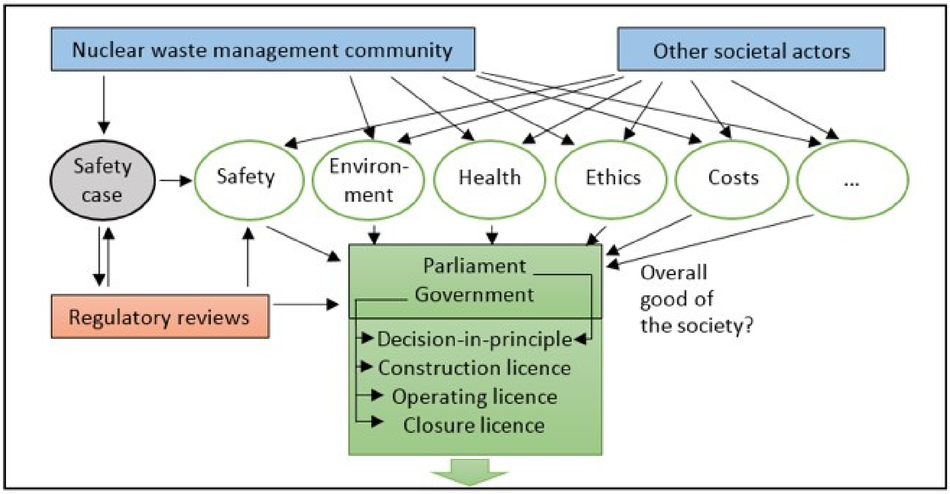

Safety case methodology for nuclear waste disposal - possible update considerations for Finnish usage

Kari Rasilainen | Heidar Gharbieh | Markus Olin | Marja Ylönen

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Preface

The report gives a description about possible expansion needs in the safety case methodology of nuclear waste disposal. We utilise the discussion in Finland concerning the safety assessment of nuclear power plants which in turn has utilised lessons learned in major nuclear accidents, e.g. at Fukushima. Along with this discussion, a concept called ORSAC (overall safety conceptual framework) has been developed.

This report is an effort to localise most relevant ORSAC points into nuclear waste management domain. The localisation does not cover all ORSAC considerations and the interested reader is referred to the original ORSAC report.

The report was inspired by the discussions between the OMT and SYSMET projects of KYT2022 research programme, and the OSAFE project of SAFIR2022 research programme.

Contents

1. Introduction

Geological disposal of nuclear wastes is currently being implemented or planned in most nuclear energy generating countries. The disposal concept and the depth of a geological disposal facility depends on the properties of the waste to be disposed of, e.g. activity, and on the local geology. For lower activity wastes surface or near surface facilities are also being considered.

In the European Union there is strong general encouragement for member states to prepare for nuclear/radioactive waste management. EU Directive on nuclear waste management (EU 2011), demanding overall structured planning of national nuclear waste management (NWM) programme, sets certain basic requirements that member states will have to comply with.

Normally, a NWM organisation will need a licence from the competent national authority to establish a disposal facility for its nuclear waste. The licencing procedure may be stepwise, like e.g. in Finland. In order to receive the licence for the waste disposal facility, the NWM organisation will have to convince the safety authority of the safety of the planned disposal facility. This is done in a safety case.

Safety case is currently a well-established and widely used methodology for safety assessment, due to many years of international collaboration, see e.g. IAEA (2012), NEA (2012), WENRA (2014). There may be some specific national features, but as a whole the methodology has been considered fit for use. The evolution of the Finnish safety case thinking has been briefly discussed in Rasilainen et al. (2013).

Shifting focus from the safety assessment of NWM to the safety assessment of nuclear power plants (NPPs), one can see an interesting on-going discussion in Finland. The discussion touches many aspects relevant for NWM, but from slightly different point of view. This discussion is mainly focused on developing a general safety concept framework based on defence-in-depth philosophy and top-down approach, with main attention paid to systems analytical, systems engineering, and organisational aspects. These are the main building blocks of the safety case as well.

The main aim of this report is to identify new worthwhile methodological aspects in the above-mentioned NPP safety discussion that could be utilized also in a safety case for nuclear waste disposal. In this work, one must of course take into account the inherent differences in an operating nuclear waste disposal facility and an operating NPP. A sealed and closed nuclear waste disposal facility is even more different to a running NPP. Notwithstanding, the fact that the safety case methodology is currently considered fit for use does not mean that there is no room for improvements.

In chapter 2, the main principles in the geological disposal of nuclear waste are presented. In chapter 3, the safety case for nuclear waste disposal is discussed briefly. In chapter 4, the main points mentioned in the safety discussion of NPPs are summarized with focus on those considered most relevant to NWM. In chapter 5, the features of safety case are scrutinised vis-à-vis the main points of the NPP safety discussion. Conclusion are drawn in chapter 6. Some comments are also made concerning possible use of safety case methodology outside formal licencing processes.

2. Geological disposal of nuclear waste

Geological disposal of nuclear waste has internationally been considered as the most viable option for the disposal of high-level radioactive waste, i.e. for spent nuclear fuel (SNF) and vitrified reprocessing waste. Possible alternatives for geological disposal, e.g. shooting into space, dumping into sees, disposal in glaciers or deep sea sediments, have, however, been studied extensively in the past, see e.g. Alexander & McKinley (2007). It may be noted here that partitioning and transmutation (P&T) has been proposed as one alternative, but this method will not remove the need of geological disposal. Furthermore, its availability and viability in the future is strongly linked to the globally much larger role of nuclear energy than currently, due to major investment needs.

Considering geological disposal as a technical project, one can distinguish two subsequent stages: pre-closure and post-closure period. One difference between the stages is that during pre-closure stage certain changes and improvements/ optimisations to the disposal plan can be made, if considered necessary, while after closure no changes are considered realistic and the system is on its own[1]. In Finnish usage, safety case is about post-closure safety of the disposal facility.

In Finland, geological disposal of low and intermediate level waste (LILW) and spent nuclear fuel (SNF) have been developed systematically for around 40 years. Two licenced repositories for LILW are already in operation, one at the Loviisa NPP site and the another at the Olkiluoto NPP site. For spent fuel disposal, the KBS-3 concept, originally outlined by Swedish NWM company SKB, has been developed in collaboration with Posiva, the Finnish NWM company. In Finland it has received construction licence at Olkiluoto in 2015 and currently Posiva is preparing for operating licence application. In Sweden, the construction licence process is underway. Fig. 1. presents a basic structure of the KBS- 3V concept.

[1] IAEA defines waste disposal as emplacement of waste with no intention of retrieval (IAEA 2018).

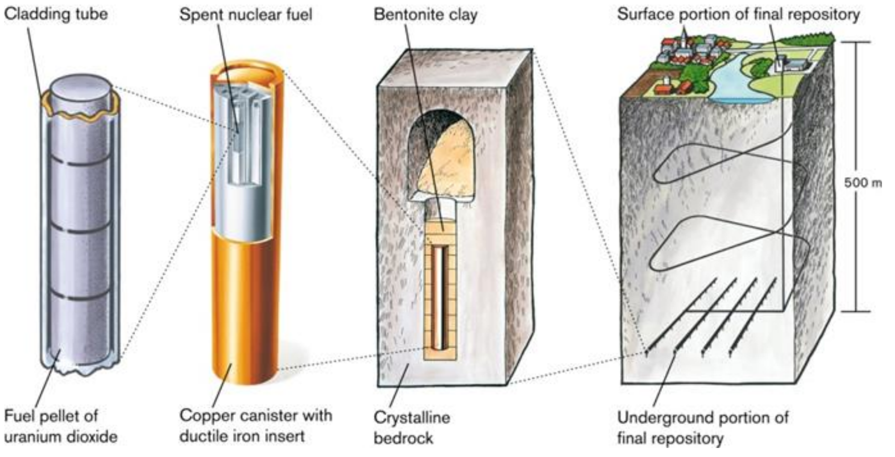

Fig. 1. KBS-3V [2]concept for the disposal of spent nuclear fuel (http://www.skb.se).

All Finnish disposal facilities are planned in crystalline bedrock well beneath the groundwater table. Groundwater is considered as the main carrier of released radionuclides. As seen in Fig. 1, there are various subsequent engineering and natural release barriers and structures in the KBS-3V concept. How these will contribute to the long-term safety of the repository, is defined in the safety functions linked to individual components. Safety functions in turn are defined in the safety case.

