eurad
European Joint Programme
on Radioactive Waste Management

4. GEOSCIENCE; THEME OVERVIEW

Host rock and geological environment for a DGR

Geoscience is of key importance for geological disposal of long-lived, higher activity radioactive waste. It is linked with all (EURAD) safety functions, i.e., isolation of waste from people and accessible biosphere, containment, retention and retardation of contaminants, minimized water flow and long-term geological stability. A broad stakeholder community ranging from interested laymen to highly specialized geoscientists will follow the role of, and the work done in geoscience, with great interest through all the phases of a deep geological disposal project described in the EURAD Road Map. Permanent, clear and transparent communication is therefore a prerequisite for gaining broad acceptance of a deep geological disposal project.

KEYWORDS: Geological environment, Geological setting, Groundwater.

KEY ACRONYMS: Host Rock (HR), Site Descriptive Model (SDM).

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TYPICAL GEOSCIENCE GOALS PURSUED BY NATIONAL RWM PROGRAMMES

This section provides a goals breakdown structure (GBS) for the EURAD roadmap theme 4 on geoscience. It is organised in a hierarchy of three levels according to theme > sub-themes > domains.

Theme (Level 1)	
4. Assemble geological information for site selection, facility design and demonstration of safety (Geoscience)	
Sub-themes (Level 2)	**Domains (Level 3)**
4.1 Provide, or confirm a description of the natural barrier and how it contributes to high level safety objectives (Site description)	4.1.1 Develop a model of the host rock and surrounding geological environment, including distributions of rock types, geometry and properties of structural features, geotechnical properties and the hydrogeological and hydrogeochemical environment (Site descriptive model)
	4.1.2 Describe bedrock transport properties (aqueous and gas transport, advection/dispersion, diffusion) including retention (sorption, matrix diffusion) of different geological materials
	4.1.3 Characterize or confirm surface ecosystem properties and their potential evolution in the future (Biosphere model, also part of 4.3)
4.2 Characterize the potential impact of disposal facility construction, operation and closure on the natural geological barrier (Perturbations)	4.2.1 Characterize or confirm the chemical, hydrogeological, geomechanical, thermal, geomicrobiological, gaseous and radiation-induced perturbations which may be caused by facility construction, operations or closure and their impacts on long-term disposal system evolution (Perturbations).
4.3 Provide, or confirm a description of the expected evolution of the geosphere (including the repository) in response to natural processes and future human actions (Long-term stability)	4.3.1 Assess the expected geological and tectonic evolution and the potential for natural disruptive events and their impacts on the stability of the natural barrier (Geological and tectonic evolution)
	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)
	4.3.3. Assess the effects of future human actions (human intrusion by exploration activities, exploitation of natural resources within, above and below the host rock)
4.4 Provide a geoscientific synthesis (Geosynthesis) with geoscientific key information with respect to long-term safety and repository concepts (layout and construction)	4.4.1 Provide commented tables with key data, key figures (conceptual models) and comments on the interrelationships of site characteristics, perturbations and long-term evolution (stability). This report should contain the so-called Geo-Datasets for long-term safety analyses and repository concepts (layout and construction) for each licensing phase.

CORE ACTIVITIES IN THE NATIONAL PROGRAMME

This section describes broadly the typical RWM activities that are required to successfully achieve generic goals in theme 4 on geoscience.

Provide, or confirm a description of the natural barrier and how it contributes to high level safety objectives (Site description)

Different situations

Many geological settings could be suitable for a deep geological disposal facility. In all national programmes the term 'host rock' (HR) is used for the formation (or rock unit) in which the disposal rooms of a repository are constructed. The geological environment, within which the host rock lies, is also part of the natural barrier system, but – depending on the overall geological setting – may play a very different role with respect to the containment and retardation of radionuclides.

