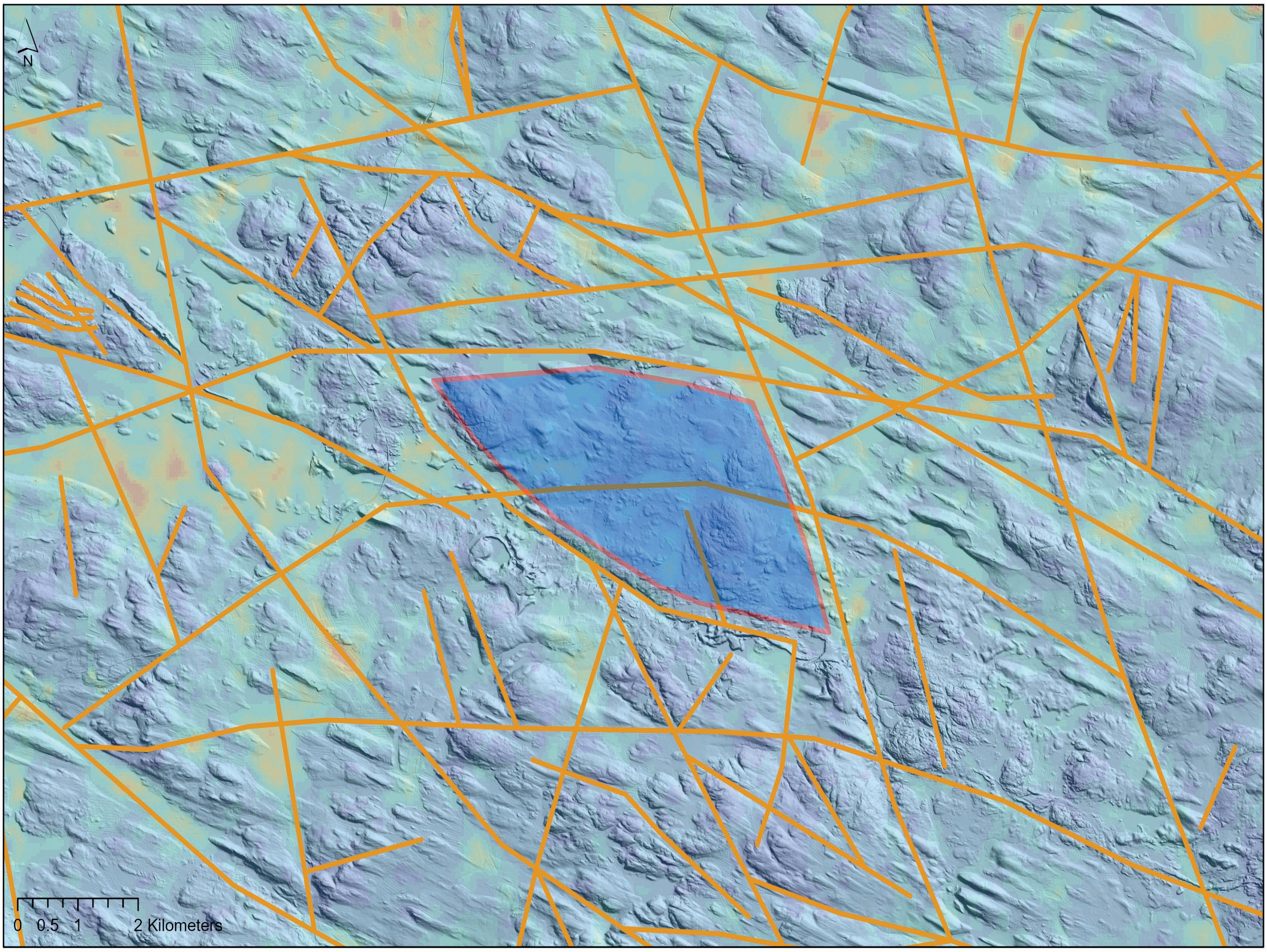
Geological Survey of Finland

2023

Geological siting considerations for small modular reactors and related nuclear waste disposal concepts in Finland

Jaakko Hietava, Ismo Aaltonen and Heini Reijonen

GTK Open File Research Report 12/2023



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Unless otherwise indicated, the figures have been prepared by the authors of the report.

Front cover: Fictional example presentation of lineament interpretation from the Archean terrain in Kuhmo with the Romuvaara investigation site highlighted, with new near-regional scale interpretations from LiDAR and electromagnetic data (LiDAR data from MML, electromagnetic data from GTK). Picture: Jaakko Hietava, GTK.

Layout: Elvi Turtiainen Oy

Espoo 2023

Hietava, J., Aaltonen, I. & Reijonen, H. 2023. Geological siting considerations for small modular reactors and related nuclear waste disposal concepts in Finland. *Geological Survey of Finland, Open File Research Report 12/2023*, 47 pages, 10 figures and 1 table.

Small modular reactors (SMRs) are being investigated globally as SMR technology progresses towards deployment. Requirements for the geological characterization of nuclear facility sites are noted in IAEA and STUK documents, but only regarding conventional nuclear power plant (NPP) sites and repositories. With no current legislation or regulation yet existing for SMRs in Finland, investigations into SMR-related geological aspects can only be conducted using applicable literature and previous research concerning conventional NPPs.

Finland is currently the only country in the world to successfully build a repository site for spent nuclear fuel and is advancing towards final disposal operations. The construction of nuclear power plants also has a longstanding tradition in the country, with two nuclear power plant sites successfully built and multiple reactors in operation.

The goal of this report is to discuss introductory geological suitability criteria for siting SMR power plants and spent nuclear fuel (SNF) repositories. This is done by applying existing literature and knowledge of geological siting aspects to SMR technology in the siting process for SMR power plants and SMR SNF repositories.

This report reviews the geological siting aspects, or geological suitability criteria, investigation methods and data needs that would be required in SMR power plant and repository siting. It also considers some novel aspects related to nuclear waste strategies, especially concerning centralized or decentralized strategy options for SMR-based waste. Deep borehole disposal concepts and their relation to SMR-based waste are also preliminarily reviewed, with special emphasis on Finnish bedrock conditions.

This report was written within the VTT-coordinated SMRSiMa project, which was funded by KYT2022/SAFIR2022.

Keywords: nuclear reactors, nuclear waste, radioactive waste, nuclear safety, nuclear energy, deep drilling, Finland

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Hietava, J., Aaltonen, I. & Reijonen, H. 2023. Geological siting considerations for small modular reactors and related nuclear waste disposal concepts in Finland. Tiivistelmä: Pienten modulaaristen ydinreaktorien ja ydinjätteen geologisen paikanvalinnan huomioita. *Geologian tutkimuskeskus, Tutkimustyöraportti 12/2023*, 47 sivua, 10 kuvaa ja 1 taulukko.

Pieniä modulaarisia ydinreaktoreita (Small Modular Reactor, SMR) tutkitaan maailmalla, ja alan teknologia on etenemässä kohti käyttöönottoa. Vaatimuksia ydinlaitosten sijoituspaikkojen geologisille tutkimuksille käsitellään IAEA:n ja Säteilyturvakeskuksen dokumenteissa, mutta ainoastaan tavanomaisten reaktorien ja niiden tuottaman ydinjätteen loppusijoituspaikkojen osalta. Koska Suomessa ei ole vielä voimassa olevaa SMR-lainsäädäntöä tai ohjeistusta, niitä varten tarvittavia geologisia tutkimuksia voidaan tarkastella vain soveltuvan kirjallisuuden ja olemassa olevien perinteisiä ydinvoimaloita koskevien tutkimusten avulla.

Suomi on tällä hetkellä ainoa valtio, joka on onnistuneesti rakentanut käytetyn ydinpolttoaineen loppusijoituspaikan ja on etenemässä kohti operatiivista loppusijoitusta. Myös ydinvoimalaitosten rakentamisella on pitkät perinteet, joista esimerkkinä kaksi onnistuneesti valittua ja rakennettua ydinvoimalaitosten sijoituspaikkaa, joissa on käytössä useita reaktoreita.

Tämän raportin tavoitteena on alustavasti tarkastella SMR-laitosten paikanvalintaan ja ydinjätteen loppusijoitukseen liittyviä geologisia kriteerejä. Työ on toteutettu soveltamalla julkaistua kirjallisuutta ja tietämystä geologian soveltamisesta paikanvalintaprosesseissa SMR-laitoksiin ja niiden tuottaman ydinjätteen loppusijoituspaikan valintaan.

Raportissa tarkastellaan paikanvalinnan geologisia näkökulmia ja soveltuvuuskriteereitä sekä tutkimusmenetelmiä ja tarpeita geologiselle tiedolle SMR-laitosten sijoittamisessa ja loppusijoituspaikan valinnassa. Raportissa tuodaan esiin myös joitain uusia näkökohtia, jotka liittyvät ydinjätehuollon mahdollisiin toteutustapoihin, esimerkiksi liittyen jätehuollon keskitettyyn tai hajautettuun vaihtoehtoon. Raportissa tarkastellaan myös syväreikäsijoitukseen perustuvaa loppusijoituskonseptia SMR-näkökulmasta painottaen erityisesti Suomen kallioperäoloja.

Tämä raportti on kirjoitettu yhteistyössä VTT:n kanssa SMRSiMa-projektin aikana, ja työn on rahoittanut KYT2022/SAFIR2022.

Asiasanat: ydinreaktorit, ydinjäte, radioaktiivinen jäte, ydinturvallisuus, ydinenergia, syväkairaus, Suomi

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1 INTRODUCTION

Small modular reactors (SMR) are a novel fission-based nuclear technology that is designed to be modular, meaning that the modules are constructed in factories and assembled on site. The power output of these reactors is small (10–300 MW) compared to conventional reactor types, but SMRs nevertheless produce nuclear waste. Spent nuclear fuel (SNF) produced by SMRs must be dealt with according to existing international and national nuclear regulations and legislation.

SMR siting is one of the first steps to consider in the preliminary planning phase of this technology. In addition to the safe siting of the power plants, the disposal of the waste produced also needs to be considered. The standards for Finnish nuclear facilities must comply with current nuclear-related and other legislation and adhere to international standards set by the IAEA regarding nuclear facility siting. Currently, the Ministry of Economic Affairs and Employment (Työ- ja elinkeinoministeriö, TEM) is drafting new legislation within the Nuclear Safety Act, which includes SMR-related issues.

The Radiation and Nuclear Safety Authority (STUK) is responsible for permitting and monitoring the siting and construction of nuclear facilities in Finland and has issued guidelines for the processes involved (YVL A.2, STUK 2019b, YVL A.5, STUK 2019c). To date, these guidelines have only considered large conventional nuclear power plants. The process of renewing these guidelines started in 2020, and the new guidelines will also include requirements for SMR facilities, with the goal of reaching technological neutrality. This technological neutrality would enable flexibility in the authorization and implementation of novel suitable nuclear technologies, such as SMRs.

No specific legislation or guidelines regarding SMR technology and related geological factors are listed in STUK or IAEA safety documents. The IAEA documents referred to in this report are mostly related to nuclear facilities in general terms and are used as applicable to discuss SMR-specific issues. With nuclear facility being the keyword here, the criteria concerning the geological requirements for SMR plant sites and SMR SNF facilities are therefore only indirectly assessed in this report.

An SNF disposal site is placed in a bedrock block deemed suitable for the final disposal of SNF. The research methods applied in the geological investigations and site selection of Olkiluoto and ONKALO® (a registered trademark of Posiva Oy) for SNF handled by Posiva Oy in Finland can also be used in assessing the issues associated with SMR-related SNF repository site selection. However, alternative concepts, such as deep borehole disposal, have been mentioned in connection with SMR design, and in this report, we therefore discuss the general differences between disposal options and what they mean regarding the geological investigations needed.

Operational waste (very low-level waste (VLLW) and low and intermediate level waste (LILW)) has been assessed by TVO and Fortum for their specific disposal solutions at nuclear power plant (NPP) sites. Operational waste is briefly discussed in this report in conjunction with waste location and management strategies.

All three major research topics presented in this report have complementary and overlapping elements. There are, however, notable differences in different stages and investigation needs. To differentiate the requirements for the SMR power plant siting process and the SMR SNF repository siting process, this report focuses on the possible general aspects and, for example, the specific data scales of SMR power plant siting, while more literature and data are available for a general approach to the repository siting process. The report is not meant to be conclusive and focuses on the geological criteria and data that the authors consider possibly most relevant for each stage of future SMR-related processes.

In addition, the data requirements for a repository in the site investigation stage are extensive when compared to SMR power plant siting at an equivalent stage. This is coupled with the fact that in addition to geological suitability, other criteria such as technical, economic, and social criteria for SMR power plants could possibly have a greater effect on the siting process than the geological suitability criteria.

The other criteria will also require further definition and research because of the novelty of SMR technology. In addition, it is important to note that this report provides a preliminary overview of the general requirements regarding the topics, and further research and upcoming site-specific projects will undoubtably encounter issues not presented in this report. Future research needs are presented in the conclusions of this report.

Figure 1 displays comparisons between operational periods and safety assessment periods with facility depths and geological data depths in known nuclear facilities internationally and in Finland. In general, the safety requirements regarding conventional NPPs and SMRs are quite similar, and research into distinguishable differences within a geological suitability framework is therefore warranted. Timescales for SNF disposal along with deep borehole disposal are considerably longer and require extensive research over long periods of time to establish the feasibility and to build a strong safety case for the facilities in question.

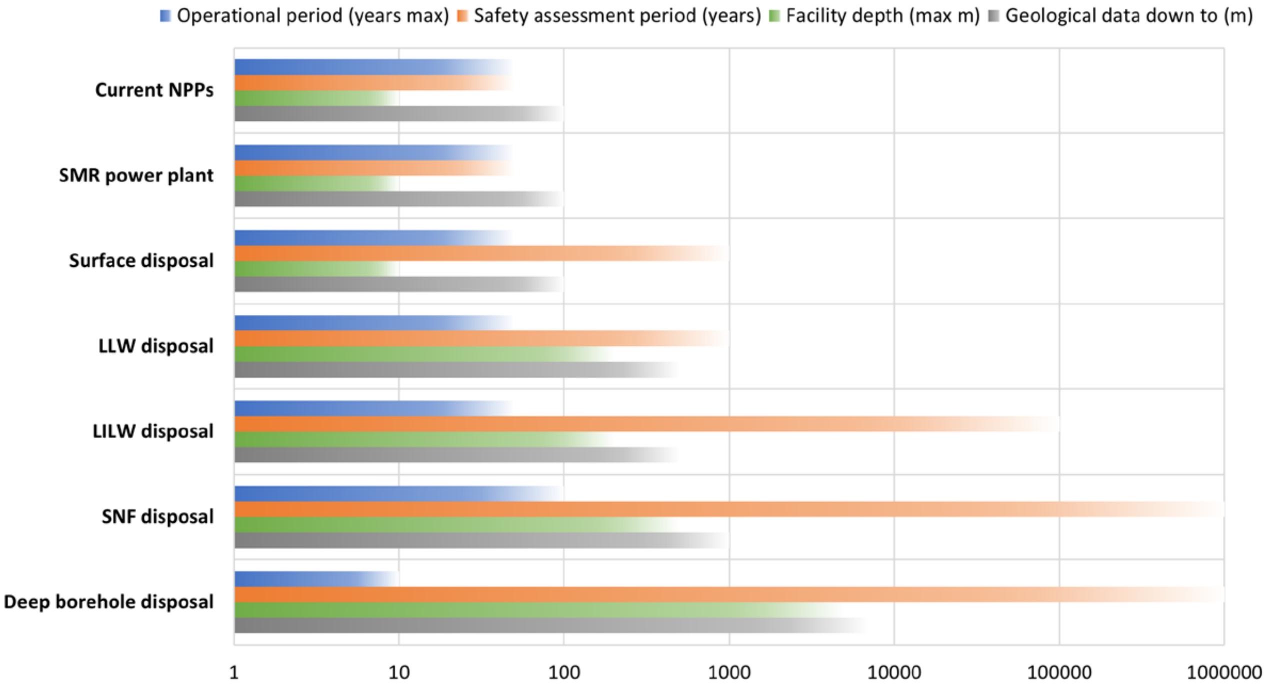


Fig. 1. Compilation of approximations of the required time scales for different nuclear facilities. Data derived from IAEA documents and STUK YVL D.5 (STUK 2018), and from experiences gathered from Finnish facilities and international references. Values are only indicative for general comparison.

2 SITING PROCESS AND GEOLOGICAL SUITABILITY CRITERIA FOR AN SMR POWER PLANT

Guideline YVL A.2 (STUK 2019b) includes descriptions of the requirements for geological, hydrological, and seismological conditions and other safety-related aspects within a specific site. Further similar guidelines for site selection for nuclear installations can be viewed, for example, in IAEA Specific Safety Guide No. SSG-35; Site Survey and Site Selection for Nuclear Installations (2015) and IAEA Specific Safety Requirements Document No. SSR-1; Site Evaluation for Nuclear Installations (2019). Geotechnical and other seismic hazards are introduced in IAEA Specific Safety Guide No. SSG-9, Seismic Hazards in Site Evaluation for Nuclear Installations (2022), with further information about related geological characteristics.

STUK guidelines (YVL) for the siting of nuclear facilities define the requirements for any nuclear facility subject to current legislation. Sites selected for the facilities must also comply with IAEA standards and protocols. The IAEA guidelines report SSG-35 (2015) suggests a rating or ranking system for the selection process. Suitable locations for nuclear facilities are given points for certain characteristics, which are individually evaluated for each site. If certain criteria regarding the geological, environmental, and other factors are considered adequate, the location or site will receive an appropriate ranking.

The site selection or siting of a nuclear installation is initiated in various stages and processes. Two processes, the siting process and site evaluation process, are further divided into five subprocesses and are displayed in Figure 2.

First, the site survey stage within the siting process involves the selection of larger areas to find potential sites, with the goal of producing a reasonable number of candidate sites. Second, the site selection stage determines the less suitable sites, which are rejected, and the remaining candidate sites are further screened for safety and other characteristics required for the selected site. This stage also includes a ranking system and point totals for different sites.

The site evaluation process extends from the final stage of the siting process towards the site characterization stage, and then to the pre-operational and operational stages. The site characterization stage is the most important one concerning site suitability. This stage includes the complete characterization of the site in question, leading to the preparation of a site evaluation report, serving as basis for a preliminary safety analysis report on the nuclear installation (SSG-35, IAEA 2015).

