KYT2022 OMT – Overall Safety of Nuclear Waste Disposal

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Confidentiality: Public
# Overall Safety of Nuclear Waste Management

## Summary

Overall safety of nuclear waste disposal forms a wide-ranging and interdisciplinary research entity including the collaboration between research organizations, regulators, and nuclear waste management organisations. At current, there does not exist a general framework incorporating long-term safety, the quality and safety of operations and the activities of involved organisations that would allow the assessment of the overall safety of nuclear waste disposal.

The main goal of this project is to initiate the development of such a general framework, starting from the safety culture perspective on the one and from the state-of-the-art safety case concept on the other hand. Different holistic approaches and frameworks in the context of nuclear safety have been analysed for the application of the defence-in-depth (DID) philosophy. After outlining the concept of overall safety based on a literature review, structured interviews with experts of several different topics relevant for nuclear waste disposal have been conducted in order to build a basic understanding of overall safety and its different facets in the Finnish context. Both, safety relevant aspects identified in the literature study and the interview findings have been discussed vis-à-vis the outcomes of the country-specific safety culture forum (CSSCF) conducted in Finland in Spring 2019.

In light of the approaching operational phase of the repository for spent nuclear fuel, issues considered to require more attention include the general organisation of research related to final disposal in Finland, the management of knowledge and the preservation and transfer of expertise. Another aspect to be possibly addressed in future in the context of overall safety concerns the communication between specialists carrying out research and the generalists involved in compiling research results and assembling the safety case.

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Preface

This report was compiled at VTT during 2019. The work performed was part of the Finnish Research Programme on Nuclear Waste Management 2019-2022 (KYT 2022) of the Ministry of Economic Affairs and Employment (TEM). The emphasis of the KYT programme is on nationally important research topics with the objective to ensure the authorities' access to competence and expertise in nuclear waste management in order to be able to compare and evaluate different approaches, methods and technologies.

The Overall Safety, Multibarrier System and Transient Phase (OMT) project was arranged as a small-scale project on behalf of the KYT2022 steering group. The objective of the OMT project during the first year was to gain a basic understanding of overall safety and its different facets in the Finnish context. For this purpose, a literature survey and a campaign of interviews with experts in the field of nuclear waste disposal were conducted. The authors sincerely thank the experts consulted for their participation in the interviews.

The OMT project manager was Heidar Gharbieh. Other VTT experts closely engaged in the OMT project were Kari Rasilainen and Marja Ylönen. Research professor Markus Olin (VTT) had an advisory role in the project. The review of this report was performed by Laura Wendling (VTT).

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The results obtained from the first phase of the OMT project were disseminated in an open seminar on overall safety held on 25 October 2019. Many thanks to our guest presenters Mikko Merikari (STUK), Anna Leinonen (VTT) and Edoardo Tosoni (Aalto University). The presentations are available online (http://kyt2022.vtt.fi/kyt2022_omt_seminar_2019.htm).

A continuation project is envisaged for 2021-2022.

Espoo 10.2.2020

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Introduction

During its first year, the Overall Safety, Multibarrier System and Transient Phase (OMT) project of the KYT2022 research program dealt with overall safety of nuclear waste disposal. Overall safety may be considered as an overarching concept including long-term safety, operational safety and the activities of involved organisations. The project goal has been to achieve a clear fundamental understanding of overall safety and to initiate the development of a general framework allowing for the assessment of overall safety.

In the nuclear power plant (NPP) domain, similar work has been carried out by Hyvärinen et al. (2016) with the Overall Safety Conceptual Framework (ORSAC). Main considerations in the ORSAC are the Defence-in-Depth (DiD) principle and top-down approach, with which the NPP architecture (systems, structures and components) is analysed as a system of systems. Having the system of systems view in mind, Hyvärinen et al. (2016) described the nuclear community with its different actors and stakeholders as an organisation of organisations. The International Atomic Energy Agency (IAEA) has developed the concept of Institutional Strength in Depth (ISiD; IAEA, 2017), which aims at fostering the robustness of the nuclear community on a national level from the organisational, inter-organisational and safety culture viewpoint. ISiD is essentially based on safety culture considerations in combination with an extension of the DiD principle from technical to organisational context. Rasilainen et al. (2019) compared the safety case methodology for nuclear waste disposal against relevant points of ORSAC and ISiD to identify possible needs for expansion of the safety case methodology and its practical application in Finland. Bearing these discussions in mind, overall safety of nuclear waste disposal has been approached in the OMT project from both the safety culture perspective and from the state-of-the-art safety case concept. The holistic socio-technical approach has benefitted from interactions with the KYT2022 SYSYMET project dealing with scenario development as well as with the OSAFE project of the SAFIR2022 research program focusing on overall safety of NPPs.

Part I of this report consists of a literature review on the relevant background for overall safety of nuclear waste disposal. National, organisational and safety culture are discussed in conjunction with the nuclear waste management community. The state-of-the-art safety case concept is presented and overlaps with safety culture aspects are highlighted. Part II of the report consists of findings related to overall safety obtained from structured interviews with experts in the field of nuclear waste disposal in Finland. Based on the results, recommendations for actions on a national scale are derived and possibilities for future research concerning overall safety of nuclear waste disposal are identified.
Part I: Literature survey

1. National culture, organisational culture and safety culture

1.1 National culture and organisational culture

The starting point of this holistic socio-technical or man-technology-organisation (MTO) approach to overall safety in nuclear waste management is the national culture. Culture is considered as the fabric of meaning in terms of which human beings interpret their experience and guide their action (Geertz, 1973). The culture, cultural values and the cultural changes depend on the history and origins of the countries, even the climate and environment where the cultures have evolved around the globe have influenced the cultural characteristics (NEA, 2016). A nations’ cultural background is reflected in common national aspects also referred to as national attributes. These national attributes have a significant, but often unconscious, influence on the behaviour of individuals and organisations, on decision-making processes, strategies and approaches and thus also on the safety culture, among many other aspects (NEA; 2018). A nation’s safety culture is seen as the fundamental basis for overall safety. Many national attributes collectively shared by a society are often deeply rooted assumptions and subconscious beliefs (NEA, 2016). Examples of such cultural traits are:

- collectivism or individualism (NEA; 2016);
- trend to maintain the status quo or to strive for continuous innovation (NEA, 2016);
- tendency to humbleness or complacency/arrogance;
- deference to or rejection of authority; and,
- frank attitude towards mistakes or fear of losing face or of being socially disgraced.

Note that cultures are rarely homogeneous and major cultural differences can exist in a country, e.g., geographical, between rural and urban areas or related to social class, religion, ethnicity, political orientation or profession (NEA, 2018). Furthermore, national cultures are evolving continuously and globalisation is increasingly influencing the national cultures (NEA, 2016). Recently, the Nuclear Energy Agency of the Organisation for Economic Co-Operation and development (OECD-NEA) and the World Association of Nuclear Operators (WANO), in cooperation with the respective national regulatory authorities, have carried out Country-Specific Safety Culture Forums (CSSCF) in Sweden (NEA, 2018) and Finland (NEA, 2019). As a result of these CSSCFs, relevant characteristics of national attributes were identified and their role in the country-specific safety culture were discussed.
The cultural background of the staff and management of an organisation greatly influence the organisation’s culture (NEA, 2019). In organisational theories, the generally intangible and primarily unconscious beliefs, values and assumptions, which are collectively shared and the national context as influenced by the organisation’s history, form the fundament for organisational culture and behaviour. Based on this fundament, organisational behaviour is manifested in a tangible and visible way. This can be described by Schein’s (1992) three-layer model, wherein the tangible manifestations of organisational behaviour become apparent in expressed values and artefacts (Figure 1-1).

Figure 1-1. Schein’s (1992) three-layer model of organisational culture as presented in Reiman and Oedewald (2002).

By directly and indirectly interacting with one another, all organisations belonging to a certain system (e.g., an industrial sector) mutually influence their respective organisational behaviours and (safety) cultures (NEA, 2016). The different organisations involved in the nuclear waste management of a particular country can be regarded as parts of a community or a complex, inter-connected socio-technical system, which does not exist in isolation but is in exchange with foreign countries and international bodies active in the field. In the context of nuclear waste management, the three layers of Schein’s model can be exemplified by:

i) Subconscious beliefs, values and assumptions: Economic profitability

ii) Expressed values: Nuclear legislation, codes of conduct, nuclear safety as the top priority
Artefacts: Organisational structures allowing for mutual checks and balances internally and externally; safety-related processes and procedures such as oversight work or periodic self-assessments and external reviews.

The tangible manifestations, i.e., the expressed values and the artefacts, can be assessed for the intangible underlying principles (IAEA, 1991; IAEA, 2013). Personal dedication, sense of accountability or a questioning attitude are examples for intangible and subconscious beliefs and principles, c.f. Schein’s three-layer model (Schein, 1992). The evaluation of how the organisational culture relates to safety (i.e., the safety culture) requires insights into the organisational culture at local and corporate levels. By interpreting the spoken word and behaviour of leaders, managers and staff and by analysing the interactions between individuals, departments and hierarchies as well as the relations with external organisations, a picture of the organisation’s safety culture can be elaborated and strengths and blind spots can be identified (IAEA, 2013; IAEA 2016). The attributes of a healthy safety culture are discussed in the next chapter.

1.2 Safety culture

As mentioned previously, the national context influences human and organisational behaviour. National attributes reflected by collectively shared values, assumptions, and ways of thinking or behaviours (cf. Schein’s three-layer model) may reinforce or, if not recognised, can weaken the overall safety performance of an organisation (NEA, 2018). It is necessary to bear in mind that comparing and grading national attributes of different countries is not expedient but that it is essential to understand the respective national context in order to achieve a strong safety culture and in turn a high level of safety (NEA, 2018). Thus, safety culture contains attitudinal and structural aspects and relates both to individuals and organisations (IAEA, 1991). In this context, the interested reader is referred to the CSSCF carried out in Sweden (NEA, 2018) and Finland (NEA, 2019). According to the IAEA (1991, 2013) and adopted by the NEA (2016), safety culture can be defined as follows:

“Safety culture is the assembly of characteristics and attitudes in organisations and individuals which establishes that, as an overriding priority, protection and safety issues receive the attention warranted by their significance”.

There exist different approaches in the nuclear community to characterise safety culture with its corresponding traits and underlying attributes in a structured way, see for example IAEA (2006a), Reiman et al. (2012), WANO (2013) or NEA (2016). As an example, the approach towards safety culture by IAEA (2006a) is represented by following five characteristics:

- Safety is a clearly recognised value
• Safety is integrated into all activities
• Leadership for safety is clear
• Accountability for safety is clear
• Safety is learning driven

In addition, IAEA (2006a) defined 37 underlying attributes. Note that these characteristics are interwoven and cannot be regarded in isolation from one another. The Finnish Radiation and Nuclear Safety Authority (STUK) has seven stated requirements regarding safety culture in the regulatory guideline “Guide YVL A.3” (STUK, 2019). Taking STUK’s requirements into consideration, the characteristics of organisations with healthy safety culture are described below. The discussion is complemented by taking into account the findings obtained from the CSSCF in Finland.

“Nuclear and radiation safety takes priority in decision-making.”

Each individual must be knowledgeable of the relevance of their activities and roles and how they contribute to safety in line with the organisation’s goals (IAEA, 2016). Within a collaborative working environment and encouraged by the leadership and management of the organisation (see below), individuals should exhibit moral courage and agility in order to ensure that their actions and decisions are driven by safety considerations. Individuals should actively raise safety concerns and withstand undue pressure due to conflicting interests that may have a negative impact on safety (NEA, 2016). Therefore, leaders and managers set and implement goals, strategies and direction without compromising safety (IAEA, 1991; NEA, 2016; IAEA, 2016). Managers encourage, praise and seek to provide tangible reward for particularly commendable attitudes in safety matters (IAEA, 1991; IAEA, 2016). According to the CSSCF in Finland (NEA, 2019), Finnish people take safety and their related responsibilities at work seriously. This commonly includes carrying out risk analyses to factor in safety issues in decision-making processes.

“The safety significance of issues is considered holistically.”