As the safety case for the operating licence application by Posiva is currently under development, we cannot study it. However, we can look at the safety case plan in Posiva (2017) and at safety functions developed jointly by Posiva and SKB as preparation for operating licence application (Posiva & SKB 2017). Overall description of main subsystems and related safety functions in KBS-3 concept are given in Table 1.

[2] KBS 3V stands for the vertical version of KBS 3 concept in contrast to the horizontal version KBS-3H that has been studied as a technical alternative. KBS-3V is currently the reference concept both in Finland and Sweden.

Table 1. Safety functions related to specific subsystems in the KBS 3V concept (Posiva & SKB 2017). Buffer refers to “bentonite clay” in Fig. 1.

Release barrier	Safety function
Canister	SF1 Withstand corrosion SF2 Withstand mechanical loads SF3 Maintain sub-criticality
Buffer	SF4 Limit advective mass transfer SF5 Limit microbial activity SF6 Filter colloids SF7 Protect the canister from detrimental mechanical loads - rock shear load SF8 Protect the canister from detrimental loads – pressure load SF9 Resist transformation SF10 Keep canister in position SF11 Retain sufficient mass over life cycle
Backfill and plug in deposition tunnels	SF12 Keep the buffer in place SF13 Limit advective mass transfer
Closure	SF14 Reduce the risk of unintentional intrusion SF15 Avoid the formation of new preferential flow paths SF16 Keep the deposition tunnel backfill in place
Host rock and underground openings	SF17 Isolation from the surface environment SF18 Favourable thermal conditions SF19 Mechanically stable conditions SF20 Chemically favourable conditions SF21 Favourable hydrogeological conditions with limited transport of solutes

Each safety function is linked to detailed performance targets and technical design requirements, but discussing these is beyond the scope of this report. The interested reader is referred to Posiva & SKB (2017). At this moment, one must note that the final safety functions will be seen only in the actual safety cases, the ones on Table 1 are plans, that of course are aimed to be used in the forthcoming safety cases. In addition, there may be slight differences between Posiva and SKB, although the disposal concept is the same.

The section above discussed mainly nuclear waste disposal, the last step in NWM, but considering the whole chain of operations, it is clear that all operations prior to disposal, called pre-disposal activities need to be implemented considering disposal needs. For relevant planning of pre-disposal operations, one needs a national NWM programme.

2.1 Nuclear waste management schedule in Finland

Nuclear waste management is in many ways a long-term project. Its steps are synchronised with the life cycle of NPPs; the planned service life of Finnish NPP can be 50-60 years, see Fig. 2. The operational period of a disposal facility can last over a century. Long-term safety assessment period starts after the sealing of the disposal facility. For disposal of spent nuclear fuel, this period will last hundreds of thousands of years.

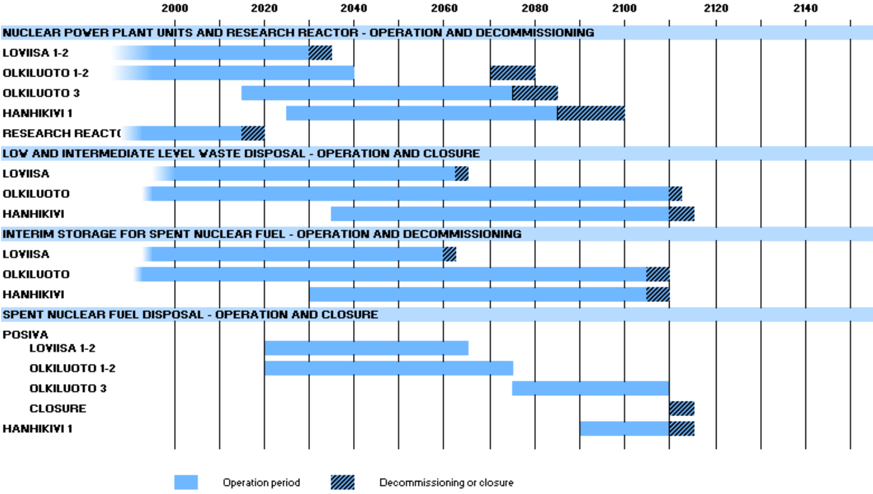

Fig. 2. Overall schedule of the Finnish NWM programme. Source STUK. Construction licence for Hanhikivi 1 NPP unit is pending. The research reactor FiR 1 at VTT is currently being decommissioned.

3. Safety case for nuclear waste disposal in brief

In this chapter, the technical function of a safety case as well as its main technical contents are more closely examined. Finally, some aspects concerning the review of a safety case are discussed. As mentioned above, the licence applicant must construct the safety case, while its review is the duty of the national radiation safety authority, which in Finland is the Radiation and Nuclear Safety Authority (STUK).

3.1 Function of safety case

In the context of NWM, safety case is used to assess the radiological impact of nuclear waste disposal to humans and the environment. It is used in decision-making, before major waste management steps are taken. As regards major nuclear waste managing facilities, decision-making in Finland is stepwise: 1) decision-in-principle, 2) construction licence, 3) operating licence, and 4) closure licence. After closure, the responsibility for the nuclear waste is transferred to the state. All decision steps require a safety case, which is developed in an iterative and stepwise manner taking into account the increasing quantity and level of detail of available information. After the operating licence is granted for the disposal facility, the licence holder will have to do periodic safety reviews (i.e. update the safety case) at least once every 15 years (STUK 2018).

Put simply, safety case is all safety argumentation with which the licence applicant supports its licence application: the burden of proof lies with the applicant. In Finland, a licence for a major NWM facility is granted by the government, and it will consider whether granting the licence is in the "*overall good of the society*". As regards decision-making as such, safety case, or safety, is one argument among others (Fig. 3). The figure shows the government's need of balancing the arguments of the nuclear waste community and of other actors in society.

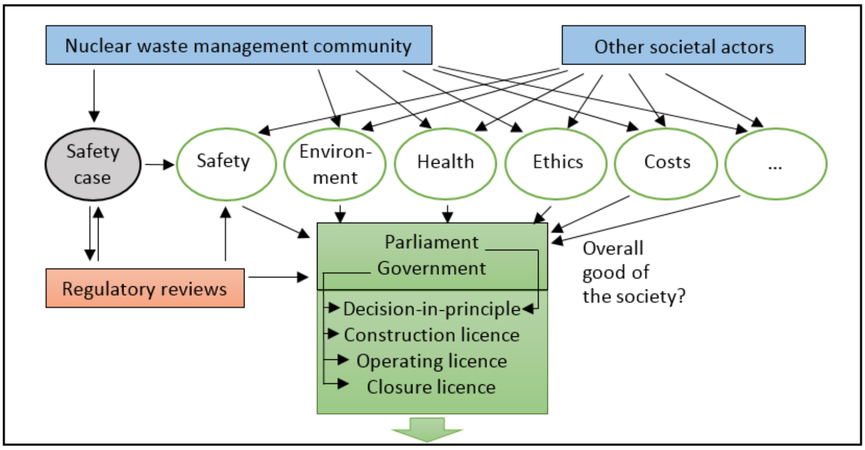

Fig. 3 Safety as one argument in decision-making about NWM. An iterative and stepwise improved safety case is required at all major decision steps.

Safety case is used to assess the long-term radiological impact of nuclear waste disposal in geological formations. Therefore, the core of a safety case is to estimate the migration of radionuclides from repository to human environment and the subsequent hypothetical radiological consequences to humans. This is done by mathematical modelling with input from experimental and modelling studies of subsystems. Mathematical modelling means essentially extrapolating the short-term experimental results to the assessment period. Comparing the calculated dose or release rates with safety criteria and compliance criteria set by nuclear safety authorities is called safety assessment. Safety assessment can be considered as the numerical part of a safety case, see Fig. 4.

