservation, KM and awareness preservation.
- Details on the scope of the data and documents to be stored, their content as well as their transmission and use will be defined in a legal ordinance that is currently being prepared by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV), with the technical support of BASE. The ordinance will also define the group of organisations that are obliged to transmit data to BASE. Finally, paragraph 26 of the StandAG defines an important condition for the timeframe of long-term documentation in Germany, based on the requirement that recovery of the stored waste packages should be possible for 500 years after closure of the repository.
- BASE is preparing to execute long-term documentation of nuclear waste disposal in Germany. In preparation for the national implementation of this activity, BASE exchanges information with RWM organisations and stakeholders as well as with the national Network of Expertise in Long-term Storage and Availability of digital Resources (nestor). BASE is primarily responsible for the creation, finalisation and preservation of the German equivalent of the SER and the KIF for higher-activity radioactive waste.
- The scope of long-term documentation is currently as broad as possible, with a focus on enhancing transparency and traceability of the selection procedure, per the StandAG. We cannot yet foresee the information needs of future generations, and the StandAG considers this. The act states, "Data and documents that are or may become significant for the final and interim storage of radioactive waste (storage data) shall be permanently stored [...]".
- This includes all data and documents:
    - on the interim and final storage of radioactive waste,
    - on the immediate history of the current site selection process and all further steps in the site selection procedure, including inputs from the public participation panels,
    - on the deliberations of the Commission on the Storage of High-Level Radioactive Waste,
    - on the history of the previously-considered Gorleben site.
- To accomplish the task set by the StandAG, BASE intends to implement the following measures:
    - Storage of data and documents on analogue and digital storage media in at least two spatially separated locations:
    - Establish transmission procedures that allow mandatory and voluntary submissions to BASE in close coordination with selected RWM organisations, as well as dedicated quality standards for cataloguing, archiving and preservation:
    - Preparation of the necessary knowledge retention and awareness preservation measures to facilitate long-term documentation for at least 500 years.
- Furthermore, BASE conducts research projects on the search for the safest possible final repository site, considering nuclear safety, transport and intermediate storage of radioactive waste as well as societal issues. BASE examines state of the art approaches to IDKM by investigating the long-term durability of various storage media (see chapter 5.3), and analysing social science and historical research on societal aspects affecting information and knowledge transmission and retention. With insights on the best paper and ink combinations for archival prints and long-term durable paper records along with the best available digital storage media configuration, BASE will be equipped to define requirements for the preservation of analogue and digital data for the timescales of nuclear waste disposal. BASE is also planning to explore

potential future marking strategies as a means of preserving awareness of a final repository in Germany.

IDKM activities at the German Federal Company for Radioactive Waste Disposal (BGE)

- Fostering a knowledge culture: BGE is implementing its KM strategy with the goal to establish a learning organisation. Therefore, BGE actively promotes a culture of KM by organising engaging events like a Welcome Day, Knowledge Cafés and fostering expert networks and learning communities. These initiatives provide platforms to connect experts with diverse specialisation for knowledge exchange, collaboration and the cultivation of expertise. Through these interactions, BGE creates an environment that encourages the sharing and dissemination of knowledge, driving innovation, continuous learning from experiences and the development of expertise in BGE.
- Development of a digital information base (DIB): The objective is to collect written, in-house, repository-specific knowledge (existing repository research) at a central location in digital form. This will represent the development of the course of research and therefore take stock of BGE´s own knowledge. The ultimate goal is to summarise and safeguard existing knowledge and deliver a decision-making basis for future issues/generations. The content of the DIB is indexed using an intelligent search engine based on semantic language processing. Documents are visualised and accessed via filters/facets. By incorporating subject-specific knowledge (glossaries, acronyms, abbreviations), search results can be improved and external web sources connected to the metasearch engine for better information retrieval.
- BGE has started an initiative to unify documentation and to establish a comprehensive knowledge base in order to empower experts with efficient access to relevant information. Relevant documentation will be systematically collected and undergo a meticulous process of unification, where a standardised format, layout and terminology will be established. This is important for the organisation to consolidate information from various sources. Additional filters and tagging systems will improve the search results. By implementing intelligent search functionality within the digital information base, experts are able to locate specific information with less effort.
- Representation of knowledge resources and support of knowledge transfer: BGE utilises knowledge maps (e.g. on-boarding, acronyms, abbreviations, etc.) as visual tools to represent and organise information from different knowledge resources as well as for the support of several knowledge transfer processes. The development and implementation of knowledge maps for new employees has successfully enhanced the on-boarding process. This map offers newcomers a visual representation of the organisation's knowledge landscape, enabling them to quickly access and navigate relevant information and resources. Furthermore, knowledge maps support expert debriefings during off-boarding processes. A structured interview was developed to capture tacit knowledge of senior experts before retirement. In addition to the documented knowledge, the developed procedure allows identification of appropriate knowledge transfer methods and effective planning for succession and seamless transition of responsibilities.
- Establishing a historical contextualization project of the site selection process for the German high-level waste repository as a first step in the process of long-term preservation: The idea was to create an archive platform, but to also show how the documents relate to each other. In order to accomplish this, the historical background and the interactions between all stakeholders involved in the site selection procedure were taken into account. This background is composed via contemporary historical research, with sets of cohesive storylines, central documents and oral history methods. The aim is to collect a variety of perspectives as an information base for future historians. Another goal is to capture information in such a way as to remain open to the multidisciplinary and transdisciplinary approaches of future social scientists.