The approach to safety should be multi-disciplinary and holistic (NEA, 2016; IAEA, 2016). Therefore, the safety approach needs to encompass the interactions between humans, organization and technology and take into account both short and long-term consequences of all actions and decisions, e.g., by applying a graded approach to effectively manage and
control the allocation of resources based on risks and hazards involved (NEA, 2016; IAEA, 2016).

“Work activities are conducted in a professional manner and individuals take responsibility.”

In organisations with healthy safety cultures, individuals strive to meet commitments and collaborate in order to contribute to the organisation’s goals. Individuals should employ a rigorous and prudent approach and have a strong dedication to and sense of personal accountability for safety, and behave accordingly taking personal ownership for his or her actions and decisions (IAEA, 1991; NEA, 2016; IAEA, 2016). The appreciation of professionalism and pragmatism as well as the emphasis on facts and science that were found to prevail in the Finnish culture (NEA, 2019) support technical rigour. The strong sense of responsibility in the own area of competence has been already been mentioned as one outcome of the CSSCF in Finland (NEA, 2019).

Each employee and working group should collaborate, co-ordinate and communicate activities across (inner-) organisational boundaries to allow for mutual checks and exchange of knowledge and experience. Leaders and managers play a crucial role in the establishment of an organisational culture that fosters a healthy safety culture and a collaborative working environment. They motivate and inspire employees by prioritising safety over other matters in daily decision-making with a high degree of integrity, transparency and consistency. Managers and leaders act as role models and provide guidance to ensure that their commitment to safety is shared with all employees (IAEA, 2016; NEA, 2016). The (senior) management shall retain accountability for safety, even where responsibility for safety is assigned to managers and individuals at other levels of the organisations (IAEA, 2016).

In addition, managers and leaders define roles, responsibilities and authority that need to be clear, documented and regularly reviewed to avoid omissions or overlaps and problems of shared responsibilities (NEA, 2016). The managers make sure that individuals understand not only their own role but also those of their immediate colleagues and their management unit, and how these responsibilities complement those of other groups (IAEA, 1991). According to NEA (2019), individuals in Finland have a strong sense of responsibility and professional pride, which, together with the generally low hierarchical structures in Finnish organisations, lead to the wish for autonomy and objection to micro-managing. Despite the low emphasis on hierarchy, participants of the CSSCF in Finland (NEA, 2019) perceived a gap between the management and the lower levels of an organisation in the form of insufficient understanding of the actual situation of the other party. In this context, the application of logical rules and processes is essential, which is related to the national traits of pragmatism and the appreciation
of fact-based argumentation. A clear communication for the reasoning behind the rules is, however, a prerequisite for the reverence for and adherence to logical rules, which is another cultural trait in Finland. This might be an issue because of the Finnish communication style, which aims for efficiency and pragmatism. This potentially leads to misunderstandings if the management is perceived as not sharing sufficient information with others (NEA, 2019).

“Working conditions are well-organised.”

The management of an organisation needs to ensure that all activities meet the applicable safety, quality and management standards, e.g., by appropriate quality assurance (QA) (IAEA, 2016). In addition, leaders and managers ensure sufficient financial and personnel resources for a working environment without undue haste or pressure (IAEA, 1991; NEA, 2016; IAEA, 2016). The managers further ensure the appropriate physical working environment, e.g., suitability of controls, instruments, tools and equipment, the availability of the necessary information and the standards of housekeeping (IAEA, 1991).

The organisation’s management is responsible for achieving and sustaining the required levels of competences of the staff members, e.g., by appropriate recruiting and internal and external trainings (IAEA, 2016). Managerial responsibilities include the implementation of a range of monitoring practices and quality assurance measures to periodically review and update training programmes (e.g., on safety culture), staff appointment procedures, working practices and information control and documentation, among other (IAEA, 1991).

“Mutual respect and trust permeate the organisation.”

An organisation needs to create a collaborative working environment that is founded on mutual trust and respect and is supportive of open, honest, transparent and free dialogue engaging all staff of the organisation. The CSSCF in Finland (NEA, 2019) found that in Finnish organisations active in the nuclear sector, trust among colleagues, co-workers and managers as well as in processes, rules and systems is generally strong. However, the high level of trust can potentially be abused, lead to blind spots and undermine a questioning attitude. Therefore, it was concluded that verification and oversight are critical (NEA, 2019). The trust in the working environment is the basis for collaborative problem solving in Finnish organisations, which, however, does not require complete consensus (NEA, 2019).

The working environment in Finland is characterised by equality - age or gender do not determine hierarchal structures (NEA, 2019). However, due to professional pride and the
strong sense of ownership and responsibility in the own area of competence, feedback might be taken personally and referred to one’s own expertise. In connection with the desire for autonomy, there is the tendency to not to interfere in other’s area of responsibility in order to avoid conflict situations, so that giving feedback is sometimes difficult as well (NEA, 2019). In addition, the straightforward way of communication in Finland may complicate giving and receiving feedback (NEA, 2019). However, the challenges in raising questions and giving feedback can be met by having a technical or fact-based argumentation (NEA, 2019).

“\textit{The atmosphere is open, blame-free and vigilant in order to identify, report, investigate and resolve factors endangering safety.}”

Other key attributes for organisations with a healthy safety cultures are continuous improvement and commitment to a learning attitude (NEA, 2016; IAEA, 2016). This is particularly important for the nuclear waste management, because the process of implementing a final repository lasts several decades and the number of experts of the involved scientific and technical fields is relatively limited.

The management needs to establish policies and mechanisms for handling differing opinions (e.g., non-concurrence and whistleblower programmes) and to enable staff to develop a questioning attitude and freely raise safety concerns or self-report of mistakes without fear of negative consequences such as retaliation, intimidation, harassment or discrimination (NEA, 2016; IAEA 2016). Errors, when committed are seen less as a matter of concern than as a source of experience from which benefit can be derived (IAEA, 1991). Reporting errors should include those without apparent important consequences (IAEA, 1991). According to NEA (2019), the Finnish trait of being solution-oriented facilitates the continuous improvement process and mistakes are seen as learning opportunities. Nevertheless, for repeated deficiency or gross negligence, managers accept their responsibility to take disciplinary measures (sanctions), as safety may otherwise be compromised. There is, however, a delicate balance. Sanctions are not applied in such a way as to encourage the concealment of errors (IAEA, 1991). Leadership by fear is not supported in Finnish culture and managers treat their subordinates with respect and strive for a working environment with absence of blame (NEA, 2019).

Improvements in safety result from a well-judged combination of innovation and reliance on proven techniques and mechanisms (IAEA, 1991). In this regard, all individuals and organisations participating in the disposal programme should periodically scrutinise themselves and one another and perform self-critical analysis and carry out suitable correction-measures (self-regulation) in a pro-active, systematic and continuous fashion (IAEA, 2013;
NEA; 2016). Self-assessments support ongoing monitoring and continuous improvement utilising detailed organisational insights in a way that periodic external assessments cannot. However, self-assessments require special consideration of bias naturally present in any culture or organisation that examines itself (IAEA, 2016). Therefore, self-assessments rely on the competence and professional knowledge of staff in order to be effective, i.e., individuals need to show readiness and ability for self-reflection and openness to other, contradictory opinions. Thus, self-reflection and self-learning behaviour should be manifested in the organisational structure and organisational philosophy, i.e., reflected in the safety culture and the corporate identity. This includes hiring criteria for staff, systematic trainings and regular interdisciplinary exchanges of people from various departments of the organisation. The leadership and management have to ensure sufficient time and resources for self-assessments and continuous improvement loops and transform the findings into action plans (NEA, 2016). The leaders and managers, who also perform self-assessments, are responsible for the correction or adaptation of previous actions and decisions and for the implementation of mechanisms for timely detection and avoidance of mistakes (IAEA, 1991; NEA, 2016; IAEA, 2016). Therefore, recognised experts in the fields of leadership, management and safety culture assessments shall be consulted (IAEA, 2016). The thoroughness of the assessments and the strength of the corrective measures are important safety culture indicators (IAEA, 1991). The effectiveness of the corrective and preventive actions taken shall be monitored and any changes in the organisation, including cumulative effects of minor changes, shall be identified, documented and analysed for safety implications (IAEA, 2016). It is important that the leaders provide guidance for the self-assessments and that the choice of the corresponding tools account for the national culture. In this manner, the staff feel free to answer easily and honestly. Self-assessments are seen as an opportunity to identify any traits of national culture that may impact the organisation’s safety culture (NEA, 2016). Regarding the Finnish context, the findings of the CSSCF in Finland for instance can serve as a starting point.

Learning from previous experience requires a knowledge management programme (Section 2.3) to transfer knowledge and history of nuclear programmes to a new generation of staff (NEA, 2016). Provisions for knowledge management are further needed to retain corporate memory and knowledge in case of labour turnover, e.g., due retirements or competition on the labour market. It is particularly important to maintain the awareness of risks over time and make sustainable efforts to enhance safety and not to fall prey to the “safety myth” that a severe error (e.g., Three Miles Island, Chernobyl, Fukushima) would not happen again, or at all (NEA, 2016).
“The management demonstrates the importance of safety and their commitment to its continuous improvement in the work practices. The management system shall support the development of a good safety culture.”

As already discussed previously in conjunction with the three layer model by Schein, the institutional values and expectations for safety are represented by organisation’s decisions, statements and actions (IAEA, 2016). Organisations demonstrate their commitment to safety by promoting behaviours, and by implementing policies and practices that support a healthy safety culture (e.g., code of conduct). Such corporate policies include a commitment to excellence, promote and prioritise safety as the overruling requirement over other competing aspects (e.g., finances or time pressures) and state how a healthy safety culture is achieved (IAEA, 1991; NEA, 2016). These guidelines establish a common understanding of the key aspects of safety culture within the organisation and should be made visible to and incorporated by all staff (IAEA, 2013; NEA, 2016). In addition, corporate policies are expressed publicly as the basis for the interaction with external organisations (see Section 1.2).

An organisation’s management system helps to enable, develop, improve and promote the safety culture (NEA, 2016), thus it is important that essential actions concerning safety culture are integrated into the organisation’s management system and that the management system maintains the coherence of these concepts (NEA, 2016). The management system of an organisation should promote proactive and responsive management (IAEA, 2016). According to the findings of the Finnish CSSCF (NEA, 2019), planning and preparedness have been identified as typical national attributes.

The management system clearly specifies the organisational structures, processes, responsibilities, accountabilities, authorities and interfaces within the organisation and with external organisations (IAEA, 2016). The management system should be controlled, clearly documented in a readable and usable manner (IAEA, 2016) and readily available. The organisational structure should include an independent internal management unit having the role of continuously scrutinizing safety related matters and ensuring the integration of safety responsibilities into the management chain. In addition, the management system should provide arrangements for independent review by external bodies and define the nature and requirements of these reviews (see Section 1.2). There should be strong lines of authority, sufficient to discharge the responsibilities, and clear reporting lines with few and simple interfaces (NEA, 2016; IAEA, 2016).
1.3 Inter-organisational aspects

Individuals and organisations do not act in a vacuum but rather should understand themselves as a part of a system, e.g., the nuclear waste management community (Section 1.4). Accordingly, the discussion of the different aspects of safety culture needs to extend across the organisations’ boundaries and even national borders. An essential matter is the appropriate and clear division of roles and responsibilities of the different actors involved in order to avoid (self-) blockades and conflicts in decision-making and to establish a system of mutual checks and balances and mechanisms for error identification and correction. This is typically a task of the national legislation. At the institutional level, the organisational culture enshrined in the management system and publicly expressed corporate policies, should promote transparency and openness to dialogue and information exchange with external parties. This, together with openness to external audits and criticism (e.g., peer reviews) help to build trusting relationships among the different actors and reinforce their accountability for safety. It is important to emphasize that the responsibility for safety shall be retained by the individual organisation, e.g., the implementer, when contracting out any process or receiving any product, item or service in a supply chain (IAEA, 2016). This is especially important considering the multinational character of the organisations and supply chains in the nuclear industry. For illustration, imagine the different organisations and sub-contractors acting simultaneously on the disposal site with parallel construction/excavation work and disposal operations. Some of the collaborators might have little or no experience with the nuclear regime and the applicable national laws, guidelines and practices (Gotcheva et al., 2017). Therefore, an organisation should act as “informed customer”, i.e., having a clear understanding of the product or service received (IAEA, 2016).