The pre-operational and operational stages belonging to the site evaluation process are only partially discussed in this report, as they form part of the later lifetime or timeline of an operational nuclear facility. However, geological monitoring and continued research are implemented in these stages to ensure the continuation of data collection and analysis, as these procedures contribute to the continuous safety protocols during the operational stages. It also must be noted that the site evaluation process by definition continues into the operational stage, as displayed in Figure 2.

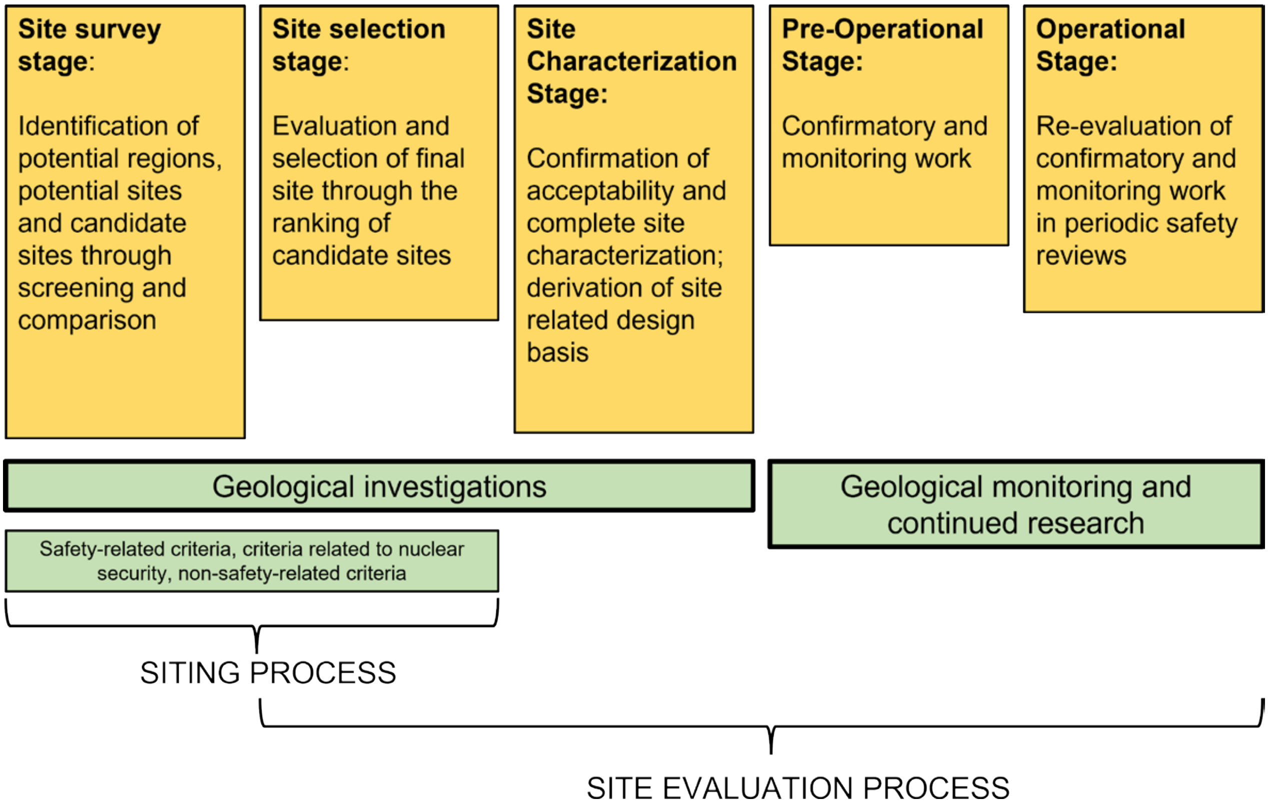


Fig. 2. The siting process and site evaluation process stages, with geological investigations, safety-related criteria, and geological suitability criteria, modified from SSG-35, IAEA 2015.

STUK document YVL A.2 (STUK 2019b) defines an emergency planning zone (EPZ) of 20 km extending from a nuclear power facility and for which authorities must include a rescue plan according to law. The document also defines a precautionary protection zone (PAZ) extending ca. 5 km from a nuclear power plant, including restrictions on land usage.

Radii for the precautionary action zone (PAZ) and urgent protective action planning zone (UPZ), along with the food restriction planning radius, have been defined by the IAEA in relation to the reactor size (IAEA-TECDOC-953, 2003). The PAZ radius for a power plant equivalent (power output 100-1000 MW) for SMR-type plants is defined as 0.5-3 km, while the UPZ radius for similar reactor sizes is defined as 5-25 km. The radius will most likely need to be adjusted to meet the needs of SMR plants or according to their specific power output.

The EPZ and the site boundary can, however, be reduced for an SMR plant due to the reduced source term of the reactor. This reduced source term refers to the total quantity of radionuclides in a reactor core available for potential dispersion and is approximately proportional to the power level. The lower power levels of SMR reactor configurations also affect the decay heat removal capabilities when using fully passive natural convection air ventilation systems, with a better heat removal performance compared to larger plant designs. The heat removal capability is due to the lower core operating power, smaller core volume and the removal of heat from the external surface area of the reactor vessel (Ingersoll 2009).

The power outputs of SMR plants also vary significantly, with commonly referenced ranges from 10 MW to 300 MW (e.g., Vujić et al. 2012, Ingersoll 2009). If there is enough variation in the suggested SMR power outputs and plant sizes, and therefore possible variation in the size requirements for the plant area, an upper limit of the above mentioned 300 MW could be used as a reference point related to other requirements and relevant safety criteria, such as geological safety or suitability criteria, although this type of process would most likely require further definition. This would effectively influence the site surface area requirements, providing more flexibility, for instance, in cases where more reactor modules would need to be constructed at completed SMR facilities. The modularization of reactor units would enable multiple units at a single site, with incremental capacity additions when needed (Locatelli et al. 2014). Thus, additional space for an individual site should be considered, and geological criteria would need to allow for this type of flexibility.

The use of SMRs in Finland would vary from district heating to electricity generation, depending on the reactor type, power output and technological maturity. The district heating reactor option would mean that the siting of individual SMR plants would be closer to population centres and urban environments than conventional NPPs. This effectively requires new approaches to zone planning and implementing emergency zones in preparation for accidents. The distance from existing heat networks would also affect the siting process of SMR reactors designed for district heat production, and the optimization of these distances should be applied.

SMR site selection should also include evaluation for underground, partially underground or surface construction possibilities for the facility. All construction configurations have advantages and disadvantages and must be fully evaluated with several safety criteria, including radiation and related safety criteria. In urban environments, underground construction would enable more enhanced external security features (TECDOC-1915, IAEA 2020). Geological constructability would be a major factor in underground construction, as rock mechanical parameters would define a suitable location for an SMR plant. Underground construction would to a degree also eliminate certain geotechnical hazards, such as soil liquefaction and slope instability, but these would have to be documented in case there is enough surface overburden material (Quaternary deposits) with a slope within a site.

Induced seismic risks associated with geothermal wells should be accounted for when considering SMR siting issues in urban and constructed environments. Geothermal energy production is rapidly increasing in Finland, and small-scale seismic events related to deep borehole projects in Finland have been documented in the St1 Otaniemi borehole in Espoo. During water injection and stimulation to expand fractures in the deep bedrock, earthquakes were subsequently documented with maximum magnitudes (M) of 1.8, with the activity declining after stimulation procedures ceased (Piipponen & Uski 2020). Distances from known geothermal

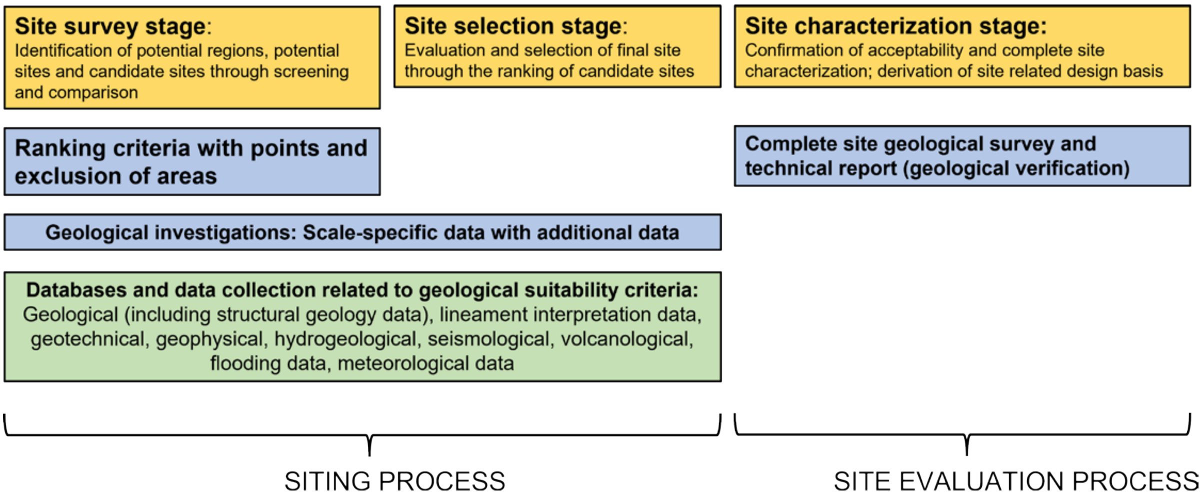


Fig. 3. Process flow chart for geological data collection in the siting process for an SMR power plant. Modified from SSG-35, IAEA 2015.

sites, large or small, should be documented and known by any SMR license operator.

Figure 3 provides more detail on the conventional NPP siting and site evaluation process stages applied to SMR siting and how data collection overlaps with different stages.

2.1 Siting process and definitions for safety- and non-safety-related criteria, including geological characteristics and geological criteria

Siting criteria form the basis for decision making involving site characteristics and different stages in the siting process. Depending on the number of sites selected for the selection stage, these will be evaluated for their geological characteristics and other criteria, such as safety-related and non-safety related criteria. Three categories of criteria are used to evaluate hazards, events, phenomena, and other aspects after the site has been investigated: siting criteria, screening criteria and specific screening criteria (SSG-35, IAEA 2015).

Screening criteria are divided into two types: exclusion criteria and discretionary criteria.

Exclusion criteria are used to discard sites that have unacceptable features or hazards for which there are no generally practicable engineering solutions. Discretionary criteria are associated with those features or hazards for which protective engineering solutions are available. If these principles were applied with geological suitability criteria, for example, seismic data along with appropriate lithology and rock mechanical characteristics (faulting and fracturing) would be among the first parameters to be evaluated. If the brokenness or weakness of the rock material on site is too high or even moderate, it would be weighed more within the exclusion criteria, where no practical engineering solution is available.

Areas of elevated seismic hazard or risk should be penalized in comparison to more geologically stable sites (SSG-35, IAEA 2015). Seismic data evaluation is further discussed together with associated fault and fracture zones with seismic hazard assessment processes and geological data for the SMR power plant siting process in chapter 4.

Discretionary criteria are used to reduce the number of possible candidate sites if their number is too large to conduct the comparison and ranking. They are also used to increase the number of candidate sites if numbers are too small or non-existent. These processes are iterative, and several sites or areas could be simultaneously evaluated.

The screening criteria and ranking criteria consist of both safety-related and non-safety-related criteria. As geological criteria form a part of the safety criteria, they can therefore be used with the ranking system.

2.2 Safety-related natural hazard criteria related to geological criteria

Geological suitability criteria and related data requirements are included in safety-related criteria. These are determined along with geological investigations during the site survey stage, site selection stage and site characterization stage. They include capable faults, vibratory ground motion due to earthquakes, volcanic hazards, and geotechnical hazards, and they are directly related to geological criteria. Water-related hazards such as flooding (including coastal and river flooding) and heavy rain are included here within geological criteria for topographical reasons, which are indirectly related to the bedrock surface conditions and elevation. Water and volcanological hazards are briefly discussed in the geological data chapter 4 due to them not being particularly applicable in Finnish conditions (volcanological data) and due to the indirect association between specific geological criteria and flooding and water-related hazards.

2.2.1 Definitions for capable faults and seismic hazard assessment processes

Assessing the potentiality of fault displacement is relevant to site selection for a nuclear facility, and fault capability must be evaluated during the siting process. It is suggested here that the seismic hazard assessment process should begin in the earliest site survey stage, and it should be interlinked with all other data collected within the database required for the siting and site evaluation processes.

Several definitions or descriptions for the capable fault concept exist within the IAEA safety guides. A capable fault is defined by the IAEA as follows in IAEA document SSR-1: "*Geological faults larger than a certain size and within a certain distance of the site and that are significant to safety shall be evaluated to identify whether these faults are to be considered capable faults. For capable faults, potential challenges to the safety of the nuclear installation in terms of ground motion and/or fault displacement hazards shall be evaluated*" (SSR-1, IAEA 2019).

Another description of a capable fault is as follows: "*Where reliable evidence shows the existence of a capable fault that has the potential to affect the safety of the nuclear installation, an alternative site shall be considered*" (SSG-35, IAEA 2015).

IAEA document SSG-9 (SSG-9, IAEA 2022) defines a capable fault as follows: "*If the fault shows evidence of past movement (e.g., significant deformations and/or dislocations) within such a period that it is reasonable to conclude that further movements at or near the surface might occur over the lifetime of the site or the nuclear installation, the fault should be considered capable.*"

The potential lifetime of a facility is thus associated with the capable fault definitions, fracture/fault zone characteristics and potential seismicity. Vessel lifetimes for different SMR reactor types have been listed by Krall et al. (2022), with lifetime ranges of 36–60 years for boiling water and pressurized water reactors, 14–70 years for molten salt reactors and ~10–150 years for sodium-cooled fast reactors.

IAEA document SSG-35 (SSG-35, IAEA 2015) defines the safety distance from a capable fault as 8.0 km, with a further definition of this distance fulfilling requirements for exclusionary criteria. Under Finnish geological conditions, regarding nuclear facility siting issues, where areas of bedrock are surrounded and penetrated by fracture and fault zones of variable size and scale, the classification and characterization of the faults and fracture zones into different categories is one very relevant question. Areas with larger scale regional fault zones would most probably or at least partially fulfil the descriptions or exclusionary criteria for capable faults and should be avoided and screened out during the siting process. Smaller scale fault zones would also nevertheless have to be analysed to determine their capability. While the bedrock of Finland can be described as an area of low seismicity (Fülöp et al. 2022, Uski et al. 2003), the potential for larger scale earthquakes up to magnitude (M) 7 is possible in association with larger fault or fracture zones, but magnitudes of this order would fall into the upper boundary, and these magnitudes would be considered to be in connection with glacially induced extreme events (e.g., Ojala et al. 2019, Saari 2012). The level of natural seismicity is low, with no earthquake known to have exceeded a moment magnitude (Mw) of 4.5 in more than three centuries (Ahjos & Uski 1992).

Larger scale fault zones indicate a higher degree of past activation or reactivation, as their size and scale is already a testament to previous movement. If the operational lifetime of an SMR facility falls within the timescale of a few decades, the probabilities of fault activation or any seismic movement and thus related damage within a low seismicity zone such as Finland would most probably remain low in most areas, given that the facility would be sited away from larger zones with reasonable evidence of indicated movement. Seismic hazard analyses assume that geological processes are stationary due to the timescale over which the analysis is needed for a site, i.e., the lifetime of the facility. This timescale is much shorter than the timescale over which the geodynamic changes or seismic activity take place (SSG-9, IAEA 2022).

The operational lifetime of the facility or site defined by IAEA document SSG-9 does affect the siting process. The probability of damage to an SMR plant from fault activation or reactivation is directly related to distances to major fault zones, regional or smaller, depending on the characteristics of a given zone. One way to calibrate the time frame for fault capability would be to evaluate the distance of the site from regional deformation zones, along with the use of longer time frames in less active areas (SSG-9, IAEA 2022). This would include indications of movement in younger geological time scales from the Pleistocene into the Holocene, thus also warranting investigations regarding postglacial faulting.

Evidence of past movements of faults and fracture zones in Finnish geological conditions are related to their age and the general evolution of the bedrock. The age and deformation history of faults and fracture zones during a siting process should be accounted for to a degree when evaluating whether a fault is capable. K–Ar age determinations from Olkiluoto (Mänttäri et al. 2007) indicate ages for fault gouge breccias ranging from 1385 Ma to 550 Ma, suggesting a rough correlation, for example, with the Sveconorwegian orogeny and on to later events. Establishing ages for significant faults or fracture zones would be one tool to assess seismic hazards for a nuclear facility site. While suitable geochronological methods for dating faults exist, appropriate data points such as drill core data or available bedrock exposures or, for instance, road cuts may not be available in all desired investigation locations. Trenching would be one available option to gather detailed structural data on fault or fracture zones during the site survey stage.

Even later events during the Holocene have been documented with attributed seismic data in postglacial faults in Finnish Lapland and at one location in southwestern Finland (Lauhanvuori) (Ojala et al. 2019). These postglacial faults indicate the potential for earthquakes during and after glaciation periods, and related and other seismic data can be used in seismic hazard assessments. They also indicate that it is possible to find postglacial faults and features in southern Finland, where SMR facilities would most probably be located.

Seismic activity of various scales of magnitude has been measured, for example, at Olkiluoto (Saari 2012), further serving as an example of seismic hazard data that can be used in both SMR power plant and repository site selection processes. Other paleoseismological studies would also have to be implemented when necessary (SSG-9, IAEA 2022).

The tectonic history of the site area would be demonstrated with studies mapping the structural geology, which would indicate the deformation age of different faults and fracture zones of the area. If it can be indicated that the brittle deformation history has occurred in past geological times, as inferred by previous geochronological studies, it is reasonably safe to assume that most of the bedrock movement has occurred in past time scales of millions to billions of years (age of the bedrock in Finland). Geochronological data would then be evaluated together with seismic data to evaluate the possible activation capability of a given fault or fracture zone. The safety distance screening value of 8.0 km from a capable fault as an exclusion criterion defined by the IAEA (SSG-35, IAEA 2015) will most likely have to be adapted to suit the needs of SMR plants, as it is currently applied to more conventional NPPs.

Faults and fracture zones generally serve as indicators of past seismic activity and brittle deformation of bedrock, and while Finland’s seismic activity is low, the overall seismic activity of the bedrock is measurable at active seismic monitoring stations countrywide (Veikkolainen et al. 2021), as well as by more focused seismic monitoring networks, e.g., at Olkiluoto (Kuusisto et al. 2021). During the siting process, all relevant historical earthquake data would be collected into a database, with a project earthquake catalogue being compiled (SSG-9, IAEA 2022).