The following four general situations can be distinguished:

1. The host rock represents the main radionuclide transport barrier and the contribution to containment from the surrounding rock units is of much lower importance (examples: Boom Clay in Belgium, Callovo-Oxfordian claystones in France).
2. The host rock has an important (in some cases the most important) containment function but the geological environment outside the host rock provides a significant additional barrier with respect to the release of radionuclides (examples: Opalinus Clay host rock and adjacent clay-rich confining units in Switzerland; the Cobourg Formation host rock and adjacent Ordovician shales and argillaceous limestones in Canada).
3. The host rock with favourable radionuclide containment properties (the host rock *sensu stricto*) is only part of a large, extended rock unit which forms a similar geological environment, but with less favourable properties than the host rock itself (examples: crystalline rocks in Sweden, Finland, Canada).
4. Rare cases where the main transport barrier for radionuclides is represented by the geological environment surrounding the host rock: i.e., the main role of the host rock is to provide a mechanically stable environment for the waste emplacement rooms (example: the oolitic limestone host rock of the Konrad repository in Germany, which is surrounded by thick, clay-rich formations).

Groups of host rocks and variability of geological settings

Host rocks are often categorized and discussed in three main rock groups (*crystalline rocks, argillaceous (clay) rocks and evaporites, such as rock salt*). At NEA there are three thematic working groups (Clay Club, Crystalline Club and Salt Club) in which recent developments in various national programmes are discussed. The first group, the NEA Clay Club, has also produced a series of state-of-the-art reports, in which the international achievements in understanding the geological environment during the last two decades have been presented.

Mainly driven by a wide variety of geological settings, another terminology for rock groups has been developed in the UK: Higher strength rocks, lower strength rocks and evaporites (Metcalf et al. 2015).

In many countries there is a wide variability of potentially suitable geological settings for deep geological disposal, which was a reason for the terminology developed in the UK. In some countries, however, there may be only one typical setting: for example, Finland and Sweden, where crystalline rocks are effectively the only feasible option.

There is also variability in potentially suitable combinations of different rock units and different cover rocks (see also Metcalf et al. 2015).

- Higher strength host rock to surface
- Higher strength host rock overlain by higher permeability sedimentary rocks
- Higher strength host rock overlain by a mixed sedimentary sequence
- Lower strength sedimentary host rock overlain by higher permeability sedimentary rocks
- Lower strength sedimentary host rock overlain by lower permeability sedimentary rocks
- Evaporite host rock overlain by other sedimentary rocks.

The geological setting has an influence not only on how a Safety Case has to be structured and on the content of the safety-relevant geological data set, but also on the exploration strategy and the state of knowledge after each site characterisation phase (e.g., host rock accessible at outcrop *versus* host rock covered by other rocks: e.g., crystalline basement under sedimentary cover).

Understanding the radionuclide transport properties of the undisturbed geosphere

Understanding the radionuclide properties of the undisturbed geosphere requires not only the direct measurement and investigation of the key transport properties of the host rock and surrounding formations (porosity, structural features, mineralogy, hydraulic properties, sorption properties etc.) but also the collection of hydrogeochemical information as independent evidence for the hydraulic properties to be used in radionuclide transport models. In addition, an understanding of the processes that have led to development of the properties of the host rock (e.g., burial history, diagenesis, tectonic evolution, past and present stress conditions, self-sealing processes) is also important for a convincing safety case.

Rock mechanical and thermal properties, stress state

Rock mechanical and thermal properties of the undisturbed geosphere (host rock and geological environment), and the stress state at a potential repository site are used not only as a basis for engineering (repository lay-out and construction) but also for the assessment of perturbations. Therefore, these aspects also have an impact on the containment behaviour of the geosphere and have to be taken into account in the planning of the characterization of the geosphere.

Characterise the potential impact of disposal facility construction and operation on the natural geological barrier (Perturbations)

In this sub-theme a wide range of thermal, mechanical, hydrogeological, chemical, geomicrobiological, gaseous and radiation-induced perturbations have to be assessed. These processes are time-dependent (e.g. heat production/radiation from waste), depend on the properties of the engineered barriers (interface between waste and surrounding geology) and on the properties and state of the natural barrier system, but may also be linked, to some extent, with the natural evolution of the geosphere (e.g. decompaction due to erosion).