KM for geological disposal in Japan

- Given that the knowledge forming the basis for geological disposal has been increasing exponentially with time, there are clear limitations to the traditional “report-based” KMS. This was recognised by the Japan Atomic Energy Agency (JAEA) (Umeki et al., 2006), which led to the development of an advanced KMS that can be linked to associated quality and requirements management systems (Umeki et al., 2006; JAEA, 2023). A web-based communication platform, CoolRep (Umeki et al., 2011), was also developed. In order to promote communication about the safety of geological disposal among a variety of stakeholders, several documents with different content tailored to the knowledge level of readers, as well as a web-based communication platform (related to CoolRep mentioned above), will be produced. These tools will increase the opportunities for users to access and easily view the knowledge and information they are interested in, at a level defined by clear and specific access rights associated with the hierarchical organisation of the electronic documents (NUMO, 2023).

- There is international consensus that it is good practice to introduce a requirements management system (RMS). An RMS supports organisations in developing safety cases that evolve but preserve traceability over the long project implementation period, ensuring that decisions are made in an open and transparent manner. An RMS integrates constraints based on environmental protection, societal acceptance and economic factors along with the fundamental principles, regulations and guidelines for geological disposal. There is a clear relationship between the RMS, which defines the decisions to be made and the KMS, which provides the knowledge to make sound decisions. The Nuclear Waste Management Organization of Japan (NUMO) demonstrates a concept for combining requirements and KM within an integrated system (NUMO, 2021).

KM for spent fuel waste disposition in the United States

A KM programme has been developed and implemented in the United States to support the spent fuel waste disposition (SFWD) campaign led by the U.S. Department of Energy. The impetus for the development of this KM strategy was a high number of impending retirements of critical subject matter experts and senior staff along with a corresponding influx of new staff members with little to no experience working on an active nuclear waste management project. It was evident that a KM programme would be a necessary and effective approach to transfer critical knowledge from senior staff to new staff members joining the campaign.

The SFWD KM strategy was deployed in a phased fashion. It began with an analysis in which critical knowledge holders and subject matter experts were identified. As nuclear waste management programmes typically operate over decades, it is very important that critical knowledge held by identified experts is captured while they are still available.

Following the identification of critical knowledge holders, focus group studies were conducted to identify preferences in learning styles and knowledge transfer across a broad range of staff levels, including new and mid-level staff as well as technical managers. Several technical workshops and “Deep Dive” sessions were subsequently held in which senior nuclear waste management experts shared their experiences, lessons learned, critical knowledge, and guidance to a broad audience. Active participation during Deep Dive sessions was highly encouraged so that discussions would include more than information already documented, but also critical tacit and implicit knowledge held by presenters. Panel sessions were included in which staff posed questions to seasoned experts, enhancing the transfer of knowledge. Each Deep Dive workshop, as well as each panel session, was videotaped and captured in an encompassing KM repository. The repository provides easy, unified, and integrated access to knowledge resources. A taxonomy was then developed to enable efficient searching of topics in the repository.

This KM strategy has become a continual and important component of the U.S. nuclear waste management program. New and junior staff have easy access to the KM repository and are encouraged to explore and utilise it. The KM repository is accessed continually by programme leaders and staff looking to deepen their knowledge and practical understanding of nuclear waste management in the U.S. User feedback has been unanimously positive. Additional Deep Dive sessions are held when the opportunity or need arises, continually expanding the breadth and depth of critical knowledge captured in the repository.

The nuclear archives of the Nuclear Decommissioning Authority in United Kingdom

In the United Kingdom, the Nuclear Decommissioning Authority has established a dedicated archive for the civil nuclear decommissioning industry, which is Nucleus: the Nuclear and Caithness Archives, located in Wick in the far north of Scotland. Nucleus opened in 2017 and already contains over 58,000 boxes of paper records.