Frequent exchanges with externals are beneficial to obtain insights in latest developments related to safety, which offers opportunities for benchmarking. In these regards, periodic colloquiums and cooperation in international expert panels (e.g., task forces) as well as reviews by external scientists/experts are useful. The collaborations should encompass a variety of different organisations to allow for a wide spectrum of opinions and approaches from various scientific disciplines. Sharing of experiences with actors of other safety critical sectors could also be beneficial to learn from events and discuss commendable practices. The described aspects of transparency and openness help to avoid a certain sense of self-importance, complacency or infallibility, which can result in isolation from other stakeholder and from the international community (NEA, 2016). In fact, the CSSCF in Finland revealed that there is a tendency to not accept foreign feedback easily due to the national pride (NEA, 2019).

In summary, it can be stated that due to their interactions, the organisations mutually influence one another. Therefore, promoting the importance of safety and the dissemination of related
knowledge enforces the safety culture of the entire nuclear waste management community of a country and eventually leads to increased public confidence (NEA, 2016; Endlagerkommission, 2016). Due to the mutual influences, the safety culture prevailing in the community and particularly in the organisations of closest cooperation, is an indicator of the quality of the own organisations’ safety culture and this should be considered as a measure for self-reflection (NEA, 2016).

1.4 Nuclear waste management community

Bearing in mind the ORSAC approach by Hyvärinen et al. (2016) and the ISiD concept developed by IAEA (IAEA, 2017; Ylönen et al. 2017), this section discusses the nuclear waste management community as an organisation of organisations. The network of relevant actors in the field of nuclear waste disposal is illustrated in Figure 1-2. In the following, their roles are discussed from overall safety perspective with special focus on the implementer-regulator-dialogue.

![Figure 1-2. An illustration of the nuclear waste management community. Organisations active in regulation and oversight (yellow), actors on the implementer side (grey), public stakeholders (blue) and supporting and international and foreign organisations (green).]

A country planning, developing or carrying out a nuclear waste management programme needs to provide a framework for the organisational structure of such a programme. This includes defining roles and assigning authorities and responsibilities to governmental institutions. The established framework should ensure efficient structures for mutual checks.
and balances and secure financial resources for decades-long activities. While regulation and oversight usually lie within government bodies, the role of the implementer can, for example, be assigned to a governmentally owned institution (e.g., the federal company for radioactive waste disposal BGE in Germany) or to a private organisation established by the owners of the nuclear utilities (e.g., Posiva Oy in Finland). The financial resources can, for example, be saved as provisions by the nuclear utilities or be collected in a publicly managed national fund, which is paid proportionally by the different waste producers (e.g., nuclear utilities, medical installations, public research institutions). The resources need to take into account the financial and personnel demands for the activities at the different stages of the development of the nuclear disposal facility. In addition, inflation and the overall economic situation should be considered (IAEA, 1991). In these regards and considering the generally long timescales, the organisation and ownership of the nuclear utilities, i.e., privately, publicly or jointly owned companies, play a role. In addition to sufficient budgets for adequate competence and staffing of the regulator and oversight organisation, the government’s tasks is to organise the authorities and responsibilities between the different governmental bodies without undue interference (IAEA, 1991). Depending on the national circumstances, this possibly concerns ministries and authorities responsible for:

- Mining activities, e.g., regarding the availability, ownership and generation of geological data for the site selection process;
- Environmental/water protection, e.g., for the environmental impact assessment including the chemo-toxicity of radionuclides; and the
- Road/traffic, e.g., for the necessary infrastructure at the disposal site.

As well as providing the nuclear regulator with the necessary finances, power and support, the government should set broad safety objectives so that safety is prioritised as the overruling concern in the nuclear legislation and to foster a national climate with a strong safety culture (IAEA, 1991). Nevertheless, the inevitable residual risk has to be taken into account in the legislation and regulatory requirements, which should be clear but at the same time not too prescriptive. In this manner a blurring of the responsibility for safety, which lies with the implementer (licensee), is avoided. In the same vein, the idea of self-assessments and correction together with the questioning attitude to be developed by the implementer is fostered (IAEA, 1991). For the assessment of the implementer’s safety culture, the regulator should consider the combination of several approaches (see IAEA, 2013 for details).

The previously discussed openness as part of healthy safety culture applies also to the dialogue between regulator and implementer, which should be initiated at a very early stage of the disposal programme. In this way, the interpretation of safety criteria and requirements
as well as discussions about disposal concepts and the R&D programme are facilitated. Particular challenges for the regulatory authority are the evaluation of new technologies or technologies adopted from other fields of science and engineering to be used in the context of nuclear waste disposal, and further, the evaluation of the disposal programme’s maturity to possibly grant licences\(^1\) for advancing in the stepwise process (NEA, 2009). In this regard, the regulator may perform corroborative analyses on its own or using external independent expertise in order to enhance its review capabilities and to increase the confidence in the safety case (Section 2) developed by the implementer (NEA, 2009). This may be considered as an additional safety layer in line with the defence-in-depth concept (Section 2.1), however, the separation of responsibilities between the regulator and implementer must not be undermined. This concerns in particular the implementer’s ultimate responsibility for safety, which also extends to all components and services received from vendors, sub-contractors, manufactures and others. The regulator should be encouraged by the government to have exchanges with international organisations (e.g., IAEA, OECD-NEA, WENRA) and foreign regulatory authorities. Note that such exchanges should be organised independent of commercial or political interests (IAEA, 1991). Similarly, exchanges between implementing organisations of different countries, including the sharing of research results, and the collaboration in joint research which are open to the public (for example EU projects) should be envisaged.

The dialogue between the regulator and the implementer should last beyond the granting of an operational licence (NEA, 2009) for, e.g., the required periodic safety case updates as well as the closure licence at the end of the operating phase. The form of meetings between the regulator and the implementer should be twofold. On the one hand, closed-door meetings should be held for efficient discussions on substance with the necessary depth. In addition, closed-door meetings without the fear of reprisal facilitate the raise of questions and safety concerns and contribute to an implementer-regulator-relationship characterised by trust and honesty (NEA, 2009). On the other hand, major meetings should be open to externals (e.g., the press, local actors or public organisations such as NGOs) to allow for transparency and traceability and eventually to increase the confidence in the (perceived) regulatory scrutiny (NEA, 2009).

Depending on a country’s societal and political realities, which are conditioned by the national culture, stakeholder participation can be organised in different ways. Usual opportunities for stakeholders and interested parties to express their concerns are the Environmental Impact Assessment (EIA), licensing hearings and, on a local level, community polls and exchanges between the host community and the implementer on a regular basis (NEA, 2009). In certain

\(^1\) In Finland, the regulator (STUK) provides guidance and recommendation to the government, which will eventually grant the license in question. Concerning the decision-in-principle, the parliament has to give its approval additionally.
disposal programmes (e.g., in Switzerland and Germany), the public is organised locally depending on the stage of the site selection process. In Germany, a National Civil Society Board (“Nationales Begleitgremium”) has been established to facilitate public participation and to act as an intervener in case of debates or conflicts between the involved organisations. It has access to the necessary documents and sufficient resources to conduct independent research studies with the aid of, for example, independent expert organisations. In addition, the National Civil Society Board can give recommendations to the parliament, e.g. suggestions for adaptations in the site selection and repository implementation process (Endlagerkommission, 2016). Again, the possibility for additional safety analysis carried out by societal stakeholders can be seen in line with the defence-in-depth principle, albeit the implementer is ultimately responsible for the safety of the disposal facility. In line with the ISiD concept (IAEA, 2017), an organisation such as the National Civil Society Board can be considered as an additional safety layer allowing for additional checks of the implementer but also of the regulator. Making the regulatory authority subject to checks by another independent body compliments the regulator’s self-assessment and reflection upon its interaction with the implementer. Therefore, the National Civil Society Board contributes to the continuous improvement of the safety culture prevailing in the nuclear waste disposal community.

As mentioned earlier, the main actors in the community, i.e., the implementer, the regulator and societal stakeholders, can make use of services and products by external organisations such as technical support organisations, research institutes and universities as well as consultancies, independent inspection companies and other commercial organisations. External producers or service providers are required to meet the high safety culture and quality standards of the nuclear regime. In this regard, it is especially important to maintain the organisations’ independency to avoid conflicts of interest, meaning to work exclusively for either the implementer or the regulator side, or at least to establish efficient measures for internal separation of working units.

2. Safety Case methodology

The development of a disposal facility is a long-lasting project spanning several years or decades and can be divided in different phases, i.e., pre-closure and post-closure phase. The pre closure phase can be sub-divided into a pre-operational phase, which includes the site investigation and selection and facility design, and an operational phase with the emplacement of waste canisters, installation of barriers and closure of the facility. The outlined phases are not distinct and may overlap. For example, parts of the repository may already be backfilled while emplacement of waste canisters continues in other disposal tunnels. In addition, the facility design may still change during the construction phase (e.g., to take into account the site
conditions encountered during the excavation work) or during the operation of the facility. Commonly, the licensing of the disposal facility is a stepwise process. In Finland, this includes the decision-in-principle, construction licence, operating licence and closure licence and at each of these key decision points, a safety case needs to be prepared. The safety case is the primary tool to demonstrate the safety of a disposal facility. It is prepared by the implementer organisation as the basis for the dialogue with different stakeholders including the regulator during the licensing process (IAEA, 2012). In Finland, the licensee is requested to periodically update the safety case at least every 15 years after the operating licence has been granted (STUK, 2018). In addition to requirements arising from national legislation, the safety case also takes into account the decision at hand, i.e., not only the transition from one stage to another in the development of a repository but, for example, choosing between different design alternatives, the refinement of waste acceptance criteria or the definition of operational procedures (IAEA, 2011).

The safety case is developed in accordance with a graded approach, i.e., the hazard associated with the radioactive waste and the stage of the development of the disposal program is reflected in the formality and level of (technical) detail of the safety case (IAEA, 2006b). In line with the graded approach and the long times associated with the disposal facility development, the safety case is developed in a stepwise and iterative manner. Considering the safety case’s purpose as a tool for communication with different interested parties, the presentation of the safety case, its level of detail and form (technical-scientific versus qualitative-descriptive language) may vary depending on the intended audience (IAEA, 2011). Anyhow, the presentation of the safety case should be clear, comprehensive, traceable and transparent. This is particularly important for the safety case review for scientific-technical aspects, regulatory aspects and non-technical aspects by the relevant decision-makers and interested stakeholders (NEA, 2013).

According to IAEA (2012), the safety case can be understood as the compilation of scientific, technical, administrative and managerial arguments and evidence in support of the safety of the disposal facility. The safety case addresses the suitability of the site and the facility design, its construction and operation. The core of the safety case form the safety assessments, which primarily aim at the systematic assessment of radiation safety and at understanding the disposal system’s behaviour considering different potential evolutions (scenarios) for the time frames over which the radioactive waste remains hazardous (IAEA, 2011) (see Section 2.2). The safety case further provides the necessary assurance of the adequacy and quality of all of the safety related work by using appropriate management systems (IAEA, 2012).

In recent years, substantial effort has been put by international organizations (e.g., IAEA, OECD-NEA, WENRA) in the harmonization of the safety case methodology. However, small
differences remain, in particular with regard to the used terminology. Figure 2-1 shows the safety case methodology according to OECD-NEA (NEA, 2013).

![Safety case methodology diagram according to NEA (2013).](image)

Figure 2-1. Safety case methodology according to NEA (2013).

In the following, elements of the safety case methodology particularly important for the overall safety discussion are described in more detail, while the interested reader is referred to NEA (2013) for a more comprehensive description.