Provide, or confirm a description of the expected evolution of the geosphere (including the repository) in response to natural processes (Long-term stability)

There are two types of natural processes that have to be taken into account in the assessment of the future evolution of the geosphere:

- endogenic processes (tectonic processes, including seismicity, uplift/subsidence and rock deformation, and volcanic activity)
- exogenic processes (climate evolution and corresponding consequences such as erosion/landscape evolution, glacial loading, permafrost, influence on the hydrogeological system)

In addition the effect of future human actions needs to be considered, which comprises – beside human intrusion into a repository (e.g., by exploration activities) – the exploitation of natural resources (hydrocarbons, ores, geothermal energy, underground space) below, within, above and nearby a repository. All these processes are strongly linked with the geological setting of a repository, which requires corresponding characterization that takes all these aspects into account.

Provide a geoscientific synthesis (Geosynthesis) with geoscientific key information with respect to long-term safety and repository concepts (layout and construction)

Good example of geosynthesis, and author selected references are provided below, ordered according to release dates.

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RECOMMENDED GEOSCIENCE ACTIONS OVER PHASES OF IMPLEMENTATION

This section provides examples of typical actions completed for geoscience, based on the experience of advanced programmes, over different phases of implementation.

Programme initiation (Phase 1)

Programme Implementation (integrated actions in theme 4 on geoscience linked to activities in other themes)

- The stepwise build-up of an experienced team for all geoscience-related themes is a prerequisite for a successful deep geological disposal programme (See Sub-theme 1.3. Programme Resources). The broad sub-domains mentioned above need to be assessed in the very first phases of a DGR programme. As a first step, this requires setting up a capable team. This first step will benefit considerably from already available information: e.g., from a national geological survey and/or from university infrastructure. Building up contacts to other programmes is also essential.

Site description (desk-based studies)

- Compile overview geological information at the national level: large-scale geotectonic units and their main characteristics with respect to tectonic complexity and age of formation (sedimentation, orogeny) and their neotectonic activities (vertical movements, seismic/aseismic differential movements, seismicity). Document the compilation in an overview report, including maps and vertical cross-sections.
- Identify general occurrences of potential low-permeability sedimentary and crystalline rocks. For sedimentary rocks, this should be based on published compilations of lithostratigraphic profiles; in crystalline rocks, on compilations of maps and vertical cross-sections showing different types of rock units and larger scale structural patterns.
- Compile indications of larger scale, low-permeability regions in underground structures, either based on specific measurements or based on analogue considerations.
- Compare the national geological situation with those considered in other world-wide DGR programmes and identify potential analogue situations. Initiate a continuous review process in order to become and stay familiar with the most appropriate analogues.

Perturbations (based on desk studies)

- Compilation of potential perturbations to identified potential host rocks formations that might be caused by repository heat-producing waste, cementitious/concrete waste forms and construction material, excavation damage, etc. Preparation of short state-of-the-art report based on an analysis of the most recent international summary reports or books.

Long-term stability (based on desk studies)

- Assemble an overview of country-wide knowledge concerning vertical and horizontal crustal movements, seismicity, glaciation, volcanicity and erosion history. This early screening phase can rely on published information at a large scale.

Geosynthesis

- Provide a summary report on the programme initiation phase (overview of the national geological situation: potential host rocks and geotectonic overview). Overview of potential perturbations of the geosphere by a repository.
- Describe/discuss analogue situations in other countries

Site identification and selection (Phase 2)

Programme Implementation (integrated actions in theme 4 on geoscience linked to activities in other themes)

- Use available national geosynthesis to support the site selection process (See 6.3 Site Selection Process).
- The waste inventory, which includes reserves for future developments, has to be allocated to the HLW and the L/ILW repositories. (N.B.: the time period considered for HLW is much longer (1 Myrs) than for L/ILW (10 to 100 kyrs), See 1.4.1 National Radioactive Waste Inventory and 1.5.2 Options and Concept selection. Based on this waste allocation, the second step involves defining the barrier and safety concepts for the two repositories (See 7.1 Safety Strategy).
- Support preliminary feasibility safety assessment (See Theme 7 Safety Case) and conceptual design (See Theme 5 Design and Optimisation).

Site description (based on regional investigations and additional desk studies)

After the initial conceptual planning during Phase 1, the siting process can be subdivided into three main activities: Screening (See also 6.1.2 Area Survey and Site Evaluation), Investigations (See also 6.2.1 Site investigation) and Selection (See also 6.2.2 Detailed site characterisation and site confirmation).