The archive serves three main functions:

- Firstly, it offers a records management service to the nuclear industry, taking in operational and other records, storing them, making them available in digital form to end users on request and destroying them in accordance with relevant legislation when they are no longer required following appraisal.
- Secondly, it selects records with an ongoing archival value to future researchers for permanent preservation. These archives will include information that will be of value to future historians of the nuclear industry, and, in the form of technical reports and other scientific papers, will also serve as the corporate memory of the industry's technical achievements.
- Thirdly, it will preserve the records relating to packages of nuclear waste, before; during and after the packages have been relocated into the relevant geological repository.

Nucleus supports the information governance and information, knowledge, data and records management mission of the UK civil nuclear industry. A records retention schedule and a metadata standard for the industry have already been published. As Nucleus transitions into a digital as well as a paper archive, guidelines for digitisation (recommended file formats and DPI resolutions for scanning) have been developed and are beginning to be implemented across the NDA Group. The next stage will be to manage the upload of thousands of digital waste package records into Nucleus, and to make them available to the waste producers as well as the waste inheritors as required. Then the process of validating those records can begin so the waste packages can be transported to their final location in the geological repository.

4. Critical background information

The section highlights specific components, key information, processes, data or challenges that have a high impact or are considered most critical for implementing geological disposal, with respect to the domain of IDKM. This section is intended to provide a high-level overview of the breadth of considerations in this field and cross-references to further reading are intended as examples.

4.1 The Role of Digital Systems and Technologies

Organisations that are early in their journey of improving their practices often regard IDKM as a retrospective activity, concerned with filing documentation that has already been produced, and managing knowledge that staff have already acquired. However, many IDKM practices should be considered prior to the content being created. This is particularly true where digital information is involved.

Much of IDKM relates to the addition of *structure* and *context* to content. *Structure* can manifest itself in the choice of headings, paragraphs, figures, etc., or something more specific to the use, such as the choice of fields in a pro-forma template. *Context* generally means that the information is affiliated with other information that helps it to be understood and used. Authors should ask themselves:

- Who is my audience and what can I expect them to know?
- Am I writing in plain and clear language1 that is likely to convey the intended meaning?
- Am I using vocabulary that differs from the dictionary sense and needs to be explicitly defined?
- What am I trying to say in each part of the content and, if deductive, what is my argument?
- Is it clear why this information was created?
- What format is best for each unit of information, for example text, graphics, tables or similar?
- How is this information connected to other information? Is it important to keep the connected information together, so it can be correctly understood?
- Is this information part of a wider set? If so, would a standardised format (pro-forma) help users, and if so, does one already exist?

[1] https://www.plainenglish.co.uk/accreditation.html

One of the difficulties with geological disposal is that potential audiences may be in the distant future and therefore it is not possible to predict what information they will have or how they will understand language, especially over significant time periods.

Standards exist to express and store vocabularies[2] and there are approaches that help to classify content (taxonomies[3]) and relate it to other content (ontologies[4]), though domain-specific examples in the geological disposal field have yet to be adopted/standardised internationally.

Digital systems can help users to access and manage large volumes of content throughout its lifecycle to ensure processes are followed, information can be found and even destroyed if/when no longer needed. Such systems allow organisations to easily define and store metadata[5] which allows additional data to be stored with the content, often referred to as 'data about the data', and may help to enforce quality standards. Interactive graphics[6] can allow data to be understood more easily and can be designed to allow users to view data in a way that helps them best, often in multiple dimensions[7].

With the advent of networked information systems, web standards for linking information ("linked data") have also been introduced so that context is better understood [8]. Linked data principles and standards can be applied locally within an organisation, or more widely to connect the organisation to the public via the internet.

Digital systems can provide extensive search capabilities both through full-text and metadata, potentially in combination, and newer systems are starting to extend to graph searches[9], which introduce the ability to search cascading relationships. This in turn can help organisations with change and configuration management for their facilities, where the impact of new information often needs to be assessed in a controlled way[10]. Some search systems have advanced to better process user questions formulated using more natural language.

As a basic principle, newly created content should be 'born digital' so that it is machine readable, offering the best chance of being used for new applications in the future. Artificial intelligence and machine learning[11] are rapidly evolving fields and offer the potential to help users carry out their jobs more efficiently in future.