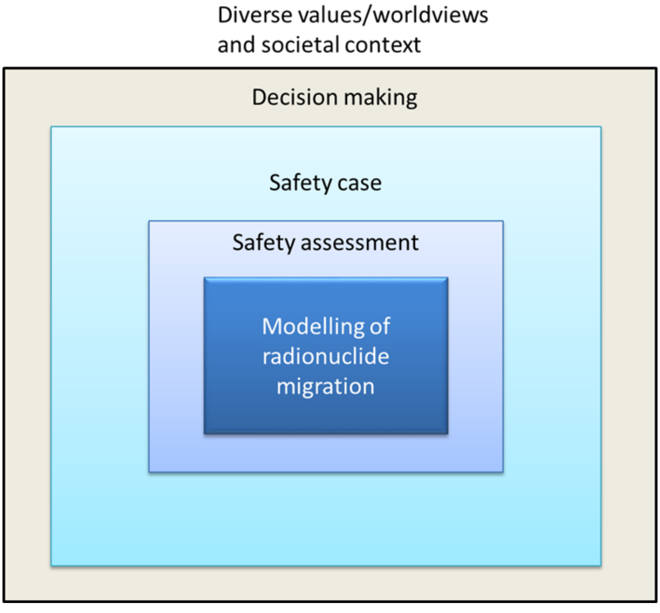

Fig. 4. The core of safety case. Note that decision-making takes place in a multifaceted communication environment with many actors in society.

When one talks about long-term impacts of a geological disposal facility, a good rule of thumb is that the time periods to be covered in a safety case can also be geological, i.e. up to hundreds of thousands or millions of years. This adds a specific challenge into the safety case.

3.2 Contents of safety case

The contents of safety case have been discussed by the international NWM community for many years, and out of this discussion a nearly universal view has been reported. Detailed examination of this discussion is beyond the scope of this report, the following sections focus on the main features reported by IAEA and OECD NEA expert groups, in which Finnish experts have participated. In addition to international safety case concepts, the latest Finnish safety case plan is touched. The corresponding safety case is being prepared by Posiva for the forthcoming operating licence application for a spent fuel disposal facility.

3.2.1 Safety case: IAEA version

IAEA defines safety case simply as "*the collection of arguments and evidence to demonstrate the safety of a facility*" (IAEA 2018). Safety assessment is defined equally simply as "*all assessments performed as part of the safety case*" (IAEA 2018). More detailed definitions can be seen in IAEA (2012).

The basic structure of a safety case, according to IAEA, is given in Fig. 5 and its main component safety assessment in Fig. 6.

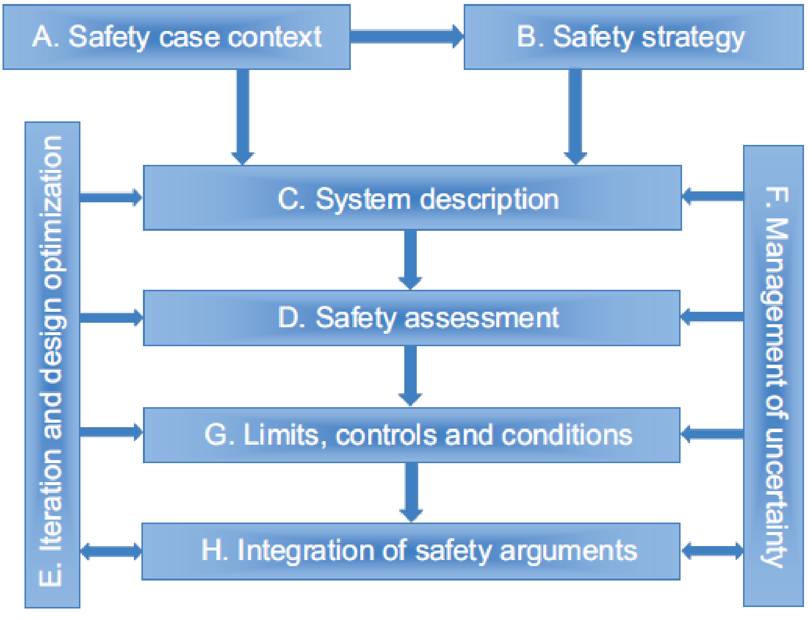

Fig. 5. Main components of a safety case (IAEA 2012).

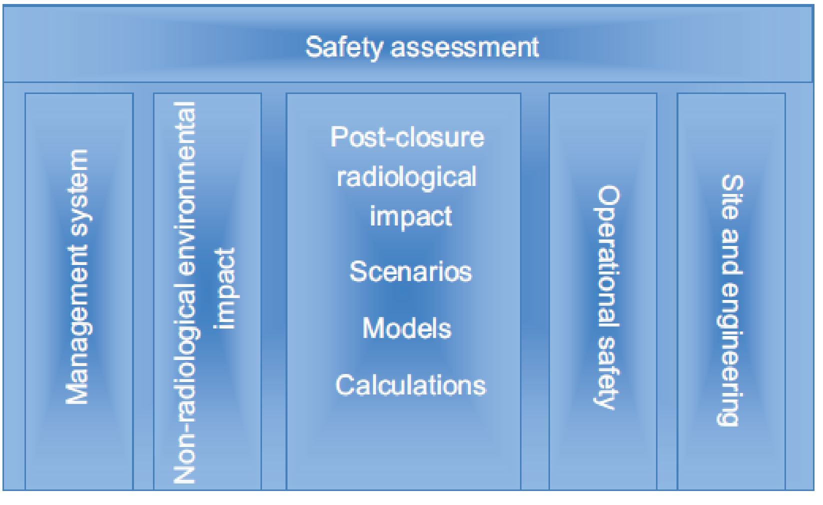

Fig. 6. Main components of a safety assessment (IAEA 2012).

For details, the interested reader gets more perspective and more detailed picture of IAEA safety case thinking in IAEA (2012) and references therein. Fig. 6 mentions also operational safety, but that is not currently included in the Finnish safety case concept. Nevertheless, operational safety will have to be assessed in a licence application.

3.2.2 Safety case: NEA version

OECD NEA defines the safety case as follows (NEA 2012):

> *"The safety case is an integration of arguments and evidence that describe, quantify and substantiate the safety of the geological disposal facility and the associated level of confidence. In a safety case, the results of safety assessment – i.e. the calculated numerical results for safety indicators – are supplemented by a broader range of evidence that gives context to the conclusions or provides complementary safety arguments, either quantitative or qualitative. A safety case is the compilation of underlying evidence, models, designs and methods that give confidence in the quality of the scientific and institutional processes as well as the resulting information and analyses that support safety."*

Safety assessment is defined as (NEA 2012):

> *"Safety assessment is a systematic analysis of the hazards associated with geological disposal facility and the ability of the site and designs to provide the safety functions and meet technical requirements. The task involves developing an understanding of how, and under what circumstances, radionuclides might be released from a repository, how likely such releases are, and what would be the consequences of such releases to humans and the environment."*

The basic structure of a safety case, according to NEA, is given in Fig. 7 and its main component safety assessment in Fig. 8.

