ACCELERATING IMPLEMENTATION OF A GDF IN THE UNITED KINGDOM

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ABSTRACT

This report discusses feasible processes for accelerating implementation of a geological disposal facility (GDF) in the United Kingdom. Recommendations are included for developing a three-phased siting program. These phases - Initial Investigation, Depiction Phase, and Site Specific Activities - are designed to provide relevant information to host communities in a timely manner and sustain decision making processes and practices.

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Accelerating Implementation of a Geological Disposal Facility in the United Kingdom

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Synopsis:

This report discusses feasible options for accelerating the implementation of a geological disposal facility (GDF) in the United Kingdom. An initial literature review was conducted on the feasibility of available and potential technologies and methods, including pre-site selection validation methods, without the need for invasive exploration activities to establish suitable sites. The report considers international experience gained from exploratory research in other countries that could assist in making more relevant site selection progress. Feasible options include indirect measurements, rock mass classification, analytical formulae, and numerical modelling. For instance, in 2016 the Japanese mapped the country based on the criterion of scientific features for geological disposal using literature reviews to determine “areas of suitability” and “areas of more suitability” to define areas of interest. This effort also noted “areas to be avoided” and “areas to ideally be avoided”. The challenge is to devise a robust pre-screening program that will allow suitable site selection processes to move forward without causing excessive delays. To maintain a forward progressing program, pre-site selection must ideally be accomplished with only limited ability to conduct more invasive studies, due to environmental restrictions. A suitable site must be selected based on pre-determined characteristics. Pre-screening methods could be derived based on site characterization methodologies similarly used for mega-sites (such as polluted brownfield sites).

The Finns and the Swiss have used and developed borehole drilling and mapping techniques that can provide evidence-based solutions to assist in developing a matrix for conditions of siting where geological and engineering aspects are integrated from the initial investigatory phase, instead of viewed separately. Repository concepts for granitic rock have been evaluated in Sweden, Finland, Switzerland, and Japan. Disposal concepts for clay/shale media have been evaluated in detail in France, Belgium, and Switzerland. A number of studies consider advances in hydraulic science and serve as a springboard for more modern investigative measures. It must be noted that while the U.K. is beginning its GDF activities/experience, previously used conventional methods for classification and site characterization have advanced in the last 20-30 years. A number of countries have underground rock laboratory sites already providing valuable in situ geological, hydrogeological and hydrogeochemical data and allow characterization of the geosphere properties and conditions that will affect repository performance. One can assume certain correlations between these programs and the UK program which will aid in developing the generic disposal concept. Additionally, these sites could provide for potential collaborative investigative

tools in the initial phases during site selection until a site-specific underground rock laboratory is devised. Furthermore, a template for progressing siting in crystalline rock, clay or salt media may be observed in similar processes for identifying suitable CO_2 storage sites, one which is analogous in many ways to the exploration for, and development of, oil and gas accumulations. Given the similarity of these processes, patterns may be devised that build upon these experiences, pushing forward initiatives for site selection processes for a GDF for radioactive waste and spent nuclear fuel.

One criterion that research shows as expediting the process of integrating technology is standardization of certain methods and techniques. This includes the use of a universal canister system and/or multiple purpose canisters for shipping and storing of the waste. This formalizes a universal system for the development of the repository setting by optimizing pre-investigative measures, analytical investigation, and design/construction techniques. This could also include integrating the site selection process to a suitable site that already has, or has had, active nuclear activities ongoing.

Tools and methods used for validating decision-making processes and chosen technologies are important in moving forward on a repository's siting, design, and development. Methods need to provide both flexibility and certainty. The initial phase should provide for quick- and-easy to compute generalized results based on established factors and characteristics. While these may not be firmly validated, they can spark interest in a chosen site/technology/method. The next phase of validation should be replicable across multiple sites, though time and computer- intensive. The last phase should be site specific and not easily replicable across multiple potential sites. While this is rather obvious, because accurate model checking may not be a complete and faithful representation of the system while the model is still under development, one will need to justify the correctness of implementing a "generic" design during the site selection process. Some research suggests that there may be a tendency to invert the two last phases, causing exploration of expensive but 'more' accurate generic investigation. An emphasis on validating model checking for accuracy can be traded off for a little more speed at the formative stage in the UK, whilst still adequately validating the minimum criteria of chosen characteristics.

The report also includes a review of the influencers on radioactive waste management programs, their impacts and pillars. Other factors researched include potential water erosion at a site that may need to be considered and investigated, as well as its impact on the environmental setting.

Table of Contents

Table of Figures

1.0 Introduction

The United Kingdom (U.K.) is proceeding with the development of a geological storage facility for spent nuclear fuel and high-level waste to be located either in England, Wales or Northern Ireland. The process for site selection potential technologies and methods will need to be made available, including pre-site selection validation methods without the need for invasive exploration activities to establish suitable sites to close the nuclear fuel cycle. Methods need to provide both flexibility and certainty, so that decision-makers in potential host communities, as well as the general public, can make timely and informed decisions. This constitutes the hallmark of any siting programme. The challenge is to devise a robust pre-screening program that will allow the advancement of suitable site selection processes to move forward without causing excessive delays. Templates and patterns may be devised that build upon international experiences to successfully push forward initiatives for site selection processes for a geologic disposal facility (GDF) for radioactive waste and spent nuclear fuel. This report considers tools, methods and frameworks that may be used for validating decision-making processes and chosen technologies. Without impacting negatively on the volunteerism aspect of the U.K.'s GDF siting initiatives, these suggested frameworks and models can be used to produce a little more speed at the formative stage in the site selection processes, whilst still adequately maintaining the sought-after desire for open and transparent government/public interactions.

1.1 Literature Review/Background

In 2011, the Radioactive Waste Management Directorate (RWMD), precursor to the current Radioactive Waste Management Limited[1] (RWM), conducted a study on accelerating the implementation of geologic disposal in the United Kingdom (U.K.). At the time, the Minster of State for Energy requested a review for bring forward the first waste emplacement to 2029. RWMD's 2011 review paper[2] (2011 Report) used a baseline program as set out in the Managing Radioactive Waste Safety (MRWS) white paper, and conducted its review considering the following key dates:

- First emplacement of legacy intermediate level waste (ILW) in around 2040.
- Emplacement of legacy high-level waste (HLW) and spent fuels in around 2075.
- Emplacement of spent fuel from new build nuclear power stations in 2130.
- Commence closure 2175.

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[1] part of the Nuclear Decommissioning Authority (NDA)

[2] NDA Report no. NDA/RWMD/083, Review of options for accelerating implementation of the Geological Disposal programme, December 2011, https://rwm.nda.gov.uk/publication/geological-disposal-review-of-options-for-accelerating-implementation-of-the-geological-disposal-programme-december-2011/?download

Though the 2011 Report is soon approaching a decade in age, it rightly acknowledges two unchanging fundamental principles, shown in Fig 1. It is recognized that any activities designed to accelerate the implementation of a GDF in the U.K. must be guided by these two principles.

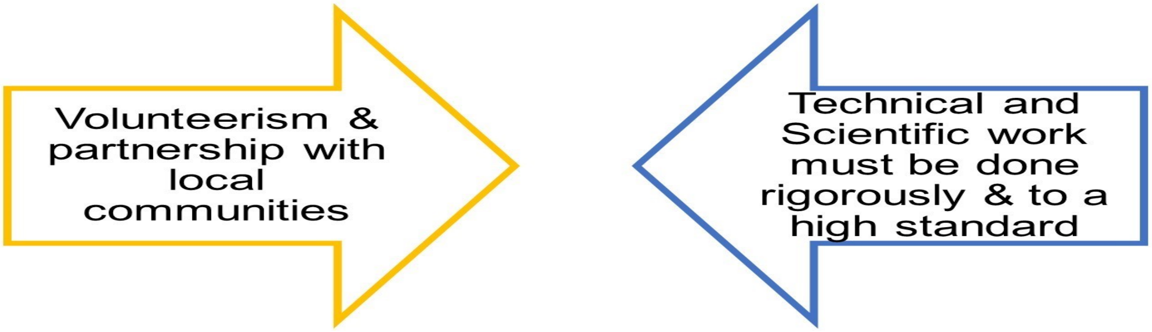

Fig. 1: The Two Unchanging Fundamental Principles for Waste Management in the U.K.

The then RMWD's review developed three scenarios with some radical approaches. It is not the intent to reproduce these scenarios in detail as the information is available, but a summarized version is detailed in Fig. 2.

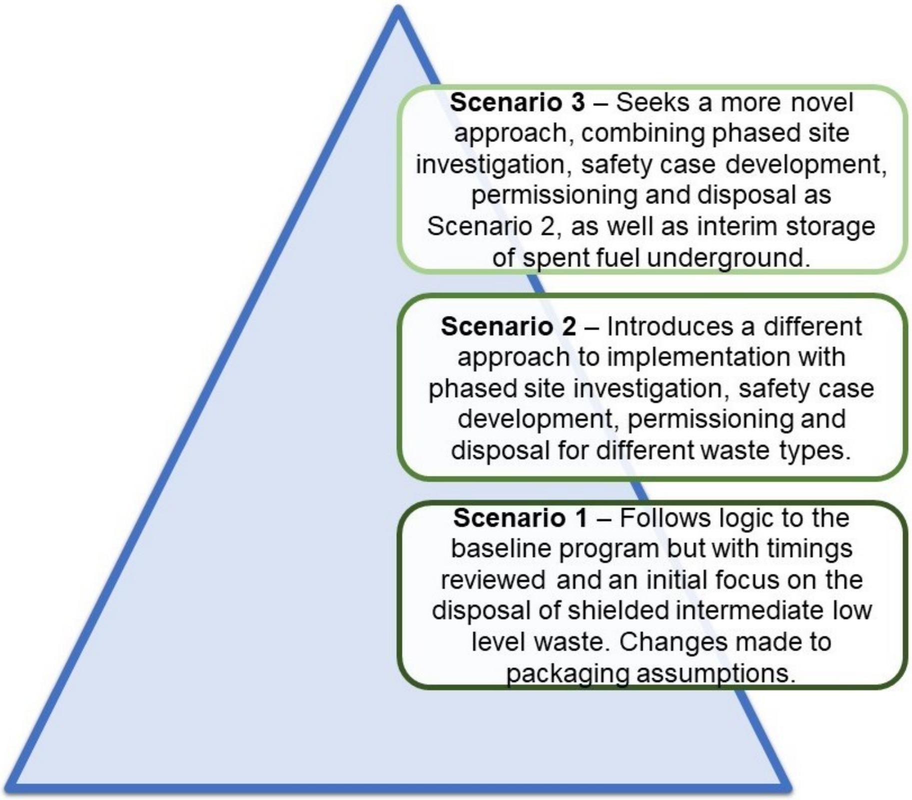

Fig. 2: Summary of RWMD's 2011 Report Proposed Three Scenarios

The 2011 Report offered confidence that the 2075 and 2130 dates can be brought forward, whilst accelerating the 2040 date for first emplacement to 2029 is more challenging and requires consideration of innovative approaches which bring with them a higher degree of risk. It is also observed that the 2011 Report finding for each of the three scenarios did not bring about much/any cost benefits and/or increased costs (Scenario 3). The 2011 Report also concluded that the options described in "Scenarios 2 and 3 have the potential for greater acceleration through adoption of innovative approaches but carry with them significantly greater risk". Additionally, the 2011 Report proposed that Scenario 1 offers the potential for programme acceleration "with the least increase in risk". Interestingly, in Section 4.2 of the 2011 Report, mention is made that commencing regulatory submissions and obtaining planning permission for drilling initial boreholes could be performed in parallel with regional geophysical investigations, bringing about a programme saving of between 1-2 years. While this is not disputed, it is less clear why more in-depth tabletop geophysical investigations/studies could not be performed earlier in the process to characterize and determine suitable sought-after sites for a GDF, so that focus is given to certain specific sites earlier on?

In January 2012, the Royal Academy of Engineering was approached by the Department of Energy and Climate Change (DECC) to provide a review of the NDA options published in the 2011 Report[3]. The Royal Academy of Engineering highlighted that some geophysical investigations which do not cause significant impact could be brought forward, so that site identification can be accelerated[4]. The Academy observed that one may not wish to commit money and resources to geophysical investigations until/after community decisions have been made. The concern, as noted by the Academy, is that bringing siting work forward may potentially prejudice community commitment to the next stage, which is highlighted in Fig. 3. Again, this demonstrates the need for establishing robust validated pre-characterization methods and pathways to provide a reasonable amount of information to decision-makers in potential host communities. As indicated in the Academy's report, early delivery of a GDF on a set date relies critically on the programme starting on time. Early progress clearly depends on the communities already in the process being prepared to take decisions about proceeding to the next stage.

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[3] See: The Royal Academy of Engineering, *Review of options for acceleration of geological disposal*, https://www.raeng.org.uk/publications/responses/review-of-acceleration-of-geological-disposal

[4] Id. – Section 19 "it would be sensible to proceed with exploratory boreholes in parallel with further geophysical investigations. The view of the panel was that for a less sensitive project, the first few boreholes would be sunk on a 'best guess' basis in order to obtain as much information on rock characterisation as quickly as possible. Bearing in mind that environmental and planning concerns may lead to the absolutely optimal borehole sites not being made available, the additional risk of using an element of 'best guess' based on a partial dataset of geophysical information does not increase programme risk as much as might be initially thought".