Some of the seismic hazard assessments can initially be addressed by the process of lineament interpretation as part of geological investigations during the siting process, where large to small-scale bedrock structures or fracture zones can be mapped with available LiDAR data. Intact bedrock blocks with limited exposure to large-scale regional fault zones can be thus inferred. These data would then be used in conjunction with seismic data for further interpretation and site selection.

Seismic monitoring programmes would need to be implemented at any SMR plant site for long-term safety considerations. A seismic monitoring network should be installed at the beginning of the site selection stage (siting process, Figs. 2 and 3). High sensitivity seismometers would be used to gather detailed data from the near region, and the design of the seismic data gathering network should be suitable for the geological setting to assess the seismic hazards on site. These new data would also be used to complement previously gathered data on fault capability (SSG-9, IAEA 2022). This seismic network would also need to be operational for the entire lifetime of the facility and should be linked to any existing regional or national seismic networks.

2.2.2 Vibratory ground motion due to earthquakes

As a part of the seismic hazard assessment of a given site, procedures could be implemented to determine a probabilistic approach considering the rate of occurrence of seismic events for all seismic sources with magnitudes between a bounded minimum magnitude and the estimated potential maximum magnitude. An annual frequency of exceedance for different levels of relevant hazard parameters should be estimated to define an appropriate design basis to perform a probabilistic seismic safety assessment with appropriate personnel and work plans. These procedures would also include vibratory ground motion parameter equations (GMPEs), where simulations based on measured seismic data would be performed to provide constraints on the scaling behaviour for magnitudes, distances or rupture planes not well represented in existing databases (SSG-9, IAEA 2022).

However, this probabilistic approach using quantitative statistical methods to model explicit uncertainties may not apply to areas of low seismicity (Finland). Thus, an alternative to probabilistic procedures would be a deterministic approach, where more direct observations, measurements, and calculations for seismogenic structures close to the site area would be performed and their effect on safety criteria evaluated, with the goal of demonstrating the absence of faulting in the site vicinity. If faults are, however, present, these should be characterized based on their direction, extent, history, and rate of movement as being older than the established definition for fault capability (SSG-9, IAEA 2022).

2.2.3 Geotechnical hazards

Geotechnical investigations to assess soil properties or characteristics are standard procedure in most large-scale construction projects in Finland. Geotechnical characteristics and geological features of subsurface materials are investigated with soil and bedrock profiles produced for the site. The variability and uncertainties concerning different soil types must be identified, assessed, and classified (NS-G-3.6, IAEA 2004).

The stability and bearing capacity of foundation materials with considerations of the potential for excessive settlement under static and seismic loading would be estimated. The physical and geochemical properties of soils and groundwater would be investigated using standardized methods (SSR-1, IAEA 2019).

Slope instability can be related to landslides attributed to earthquakes. Higher topography in conjunction with quick clay deposits or similar characteristic soil types in proximity to an SMR facility would increase the probability of such an event. Soil liquefaction in combination with steeper landforms is known to occur and can be attributed to post-glacial faulting and subsequent paleolandslides (Sutinen et al. 2018).

Areas of known flooding associated, for example, with large or small glacial lacustrine and clay deposits having a significant water retention potential should be assessed during site surveys. Quick clay deposits are known to exist in Finland in small occurrences. These conditions could become exclusionary criteria when enough evidence is provided that certain soil conditions can cause safety concerns.

The uplift, subsidence and collapse potential would need to be assessed. These would be generally confined to areas with a known potential for postglacial faulting and areas of thick overburden on top of bedrock. In an urban environment, the subsidence or collapse potential could be attributed to older underground infrastructure, such as old mines and other underground construction (NS-G-3.6, IAEA 2004). Possible permafrost conditions would also be included in geotechnical hazard assessments.

If a site selection is to be carried out in an area of flat topography and directly on top of bedrock or even underground, the aforementioned geotechnical hazards could mostly be avoided.

2.3 Specific screening or ranking criteria considering geological criteria

These criteria, as defined by IAEA, are part of the site safety requirements, along with other requirements such as operational and radiological safety. IAEA document SSG-35 (SSG-35, IAEA 2015) states that the development of ranking criteria is needed to provide reasoning for a better comparison between candidate sites. Geologically stable areas or sites with a lower risk of seismic hazards are ranked higher than areas with poorer geological and seismological conditions. This must be accompanied by the combination factor for seismic events associated with flooding, i.e., a lower flooding hazard does not override seismic hazards, and vice versa.

The ranking criteria system with specific geological characteristics will be further developed as research efforts progress towards preliminary site selection processes. The overall ranking criteria concerning geological criteria require site-specific data points across various scales, and thus the development of detailed ranking criteria is unwarranted at this point in time. Preliminary matrix-based ranking system forms are, however, described for SMR power plant siting processes and SMR SNF repository siting processes in chapters 3 and 6.

2.4 Natural hazard safety-related criteria and other criteria

Safety criteria not directly related to natural hazards or geological safety criteria are listed here but are not discussed further for reasons of brevity. Criteria related to nuclear safety are also not listed here, as these are beyond the scope of this report. The following criteria are derived from IAEA document SSG-35 (SSG-35, IAEA 2015). Natural hazards include but may not be limited to:

- High winds
- Sand and dust storms
- Forest fires
- Credible combinations of events, such as seismic events with flooding, or wind together with snow

Potential impacts of human-induced hazards or events that can affect the safety of a nuclear installation from stationary sources include:

- Other nuclear installations
- Oil and gas operations
- Chemical plants
- Processing of hazardous commercial materials for manufacturing or storing munitions
- Broadcasting and communication networks
- Mining or quarrying operations
- High energy rotating equipment (wind power plants or farms)
- Hydraulic engineering structures (dams, hydroelectric power plants).
  Mobile sources:
- Temporary or permanent military facilities
- Shooting ranges and arsenals
- Surface transportation infrastructure such as railways and roads
- Oil, gas, and other pipelines
- Airport and harbour zones

The possible release of radioactive material from a nuclear installation is included in the safety criteria. The following phenomena should be included in the safety analysis:

- Atmospheric dispersion of radioactive material
- Dispersion of radioactive material in surface water and groundwater
- Population density, population distribution and distance to population centres, including projections for the operating lifetime of the nuclear installation

The implementation of an emergency plan must be demonstrated for a nuclear installation. The following factors must be considered:

- Physical characteristics of the site that would hinder the implementation of the emergency plan (geographical features such as islands, mountains, and rivers)
- Infrastructural characteristics related to local transport and communication options
- Considerations of special populations such as elderly and disabled persons
- Hospital patients and prisoners
- Land and water use considerations
- Specific requirements of the regulatory body for

special zones, such as emergency planning zones and distances
- Industrial facilities that could involve potentially hazardous activities
- Impacts of concurrent external hazards on infrastructure

2.5 Non-safety-related criteria related to geological criteria

These include criteria that are not directly related to nuclear safety but are nonetheless related to geological criteria and are listed in IAEA document SSG-35 (SSG-35, IAEA 2015). These criteria should also be included in the ranking of sites and are comprised of two factors: cooling water and topography. Other listed non-safety-related criteria are access to electrical grids, non-radiological environmental impacts, and socioeconomic impacts.

Cooling water is one relevant issue with SMRs, where it is expected that water-cooled reactors will be the first commercial reactor types to reach the market due to their technological maturity (STUK 2019a). Other reactor types, such as gas-cooled or molten salt reactors, have different cooling configurations and needs. However, this report will not discuss the general water management issues of a given site, since each site will most likely have unique characteristics affecting water management at the site level, if local water resources are to be used in the facility processes. Due to possible climate change-associated issues and related inland water level changes in lakes and rivers, analyses of water level change would be recommended. General recommendations and requirements for water management at SMR sites should be discussed separately due to site-specific conditions.

3 RANKING PROCESS FOR SMR POWER PLANT SITING

The ranking process for site selection criteria from a geological point of view for an SMR nuclear facility should include a ranking protocol with the following geological suitability criteria, specifically considering Finnish geological and related conditions. The following primary geological selection criteria are from Salmi et al. (1985):
- Bedrock block size
- Bedrock topographic conditions and relief
- Faulting
- Fracturing
- Outcrop exposure rate (investigability)

These principles or primary criteria are similar to those used in the selection of repository sites for spent nuclear fuel in Finland, which are described in chapters 5 and 6. These criteria are more noteworthy and have added significance in the SNF repository site selection process. However, the same criteria also apply on a smaller scale, which is necessary due to the potentially smaller surface area requirements for an SMR power plant site and given that similar criteria are applicable to SMR power plant site selection.

It is suggested here that all other geological suitability criteria or geological data are subject to these five criteria. This is due to these issues being the most dominant factors or parameters within the criteria when considering the ranking system. In other words, if one cannot locate a suitable area with a sufficient distance from regional-scale faults, and the area is heavily covered by faulting or fracturing, the area might be immediately discarded, while there would be a sufficient number of outcrops to investigate. Therefore, an adequate combination of these criteria would serve as a starting point for the entire siting process. It must also be noted that these major factors would serve as a starting point for the site survey stage, and unsatisfactory results from these parameters would result in the rejection of a site.

In addition to these geological criteria, other criteria such as city or municipality zone planning issues could become more defining factors in the site selection process. These zoning criteria would then need to be compatible with geological criteria and associated safety criteria, warranting evaluation from appropriate authorities, such as STUK.

Bedrock block size refers to the size of a block within the bedrock delineated and bordered by either large-scale (regional or suitable for adequate boundary conditions within the context) faults or fracture zones or by smaller scale fracture zones. The size of the area should be large enough to fulfil the geological criteria regarding distances from major fault zones or capable faults. An intact regional-scale block would include the investigation area, which is then analysed at different scales with geological, geophysical, and other suitable methods to determine the suitability of the area for an SMR site.

Higher relief or high bedrock topography conditions could provide predictability for higher fracturing and fracture zone conditions, where the probabilities of encountering high fracturing or fracture zones are lower than under low topography conditions, such as in valleys. Small-scale topography must be analysed with large-scale topography, as topographic features with gently sloping bedrock can imply good bedrock constructability or better excavation characteristics. However, fracturing conditions also have a strong correlation with lithology, where, for example, massive textured granitic rocks would behave differently compared to metamorphosed schistose or gneissic rock (Korhonen et al. 1974). Higher bedrock topography can also induce conditions favourable for loose rock formations, such as weathered and unconsolidated rock material.

Faulting would be almost inevitably encountered in any case within a site perimeter/area. The degree of faulting and associated characteristics, such as fault/fracture density, would need to be investigated and fault population data should be documented. Fault relationships should be established, as some faults will be younger than others and their cutting relationships should be evaluated. Age determinations of faults from fault gouges with clay materials could be attempted with K–Ar methods, where available.

Fracturing of the bedrock block would need to be described in detail in the site selection stage at the latest. During the ranking process, fracturing would be evaluated with geological mapping programmes, where fractures would be investigated at the outcrop scale. Measurements of fracture density, aperture, direction, and orientation, among other features, would be performed. Areas of high fracturing would nevertheless be discarded. The overall fracturing characterization of a site would be important, especially in relation to underground construction options.

The outcrop exposure rate refers to the number of outcrops within a site survey area and is related to the investigability of the SMR site. In general terms, a larger number of outcrops will increase the amount of geological data derived from an area and will further establish confidence in the siting process and ranking of different areas. However, given that Finnish terrain is heavily blanketed by glaciogenic sediments, it is not a given fact that a sufficient number of outcrops will be available. False colour satellite imagery, LiDAR-based elevation models and existing general maps can be used to assess the number of bedrock outcroppings for research purposes.

The ranking system using the data described in this chapter should be implemented no later than in the site selection phase, although there might be overlap between the site survey and site selection stages (Figs. 2 and 3). Coherent data should be collected from all potential sites or areas to facilitate justified comparison and site selection. Additions and complementary data will most probably be added to each data set during the process, being iterative in function. All described data, plans, documentation and developed databases, along with the ranking process, would be subject to independent peer review processes to establish a valid scientific basis for the geological suitability criteria for SMR site selection under Finnish conditions.

A full technical report concerning geological suitability containing all relevant analysed data needs to be written and all data should be available for further research purposes. The evaluation and review of the geological suitability criteria and the final selection of the SMR sites will be carried out by the relevant licensing authorities, who will grant the final approval for the siting process.

At this point, with no current SMR related legislation in place, there is, however, a need to initially define or describe the ranking system in some detail. Ranking systems will most certainly be developed further as projects related to siting processes begin in the future. A matrix-based ranking form could be used to assess the characteristics and parameters of different sites (SSG-35, IAEA 2015).

4 GEOLOGICAL DATA NEEDS IN THE SMR PLANT SITING PROCESS

With the required general safety criteria relating to the siting process discussed, further considerations for geological investigations can be assessed. IAEA guidelines (SSG-35, IAEA 2015) call for a database to be developed regarding the site characteristics. This should include data from all the geological criteria listed within the ranking process. Exact details of the database structure or software used will not be discussed in this report, as it focuses more on describing the geological data contents and their requirements.

A comprehensive database including geological, geophysical, geotechnical, and seismological data should be compiled to fully evaluate the seismic hazards associated with earthquakes. Specifically, the evaluation and data collection for seismic hazards should be conducted at four geographical scales starting from the regional scale. These would be followed by investigations at the near regional, site vicinity and site area scale, respectively, with a progressively increasing level of detail towards the smaller scales.

The radius for the site survey would be dependent on the stage of the survey process. IAEA document SSG-35 (SSG-35, IAEA 2015) states a typical general radius of 150-300 kilometres, depending on the seismotectonic setting of the site, site installation type and method of hazard assessment. Given that the site installation type would be an SMR site with possibly different power output levels, the radius of the survey area would have to be more adequately defined to suit the needs of different SMR plant configurations. Preferably, the radius should be such that, as far as possible, the data needs could be satisfied with the data collected within Finnish territory. The seismotectonic setting in different areas of Finland would also influence the site survey radius.

In the site selection stage, investigations would scale towards a 5 km radius (SSG-35, IAEA 2015), with more detailed versions of existing interpretations of seismotectonic fault and fracture zones.

All scales should be presented as maps, models, or geographical information system (GIS) platforms, where data would readily be available and interpretable. This would also enable the production of scale-specific maps and reports using available GIS platforms. This concurs with the recommendations of using GIS systems to document the different processes related to data presentation and acquisition (SSG-9, IAEA 2022).

4.1 Lineament interpretation data

Using modern LiDAR (light detection and ranging) methods, it is possible to collect and analyse detailed ground morphological or geomorphological data. The coverage and quality of this type of remote sensing data has evolved rapidly in recent years, producing higher quality digital elevation models (DEMs), and these data can complement other existing data sets with great accuracy. The lineament interpretation process used in the selection of the spent nuclear fuel repository for SMR waste would also be used as an initial step in the selection of the SMR plant site (Fig. 4).

Lineament interpretation data are discussed here first due to being the controlling factor for the siting process, as the seismic hazard assessment process is highly concerned with larger faults having the highest probability of seismic activity and reactivation. Large-scale bedrock features are distinguishable from LiDAR data with reasonable accuracy, given that a person or persons of sufficient knowledge is performing the process. Elongated linear features in topographical data, such as valley systems, express structural features in bedrock, such as weakness zones, schistose zones, or fracture systems (Korhonen et al. 1974). However, the exact nature of the lineaments should be confirmed in additional studies.

Lineament interpretation is heavily dependent on the effect of the scales used in the process. When investigating linear bedrock features at a given scale, it must be noted that different scales will produce different results. Thus, when changing scales, the interpretation will also change, because the resolution of data is higher at smaller scales and lower at larger scales. It is therefore important that during a lineament interpretation process using a fixed scale, the scale is not to be changed or modified in any way to ensure the integrity of the interpretation. Lineament interpretation data are thus scale-dependent, and when changes are, for example, unintentionally made between scales, data validity is compromised. If one uses a scale

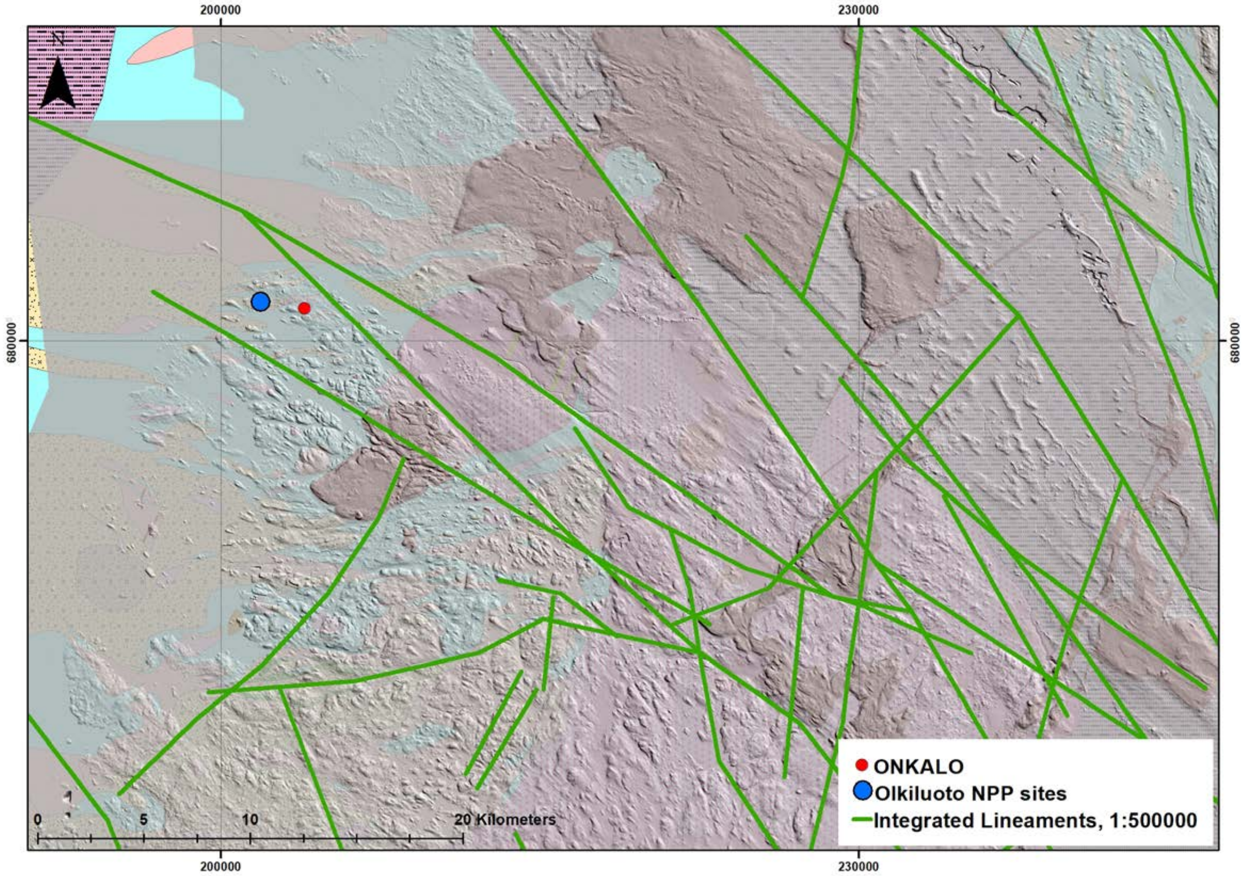


Fig. 4. Map of the Finnish west coast area (scale 1:250 000) with integrated lineaments (1:500 000; Engström et al. 2023), lithological units (Bedrock of Finland - DigiKP) and the ONKALO and Olkiluoto sites. Lithological units are not discussed here due to reasons of brevity. LiDAR data from MML (National Land Survey of Finland).

that is more flexible for various reasons (i.e., variations in scale could be named so that the process reflects the scale changes), data flexibility should be noted in the metadata. Efforts to combine or link indicated and inferred lineaments between scales would be warranted, if necessary.