Digital systems may face obsolescence over time. File formats and even character coding can be difficult to 'read' in the long-term, especially if metadata is undocumented or lacking. A number of standards exist to store/transfer data[12] and to allow different systems to interoperate. When selecting formats and systems, organisations should consider the entire lifecycle of the information and how data can be extracted if needed in the future. Ideally, this should be included in initial contracts for systems – it is not necessarily forefront in vendor plans when creating new technology, nor necessarily in their interest[13] – changes in technology can be significant in a relatively short time. As part of their accession requirements, archives often require particular metadata to be included, preferably created by the author, and they may accept only a limited number of formats.

When developing strategies and planning an organisational structure, it is important that organisations have or can access appropriate technical and digital expertise, which will vary in type and scale as the repository phases advance. Staff must be trained in the systems they use to deliver expected benefits.

[2] e.g. ISO, SKOS
[3] Sample taxonomies
[4] Ontology examples
[5] https://www.oecd-nea.org/jcms/pl_15062 (NEA, 2018)
[6] Sample interactive graphics
[7] 3D models, BIM etc.
[8] Linked data/RDF/REST
[9] SPARQL etc.
[10] Change control and configuration management, OSLC
[11] AI links
[12] XML, JSON, CSV etc.
[13] Vendor lock-in

Organisations should also stay informed on digital advances that may address their specific needs, as this is area is still changing rapidly.

4.2 NEA RK&M Toolbox, SER, KIF

The NEA initiative on the Preservation of Records, Knowledge, and Memory across Generations (RK&M initiative, 2011-2018) took special care to consider the issue of IDKM in the post-closure phase of a repository and the very far future, focusing more on archiving as well as knowledge and awareness preservation. The “RK&M Glossary”, defining the key terms used by the RK&M initiative, is published as Annex 1 of NEA (2019b) and may be useful as reference for the keywords used in this domain insight. The key approaches, methods and mechanisms developed by this initiative are set out below.

4.2.1 RK&M Toolbox

One objective of the NEA RK&M initiative was to develop and publish a “menu” or toolbox of approaches and mechanisms to preserve awareness about radioactive waste disposal facilities. National disposal programmes can select components from this toolbox to create a system for maintaining and preserving information and awareness about a repository for future generations while meeting the legal requirements in force. The toolbox approaches all aim to avoid inadvertent intrusion into a repository and to enable informed decision making for as long as reasonably possible (NEA, 2019c).

The “toolbox” is meant to allow stakeholders to identify elements of a strategic action plan that suit the needs of individual national programmes. Like building blocks, these elements can be selected, adapted and combined to achieve a context-responsive, systemic awareness preservation strategy (NEA, 2019c). The NEA RK&M initiative found that there is no single approach or mechanism that would achieve, on its own, the preservation of awareness over centuries and millennia.

The combination of preservation approaches and mechanisms should aim to carry on the history of the repository so that people today and in the future can understand the specific context of the repository and its content on a generic level. The approaches and mechanisms for preservation should also point to sources of more specialised and detailed information on the repository (NEA, 2019c).

Toolbox approaches include: memory institutions; time capsules; markers; culture, education and art; oversight provisions; international mechanisms; regulatory framework; KM; and dedicated record sets and summary files, e.g. the KIF and the SER discussed below.

4.2.2 The Key Information File

The KIF is a single, relatively short document (~40 pages) intended to provide basic information on the repository, the waste it contains and its intent to people without specialised knowledge in the field. To achieve this, it should be produced and updated in a multidisciplinary and participatory manner (NEA, 2019b). Its concise form allows many copies and a wide distribution (e.g. at the disposal site, in the town hall, in libraries and archives, on websites of international agencies, in schools, etc.) to facilitate awareness about the existence and purpose of the KIF in society. The information it contains should be sufficient to allow society to learn about the repository and to reduce the likelihood of inadvertent human intrusion. By pointing to the location of more detailed information (e.g. the SER, see below) – and to some degree also on its own – the KIF can contribute to informed decision-making processes in the future. Although the KIF is primarily directed at timescales of a few centuries after repository closure, it could possibly support awareness preservation far longer into the future.

4.2.3 The Set of Essential Records

The SER can be understood as a collection of the most important records about a facility and its waste, selected from the vast number of records produced during the lifetime of the repository, and intended for permanent preservation (NEA, 2019a). Since records are produced during all phases of a repository programme, the development of the SER will be an ongoing process that should be under continuous maintenance and be regularly reviewed until repository closure. The SER aims to provide sufficient information for current and future generations to ensure an adequate understanding of the repository system and its expected performance. This will enable responsible parties to review and verify the repository performance and make informed decisions regarding the repository.