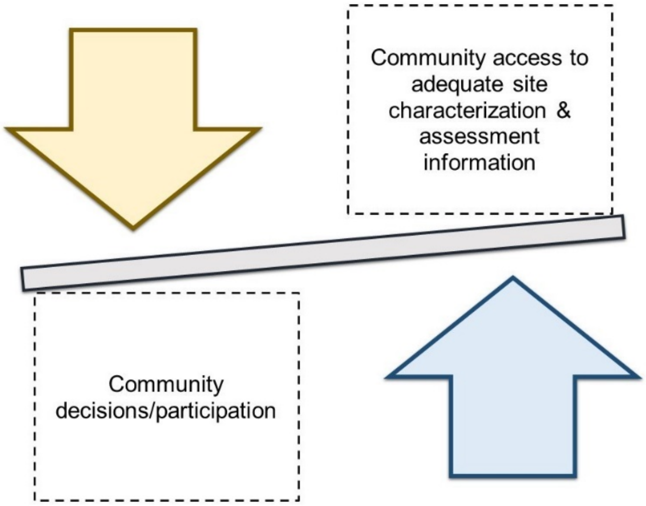
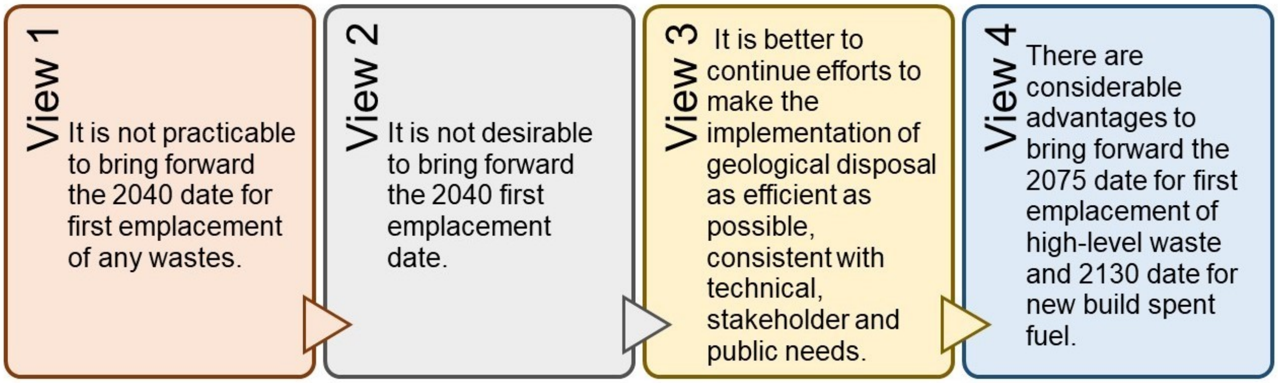


Fig. 3: Challenge to Community Decisions and Access to Adequate Site Characterization Information

The Committee on Radioactive Waste Management (CoRWM) advised in its 2012 consultation report[5], that acceleration should focus on bringing forward the dates for first emplacement of HLW, legacy spent fuels and new build spent fuels and on shortening the emplacement programmes for intermediate level waste (ILW), HLW and all spent fuels. Furthermore, CoRWM encouraged the Government to follow a structured approach, with stakeholder consultation, for the decision on whether and how to accelerate the geological disposal programme. CoRWM emphasized that there should be a focus on continuing to proceed as efficiently as possible, taking into account stakeholder and public views. CoRWM's view was that because of the process dependent nature of siting and constructing a GDF, this would limit an ability to accelerate implementation from both a technical and public participation standpoint. CoRWM's views are summarized in Fig. 4.


View 1 It is not practicable to bring forward the 2040 date for first emplacement of any wastes.

View 2 It is not desirable to bring forward the 2040 first emplacement date.

View 3 It is better to continue efforts to make the implementation of geological disposal as efficient as possible, consistent with technical, stakeholder and public needs.

View 4 There are considerable advantages to bring forward the 2075 date for first emplacement of high-level waste and 2130 date for new build spent fuel.

Fig. 4: CoRWM's Views on the Key Issues of the 2011 Report

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[5] CoRWM doc. 3006, *CORWM'S ADVICE TO GOVERNMENT ON OPTIONS FOR THE ACCELERATION OF THE iMPLEMENTATION OF GEOLOGICAL DISPOSAL*, 18 July 2012, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/225359/Geological_disposal_options_CoRWM_s_government_advice.pdf

1.2 Factors Influencing Radioactive Waste Management

A parallel requirement accessing the stable, clean, and plentiful sources of power production that nuclear power generation can provide is to demonstrate the ability to successfully close the fuel cycle in a cost effective and environmentally friendly manner [1]. To ensure the sustainability of a nuclear waste management program, typically one considers four compartments of sustainability. Shown in Fig. 5, one considers (1) the economic viability of a nuclear waste disposal facility; (2) environmental concerns are resolved using current science and technology; (3) the waste management facility siting, design, construction and operation reflects the desires and will of the host community; and, (4) policy making decisions are taken through informed decision-making processes that are open and transparent [2].

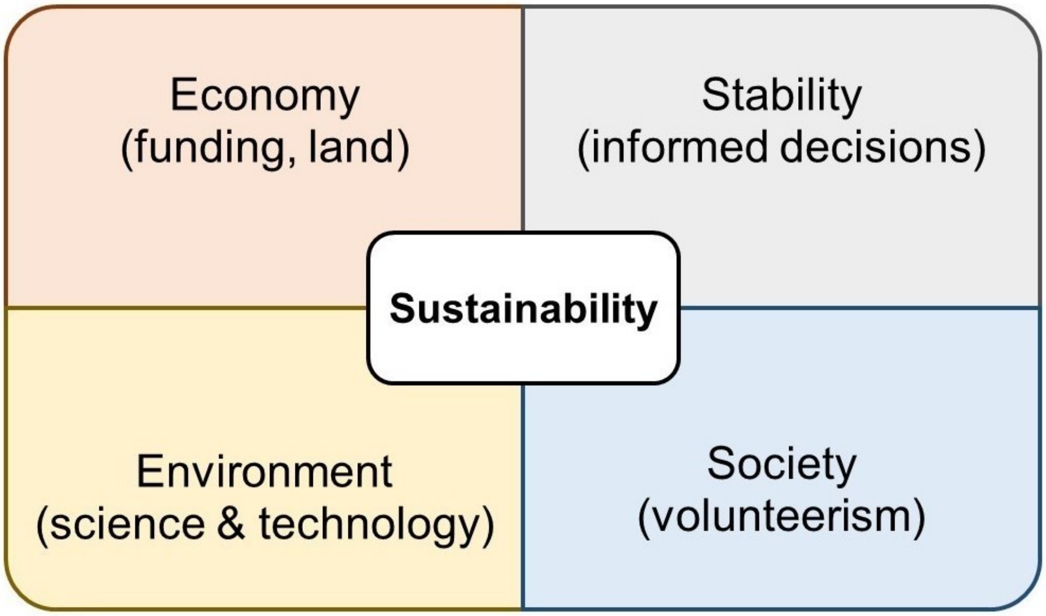

Fig. 5: Radioactive Waste Management Sustainability Model

Of course, there is a 'no-one-size-fits-all' solution to developing a radioactive waste management program. However, certain common factors can be observed in the various ongoing programs around the world. A radioactive waste management program that strikes the right balance among these factors has a greater potential to lead to the successful completion and operation of a long-term deep geologic disposal facility. One can observe a number of core influences that impact the character, development, and outcome of a radioactive waste management program. Collaboratively brought into practice, these influencers and their supporting pillars contribute to patterns of success. Ten influencers can be identified, through only the 'core' influencers are described in Fig. 6.

Fig. 6: Radioactive Waste Management Core Influencers

2.0 Site Selection

Site selection is a crucial process that is "not only for economic benefit, but also the sustainability, reputation and longevity of an… industry as a whole" [3]. Therefore, the process not only supports the long-term sustainability of radioactive waste management activities, but also nuclear power generating programs. A Geotechnical site characterization program serves to develop the base qualitative and quantitative knowledge below the subsurface at a given site, as shown in Fig. 7 [4]. Geotechnical assessments may also require that a decision-making body consider a resiliency strategy that "accommodate[s]… climate change into planning and design of system(s)]" [5]. Applying the use of non- or low-invasive pre-screening techniques can assist in directing and focusing more expensive subsequent investigation methods, as shown in Fig. 7 [6]. Following a similar pattern, Japan's Final Disposal Act[6] outlines the procedures for site selection in three stages: (1) literature survey; (2) preliminary investigation stage; and, (3) detailed investigation stage. Furthermore, the Japanese cabinet revised the Basic Policy in 2015 to provide for the identifying of potential areas for a repository using a three-tiered system[7] by applying a set of scientific site screening criteria, prior to the three-step selection process. An Organization for Economic Co-operations and Development, Nuclear Energy Agency, international peer review of Japan's siting system concluded that these processes are "generally in accordance with

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[6] Act No. 117 of 2000

[7] These were compartmentalized into: (i) potentially less suitable areas; (ii) potential suitable areas; and, (iii) potentially more suitable areas. See also: NUMO, On the publication of the "Nationwide Map of Scientific Features for Geological Disposal", https://www.numo.or.jp/en/what/topics_170801.html, Accessed April 23, 2020; Also see: Matsumoto, et. al. 2017, Scientific Basis for Nationwide Screening of Geological Disposal Sites in Japan, 6th East Asia Focus on Radwaste Management Conference, Osaka, Japan, November 27-29, 2017, http://eaform2017.aesj.or.jp/file/PapersList/Session1/(1C-2)_T.Matsumoto%20(NUMO).pdf, Accessed April 23, 2020.

international practice" and that such a step wise approach "allows the needs of individual communities to be addressed in stages"[8].

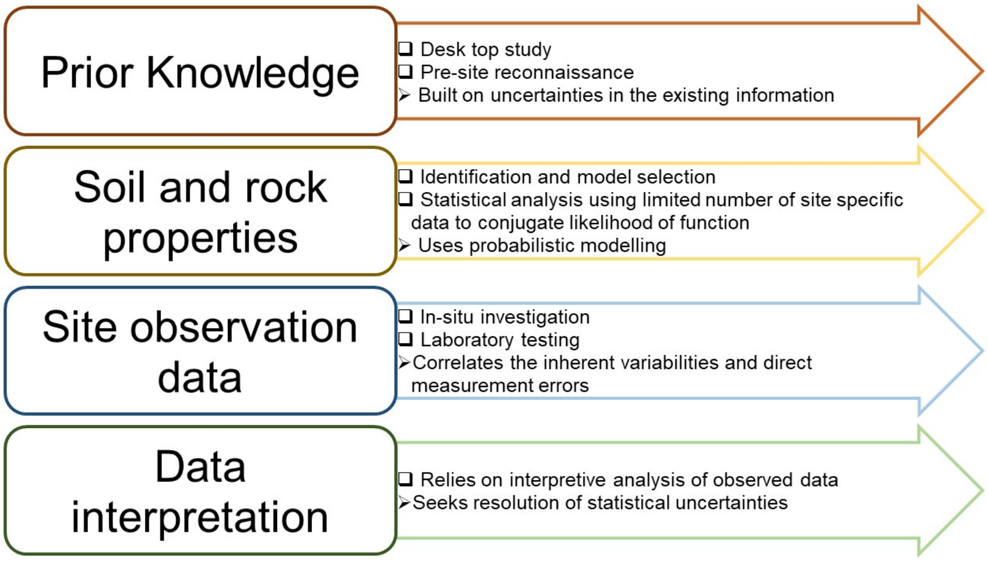

Fig. 7: Geotechnical Site Characterization Scheme

Site selection[9] of a deep geological repository begins with initial characterization[10] using indispensable applications associated with engineering geology and geotechnical engineering,

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[8] Organization for Economic Co-operations and Development, Nuclear Energy Agency, Japan's Siting Process for the Geological Disposal of High-level Radioactive Waste – An International Peer Review, (2016), https://www.meti.go.jp/shingikai/enecho/denryoku_gas/genshiryoku/hoshasei_haikibutsu/pdf/028_s02_00.pdf, Accessed April 23, 2020

[9] "Despite internal validity and massive replication, program evaluations may bias out-of-sample predictions and thus misinform policy discussions", *Wible, B. (2015). Uncovering site selection bias. Science, 349(6255), 1501-1502*; "Before applying…formulas, an individualized statistical analysis… must be made in a rather heuristic way", *Brunn, P. (2005). SITE SELECTION. Journal of Coastal Research, 23-35*; Heuristic analysis is an expert based analysis that determines the susceptibility of a system towards particular threat/risk using various decision rules or weighing methods; "Site selection still has to be a blend of art and science", *Tanyeri, D. (2018). Site Selection. Restaurant Development Design, 6(1), 42-47*; It is suggested by Potter, et. al., (2011) that "the approach to site selection [should] move beyond an informal process (i.e., interested sites sign up for participation) to a more objective, standardized, systematic approach", *Potter, J., Donovan, D., Weiss, R., Gardin, J., Lindblad, R., Wakim, P., & Dodd, D. (2011). Site Selection in Community-Based Clinical Trials for Substance Use Disorders: Strategies for Effective Site Selection. The American Journal of Drug and Alcohol Abuse, 37(5), 400-407.*

[10] "Geotechnical materials are natural materials, and their properties are affected by various factors during their formation process, such as properties of their parent materials, weathering and erosion processes, transportation agents, and conditions of sedimentation", *Cao, Wang, Li, Wang, Yu, & Li, Dianqing. (2016). Probabilistic approaches for geotechnical site characterization and slope stability analysis. Berlin: Springer*; "Interpolation or extrapolation from known data is required in order to form a prediction of the ground characteristics at any particular location. There is therefore inherent uncertainty in every ground model", *Paul D. (2019) A Simple Method of Estimating Ground Model Reliability for Linear Infrastructure Projects. In: Shakoor A., Cato K. (eds) IAEG/AEG Annual Meeting Proceedings, San Francisco, California, 2018 - Volume 2. Springer, Cham*;; "The technical forensic investigation requires collection of data, problem characterization, development of failure hypotheses, a realistic back-analysis, observations in situ and in some cases performance monitoring, and most importantly quality control of not only the formal but also the technical aspects of the work", *Lacasse S. (2016) Forensic Geotechnical Engineering Theory and Practice. In: Rao V., Sivakumar Babu G. (eds) Forensic Geotechnical Engineering. Developments in Geotechnical*

coupled with societal imperatives. However, it must be observed that during the initial stage of site characterization, one is having to work with numerous unavoidable variabilities[11] and uncertainties[12]. Added together, these different variabilities and uncertainties comprise the "total variability[13]" of site investigative inputs. The "total variability" input contains an internal core comprised of the "actual variability[14]" of soil and rock properties, coupled with other knowledge uncertainties, such as measurement errors and statistical uncertainty. It is the "actual variability" properties that structure site characterization selection processes. The "actual variabilities" directly affect the performance of geotechnical and geological systems that are of primary interest in site characterization [7].