Figure 4 displays a map covering the Finnish west coast (the Olkiluoto and ONKALO site areas) with lineament interpretations using combined or integrated interpretations of lineament data from GTK (Engström et al. 2023). The integrated lineament interpretation is comprised of interpretations based on a LiDAR DEM and geophysical electromagnetic and magnetic data. Due to the interpretation being scale-dependent, not all lineaments line up with the observed topography. The bedrock topography is also observable, especially near the coast, which is not masked by Quaternary overburden, indicating linear features in the bedrock on a smaller scale. From these types of lineament interpretation maps, it is possible to delineate intact bedrock blocks for further research and study.

Based on these data types, the location, occurrence, dimensions and classifications of fault and fracture zones, i.e., lineaments, can be initially investigated. Statistical analyses of lineament trends can also be performed, and their connection with bedrock deformation phases evaluated with further connections to either ductile deformation or brittle deformation (e.g., Paananen & Kuivamäki 2007, Korhonen et al. 2005).

Due to the smaller surface area requirements with regards to the lower power output from SMRs, the smallest scale for lineament interpretation would need to be much smaller than for conventional NPP site selection and current SNF repository designs. Larger scale lineament interpretation would nevertheless inevitably be a part of the process, due to the requirements for different scales, from regional to local scales, as defined by IAEA document SSG-9 (SSG-9, IAEA 2022).

4.2 Geological and other data at regional, near-regional, site vicinity and site area scales

Geological data regarding the siting process would include general geological characterization at different scales. Lithological determinations would be derived from existing geological maps and further studied at the site scale, where more precise lithological determinations would be needed. Geological maps with lithological descriptions at the scales of 1:1 000 000 and 1:200 000 are readily available from the databases of the Geological Survey of Finland. Chapters 4.3–4.9 include additional information related to data types not directly linked with scale-specific data.

It should also be noted that several data types using larger scales can be found in map formats or data formats from different sources. Data are readily available from the Geological Survey of Finland and the National Land Survey of Finland. New data collection can mostly focus on the site vicinity and site area scales.

The collection of preliminary lithological data would begin in the site survey stage (regional scale), and more detailed geological mapping programmes would be implemented in the site selection stage (site vicinity scale), where more detailed geological mapping data would be collected. More precise geological maps would possibly also be produced, with the scales for these data to be in the order of 1:50 000 to 1:20 000, depending on the research requirements for each survey stage.

Regional scale data would include existing lithology, geomorphology, stratigraphy and fault data to evaluate the general geodynamic setting and current tectonic regime (SSG-9, IAEA 2022). Geological cross-sections and geological maps would be produced, and stratigraphical interpretations of the site area would be studied to assess the general geodynamic and current tectonic regime (SSG-9, IAEA 2022). However, given that regional-scale data are in the order of hundreds of kilometres, it would be beneficial to contemplate the validity and added value of stratigraphical studies and geological cross-sections at this scale, especially under Finnish geological conditions. The resolution of these types of data would most probably remain too low to reach meaningful conclusions. Regional-scale data relating to capable faults, fracture zones or fault displacement would be interlinked with lineament interpretation data.

Regional-scale fault data should include all assumed seismogenic structures that could affect the safety of the nuclear installation, with the extent of few hundred kilometres in radius, or in keeping with the national requirements of the State (SSG-9, IAEA 2022). Lithological data, stratigraphy, geophysical and geomorphological data should also be included. It has to be noted here that different radii for certain scales have been already discussed within this report. Given that no guidelines for exact safety distances have been adequately established for SMR facilities, it is again assumed that these radii will be adjusted to fit the needs of SMRs with different power outputs and nuclear safety requirements. This is supported by the fact that general requirements for the area to be investigated can be decided and defined at the beginning of the seismic hazard assessment project (SSG-9, IAEA 2022).

The occurrence of large-scale regional tectonic structures could be documented using the latest LiDAR data and other lineament data based on geophysical data, such as electromagnetic, magnetic, and integrated lineament data for a regional survey area of a given size. The scale of a few hundred kilometres would be beneficial to assess the largest regional-scale tectonic features. LiDAR data would also provide geomorphological data, which could be combined with lithological data of an appropriate scale. In addition, all available prehistorical and historical earthquake data should be incorporated into the regional-scale model. Regional geophysical data are also available from the databases of the Geological Survey of Finland and should be used to in conjunction with other data.

The near-regional scale would include an area of not less than 25 km in radius from the site boundary. However, this dimension should be adjusted to reflect local geological, morphological, seismotectonic and environmental conditions (SSG-9, IAEA 2022). Geological maps with a scale of 1:50 000 or larger should be used, with different types of data and appropriate cross-sections used. This scale would be appropriate to include a more detailed lineament interpretation study, together with the fact that a radius of 25 km would enable the incorporation of possible large-scale lineaments and bedrock features at this scale from the regional scale. This would enable intact bedrock blocks bounded by larger-scale bedrock features to be inferred. Digital elevation models based on LiDAR data would be produced at this scale.

Investigations of Quaternary geological landforms would be performed at this scale using remote sensing techniques such as aerial and satellite photos and LiDAR methods. The focus would be on soil types, their geotechnical properties, the thickness of the overburden and groundwater conditions. Existing stratigraphical studies with geochronological methods would be used, with subsurface data from existing boreholes and geophysical data based on seismic reflection and/or refraction profiles and gravimetric, electric, and magnetic tomography techniques. This would increase the possibilities to characterize identified seismogenic structures within this scale. Hydrogeological investigations, including measurements from existing boreholes, would be conducted. Paleoseismic investigations with trenching would be performed as needed, based on the analysis methods stated above.

Investigations at the site vicinity scale would be performed within an area of not less than 5 km in radius from the site boundary. Detailed field geology mapping programmes would collect more detailed information on lithology and fault and fracture zones. Structural geological investigations would focus on mapped faults and fracture zones, with parameters such as the strike and dip, fault plane lineation, indications of dextrality or sinistrality, fault or fracture zone dimensions, and all related detailed structural geological data that indicate movement within a fault zone, including age determinations in all identified seismogenic structures where these are feasible. Fracture zone classifications would also be relevant data at the site vicinity scale. Geological mapping with lithological cross-sections would be performed at the site vicinity scale. This could be designed in conjunction with drilling programmes planned in the site vicinity, if feasible.

The site area scale is the most detailed scale of investigation within the scale-dependent data collection process, with further additional investigations (some overlapping with previous scales) regarding geological, Quaternary geological, geophysical, geotechnical, environmental, and seismological studies. The primary objectives for the site area investigations would include the confirmation of features relevant to siting: the potential for earthquakes or ground displacement of any kind, and information about the static and dynamic properties of rock and soil material in terms of constructability and safety (SSG-35, IAEA 2019). Stratigraphical studies concerning bedrock stratigraphy and Quaternary geology would continue at the site area scale, applying subsurface information collected from drilling campaigns.

Diamond drilling would be performed to collect detailed lithological, rock mechanical and geochemical data and structural geological data. Drilling could commence at the site vicinity scale in some cases to extend the level of detail in lithological data and geochemical determinations, but it is more likely and more economical to focus drilling on the site area scale. Another option is to use available historical drill core and core logging data within the site vicinity scale, if available from the Geological Survey of Finland.

Drillholes or boreholes would also be used to collect geophysical, hydrogeochemical and hydrogeological data. The drilling of a sufficient number of boreholes would validate the geological data needed in further technical reporting. At this stage, a preliminary lithological 3D model based on drilling data would also be produced, and this model would be further developed at the site area investigation scale. In addition, preliminary hydrogeological models would be constructed.

Drillholes or boreholes at the site scale would be used for various research purposes. Optical and acoustic borehole imaging techniques (OBI/ABI) would produce more detailed fracture density and fracture orientation data for use in fracture characterization processes within the site. Data on drillhole fracture density would be correlated with fracture zone characterization data from drill cores. These would then be used in conjunction with geophysical survey data to evaluate the dimensions of fracture and fault zones at the site scale.

The site area scale would include fracture zone classifications with more detailed descriptions. Preferably, the fracture zone classification (Korhonen et al. 1974, Gardemeister et al. 1976) developed for Finnish bedrock conditions (Finnish Engineering Geological Rock Classification; used widely in the Finnish mining and infrastructure industries) should be used to ensure data compatibility with previous work in mining and bedrock construction projects in Finland. General observations of fracturing should be made at this scale of investigation.

Dynamic properties or parameters regarding rock quality would most likely consist of rock mechanical parameters such as RQD (Deere 1963) and Q classifications from drill cores (Barton et al. 1974). Other rock mechanical parameter testing, such as uniaxial compression strength and triaxial compression tests, would be performed on drill cores to provide evidence of rock characteristics. Other measured static and dynamic properties for drill core samples could be Poisson's ratio, Young's modulus, shear modulus, density, and shear strength for use in engineering models. Seismic *in situ* (drillhole) and laboratory measurement (drill core) parameters might include P and S wave velocities (SSG-9, IAEA 2022). Rock mechanical parameters would be essential data in the design of underground constructions for SMR power plant sites.

Soil profile testing would be performed to ensure that enough evidence regarding Quaternary deposits is gathered, with grain-size distribution analysis performed at the site area scale. Quaternary geological models would also enable better engineering models or 3D models, which are required in many current construction projects, with the same principle also applying to bedrock engineering geological models and 3D models. Knowledge of the soil cover is particularly important if the SMR construction cannot be based on a bedrock foundation. Hydrogeological investigations in boreholes and other techniques should be used to determine geometric, physical, and chemical properties, along with measurements of the water table depth, recharge rate and transmissivity (SSG-35, IAEA 2019).

Table 1 lists the currently suggested scales to be used in data collection and analysis for a given nuclear facility site. While these are not specific to SMR siting processes, they are reasonably accurate at this stage due to differing SMR power outputs and site space or area requirements. For example, an SMR facility used for district heating purposes and having a power output of 10 MW would represent a lower percentile of the total power outputs of possible SRM plant sizes, and a facility of 300 MW would represent a higher percentile of power output and size. Both represented percentiles and all actualized or executed plant sizes in between would have to meet seismic hazard assessment criteria and safety criteria regarding geological and other criteria.

Table 1. Compilation of investigation scales and associated geological data. Note that given scales are not specific for SMRs, but for nuclear facilities in general. Scales indicated with * are based on IAEA requirements, while others are examples of possibly usable scales.

Type of scale	Regional scale	Near-regional scale	Site vicinity scale	Site area scale
Investigation area radius (km)	150–300 (a few hundred km)*	25*	5*	< 1*
Scale of investigation	1:500 000	1:50 000	1:5000	1:500
Investigation type and focus	Regional seismic hazard, regional structural interpretation (lineaments), lithology	Detailed lineament study, DEMs	Drill core data, structural geology measurements	Detailed geological, geotechnical, hydrogeological, and structural investigations, fracture zone classifications
Lineament interpretation scale	1:500 000	1:200 000	1:20 000	N/A or possibly adjustable
Scale of lithological maps	1:1 000 000 to 1:200 000	1:100 000	1:20 000	1:5000

4.3 Geotechnical data

Geotechnical data should be represented in the database with Quaternary geological maps from regional to site scales. The data would include geotechnical drilling data and mapping data, with accompanying interpretations of the influence of Quaternary deposits on possible safety issues, such as potential postglacial faults, soil liquefaction and subsidence. The influence of possible weathered rock should be estimated from surface drilling data. Weathered bedrock (saprock) can be encountered under Finnish bedrock conditions in conjunction with, for example, fracture zones with hydrothermal alteration (e.g., Hall et al. 2015). High-grade bedrock weathering patterns may also be encountered in granitic areas in central Finland and Ostrobothnia, and in rapakivi areas in southeastern Finland (Korhonen et al. 1974).

Geotechnical data collected at various scales would include geotechnical parameters from soil drillings and testings. These need to be analysed for different purposes, such as hydrogeological properties, groundwater flow and quality near the site and in the site area, and for possible radionuclide migration assessments. Parameters would include grain-size distribution graphs and other technical parameters derived from soil drilling data.

4.4 Geophysical data

Examples of geophysical data would include existing regional (airborne) and more local (field survey) data, e.g., magnetic, electromagnetic and gravity data. These would be used to enhance interpretations of geological data and structural geological data, for example, relating to capable faults and fault displacement. They should be used in conjunction with more specific methods, such as geophysical drillhole or borehole measurements. Examples of drillhole measurement data used in bedrock characterization of spent nuclear fuel repository research or site research include several methods. Electrical methods, such as mise-a-la-masse methods (charge potential), can be used to assess the characteristics of faulting and fracturing in bedrock (Paananen 1997). Geophysical drillhole measurements beneficial for investigations at the site area scale would also include density, magnetic susceptibility, and electrical resistivity methods. Ground penetrating radar data would be useful for characterizing fractures at the site area scale.

4.5 Hydrogeological data

Hydrogeological and hydrogeochemical data would first be collected from existing sources and literature, with further studies incorporating the influence of Quaternary deposits on local hydrogeological and groundwater chemical characteristics. Hydrogeological and hydrogeochemical data would also be extended to data derived from bedrock, with water flow measurements from existing and future drillholes to establish, for example, the water table depth and hydrogeological zones within measured water flow in bedrock. Hydrogeological maps from national and local archives would be used to assess the hydrogeological conditions in each site survey area. Under Finnish conditions with different glacially derived soil deposit types, Quaternary geological investigations would be performed to assess the influence of Quaternary deposits on, for example, groundwater characteristics, the water flow rate, and other parameters.

4.6 Seismological data

Seismological data would be collected and analysed by existing literature and seismological data, available from the Institute of Seismology in Finland. Existing earthquake point data would be combined with data from lineament interpretation at different scales to identify possible seismic zones attributed with mapped lineaments, faults, and fracture zones.

Seismic source models based on coherent integration of geological, geophysical, geotechnical and, for example, geomorphological data such as LiDAR data should be developed, and seismic hazards based on these models should be assessed. Previously defined seismic zones (e.g., Saari 2012, Fülöp et al. 2022) should be incorporated into any seismic source model analyses.

Diffuse seismicity, which usually consists of small to moderate earthquakes and is defined as not attributable to specific seismogenic structures, should also be assessed. Within the seismic hazard process, diffuse seismicity represents a complex problem and presents greater uncertainty due to the fact that earthquakes attributed to their causative faults are not well understood (SSG-9, IAEA 2022).

The isostatic uplift potential, especially in SMR site surveys in Finnish coastal areas, should be included in seismic analysis.

4.7 Volcanological data

Volcanic hazards are not a direct natural hazard under Finnish geological conditions. However, indirect threats can be identified in the form of volcanic ash clouds and related tephra deposition originating from volcanic eruptions of a sufficient size in the European continental area and elsewhere.

4.8 Flooding data

Hazards involving flooding-related phenomena would have to be assessed, with natural and human induced events, including their possible combinations. The potential for extreme precipitation or heavy rain models, along with meteorological, hydrological, and related models, should be developed for the site to assess flooding hazards. Other natural causes, such as storm surges, wind-generated waves, and possible tsunamis, should be accounted for in the analysis. Instability analysis for sites in coastal areas or river channels concerning sedimentation should be investigated.

Tsunami hazard analyses should include using historical records regarding pre-historic floods, with the potential for phenomena related to other than seismic sources, such as submarine landslides. Data sets for tsunami hazard assessment should use nearshore bathymetric data and coastal topographic data. Upstream water control structures, such as dams, should be analysed for potential dam failures in combination with flooding from other causes (SSR-1, IAEA 2019). Data on coastal flooding and river flooding would include water-level data from existing sources and the literature, in addition to available tidal data.

4.9 Meteorological data

Meteorological data, including wind speed, precipitation, snow and ice, air and water temperature, humidity, storm surges, lightning, sand, or dust storms, as well as their credible combinations, would be evaluated for extreme values based on available data and records (SSR-1, IAEA 2019). Current information is available at the Finnish Meteorological Institute (Ilmatieteen laitos). Incorporating historical meteorological and weather data with numerical models and simulations would also be relevant for the database, if necessary. Snow and ice conditions should include avalanche conditions. While avalanches do occur in Finland under conditions where enough snow accumulation has taken place, known occurrences are generally confined to the high fell areas of northern Finland. If an SMR reactor plant does use local water resources, for instance, for cooling purposes, possible droughts and related meteorological phenomena should be included in meteorological data analysis. Climate change-related issues would also be relevant in flooding and meteorological data analyses.

5 SITING OF THE SMR SPENT NUCLEAR FUEL REPOSITORY

5.1 Status and history of geological disposal research in Finland

During past decades, with rigorous research and development efforts, site selection processes for spent nuclear fuel in Finland have become well established, with modern technology giving faster and cost-effective opportunities for collecting high-resolution and -quality data for research and decision-making. Geological suitability criteria for the SNF facility in ONKALO are well known, and this expertise can be applied to establish the basis for the siting and waste management requirements for SMR technologies.