The SER should serve as a source of detailed data and information on the repository system, primarily for specialists and researchers, as well as for decision makers, regulators and other authorities (noting its volume, technical language and accessibility). To allow future generations to efficiently discover the information, search tools based on international archival description standards as well as an explanation document should be part of the SER. It is crucial that the most recent and approved version of the SER is made available in the dedicated archive/information centre (NEA, 2019a).

5. IDKM Maturity

The maturity of human knowledge is a dynamic process: as we gain new information, insights and experiences, our knowledge evolves and matures. New discoveries, advancements in technology and changes in societal norms and values can also influence the maturity of knowledge. Human knowledge is constantly evolving and expanding, with varying levels of maturity in different fields.

Organisational KM maturity levels are assessed according to the organisation's performance around areas of culture, processes and technology. These maturity level metrics can be expanded to accommodate for the organisation's specific needs and activity areas. The goal of KM maturity is to move the organisation from an ad-hoc approach to a strategic, integrated approach to managing knowledge. By improving KM practices, RWMOs and other organisations can improve decision-making, increase innovation, reduce duplication of effort and improve overall performance.

One measure of information technology maturity is its fitness for purpose. By this measure, today's information technology supporting KM is relatively mature, although significant improvements continue to be made as digital systems evolve. Many organisations have adopted sophisticated KMS and tools to manage their knowledge assets, including explicit knowledge such as documents, databases and best practices, as well as capturing tacit knowledge such as expertise, skills and experience. These information technology tools enable RWMOs to access, search and retrieve information quickly and easily, and to collaborate and share knowledge across organisational units.

Data is considered the raw information that has not yet been organised or processed in a meaningful way. Data maturity requirements include data integration, validation and transparency. Technology can help to improve data quality but the people (user) aspect cannot be neglected.

Even though much research and effort has been put into improving the maturity of IDKM, organisations such as EURAD, NEA, IAEA and others continue their efforts to further improve this discipline.

5.1 Advancement of safety case

Over the last decades, the safety case has become a powerful and essential tool to support decision-making throughout a geological disposal program. Beyond its role as a demonstration of safety and technical feasibility, the safety case is also a platform for discussion both within a waste management organisation and between different parties. The safety case concept is now quite mature.

Compiling the safety case for a disposal facility is a highly technical undertaking involving a number of scientific disciplines, as well as the principles and mathematics of engineering and design. Large volumes of data, information and knowledge are required to carry out the safety analysis and create the safety case for a radioactive waste storage or disposal facility. It is a stepwise process covering many decades during the lifecycle of the facility from site selection up to repository closure. Throughout the lifecycle, the available information will increase in type, detail and volume. The transfer of information between the different stages of the disposal programme, in the form of data, criteria, liabilities, decisions and requirements, is key for the successful iteration of the safety case towards implementation and closure. Therefore, organisations involved in RWM are developing and applying methodologies and tools for KM including records and requirement management systems.

Research is being conducted and organisations are taking steps toward improving methodologies and establishing digital safety cases, exploring the capabilities that advanced digital technologies and tools (artificial intelligence, machine learning, natural language processing (NLP)) offer and their application to development of the digital safety case (see below, past and ongoing RD&D projects).

5.2 Optimisation challenges and innovations

Technology plays a significant role in supporting KM. There have been significant advancements in technology platforms, such as KMS, content management systems, collaboration tools, artificial intelligence and machine learning, which have improved the ability to capture, store, share and analyse knowledge. However, integration of these systems and the quality of user input often continues to be an area for improvement.

Shifting organisational cultures towards better KM and sharing practices often proves to be a challenge, even though the technology and tools to support these sharing activities are widely available. IDKM practices also tend to be lacking or ignored when close deadlines are involved.

The advancements made in machine learning, NLP and other forms of artificial intelligence have the potential to significantly improve IDKM maturity. These technologies can help automate KM processes such as data classification and information retrieval, and even create new knowledge by analysing patterns and identifying insights from large volumes of data.