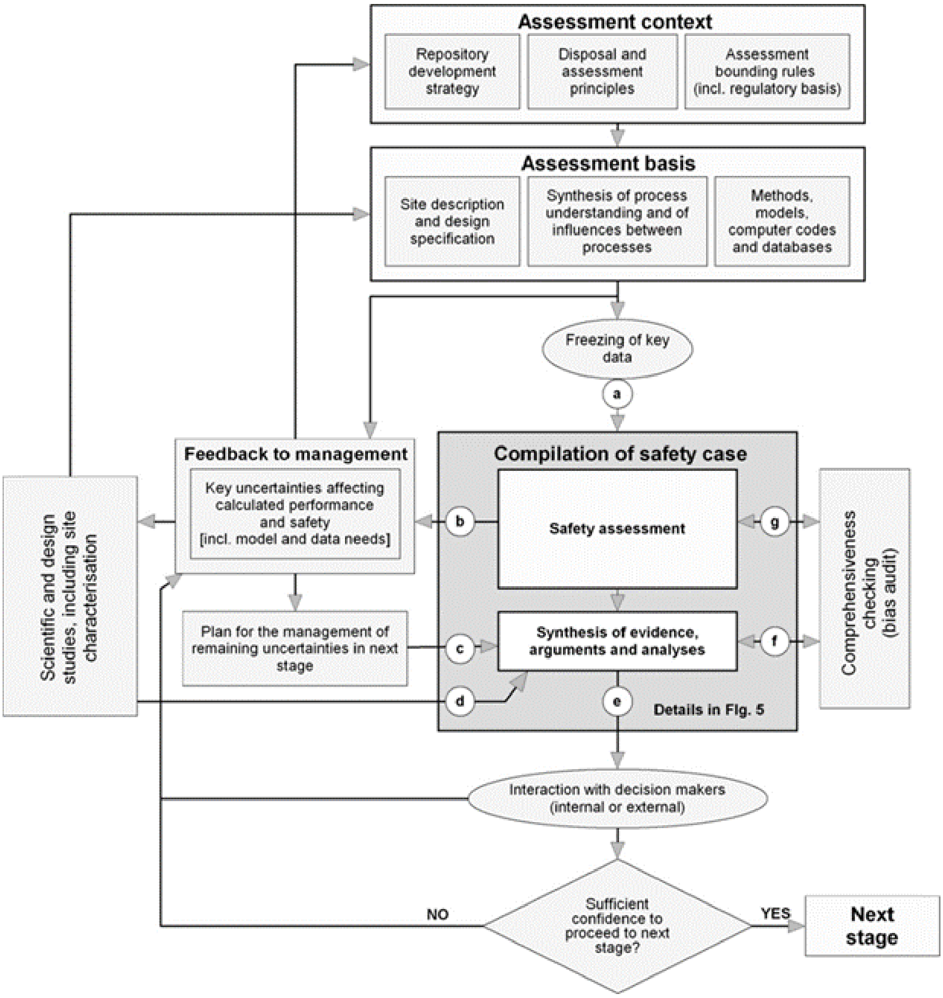

Fig. 7. Main components of a safety case (NEA 2012). The arrows with letters correspond to those in Fig. 8.

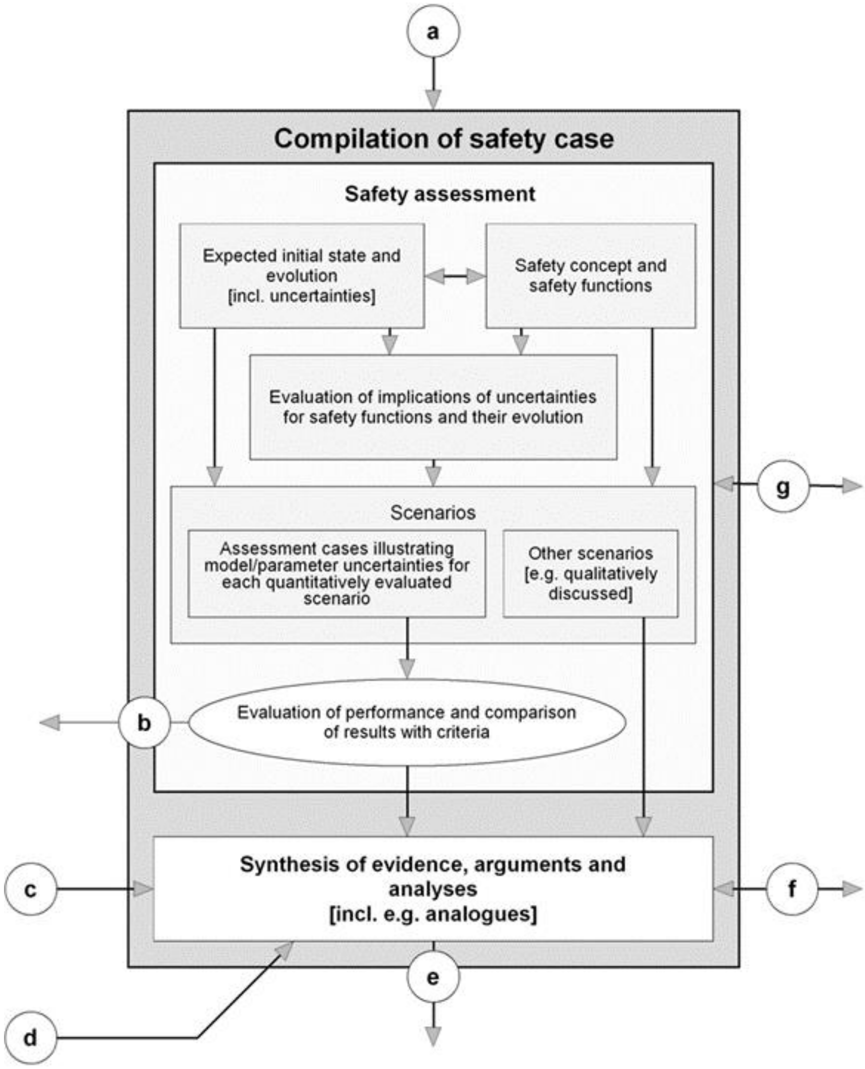

Fig. 8. Main components a safety assessment (NEA 2012). The arrows with letters correspond to those in Fig. 7.

For details, the interested reader gets more perspective and more detailed picture of NEA safety case thinking in NEA (2012) and references therein.

3.2.3 Safety case: Posiva version

The spent fuel management programme by Posiva is currently the most extensive and detailed NWM programme in Finland. As regards safety case, Posiva has developed its plan stepwise along with the development of international safety case thinking and according to the feedback from STUK. Currently Posiva is applying plan number 4; for a quick glance of the first three, the reader is advised to Rasilainen et al. (2013) and references therein.

For the purpose of this report, the latest version of safety case plan by Posiva is touched briefly in the following. The aim is not to go into details, but rather to study the overall views of version number 4. Posiva considers safety case as a "*portfolio of 8 main reports*" see Fig. 9; this is a straightforward view, but in line with the function of safety case and the fact that the burden of proof lies with the licence applicant. The main reports will be supported by more detailed substance reports.

Synthesis
Description of the overall methodology of analysis, bringing together all the lines of argument for safety, and the statement of confidence and the evaluation of compliance with long-term safety constraints
Design Basis (DB)
Safety functions, performance targets and design requirements, their basis and the links between them
Initial State (IS)
Initial state of the repository system and the present conditions of the surface environment
LILW Repository Assessment (LILW-RA)
Assessment of the long-term performance of the repository for LILW from the encapsulation plant and identification of interactions with the SNF repository
Performance Assessment and Formulation of Scenarios (PAFOS)
Assessment of fulfilment of performance targets taking into account the expected and alternative climate and surface environment evolutions. Scenarios formulation based on uncertainties/deviations identified in the assessment
Models and Data (M&D)
Model network and data management approach for performance assessment and the analysis of releases
Analysis of Releases (AOR)
Overview of the main results from the radionuclide release and transport modelling from the repository system to the surface environment and evaluation of radiological consequences
Complementary Considerations (CC)
Supporting evidence for safety including natural and anthropogenic analogues

Fig. 9. Planned safety case portfolio for operating licence application (Posiva 2017). Note that in the vicinity of the spent nuclear fuel repository, there is also a LILW repository, Fig. 10.

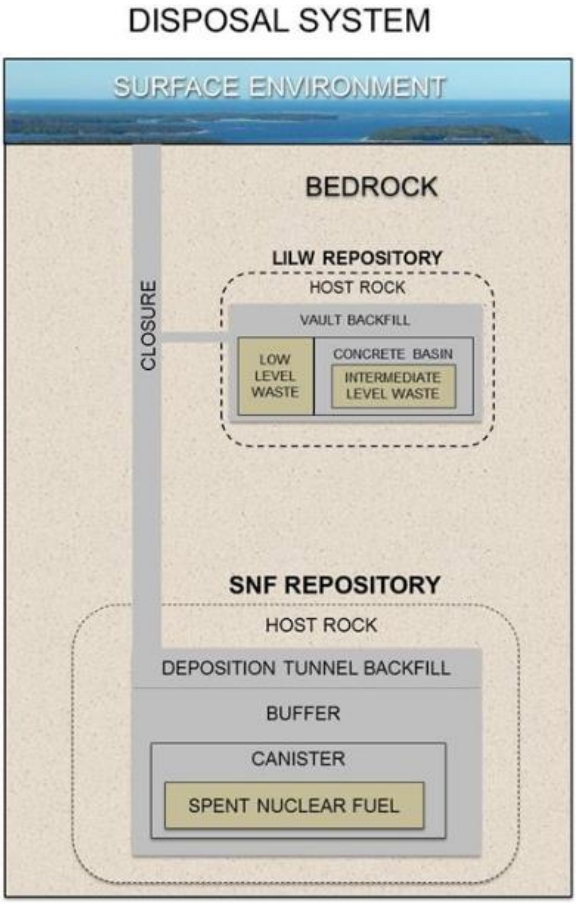

Fig. 10. Schematic presentation of the components of Posiva's planned disposal system (Posiva 2017). Interactions of the LILW and SNF facilities need to be assessed in terms of long-term safety.