Engineering. Springer, New Delhi; "there are design problems where only a more sophisticated analysis yields a more accurate answer", *Raju V., Daramalinggam J. (2019) Modern Geotechnical Practices. In: Ilamparuthi K., Robinson R. (eds) Geotechnical Design and Practice. Developments in Geotechnical Engineering. Springer, Singapore.*

[11] An explicit way of handling variability is to define variability using a stepwise resolution of variation points, *Jörges, S., Lamprecht, A., Margaria, T., Schaefer, I., & Steffen, B. (2012). A constraint-based variability modeling framework. International Journal on Software Tools for Technology Transfer, 14(5), 511-530.*; "Variability explicitly introduced in[to] the life cycle can help reduc[e] the uncertainty constraining the behavioral analysis into well-defined boundaries", *Dhungana, D., Seichter, D., Botterweck, G., Rabiser, R., Grünbacher, P., Benavides, D., & Galindo, J. (2013). Integrating heterogeneous variability modeling approaches with invar. Proceedings of the Seventh International Workshop on Variability Modelling of Software-intensive Systems, 1-5*; "Numerous variability modeling approaches exist today to support… application engineering activities", *Czarnecki, K., Grünbacher, P., Rabiser, R., Schmid, K., & Wąsowski, A. (2012). Cool features and tough decisions: A comparison of variability modeling approaches. Proceedings of the Sixth International Workshop on Variability Modeling of Software-intensive Systems, 173-182*; Domain engineering involves creating and maintaining a set of reusable artifacts… whilst during application engineering, these reusable artifacts are used to build the products and systems of the site. Application engineers can make specific choices (extension, change, customization, or configuration) that suit the required functionality for the designed features or systems, *Sinnema, M., & Deelstra, S. (2007). Classifying variability modeling techniques. Information and Software Technology, 49(7), 717-739.*

[12] When taken into consideration, the uncertainties applied to both interaction model and physical parameters "inspires [the] use of adaptive technology", *Xu, Z., Li, S., Zhou, X., & Cheng, T. (2019). Dynamic neural networks based adaptive admittance control for redundant manipulators with model uncertainties. Neurocomputing, 357, 271-281.*

[13] "aims at increasing the effectiveness of engineering by using models as key artifacts in the development process", *Liebel G., Marko N., Tichy M., Leitner A., Hansson J. (2014) Assessing the State-of-Practice of Model-Based Engineering in the Embedded Systems Domain. In: Dingel J., Schulte W., Ramos I., Abrahão S., Insfran E. (eds) Model-Driven Engineering Languages and Systems. MODELS 2014. Lecture Notes in Computer Science, vol 8767. Springer, Cham*; Can be viewed similar to a "brainstorming-oriented approach to problem solving that attempts to understand a problem from diverse perspectives", *Mussbacher G. et al. (2014) The Relevance of Model-Driven Engineering Thirty Years from Now. In: Dingel J., Schulte W., Ramos I., Abrahão S., Insfran E. (eds) Model-Driven Engineering Languages and Systems. MODELS 2014. Lecture Notes in Computer Science, vol 8767. Springer, Cham*; Allows for several scenarios to be devised to adjust for compatibility with observed proportions, *Pawlowsky-Glahn, V, Egozcue, JJ, Tolosana-Delgado, R, & Egozcue, JJ 2015, Modeling and Analysis of Compositional Data : Modeling and Analysis of Compositional Data, John Wiley & Sons, Incorporated, New York. Available from: ProQuest Ebook Central.*

[14] Knowing the reliable distributed variability "is valuable for improving the parameterization of hydrological models and land surface schemes over large areas", *Armstrong, R.N. 2011, Spatial variability of actual evaporation in a prairie landscape, The University of Saskatchewan (Canada)*; "direct observational constraints… [can] led to several conflicting hypotheses concerning the drivers [for designing a system]", *Feng, T., Su, T., Zhi, R., Tu, G., & Ji, F. (2019). Assessment of actual evapotranspiration variability over global land derived from seven reanalysis datasets. International Journal of Climatology, 39(6), 2919-2932*; "provides a great deal of information concerning the dynamic characteristics of a system", *Sofi, A., Muscolino, G., & Elishakoff, I. (2015). Natural frequencies of structures with interval parameters. Journal of Sound and Vibration, 347, 79-95.*

Information desired for the characterization of a particular site of interest is gathered through various means, as shown in Fig. 8. This information is then compiled to develop an analysis framework for directly quantifying the actual variability of the desired system [8].

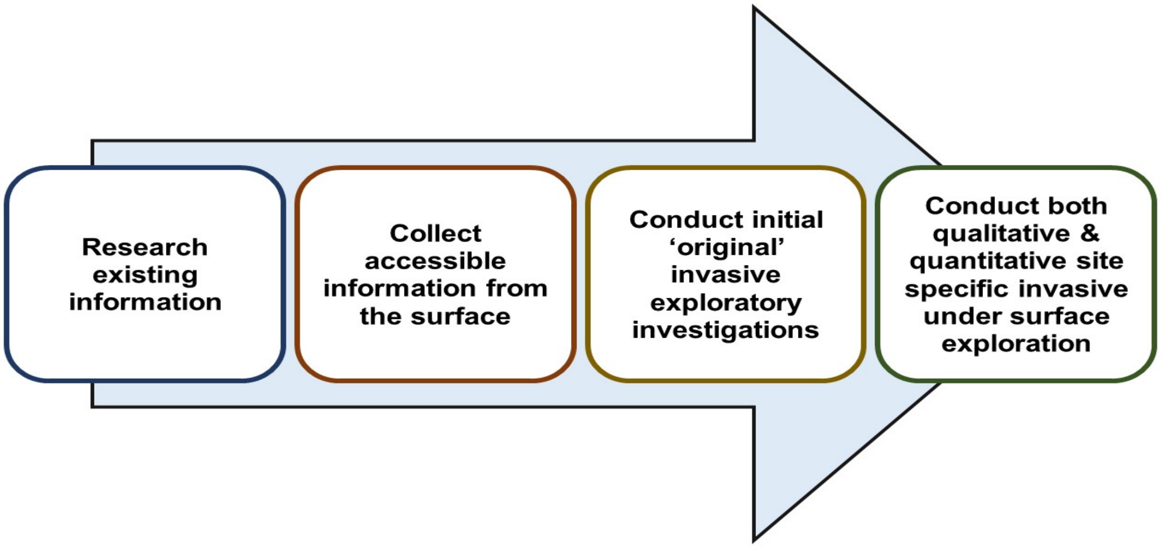

Fig. 8: Site Characterization Process

The quantification of "actual variability" is formulated as an inverse analysis problem for inferring the actual variability of the chosen characteristics imputed into the model output. The inverse analysis model must acknowledge statistical uncertainty during site characterization from observation data in geotechnical literature and practice. Shown in Fig. 9, assessing how much investigation conducted during various stages requires an assessment of how much uncertainty can be tolerated within these stages. Thus, one must carefully assess the specificity value of any information collected and presented at a certain stage in the siting process.

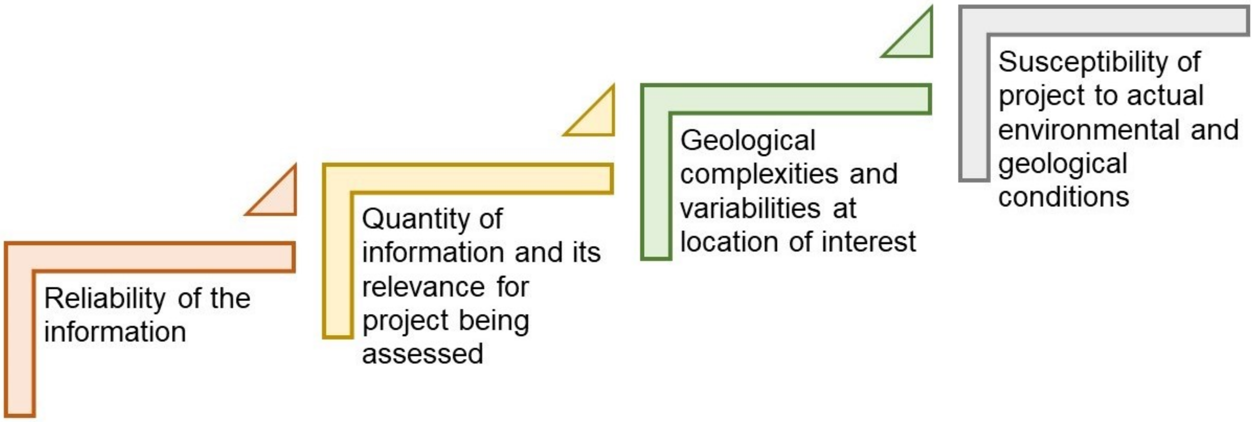

Fig. 9: Developing Usefulness of Information during Various Stages

To understand the possibility of using a site during the initial selection process, pathways or a conceptualized framework should be established and specific objectives identified. Collaborative processes should ideally be established early on between persons collecting relevant data (e.g., field data and samples) and those tasked with modeling the desired system [9]. Modeling that incorporates logical constancy, coherence with known facts, and reproducibility better formalizes into language a picture of how the designed system should work under sometimes uncertain assumptions. This will especially be of concern during initial "pre"-site investigation and first community involvement. The first stage of the site characterization process, as shown in Fig. 9, will rely heavily on expert judgement hypothesizing on the concepts and principles being submitted for consideration by the volunteer communities. Therefore, a suggested site characterization pathway can be derived, consisting of numerous steps including the collection of relevant environmental data, with the final goal of identifying optimal site conditions [10]. This site characterization pathway is presented in Fig. 10.

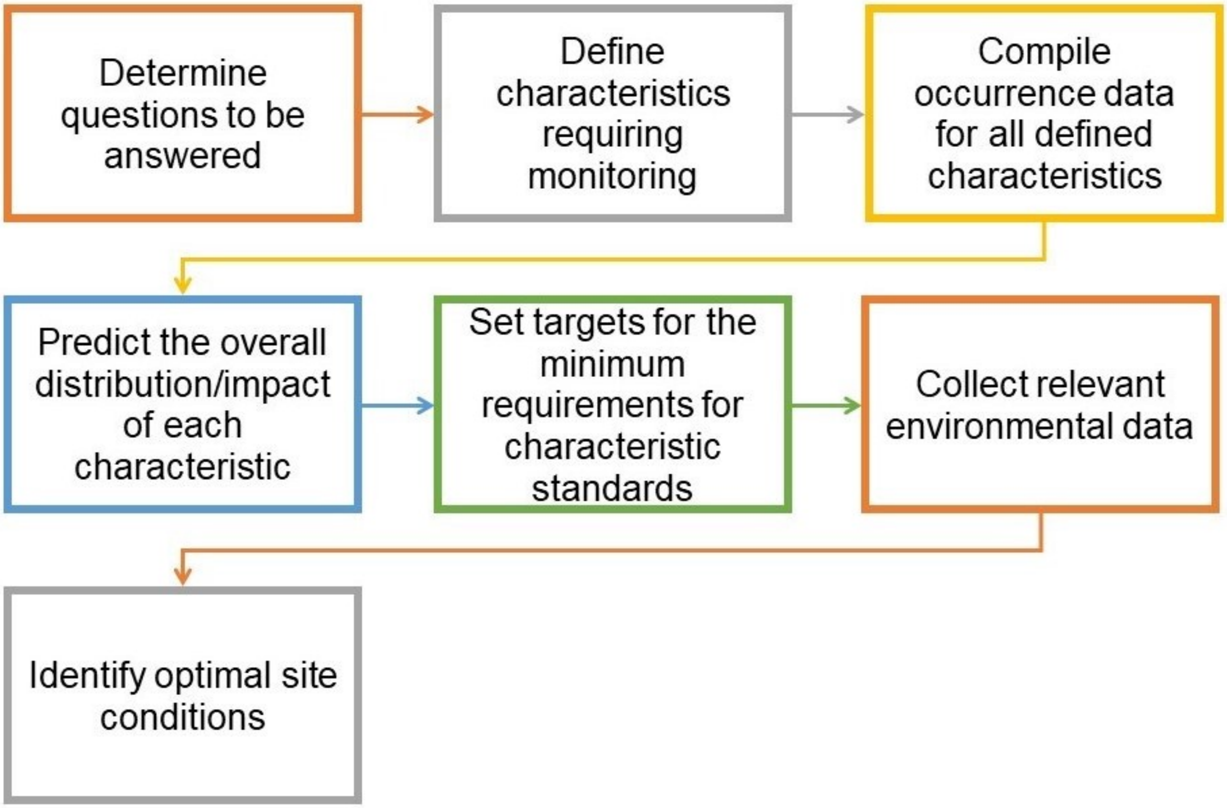

Fig. 10: Generic Site Characterization Pathway

2.1 Pre-site Characterization and Methods

Performing detailed analysis of features, technologies and processes that have the potential to impact the environment, human health and safety, economics, and/or project milestones is essential for developing a well-constrained risk analysis for project success. This requires that a project operator and regulators develop adequate risk analysis parameters identifying potential problem areas, which are validated through computational tools, to provide guidance on the probability of success. Such analyses can inform early decisions in the site characterization process for siting, exploratory investigations, technologies developed/used, as well as construction techniques. In the absence of site-specific data, this requires the analysis of subsurface strata using numerical simulations that rely on availably accessed data from the surrounding region [11]. Developing a pre-impact environmental site characterization model will assist in accelerating the implementation of a GDF in the U.K., by providing planning certainty and regulatory stability. A suggested three step pre-site characterization model is shown in Fig. 11.

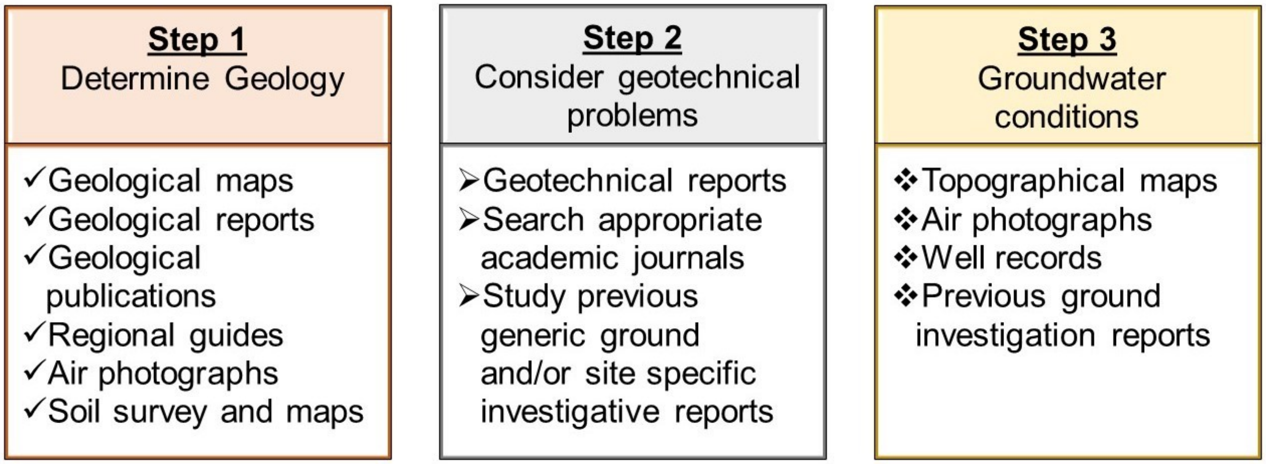

Fig. 11: Site Pre-Screening Step Model

Robust pre-site screening models and methods are essential in predicting potential project benefits and challenges at a potential site[15]. Where one is able to correlate successfully pre-investigations to actual conditions, numerous cost savings may be obtained at this juncture of the siting process. Similarly, when this is not possible, real costs are increased[16]. Determining within reasonable

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[15] "A "preliminary" determination that a site is suitable for development is a determination that it is one of several bona fide options from which one suitable site can be selected", *James H. Davenport. (1986). THE LAW OF HIGH-LEVEL NUCLEAR WASTE. Tennessee Law Review, 53, 481-799;* "[a] matrix of alternatives, portions of which have been considered by previous studies… may be a critical determinant of effectiveness…of [the] mission", *Salkeld, R. (1969). Multiple-based air- and ground-launch for inspection, rescue, and other space missions. Journal of Spacecraft and Rockets, 6(12), 1448-1453*; "Studies of parallel adaptations… are a complementary approach to understanding the repeatability of [a chosen system or design]", *Ellison, C., & Bachtrog, D. (2019). Contingency in the convergent evolution of a regulatory network: Dosage compensation in Drosophila. PLoS Biology, 17(2), E3000094.*

[16] Deterministic "methods hav[ing] applicability to obtaining vital factors for back analysis… allow costlier and difficult investigation methods to be avoided", *Saeidi, A., Maazallahi, & Rouleau. (2016). Assessment of slide surface and pre-slide topography using site investigation data in back analysis. International Journal of Rock Mechanics and Mining Sciences, 88(C), 29-33*; Cervantes & Wohlstetter (2006) used the following questions to determine suitability: "How are resources used to implement the promising practices successfully? What challenges [are] faced in implementing the promising practices and how [are] they addressed? What evidence exists that the promising practices [will result] in positive…outcomes?, *Cervantes, R., & Wohlstetter, Priscilla. (2006). Improving Literacy for English-language Learners: A Study of Promising Practices in California Charter Schools, ProQuest Dissertations and Theses*; "Not only must the geologist digest and analyze the field evidence, he must also satisfy the constraints imposed

accuracy cost estimations during the pre-site selection phase is critical for supporting project managers in the decision-making process. This allows sufficient leeway for decision makers to choose adequate alternatives and to avoid misjudging of solutions before significant investments have been made. The true cost to any construction project is impacted significantly by the decisions taken during the pre-site selection phase [12].