2.1 Long-term safety strategy and defence-in-depth

The safety strategy sets out how safety is achieved during the entire lifetime of a disposal facility. It can be considered as the high level approach integrating all aspects relevant for safe disposal of radioactive waste. The general safety philosophy provides for an iterative and step-wise approach and thus, allows for flexibility, learning and optimisation in the long lasting process of implementing disposal facilities for radioactive waste. Accordingly, the safety strategy should not only be produced already at the very early stage of a disposal program but should also be periodically revised (IAEA, 2012). In accordance with the fundamental safety principles set out by the IAEA (IAEA, 2006b), radioactive waste must be managed in such a way as to avoid imposing an undue burden on future generations. Therefore, the long-term safety of radioactive waste disposal should rely on the passive engineering and natural features of the disposal system. Additional active measures to support passive safety should
be minimized and reliance can only be placed upon for timescales limited by the confidence in institutional and financial stability (up to a few centuries) (IAEA, 2014).

Passive post-closure safety is ensured through the disposal system’s main safety functions containment and isolation. These main safety functions are provided by a series of engineered and natural barriers with multiple complementary and compatible lower-level safety functions preventing the release of harmful substances or retarding their migration into the biosphere to an acceptably low level set by applicable regulatory limits. In such a multibarrier system, a number of safety functions may be assigned to a single barrier, while a particular safety function may be performed by a number of barriers (IAEA, 2012, 2014). Hence, the disposal system is comprised of several structural and functional defence lines. The various safety functions may be effective over different timescales in the post-closure period and thus, the relative importance of the barriers and assigned safety functions will vary with time (IAEA, 2012). In the context of a multibarrier system, compatibility means that the engineered and natural components of the disposal system mutually favour, or at least do not unduly hamper, the fulfilment of their assigned safety functions.

The described multiple structural and functional defence lines form the basis for the defence-in-depth concept (DiD). Defence-in-depth implies that safety does not unduly rely on a single feature of the disposal system and that a degradation or a loss of a safety function provided by one or multiple barriers is compensated by other safety functions for the relevant timescale (IAEA, 2012, 2014). Besides the interplay of favourable engineered and natural features of the disposal system and the set of multiple complementary and compatible safety functions, defence in depth is provided by controlling the inventory (and waste form), operating procedures and institutional and administrative controls (IAEA, 2012, 2014). The DiD principle can further be complemented by active means, such as Preservation of Records, Knowledge and Memory (RK&M; NEA, 2015) or post-closure monitoring. However, active means must not jeopardize and can only support the system of passive measures for ensuring long-term safety.

Taking into consideration the stepwise and iterative development of the disposal facility and the safety case during the likewise stepwise licensing procedure, one could speak of a procedural and a temporal dimension of DiD (Rasilainen et al., 2019). As the knowledge accumulates and analyses become less generic and more detailed over time, the arguments and evidence presented in safety cases also become more substantial. In this regard, the successive reduction of uncertainties and the handling of the remaining ones is crucial (see Section 2.2.2). In fact, the continuous optimisation provided by the stepwise and iterative approach resonates with the learning attitude described in Section 1.2 as a characteristic of a healthy safety culture. The use of multiple lines of reasoning (e.g., results of the safety assessments, uncertainty management and using natural and archaeological analogues as
additional evidence and arguments) to build confidence in the assessments and the safety statement, can be considered as another form of defence-in-depth applied in the safety case. Depending on the national conditions, also several institutional defence lines can be identified. Common in nuclear waste disposal programs is the implementer-regulator duality. In Finland, an additional defence layer from the institutional perspective is the government as the licence issuer. Note that the decision-in-principle additionally needs to be approved by the parliament. This is in line with the concept of Institutional Strength in Depth (ISiD; IAEA, 2017), where every member of the nuclear waste management community (Section 1.4) is considered to act as an independent safety layer being further enhanced by multiple internal barriers, such as competent actors, a safety management system (Section 2.3) and a vivid safety culture. The interested reader is further referred to the discussion regarding the organisation of organisations within the ORSAC framework by Hyvärinen et al. (2016).

2.2 Safety assessment, evidence and arguments

As mentioned previously, safety assessments constitute the central part of a safety case. They primarily aim at the assessment of the post-closure radiological impact on humans and the environment resulting from the potential release of radionuclides from the disposal facility and their migration into the biosphere. On an international scope, however, the tendency is to understand safety assessment/case more broadly. According to the IAEA (IAEA, 2012), safety assessments can additionally involve the assessment of the non-radiological environmental impact, operational safety assessment, assessment of the adequacy of the site and the engineered systems and assessment of the appropriateness of the management system (Figure 2-2). In Japan, for example, the safety case is used to demonstrate safety during all phases of the disposal program and includes the evaluation of operational safety, long-term safety, an environmental impact assessment and the assessment of socioeconomic effects (Umeki & Takase, 2017). In Finland, safety case and safety assessments are used in the context of post-closure radiological safety. Nevertheless, operational safety needs to be assessed and an environmental impact assessment is also required for the licensing of the final disposal facility for spent nuclear fuel currently under construction at the Olkiluoto NPP site. The assessment of the post-closure radiological impact as the main element of safety assessments is briefly discussed below.
2.2.1 Scenarios

The uncertainties inherent in the evolution of the disposal facility and its environment over the assessment period lead to the definition of hypothetical scenarios illustrating the expected evolution under normal conditions and under the consideration of likely and less likely disruptive events. Different approaches for the construction of scenarios can be employed and are primarily used in a complementary manner. In a bottom-up approach, scenarios are constructed by combining features events and processes (FEPs) relevant to the disposal system provided by a solid assessment basis with information about the natural and engineered features and the relevant scientific and technical understanding. In addition, international and national compilations of FEPs exist covering factors connected to the different compartments of the disposal system (e.g., near field, geosphere and biosphere) and external factors such as earthquakes (see, for example, NEA, 2019). Starting from a top-down approach, the safety functions (e.g., retardation of radionuclide transport) assigned to the different components of the disposal system (e.g., bentonite buffer) are analysed for potential impairment due to different internal and external factors (NEA, 2013; IAEA, 2014). The use of complementary techniques for scenario development in combination with checks against FEP lists add to the comprehensiveness of scenarios and FEPs considered as relevant, and may be seen as consistent with the defence-in-depth principle. In any case, a formal process for scenario development, selection and subsequent assessment is required in order to ensure traceability and transparency. Regarding formal procedures for scenario development, the interested reader is referred to STUK’s YVL D.5 guide (STUK, 2018) and to the KYT2022.
2.2.2 Model calculations and uncertainty management

In line with the scenarios chosen to be included in the safety assessment, numerical models are developed to assess the radiological impact associated with the potential evolutions of the disposal system. In this regard, a quality controlled model qualification is crucial including the verification and, as far as possible, validation of the model(s) and used computer code(s). This forms another link to the quality assurance program to be established as part of the management systems (see Section 2.3). Process-level models represent single or coupled processes and help to increase the understanding of certain features of the disposal system. System-level models aim at the interaction between different system components and at representing the disposal system as a whole. The model calculation results are compared against performance targets and/or assessment criteria. The calculation of radiological consequences and the comparison against regulatory compliance criteria such as annual dose or risk is a prominent example. The use of other safety indicators (e.g., radionuclide concentration in certain compartments of the disposal system) can contribute to a more thorough understanding of the behaviour and interplay of different barriers or components of the disposal system behaviour (IAEA, 2011, 2012; NEA, 2013). The complementary use of various metrics and criteria to assess the performance of the disposal system represents another application of the defence-in-depth principle.

However, it should be kept in mind that models only provide illustrations of possible evolutions of the disposal system and the calculation results need to be understood as estimates and be interpreted in the light of the underlying assumptions and uncertainties. With regard to underlying assumptions, alternative models, particularly on a conceptual level, can be developed to study the importance of the underlying assumptions of different models (NEA, 2013). The consideration and application of alternative models requires a wide range of expertise and, therefore, should be subjected to peer review (IAEA, 2002, 2011; NEA, 2013). It also helps increasing the fundamental understanding of important processes and features forming a link to the FEPs used in scenario development. In fact, the multidisciplinary approach and the use of (external) experts for peer review culminating in the representation of processes and phenomena by different (conceptual) models can be considered as facets of the defence-in-depth concept. Uncertainties not only stem from the impossibility of an accurate prediction of the future evolution of the disposal facility, particularly in terms of the biosphere and the involved dynamic processes. They also originate from the approximations/simplifications of the physical reality related to the lack of knowledge concerning data, models and parameter. Substantial effort in safety assessments/ safety case is devoted to the systematic management
of uncertainties (see, for example, IAEA, 2011, 2012; NEA, 2013) including the identification, quantification (where possible) and treatment of uncertainties. Uncertainties can be classified as epistemic uncertainties, which principally can be reduced by, for example, further research or design adaptations, and aleatoric/stochastic uncertainties, which are linked to random spatial and or temporal variability of a quantity that cannot be determined further with existing methods (e.g., the exact groundwater flow field and its evolution over time).

Different approaches exist to handle persisting uncertainties. If a reliable quantification is possible, the irrelevance of an uncertainty may be shown due to a very low probability and/or consequences. Uncertainties connected to the biosphere and the future human behaviour can be treated by a stylised approach bounding the hypothetical future habits to the present ones (e.g., food consumption patterns) (NEA, 2013). Commonly, a mix of simplified/conservative and complex/realistic model calculations is used. Conservative assumptions, when justified and deemed meaningful in the studied context, can be applied in order to demonstrate the robustness of the disposal system (IAEA, 2002). Similarly, what-if scenarios are formulated to study the system’s evolution and the significance of its different components under conditions lying outside the expected range that are either still physically possible (e.g., extreme unfavourable sorption properties) or not at all physically possible (e.g. disregarding any solubility limits). In the context of conservatism applied in the safety assessments, the system’s behaviour under extreme or worst case conditions can be studied by scoping or bounding calculations. Conservative estimates can be obtained from deterministic calculations representing extreme or worst case conditions. However, deterministic calculations (i.e., using single-valued parameters) are often combined with probabilistic calculations, for which parameter values are randomly sampled from probability functions to carry out an array of assessment cases for studying the relative importance of parameter choices and of parameter value combinations on the assessment output (sensitivity analysis). Taking into account the complex interdependencies in the models and the large quantity of model parameter/range of possible parameter values, probabilistic simulations are also interesting, because they allow for the identification of parameter value combinations leading to worse calculation results (e.g., higher annual effective dose) than possibly identified by a deterministic approach (see, for example, Ciecior, Röhlig & Kirchner, 2018). Probabilistic sensitivity analyses can further be useful to illustrate the influence of different design or material alternatives and how certain aspects of the system are represented by the models (e.g., transport phenomena that act three-dimensionally in nature but are represented in 1D or 2D axisymmetric conditions based on the applied numerical abstractions). The results of probabilistic calculations can also provide input to deterministic calculations in terms of parameter value choices (NEA, 2013). The use of different techniques to treat uncertainties, i.e., conservative/deterministic and
complex/probabilistic methods, increases the confidence in the safety assessment results and is another form of the applied defence-in-depth principle.

The results of safety assessments are used to inform the R&D program and facility design, essentially contributing to the iterative development of the disposal facility and the safety case (NEA, 2013). Many of the discussed elements of the general safety case and safety assessment methodology go hand in hand with the attributes of a vivid safety culture described in Section 1.2. These are in particular the need for QA in scenario development, uncertainty management and the verification/validation of models. Furthermore, the use of peer review by external multidisciplinary experts is in line with the openness for exchange with external organisations as required for a healthy safety culture. In fact, a healthy safety culture of the implementer organisation and contractors has been recognised as an additional argument to support the safety statement in a safety case (IAEA, 2003). With the safety case methodology (Figure 2-1) in mind, many safety culture aspects can be localised in the management strategy and the application of management systems, which has been already briefly discussed in Section 1.2 for establishing a healthy safety culture in an organisation. A more thorough discussion about management systems in the context of safety case development is provided in the subsequent Section 2.3.