3.3 Review of safety case

The preparation of a safety case in a licence application is the duty of the licence applicant. The review of the safety case is the duty of the competent authority, in Finland STUK. Both use external experts as subcontractors in the detailed subsystem level analyses and reviews.

As concerns the review process, there are international recommendations, e.g. in IAEA (2012) and WENRA (2014). These general recommendations may guide the competent authority in each country to construct its own regulations and guides for NWM. Following the requirements of the national authority is an unavoidable technical must for the licence applicant when preparing the safety case. However, one must keep in mind that the regulations in Finland have been and will be updated as needed, and in these update moments many organisations, including the licence holders/applicants can give feedback to the regulator.

For the technical review of a safety case, STUK has outlined the content it expects to see in the annex of STUK (2018). In the following the items in this annex will be given as a checklist type of presentation:

1. Description of the disposal system
2. Definition of barriers and long-term safety functions
3. Definition of performance targets for long-term safety functions
4. Definition of scenarios
5. Models and input data
6. Safety analysis and rare events impairing long-term safety
7. Treatment of uncertainties
8. Complementary considerations
9. Comparison of the outcome of the analyses with the safety requirements
10. Structure and documentation of the safety case
11. Quality of the safety case.

3.3.1 Comment on scenarios

Scenarios have been mentioned many times in this chapter, and in this respect what safety authority expects is of most interest. Scenarios are identified, constructed and analysed to study the effect of alternative thinkable evolutions on the long-term safety of the disposal system. No single scenario is intended to cover everything, rather it is the set of scenarios that is used to cover a reasonably representative sample of possible futures. STUK (2018) states that scenarios must cover at least:

- external factors, such as climate changes, geological events or human actions
- radiological, mechanical, thermal, hydrological, chemical, biological and radiation-related factors internal to the disposal system
- quality non-conformances in the barriers, and the combined effects of all the aforementioned factors.

This list can be considered to utilise bottom-up approach, in NWM compilations of safety-relevant features, events, processes (FEPs), for instance. FEPs represent things (or factors, as above) that in principle could happen to the disposal system, they are further discussed in section 4.1.2. and Appendix A.

Three categories of scenarios are required:

- the base scenario shall assume that the performance targets defined for each safety function are met
- variant scenarios are used to analyse the influence of declined performance of one or several long-term safety functions
- disturbance scenarios shall be constructed for the analysis of rare events impairing long-term safety. At least rock movements, boring medium-deep water well, and core drilling hitting a waste package shall be covered.

This list can be considered to utilize the top-down approach, focusing on individual safety functions or their combinations. For details in the above items, the interested reader is referred to STUK (2018), as studying the items in detail here falls outside the scope of this report.

4. NPP safety discussion in summary

4.1 ORSAC framework for overall safety

Hyvärinen et al. (2016) have proposed an overall safety conceptual framework (ORSAC) for nuclear power plants. The framework would allow for integrating all the different varieties of “safety”: nuclear safety, nuclear security, and nuclear material non-proliferation (safeguards) in the future. The proposal thus provides a practical platform for an extension to 3S framework in the future (safety, security, safeguards). In principle, the framework could be extended to 5S (safety, security, safeguards, society, sustainability) in the future. At current, however, focus in ORSAC work is steadily on safety.

In the following, some points considered relevant for the safety case thinking of nuclear waste disposal will be picked from ORSAC framework, and discussed briefly. The discussion is by far not comprehensive and the interested reader is referred to Hyvärinen et al. (2016).

4.1.1 Defence-in-depth

The basis for ORSAC is the defence-in-depth (DID) approach, which has been extensively discussed by e.g. IAEA and WENRA; for good discussions see IAEA (2016) and WENRA (2009); for basic definitions see e.g. IAEA (1996). Hyvärinen et al. (2016) describe the development of the DID principle on the basis of historical examples: after major NPP accidents, e.g. Three Mile Island, Chernobyl, Fukushima there have been major inputs into international DID thinking from the lessons learned. Considering DID as a socio-technical system and using the terminology of Taleb (2012), we can see that the system is antifragile in the sense that it has benefitted from major learnings after disasters.

Functional DID exists to protect structural DID, Fig. 11 shows the conceptual barrier system in a NPP against radionuclide release:

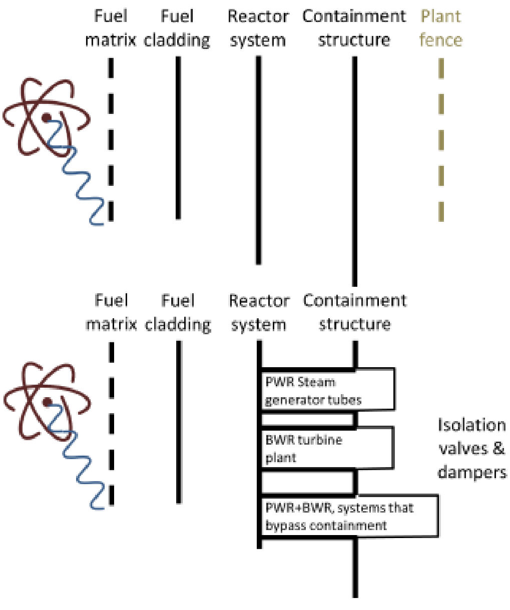

Fig. 11. Theory (top) and practice (bottom) of structural barriers against radionuclide release from NPP. In practice, the assumed independence of barriers is often compromised (Hyvärinen et al. 2016).

The barrier system against radionuclide releases shown above represents safety thinking. Expanding to security thinking one can detect interesting parallels between release barriers and postulated security zones, Fig. 12:

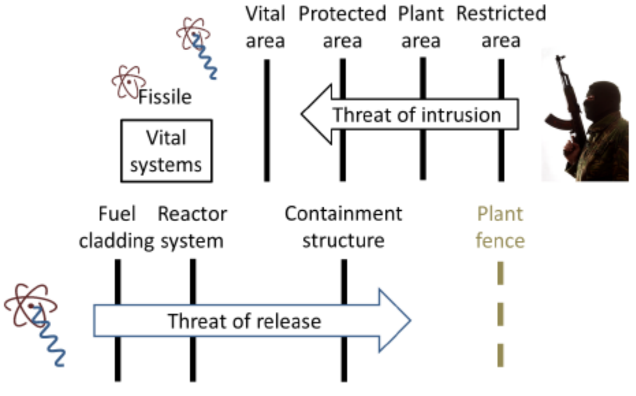

Fig. 12. Parallels between release barriers (below) and security zones (above). Protected area is typically defined as buildings housing the vital areas; these are not limited to the (outer) containment but also include safety system buildings (if separate from the outer containment), and storage buildings for fresh and spent fuel (Hyvärinen et al. 2016).

Expanding further to safeguards, one can still see some parallels between release barrier system and postulated material balance area, Fig. 13:

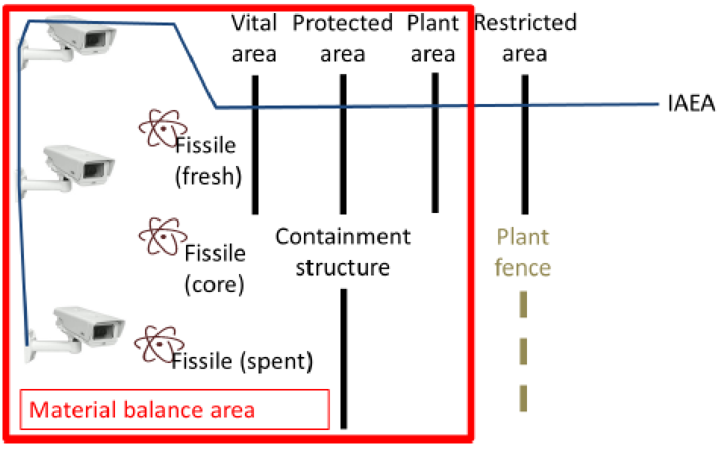

Fig. 13. An example of a material balance area (Hyvärinen et al. 2016). Safeguards monitoring system (camera data) information must be transferred out from the plant vital areas to IAEA headquarters in Vienna, Austria.