Screening (country-wide)

- Screening is based on more detailed compilations of existing information than during the Initiation Phase.
- At the end of the Screening activity, the large-scale geological-tectonic situation is assessed with respect to the extent of suitable rock masses. In addition, aspects concerning long-term geological stability (see below) are also taken into account. Finally, large-scale areas (geotectonic units) that remain under consideration are defined.
- This should allow narrowing down to a limited number of regions to be looked at in more detail. Some programmes have opted to identify geological exclusion criteria at this stage, to identify regions that are clearly technically unsuitable for a DGR (e.g., based on tectonic factors). Any non-excluded area of the country can then be assessed for potential, based on its specific merits.

Investigations (in the most promising regions)

- The Investigation activities are focused on the remaining regions and comprise a detailed and project-oriented evaluation of existing information at the regional scale, and specific site investigations.
- Existing and available information covering a wide range of geoscience disciplines: comprises smaller scale geological maps, information from existing boreholes and previous geophysical surveys (airborne geophysics, reflection seismic surveys etc.) carried out by other organisations, for other purposes. If necessary, information can be complemented by selective laboratory investigations on existing cores or on outcrops.

- Site investigations will include 2D and 3D seismic surveys, high-resolution airborne geophysical surveys and deep boreholes with a broad spectrum of investigations focused on aspects of long-term safety and repository layout and construction. The type of investigations depends on the geological setting. For example, in the case of outcropping host rocks, mapping and airborne geophysical surveys play a more prominent role than in a situation with a host rock in crystalline basement under sedimentary cover. Also, the state of knowledge and geoscientific understanding of a site during the site investigation activities depends on the geological setting. Sites with crystalline host rocks need a much larger number of boreholes than sites with sedimentary host rocks.
- Key geoscience aspects concerning long-term safety are: Radionuclide transport properties of potential host rocks and surrounding formations : i.e., information on mineralogy, porosities, permeabilities, detailed characterization of water-conducting features with respect to radionuclide transport (including aspects such as matrix diffusion and flow-channelling), hydrogeochemistry (natural tracers as independent evidence for water age and transport mechanisms, definition of reference water composition), gas transport properties. Other important parameters include diffusion and sorption coefficients.
- Key input for repository concepts (layout and construction) are the stress conditions at depth, rock mechanical parameters of potential host rocks and geotechnical conditions for repository access structures (shafts, ramps).
- Site Descriptive Models have to be developed covering all important aspects (structural geology, hydrogeology, hydrogeochemistry, stresses and rock mechanics, thermal properties).

Selection

- In a first step the preferred host rock formations within the large-scale geotectonic units still under consideration are selected. The geological setting and the definition of a containment-providing rock zone have to be taken into account.
- Experience from other national deep geological disposal programmes, including underground research facilities, and from other areas (oil and gas industry, geothermal projects, road and railway tunnels, mines) should be taken into account in order to strengthen the arguments for the proposed host rock selection.
- Based on the regional investigations and national policy, one or more potential sites are proposed for detailed investigations at the site scale, which could vary from a few up to many tens of square km, depending on the geological situation and setting, and the size of the planned repository. The final selection of the site needs to consider long-term stability: see below.

Perturbations

- Build-up know-how and general understanding of potential repository-induced perturbations in identified potential host rock types, based on a detailed international literature survey.
- Follow up of international developments and achievements in various international conferences and activities (DECOVALEX, NEA Clay, Crystalline and Salt Club meetings ad state-of-the-art reports).
- Participation in URLs that are already in operation in the host rock type(s) being considered is also recommended.

Long-term stability (based on regional investigations and desk studies)

Following the rough overview in Phase 1, the focus in Phase 2 should be on the build-up of a detailed national understanding of the geoscientific aspects of long-term geological stability. In addition, more focused studies at smaller scales should be carried out *in potential siting regions* (e.g., by increasing the density of measurement/monitoring points, or the frequency of measurements, or by refinements in the measurement methods). This may in a later stage include the implementation of a project-specific regional monitoring system (geodesy, seismicity).