The pre-site selection methods rely on project management[17] to navigate complex processes, where measuring success and/or failure depends on the management strategy[18]. Successful projects are managed by "employing a subtle combination of elements… software tools and human expertise" [13]. Project management systems include a variety of management tools and techniques that are not equally applicable across all projects. Therefore, it can be difficult for project management to choose the appropriate tools and software packages in line with sought after project management theories. Again, having a robust validation program that can quickly and fully validate a chosen technology, risks, sensitivities and project success criteria is of paramount importance during pre-site and pre-design phases. Pre-investigations include mapping of the surface topography, mapping of the planned intersecting tunnels, drill holes and core samples[19], in situ and laboratory tests. Geological mapping in the study area includes rock identification, determination of the weak zones, and mapping of the significant fractures [14].

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by interpretation of the geologic history of the flanking regions"; *SCHUBERT, C.E. 1977, Seafloor Structure And Tectonics East Of Northern Lesser Antilles Islands, University of Miami.*

[17] In discussing the decommissioning of the Trojan Nuclear Plant in the late 1990's, one of the biggest observed challenges was a change of mindset from an "operating company" to a "project management" organization. An operating company uses basic project management techniques but focus its energy on executing operations. A "project management" organization focuses its energy on project management. There is a tendency to revert to old way of doing things. Simply, a GDF project must contain within the organization a flexibility to move between "operations" and "project management" focuses depending on the stage of development. The flexible ability to navigate between these two concepts will be key to accelerating the development of a GDF, *Milosevic, DZ, Patanakul, P, & Srivannaboon, S 2010, Case Studies in Project, Program, and Organizational Project Management, John Wiley & Sons, Incorporated, Hoboken*; "Unfortunately, not all organizations secure the enduring benefits initially promised by techniques. Many remain ineffective at managing and controlling change in order to achieve sustained benefits from their initiatives", *Project Management. (2011). BUSINESS: The Ultimate Resource*; "[Requires an] ability to see the big picture of the project through the identification of patterns or interconnections between situations that are not obviously related", *Chen, Tao, Fu, Meiqing, Liu, Rui, Xu, Xuanhua, Zhou, Shenbei, & Liu, Bingsheng. (2019). How do project management competencies change within the project management career model in large Chinese construction companies? International Journal of Project Management, 37(3), 485-500.*

[18] "The pre-implementation phase is the period of time between the three- and six- month anniversaries of the project's start", *Milosevic, DZ, Patanakul, P, & Srivannaboon, S 2010, Case Studies in Project, Program, and Organizational Project Management, John Wiley & Sons, Incorporated, Hoboken*, and indicates that from the time a site volunteers for selection that a robust pre-defined matrix should determine which sites or "less" or "more" suitable. Given the complexities of siting a GDF, a year to two-time frame would be reasonable to make such a determination.

[19] Prior to the new research boreholes in Viernheim and Heidelberg, geophysical pre-site surveys were performed to identify borehole locations that best achieve the projects requirements. These activities were based on knowledge previously ascertained about the deeper subsurface through seismic profiling and evaluation of boreholes of the oil and gas industry, which was quite intensively done in this area, *H. Buness, G. Gabriel, & D. Ellwanger. (2009). The Heidelberg Basin drilling project: Geophysical pre-site surveys. Eiszeitalter Und Gegenwart, 57(3/4), 338-366*; "The distribution of geoacoustic properties correlates with the areal distribution of surficial sediment physical properties, including grain size, porosity, and sediment bulk density, which supports the proposed links between environmental process, sediment physical properties, and sediment geoacoustic behavior", *Richardson, M., Lavoie, D., & Briggs, K. (1997). Geoacoustic and physical properties of carbonate sediments of the Lower Florida Keys. Geo-Marine Letters, 17(4), 316-324*;

Accelerating a GDF in the preplanning or during pre-site investigations will also require competences to be developed by those tasked with project implementation to reflect and make changes as needed. Such reflective flexibility during project implementation does not come naturally [15]. In fact, Canada's Nuclear Waste Management Organization includes such a scheme in its adaptive phased management system in order to maintain adaptability throughout all processes. Thus, 'action learning[20]' is incorporated into the process as a requirement to constantly "re-evaluate decisions where warranted, maintaining the option to change course and being prepared to act on new knowledge or information" [16].

2.2 CO_2 Siting Experiences

As the race to find solutions to the climate change challenge intensifies, countries are turning to novel solutions, including carbon capture and sequestration (CCS) initiatives. Communities are trying to correlate an understanding between technological projects that they are unlikely to have come across along with their "appropriate economic, social and political context[21] [17]. Through observing CCS siting activities with a view to understanding the prior knowledge and experiences of CCS technologies within potential host communities, a template for siting a GDF can be seen. CCS is the process where captured CO_2 is compressed into a dense liquid (technically a supercritical fluid). At chosen sites, this liquid is injected into appropriate geological formations a kilometer or more below the surface. There, the CO_2 is permanently disposed, or "sequestered,"

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[20] "The goal of risk management is to improve project performance by systematically identifying and assessing potential risks, developing strategies to reduce or avoid them, and maximizing opportunities", *Kim, M., Lee, I., & Jung, Y. (2017). International Project Risk Management for Nuclear Power Plant (NPP) Construction: Featuring Comparative Analysis with Fossil and Gas Power Plants. Sustainability, 9(3), 469*; It is within the early stages of large projects, when the project generally takes on the character that will come to define it through its lifespan. Given the wide array of choices and possible directions, certain pathways are decided upon and commitments to them escalate. A "path-dependent process may lead to a lock-in", even while these early stages are still fluid for traditional project management and governance mechanisms to be applicable; *Hellström, M., Ruuska, I., Wikström, K., & Jåfs, D. (2013). Project governance and path creation in the early stages of Finnish nuclear power projects. International Journal of Project Management, 31(5), 712-723*; Saunders, et. al., (2016) conclude that even though the civil nuclear sector exhibits a "highly process-orientated approach to uncertainty, [that is] proactive and comprehensive, ***[this] also had an undesired consequence – that of slowing progress on projects, and leading to an inexorable shift of deadlines into the future***, *Saunders, F., Sherry, A., & Gale, A. (2016). Dualities and dilemmas: Contending with uncertainty in large-scale safety-critical projects. Construction Management and Economics, 34(9), 657-675.*

[21] Note Morgan, et. al. (2012), discussion surrounding public participation and engagement: "Successful commercial deployment of CCS will be at least partially contingent on local community acceptance of individual geological sequestration (GS) projects. While this is true for all large infrastructure developments, it is especially critical in the case of GS ***because there is a lack of awareness and understanding of GS among the general public, and host communities of existing pilot-scale and commercial-scale GS projects have been found to raise more concerns and questions than those of more established industries and technologies***." This is not dissimilar to findings and experience with GDF siting for nuclear waste. Most interesting is Jones, et. al., (2017) recommendation that US Federal legislation should ***"declare that sequestering carbon dioxide (CO2) in geologic formations to mitigate the detrimental effects of climate change is in the public interest"***; "Social acceptance, or the extent to which an innovation (e.g., a policy, technology) is endorsed or rejected by key social actors (e.g., politicians, financiers, and publics), is recognized as being necessary for the successful introduction and commercial success of such innovation", *Jones, C., Olfe-Kraaaaaeanutlein, B., Naims, H., & Armstrong, K. (2017). The Social Acceptance of Carbon Dioxide Utilisation: A Review and Research Agenda. Frontiers in Energy Research, 5, Frontiers in Energy Research, June 9, 2017.*

from the atmosphere[22] [18]. In 2010, the United States Environmental Protection Agency promulgated a new rule for geologic sequestration creating a Class VI well category[23]. Class VI rules apply only to wells that inject CO_2 for geologic sequestration. The main requirements for siting as established in Class VI rules is displayed in Fig. 12.

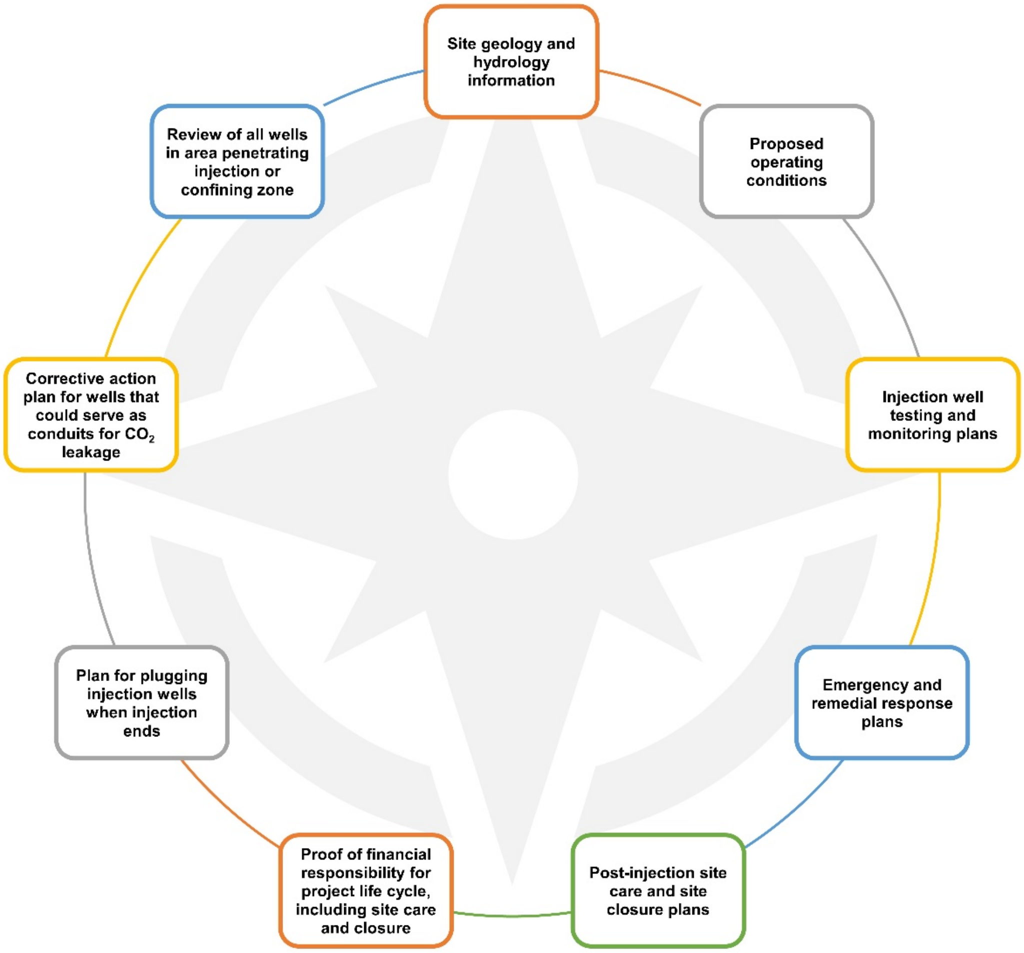

Fig. 12: EPA's Class VI Well CO_2 Geologic Sequestration Siting Requirements

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[22] CCS activities are considered to close the carbon cycle since the carbon contained in the fossil fuels came from the ground, and is returned to the ground. This is not dissimilar to the closing of the nuclear fuel cycle by storing radioactive waste in a GDF; "One of the main risks of CCS (Carbon Capture and Storage) is CO2 leakage from a storage site"; *Payán, M., Verbinnen, B., Galan, B., Coz, A., Vandecasteele, C., & Viguri, J. (2012). Potential influence of CO2 release from a carbon capture storage site on release of trace metals from marine sediment. Environmental Pollution (Barking, Essex: 1987), 162, 29-39.*

[23] Fed. Reg.Vol. 75, No. 237, Friday Dec. 10 2010: 2010; Vol. 40 C.F.R. Parts 124, 144, 145, 146, and 147, pp. 77230–77303, See https://www.govinfo.gov/content/pkg/FR-2010-12-10/pdf/2010-29954.pdf#page=59, Accessed March 24, 2020.

There are similar concerns for CCS Siting and GDF siting surrounding public acceptance. This is the area of greatest uncertainty and cause for delay. However, nuclear power is a relatively ‘old’ form of energy production, with generally formed opinions among population groups. There is limited research on public opinion with CCS siting because this is still a relatively new technology not widely employed. Commentators suggest that because this technology is largely unfamiliar to the public, opportunities most likely still “exist to influence public opinion in a way that could moderate community opposition to the siting of CCS infrastructure projects”[24] [19]. A dissertation submitted by Parfomak in 2012 found that greater familiarity with geologic sequestration has little influence on local site acceptance. Multivariate analysis found that “landowner acceptance of sequestration sites derives primarily from gender, concern for the local environment, trust in government, experience with industrial activity, and belief in the potential of conservation/renewables. Because views on these issues are persistent, it may be difficult to overcome landowner opposition through education” [20]. Parfomak concluded that due to these findings, the government would need to lower expectations for deploying this technology in the US. It is observed that other informal factors play a key role in determining public acceptance of siting a specific plant or activity system. These include “awareness and understanding of projects, fairness and trust, ownership of projects, scale and type of technology, or environmental concerns” [21]. A generic public engagement plan for siting CO_2 sequestration projects is shown in Fig. 13. Note that in many aspects this has similar features to siting a GDF.