The process that resulted in the selection of Olkiluoto as the site for the final disposal repository began with systematic studies in the late 1970s. During site identification and the screening process, several hundreds of areas in Finland were studied with varying degrees of accuracy to assess the geological suitability of a specific site. This resulted in the selection of targeted areas, which included stable blocks in the bedrock bounded by large-scale fracture zones. The block area for the site was considered large enough to host a repository and represented an area where most of the research and development would occur (McEwen & Äikäs 2000, Paulamäki et al. 2011).

ONKALO, situated in Olkiluoto, Eurajoki, will house the spent nuclear fuel from the reactors of TVO (Teollisuuden Voima) and Fortum, situated in Olkiluoto and Hästholmen, Loviisa. The spent fuel rods will be contained in copper canisters and deposited in geological formations in an engineered multi-barrier system, with bedrock serving as the geological barrier, providing stable conditions for the repository, and protecting the environment from radionuclide contamination.

During the long history of research and development of nuclear waste management (NWM) and the selection of Olkiluoto as the final disposal site, several other sites were also investigated in detail. All sites selected for the preliminary site investigations have specific geological qualities and span from older Archean basement rocks (Romuvaara and Veitsivaara) to younger Svecofennian island arc rocks (Olkiluoto, Kivetty and Syyry) and younger batholithic rocks (Hästholmen). This approach allowed the comparison of bedrock environments differing in geological evolutionary history. During detailed site investigations at the Olkiluoto, Kivetty, Romuvaara and Hästholmen sites, studies continued at the site area scale on geological, rock mechanical, hydrogeological and geophysical characteristics for bedrock constructability (Äikäs et al. 1999a,b,c,d, Paulamäki et al. 2011). After the selection of Olkiluoto as the site of final disposal, confirmation investigations were launched. The data density and the amount of research for Olkiluoto are naturally the most comprehensive, and the continuous research at Olkiluoto serves as an example of the data quality and quantity that a selected repository site should include in the long term.

Considerable regional and site-scale data from the previous siting programme still exist and are valid for future use. For example, data and/or reports on geological, hydrogeological, and geophysical investigations, and the drillholes and drill cores are available. Naturally, new methods may allow more specific and higher resolution studies, but the basic characterization information provides a sound basis for continued activities. However, revisiting of the screening process is required, for instance, due to the expansion of population centres, nature preservation areas and other development in land use practices in the last 40 years.

5.2 Site selection process for an SMR-based SNF repository

The Radiation Safety Authority (STUK) defines the general guidelines and safety requirements for the final disposal facility with the document YVL D.5 (STUK 2018). In this document, it is defined that the chosen location of an SNF disposal site, at its final deposition depth, should have *large and intact bedrock blocks* that are favourable for the deposition of the final disposal spaces and placement of SNF (Fig. 6). While the document is related to SNF from conventional NPPs, the document can serve as a general guideline for nuclear installations, allowing credence for use in these preliminary concepts for SMR-related issues.

It is not a given fact that ONKALO would be able to house the future waste products from SMR plants, and the waste management topic in general requires more research on all aspects, as at this point, research regarding SMR waste and waste disposal is limited. Some geological requirements for SMR-based waste could prove to be different compared to conventional waste from conventional NPPs. These differences could include the final or appropriate depth for the repository, the volume of rock required for the waste amount, and the required parameters for engineered barrier systems to manage possibly different waste types and restrict nuclide migration. Mirroring the amount of research that has been performed in ONKALO, SMR-based waste repositories will require significant research efforts that will advance in conjunction with the current situation with legislation processes and related issues.

Options for deep geological disposal sites or repository sites for SMR-based waste stream facilities will most likely include evaluation between a centralized option vs. a decentralized option. These comparisons are necessary to determine the effects of such a decision that will have effects on a long timescale. These comparisons are briefly addressed in a separate chapter (chapter 8) but require more specific research. Other factors than geological factors may be more decisive in the final selection processes, such as proximity to population centres and other economic and social factors.

Similar processes to the siting process of SMR power plants would also be used in siting processes for SMR spent nuclear repository sites. However, there are notable differences in the process with regard to site size and characteristics due to the significantly longer lifetime of a repository. The data extent rises with the level of detail in geological investigations towards the site characterization stage (Fig. 5). The depth and dimensions of the host rock must be larger, and the volume is calculated or estimated on the basis of waste amounts. The predictability of the geological conditions affecting the resiliency and long-term safety of the repository in the future demands more detailed studies from a new perspective.

Initial area survey stages would assess regions of interest with different criteria related to geological and other data. Screening and ranking of these areas of interest would be performed at the regional scale, and more potential sites would be more thoroughly investigated with more site-scale geology-related data. After sufficient analysis, one or more potential sites would be selected for more detailed studies during a site investigation stage (SSG-14, IAEA 2019).

The primary goal for a geological nuclear waste repository is to provide passive safety over very long periods of time, in the order of thousands of years and longer, with passive safety based on the characteristics of the geological formation. Moreover, the host rock geology will serve as a natural barrier along with engineered barriers, significantly reducing the influence of climatic and surface processes (SSG-14, IAEA 2019). The requirements for a geological repository in terms of geological suitability differ significantly from a power plant when considering specific details.

Other notable requirements set by YVL D.5 (STUK 2018) include the stability and denseness of the bedrock, a low groundwater flow rate, favourable groundwater chemistry, the retardation of radioactive materials in bedrock and protection from natural phenomena and human activity. Discretionary criteria include economic mineral deposits and other natural resources, large rock stress fields when compared to rock strength, exceptionally large seismic or tectonic activity, exceptionally hazardous groundwater characteristics, such as a lack of redox potential and large concentrations of elements, which can weaken long-term safety features.

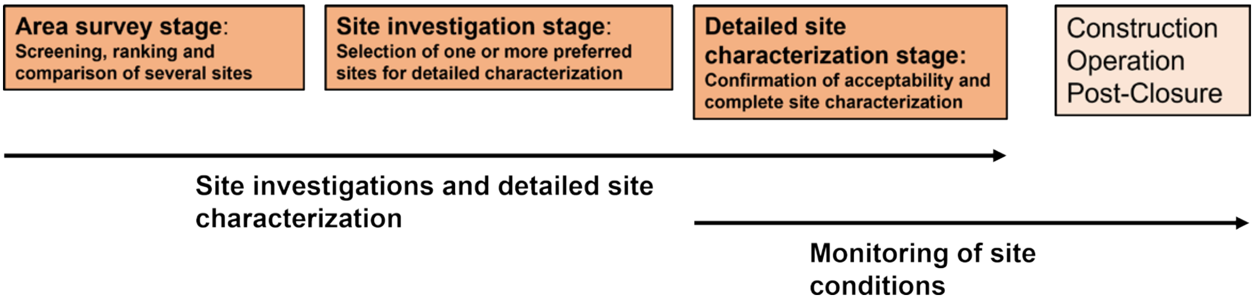


Fig. 5. The timeline for developing a spent nuclear fuel repository for waste from conventional NPPs. Modified from SSG-14, IAEA 2019.

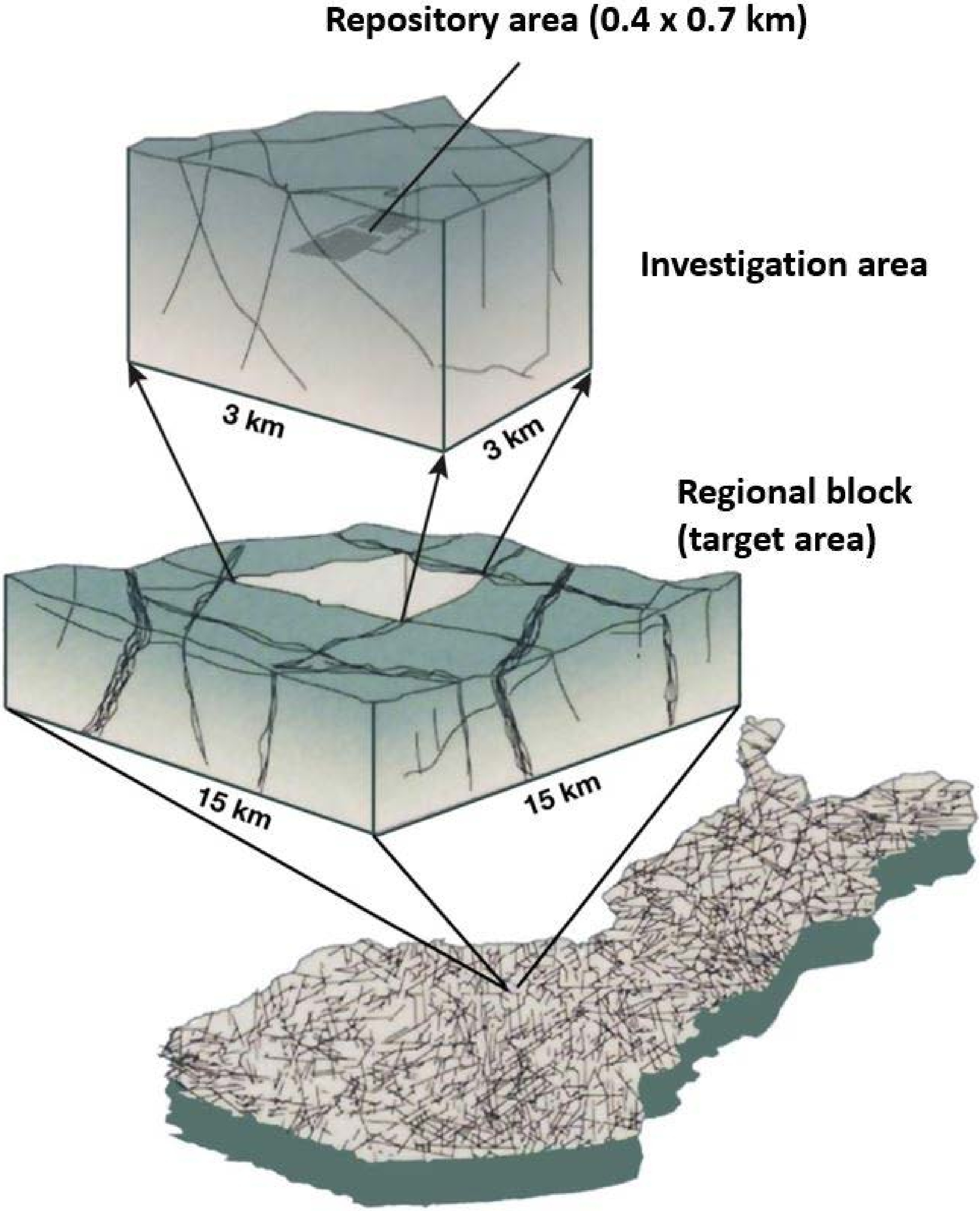


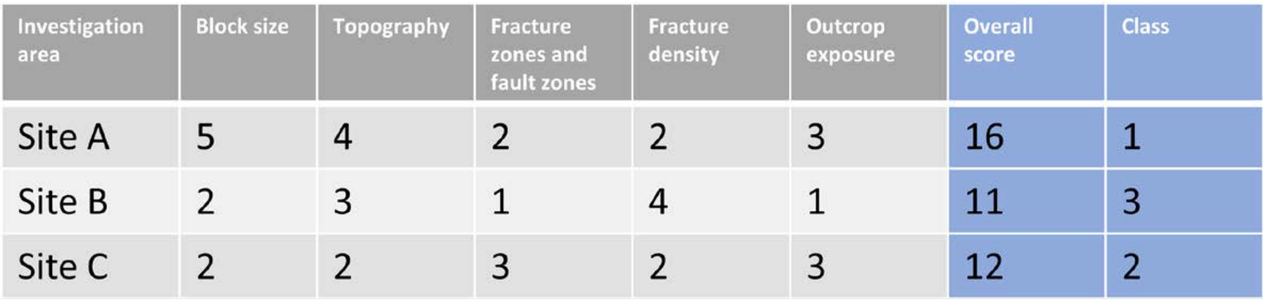
Fig. 6. Site selection principle with regional bedrock blocks delineated by major regional fracture zones and size examples of different concept areas. Modified from McEwen & Äikäs 2000.

6 RANKING PROCESS FOR SMR SNF REPOSITORIES

A site selection process following the ranking system allows point totals to be determined for each category. A suggested ranking system could use the following guidelines, based on geological suitability categories provided by GTK (Salmi et al. 1985):

- Bedrock block size, where larger blocks receive a higher score.
- Topographical conditions and the relief of the site: areas with subdued or lesser relief receive higher scores due to potentially more favourable rock stress conditions and a lower hydraulic gradient.
- Faulting: intact blocks are preferred, as intensive faulting and fracturing is seen as a negative feature, with possible exclusionary procedures.
- Fracturing: as with faulting, too much fracturing is viewed as a negative feature.
- Outcrop exposure rate: a good number of surface outcrops or well-exposed areas is preferred.

After initially estimating the suitability of each surveyed area as suggested above, investigation areas could be divided into classes, with appropriate ranking given to investigation areas having higher point totals. This would be carried out using a matrix-based ranking form, with each geological criterion given a range of values, including verbal definitions for the different criteria. Each of the evaluated criteria, along with their verbal and numerical definitions, would need to be evaluated for their usefulness. Different criteria should also be compared and added and rejected if deemed necessary. Weighting factors can be used to increase the relative importance of some criteria over less critical features. Unsuitable areas with lower point totals would be processed iteratively and rejected if necessary. This type of matrix-based system would require development to fully evaluate its functionality (Fig. 7).



Investigation area	Block size	Topography	Fracture zones and fault zones	Fracture density	Outcrop exposure	Overall score	Class
Site A	5	4	2	2	3	16	1
Site B	2	3	1	4	1	11	3
Site C	2	2	3	2	3	12	2

Fig. 7. An example of a matrix-based ranking form with geological criteria and descriptive point totals for fictional sites.

- **Class 1**: **<u>Primary sites</u>** with well-exposed areas allowing detailed geological observations, with the site fulfilling the geological criteria. Areas for which there is a high level of confidence.
- **Class 2**: Secondary sites with less well-exposed areas but lacking clear negative features. Geological characterization is less reliable than in Class 1.
- **Class 3**: Recommended with reservations. Weakly exposed or small areas or some criteria are not wholly satisfied.
- **Class 4**: Rejected sites. Fail to satisfy the structural criteria.

It must be noted that geological criteria are not the only possible criteria classifications affecting the site selection process. Population issues, protected areas, land use and ownership, transportation routes, groundwater resources and other issues relevant to repository site selection would also be relevant criteria for similar kinds of classification schemes (McEwen & Äikäs 2000). This type of iterative ranking process is generally subject to inevitable constant changes during a site selection process.

7 GEOLOGICAL SUITABILITY CRITERIA FOR SMR SNF REPOSITORIES, DATA NEEDS AND INVESTIGATIONS

Bedrock characteristics or geological suitability criteria for a spent nuclear fuel repository must fulfil the requirements set by the IAEA and STUK. IAEA requirements are stated, for example, in IAEA document SSG-14 (2011). It should be noted that while the following geological criteria are suitable for waste streams from conventional reactors, they can be used to discern suitability for SMR-based waste streams. The criteria are comprised of several data sets discussed in the following subchapters. The following data sets are not necessarily a complete list of data requirements for an SMR repository but are nevertheless based on previous research concerning conventional waste forms from NPPs.

Final determinations for SMR-based waste repositories concerning geological suitability criteria will also depend on the characteristics of the waste products and calculated or simulated nuclide inventories will affect the final safety requirements.

The following geological criteria and geological data are focused more on the detailed site characterization phase of a spent nuclear fuel repository for conventional reactor-based waste. This is due to the wider data extent closer to the final phase of site selection than in earlier site selection stages. However, most of the geological data sets can overlap with previous stages. In addition, the issue with scale-dependent data is more pronounced with some data sets than others.

Similar data types are used in SMR power plant siting issues, and the following data sets and geological criteria are more focused on requirements previously used in Finland in SNF site selection processes and SNF site characterization and are mostly also applicable for SMR-based waste repository investigations. Due to the similarities in data types between SMR power plant siting and SMR repository siting, it is not essential to list all the possible data types in a similar fashion to the previous chapters discussing SMR power plant siting. This is because certain data have more significance regarding repository siting than power plant siting. Moreover, investigations with certain types of methods would be performed regardless of their distinct significance. These investigation methods would include, for example, geophysical methods. In addition, certain data types, such as topographic data from LiDAR and contour maps, can be used intermittently between and across stages and scales.

These criteria can be investigated even if the general surface area requirements for an SMR power plant are smaller than for conventional NPPs. The exact investigation scale related to the geological criteria can be modified without greatly compromising the international and national requirements for nuclear facility site selection.

7.1 Lineament interpretation data

Site selection processes from a geological point of view would begin with regional-scale lithology identification, together with regional-scale lineament interpretation. Suitable lithological domains with identifiable bedrock blocks delineated by large-scale geological structures would be identified and areas selected for further investigation (Fig. 6).

Lineament interpretation data are used across different scales in the site selection process. In recent years, GTK has performed lineament interpretation based on electromagnetic, magnetic and LiDAR data at a scale of 1:500 000 for the entire country. Additional interpretation has also been conducted in certain areas with a scale of 1:200 000. The use of scales in lineament interpretation is an important process to delineate and determine the prevailing bedrock conditions in a given area. These data can be used for the preliminary assessment of bedrock blocks free of large-scale bedrock structural features. By defining the bedrock blocks bordered or delineated by major regional faults or fracture zones, the individual bedrock blocks can then be further evaluated for geological suitability criteria (Figs. 8 and 9).

Further lineament interpretation and analysis should be performed at a site-specific scale. The scale will vary along with the total area or space requirements for a specific site, but smaller scales such as 1:100 000, 1:50 000 and 1:10 000 could be beneficial. Modern LiDAR geomorphological data would be the most useful tool for smaller scale lineament interpretation studies, but also with regional scale investigations.

The lineament interpretation data would be used with heavy emphasis on lithological data to assess the host rock suitability. For site selection purposes, lineaments can be classified into the following classes, according to McEwen & Äikäs (2000) (Fig. 9):

- Class I: The width of the lineament is approximately 1 km, and the corresponding length of the zone is dozens or hundreds of kilometres.
- Class II: The width of the lineament is hundreds of metres. The length of the zone varies from 5 km to dozens of kilometres. These zones often border a bedrock block chosen as a "target area" (size approximately 100–200 km^2).
- Class III: Crushed (or Crush) lineaments inside the above-mentioned "target area", with a width from dozens of metres to a hundred metres. Commonly border an "investigation area", which is a block more intact than the surrounding area (size approximately 5–10 km^2).
- Class IV: Fractures and fracture lineaments inside an investigation area, the number of which needs to be small.