- Provide an understanding of neotectonic activity based on:
- Compilations of geodetic information (vertical and horizontal crustal movements based on geodetic precision levelling, GPS surveys)
- Seismicity maps and palaeoseismicity studies
- Identification of differential movements along existing faults (published information using various methods)
- If present, compile a report on spatial distribution of young volcanic rocks, age dating, and direct/indirect evidence of volcanic activity or potential for activity.
- Compile information (national and neighbouring regions) on past climate evolution (focus on Quaternary) and compile maps of the extent of different glaciations.
- Quantify erosion rates based on:
- Topographic maps (ordinary topographic maps and LIDAR surveys)
- Bedrock elevation maps/models (elevation model of the base of the Quaternary)
- Age determination of gravel terraces to provide semi-quantitative information on landscape evolution (uplift and incision by fluvial erosion, determination of erosion base-level)
- Comparison with sediment budgets (if available)
- Shallow boreholes with detailed characterization of Quaternary deposits
- Compile the current knowledge concerning natural resources (with respect to potential conflicts of interest for land use).

Geosynthesis

- Provide a geosynthesis report with commented tables of key data, key figures (conceptual models) and comments on the interrelationships of site characteristics, perturbations and long-term evolution (stability).
- Support the choice of host rock by multiple lines of reasoning, including comparisons with host rocks from other countries.
- Show links to safety assessment and repository engineering (geotechnical).

Site characterisation (Phase 3)

Programme Implementation (integrated actions in theme 4 on geoscience linked to activities in other themes)

- It is assumed that this Phase ends with the construction of underground access structures (shafts, ramp etc.) with detailed rock characterisation (See 6.2 Detailed site investigation).
- Support site-specific safety assessment (See Theme 7 Safety Case) and site-specific design (See Theme 5 Design and Optimisation).

Site description based on detailed localized site-specific investigations from the surface

- Investigations focused on the selected site. Detailed investigations in numerous boreholes, and (if necessary) completing site-specific seismic and airborne geophysical surveys, providing a basis for 3D Site Descriptive Models
- Detailed geological mapping (in case the host rock crops out at the surface), including trenching in thin Quaternary cover (if necessary).
- Development of 3D Site Descriptive Models that incorporate all key geoscience topics, including structural aspects (e.g. fracture systems at all scales), stress regime and rock strength models, hydrogeological zones and groundwater flow models, hydrochemical zones, evolution models for the deep hydrogeochemical system etc.

- Before going underground (or before any large-scale pumping tests are performed causing significant disturbance of the natural groundwater system), so-called Baseline Conditions in the undisturbed geosphere have to be established. Baseline Conditions include an understanding of seasonal and annual variations in groundwater pressures and hydrochemical conditions (mainly the presence of young groundwaters), as well as the influence of earthquakes on groundwater pressures. Baseline Conditions can only be established by measurements in long-term monitoring systems.
- Depending on the geological environment, this stage of the programme can also involve the definition of a ‘rock suitability classification’ system, which identifies specific geotechnical criteria for accepting or rejecting a volume of rock for waste emplacement. This system will then be deployed during the subsequent construction phase.

Site description based on in-situ investigations in the underground

- The last sections of access structures (shafts, ramp) at repository depth will have the function of a short-term rock characterization facility. Some programmes have opted to construct and operate a longer-term underground rock laboratory adjacent to the volume of rock eventually to be used for disposal. The important aspect is to perform key test and characterisation work related to perturbations (excavation damaged zone and excavation disturbed zone), radionuclide transport and gas migration under repository in-situ conditions.

Perturbations

- Monitoring of hydrogeological and mechanical responses (e.g., groundwater pressure changes, displacements in the rock) during construction of access structures and any RCF or URL can provide confirmation of the validity of geoscience models used in the safety case.

Long-term stability

- Continuation of measurements started during the regional Site Investigation stage.

Geosynthesis

- All geoscientific data and information and Site Descriptive Models needed for site confirmation and for a construction license should be compiled in a geosynthesis report that serves as a key reference document and should contain the Geo-Datasets for long-term safety analysis and repository layout and construction. One of the aims of the geosynthesis report is also to show the consistency of models and data from different geoscientific disciplines.

Construction (Phase 4)

Programme Implementation (integrated actions in theme 4 on geoscience linked to activities in other themes)

- Construction of the disposal tunnels/vaults, partially in parallel to operation of the repository (See Theme 5 Design and Optimisation)

Site description

- Detailed mapping of all underground structures encountered as construction proceeds (testing model predictions). This may also include structural, stress and hydrogeochemical characterisation activities related to rock suitability classification to identify acceptable rock volumes for emplacement of waste packages.