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[24] In California, two communities participating in siting for actual sites raised concerns that "risk [of] carbon dioxide release, may lower property values, may increase the likelihood of natural disasters such as earthquakes, may change the 'character' of the town, would involve the construction of a pipeline infrastructure, and [would be] expensive." *Gabrielle Wong-Parodi, Isha Ray, and Alex Farrell, "Community Perceptions of CCS in California's Central Valley," Unpublished memorandum to CRS (Energy and Resources Group, Univ. of California, Berkeley: April 8, 2008)*; “benefits and costs of CCS depend on where power plants and processes in the supply chain are located*”, Sekar, A., Williams, E., & Chester, M. (2014). Siting is a constraint to realize environmental benefits from carbon capture and storage. Environmental Science & Technology, 48(19), 11705-11712*; “For a conceivable fossil-fuelled electricity production strategy with CO_2 capture, the availability and location of storage options play a key role for [power] plant siting… [additional consideration would be] CO_2 transport infrastructure… required between the plant and the storage locations, [and thus on should seek] to minimise the associated distance, …or alternatively to locate fossil-fuelled power plants close to CO_2 storage sites”, *Baufumé, S., Hake, J., Linssen, J., & Markewitz, P. (2011). Carbon capture and storage: A possible bridge to a future hydrogen infrastructure for Germany? International Journal of Hydrogen Energy, 36(15), 8809-8821*; “four technologies have notably risen to the forefront of academic and public discourse: nuclear power, carbon capture and storage (CCS), wind power, and geoengineering. The particular interest of these four approaches lies in the fact that they reflect both energy production and climate control technologies, are often socially controversial, and present complex challenges of governance”, *Poumadere, M., Bertoldo, R., & Samadi, J. (2011). Public perceptions and governance of controversial technologies to tackle climate change: Nuclear power, carbon capture and storage, wind, and geoengineering. Wiley Interdisciplinary Reviews, 2(5), 712-727*; “The final stage of CCS is the storage (or disposal) of carbon dioxide (CO_2) away from the atmosphere, typically in a deep geological formation. ***Although the risks posed by CO_2 differ from those presented by nuclear waste and spent fuel, the similarities—most noticeably the vast time scales involved and the preference for concentration and containment—make a comparison of regulatory approaches to such risks relevant and informative***”, *Langlet, D. (2010). Resting in Peace? Regulating the Geological Storage of Radioactive Waste and Carbon Dioxide: Swedish and European Perspectives. Risk, Hazards & Crisis in Public Policy, 1(4), 108-134.*

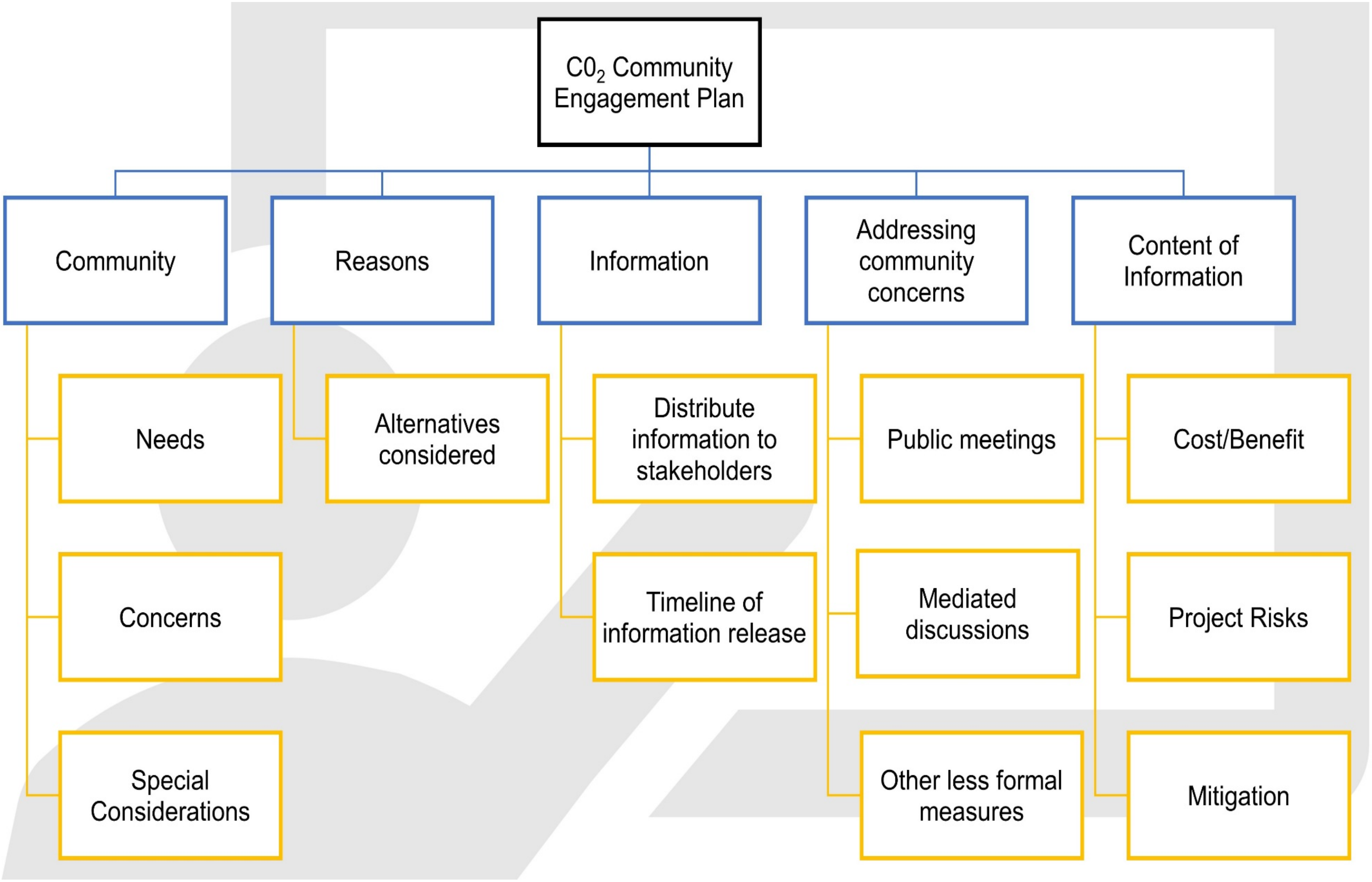

Fig. 13: Generic Public Engagement Plan for CO_2 Geologic Sequestration Siting

To determine areas of interest for siting CCS, research seeks to estimate CO_2 storage capacity in deep geologic formations as a pre-requisite for an efficient and safe application of CCS. Potential siting methods use several static algorithms and dynamic methods, on a variety of scales ranging from country[25] to site-specific for seeking estimates of storage resource capacities for CO_2 geological sequestration[26]. Cantucci, et. al. (2016) remark that CO_2 storage capacity estimation using presumed sites is still a challenge since many approaches are available [22].

3.0 Geology

The chosen geology of a GDF is a central factor as engineered barriers must perform the chosen natural environment over geologic time periods. Thus, the engineered barriers become part of the natural system. However, these chosen natural environment are difficult to know and predict. The performance of the engineered barriers depends, foremost, on the geologic environment near the waste canisters. How the geological environment behaves over time is difficult to assume and relies on modeling for excessive time periods [23]. This is, of course, a departure from standard project management practices. Usually, one plans project spans for tens and up to a hundred or so years. In this instance, one plans for a project for hundreds and thousands of years.

The process for beginning to look for an acceptable GDF site geology begins with a consideration of "geomorphology, geological structure, tectonic regime, and hydrogeology of the region, mineral composition and petrophysical and sorption properties of the host rocks, geochemistry of radionuclides, etc." [24]. Using these data, computer models of the proposed system are predicted within a reasonable degree of certainty of the time and scale desired for the system. A number of host geology have been studied and/or chosen as a GDF suitable host environment. As with everything in life, each potential host environment comes with its pluses and negatives. Rocks that have low water content and water penetrability, enhanced thermal conductivity and sorption capacity, and geological bodies much larger than repositories and located at depths unsusceptible to weathering, are considered favorable, as long as these allow for ease of mining activities. It

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[25] Large scale CO_2 reservoirs (over 1Mt/year) are limited in Japan due to the complicated geological situation, *Kimura, S., Honda, K., Kitamura, K., Taniguch, I., Shitashima, K., Tsuji, T., & Fujikawa, S. (2014). Preliminary Feasibility Study for On-Site Hydrogen Station with Distributed CO2 Capture and Storage System. Energy Procedia, 63, 4575-4584*;

[26] "Applying the lessons learned from the oil and gas industry in such areas of research as geology, geophysics rock mechanics, fluid flow, drilling, computer modelling and simulations, enables us to predict what with happen to CO_2 in the subsurface", *Cook, PJ 2012, Clean Energy, Climate and Carbon, CSIRO Publishing, Victoria*; "Data and understanding of the reservoir characteristics built up over the lifetime of oil and gas extraction in UK waters means that the oil and gas storage sites are well understood, and there is a high level of confidence associated with the models used to simulate the process of geological storage". Mander, et. al., (2011) also note methods used to identify the elements of the reservoir assessment, which are associated with the greatest uncertainty, are similar to that used in the nuclear industry, *Mander, S., Polson, D., Roberts, T., & Curtis, A. (2011). Risk from CO2 storage in saline aquifers: A comparison of lay and expert perceptions of risk. Energy Procedia, 4, 6360-6367*; For windfarms, Luengo & Kolios (2015) recommend developing methodology for extrapolating failure modes and risk identification and an assessment of the factors that influence costs should be carried out, as well as assessing the systems overall health, *Luengo, M., & Kolios, A. (2015). Failure Mode Identification and End of Life Scenarios of Offshore Wind Turbines: A Review. Energies, 8(8), 8339-8354*; "understanding how a specific decision choice will fit and impact on a local context is key to identifying sustainable solution", *Zurbrügg, C., Caniato, M., & Vaccari, M. (2014). How Assessment Methods Can Support Solid Waste Management in Developing Countries-A Critical Review. Sustainability, 6(2), 545-570.*

should be noted that no natural rocks meet all the above requirements. Salts have poor sorption properties, and clays are too sorptive. While clays allow facile mine working conditions, the mines require reinforcing structuring actions. Crystalline rocks are quite hard, which makes mine working in them much more difficult than in salts and clays. However, mines and tunnels in crystalline rocks preserve their shape almost indefinitely. Crystalline rocks are resistant to high temperatures associated with HLW heat release [24].

3.1 Crystalline Rocks

The disposal of spent nuclear fuel in granitic rocks have been the major focus in the search for a suitable repository. The Forsmark site, in Sweden, included the mapping of more than 2000 outcrops at the current ground surface. Such data taken together with other airborne and ground magnetic data, formed the basis for the construction of a bedrock geological map providing significant insight into the spatial distribution of different rock units and the more significant ductile and brittle structures on this surface [25]. Due to high-level nuclear wastes' radioactivity, significant amounts of heat for thousands of years are released. The released heat increases the temperature of the waste packages, and then the temperature of the rock that forms the repository tunnels. Interactions among the rock, water, and waste with the increased temperatures may affect the repository's safety. Despite their complexity, these processes can be predicted closely enough to help forecast the repository's long-term behavior. These thermally driven processes fall into three categories, as shown in Fig. 14.

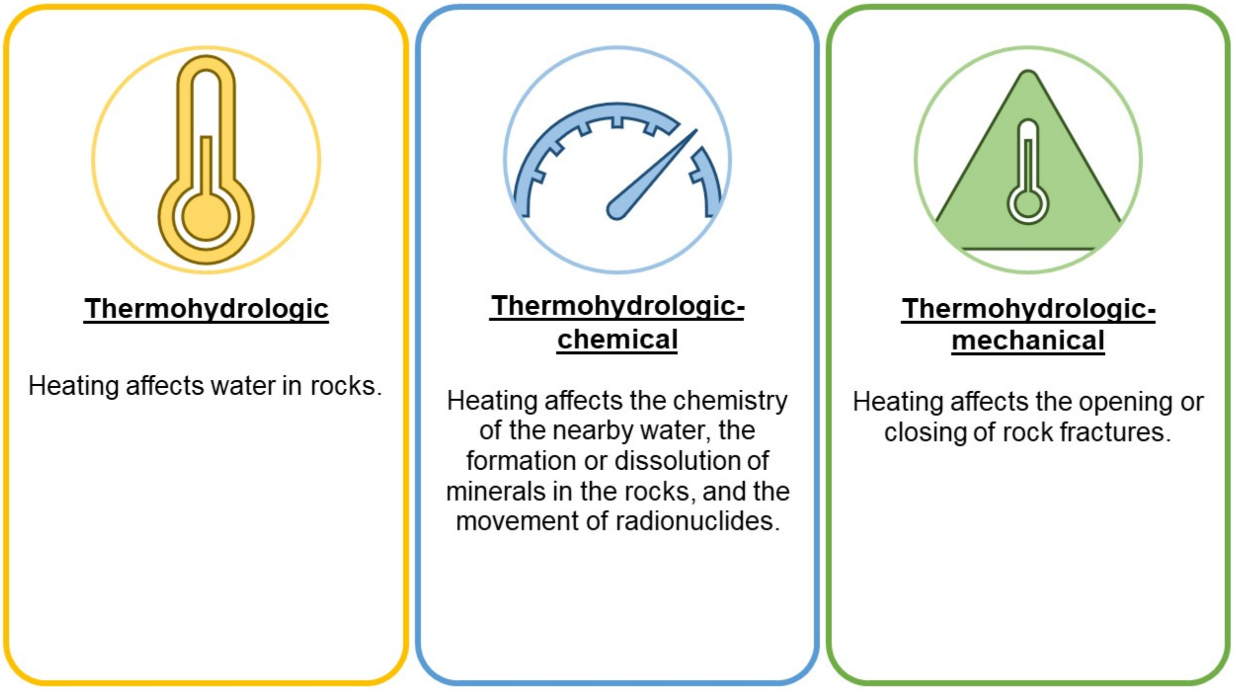

Fig. 14: Thermally Driven Processes

Each of these processes could affect repository performance in important ways, such as by increasing water seepage into emplacement drifts, easing the flow of water between emplacement drifts, altering the chemical composition of seeping water, and accelerating the transport of radionuclides from the drift floor through the underlying rock. [23].