5.3 Ongoing RD&D projects

A significant number of RD&D projects related to IDKM are ongoing in different industries, and many of these could be adopted in DGR activities. A brief list of ongoing projects related to the nuclear industry is provided below:

- NEA WP-IDKM/EGSSC14/Global Task 5 - Advanced digital technologies (ADTs): The ADT activity plans to explore the capabilities that advanced digital technologies and tools (artificial intelligence, machine learning, NLP) offer and their application to the development of the digital safety case. The activity plans to engage experts from other NEA IDKM expert groups as well as to involve academic experts to better understand the opportunities and challenges that these technologies present and to define specific applications to support the development of the digital safety case from the different perspectives.
- EURAD-Work Package 12 - Guidance on developing a requirements management process for disposal solutions: A guidance document on "requirements management" will be developed and put forward for discussion. It will discuss the nature of requirements management ("what does it mean") and its role in the overall planning process ("how will it be used"). More specifically, the guidance document will clarify (i) the different elements of requirements management ("what needs to be done when developing requirements"), (ii) the process of requirements management and its interaction with other planning activities, (iii) the process of implementing/running requirements and (iv) key rules to be obeyed in requirements management.
- NEA IGSC - Ad hoc group on MeSA215: This activity of the Integration Group for the Safety Case (IGSC) aims to expand the description of the interaction between the safety case and the development of the design basis for a radioactive waste repository. In particular, the group will consider lessons learned and methodologies related to requirements management that have been gained and developed in advanced programmes approaching construction and operation of a DGR. This activity is based on a previous NEA project on methods of safety assessments (Organisation for Economic Co-operation and Development, 2012). The outcome should be a report in which the derivation of technical requirements and their interplay with assessment activities is described in a systematic way. Issues to be considered are technical feasibility, long-term safety and operational safety as well as compliance with the regulatory framework.

[14] Expert Group on a Data and Information Management Strategy for the Safety Case (EGSSC)
[15] Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste 2

- “Langzeitbeständigkeit von Papier (Labest Papier)” - The BASE performed a research project in collaboration with the Department of Paper Manufacturing and Mechanical Process Engineering (PMV) at the TU Darmstadt on long-term durability of paper. The project examined how to preserve current paper documents and identified the best paper ink combination for long-term durability. The final report of this two-year project is expected by the end of 2023.
- NLP Semantic Search University of Rome - Semantically aware machine learning coupled with NLP enables advance retrieval of relevant information across large bodies of information of dissimilar format, age and source. The technology can deliver:
  1. identification of the relevant concepts across the whole corpus of documents in a minimally supervised automatic way;
  2. retrieval through natural language complex queries of any information across the corpus;
  3. reveal logical and semantic connections across topics that are inaccessible to human analysts due to the sheer size of the corpus.
- Swedish KIF - This activity, commissioned by the Swedish nuclear waste management company, SKB, focuses on the writing of the KIF for a high-level nuclear waste (spent fuel) repository in Forsmark, Sweden. In doing so, the activity critically evaluates which social scientific and natural scientific methods are suitable for the communication of information, records and memory of nuclear waste repositories over hundreds and thousands of years. Since 2021, the activity has produced a draft document of the KIF that is currently under review. In producing this draft document, activity members have consulted with NEA Expert Group on Awareness Preservation after Repository Closure (EGAP) and experts across NEA IDKM projects. In the future, the activity will finalise the KIF by deciding which file types and printed mediums meet the requirements for communicating over large time horizons. It will also investigate the international differences between KIF files currently being produced across nuclear waste producing nations and provide recommendations for improving international alignment.

5.4 Lessons learnt

The KM efforts of organisations may erode over time without continuous top and middle management support. To garner and sustain this support, it is important to highlight the direct user benefit from applying IDKM principles. Organisations should also understand that successful IDKM must include a monitoring aspect that helps to identify corrective actions to be taken to ensure adherence to IDKM processes and practices. Continuous monitoring and evaluation is key to maintaining the organisation’s maturity level and critical to lay the foundation for further growth.

Despite the advancements in information technology, human intervention, guidance and discipline is required to ensure that technology is effectively supporting the organisation’s IDKM practices. A comprehensive strategy and governance framework contributes to ensuring that technology effectively supports the organisation's IDKM goals. Overreliance on technology without consideration for human factors involved will almost certainly result in insufficient or unsuccessful IDKM efforts.

An organisation’s change readiness and ability to adopt new practices and technologies needs to be considered prior to formulating a programme to improve the IDKM. Introducing too many changes in a short time could prove to be counterproductive and not provide the intended benefits.

6. Uncertainties

Short-term uncertainties include decisions on which file formats or standards are to be adopted, which information technology systems and approaches will prevail and how emerging technologies will change the strategy for IDKM. These uncertainties need to be calculated and addressed during the various repository phases.