2.3 Management systems

Essential to the safety strategy, which is an element of the safety case methodology (Figure 2-1), is the use of appropriate management systems to ensure the required quality of all activities carried out and all decisions taken throughout the entire lifecycle of the disposal facility including the pre-operational, operational and post-closure period. At all times, the management systems are part of the iterative development of the safety case and are subject to periodic safety assessments as depicted in in Figure 2-2 (IAEA, 2012). Whenever possible, management systems should be in accordance with national or international recognised standards, codes and regulations and should be evaluated regularly by independent bodies (IAEA, 2014)

The management system needs to describe the mode of interaction between the implementer organisation and other stakeholders of the nuclear waste management community (IAEA, 2014), which has been discussed with the inter-organisational aspects of a healthy safety culture in Section 1.4. This is of special importance for external reviews, checks and verifications during the entire repository lifecycle to be undertaken by independent and skilled individuals or organisations (IAEA, 2014).
With respect to the implementer, the management system needs to ensure an effective coordination of the different organisational units and the various interrelated scientific and technical disciplines involved in the implementation of a disposal facility. This is particularly crucial for the integration of information (e.g., geosynthesis) and the communication between the researchers (specialists) and safety assessors (generalists) (IAEA, 2014; NEA, 2013). The long-lasting process of the repository development is accompanied by an accumulation of a vast amount of different kinds of data and information to be used in safety assessments and in supporting the decision-making. The information sources are various including field, laboratory and theoretical studies (NEA, 2013). The information basis needs to be updated regularly (e.g., ongoing research on component behaviour and the suitability of materials) and made available to the affected persons and groups allowing for a well-founded iterative decision-making (IAEA, 2014; NEA, 2013). Therefore an adequate information management and documentation should be part of the overall management system and become effective already in the very beginning allowing for traceable and transparent decision-making and for future reassessments, if desired (IAEA, 2014). As an example, the knowledge management system (KMS) developed by the Nuclear Waste Management Organisation of Japan (JAEA) is presented in Figure 2-3, which takes advantage of advanced knowledge engineering and information technology (IT) tools.

![Figure 2-3. The JAEA knowledge management system (Umeki et al., 2008).](image)

In contrast to the traditional way of creating and structuring databases based on the technical/scientific discipline, the KMS allows for structuring the existing knowledge having a
specific application in mind and provides for linking the information across disciplines. Prerequisite for the efficient use of search engines and other software is strict terminology/ontology, which, taking into account the many different disciplines active in nuclear waste management, can be challenging. The KMS supports the identification of knowledge gaps in the knowledge base and hence, guides the R&D program that feeds back the knowledge base. Bearing in mind the long timescale associated with the disposal program, a think tank further helps to consider future trends in science and technology and the impact on the disposal program in order to complement the setting of R&D priorities. Even in their own field of expertise, it is increasingly challenging for experts to maintain a broad overview of the existing information and keep up with the scientific production. This becomes particularly difficult in a multidisciplinary research environment such as nuclear waste disposal. In this regard, the KMS automatically feeds the knowledge base from relevant information available on the internet (i.e., explicit knowledge). In addition, it allows for synthesising and presenting the information in form required by the user ranging from technical experts, radwaste generalists, politicians and the general public (Umeki & Takase, 2017).

In order to automatize the collection, analysis, quality assurance, structuring, integration and synthesis of information, the KMS includes tools for both, explicit and tacit knowledge. In terms of explicit knowledge, rule-based systems based on forward and backward chaining support planning activities (e.g., borehole drilling and measurement program for the site investigation) and interpretation of results (e.g. dominant factors determining the measurement results), respectively (Umeki & Takase, 2017). Tacit knowledge, in contrast, is knowledge, which is only known by individual experts. Thus, it bears the danger of knowledge compartmentalization, i.e., the isolation of knowledge that is not communicated to others and hence, not thoroughly taken into account, e.g., in safety case. The acquisition of tacit knowledge is generally accomplished by interviewing experts. Computer based tools have been developed for the elicitation of relevant information, its analysis in a given context and formal structuring so that it can be used by other software. The process can be facilitated by experienced generalists in nuclear waste management ensuring the completeness and logic of the argumentation chains obtained from the interviews. In addition, machine learning techniques can be useful in this regard, especially for repetitive tasks such as the classification of fractures observed in course of the site investigation (Umeki & Takase, 2017).

For tacit knowledge in particular, but also crucial for explicit knowledge, is the knowledge transfer. The possibility of the KMS to provide for the synthesis and presentation of information in a specific form is useful in terms of training of staff with different scientific/technical background working in different areas of nuclear waste management. Similarly, the communication of tacit knowledge is facilitated reducing the risk of the aforementioned compartmentalization of knowledge. The communication interface makes the information
available to every actor in nuclear waste management and the general public. The communication interface further introduces the possibility for feedback with regard to the presentation of information and what kind of information should be added to the knowledge base giving input to the different knowledge generation tools (e.g., R&D and automatic web search). This also helps bridging the knowledge asymmetry between experts on the one and non-specialists like politicians and members of the general public on the other hand, eventually leading to an increased confidence in the safety of the disposal facility perceived by the different stakeholders (Umeki & Takase, 2017).

With regard to the synthesis of arguments into a safety case (Figure 2-1), the KMS allows for a formal development and structuring of arguments in a top-down manner. Naturally, the level of technical detail, complexity and the tendency to duplicate information increases rapidly with every sub-argument. Arguments can be or not be in favour for the safety of the disposal system. However, counter-arguments can in turn lead to further contradicting but also supporting arguments and the other way round. Therefore, a classification of arguments (e.g., established knowledge vs. working hypothesis, “hard” laws of physics vs. “softer” arguments, e.g., related to public acceptability) and cross-linking is necessary (Umeki & Takase, 2017). The formalised argumentation model is accessible online and is complemented by animations and videos matching with the level of detail and complexity of the respective argumentation (sub-) level (Umeki & Takase, 2017).

Modifications to component or equipment specifications, procedures and conditions established in the safety case and license documents must be clearly documented, justified and assessed in the light of operational and long-term safety. Remaining uncertainties and their treatment are of central concern in the safety case and the management system must ensure the documentation (IAEA, 2014). Similarly, an assumption management should be in place. This is of particular importance for the modellers carrying out the simulations and safety assessments, since the underlying assumptions determine the choice of input data and the evaluation of the assessment outcomes. For more details, see Section 2.2.2. Consistent with the iterative approach, the safety case and affected licencing documents must be updated accordingly. When introducing new safety relevant information, for example with respect to site characterization data, modification in the engineered barrier system (EBS) design or experimental or simulation results leading to the re-assessment of uncertainties or underlying assumptions, the KMS with its linking capability is able to automatically re-run performance and safety assessments and to update related tables, figures and reports. Similarly, the argumentation model described above is automatically updated considering the newly introduced information (Umeki & Takase, 2017).
Important parts of the management system are quality control (QC) and quality assurance (QA) programmes. These include staffing requirements, training, education and certification of workers contributing to a healthy safety culture (Section 1.2) and ensuring the relevant competences to perform all activities with the necessary quality in a safe working environment. In the described KMS, this can be coupled to the content and type of training of staff (Figure 2-3). In line with a questioning and learning attitude to be developed as part of a healthy safety culture as described in Section 1.2, the effectiveness of the training and certification programmes are regularly assessed and updated to take into account new insights and gained experiences, e.g., from the operation of the disposal facility (IAEA, 2014). Adequate QC and QA programmes are used to ensure that the design, manufacturing/production and construction/installation of all systems, structures and components relevant for the safety of the disposal facility comply with the requirements and specifications set in the safety case, so that ultimately the assigned safety functions can be fulfilled (IAEA, 2014; NEA, 2013). This is naturally interlinked with the site characterisation and selection process, in which QC and QA programmes should be applied to ensure the quality, usability and availability of data (IAEA, 2014). As described above, this can be carried out within the framework of a KMS. As already discussed in connection with the attributes of a healthy safety culture (Section 1.2), the QC and QA ensures sufficient and secure financial resources of the decade spanning disposal programme (IAEA, 2014). During the operational phase, the receipt, transport/handling and possible storage of waste packages, waste emplacement, installation of barriers and closure of the disposal facility, should be carried out according to quality controlled and quality assured procedures. This implies that those procedures are well documented and accessible to all individuals and organisations including external companies and subcontractors working on the site (IAEA, 2014), which has been touched by the safety culture related discussion in Section 1.2. Since the operational period may last several decades, an adequate ageing and maintenance management should be employed for the active and but also for the passive systems relevant for the safety of the facility. In this context, a suitable aging management aims at minimizing the need for maintenance of safety relevant (e.g., waste handling equipment, shielding) and support systems (e.g., civil and electrical systems) by means of regular inspections, testing and, when needed, restoring of their functionality in accordance with the procedures defined in the QC and QA programme (IAEA, 2014). Besides operational safety considerations, the aging management programme aims at detecting occurrences during the operational period with negative implications for long-term safety, which would remain undiscovered until after closure (IAEA, 2014).

Record keeping is important during the generally long-lasting development of a disposal facility and, depending on the national requirements, for a possible institutional control period after closure. Record keeping includes the safety case and safety assessments as well as related
inventory data and waste package information, site investigation and monitoring data, design documents, information on construction work and on operational and closure activities. The applied QC and QA systems themselves are part of the record preservation indicating how the required quality has been achieved and all requirements and specifications set in the safety case have been met (IAEA, 2003, 2014). The records are continuously extended by the periodic safety case updates, which, according to STUK (2018), are foreseen in Finland at least every 15 years after the start of the facility operation. Additionally, the applicable laws and regulations, licence documents and the provisions and measures during a possible institutional control period are to be thoroughly documented (e.g., the record keeping activities themselves, post-closure monitoring or the use of durable markers. The results of post-closure monitoring, if in place, are also part of the record keeping. Records should be kept in physical and electronic forms in appropriate archives (IAEA, 2014). International co-operations may ease the technical and administrative challenges related to the long-term record keeping (IAEA, 2003). In this regard, the presented KMS is a valuable tool provided that information remains readable and fully searchable by means of adequate up-keeping of format standardisation.

Part II: Interviews

3. Strategy and interview themes

The aim during the first year of the OMT project has been to achieve a basic understanding of overall safety, which is a new concept in the field of nuclear waste disposal. Therefore, in addition to the literature review on safety culture and safety case presented in Part I of this report, structured interviews were conducted with experts of different scientific and technical disciplines relevant to nuclear waste disposal. It should be noted that, although a nation-wide survey including representatives from various organisations in the field would have been desirable, in total only 17 researchers working at VTT have been interviewed in the course of this small scale project with limited temporal and financial resources. Nevertheless, the interviewees’ wide-ranging expertise and long experience in the field of nuclear waste disposal are considered to counterbalance to a reasonable extent the representativity of the interview findings. With that in mind, the following discussions should be understood as a starting point for further overall safety research in Finland. The outcomes of the interviews were communicated in an open seminar held on the 15.10.2019 at VTT in Espoo with approx. 35 participants. In addition to VTT’s contributions, presentations on topics related to overall safety were delivered by Aalto University and STUK. The presentations are available online via the following link: http://kyt2022.vtt.fi/kyt2022_omt_seminar_2019.htm.
Based on the six interview themes listed hereinafter, a questionnaire comprising approx. 50 questions (see Appendix) has been developed.

- Overall safety
- Safety culture
- Collaboration and information flow
- Integrity
- Safety case
- Assumption and uncertainty management

However, the interviews were carried out avoiding a too strict structure to create an atmosphere where the interviewees can answer freely and to account for the different academic backgrounds and professional expertise. Naturally, the received answers were very heterogeneous. In fact, in some cases valuable information has been obtained on another relevant issue than actually asked for, which demonstrates the strong interconnection of the interview themes. The duration of the interviews varied between 30-60 min. The content of the interview data was analysed in terms of the above mentioned themes. The interview findings concerning the different themes are synthesised in the following section.

4. Interview findings

4.1 Overall safety

During the interviews, overall safety has been described as an all-encompassing concept that is not limited to technology and engineering but also takes into account human and organisational factors as well as the mutual influences between the different thematic areas. For example with respect to technical safety, the possible influence of the operations on the long-term safety (e.g., installation or manufacturing defects) has been brought up by the interviewees. Regarding human and organisational factors, the importance of a healthy safety culture in terms of attitudes towards and commitment to safety has commonly been emphasised during the interviews (see Section 4.2 for details). In order to promote safety culture on the national scale, a safety-oriented legislation that is clear and unambiguous has been considered crucial. General aspects like political stability and political will and commitment (e.g., deep geological disposal is deemed to be safest solution) have been pointed out as necessary boundary conditions to carry out a decades lasting disposal
In the Finnish context, the tendency to pragmatism, which has been identified as a national attribute in the CSSCF in Finland (NEA, 2019), and generally flat hierarchies are regarded as beneficial by the interviewed experts. On the organisational level, the relevance of management systems ensuring the quality of the work carried out and decisions made has been stressed.