Sweden's siting activities at Forsmark used a cross disciplinary model. Site investigations were interpreted and evaluated into a cross-disciplinary site-descriptive model (SKB 2008[27]), see Fig. 15. Using the site-descriptive model shown in Fig. 15, an understanding of the site's properties within the different disciplines could be ascertained, as well as an initial assessment of the uncertainty in these properties. Geologically, the Forsmark area consists of crystalline bedrock that belongs to the Fennoscandian Shield. The area is located on the Precambrian peneplain along the shoreline of the Baltic Sea [26].

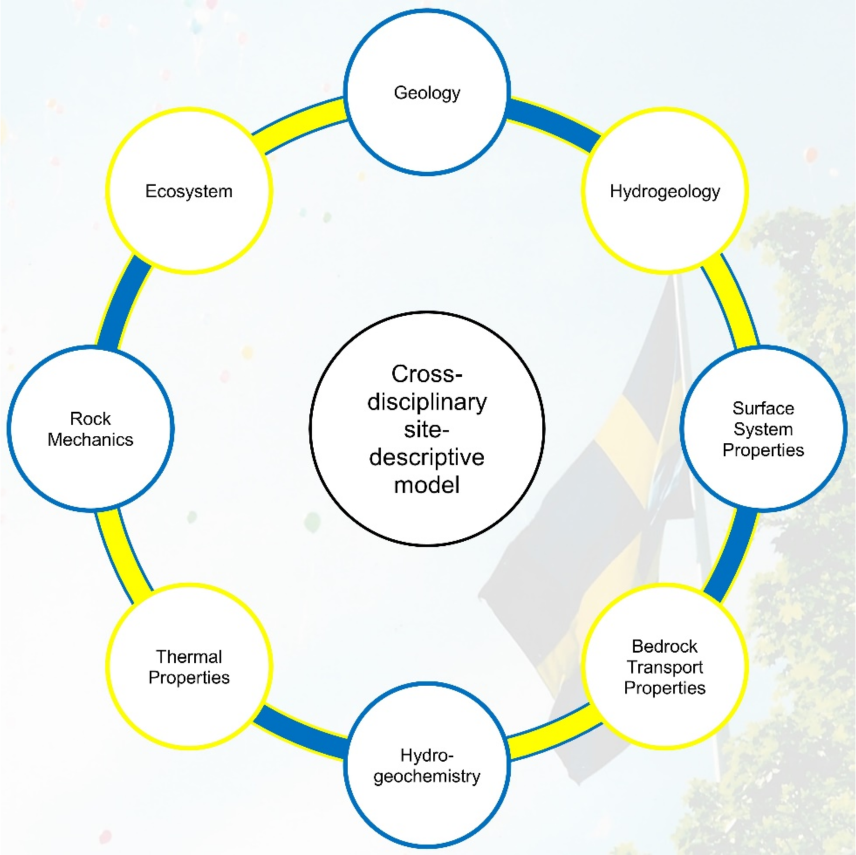

Fig. 15: Forsmark Site Descriptive Model

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[27] SKB (2008) Site Description of Forsmark at Completion of the Site Investigation Phase. SDM-Site Forsmark. SKB Technical Report TR-08-05. Swedish Nuclear Fuel and Waste Management Co, Stockholm, 539 pp, https://skb.se/publication/1868223/TR-08-05.pdf; SKB (2011) Long-term Safety for the Final Repository for Spent Nuclear Fuel at Forsmark. Main Report of the SR-Site Project. SKB Technical Report TR-11-01 , Vol I - III. Swedish Nuclear Fuel and Waste Management Co, Stockholm, 892 pp, https://skb.se/upload/publications/pdf/TR-11-01_vol1.pdf, https://skb.se/upload/publications/pdf/TR-11-01_vol2.pdf, https://www.skb.se/publikation/2345580/TR-11-01_vol3.pdf

Fig. 16 demonstrates Swedish Nuclear Fuel and Waste Management Co's (SKB) site characterization and exchange of information pathways for developing models for input into the characterization process at Forsmark.

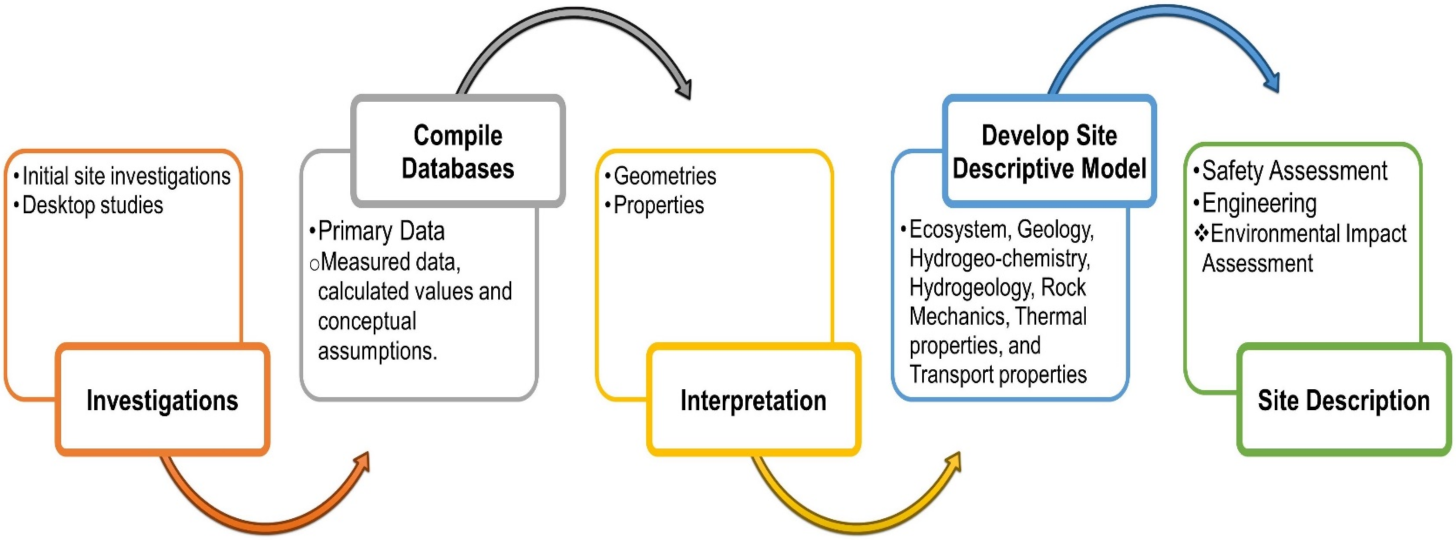

Fig. 16: Forsmark Information Exchange and Site Path Descriptive Model

3.2 Bentonite Clay

Bentonite is used for many industrial and household applications. Owing to its plasticity, low permeability and swelling capacity, compacted bentonite is also used as seal, backfill and buffer for nuclear waste repositories[28] [27]. A number of sites, especially in Europe (e.g., Bure site, France, Mont Terri site, Switzerland, and Boom clay at the Mol site, Belgium), have all been under intensive scientific investigation[29]. Studies have occurred both in the field and on laboratory scale for understanding a variety of rock properties and their relationships to flow and transport processes associated with geological disposal of nuclear waste. Bossart et. al. (2018)[30] specifically raises the question - "[can] a rock laboratory like Mont Terri alone [be] sufficient to assess the performance of a geological repository at a real site"? Bossart et. al. (2018) believe that this is not the case. According to Bossart et. al. (2018), because there will be geological differences between proposed sites in northern Switzerland (e.g. flat-lying Opalinus Clay with very few faults, different

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[28] See *Rutqvist, J., Zheng, L., Chen, F., Liu, H., & Birkholzer, J. (2014). Modeling of Coupled Thermo-Hydro-Mechanical Processes with Links to Geochemistry Associated with Bentonite-Backfilled Repository Tunnels in Clay Formations. Rock Mechanics and Rock Engineering, 47(1), 167-186.*

[29] There are two type of underground rock laboratory (URL), generic and site specific. 40% of URLs are constructed in granite, while 60% are in sedimentary rocks, such as bedded salt/salt domes, clays, tuffs.

[30] Recommended - contains a selection of research results from over 20 years of research. *Bossart, Milnes, Bossart, Paul, & Milnes, Alan Geoffrey. (2018). Mont Terri Rock Laboratory, 20 Years Two Decades of Research and Experimentation on Claystones for Geological Disposal of Radioactive Waste (1st ed. 2018. ed., Swiss Journal of Geosciences Supplement, 5). Cham: Springer International Publishing: Imprint: Birkhäuser.*

sub-units, confining rocks, stress situation, burial history etc.), additional site-specific investigations are required for developing a repository safety case. Bossart et. al. (2018) adds that the Mont Terri project can, however, "deliver strong arguments for a safety case through confident characterisation of properties governing repository evolution" [28]. Therefore, while there are lessons to be learned from such investigative activities, it is not likely that one to one comparison will be able to be achieved in advancing progress for speeding up a geologic repository in clay media.

Carbon steel, compacted bentonite and concrete have all been proposed as candidate materials for the engineered multi-barrier system in clay formations[31]. Carbon steel and compacted bentonite can be used as overpack and buffer, respectively, while concrete and cement are used for mechanical support in shotcrete, tunnel seals and plugs. The interactions of these materials with clay host rock produces a hyper-alkaline fluid, which could potentially affect the physical and chemical properties of the host geology [29]. Canada's NWMO plans to emplace copper-coated steel containers surrounded by a bentonite clay buffer for its waste in a GDF[32]. As mentioned,

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[31] See also *Herry Poernomo. (2010). SORPTION AND DISPERSION OF STRONTIUM RADIONUCLIDE IN THE BENTONITE-QUARTZ-CLAY AS BACKFILL MATERIAL CANDIDATE ON RADIOACTIVE WASTE REPOSITORY. Indonesian Journal of Chemistry, 10(3), 276-284*; In Sweden, oxygen and sulphide are potential corrosive elements that may threaten the integrity of the copper canisters. "The importance, for a HLW repository, of the results obtained on the survival and activity of microorganisms in compacted bentonite can be summarized as follows: at the start of the deposition, there will be a canister, bentonite blocks and a hole in the rock. Microorganisms indigenous to the bentonite, and possibly introduced during bentonite block production, will be present inside the bentonite. The results obtained for survival of non-spore-forming microorganisms in bentonite, reported above, suggest that the number of viable microorganisms will decrease rapidly and that very few viable cells will be present at full compaction. The only survivors will be microorganisms that have formed spores", *Pedersen, K., Motamedi, M., Karnland, O., & Sandén, T. (2000). Cultivability of microorganisms introduced into a compacted bentonite clay buffer under high-level radioactive waste repository conditions. Engineering Geology, 58(2), 149-161*; "presents a numerical model to deal with the pore water composition in bentonite barrier in the evolving geochemical environment which includes bentonite, concrete and clay in a high level radioactive waste repository designed in clay formation, the model considers the following processes: advection, diffusion, aqueous complexation, mineral dissolution/precipitation and cation exchange", *Yang, Q., Lu, W., & Li, P. (2011). A Numerical Sensitivity Analysis to Bentonite Parameters for a Long Term Geochemical Evolution of a HLW Repository in Clay. Advanced Materials Research, 356-360, 1258-1261*; The paper presents a fully coupled thermal, hydrological, chemical, and mechanical (THMC) simulation of a nuclear waste repository in a clay formation with a bentonite-backfilled EBS for 1000 years. Two scenarios were simulated for comparison: a case in which the temperature in the bentonite near the waste canister can reach about 200 °C and a case in which the temperature in the bentonite near the waste canister peaks at about 100 °C. The model simulations demonstrate some degree of illitization in both the bentonite buffer and the surrounding clay formation. The modeling scenarios show a calculated decrease in smectite volume fraction in bentonite ranges from 1 to 8% of the initial volume fraction of smectite in the 100 °C scenario and 1–27% in the 200 °C scenario. Chemical changes in the 200 °C scenario could also lead to a reduction in swelling stress up to 15–18% whereas those in the 100 °C scenario result in about 14–15% reduction in swelling stress for the base case scenario. Model results also show that the 200 °C scenario results in a much higher total stress than the 100 °C scenario, mostly due to thermal pressurization, *Zheng, L., Rutqvist, J., Birkholzer, J., & Liu, H. (2015). On the impact of temperatures up to 200[degrees]C in clay repositories with bentonite engineer barrier systems: A study with coupled thermal, hydrological, chemical, and mechanical modeling. Engineering Geology, 197, 278.*

[32] See also: *Marshall, Michaela H.M, Mckelvie, Jennifer R, Simpson, André J, & Simpson, Myrna J. (2015). Characterization of natural organic matter in bentonite clays for potential use in deep geological repositories for used nuclear fuel. Applied Geochemistry, 54, 43-53; Samper, J., Naves, A., Lu, C., Li, Y., Fritz, B., & Clement, A. (2011). Conceptual and numerical models of solute diffusion around a HLW repository in clay. Physics and Chemistry of the Earth, 36(17), 1714-1720*; Contains hydrothermal experiments performed using flexible Au/Ti Dickson reaction cells mounted in an externally heated pressure vessel at 150–160 bars and temperatures up to 300 °C for five to six-weeks. *Cheshire, Caporuscio, Rearick, Jové-Colón, & McCarney. (2014). Bentonite evolution at elevated pressures*

while copper is generally thermodynamically stable, corrosion can occur due to the presence of sulphide under anaerobic conditions. A 2017 study sought to understand transport of sulphide through the engineered barrier system to the used fuel container. Three-dimensional modelling results suggest sulphide transport through a bentonite buffer to be non-uniform due to the unique geometry of the used fuel container. The 3D transport modelling presented in the study was able to determine sulphide flux distributions at the used fuel canister (UFC) surface that would not be possible using 1D or 2D models. The variation of sulphide flux values at the UFC surface using 3D modelling can be used for scoping calculations, analysis of parameters, and refinement of the EBS design. [30].

A Korean study in 2018, employed a numerical model using the coupled relationship between the initial conditions of dry density and thermal–hydraulic properties of the compacted bentonite buffer in high-level waste repositories. In addition, the study applied the firefly algorithm to identify the optimal initial condition of the buffer, based on the numerical model. Results showed the minimum peak temperature was 77.89 °C at the optimal initial condition where the dry density was 1683 kg/m^3. The results were verified using the convergence test and parametric study. This finding gives a guideline for producing a bentonite buffer condition in the design of a repository [31].

In Switzerland, a well-defined siting selection process in the clay media has been developed. Using a three staged investigative process, it incorporates a blended science and consent-based model. The Swiss Siting Stages and Framework are presented in Fig. 17 [32].