These different types of classifications are useful at a larger scale in these types of site selection scenarios. When proceeding to a smaller scale or investigation area scale (site area scale), one could use the Finnish Engineering Classification Rock classification system for classifying Class IV-type lineaments. A Class I-type lineament could be classified as a regional-scale lineament based on its dimensions, but more detailed methods, such as statistical distribution or scaling law methods, would be required for such classification needs.

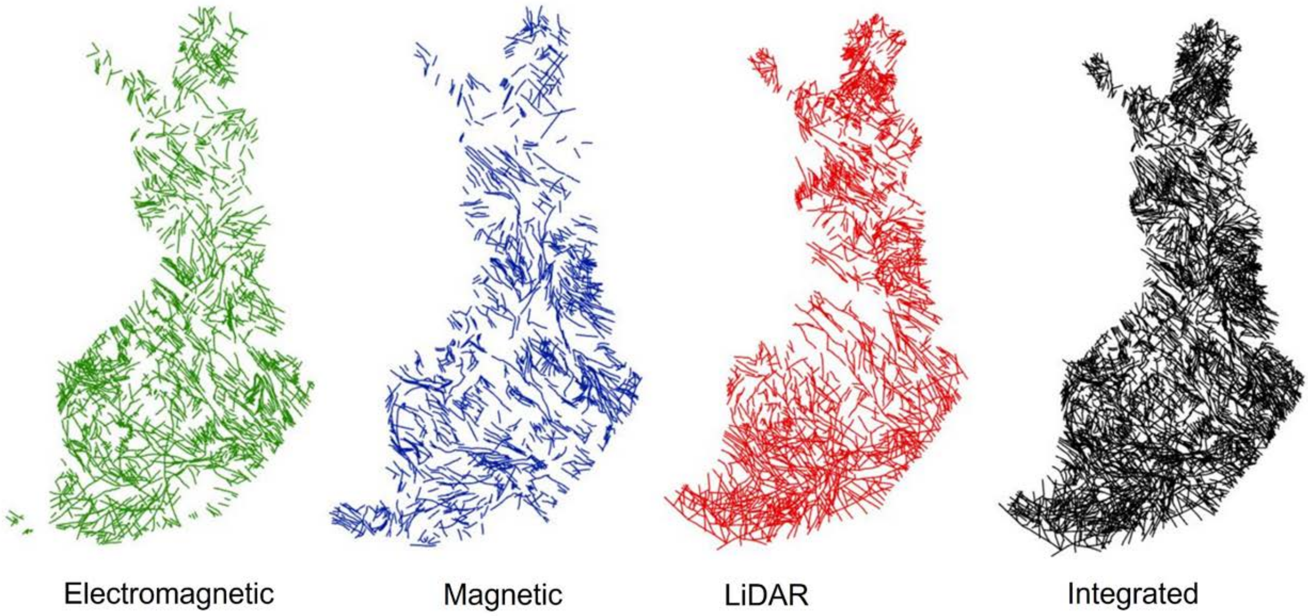


Fig. 8. Updated lineament interpretation data for Finland with different data source types. Scale 1:500 000, data from GTK (Engström et al. 2023).

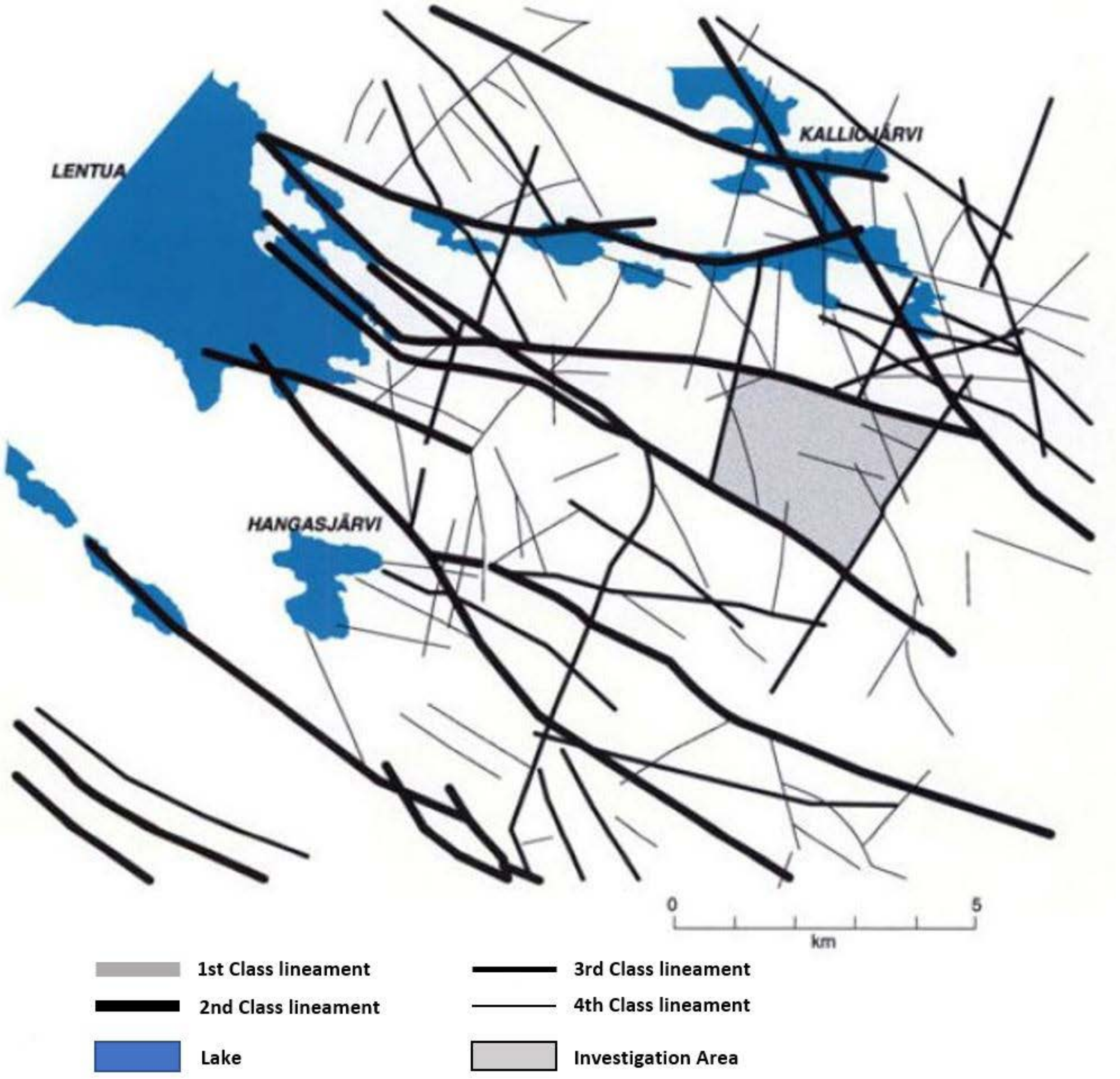


Fig. 9. Fracture zones at the Romuvaara site displaying the concept of fracture zone classification, depending on their dimensions. Modified from McEwen & Äikäs 2000.

7.2 Exclusion of areas with mineral exploration potential

Mineral exploration potential can be viewed as an exclusionary criterion when considering site suitability for SNF repositories. The exclusion of these areas is necessary so that future utilization of natural resources would not be compromised, and the risk of unintentional human intrusion into the repository in the future could be reduced. This includes metallic mineral and industrial mineral deposits. Known mineral deposits, occurrences, and mineralized boulder data in relation to the investigation areas should be documented in the earliest possible investigation stage. Identification of metallogenic areas or zones should also be included in the analysis. All related data can be found via GTK.

Basic or mafic rocks (e.g., gabbros and peridotites) were not included in the previous repository selection processes due to often being associated with ore-forming minerals (mineral potential), and thus with a human intrusion risk. Mafic rocks also tend to be less extensive areally and therefore make the investigation more difficult (McEwen & Äikäs 2000).

7.3 Geological unit size and host rock investigability

The sufficient size of the geological host rock unit for the repository must preliminarily be established prior the area survey stage. As seen in Figure 6, an example size for a conceptual final investigation site in a given area would be in the range of ca. 3 x 3 km (9 km^2, or a range of 5-10 km^2), with the final size of the idealized repository being smaller than this (0.4 x 0.7 km) (McEwen & Äikäs 2000). In the case of SMR waste repositories, the final geological unit size would also depend on the projected waste amounts, and while the aforementioned example size for SMR SNF repositories could be considered conservative, this size could serve as a possible starting point for further evaluation of the appropriate size for the host rock complex.

The feasibility of possible expansion of the site should also be accounted for in the decision-making processes. This could be due to extending the reactor life cycle of existing facilities and the construction of more reactors (McEwen & Äikäs 2000). This would be essential in SMR-related scenarios, where the modularity of the reactors would possibly allow the expansion of production in SMR power plant facilities. The waste centralization strategy, discussed further in Chapter 8, would have effects on the geological host rock unit size. Possibly larger investigation areas would have to be the goal of site characterization stages to ensure maximum flexibility of the repository design to accommodate HLW (high-level waste).

Geological and lithological homogeneity would serve as a positive ranking criterion for the host rock complex. Similar lithological units would increase the predictability of bedrock characteristics and behaviour in considering the required lifetime of the repository. A sufficient number of available outcrops for geological investigations would also be a positive geological criterion. Outcrop data (e.g., lithology, structural geology data), their quality and availability can already provide enough information to affect the selection process positively or negatively.

7.4 Lithological data

Data on rock types or lithological data on the host rock complex would serve as an important feature for the SMR repository design and construction activities. Building a safety case around an SNF repository would need reliable lithological determinations, with additional measured mineralogical and geochemical data (Chapter 7.5).

The goal of a geological model is to represent the spatial distribution of texturally and structurally fixed and genetically related bedrock units, which from the perspective of underground construction and long-term safety would have sufficiently constant properties (Aaltonen et al. 2016).

The definition of lithological units within an SMR repository would begin in the earliest stages, with the lithology first being defined in desktop studies. Depending on the scale at which the individual rock unit would be examined, variations in mineralogical and chemical classifications, especially with intrusive igneous rocks within the host rock complex, would be expected. Thus, scale-related issues are of relevance, and site-scale modelling would concentrate in creating lithological units based on their geochemical composition, geological continuity, geological genesis, texture (degree of foliation), grain size, degree of weathering and other properties, such as metamorphic grade (if applicable). In a site-scale modelling process in which for example, metamorphic rocks such as gneisses would be modelled and classified into lithological units, the principle of the prevailing or dominating rock type should be applied. This type of iterative process of defining lithological units requires data from the drill core scale to the surface model scale, and these scales would be integrated to achieve the appropriate level of detail for a site-scale lithological model.

Lithological data can be best preserved and presented with 3D modelling software having appropriate geodatabase links, and geological modelling of the repository host rock would use all available data, such as topographic data, fault and fracture zone data, lithological data from geological maps and drill core lithological data.

Geochronological data for each rock type within a site survey area would be advantageous, especially if the site survey area contains different types of cutting rocks, such as diabases or pegmatitic dyke rocks. The age relationships of these types of rocks would be evaluated against other host rock types.

7.5 Geochemical data

The role of geochemical data in the site selection process, especially in site characterization stages, will become dominant, as lithogeochemistry is a tool to demonstrate the suitability of a site regarding, for example, the host rock nuclide retention capacity and other geochemical properties, such as hydrogeochemical properties. The host rock type should also be able to provide, maintain or recover reducing geochemical conditions under changing hydrogeological events. Reducing or anoxic conditions serve as an important design feature for engineered barrier systems in a repository (ONKALO) (Tuomi et al. 2020). Similar chemical design features at this point would also apply for SMR-based waste repository designs, or at least should be considered relevant.

Lithological determinations (rock type determinations) require precise methods to classify the host rock lithologies into their respective rock types. Petrographic data using thin sections would be essential to provide mineralogical evidence and further details for lithological determinations. Petrography with detailed mineralogical data would also provide information about the sorption properties of the host rock. The geochemical retention or retardation processes that dictate the consequent rate and quantity of radionuclide migration include diffusion, precipitation, sorption, ion exchange and chemical interaction processes, and they need to be analysed (SSG-14, IAEA 2019).

These processes are directly related to the lithology and mineralogy of the host rock types. Geochemical data gathering would be initiated in the first possible stages, most likely involving desktop studies with available Quaternary and bedrock geochemical data from GTK. Detailed drill core geochemistry data would also be analysed in the earliest possible stages. Drill core analyses should also include fracture mineralogy studies, where fracture infillings would be investigated for their specific mineralogy.

Hydrogeochemical data can also be attributed to lithogeochemical data because the chemistry of the host rock affects the groundwater chemistry. However, in shallow systems, the contribution of meteoric waters may be more important. These types of data needs could only be properly assessed in the site characterization stage, because drillholes are required for hydrogeological testing and sampling of groundwaters. Groundwater conditions have implications for the performance and durability of the EBS (engineered barrier system) component. Groundwater flow is also the only mechanism that can disperse radionuclides in the subsurface and potentially to the biosphere.

7.6 Geotechnical data

The collection of geotechnical data on SMR repository sites would be similar to geotechnical data collection with SMR power plant sites. Notable differences with repository-related data would possibly include more precision in soil deposit-related data and soil classification.

The specification of areas susceptible to landslides, unstable slopes and increased liquefaction potential would need to be estimated and the related data documented (SSG-14, IAEA 2019).

Quaternary geological investigations with trenching have been performed in multiple locations at Olkiluoto, producing grain size distribution graphs and parameters for different Quaternary soil types (Huhta 2009, 2013). These investigation methods can be used to detect possible glacial flow directions, post-glacial faulting, bedrock surface topography, weathered bedrock, and other soil disturbances, and would be beneficial in determining the Quaternary history of a specific study area for an SMR repository site.

7.7 Seismological data

Seismic data concerning spent nuclear fuel repositories must include current and projected future seismic events to establish safety parameters for the required repository lifetime. The definitive lifetime of a repository for SMR-based waste is difficult to estimate at this point due to uncertainties regarding the overall waste characteristics, but it can be stated that the lifespan or safety planning should extend to the order of thousands of years, and also consider future glaciation periods within Fennoscandia. The origins of tectonic activity in a site investigation area should be assessed with previous research and observations, so that causalities with the most obvious tectonic forces could be recognized.

The current stress pattern in Finland has been verified via earthquake fault plane solutions, *in situ* stress measurements and geodetic information, with the tectonic stress field (horizontal stress field) rather consistently being in a NW–SE direction and the stress pattern being less uniform in the northern Fennoscandian area (Saari 2012).

Future seismicity at a given site within Finland can also be assessed by combining post-glacial faulting data with projections of future glaciation periods. Current knowledge suggests that major seismic events occurred during and after the last deglaciation and suggest reactivation of existing fracture or fault zones (Hutri 2007, Ojala et al. 2019). The data from offshore areas support the idea of postglacial activity also being potentially intense in southern Finland, although the indications on dry land are less prominent, probably due to their weaker observability through the thick cover of postglacial Baltic Sea sediments. Implications of isostatic crustal uplift (directly related to shoreline displacement) are also relevant, with uplift rates being higher in current western coastal areas of Finland (Saari 2012). This has possible consequences with regard to areal SMR repository siting in Finland. Uncertainty factors, such as evaluating the probability of fault activation, can be difficult in low-seismicity intraplate environments due to blind seismogenic sources remaining and short (5 km) faults possibly producing damaging earthquakes (Fenton et al. 2006).

The analysis of present and future horizontal and vertical stress components should be included in an SMR repository siting process and correlated with general seismic models and documented fracture zones and faults. The scale of correlated fracture zones and faults would be dependent on the siting process stage but would also be independent of the scale when approaching site characterization and even further during site operation and seismic monitoring.

7.8 Hydrogeological data

The approach with hydrogeological data collection regarding SMR repositories differs from the collection of most other data types due to the extent and effect of data through all stages in repository selection. The hydrogeological characteristics of a repository site should be able to restrict groundwater flow within the site and support the safe containment and isolation of waste for the required time. The terrain of the site should be gently sloping to minimize the hydraulic gradient, and the repository should be situated as far as possible from fracture zones that represent aquifers, along with the bedrock block hosting the repository being hydraulically isolated from other blocks and containing as little groundwater as possible (Salmi 1985). In addition to local hydrological conditions, regional hydraulic gradients should also be considered in repository site selection, although this effect might in any case be limited due to the generally subdued or low topographic gradient of Finland (McEwen & Äikäs 2000).

Hydrogeological flow patterns and potential within Quaternary deposits would need to be correlated or modelled in conjunction with bedrock structures. Recharge and consequent understanding of the groundwater formation potential in Quaternary deposits should be assessed due to the required longer time scales of repository timelines. Groundwater investigations should be extended to deeper levels, well below the anticipated depth of the repository, to determine the stratification of the groundwater system and the depth of stagnant saline waters. Groundwater-related conditions are important factors that have impacts on the preferred depth of the repository.

Natural features, such as fracture zones or other possible aquifers, are potential release pathways for radionuclides. Characterizing the water flow rate in geological structures or hydrogeological zones within the site would be essential to evaluate known bedrock structures and their radionuclide retention potential to deter the migration of nuclides to the surface. Irrespective of the characteristics of the nuclear waste or the disposal option, a suitable geological and hydrogeological environment would contribute to flow restriction from and towards the repository, preventing unacceptable radionuclide release to the environment (SSG-14, IAEA 2019). SMR-based waste facilities should thus follow the hydrogeological guidelines presented from previous studies regarding waste from conventional NPPs.

The connectivity of the structures and fractures has direct effects on the capabilities of the geosphere to function as a proper natural engineering barrier. These could initially be analysed in earlier stages of the investigation. Structural drill core data would then be used to correlate and guide hydraulic drillhole measurements, such as transmissivity and hydraulic conductivity measurements (water flow rate), to establish adequate hydrogeological zone models. This type of data collection and analysis and model updating would also continue in the construction, operation, and monitoring stages of a repository site project. Hydrogeological monitoring data from Olkiluoto have been extensively researched, and examples of established hydrogeological zones, where documented fracture zone data are combined, for instance, with transmissivity data and drillhole data, are reported in Laakso et al. (2022).

The data needs for hydrogeological data, irrespective of the scale and site selection stage, would include the dilution capacity, the identification and characterization of hydrogeological units (location, extent, interrelationships), recharge and discharge estimates within local and regional hydrogeological units, host rock hydrogeological characteristics (porosity, hydraulic conductivity, head gradients) and the paleohydrogeological evolution of the site (SSG-14, IAEA 2019).