IAEA defines the concept of a safety function as "*what must be accomplished for safety*" (see, e.g. IAEA 2014, 2018). The document IAEA (2014) describes the process by which structures, systems and components (SSCs) important to safety in a NPP can be derived from the fundamental safety objective.

The link between SSC's and safety functions in a NPP reminds closely the link in NWM between release barriers and their respective safety functions. The difference is that in NWM the properties of the natural release barrier (host rock) cannot be "improved": they are what they are. The role of engineered barrier system (EBS) is to adjust the whole disposal system consisting of the repository and the host rock so that it will meet safety criteria with high confidence.

4.1.2 Top-down approach

ORSAC framework follows a top-down approach, which helps identifying and structuring safety significance of different issues in a transparent manner. Looking at the safety of NPP, the top-down approach forces one to keep the big picture in mind, which in a way provides theoretical support to graded approach[3]. The top-down approach also helps in understanding and quantifying the effect of real life compromises in independence and amount of equipment and structures in the NPP.

[3] Safety-related measures are dimensioned according to the safety significance of the subsystems. Focus is on most safety significant subsystems.

Safety cases of nuclear waste disposal are mostly top-down exercises as well. In past years there have been attempts to construct safety case scenarios from bottom-up (see e.g. SKI 1997), but usually a bottom-up effort turns into a top-down exercise when scenarios are finally constructed, due to the large amount of work in a pure bottom-up effort[4]. When one starts a bottom-up exercise for a nuclear waste disposal facility, one of the first question is what could happen to the disposal system. In NWM this question is approached when analysing features, event and processes (FEPs).

International NWM community has compiled structured data banks containing FEPs; the data banks essentially are compilations of possible/thinkable things that could take place in or for the disposal facility. The number of thinkable FEPs is so large that a systematic combination of all possibilities is not feasible, see e.g. the latest NEA FEP list that includes external factors[5] as well as waste package, repository, geosphere, and biosphere related factors (NEA 2019). Altogether the compilation, called IFEP list (International Features, Events, Processes list) contains 268 FEPs (including FEP groups and subgroups). The IFEP list can be a relevant check list for the completeness of scenarios, conceptual models and for implementation in software, for instance, for one's current safety case needs.

A more detailed grouping of IFEPs is given in Appendix A. For a complete picture of the latest FEP compilation the interested reader is referred to NEA (2019).

4.1.3 System of systems and organisation of organisations

ORSAC framework considers the NPP systems, structures, and components (i.e. plant architecture) as a system of systems. Focusing on plant architecture provides a top-down approach to identify safety significance of any issue in the plant. Hyvärinen et al. (2016) consider that current regulations for DID are a result of historical evolution, coming mostly from bottom-up, with vaguely defined plant architecture goals. One logical result of such bottom-up regulations is that they also are largely discipline-driven. The authors consider ORSAC framework as a possible platform to fix existing discrepancies and inconsistences in regulations.

After describing a NPP as a system of systems, Hyvärinen et al. (2016) expand to consider the nuclear community as an organisation of organisations. Many efforts in human and organisations research have been focused on the performance and behaviour of individual organisations. The authors suggest that the whole community, as an organisation of organisations, acts according to unspoken if not unconscious fundamental beliefs, see Fig. 14. For instance, there is generally

[4] For example, if there are 10 uncertainty factors (say FEPs) that each have four different levels, there are mathematically $4^{10} \approx 1\ 000\ 000$ possible combinations of factor-specific levels, thus making it impossible to study all possible combinations by hand. Seeve (2018) has presented an approach to identify and visualize scenarios.

[5] External factors include 1) repository issues (pre-closure), 2) geological factors, 3) climatic factors, 4) future human actions, and 5) other external factors. Thus external factors include also institutional and societal things.

strong confidence in own excellence which, however, has been shaken somewhat by nuclear accidents.

Functional Level	1 Operation	2 Ownership	3 Technical oversight	4 Administration: By law	4 Administration: By opinion
Organisation	Operating organisations (Fortum Loviisa, TVO, Fennovoima, Posiva)	Plant owners (Fortum P&H, PVO, VSF)	Technical Regulator (STUK)	TEM / Govern-ment	Parliament
Support / Stakeholder	Inspection Organisations (independent); O&M contractors	Expert services by TSOs, universities; Inspection Organisations (independent)	Expert services by TSOs, universities; IOs, accredited	Intervenors	Intervenors; Local population General public

Fig. 14. The Finnish organisation of organisations, with focus on nuclear plant operations (Hyvärinen et al. 2016). No exact correspondence to the defence levels of Fig. 11 is intended, but the analogue appears useful nevertheless.

The system of systems and organisation of organisations thinking considered for NPPs can be directly transferred to nuclear waste disposal facility and NWM community (c.f. Fig. 14). As a system, a running NPP is of course more complex than a running nuclear waste disposal facility, not to mention a sealed and closed disposal facility.

4.2 Institutional strength-in-depth (ISiD)

After the Fukushima accident and lessons learned, the IAEA's international expert group introduced the concept of institutional strength-in-depth (ISiD) (IAEA 2017). ISiD aims at providing tools to construct a robust overall nuclear safety system at national level. The concept is based on the idea that it is not enough that there are good technical tools and safety standards, but these need to be implemented efficiently. The ISiD refers to a network of organisations, such as government, industry, regulatory body, media and NGOs, and interfaces between them that assure that the tools and safety standards are efficiently applied.

ISiD builds on the existing safety principles, such as the safety culture, and the DID principle that is extended from technical context to organisational context. In the organisational context, the philosophy of DID means that each of the key organisations, i.e. industry, regulator, government and stakeholders in the nuclear domain, forms an independent safety layer or barrier that is further strengthened by multiple internal barriers, such as competent actors, safety management system and vivid safety culture (IAEA 2017). Between the organisations, openness, transparency and questioning attitude shall prevail. As such ISiD complements the DID thinking. Furthermore, the INSAG-27 report suggested that the IAEA should develop formal ISiD guidelines.

Ylönen et al. (2017) have discussed ISiD with an eye on ORSAC methodology. With a view on ISiD model, they consider the communication of organisations in nuclear community challenging because different organisations have different communication codes, that can be described with binary logic. Applying the communication codes of different social systems given in Ylönen et al. (2017) based on Luhmann (1995), for instance the following three Finnish organisations in nuclear plant operation shown in Fig. 14 have quite different communication codes:

1. plant owners: profit vs. loss
2. technical regulator (STUK): safe vs. non-safe
3. TEM/government: overall good of the society vs. not.

Nuclear safety field is considered inherently complex as many different social systems are involved, e.g. law, politics, science, economy. This in turn will require extra clarity in communication so as to get one's message understood.

Open discussion about nuclear safety between core stakeholders is in principle possible, but e.g. in Finland there is no standing neutral platform for it. Not all stakeholders, however, are experts in the substance matter. The role of STUK in open discussion is somewhat challenging and STUK requires balancing between participation and maintaining its independence. Normal scientific discussion of course benefits from challenging and questioning attitude, but due to lots of intersecting actors and related interests this attitude may sometimes be difficult to maintain.

Ylönen et al. (2017) study the pros and cons of the ISiD model and consider that it is in principle compatible with ORSAC methodology, keeping in mind that both are still under development. The novelty is that ISiD focuses on organisations in the DID context. ISiD model is considered to require elaboration for instance on the roles of owners, subcontractors, and long supply chains in general. Independence of different organisations is not self-evident and some may have a double role, e.g. parliament's legislative power vs. the fact that it is at the same time also the object of diverse lobbying.

5. Safety case against main NPP safety discussion topics

In this chapter, it is discussed how the above touched main points in the ORSAC and ISiD models have been taken into account in the safety case methodology. The points to be discussed are those considered most relevant to NWM.

5.1 Defence-in-depth

The DID philosophy is applied in NWM. In order to protect humans and the environment from the waste, a system of engineered and natural release barriers is constructed between the waste and the living biosphere. The planned role of the barrier system is 1) to prevent, and 2) after containment is lost, to limit and retard the release and the migration of radionuclides. This can be considered as a textbook example of DID. Safety functions listed in Table 1 provide a more detailed picture for KBS-3V type facility for spent fuel. Fig. 15 gives an overview of KBS-3V disposal facility in the sense of DID.