Future society's valuation of a final repository and its archived information can change in a way that we cannot predict today (Bandolin and Sverker Sörlin, 2007; Holtorf and Högberg, 2014). Determining which information should be preserved is therefore a challenge. We cannot know for sure what information future generations will value the most. Initially, it may therefore be better to save "too much" rather than "too little" information. Ultimately, the amount of information and data that can be preserved, i.e. is archived, over the long term depends largely on the means available to ensure the availability and comprehensibility of the material over time. The strategy of saving all information as long as possible can be associated with high costs and a risk of important information being buried, i.e. the information exists but is not traceable. Regardless of the extent to which information is collected, an information hierarchy can increase the availability of the information over time and thereby support the collective awareness of a site.

It is important to address potential factors that could result in epistemic or physical loss of information and devise strategies to mitigate those factors. The associated risks differ depending on the timescale of the information transfer. Three different relative time-horizons can be considered:

- Information transfer within the current generation to ensure that the necessary information exists so that RWMOs, authorities and others can have access to the safety case and the information that underpins it.
- Information transfer to the next generation to ensure that the national programme evolves as planned.
- Information transfer over multiple generations, far into the future to ensure future societies' right to autonomy and to reduce the risk of unintentional human intrusion in a closed repository for radioactive waste.

The last IDKM domain phase, spanning centuries or longer, has the most considerable challenges; however, perhaps the most crucial challenges exist in the time before repository closure, when information transfer must succeed if there is to be any hope of longer-term preservation of information.

In the time-horizons dealing with information transfer within the current generation and to the next, there are important lessons to be learned from the management of radioactive waste. Aside from unexpected, major social changes, the factors that have the largest impact on record loss are related to:

- deficient regulatory guidelines and their enforcement;
- lack of funding, lack of organisational/institutional continuity;
- carelessness (disinterest, negligence, ignorance or incompetence) or wilfully forgetting.

Therefore, a transparent and open decision-making process with clear actors and an equally clear division of responsibility, where a distributed responsibility between many actors can be avoided, is fundamental for capturing information and avoiding the loss of records in the short-term.

If the preservation of awareness requires the selection of relevant information that is produced and its transmission over the generations, the preservation approaches currently used and being studied attempt to alleviate the problems in the repository post-closure phase (and beyond). However, these approaches may not be very useful in the repository phases of programme initiation through closure. To ensure the adequate transmission of knowledge, it is necessary to constantly question the relevance of the information/knowledge and the performance of the preservation approach, so that there is successful transmission from one generation to the next and subsequent generations. Thus, it is not only necessary to prepare information and systems for the time after the repository closure, but also to ensure that they are adequate for their purpose throughout the repository development.

When considering KM, one must first have the means to identify and decide which situations to prioritise. Even in the phases before repository closure, it may seem uncertain what knowledge should be accumulated and transferred. This uncertainty can be reduced by considering what constitutes critical knowledge. This may be assessed based on the alignment of activities with the organisation's strategic plans and the risk potential, i.e. the operational stakes, of these activities. Indeed, knowledge required to perform an activity critical to the organisation is itself critical and therefore should be managed.

KM for RWM activities faces additional constraints of complexity and uncertainty due to the specificity of these activities and projects. Some of these specific complexities include: the disjunctive timeframes of knowledge production and exploitation, e.g. discontinuities of several decades; the diffused location of knowledge within the ecosystem of actors and the movements of knowledge ownership between the different structures caused by industrial opportunities, research policies, the mobility of carriers, etc.; the trajectories of institutional evolution, organisational adaptation and modification of the ecosystem of actors.

7. Guidance, Training, Communities of Practice and Capabilities

This section provides links to resources, organisations and networks that can help connect people with communities, focussed on the domain of *IDKM*

Guidance
NEA Preservation of Records, Knowledge and Memory (RK&M) Across Generations: Final Report of the RK&M Initiative https://www.oecd-nea.org/jcms/pl_15088 NEA Preservation of Records, Knowledge and Memory (RK&M) Across Generations: Developing a Key Information File for a Radioactive Waste Repository https://www.oecd-nea.org/jcms/pl_15060 NEA Preservation of Records, Knowledge and Memory (RK&M) Across Generations: Compiling a Set of Essential Records for a Radioactive Waste Repository https://www.oecd-nea.org/jcms/pl_15090 NEA Metadata for Radioactive Waste Management https://www.oecd-nea.org/jcms/pl_15062 IAEA Guide to Knowledge Management Strategies and Approaches in Nuclear Energy Organizations and Facilities https://www.iaea.org/publications/14698/guide-to-knowledge-management-strategies-and-approaches-in-nuclear-energy-organizations-and-facilities IAEA Knowledge Loss Risk Management in Nuclear Organizations https://www.iaea.org/publications/10921/knowledge-loss-risk-management-in-nuclear-organizations IAEA Knowledge Management Assist Visit https://www.iaea.org/services/review-missions/knowledge-management-assist-visit-kmav
Training
IAEA School of Nuclear Knowledge Management https://www.iaea.org/services/education-and-training/schools/school-of-nuclear-knowledge-management
Active communities of practice and networks
OECD NEA Working Party on Information, Data and Knowledge Management https://www.oecd-nea.org/jcms/pl_25233/working-party-on-information-data-and-knowledge-management-wp-idkm OECD NEA Expert Groups on Radioactive Waste Information, Data and Knowledge Management https://www.oecd-nea.org/jcms/pl_46350/new-expert-groups-on-radioactive-waste-information-data-and-knowledge-management