7.9 Rock mechanical data

Preliminary investigations regarding the rock mechanical behaviour of an underground SMR repository site would begin indirectly and interpretatively in the first stages, where the fracturing of the selected bedrock block would be evaluated along with lineament interpretation data. Observations of rock mechanics would be conducted during geological mapping at the outcrop scale, where initial fracturing data would be collected from outcroppings and investigation trenches.

Detailed rock mechanical data collection would begin with the first drilling operations in the site survey stage. Rock mechanical classifications according to the Finnish Engineering Geological Rock Classification scheme (Korhonen et al. 1974, Gardemeister et al. 1976) would be performed on drill cores to estimate the bedrock quality classifications and general geological constructability characteristics, including classifications for fracture zones. Rock quality designation (RQD) measurements (Deere 1963) would be performed to describe the quality of the rock mass and the fracture density and to further delineate zones of poor quality (i.e., fracture zones). The initial use of the Q classification system (Barton et al. 1974) would be implemented to produce rock mechanical parameters from drill core data related to jointing, such as the joint set number (J_n), joint roughness number (J_r) and joint alteration number (J_a). Other Q classification jointing-related data would include the joint water reduction number (J_w) and stress reduction factor (SRF), but these would be implemented in later stages of repository tunnel construction, when data collection for these parameters would be possible.

Rock mechanical parametrization would enable the creation of an engineering geological 3D model with various types of modern geological data software. A 3D rock mechanical or engineering geological model would be developed for the repository site and it should incorporate all available bedrock structural elements, such as fracture zones and fault zones. A block model comprising the aforementioned rock mechanical parameters could be constructed to analyse the relationships between lithology and rock mechanics and thus geological constructability.

Some of the rock mechanical parameter measurements would be taken to analyse principal rock stresses within a survey site. The existence of large *in situ* stresses would serve as an indicator of unsuitable characteristics for a nuclear repository (McEwen & Äikäs 2000, STUK 2018). Thus, it is imperative to gain an understanding of principal stress field parameters in the appropriate initial stage. Individual *in situ* stress parameters would be comprised of maximum, minimum and vertical stress components. Measurements for stress states could be conducted with borehole measurements using the overcoring method, and the differences in stress states between host rock types should be documented (Äikäs et al. 2000). For more examples of stress field measurements at a nuclear waste repository site (Olkiluoto), the reader is directed to Mattila et al. (2022).

7.10 Structural geology data

The level of detail concerning structural geology data would range from lineament interpretation in the site survey stage to detailed fracture studies from drill core during the site investigation stage.

Fracture zone classifications in the site investigation stage would enhance the structural geology data collected at a larger scale during the area survey stages. The detailed analysis and re-classification of previously documented fracture zones would most likely be performed on the most prevalent fracture zones, with site-scale nomenclature in a similar fashion to the nomenclature for brittle fracture zone (BFZs) in Olkiluoto (Aaltonen et al. 2016), with descriptions added for fault cores and damage zones where applicable to gain further understanding of the evolution of brittle deformation. Brittle and ductile deformation models would be further developed for the site to understand the geological evolution of the structural geology regimes. Ductile deformation can be a precursor for brittle deformation, and investigation into both structural regimes is necessary to validate the structural geology model.

Fracture mineralogy analysis would start with detailed fracture analysis from drill cores, where individual fracture minerals in a fracture surface would first be visually inspected. Further analysis could be conducted via modern hyperspectral methods to gain qualitative data on fracture mineralogy facies. Individual fracture data collected from drill cores would include fracture characteristics such as the fracture orientation (strike/dip), fracture density, fracture mineralogy and fracture morphology. Although some of these are already described within rock mechanical parameters, fracture mineralogy is particularly useful in evaluating the radionuclide retention potential of different minerals within fracture and fault zones. In some cases, fracture infillings have implications for bedrock stability, i.e., swelling clays, graphite and talc may reduce friction and increase the caving potential.

Fracture populations would be described with stereographic projection techniques using lower hemisphere projection, including fracture data and fault data points.

Initial discrete fracture network (DFN) models using structural geology data would be beneficial to evaluate fracturing conceptually and statistically at a given site in a certain stage. Discrete fracture networks can provide predictability in bedrock fracturing behaviour if enough data is available. Once data amounts increase in a survey area via additional mapping and drilling, DFN models can be further validated and evaluated in terms of their usefulness.

The question of determining what the appropriate amount of data would be to initiate a discrete fracture network model remains open, but it can be assumed that once, for example, enough surface mapping data and drillholes at a suitable distance from each other have been completed and fracture data have been analysed, a preliminary DFN model could be pursued. DFN-based data models can be used to evaluate various structural geology phenomena, including ductile domains and brittle domains with differing fracture characteristics. The evaluation of fracture properties with DFN models also plays a significant role in safety assessments, affecting the safety functions and performance targets of the geosphere and the engineered barrier system (Hartley et al. 2018).

7.11 Environmental and other data

Geological disposal facilities must adhere to the requirements for conservation of the environment and other relevant issues of non-radiological concern. Environmental impact assessments would be a very relevant topic in any SMR repository siting process, and related data should include the location and classification of nature conservation areas of different types, such as natural parks and natural conservation areas. Impacts on plant and animal life would be evaluated along with related economic and social aspects. Social impact data would include different types of population-related data, employment-related data, community services and infrastructure data, and housing supply and demand data, all of which would potentially affect the development of a repository site (SSG-14, IAEA 2011).

Other factors related to human activities could include other natural resource exploitation, such as the construction of storage activities, and any significant geothermal resource potential should be evaluated to prevent human intrusion into the repository (SSG-14, IAEA 2011).

Any relevant meteorological data within a repository site survey area would be investigated, along with water-related phenomena, such as flooding data (historical and current data) related to lakes, rivers, and estuaries. Especially in coastal areas, flood analysis should also include tsunami hazard analysis. The link between meteorological data and future weather phenomena should also be established to ensure the analysis of climate change. Climate evolution with glacial cycles may represent changes in the hydrosphere and sea levels and other geological processes (SSG-14, IAEA 2011). Documented glacial cycles in Fennoscandia and Finland must be considered in the safety case assessments of future SMR repository designs.

8 GENERAL CONSIDERATIONS FOR SMR SNF REPOSITORY SITE CHARACTERISTICS AND WASTE MANAGEMENT STRATEGIES

The general consensus is that the KBS-3 disposal method could be applicable to dispose of spent nuclear fuel from light water cooled SMRs with UO_2 fuel, considering that the spent fuel characteristics are comparable to the fuel currently produced in Finnish NPPs (Keto et al. 2022, 2023). The possibly lower decay heat rate from SMR-based SNF could alter the disposal concept with regard to disposal tunnel spacing and canister spacing, possibly allowing more efficient use of the repository host rock for disposal (Keto et al. 2022). However, this remains to be confirmed, considering the amount of spent nuclear fuel that can be disposed per canister, as well as other factors such as the potentially higher post-irradiation of SMR spent fuel (Keto et al. 2023). Overall, the repository requirements would be different regarding repository tunnel design and canister placement hole spacing. However, precise calculations of waste amounts, spent fuel characteristics and canister dimensions, along with other technical details of the spent fuel assembly configurations, are required for any further assessment of feasibility. To preserve the thermal, hydraulic, mechanical, and chemical integrity of the repository system, the capacity and spacing of SNF disposal canisters should be configured to influence the dissipation of decay heat (Krall et al. 2022).

Waste stream issues regarding SMR-based nuclear waste still require more studies to determine the exact waste stream types from different reactor types. Different reactor type waste streams must be analysed, as only a limited number of reactor designs have been analysed so far. Waste stream analyses for district heat LW (light water)-SMRs exist (Keto et al. 2022, 2023), along with discussion concerning waste streams originating from other reactor types, such as graphite-cooled reactors, fast-breeder reactors, molten salt reactors and thorium-based reactors.

The thermal properties of the rocks would most likely have to be investigated for their specific effect on the repository design and dissipation of decay heat. These types of studies would be initiated in the site characterization stage or even later, when appropriate media (drill core) would be available for petrophysical measurements. Measurements for petrophysical properties such as thermal conductivity, specific heat capacity, density and thermal diffusivity have been conducted both in the laboratory and *in situ* for Olkiluoto rock types (Kukkonen 2015).

Similar measurements would most likely be beneficial due to the canister deposition hole spacing and the spacing between deposition holes being dependent on the heat generation of the fuel, the properties of EBS (e.g., conductivity of waste packages and buffer materials) and the thermal properties of the rock (Ikonen & Raiko 2012). This is of course assuming that an SMR spent nuclear fuel repository would use deposition holes in an excavated tunnel similar to KBS-3V. It is assumed at this point that the thermal properties of the host rocks and their effect on the SNF would also depend on the deposition depth or the final depth of the repository. This is mostly due to an increasing geothermal gradient at depth, evidenced, for example, in deep borehole studies (Ahonen et al. 2011).

Centralized vs. decentralized, with possible hybrid SMR waste management options within a Finnish framework for the final disposal facilities of SMR-based waste were initially discussed by Keto et al. (2022). Deposition options for VLLW and LILW waste types within individual SMR power plant sites were also initially discussed, with remarks that the near-surface disposal of VLLW could be viable at an individual SMR power plant site. Final disposal of LILW waste could be handled in a centralized option with an intermediate depth geologic repository.

A centralized or hybrid option for an SMR waste repository currently outweighs the decentralized option. A fully decentralized waste disposal strategy for SMR waste does not appear viable due to technical, economic, and social issues (Keto et al. 2022). While VLLW and LILW waste types could be stored (interim storage) within individual SMR power plant sites closer to the surface due to their lower requirements for radiological safety, high-level waste repositories would have to be built deeper into the bedrock. In a decentralized strategy, this would effectively mean decades of studies concerning deeper bedrock in multiple types of geological media in different locations. The characteristics and safety requirements of certain types of geological media would have to be verified in all areas, creating multiple uncertainty factors for a decentralized strategy.

Also from a purely geological suitability viewpoint, a centralized repository strategy is currently more favourable. This is due to the high quantity and quality of geological investigations required in each surveyed area, coupled with the fact that the nuclear safety of a repository is also linked to geological monitoring activities during and after construction.

SMR power plants would most likely be built in multiple locations in Finland, depending on the energy needs. The overall implications of the SMR-based Finnish nuclear industry are still largely unknown, but in terms of geological suitability and possibly suitable research areas, Finnish bedrock conditions overall offer a good opportunity to site SMR plants, but also to demonstrate the feasibility of an SMR-based waste repository. In addition, it would not be logical to completely ignore the possibility for detailed investigation into multiple repository sites or a hybrid decentralization strategy, based on the overall good suitability of Finnish bedrock conditions and available geological media.

Currently, the problem with possibly volumetrically larger amounts of SNF from a geological repository point of view can only be addressed by selecting and investigating areas large enough to be expanded in the case of more reactor and reactor types being assembled and put into production. Krall et al. (2022) analysed three distinct SMR designs (both LW-SMRs and non-LW-SMRs) and concluded that the energy-equivalent volumes of long-lived LILW and short-lived LILW would increase by factors of 30 and 35, respectively, with total volumes of HLW being in the order of 5.5 times higher, when compared to conventional gigawatt-scale reactor waste. Similar results concerning increased volumes of waste produced from certain SMR designs can be observed in Brown et al. (2017).

SMR-based LILW can be divided into long-lived LILW and short-lived LILW, and these wastes are mostly comprised of steel and concrete components that have absorbed neutrons from reactor cores and may require geological disposal. LILW would also include short-lived waste in the form of graphite used in moderators and reflectors in molten salt reactors, and liquid metal and salt coolants, such as sodium, in considerable volumes. More thorough descriptions and details of these types of SMR-based LILW can be viewed in Krall et al. (2022).

Geological suitability factors, such as bedrock block identification, lithology, rock mechanical qualities (constructability) and rock stresses, must be analysed in detailed site-specific investigations. In the Finnish site selection process for the final SNF disposal site, all four final phase target sites were evaluated for their lithological and rock mechanical properties (Äikäs et al. 1999a,b,c,d). These studies, as well any other study concerning repository site selection in Finland, serve as examples of the magnitude of geological research required to build an adequate safety case for a deep geological repository. Previous research areas and data can also be revisited, providing opportunities for evaluating the suitability of these areas for current SMR-related research themes.

9 DEEP BOREHOLE DISPOSAL CONCEPT

9.1 Introduction, review of DBD-related research and deep bedrock characterization methods

Deep borehole disposal (DBD) refers to the concept of nuclear waste disposal in deep bedrock via larger diameter boreholes, with possible depth ranges of several kilometres (Fig. 10). While the concept of DBD is not novel, it has gathered renewed interest in recent years as drilling technology has advanced (Muller et al. 2019). In addition to the basic principle of a thick geological barrier, the role of engineered barrier systems would decrease with depth as the role of the geological barrier increases. Borehole disposal would also offer options for depth, depending on the engineered barrier system applied and the geological environment and characteristics selected for the DBD host rock (IFNEC 2020, Fig. 10). The selected engineered barriers within a DBD scenario would vary along with the borehole diameter, and the inhibition of radionuclides will heavily rely on the geosphere (Krall et al. 2020).

Deep borehole disposal concepts enable greater natural isolation from the surface and near-surface environment (Arnold et al. 2011). The low permeability in deep bedrock along with higher salinity and geochemically reducing conditions would also be some of the key requirements for deep borehole disposal concepts, with the notion that these conditions are dependent on the geological setting (Krall et al. 2020). In general, Finnish crystalline bedrock exhibits these characteristics, but site-specific investigations are required to demonstrate these conditions reliably to build a possible safety case for deep borehole disposal. In addition, the required depths compared to the KBS-3 method set challenges for acquiring information from the sub-surface.

Previous research regarding deep borehole disposal and deep bedrock studies focusing on the Fennoscandian Shield has been conducted, along with research in different countries with similar research goals. SKB produced a report on the very deep hole concept (Juhlin et al. 1998), with emphasis on geological conditions in the Baltic Shield (Fennoscandian Shield), also outlining important deep borehole investigation parameters, such as lithology and structural geology, fracture mineralogy, fracturing (porosity), temperature, permeability, pore pressure, mechanical properties, the state of stress, fluid composition and bacteria, and natural seismicity. A review of selected European geothermal boreholes, including Finnish and Swedish deep boreholes, with their geological and hydrological characteristics was presented by Marsic & Grundfelt (2013).

The level of knowledge in Finland regarding deep bedrock characteristics on a larger scale has been examined in several projects. The FIRE project (Finnish Reflection Experiment 2001-2005) was conducted in the central part of the Fennoscandian Shield within Finnish territory to understand crustal structures and evolutionary history. Several seismic reflection survey lines were implemented across multiple geological boundaries covering the major geological domains, such as the Svecofennian Domain, Karelian Domain with Archean crust and the Lapland Granulite Belt (Kukkonen et al. 2006). Geological interpretations or geological profiles were produced within the upper crust, with correlations to surface lithologies and structural features, such as shear zones. Additional interpretation regarding fracturing and faulting (line drawings) was carried out on the measurement profiles. These data could be used in deep borehole disposal studies to delineate study areas with the very necessary depth dimension available from the seismic interpretations.

Experience in Finland and elsewhere in drilling multiple deep or very deep boreholes, with the increasing technological maturity of drilling technology, has increased over the past few decades. Deep boreholes have been successfully drilled in Finland (e.g., Outokumpu, Otaniemi), serving as technological demonstration examples under Finnish bedrock conditions. A comprehensive report on research conducted in the Outokumpu deep borehole (depth 2.5 km) was presented in Kukkonen (2011), discussing reflection seismics, hydrogeology, petrophysical properties, hydrogeology, and geothermal properties (especially the geothermal gradient) and other geological research topics. The Outokumpu deep borehole has also been used in research estimating the origins and evolution of deep fracture fluids and noble gases (Kietäväinen et al. 2013). The St1 Otaniemi deep geothermal borehole (depth approximately 7 km) is being investigated with a view to generating deep geothermal energy, along with other geothermal projects in Finland (Piipponen & Uski 2020). Deep boreholes have also been successfully implemented all over the world in areas of varying geological conditions (Krall et al. 2020, and references therein). Multiple research topics in a single or multiple deep boreholes represent the potentiality of them serving as research platforms for further DBD studies.

The deep borehole disposal concept generates new possibilities and uncertainties pertaining to borehole site selection. Depending on the general waste management strategy, it would be possible to locate the boreholes directly adjacent to existing nuclear facilities, such as repositories or power plant sites, or at a separate borehole site, if an individual site fulfils the future regulatory requirements. However, the advantages and disadvantages of these possible hybrid strategies must also be analysed. The regulatory requirements for deep borehole disposal concepts and their feasibility (related both to operations and safety) have not yet been properly discussed. In addition, several other scenarios, such as multiple boreholes at a single site, should be investigated. Multiple borehole placement in a nuclear waste disposal scenario will affect the borehole site selection process, as inevitably the spacing of boreholes would require a larger area of land use, while a single borehole would have the advantage of a smaller land use footprint.