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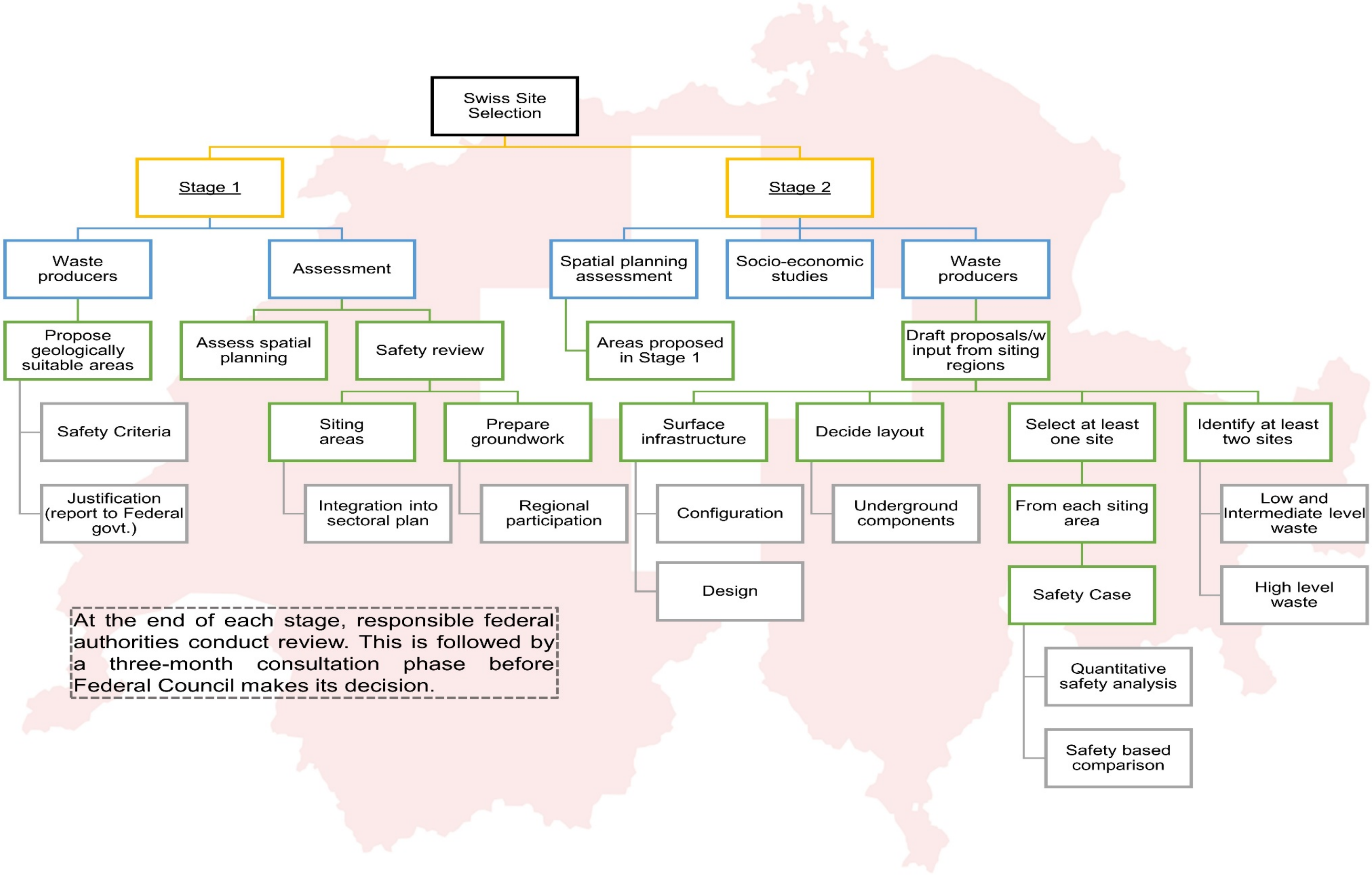
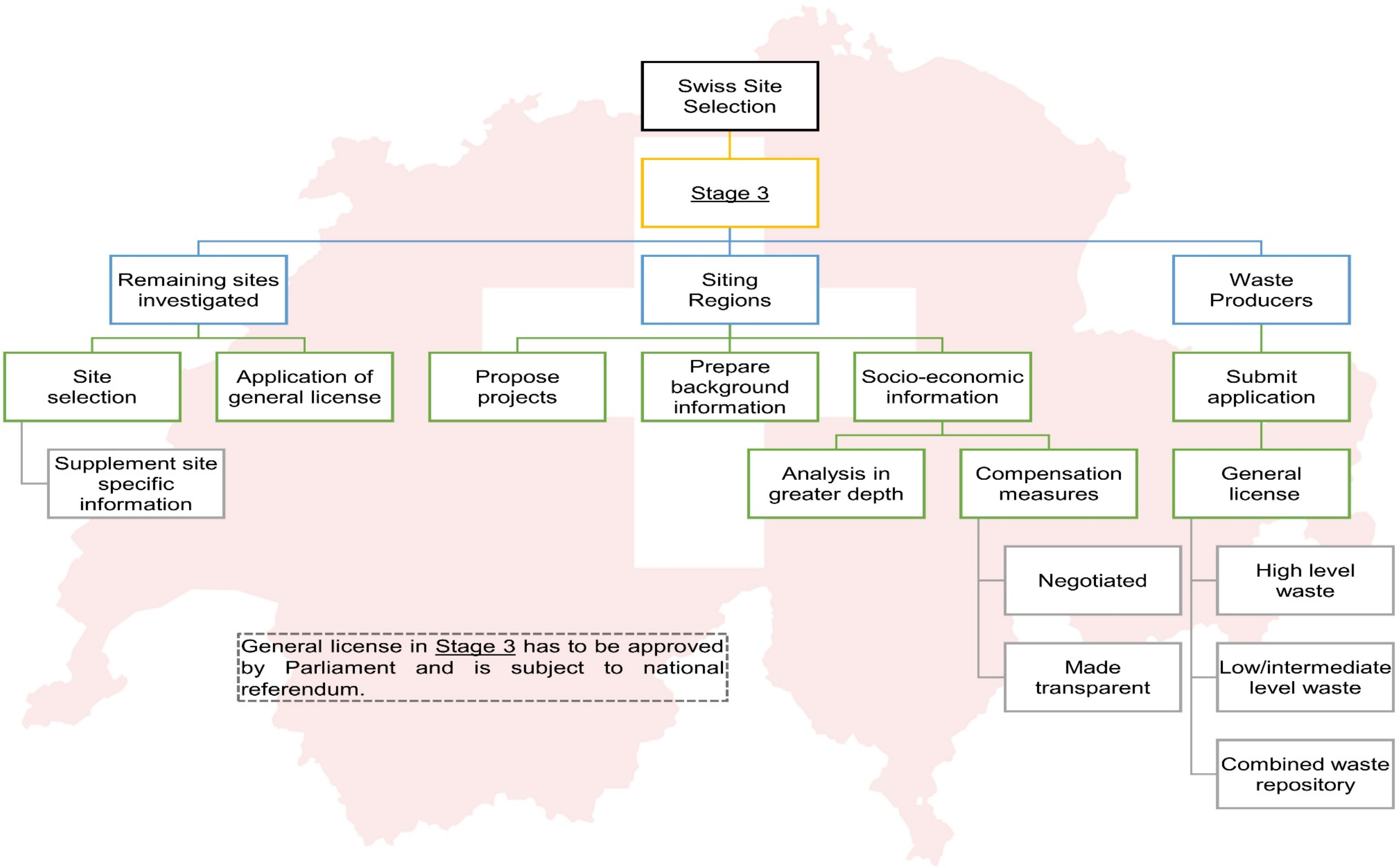
and temperatures: An experimental study for generic nuclear repository designs. The American Mineralogist, 99(8-9), 1662-1675; A study of the French design considers the interactions between groundwater and bentonite, as well as between the corrosion products of steel overpacks and bentonite, may modify the chemical and physical properties of the selected swelling clay buffer, *Marty, N., Fritz, B., Clément, A., & Michau, N. (2010). Modelling the long-term alteration of the engineered bentonite barrier in an underground radioactive waste repository. Applied Clay Science, 47(1), 82-90.*



At the end of each stage, responsible federal authorities conduct review. This is followed by a three-month consultation phase before Federal Council makes its decision.

Fig. 17a: Swiss Siting Stages and Framework – Stages 1 & 2



General license in Stage 3 has to be approved by Parliament and is subject to national referendum.

Fig. 18b: Swiss Siting Stages and Framework – Stage 3

3.3 Salt

Rock salt is considered a potential medium as a host geology for a GDF because of several assets. In particular, its near-zero primary permeability (i.e., undisturbed salt is water and gas tight), its very low porosity, its high ductility, its healing capacity and its relatively high thermal conductivity as compared to other shallow-crustal rock types make it a suitable geology. It is this ability to easily mine and work such stable geological areas with hundreds of years' experience that make this medium so attractive. Additionally, the run-of-mine salt may be used to backfill mined open emplacement areas. Because of these advantages, rock salt has been studied since the 1960s.

One of the world's first GDF began operation in 1999 at the Waste Isolation Pilot Plant Site (WIPP) for disposal and isolation of defense-related transuranic nuclear waste (equivalent to long-lived, intermediate-level waste) [33]. Transuranic, or TRU waste[33] began accumulating in the 1940s with the beginning of the nation's nuclear defense program. As early as the 1950s, the US National Academy of Sciences recommended deep disposal of long lived TRU radioactive wastes in geologically stable formations, such as deep salt beds. Bedded salt is free of fresh flowing water, easily mined, impermeable and geologically stable. This creates the ideal environment for permanently isolating long-lived radioactive wastes. An additional value in using deep salt beds is the way salt rock seals all fractures and naturally closes all openings[34]. Throughout the 1960s, government scientists searched for an appropriate site for radioactive waste disposal, eventually testing a remote desert area of southeastern New Mexico where, 250 million years earlier, evaporation cycles of the ancient Permian Sea left a 2,000-foot-thick salt bed [16]. The WIPP characteristic's siting criteria is presented in Fig. 18 [34].

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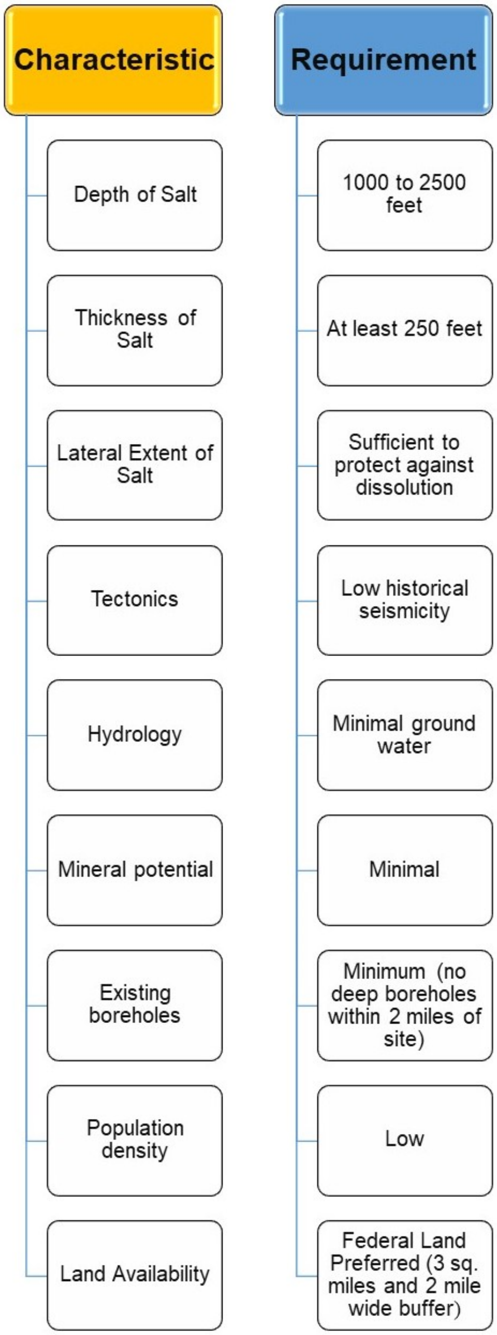
[33] Transuranic radioactive waste, or TRU, is one of several types of waste handled by the U.S. Department of Energy (DOE). Transuranic waste contains manmade elements heavier than uranium, such as plutonium, hence the name "trans" or "beyond" uranium. Transuranic waste material is generally associated with the human manipulation of fissionable material dating back to the Manhattan Project through today, and primarily consists of clothing, tools, rags, residues, soil, and debris. There are two categories of TRU waste. The handling of TRU waste is determined by its composition. Contact-handled (CH) TRU waste can be safely handled by workers under controlled conditions. Waste that is considered Contact-Handled means that it can be safely handled without remote equipment, although workers never actually touch the waste without protective barriers provided by special clothing or equipment. CH TRU waste will make-up approximately 96 percent of the total volume of waste to be disposed at WIPP. *See: Transuranic Waste and Waste Isolation Pilot Plant (WIPP), https://www.energy.gov/em/services/waste-management/waste-and-materials-disposition-information/transuranic-tru-waste; Backgrounder on Radioactive Waste, https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/radwaste.html; and, Transuranic Waste Processing – UCOR www.ucor.com/docs/TRU_waste_fact_sheet.pdf.*

[34] These geologic formations consist mainly of sodium chloride rock. The primary salt formation containing the WIPP repository is about 2,000 feet thick, beginning 850 feet below the surface. Salt offers the following advantages: (1) Most deposits of salt are found in stable geological areas with very little earthquake activity; assuring the stability of a waste repository. (2) Salt deposits demonstrate the absence of flowing fresh water that could move waste to the surface. Water, if it had been or were present, would have dissolved the salt beds. (3) Salt is relatively easy to mine. (4) Rock salt heals its own fractures because of its plastic quality. That is, salt formations will slowly and progressively move in to fill mined areas and safely seal radioactive waste from the environment. *See: WHY SALT WAS SELECTED AS A DISPOSAL MEDIUM, Waste Isolation Pilot Plant, U.S. Department of Energy, http://www.wipp.energy.gov/fctshts/salt.pdf.*



Characteristic	Requirement
Depth of Salt	1000 to 2500 feet
Thickness of Salt	At least 250 feet
Lateral Extent of Salt	Sufficient to protect against dissolution
Tectonics	Low historical seismicity
Hydrology	Minimal ground water
Mineral potential	Minimal
Existing boreholes	Minimum (no deep boreholes within 2 miles of site)
Population density	Low
Land Availability	Federal Land Preferred (3 sq. miles and 2 mile wide buffer)

Fig. 19: WIPP Characteristics and Required Siting Criteria

Furthermore, in Germany, a complete safety assessment analysis was performed for the Gorleben site, describing all aspects which are of importance for a heat-generating nuclear waste repository in rock salt. Initially, Germany pursued a geological repository rock in salt because it is viewed as particularly favorable as a host rock for the final disposal of high-level waste. Germany felt it has the necessary scientific experience and extensive mining knowledge for final waste disposal in rock salt. The German Disposal Concept before 2013 is presented in Fig. 19. German studies indicated that under natural stratification conditions, the permeability of the rock salt toward gases and liquids is extremely low. Additionally, it was determined from German studies that rock salt exhibits a high level of specific thermal conductivity. For this reason, rock salt is particularly well suited as a host rock for high-level waste since the heat can be dissipated to the surrounding rock far better than in the case of crystalline or argillaceous rock, for example [35].