In short, overall safety in the context of nuclear waste disposal requires that safety has the primary priority and aims at the protection of humans and the environment, with radiation safety being a main concern. Owing to the professional background of the interviewees, safety is largely associated with meeting safety criteria (i.e., radiation dose constraints stipulated by regulatory requirements) and is first and foremost achieved through technical means. In this regard, the multibarrier philosophy and the concept of robustness have been underlined. The latter being primarily viewed in the context of science and technology, could be extended to human factors (e.g., human errors in designing and constructing the disposal facility) according to the interviewees. The interviewees noted a general discrepancy in the safety perception between scientists and engineers on the one and politicians and other decision-makers on the other side. As well as comparisons to other safety-critical fields (e.g., aviation industry), the interviewed experts highlighted the role of the regulator in developing a legislation that satisfies societal expectations but also paves the way for a practical and effective implementation of a final disposal programme (e.g., by establishing reasonable dose constraints). Similar to the CSSCF in Finland (NEA, 2019), the general high trust prevailing among Finnish society was mentioned during the interviews. This applies especially to governmental institutions and consequently, the work and decisions of the Finnish regulator are generally not questioned. According to the interviews, this has the potential for blind spots in the legislation or in the execution in the regulatory and supervisory work. In addition, it has been noted that due to continuous changes in society, the level of basic trust might decrease in future. The interviewees noted that the formation of an independent third party besides the regulator and implementer (see Section 1.4) as a main actor in nuclear waste disposal could be beneficial. However, its practical implementation is considered difficult without risking conflicts of interests, given the limited quantity of qualified experts in Finland.

While it has been unanimously stated by the interviewees that overall safety considerations need to include the entire repository life-cycle, no such clarity exists about the boundaries of overall safety, regarding, for example, which stages of the wider nuclear fuel cycle starting from uranium mining should be taken into account. In addition, the combination of safety and security aspects such as nuclear safeguards was mentioned (cf. the discussion by Hyvärinen et al. (2016) regarding overall safety of nuclear power plants). According to the interviews, a breakdown of the individual parts of overall safety appears to be necessary since an integration of quantitative and qualitative aspects into a single metric might be challenging. As a possible
tool facilitating the quantification of overall safety, multi attribute analysis has been mentioned. Therefore, according to the interviewed experts, it seems clear that several different fields of expertise need to be combined, while its practical realisation is affected by the organisation of research in general and by internal structures and processes of the organisations involved in nuclear waste disposal (e.g. separation of research topics between organisations and between research managers inside an organisation, see Section 4.3).

The current transition of the Finnish nuclear waste disposal programme from being research-oriented towards the actual implementation of the repository involves several implications. Approaching the start of the operational phase, the interviewed experts have experienced a shift in research focus and an ongoing reduction in funding over the past years and the trend is expected to continue or even to accelerate. In addition, according to the interviews, the dependency of the research funding on the economic success of the implementer’s parent companies (i.e., the NPP operators) had been clearly perceptible in the past, especially with respect to the delay in the completion of the OL3 reactor. The decrease in funding is considered as a severe challenge for the competence development and maintenance in the field of nuclear waste disposal in Finland, which does not exclusively pertain to research organisations but equally affects the regulatory body and other actors. With regard to the periodic safety case updates required after the start of the operations, this could lead to an undue dependency on foreign organisations for both the development of the safety case and its review. Therefore, according to the interviewed experts, it is advisable to dedicate substantial effort in maintaining expertise in critical areas on a national level. Public funding mechanisms such as the KYT research programme are considered as useful to this end. The interviewees stressed that the problem of important decisions being taken in Finland based on the opinion of relatively few experts in nuclear waste management may intensify in future. In addition, the interview participants identified the problem that individual experts may be occupied with a single specific topic over years in the long-lasting process, which may result in becoming blind for other relevant topics and the interrelations between them. A potential consequence could be overconfidence in own legislation, safety requirements and expertise in general. Therefore, a continuous exchange of experience and ideas between countries and the joint development and review of safety requirements have been considered important.

4.2 Safety culture

Commonly, the interview participants highlighted the important role of leaders and managers in establishing a safety culture, with the ultimate responsibility lying with the upper management including the CEO. The interviewees pointed out the leadership’s role to encourage the staff to adopt a healthy safety culture, to monitor individuals’ behaviour and to
take correction measures when needed. Besides this, leaders acting as facilitators in solving of (personal) conflicts are appreciated. Management principles brought by leaders with experience in the industrial sector to the formerly mostly research dominated working environment have been appreciated and have contributed to the development of the safety culture. Also the importance of regulatory requirements (e.g., Guide YVL A.3 issued by STUK) demanding for a vivid safety culture has been mentioned. Similar applies to the cooperate policy on the organisational level, which, together with regular training courses, helps the interviewees to familiarise themselves with safety culture. Safety culture attributes like personal dedication, individual attitudes and individual responsibility including the commitment of workers to safety and to follow safety instructions have been underlined as important during the interviews. It was further noted that these attributes also need to be expressed and demonstrated to outside experts and organisations. This is in line with the idea of enhancing the robustness of the nuclear community by the mutual influence of organisations, as expressed in the ISiD concept (IAEA, 2017; Ylönen, 2017) Furthermore, the interview participants underpinned that the organisational culture must allow for mistakes and the possibility to admit these mistakes and a lack of knowledge. In this regard, the project managers’ openness for discussion and the possibility to raise concerns and questions, e.g., in project meetings, has been acknowledged. However, it has been noted that the high level of specialisation can be a challenge for discussing substance related matters with project leaders or other project members on a very detailed level. The necessity for an open and honest working atmosphere has been mentioned in order to be able to learn from the past and former (sometimes subconscious) patterns of organisational behaviour, and to strive for continuous improvement. Concerning this, the currently ongoing decommissioning of the FIR 1 research reactor has taught valuable lessons according to the interview participants. Regarding the continuous improvement of safety culture, the possibility of employees to express their concerns and to provide feedback in a bottom-up way in the course of regular anonymous online surveys has been appreciated.

Special importance has been devoted by the interviewees to quality control and quality assurance. In terms of laboratory work, this includes:

- accreditation of facilities and laboratory equipment
- calibration of laboratory equipment
- regular internal and external audits regarding physical health and safety
- following specified procedures and safety instructions
- clear documentation of ongoing experiments and experimental results
- in-house reviews.

It has been stated that lab procedures and safety instructions must be practical and very concretely defined to be understood and applied. If they otherwise are felt to unduly hamper and slow down practical work, there is a risk that laboratory staff tries to find ways to circumvent them, especially in situation of work overload and tight schedules. In this regard, the need for an appropriate wellbeing at work has been mentioned in order to being able to work according to the safety culture standards. In addition, the quality of experimental results is assured by replicating samples and experiments, which is, however, often limited by financial constraints. With regard to quality assurance of modelling work, verification and validation of models and computer codes have been mentioned during the interviews as typical measures. According to the interviewed experts, the practice of in-house reviews might be compromised by the lack of in-depth knowledge of colleagues or superiors and reviewers need to rely unduly on the expertise of their colleagues. "Blind trust" was also identified in the course of the CSSCF in Finland (NEA, 2019) as an issue with the potential to undermine a questioning attitude and compromise safety.

On the inter-organisational level, the interviewees have recognised, that honesty and speaking up in case of noticing a mistake or other issues is appreciated by customers (e.g., the implementer). However, according to the interviewees, proper conditions in terms of schedules or budgets are not always given in order to adequately address the mistake or concern. Similar as within the own organisation, it has been noted that detailed discussions on scientific substance with the customer or other project partners are not always possible due to a lack of redundant expertise on certain aspects in the Finnish nuclear waste management community (see the discussion on critical knowledge and compartmentalization of knowledge in Sections 4.1 and 4.3). Notwithstanding, the interview participants appreciate the iterative discussions with the implementer and regulator that support continued learning and improvement. As one manifestation of the compartmentalization of knowledge, there are experts working for one particular client (e.g., the implementer) on one specific subject in long-term projects. This can cause an isolation within the own organisation and that the expert feels more linked to the customer and is less affected by the own organisation's culture and practices. In addition, the isolated work confined to a single topic favour the development of blind spots, in a sense that it can distract from the bigger picture of the research question (i.e., the safe disposal of nuclear waste) and that relevant aspects or links to other relevant aspects might be overlooked. There has been a common view among the interviewees that it is the implementer's responsibility to choose only organisations as contributors to the final disposal project, which fulfil the requirements of a healthy safety culture. The interviewees also highlighted the importance of the implementers’ selection of appropriate external reviewers for
the conducted research. The interviewees observed that the implementer has been undergoing a change in mind-set and organisational culture during the transition from a research focused organisation towards a company operating a final disposal facility. In this regard, the importance of quality control and quality assurance as part of the construction plans and operating schemes have been noted in the course of the interviews.

4.3 Collaboration and information flow

It has been commonly stated by the interviewees that working in projects with different experts is the primary mean for collaboration and information exchange. This concerns in particular project meetings with the client¹ and possibly other external project members. Among the interviewed experts, usually a good co-working atmosphere and exchange of information between seniors and juniors have been experienced. However, it was pointed out that it feels easier for experienced researchers to raise questions or criticism towards the client or external partners. As mentioned before in Section 4.2, the implementer has been perceived by the interviewees as open and encouraging for discussions of worrisome issues such as mistakes or concerns regarding project schedules. This form of relationship between organisations has been acknowledged as valuable by the interviewed experts since they can freely speak up and the discussions are not unduly compromised by commercial considerations, even though for many years a significant part of their working time has been in projects financed by the implementer. However, according to the interviewees’ perception, the mistakes or concerns put forth unfortunately cannot always be addresses adequately due to time or financial bottlenecks.

Besides project work and meetings, open seminars (e.g., within the KYT research programme) have been highlighted during the interviews as good opportunities to discuss research advances and challenges and further to gain a better understanding of each other’s work and needs across the different organisations. It has been emphasised that the collaboration between experts of different fields is crucial since components of the disposal facility cannot be studied in isolation. Therefore, studying barrier interfaces (e.g., in KYT excellence projects such as BROCTIO) is seen as especially beneficial by the interviewed experts. In this regard, it has been pointed out that the communication between different researchers and research teams internally and externally is crucial and that it is the responsibility of leaders and (project) managers to create possibilities for exchange and to encourage cooperation and sharing of information. According to the interviewees, this also facilitates the preparation and execution of research projects. In addition, in the opinion of the interviewees, it is advantageous that

¹ VTT’s client in nuclear waste management has been primarily the implementer, as it dominates in Finnish research funding.
expertise relevant to nuclear waste disposal is not concentrated in a single institution but instead is integrated into various research areas and thus, is connected to the broader scientific community. During the interviews it has been stressed that personal dedication and effort is required in order to keep on track with the state-of-the-art and research advances on a national and international level. A useful tool in this regard could be a knowledge management system (Section 2.3) that, depending on the user, automatically searches for new relevant information online, updates the knowledge base and provides for a synthesis and useful presentation of the information. In that respect, it has been appreciated by the interviewed experts to regularly receive updates by the implementer or colleagues in the field on, for example, new relevant publications. Commonly, the interviewed experts indicated the possibility to straightforwardly ask others for information and to contact corresponding authors of the publications in question. This is seen as particularly important in the decade-lasting disposal project, since related research often has a long history and the traceability is not always sufficient.