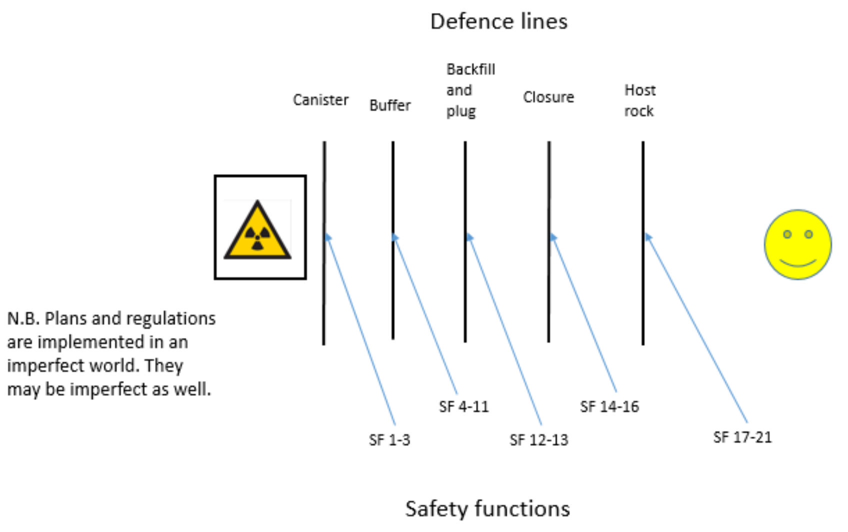

Fig. 15. KBS-3V disposal concept viewed in DID spirit. Safety functions related to subsequent release barriers are taken from Table 1. Host rock is a natural barrier, others belong to the engineered barrier system (EBS).

As regards security and safeguards aspects vis-à-vis nuclear waste disposal facility, unauthorized removal of radioactive waste will not be easy, because in order to do it safely, one must take radiation protection into account, otherwise it may be a pretty suicidal effort. For instance, spent nuclear fuel is so active that international expert groups, e.g. NEA expert group WPFC/AFCS (Expert Group on Advanced Fuel Cycle Scenarios of the Working Party on Scientific Issues of the Fuel Cycle), have been calculating and measuring "self-protection" ability for it, see e.g. Eschbach et al. (2017). Currently it is considered by NRC and IAEA that that the gamma dose limit 1 Sv/h at a distance of 1 m from a spent fuel bundle is enough to "protect" it. This radiation dose will be received from a PWR spent fuel bundle after 30 a cooling time.

The overall safety case and in particular safety assessment methodology with a chain of subsequent analyses can be seen following the course of radionuclides spreading from the waste towards the living biosphere, i.e. starting from release rate assessment and ending with the assessment of the exposure of humans. It thus follows the structural DID course.

Looking at the stepwise decision-making process in NWM, i.e. the successive decisions concerning decision-in-principle, construction licence, operating licence, and closure licence, one can say that the decision-making process has an element of procedural DID. The safety cases will become more detailed and focused from one decision step to the next and so will the reviews as well. There is also an element of temporal DID as the successive decision steps will be separated by many years, Fig. 16.

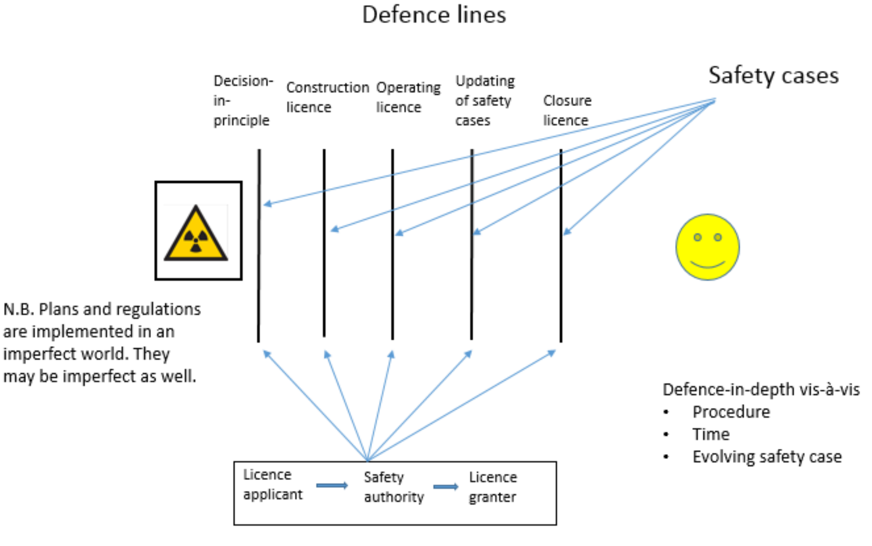

Fig. 16. DID features in the decision-making process of NWM. At each decision step there is a safety case and the related interaction loop between licence applicant, safety authority and licence granter.

One can see organisational DID also in the dialogue between the implementer and regulator (i.e. licence-applicant and safety authority) during the decision-making process. This dialogue is important in that substance related comments by regulator will not remain unanswered, and for instance in Finland the dialogue between Posiva and STUK has furthered the technical planning of the KBS-3V concept, and relevantly for this report, especially the planning of safety case. As such, there is no formal expert body in Finland to supervise STUK.

In summary, DID philosophy is in active use when safety cases are constructed and used.

5.2 Top-down approach

In a safety case and in particular in safety assessment, the disposal system is subject to quantitative analysis (i.e. simulations) having its roots deep in systems analysis. Safety significance of certain issues can often be assessed quantitatively only after simulations have been done. Simulations help also when one studies the main triggering factors. In reality, release barriers are not completely independent from each other and therefore certain initiating factor (e.g. failing safety function in Table 1) can start or accelerate a safety-relevant chain of events. The most effective triggering factors are of most interest. From this point, top-down approach is actually indispensable.

Due to the practically unmanageable amount of work in a pure bottom-up approach to derive scenarios, scenario development should be complemented by a top-down approach based on safety function considerations. Therefore, YVL D.5 requirements actually have a clear component of bottom-up approach that starts from FEP considerations, and top-down approach that starts from safety functions, c.f. section 3.3 above. Therefore, one can say that the safety case is a top-down study with some bottom-up elements.

5.3 System of systems and organisation of organisations

Nuclear waste disposal facility can be considered as a system consisting of separate but interconnected subsystems. It can be viewed as a structure of nested subsystems that affect each other. It can and indeed it has been analysed from systems theoretical viewpoints. In comparison with a NPP, one can see that a disposal facility contains less subsystems and, in addition, the dynamics of disposal facility subsystems are much slower. This means that in case of an unfavourable occurrence like a component or barrier failure, a disposal facility does not run out of control in the same ways (and as rapidly) as an NPP, e.g. explosions are less probable because normally there are no large temperature or pressure differences.

Safety in a nuclear waste disposal facility can be divided to operational safety and long-term safety. Operational period is the time before the facility is closed and sealed. However, operational safety plays a role during closure activities as well. Operational safety assessment resembles more that of an NPP in that it looks more into human activities. For instance, fire safety is something that must be taken into account very carefully. Long-term safety on the other hand is based on laws of nature and must not at all rely on human control or activities. Rather, future human activities are considered as possible threats, and their effects to long-term safety need to be assessed in human intrusion scenarios. According to current Finnish definition, safety case is only about long-term safety.

The ORSAC approach describes the nuclear community as an organisation of organisations (c.f. Fig. 14) in that, although consisting of many organisations with partly different duties, it still follows features of an organisation. Thus, there may be some unspoken if not unconscious fundamental beliefs as well as unchallenged assumptions. The NWM community can be considered as an organisation of organisations, too. It, as well, has highly skilled experts with high confidence in own excellence. Also, the danger of intellectual in-breeding is lurking in the same way in NWM community, like in all like-minded groupings.

5.4 Institutional strength-in-depth

As regards institutional strength-in-depth (ISiD), the NWM community has many features similar to the nuclear community, being essentially a subset of it. Therefore, same considerations are valid in nuclear waste community as discussed in section 4.2. NWM appears sometimes even more delicate than nuclear in general. For instance, the acceptability for a nuclear waste disposal facility has been assessed in some countries (e.g. Japan) to be smaller that of NPP, even though the radiological risks involved are normally considered smaller than for an NPP.