Capabilities (Competences and infrastructure)
NEA IDKM of Radioactive Waste Management https://www.oecd-nea.org/jcms/pl_29865/idkm-of-radioactive-waste-management IAEA Nuclear Knowledge Management https://www.iaea.org/topics/nuclear-knowledge-management https://www.iaea.org/about/organizational-structure/department-of-nuclear-energy/division-of-planning-information-and-knowledge-management/nuclear-knowledge-management-section IAEA Nuclear Energy Management School https://www.iaea.org/services/education-and-training/schools/school-of-nuclear-energy-management International Nuclear Management Academy https://www.iaea.org/topics/nuclear-knowledge-management/international-nuclear-management-academy https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1795_web.pdf EC EURAD Knowledge Management https://www.ejp-eurad.eu/implementation/knowledge-management

8. Further reading, external Links and references

8.1 Further Reading

IAEA Knowledge Management and Its Implementation in Nuclear Organizations https://www.iaea.org/publications/10849/knowledge-management-and-its-implementation-in-nuclear-organizations

IAEA Knowledge Management for Nuclear Research and Development Organizations https://www.iaea.org/publications/8644/knowledge-management-for-nuclear-research-and-development-organizations

Comparative Analysis of Methods and Tools for Nuclear Knowledge Preservation https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1494_web.pdf

IAEA Exploring Semantic Technologies and Their Application to Nuclear Knowledge Management https://www.iaea.org/publications/13469/exploring-semantic-technologies-and-their-application-to-nuclear-knowledge-management

IAEA Mapping Organizational Competencies in Nuclear Organizations https://www.iaea.org/publications/12296/mapping-organizational-competencies-in-nuclear-organizations

Metadata for Radioactive Waste Management https://www.oecd-nea.org/jcms/pl_15062/metadata-for-radioactive-waste-management

Waste Package Library - A Report of the Radioactive Waste Repository Metadata Management (RepMet) Initiative https://www.oecd-nea.org/jcms/pl_66896/waste-package-library-a-report-of-the-radioactive-waste-repository-metadata-management-repmet-initiative

Site Characterisation Library - A Report of the Radioactive Waste Repository Metadata Management (RepMet) Initiative https://www.oecd-nea.org/jcms/pl_66894/site-characterisation-library-a-report-of-the-radioactive-waste-repository-metadata-management-repmet-initiative?details=true

Repository Library - A Report of the Radioactive Waste Repository Metadata Management (RepMet) Initiative https://www.oecd-nea.org/jcms/pl_66908/repository-library-a-report-of-the-radioactive-waste-repository-metadata-management-repmet-initiative?details=true

RepMet Tools and Guidelines - A Report of the Radioactive Waste Repository Metadata Management (RepMet) Initiative https://www.oecd-nea.org/jcms/pl_66909/repmet-tools-and-guidelines-a-report-of-the-radioactive-waste-repository-metadata-management-repmet-initiative

ISO 30401:2018 Knowledge management systems — Requirements https://www.iso.org/standard/68683.html

ISO 8345 Application of Knowledge management to Radioactive Waste Management (prepared with IDKM's involvement, to be published!)

ISO/IEC 27001 Information security management systems — Requirements https://www.iso.org/standard/27001

ISO 8000 (series) Data quality https://www.iso.org/standard/81745.html

ISO 30301:2019 Information and documentation — Management systems for records — Requirements https://www.iso.org/standard/74292.html

ISO 14721:2012 Space data and information transfer systems — Open archival information system (OAIS) — Reference model https://www.iso.org/standard/57284.html

ICRP-122: Radiological protection in geological disposal of long-lived solid radioactive waste, ICRP Publication 122. Ann. ICRP 42(3), 2013, http://journals.sagepub.com/doi/pdf/10.1177/ANIB_42_3

8.2 External Links

https://www.oecd-nea.org/jcms/pl_25233/working-party-on-information-data-and-knowledge-management-wp-idkm

8.3 References

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