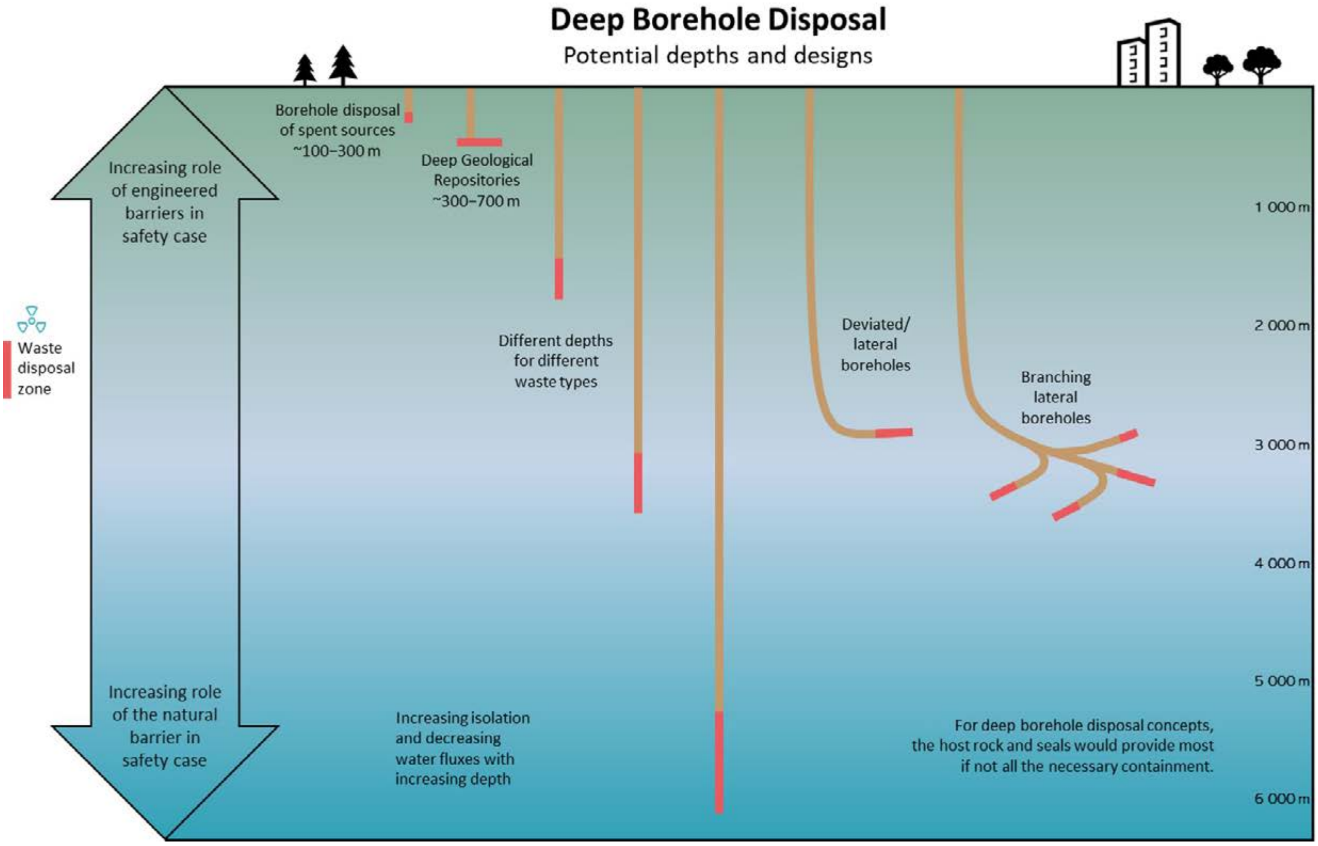


Fig. 10. Generalization of the deep borehole concept. Modified from IFNEC 2020.

9.2 Identification of investigation needs and research methods in DBD concepts

The characterization of bedrock properties concerning deep borehole disposal concepts would begin with identifying potential regions for borehole disposal. The methods used would initially be similar to methods for studying the siting of NPPs, SMR power plants and repositories, but the depth aspect sets possible limitations for many investigation methods. Regional-scale lithological data would be combined with lineament interpretation data to infer intact stable bedrock blocks bounded by large-scale fracture or fault zones, but again, their extent at depth should be assessed. The selection of appropriate lithology would be accompanied by investigations on local hydrological and hydrogeological conditions, but as above, the increasing depth makes acquiring data difficult. Structural geological studies regarding fracturing and the identification of fault and fracture zones would be in a prominent role within the investigation area, with accompanying seismic models generated from available seismic data.

The evaluation of groundwater characteristics should consider the chemical conditions within the studied area. Reducing chemical or geochemical conditions are a prerequisite for the KBS-3V concept in a mined geological repository (Tuomi et al. 2020). This principle of a reducing geochemical environment would also be an important site selection criterion regarding borehole siting to reduce the mobility of certain actinide elements, along with fluid stratification preventing groundwater migration upward. The low permeability of deep crustal rocks under lithostatic pressures would also reduce fluid flow rates, inhibiting radionuclide advection away from the disposal zone, which would also be beneficial in a BDB scenario (O’Brien et al. 1979). Brackish/saline groundwater and reducing conditions are also characteristic of deeper bedrock sections in documented repository settings such as in Olkiluoto (Pitkänen et al. 2022) and in the Outokumpu deep drillhole (Ahonen et al. 2011).

Establishing enough data on the geothermal gradient within local deep borehole host rock complexes would be essential. In deep boreholes, decay heat from spent nuclear fuel will be compounded with the prevailing geothermal gradient, inducing higher ambient temperatures with increasing depth (Krall et al. 2020). Gas formation within a deep borehole scenario would also need to be evaluated, especially when considering vertical drillholes. The decay heat from SNF would possibly induce thermal expansion and pressure increases due to corrosion forming a volume increase, producing hydrogen gas and metal oxides. However, these effects would be expected to be minor. The low permeability of the host rock could possibly induce the transportation of radionuclides in an axial direction along the drillhole, while transport velocity is considered to be very low because of absorbing backfill material and installed plugs (Muller et al. 2019). The decay heat effects, however, are entirely dependent on the characteristics of the SNF material in question.

The size of the area required to host a deep borehole disposal hole would need to consider the depth and/or the volume of drill site host rock as an important criterion. When considering depth as a major factor for deep borehole disposal, one important feature would be the 3D extent, dimensions and shape of fracture zones and fault zones within the study area. The area should be void of major vertical to subvertical fault and fracture zones due to possible complications of interaction with different drillhole dimensions, and more specifically with vertical drillholes or boreholes during drilling operations. If a vertical borehole were to dissect a vertical or subvertical fracture zone of sufficient size, hole stability issues could possibly ensue. In addition, the presence of water within the fracture zone could induce problems with the drillability of the hole. The selection of areas known for their low hydraulic gradient in bedrock, along with lesser documented fracture zones from the surface, would mitigate this problem to a degree.

Horizontal drillhole disposal has become feasible due to the development of directional drilling technology in the last two decades (Muller et al. 2019). This would effectively enable the selection of appropriate geological media for deep borehole disposal at least in a more stratified geological environment. Hard rock crystalline environments such as in the Fennoscandian shield area, with differing structural geological and hydrological characteristics, would, however, be a different operating environment.

Although current drilling technology can execute inclined drillholes, even in hard rock conditions, with modern geosteering tools, no technology demonstrations with large-diameter directional horizontal drilling (equivalent to deviated/branching borehole examples in Fig. 10) have been achieved in Finnish conditions (not including deviated drillholes in mineral or mine exploration). The St1 Otaniemi geothermal borehole is the best example of the current large-diameter capabilities of modern deep drilling technology in Finnish bedrock conditions. Vertical drillholes would most likely be more feasible, with the added benefit of existing borehole research methods being more applicable and reliable in vertical drillholes to study the borehole geological characteristics.

The possible operational research drilling strategy would first include the drilling of a pilot hole or an exploration type borehole in an area deemed suitable for further research, after careful and extensive initial evaluations of bedrock block stability, lithology, fracturing, and seismic and hydrogeological conditions. Using a core drilling technique of an appropriate diameter, drill core samples could be obtained from depth to evaluate the lithology, rock mechanical characteristics and conditions deeper in the bedrock. The pilot hole would have to reach adequate depths to verify salinity conditions with suitable methods. Second, a larger diameter drill bit capable of producing a borehole with a sufficient width to serve as a research borehole would be needed to test and develop suitable geophysical instrumentation and methods relevant to deep borehole disposal and other geological research.

Fracturing conditions in deep bedrock would be a major factor in DBD research. Fracture frequency, orientation, and fracture roughness determinations, along with fracture mineralogy in deep bedrock, would provide the necessary data to estimate the effect of fracturing on, for example, hydrogeological conditions. The fracture frequency in bedrock near the surface is generally higher than at depth in the Outokumpu deep drillhole, and in deeper sections of the bedrock, where lithostatic pressure influences the closure of fracturing, producing conditions for lower hydraulic conductivity within deeper bedrock. However, measured fluid flow from deeper sections also provides evidence of water-bearing fracture zones at depths of more than 2 km, indicated by electrical conductivity methods (Ahonen et al. 2011). Faulting conditions would have to be managed specifically regarding canister placement within the borehole. The generation of new faults and reactivation of existing faults needs to be considered due to the possibility of one or several canisters being sheared if placed within or too close to fracture zones or fault zones. Standoff distances of 100 metres from active faults are suggested to mitigate the risk of damage to the drillhole and canister (Muller et al. 2019). Given the complexity of bedrock structures at depth in crystalline hard rock conditions in Finnish bedrock, cutting relationships (e.g., dextrality vs. sinistrality) between faults should be established and suitable research methods developed for deep bedrock conditions regarding faulting.

9.3 Uncertainty factors, possible advantages, and disadvantages

Uncertainty factors and rock stress conditions concerning deep borehole disposal can be addressed with rock mechanical studies to some degree and to establish boundary conditions. Primary research methods would include drill core sample testing. Compressive strength and tensile strength tests performed on drill core samples would produce preliminary results on rock strength with each lithology observed in a single borehole.

Spalling of boreholes is a well-known phenomenon, resulting in the deterioration of the borehole wall if the rock stress conditions are conducive to such behaviour. This can be partially mitigated with appropriate casing of the borehole, with consideration of the casing depth. General rock stress conditions, such as the principal stress field conditions within the geological domain, must be recognized, along with horizontal and vertical stress field directions. Rock mechanical characteristics in deep bedrock should include estimations of lithostatic pressures at depth.

The unpredictability of geological conditions at depth when considering deep borehole disposal is the most concerning issue regarding the entire borehole disposal concept. Geological data collection regarding safety assessments in mined repositories vs. deep borehole concepts is one of the most compelling arguments against deep borehole disposal. When considering the overall amount of geological data collected from mined repositories, uncertainties related to geological data collection in deep boreholes are considerable. These uncertainties include, for example, insufficient resolution of geophysical surface methods in bedrock characterization, meaning that anomalies are observed but their nature can remain obscured. Although previous deep drillholes in Finnish conditions have been successful in data collection using different methods, uncertainties arise especially considering data quality at depths of several kilometres. Compared to the quality of data that can be reliably collected from mined repositories, the uncertainties are compounded.

The borehole disposal concept does offer some favourable characteristics, especially considering project economics, which include limited land area use and limited infrastructure, short periods of construction, operation and closure, and a low probability of human intrusion into the borehole (NW-T-1.3, IAEA 2014). Additional advantages could include lesser costs in relevant infrastructure needed for initial construction and encapsulation procedures and related facilities. Added flexibility in interim storage options for different types of nuclear waste would be an advantage, but this would also be very much dependent on the interim storage strategy in general. If the DBD facility would be built at the waste producing site (i.e., the power plant), it would eliminate certain logistical and transport issues concerning SNF, thus creating more local flexibility while considering the waste inventory and local geological conditions (Muller et al. 2019). However, due to the uncertainty regarding the geology of a particular location being applicable for building an adequate safety case, it is unlikely that this type of decentralized strategy would be applied for deep borehole disposal (Krall et al. 2020).

In the United States, improvements in options for the retrievability of SNF waste from deep boreholes have been progressing due to regulation and U.S. legislation requiring retrievability up to 50 years after initial waste emplacement. The requirements were established due to the possibility of a better disposal option or the advancement of reactor technology. Technical descriptions related to retrievability issues can be viewed in Muller et al. (2019).

10 DISCUSSION

Geological investigations involving SMR power plant site selection, SMR spent nuclear repository site selection and deep borehole disposal all contain overlapping and interlinking research areas and data documentation methods. All schematics and suggested models presented in this report should at this point be conceived as conceptual due to limited understanding and uncertainties related to SMR plant siting, SMR repository siting and deep borehole disposal. Since all of these areas of research are still in early phases of development, definitive conclusions about their feasibility are unwarranted at this point. However, previous research concerning nuclear facility site selection in Finland does suggest that with further research and development, relevant issues can be solved and the basis for decision-making processes will become easier with time.

Dividing research efforts between research and commercial organizations is recommended to gain knowledge and data on SMR technology. Individual areas of research concerning, for example, geological and other research should be split into smaller scale projects to approach research questions in a more precise manner. This would ensure enhanced data resolution and thus higher quality decision-making processes. The siting of an SMR power plant, especially for district heating purposes, is likely to also be affected by optimization of the site concerning distance from the city and location of the currently existing district heating network. In this case, the process may be different, so that a site may be suggested by a city and its applicability for housing an SMR plant might then be estimated based on criteria set for any relevant NPP.

10.1 SMR power plants

Detailed lineament interpretation studies should be performed as the very first steps within a site survey process. These interpretation studies can be performed with a relatively low cost, and they should be based on all existing geological data and regional to local geophysical data (including magnetic, electromagnetic and gravity, among other data). These studies should be followed by appropriate geological analysis to establish an adequate safety case for an SMR power plant. Interim storage strategies for operative waste (VLLW, LILW) within the SMR power plant site should be evaluated at a suitable time during the siting process. In addition, DBD concepts could also be initially discussed in conjunction with the SMR power plant site selection process, while considering the related uncertainties.

The variability in SMR reactor sizes and plant surface area requirements in terms of geological suitability demand new definitions, legislation, and focused research projects. First, the scale of data in relation to distances of SMR power plants from seismogenic zones and capable structures (faults) would need to be defined and developed to suit SMR needs. Existing definitions of 8.0 km minimum distances from capable faults may not be applicable to all SMR power plant sites, due to the possibly varying power outputs of different reactor types. Solutions to narrow this requirement down would thus be necessary, or alternatively, specific nuclear safety related requirements for distances could be generated for different SMR reactor power outputs. Statistical methods focusing on probability factors using, for example, seismic data in combination with relevant geological data is one possible method to generate solutions for such data scale and distance problems. However, while such long distances from possible capable faults are conservative, it is reasonable to use these initial safety distances of 8.0 km as workable references. If the power output of a conventional NPP would be in the order of 500 MW and an SMR power plant would operate in the 300 MW range, the need to redefine safety distances would essentially be invalidated, and existing safety distance definitions would be reasonably adequate.

10.2 SMR repositories

In general, the KBS-3 concept is considered applicable for light-water-cooled SMRs with UO_2 fuel. Open questions regarding the application of this concept are mainly linked to spent nuclear fuel characteristics potentially affecting the canister design (e.g., how much spent fuel can be placed in each canister) and the thermal dimensioning of the repository. The role of repository siting is to confirm that the site characteristics are compatible with the EBS and support the long-term safety of the repository for SMR waste. Considering more exotic SMR designs that are not based on conventional light-water reactor technology, and especially those with other than UO_2 fuel, there is more need for development of the concept and barrier design, since in this case the spent fuel characteristics may be very different, as well as in analysis of the effects of site characteristics on the performance of the disposal concept. Thus, the siting requirements for SMR-based SNF waste disposal are similar to those for waste from conventional NPPs.

Considering a centralized or hybrid waste management strategy, the siting of a new repository might be needed. In addition to interim storage options, the final disposal options for SMR-based VLLW and LILW should be noted in any repository option or scenario.

The role of any other data than geological data or characteristics, whether economic, environmental, or social, could override geological suitability criteria in selection processes for SMR-related facilities. Differences in the overall geological suitability criteria between surveyed areas may not be too significant so that a particular area that has initially been discarded cannot be later chosen for further study or use.

10.3 Deep borehole disposal

The deep borehole disposal concept is one possible alternative for SMR-based waste. An analysis by Krall et al. (2022) indicated that the quantities of VLLW and LILW waste types may significantly increase for specific SMR types, including both LW and non-LW SMRs. Radiological safety requirements for the disposal of VLLW and LILW are not as high as for HLW. This provides opportunities to assess the suitability of deep borehole disposal systems for these types of waste. However, the possibly larger amounts of waste generated by SMRs will require further evaluation and research regarding DBD concepts. The thickness of the natural barrier provided by geological media does suggest a certain viability for this concept, but nevertheless, further R&D is required. It is very important to recognize the uncertainties prevailing in deep bedrock conditions, and these uncertainties will have to be defined with very high precision.

Currently, there is not enough information or specific research projects and data to fully evaluate an individual safety case for deep borehole disposal in Finnish bedrock conditions. However, existing, and future deep boreholes and drillholes in Finland and elsewhere do offer opportunities for DBD-related research. Alternatives with regards to the deposition or waste emplacement zone depth provide opportunities to evaluate depth as a specific factor and major criterion for DBD. While the development of drilling technology is increasing at a fast pace and demonstrations of deep drilling have been successfully completed, for example, under the geological conditions of the Fennoscandian shield, further development and demonstrations are needed to test different configurations and the reliability of DBD concepts.

Every nation with a nuclear energy programme will need to develop functional strategies for nuclear waste disposal. Nations with a smaller nuclear programme might find DBD concepts appealing, given their SNF inventories in terms of volume, compared to nations with larger programmes and SNF inventories (Krall et al. 2020).

Due to the combination of unique and specific engineering solutions and geological requirements used in deep borehole disposal concepts, future legislation would also have to be specific for this topic. Building a safety case for deep borehole disposal would require a combination of functioning and adequate regulation, geological safety criteria and appropriate engineered barriers within a DBD framework. The possible regulatory framework for DBD facilities is discussed in IAEA document SSG-1 (2009).

11 CONCLUSIONS

Small modular reactor plants along with associated waste streams and their special requirements present new and unique challenges for developing appropriate geological suitability criteria. Currently, no guidelines or regulations exist for the siting aspects of SMR power plants or final disposal repositories. The variability in SMR power plant types, sizes and surface area requirements necessitates multiple research projects focusing on different topics. Moreover, the general novelty of the SMR research field related to geological aspects restricts the amount of available reviewable research.

This report mainly discusses the geological data and geological criteria needed to initially describe the problematics related to SMR power plant siting, SMR spent nuclear fuel repository siting and deep borehole disposal. All of these research topics are extensive in their own right. For the next steps to take place, research should focus on more specific and adequately defined study cases. These would include initial desktop surveys of specific sites with subsequent field studies, where selected research methods would be applied to collect more geological data regarding SMR technology-related concepts.

Considering the likely commercial nature of future SMR projects, the transparency and availability of research projects and data are important to ensure the viability of small-scale nuclear power from a societal point of view in Finland. The geology of the Fennoscandian Shield, with its favourable and stable, low seismicity environment within Finnish territory, does provide good opportunities for SMR power plant placement and related research. Existing experience in SNF repository research and construction creates sustainable and progressive opportunities to evaluate nuclear waste management strategies.

ACKNOWLEDGEMENTS

The authors would like to give very special thanks to Paula Keto and the VTT team for support during the project and reviewing the report. Timo Ruskeeniemi, Markku Paananen, Taina Karvonen and Jon Engström from GTK are thanked for their contribution in reviewing and helping with the report. Roy Siddall is thanked for correcting the English language, and Päivi Kuikka-Niemi from GTK is thanked for editorial handling and layout of this publication.

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