Perturbations

- Monitoring of the disturbance of the natural HMC system, including comparisons with model predictions for continued validation of safety case models.

Long-term stability

- Continuation of measurements and monitoring programmes started during regional Site Investigation.

Geosynthesis

- A report high-lighting the comparisons of model-predictions and actual findings during construction.
- Periodic update of geological understanding as part of the periodic safety case updates.

Operations & Closure (Phase 5)

Programme Implementation (integrated actions in theme 4 on geoscience linked to activities in other themes)

- In some National Programmes (e.g., the Swiss, Finnish and Swedish programmes) there is no clear distinction between a ‘Construction’ and an ‘Operation’ Phase, because disposal tunnels/vaults are excavated in some parts of the repository simultaneously with waste disposal taking place in other areas of the DGR. For a small DGR with a small, existing waste inventory, it might be appropriate to carry out all construction before emplacement operations commence. Terminology used by a programme and top level milestones are typically set as part of the licensing framework at a national level (See, 1.2.1 LIcensing Framework).
- In addition the sealing strategy for larger DGRs might require a step-by-step closure of individual emplacement rooms before final closure of the main access structures (See, 5.4 Operational Safety, and 5.1.1 Design Specification).
- In all cases, some specific additional characterisation activities will likely be required in order to make final decisions on the design and location of closure and sealing structures for the whole DGR, which could take place many decades into the future, using the best technologies available at the time (See 6 Licensing, and 5.5.2 Monitoring during Construction and Operations).

Site description

- No major activities, but extended monitoring of changes in the near- and far-field of the repository (see below).
- Characterisation of rock in locations of seal structures for final DGR closure.

Perturbations

- Monitoring of both the disturbance of the natural system caused by heat and gas producing wastes, and the reestablishment of the natural system (mainly groundwater pressure and chemistry).
- Comparisons of monitoring data with model predictions

Long-term stability

- Continuation of measurements and monitoring programmes started during regional Site Investigation.

Geosynthesis

- In order to get a ’closure permit’ it is assumed that the geoscientific information gathered during operation will have to be compiled and final conclusions have to be drawn with respect to long-term safety. This will be based on existing Site Descriptive Models, taking into account the latest geoscientific data from monitoring and sealing.

AVAILABLE CAPABILITIES: STATUS AND OUTLOOK

This section describes programme capability needs (including infrastructure) that are required to successfully complete the activities and actions recommended to achieve generic goals on geoscience.

Knowledge and understanding

- Step by step build-up of a core team with experienced individuals covering geology, hydrogeology, hydrogeochemistry and rock mechanics, with hands-on experience in deep geological disposal projects (including a basic understanding of perturbations caused by the repository). If such experience is not available nationally, a group of experienced people from one or more contractors or from sister waste management organisations should be built up on the basis of long-term contracts.
- Continuous training of staff is essential.
- Different capabilities are needed: oversight and ability to make syntheses, specialists in detailed areas (tectonics/long-term evolution, sedimentology, hydrogeochemistry, field work (geophysics, drilling/sampling/testing), laboratory work etc.
- For non-standard geoscientific work it is recommended to build-up and collaborate with so-called competence centres (groups of nationally/internationally recognized scientists with well-developed know-how, working on the basis of long-term contracts or letters of intent (so as to avoid loss of know-how).
- Quality assurance system for all measurement, monitoring and characterisation work (including an internal data clearance system)
- Step by step build-up of a permanent, preferably international Geoscience Review Board from the beginning. The review process is part of the QA-system and has to be documented.
- Continuous follow up of international developments
- It is important to point out that assembling geoscientific data and achieving a complete data set without important gaps is only one aspect of the geoscience work. This has to go hand in hand with development of an adequate understanding of all important processes in the geosphere and their interactions and dependencies.

Experts and practical skills

The most mature DGR programmes have moved through three or four decades of work on siting and initial surface-based characterisation. A generation of geoscientists have spent their whole working careers developing the approaches needed to reach the point of DGR construction but are now retiring. Other programmes are just starting along this road. Experience in the mature DGR programmes suggests that critical expertise can be lost within 20 years or less, unless efforts are made to transfer information from retiring staff to new employees. This can lead to a tendency to ‘reinvent the wheel’, perhaps simply because there are new or updated technologies available that are more familiar to younger generation staff. There are examples where projects from the 1980s and 1990s that have generated valuable information are already being overlooked when designing new projects or seeking data – largely because newer staff are unaware of their existence.