The stepwise approach in decision-making of nuclear waste disposal facilities can be seen from ISiD point of view. At least the trio implementer–regulator-licence issuer[6] can be considered to be located in a structured set of defence lines. Another viewpoint is that as the safety case will have to be developed further in each subsequent steps in decision-making (decision-in-principle, construction licence, operating licence, closure licence). The repeated processes provide also time for possible reconsideration for institutions involved. Thus, the stepwise and iterative decision-making process over a longish time span may enhance institutional strength-in-depth, c.f. Fig. 16.

The ISiD model has brought up the need to study how well core organisations actually work individually and in collaboration with other organisations. In this regard, one may note that one of the things STUK will review in a safety case is the quality of the safety case and under this title, the management system of the licence applicant will be reviewed. This addresses clearly the core function/structure of the licence-applying organisation. The question that may be posed is what is meant by management system, in other words what are the boundaries meant in YVL D.5 (STUK 2018).

Even if there is institutional strength-in-depth in the decision-making process, this does not remove the scientific challenges in the disposal facility question. Scientific challenges stem from the very demanding studies that are needed. Scientific research takes its time and one major challenge is linked to relatively tight schedules in disposal projects (e.g. due to limited capacities of temporary waste storage): is the scientific method allowed enough time? If this is doubtful, who will call a time out?

[6] In Finland it is the government that grants licence to all major NWM facilities. The decision-in-principle has to be approved by the parliament.

6. Summary and conclusions

In this report, the main features in geological disposal of nuclear waste have been discussed. Safety case for the disposal has the dedicated role of demonstrating the safety of a nuclear waste management facility in a licence application. At the same time, it is a documentation of all safety-relevant work done for the licence application. The basic methodology of safety case has been developed in international collaboration. As such, the methodology has been considered fit for use.

Safety assessment of nuclear power plants has many features in common with safety case of nuclear waste disposal. Therefore, the discussion in Finland, currently looking for a more holistic approach on NPP safety assessment, is relevant also from nuclear waste disposal point of view. The holistic approach is, for the time being, called overall safety. For this report we selected points from overall safety discussion that were considered most relevant for NWM and compared them with safety case practices.

From ORSAC framework we discussed three points. (1) defence-in-depth philosophy (DID) is considered to be in active use in NWM and in safety case. We could distinguish functional and structural DID in radwaste disposal itself, and procedural as well as organisational DID in Finnish licencing approach concerning NWM facilities. (2) top-down approach is also in active use when planning a safety case. In some components of safety case, e.g. in scenario identification the approach is a hybrid one based on both top-down (using mainly safety functions) and bottom-up (using mainly FEPs). (3) system of systems and organisation of organisations observations apply to NWM safety assessment as well as to NPP safety assessment. Both systems consist of a number of subsystems coupled to each other, and as couplings may be non-linear in nature, and with different dynamics, it is essential to understand them. NWM community is composed of many organisations with different obligations but may still share some unspoken beliefs and unchallenged assumptions. It, too, has high confidence in own excellence.

In addition, institutional strength-in-depth (ISiD) has been discussed. It focuses mainly on the performance of organisations internally and externally with other organisations. The concept was discussed within e.g. IAEA after Fukushima accident. ISiD has much in common with DID and as concerns NWM, it can be concluded that safety case has currently possibilities to consider organisational aspects, for instance via scenarios and via review of the safety case, e.g. via review of the management system of the licence applicant. Notwithstanding, the basic reasoning behind ISiD is valid: despite technical tools and safety standards, all plans must be implemented in an imperfect real world. An additional challenge arises from the fact that also plans, e.g. safety case, may be imperfect.

This discussion of the overall safety points, is actually a localization of the ORSAC framework to NWM domain. As such the localisation is intended as an input to wider discussion in NWM community about whether changes in safety case methodology are necessary. It appears that many things in the overall safety framework are already covered, at least on headline level, but the depth and extent of analysis may have room for further assessment.

As concerns the use of safety case methodology outside direct licensing of NWM facilities, it appears reasonable to do system level studies to complement and balance subsystem level detailed studies so as to apply the principle of graded approach and to keep the big picture in mind. As the NWM programme in Finland is the most advanced in the world, the possible needs for these studies may also be found first here. One example is the aim in nuclear power companies and Posiva to industrialise NWM with technical optimization efforts. It is important to check at times whether these partial optimisations have implications to long-term safety, before full-scale licence application is submitted. In the spirit of graded approach, here system level studies may also mean partial safety case. System level studies of NWM appear also worthwhile when considering possible implications of small modular reactors (SMR) scenarios to company level and nationwide NWM.

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Appendix A: Latest NEA features, events and processes grouping (NEA, 2019)

Table of contents

Series title and number

VTT Technology 364

Title	**Safety case methodology for nuclear waste disposal - possible update considerations for Finnish usage**
Author(s)	Kari Rasilainen, Heidar Gharbieh, Markus Olin &, Marja Ylönen
Abstract	The report gives an introduction to the geological disposal of nuclear waste. In the licensing of nuclear waste disposal facilities, safety case is a widely used tool for the safety demonstration. Safety case methodology is described briefly touching e.g. its function and content. Three safety case references are discussed briefly, namely IAEA, OECD NEA and Posiva versions. Safety assessment methodology for nuclear power plants have been improved along lessons learned from nuclear accidents, e.g. at Fukushima. Current discussion in Finland is based on defence-in-depth philosophy, top-down approach, and views about system of systems. A Fukushima-inspired topic is institutional strength-in-depth. The aim of this report is to discuss whether these topics need to be transferred to nuclear waste management as well. Analysing safety case methodology vis-à-vis the four previous topics indicates that in principle all of them are already covered in safety case. However, the desired extent and depth of organisational analysis may require wider discussion in nuclear waste community. In current safety cases organisational questions are mostly discussed in scenarios and in the description of licence applicant's management system.
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Julkaisun sarja ja numero

VTT Technology 364

Nimeke	**Turvallisuusperustelun metodologia ydinjätteiden loppusijoitukseen - päivityspohdintoja suomalaisessa käytössä**
Tekijä(t)	Kari Rasilainen, Heidar Gharbieh, Markus Olin, Marja Ylönen
Tiivistelmä	Raportissa on johdanto ydinjätteen geologiseen loppusijoitukseen. Ydinjätteen loppusijoituslaitosten luvittamisessa turvallisuusperustelu on laajalti käytetty työkalu laitoksen turvallisuuden osoittamiseksi. Turvallisuusperustelun metodiikkaa kuvataan lyhyesti, esim. sen tarkoitusta ja sisältöä. Kolmea näkemystä turvallisuusperustelusta käsitellään lyhyesti, nimittäin IAEA:n, OECD NEA:n ja Posiva Oy:n versioita. Ydinvoimalaitosten turvallisuuden arviointimenetelmiä on parannettu ottamalla opiksi ydinonnettomuuksista, esim. Fukushimassa. Nykyinen keskustelu Suomessa perustuu syvyyspuolustukseen, ylhäältä alas -lähestymistapaan ja näkemyksiin järjestelmien järjestelmästä. Fukushiman synnyttämä aihe on institutionaalinen syvyysvahvuus. Tämän raportin tarkoituksena on pohtia, onko nämä keskustelunaiheet siirrettävä myös ydinjätehuoltoon. Turvallisuusperustelumetodiikan analysointi suhteessa neljään edelliseen aiheeseen osoittaa, että periaatteessa kaikki ne on jo katettu turvallisuusperustelussa. Toivottu organisaatiotarkastelun laajuus ja syvyys voi kuitenkin edellyttää laajempaa keskustelua ydinjäteyhteisössä. Nykyisissä turvallisuusperusteluissa organisaatiokysymyksiä pohditaan enimmäkseen skenaarioissa ja luvanhakijan johtamisjärjestelmän kuvauksessa.
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Safety case methodology for nuclear waste disposal - possible update considerations for Finnish usage

In the context of nuclear waste management, safety case is used to assess the radiological impact of nuclear waste disposal to humans and the environment. It is used in decision-making, before major waste management steps are taken.

Safety case is currently a well-established and widely used methodology for safety assessment, due to many years of international collaboration. There may be some specific national features, but as a whole the methodology has been considered fit for use.

The report gives a description about possible expansion needs in the safety case methodology. We utilise the discussion in Finland concerning the safety assessment of nuclear power plants which in turn has utilised lessons learned in major nuclear accidents, e.g. at Fukushima.

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