A series of interview statements can be subsumed under compartmentalisation of knowledge, meaning that certain knowledge exists isolated within a research group or even is only known by an individual expert. One cause for this is the organisation of research related to the final disposal of nuclear waste in Finland. The implementer’s solely responsibility to plan and carry out the research programme also involves the freedom and power to organise the research work. The implementer decides if research topics are studied separately or jointly (e.g., research projects concerning the interfaces of barriers or the couplings between different processes occurring in the disposal system) and which organisations and which of the different scientific and technical disciplines are involved. As already mentioned in Section 4.2, there are examples of experts, who work exclusively on a specific research question during several years for the implementer. Even the most experienced researchers and brightest minds require possibilities for exchange of ideas and concerns, but in some cases, there are no or only very few experts with similar in-depth understanding of the matter in question available in the own organisation or at the customer side. In such situations, the expert draws back on, for example, the client support of the used modelling software, with whom possibly a more frequent and intensive exchange persists than with other colleagues. This compartmentalisation of knowledge potentially gives rise to tacit knowledge (see Section 2.3), which is not adequately preserved nor communicated. In combination with the sometimes missing equivalent redundancy of expertise on a national scale, this can involve the risk of a loss of knowledge, for example, in case of retirement or changes in the professional path of an expert. According to the interviews, this not only affects organisations working for the implementer and the implementer itself, but the preservation and transfer of knowledge equally concerns the regulator and any other actor working in the field. Based on the interviews, the preservation of knowledge is needed for at least:
• staying up-to-date with the developments in disposal programmes of other countries;

• the evaluation and selection of alternative buffer and backfill materials and barrier designs that might be employed during the operational period lasting approx. one century;

• the periodic safety case updates after granting the operational licence; and,

• the preparation of the required closure licence and closure of the facility.

In this regard, the interviewees stated that for organisations depending on commercial projects, however, the start of the operation of the final disposal facility is expected to be accompanied by a further reduction in research funding from the nuclear industry, which will introduce additional challenges to the preservation of expertise within the affected organisations. Besides being close to the solution of the final disposal problem with no major alterations in the disposal concept or site to be expected, the interviewees listed other factors possibly reducing the attractiveness of work in the field of nuclear waste disposal in Finland and hampering the transfer of knowledge to the next generation of experts. The remote locations of Finnish nuclear power plants (NPPs) and disposal sites have been mentioned as possible obstacles for the recruitment of young and top experts. Although Finland will continue to rely on nuclear power during the upcoming decades, the fleet of NPPs is believed to remain approximately stagnant or at least no significant increase is expected. In addition, the uncertainty about the future reputation of nuclear power and the public perception prevailing in Finland as well as globally may influence the professional choices of young experts.

In addition, it has been stated by the interviewees that the implementer divides and distributes information (e.g., internal memos or other confidential documents) to the different contractors, on which basis the research or design work is carried out, and subsequently merges on its own the results obtained from different research groups or organisations. As a consequence, the information flow between researchers and organisations is heavily affected. In this regard, it has been noted during the interviews that it can be challenging for the individual expert to see the bigger picture, meaning to fully understand what other researchers need or expect from the own work and how the different research outcomes are eventually integrated by the client (implementer). Based on the interviews, confidentiality issues and publication restrictions have been identified as other causes for compartmentalisation of knowledge. It has been mentioned by the interview participants, that the extensive confidentiality practises in the nuclear field can lead to situations where experts working in the same organisations are only allowed to share information with each other if they are officially named as members of the same project. Otherwise, the clearance of data by the implementer needs to be requested, which implies that it is the implementer deciding which data is shared in which level of detail, and not the affected
experts. This also involves that the expert needs to know that certain knowledge or data exists elsewhere (i.e., data produced by another organisation and available at the implementer but not originally shared), which due to the described practise of information distribution by the implementer might be questionable. Again, an effective knowledge management system (Section 2.3) accessible to and commonly fed by every national actor relevant in the field of nuclear waste disposal could be useful in this regard. Therefore, the interviewees emphasised the importance of public research programmes such as KYT to freely exchange research results. On the other hand, it has been noted during the interviews that there is an efficient separation of experts working either for the implementer or the regulator, which is an advantage of the applied confidentiality practices. The interviewed experts, for the most part, noted that it has been becoming increasingly difficult to publish (e.g., in working reports) their research conducted in commercial projects. This is conditioned by the ongoing transition of the implementer from a mostly research focused to a commercial organisation constructing and possibly soon operating a final disposal facility for spent nuclear fuel. This transition is also characterised by the foundation of the implementer’s subsidiary “Posiva Solutions Oy” and the intensified commercialisation of experience and knowledge gained over the past decades. In addition, the published documents sometimes do not contain all information that have been produced in the course of a project (e.g., additional experimental series outside of the direct scope of the project) but is retained only with the project manager at the implementers’ side. The increasing restriction on publications is seen as unfavourable for research driven organisations that commonly pursue scientific productions such as journal articles or other publications. Besides the aforementioned possibility to work in public projects (e.g., within the KYT programme or in EU projects), the production of open access publications have been perceived as important in this regard. In terms of possibilities for international collaborations, EU projects and international workshops (e.g., task forces) have been brought up during the interviews. Furthermore, the wish has been expressed to intensify again the collaboration between Finland and Sweden, which has been decreased during the past years mostly due to commercial reasons, since the respective waste management organisations’ subsidiaries “Posiva Solutions Oy” and “SKB International AB” are competitors on the international market for products and services related to the safe disposal of nuclear waste.

4.4 Integrity

As already mentioned in the discussions concerning the interview themes safety culture and collaboration and information flow in Section 4.2 and 4.3, respectively, generally an open culture prevails in the Finnish nuclear waste management community. Honesty and speaking up are appreciated to minimize the negative effects of a noticed mistake and to ensure the quality and meaningfulness of research results. According to the interviewees, hiding or
supressing inconvenient discoveries is practically impossible in the long-term in a small country like Finland, where the relatively few organisations involved in the field of nuclear waste disposal solicitously aim at maintaining a trustful and collaborative culture. Unfavourable results are accepted by and an adequate solution is sought together with the customer. This is in line with the national attribute technical rigour (emphasis on pragmatism, facts and science) identified in the course of the CSSCF Finland (NEA, 2019). However, according to the interviews, busy timetables or tight budgets sometimes hamper to adequately address the identified concern. The iterative way of working and discussions with both the implementer and the regulator have been highlighted during the interviews to be helpful in finding the best solutions. The interviewees stated that in most cases redundant expertise is available for thorough cross-checks and reviews of research results. However, for certain expertise a missing equivalent redundancy has been noted during the interviews, which complicates discussions on a very detailed level and thorough review work. Similar to the findings of the CSSCF Finland (NEA, 2019), it seems to be easier to point out own mistakes than criticising other’s work, because of fearing that the criticism is taken as a personal insult and doubting of someone else’s expertise. NEA (2019) states a tendency to avoid conflicts as reason for this. Another possibly reason identified in the course of the interviews, as well as in NEA (2019), is related to the traits of modesty and trust. Generally, it is believed that an expert knows best in her or his field and that interfering in someone else’s expertise and area of responsibility is not expedient. This can lead to “blind trust” and undermines a questioning attitude necessary for a healthy safety culture (Section 1.2).

Besides the need for an open and trustful working atmosphere, the interviewees emphasised the relevance of an effective organisational structure with clear responsibilities and accountabilities and encouraging leaders in the different hierarchal levels. This is important for expressed concerns or worries to be communicated to the affected people internally and externally, including those with the mandate to intervene and to take countermeasures (e.g., project leaders and managers). In addition, the existence of whistle blower programmes have been praised by the interviews.

4.5 Safety case

With the general safety case methodology (Figure 2-1) in mind, the interviewed experts, owing to their experimental research and modelling work, recognised their own role to be related predominantly to the assessment basis and partly to safety assessments. Generally, the role of the safety case in the licencing process and as the primary tool to demonstrate the safety of the disposal facility is understood and internalised well by the interviewees. Safety is understood as the compliance with regulatory guidelines stipulating radiological dose limit
constraints, which needs to be demonstrated using sound science, which coincides with the national attribute of relying on science and fact-based argumentation as determined during the CSSCF in Finland (NEA, 2019). For this purpose, the interviewed experts have stated unanimously that data of good quality and valid within the boundaries relevant for the expected repository conditions is indispensable, forming the link between safety case and the R&D programme. The interviewees highlighted that the amount, types and quality of experimental data have increased significantly over the years. Therefore, effective means to ensure a clear and traceable documentation taking into account the changing saving formats are required, starting from one’s own working computer and ranging to long-term record keeping. However, according to the interviews, the correlation of safety with the quantity of data has its limitations, meaning that, for example, too many investigation drillings in the site characterisation or sensors used in an experiment can jeopardise safety or distort measurements, respectively. Therefore, not only appropriate management systems are necessary to ensure the quality and meaningfulness of data but it also requires the individual expertise for the responsible generation, judgement and selection of data. This sense for responsibility and ownership of actions links to the characteristics of a healthy safety culture described in Section 1.2.

As a general observation based on the conducted interviews, the depth of knowledge and understanding of the safety concept and its different components (Section 2) depends on the expert’s academic background and experience working in the field of nuclear waste disposal (e.g., concerning the barriers their research is associated with). Commonly, the interviewees know about the meaning of the main safety functions of a disposal facility, the use of scenarios and the analysis of radiological consequences by mean of models and simulations. Regarding the latter, the experts are aware that the simulations are not of predictive but rather illustrative character and care needs to be taken in the interpretation of their outcomes.

The interviewed experts understand the importance of their own contributions to the safety related research. However, the link of the own research to that of others and the relative importance of research topics for the safety case is not always clear. As a specialist, the focus is on research in the field of own expertise, while assembling the safety case based on the results of different research areas is not of primary interest. Therefore, while the interviewees are specialists in their respective area of research, the knowledge about the safety case methodology is rather superficial. In particular, the experts seem to be less familiar with how the information coming from various scientific and technical disciplines is integrated in the safety case and besides this, the used terminology\(^1\) appears to be confusing or ambiguous. In fact, despite major efforts for harmonisation, the methodology and related terminology and

\(^1\) A prominent example is the mixed use of the terms "safety case", "safety assessment", "safety analysis", "performance assessment", etc.
definitions established by different international organisations vary (see for example, WENRA, 2014; IAEA, 2012; NEA, 2013), not to mention the variations on a national level. On the other hand, the interviewed experts expressed their concerns that, in spite of attaching importance on clear and thorough reporting of their research, the people in charge of developing the safety case (i.e., generalists) might not fully understand their research results or not recognise the underlying assumptions (see Section 4.6). The interviewees were worried that this could lead to a misinterpretation of results or to the invalid use of data in a context outside the boundaries/conditions of the conducted research (e.g., sorption coefficients determined experimentally in a certain pH range). However, an essential purpose of the safety case and safety assessments (Section 2) is the handling of knowledge gaps and uncertainties concerning, for example, experimental data.

In summary, a discrepancy or cultural gap has been identified between the specialists on the one, and the generalists preparing the safety case on the other side. In order to address the above described discrepancies and knowledge gaps, the interviewees have expressed the wish and willingness to participate in training focused on safety case, additionally to the regularly held YJK nuclear safety training course that includes safety case as one of many other topics. The training could be organised in seminar form with informative presentations for a better general overview, which, according to the interviews, is considered to help aligning the research with safety case needs and consequently to improve project proposals.

4.6 Assumption and uncertainty management

Since the interviewed experts are mainly concerned with experimental studies and modelling work, the importance of good scientific practise as an aspect of a healthy safety culture (Section 4.2) has been highlighted. Concerning the management of assumptions underlying and uncertainties inherent to the experimental and modelling studies, the interviewees stated that the analysis of the used data in terms of traceability, comprehensiveness and quality (including error estimates) is crucial. In addition, the interviewed scientists emphasised the use of multiple sources of information, which is not always given in the highly specialised field of nuclear waste disposal and due to the singularity of each disposal facility (e.g., unique site conditions and a tailored repository design). With regard to quality assurance of modelling work, code verification and validation (a far as possible) have been recognised as important by the interviewees. As described in Section 4.5, the interviewees are aware of the non-predictive character of simulations and thus, simulations results are considered to only illustrate the repository evolution. To this effect, the interviewed experts have demonstrated a questioning attitude by expressing their scepticism towards the used model parameters and modelling outcomes. Therefore, a clear documentation of uncertainties and an analysis of their
sources are needed according to the experts. Uncertainties are gradually reduced by increasing the knowledge through research and development work (e.g., replacing guess values or generic literature data by site-specific data). In addition, the possibility of design adaptations to treat uncertainties has been noted during the interviews. It has been recognised that the reduction of uncertainties, however, has its limitations (see Section 2.2.2), and thus, a systematic treatment of remaining uncertainties is necessary. Besides performing sensitivity analysis to identify the relevant model parameter and uncertainties, the interviewees mentioned the possibility to use simpler models with less parameters and more certainly known parameter values for the conditions under consideration (e.g., simplified calculations using basic physical principles). Safety margins and conservatism are commonly used by the interviewed experts to deal with uncertainties.