For new staff, transferring knowledge requires more than just ‘reading in’ to the subject. Active and structured steps need to be taken to extract from retirees critical knowledge and the understanding of how and why decisions were taken. WMOs need to maintain a certain level of expertise and understanding in-house, in order to act as ‘intelligent customers’ for their contractors and to be able to integrate geoscientific information and use it to make key programme decisions. Teams need to be built within WMOs and within their key contractor organisations and operated over several years in such a way as to enable progressive knowledge and experience transfer across generations. This is a relatively urgent matter today. Keeping 'alive' all of the external competences that are used by a WMO requires a big effort on their part. This can involve, for example, letters of intent and long-term contracts with external competence centres, to ensure that they do not lose their best people due to career uncertainty or lack of clear, long-term perspectives concerning their jobs.

Laboratories and centres of excellence

There are also geoscientific lab techniques that are only properly understood and practised within the area of RWM. These include porewater characterisation of clay rocks, radionuclide / host rock interaction and reference water composition (sorption, solubilities), and geomechanical testing of clay rocks. The skills for high-sophisticated experimental techniques (e.g., radionuclide transport experiments under controlled atmosphere) can be lost within a few years if there is no continuity in training young people to work on such a level. Similarly, the wide-ranging skills required to integrate diverse geoscientific data and interpretations into site descriptive, geosynthesis models and forecasts of future evolution – necessary for both siting and licensing – is specific to RWM, and the major national programmes are reaching a point where this work is being completed. In twenty years, they might not be doing this work any longer and new programmes might have to start again, at a conceptual level.

The examples above suggest that, with newer programmes unlikely to be reaching the construction stage of the currently advanced programmes until mid-century and the advanced programmes passing their 'peak geosciences' point soon, there is likely to be a gap in practical application activities and consequent loss of skills. Steps need to be taken to ensure that knowledge is not restricted to reports, which often lack context. One solution, adopted by some national programmes, is to establish long-term competence centres with the aim of sustaining expertise specific to their own programmes. If this were to be co-ordinated on a European scale, it would clearly be advantageous for new generations of RWM geoscientists.

Equipment, tools and technology

Some geoscientific techniques have been developed specifically for RWM applications and, when they are no longer being deployed widely, the expertise to use them and interpret the data arising will certainly dwindle. A key challenge in RWM applications is hydraulic testing in low-permeability formations (hydraulic conductivities < c.10-12 m/s). For example, the most advanced programmes working in hard, fractured rock have initiated and developed the whole field of fracture characterisation/classification, fracture hydrogeology and fracture network modelling. For the programmes working in very low permeability clay formations, one of the challenges is the choice of borehole testing fluids that fulfil the requirements of both borehole stability and testing (borehole fluid interaction with clay rock). The likelihood that the leading hard rock and clay programmes will complete their operational licensing within the next decade or so as they move to DGR industrialisation, means that the practice of these skills will diminish sharply. A new DGR programme entering the field in 20 years' time might have difficulties finding skilled practitioners to work with them.

Contractors and human / material resources

Expertise in DGR geosciences lies within WMOs, specialist contractors, national geological survey agencies, universities and dedicated RWM centres of excellence. Most of these organisations currently work together on common R&D projects and share ideas and methodologies. Several key skills are also used more widely than in RWM: in mining, environmental analysis, resource exploitation and civil engineering. They do not depend on RWM projects to sustain and advance them. Borehole drilling and logging, surface-based and airborne/satellite geophysical surveying and underground rock engineering are among these skills. At present, the 'peak activity' state of the most advanced DGR programmes combined with general commercial applications means that all the skills necessary for surface-based and underground geoscientific work are available at market level, both within Europe and worldwide.

Specific problems can arise where techniques are only available from contractors who are unwilling to disclose commercially confidential details of how measurements and their quantitative interpretation are made. As time passes, observations made in this way can lose their value if it is not feasible to reinterpret them fully.

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