Similar as with uncertainties, the importance of a thorough documentation of assumptions underlying the research work has been emphasised during the interviews. Despite the careful reporting, the interviewed experts expressed their worries that research results are not always seen in the light of the underlying assumptions, when used as input in other’s research or as arguments in the safety case. Research outcomes might be taken as valid in other than the actual boundaries of the conducted research. This adds up to the discussion in Section 4.5 concerning the cultural difference between specialists conducting research and generalists involved in the development of the safety case. According to the interviewees, results might be taken as valid in other than the actual boundaries of the conducted research. Nonetheless, the interviewees pointed out that nobody is immune to this, since, in the multidisciplinary field of nuclear waste disposal, it is practically impossible for an individual researcher to be aware of all assumptions underlying the models or experiments carried out by others and utilised in their own work. Therefore, it can be concluded that there is a certain need for basic trust in the scientific community (i.e., professional and research ethics) in order to be able to rely on each other’s work, which relates to the (safety) cultural aspects discussed in Sections 1.2 and 4.2.

5. Summary and outlook

In Part I of this report, a literature study on safety culture and the safety case concept has been carried out and aspects deemed relevant for overall safety of nuclear waste disposal have been discussed. Overlaps between safety cultural aspects and the safety case methodology have been identified. In this regard, the importance and usefulness of management systems and, in particular, knowledge management systems has been discussed. The discussions initiated in Rasilainen et al. (2019) about the applicability of existing holistic approaches such as ORSAC (Hyvärinen et al., 2016) and ISiD (IAEA, 2017), on evaluating the safety of nuclear waste disposal have been deepened, particularly with regard to the defence-in-depth (DiD)
philosophy. After outlining the concept of overall safety based on the literature review, structured interviews with experts of several different topics relevant for nuclear waste disposal have been conducted in order to build a basic understanding of overall safety and its different facets in the Finnish context. To this end, a questionnaire covering the themes overall safety, safety culture, collaboration and information flow, integrity as well as assumption and uncertainty management has been developed. It should be noted, however, that the findings are based on one interview campaign carried out at VTT with only 17 interviewees and therefore reflect only views at VTT. An extension of the interview survey including more organisations active in nuclear waste disposal in Finland is intended at a later stage (see below). The results obtained from the interviews have been disseminated in an open seminar on overall safety and the presentations are available online ([http://kyt2022.vtt.fi/kyt2022_omt_seminar_2019.htm](http://kyt2022.vtt.fi/kyt2022_omt_seminar_2019.htm)). Both, safety culture aspects identified in the literature study and the interview findings have been discussed vis-à-vis the outcomes of the country-specific safety culture forum (CSSCF) in Finland (NEA, 2019). In the following, the main findings relevant in the context of overall safety of nuclear waste disposal in Finland are summarised.

One issue concerns the general organisation of research related to nuclear waste disposal in Finland leading to a phenomenon that can be termed as compartmentalisation of knowledge. Compartmentalisation of knowledge describes that certain knowledge exists isolated within an organisation, research group or is even only known by an individual expert and that the information flow is largely inhibited. Different causes for this have been identified and are briefly presented hereinafter. The Finnish implementer is in charge of the research programme, for which purpose several external organisations (e.g., universities, research centres and engineering consultancies at home and abroad) have been utilised during the past decades to carry out a substantial part of the research and design work. The implementer divides and distributes the information considered necessary to conduct the work to the different contractors and pieces together the research outcomes to finally prepare the safety case as the basis for the licensing process. On behalf of the implementer, external experts in some cases work isolated and exclusively on a certain research topic for many years accompanied by an accumulation and concentration of specific in-depth knowledge and understanding. The information exchange of the expert is for the most part limited to the interaction with the responsible research managers of the contracting company. Due to a lack of equivalent redundant expertise, discussions on certain topics are hampered on a detailed level and as a possible consequence, important decisions are taken based on very few individual opinions. In addition, the information flow is likely to be conditioned by the implementer's internal organisation of research lines and the communication between the responsible research managers. Apart from that, the commercial nature of the implementer, being a subsidiary of
the nuclear power plant owners, and accompanying confidentiality issue further constrain the exchange of information between experts of different organisations and even within a single organisation. In the same vein, the collaboration and exchange of research outcomes between Finland and Sweden, both pursuing very similar disposal concepts and schedules, is potentially affected by commercial considerations, especially with regard to the activities on the international market by the implementer's respective subsidiaries Posiva Solutions Oy and SKB International AB.

Another issue relates to the management of competence and knowledge, which is linked to the previously described compartmentalisation of knowledge. The isolation of expertise and impediment of information exchange promote the creation of tacit knowledge, hamper the knowledge transfer and can potentially lead to a loss of key knowledge, e.g., in case of professional reorientation or retirement. In addition, the implementer has been undergoing a change in mind-set and organisational culture during the latest phase characterised by the transition from organisation mainly driven by research questions towards a company constructing and perhaps soon operating a final disposal facility for spent nuclear fuel. In this regard, practical questions (e.g., construction plans, operating and related quality control and quality assurance measures) have become more and more important, while research is progressively shifted to the background, which, having in mind the envisaged time for the operating licence application, is a plausible development. The corresponding decrease in research funding from industry side will pose challenges for the affected organisations, particularly in terms of knowledge transfer. Experts will need to redirect their focus on other research areas and might not be available when specific expertise on nuclear waste disposal topics is needed again at a later stage (e.g., following safety case review). Positions without the prospect for a sustainable amount of project work will no longer be filled in case of a retirement and expertise will not be replaced. Similarly, research equipment and experimental capacities can be affected, which, in turn, reduces the possibilities to train and educate staff.

In this regard, the recently completed Centre for Nuclear Safety (CNS¹) at VTT is to mention, together with VTT's traditional role of educating and training experts in the sector of nuclear waste disposal. Teaching in Finnish universities of the long-term safety of nuclear waste disposal has been practically non-existent and no significant increase is currently planned. As an overall result, this might create an undue dependency of both the implementer and regulator on foreign organisations and expertise in questions, for example, related to upcoming periodic safety case updates and the closure of the disposal facility. Therefore, it appears reasonable to analyse what expertise is considered critical in future for the safety of nuclear waste, where that expertise should be localised and preserved in Finland and how to ensure the knowledge

¹ The CNS is a major national investment on experimental nuclear research and the facilities and related expertise are at the disposal of the whole nuclear community.
transfer. Public funding mechanisms such as the KYT research programme are probably part of the solution but it is open to question if its current form and extent is sufficient. The preservation and transfer of knowledge and expertise is by no means a trivial task for Finland as the first country in the world being at the stage of facing the transition towards the operation of a final disposal facility for spent nuclear fuel. Therefore, being the first one at this point, probably no existing concepts and strategies applied elsewhere can be straightforwardly adapted and embedded in the Finnish context.

A continuation of the KYT OMT project is envisaged for a two year period in 2021-2022. A major part of the planned work will be dedicated to an extended interview survey including more stakeholders in the field of nuclear waste disposal in Finland such as the implementer organisation Posiva Oy, regulatory authority STUK, Ministry of the Environment, Ministry of Economic Affairs and Employment, universities and engineering consultancies. In this manner, the representativity of the study on overall safety will be increased and additional findings will provide a more holistic understanding on overall safety and its different aspects. The discussion on key or critical knowledge will be integrated to the interviews and strategies for its preservation and transfer will be developed. This will provide guidance on the funding of future research related to nuclear waste disposal. In addition, the extended survey can be utilised to further study the interaction between specialists with in-depth knowledge on specific topics and the developers of the safety case being rather generalists with a more broad understanding than specialists. This will shed light on how assumptions and uncertainties linked to the research are communicated and treated in the safety case. The demand of additional training of researchers in safety case matters can also be evaluated with the aim of facilitating the preparation of better targeted research proposals in future. Including more interviewees with diverse backgrounds and areas of responsibility could also be used to study the differences in safety perception and the view on overall safety between researchers and decisions-makers. This can potentially be extended to other safety-critical fields such as disposal of hazardous wastes, and the oil and gas or aviation industries. In consideration of the Country-Specific Safety Culture Forum (CSSCF) in Finland, the investigation on the national attributes and the relation to safety culture can be deepened in coordination with STUK. In addition, it is planned to continue collaborating with the KYT SYSMET project to include overall safety considerations in the development of scenarios for the safety assessment. Moreover, international collaboration with the SITEX (Sustainable network for Independent Technical EXpertise on radioactive waste management) network on overall safety of nuclear waste disposal is envisioned.
References


Appendix Interview questionnaire

INTERVIEW THEMES
I BACKGROUND
1. (Interviewee’s education, experience, how long interviewee has worked in the organization)
2. Please, describe what is your field of expertise
3. Please, describe what you do in your work

II Overall safety (main aspects, similarities/differences in definitions between disciplines)
4. Have you faced the concept of overall safety in your work?
5. What is overall safety? (describe in your own words)
6. What kinds of aspects does it include?
7. How would you measure it?

III Safety culture (main aspects, missing parts, emphasized aspects)
8. What is safety culture? (own words).
9. How have you familiarized yourself with the safety culture?
10. How safety culture is shown in your own work/working habits?
11. How safety culture is shown in your organization?
12. (If we show DISC-model of safety culture, we can ask interviewee to mention, which aspects are missing in their work/organization)

IV Collaboration and information flow between experts and stakeholders (draw network of information flow, analyzes it for strengths and weaknesses)
13. How many expert areas affect your work?
14. On how many expert areas/experts’ work your work has impacts?
15. How interaction between experts is organized in your company?
16. Do you have regular meetings? /other ways to collaborate
17. With whom you collaborate in your work?
18. How efficiently does exchange of relevant information/knowledge flow?
19. How do you integrate information and knowledge coming from different fields related to RWM (fuel/source term, canister, bentonite experimentalists, EBS design, material experts (concrete, metals, bentonite))
20. How is the information flow within VTT?
21. How is the information flow between VTT and other organizations working for Posiva?
22. What kinds of information Posiva shares and with whom?
23. Is there needs to improve collaboration/information flow at VTT/other organizations working for Posiva?
24. Whose task it would be?
25. Have you communicated the needs to your colleagues or manager?

V Integrity
26. If you notice some worrisome aspects that can cause risks in the object you are working with, what do you do?
27. If you afterwards notice you made a mistake, even if it is not really relevant, do you aim for correction?
28. Are you taught what to do? By whom?
29. Whom to inform? How? (Back coupling to information flow within and between organizations)
30. Is it easy to speak up?
31. In what kind of situations it would be difficult to speak up?
32. Have you faced those kinds of situations?
33. When and how is expert judgment used?

**VI Safety case (main aspects),**
34. Could you explain what is safety case (in your own words)?
35. Is safety case relevant in your field? Why?
36. Could you give example how your work is related to safety case? (afterwards show safety case methodology scheme and ask again)
37. How do you communicate with those preparing the safety case?

**VII Assumptions and uncertainty management**
38. Have you reflected on what kinds of assumptions are related to your work?
39. What assumptions do you use and how are they justified? E.g. by conservatism?
40. Could you give example of some assumptions related to your work
41. Are you aware of all assumptions related to your work?
42. How these assumptions affect your work?
43. Do you communicate these assumptions to other stakeholders, whose work is affected by those assumptions?
44. Do your colleagues/other experts/ communicate assumptions underlying their work that could affect your work?
45. Are your assumptions properly taken into account/explained in the safety case?
46. What role does risk management play in your work?
47. Where do you face uncertainties in your work?
48. How are these uncertainties categorized and treated?
49. Do you use various sources of information?
50. What types of evidence support the applicability of model and associated databases?
51. How do you study long-term processes?
52. What kinds of methodologies do you use for checking plausibility and reliability of assessments? (performance, safety)