Blanco et.al. (2015) conducted a modeling effort to investigate the long-term response of a generic salt repository for heat-generating nuclear waste, including processes that could affect the geological (natural salt host rock) and geotechnical (backfill) barriers. Using a TOUGH-FLAC sequential simulator for coupled thermal–hydraulic–mechanical processes, modeling has recently been provided with a capability for large strains and creep. The responses of the saliferous host rock and the crushed salt backfill are modeled using dedicated constitutive relationships. Similarly, the coupling between the geomechanics and the flow sub-problems was performed on the basis of theoretical and experimental studies. The simulation results suggest that the excavation damaged zone is healed within the first few years. Once damage processes are over, predictions show that the initial tightness of the host rock is restored [33].

Germany's Federal government engaged in three site selection processes from the late 1950's through the 1970's (Figs. 20-22). Additionally, four phases of the selection process were conducted by the Land of Lower Saxony between 1976-77. A score was given depending on the degree to which the individual criteria were met and the criteria themselves were assigned a specific weighting. In Phase 4, the four sites near the salt domes at Wahn, Lichtenhorst, Gorleben and Höfer underwent another intensive investigation and were the subject of various discussions. The Höfer site was regarded as rather disadvantageous since it had been a salt mine. There were reservations concerning an army training ground at the Wahn site which the army did not want to surrender. The salt dome at Lichtenhorst had the disadvantage that it was located in the groundwater priority area for Hanover. The Gorleben site had the advantage that the salt dome extended for approximately 40 km^2, it had a depth of 300 to 3,500m and had not been previously mined. The Federal Ministry of Economic and Technology determined:

> "*The findings from exploration work conducted at Gorleben to date do not reveal any cause to doubt the suitability of the salt dome. The extension of the homogenous rock salt areas earmarked for the final disposal of high-level waste in the part of the salt dome explored up to now is actually bigger than originally presumed. Reports forecasting an impermeable layer of rock with a sufficient barrier function were positively reaffirmed. Due to its particular rock mechanical properties, it is very well suited to host a repository for high-level waste.*" [35].

However, as CoRWM observed in 2012, the process of siting, designing and constructing a GDF is heavily process dependent. On 27 July 2013, the *Act on the Search and Selection of a Site for a Repository for Heat-Generating Radioactive Waste and for the Amendment of Other Laws* (Repository Site Selection Act – StandAG) [1A-7a] entered into force, which provides for a newly revised consent and science based siting process to select comparative sites throughout Germany. This new process for locating a repository site covers all the potential host rock types occurring in Germany (i.e. salt, clay and crystalline rock) [16].

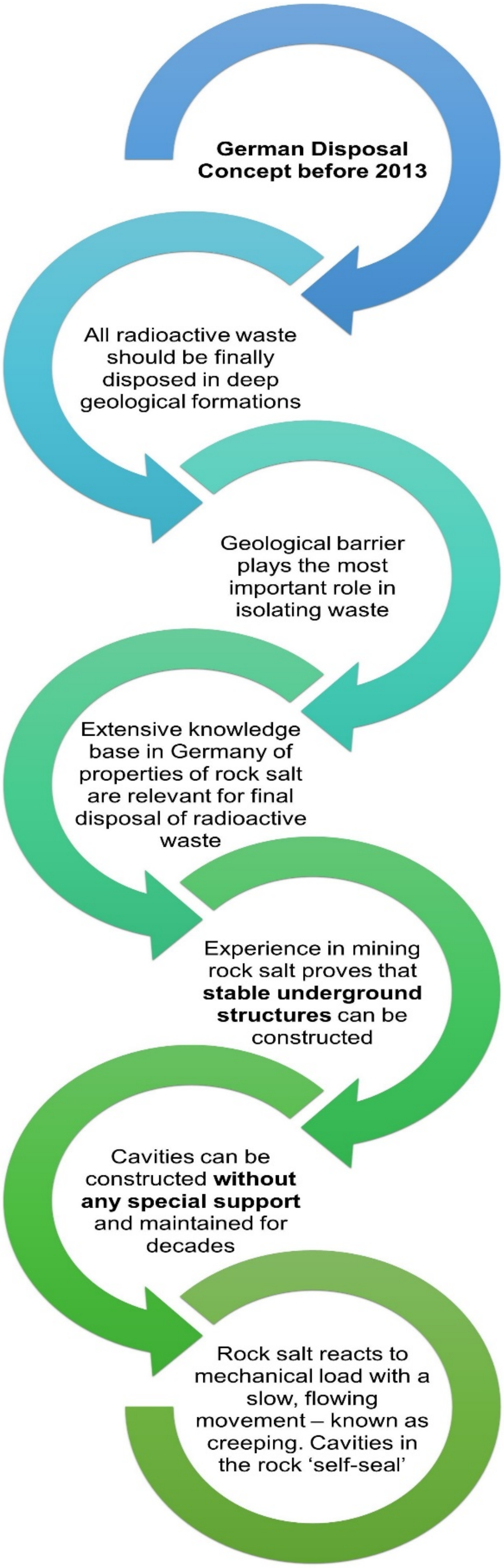


Fig. 20: Germany's GDF Concept before 2013

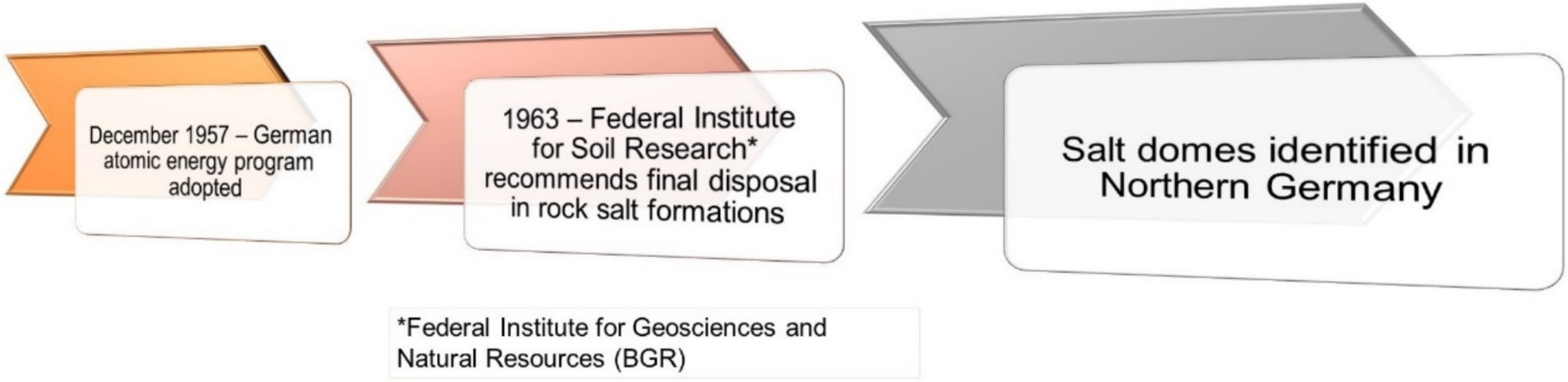
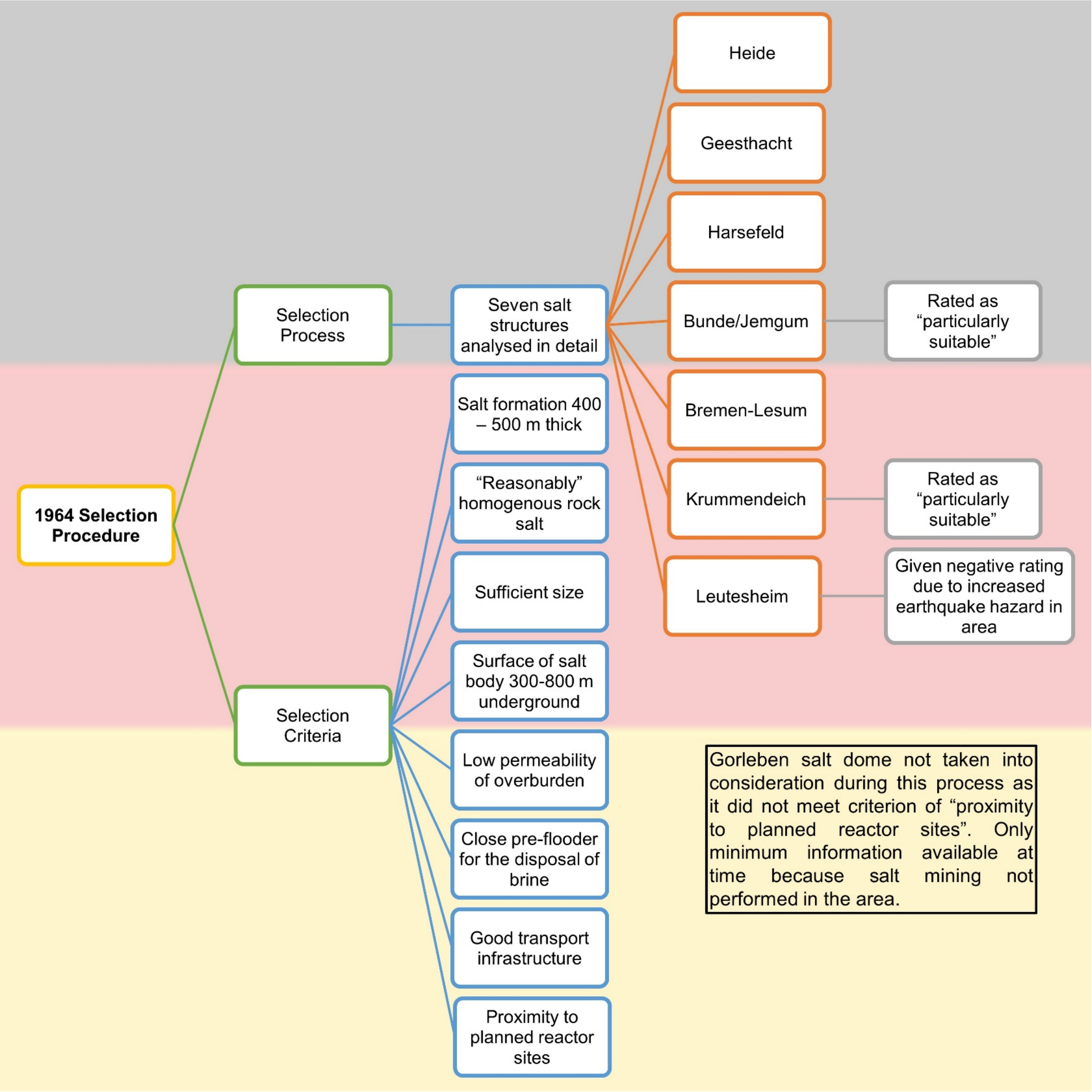


Fig. 21: Germany's First GDF Siting Initiatives (Stage 1)



Gorleben salt dome not taken into consideration during this process as it did not meet criterion of "proximity to planned reactor sites". Only minimum information available at time because salt mining not performed in the area.

Fig. 22: Germany's GDF Site Selection Process circa 1964 (Stage 2)

The selection focused on spatial planning and nature conservation. On account of the requirement that the site should not be a “local recreational or holiday area”, the entire Lüchow-Danneberg district with the Gorleben salt dome was eliminated.

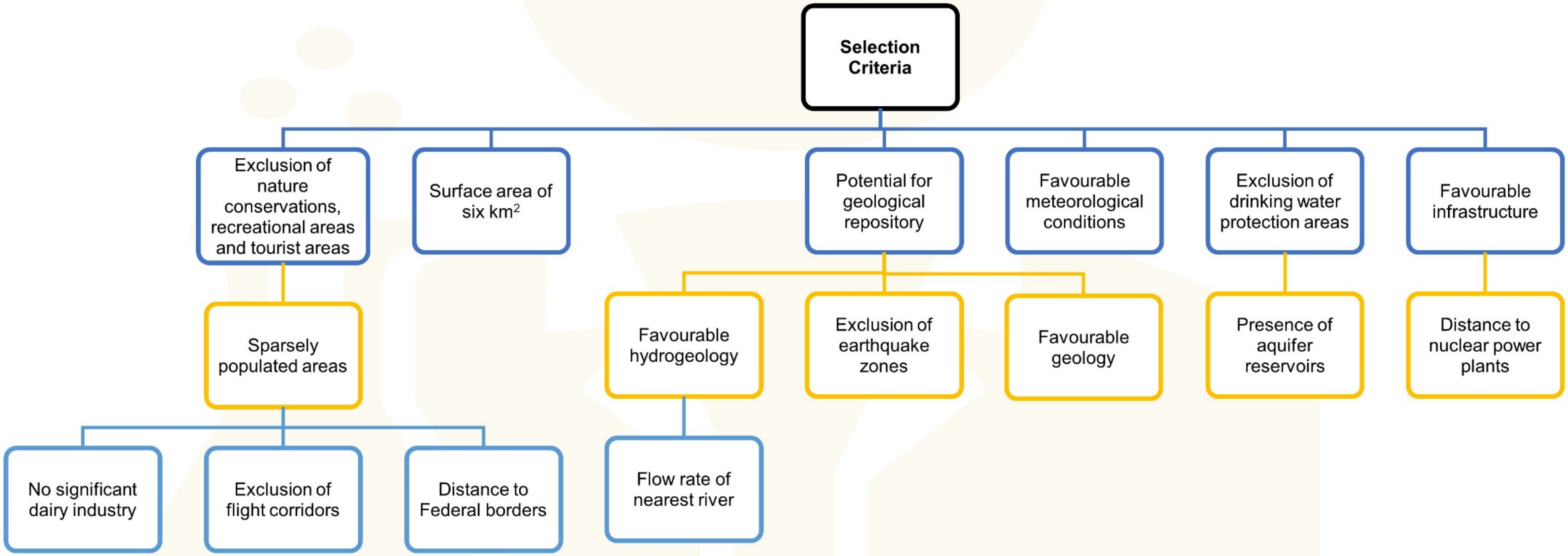
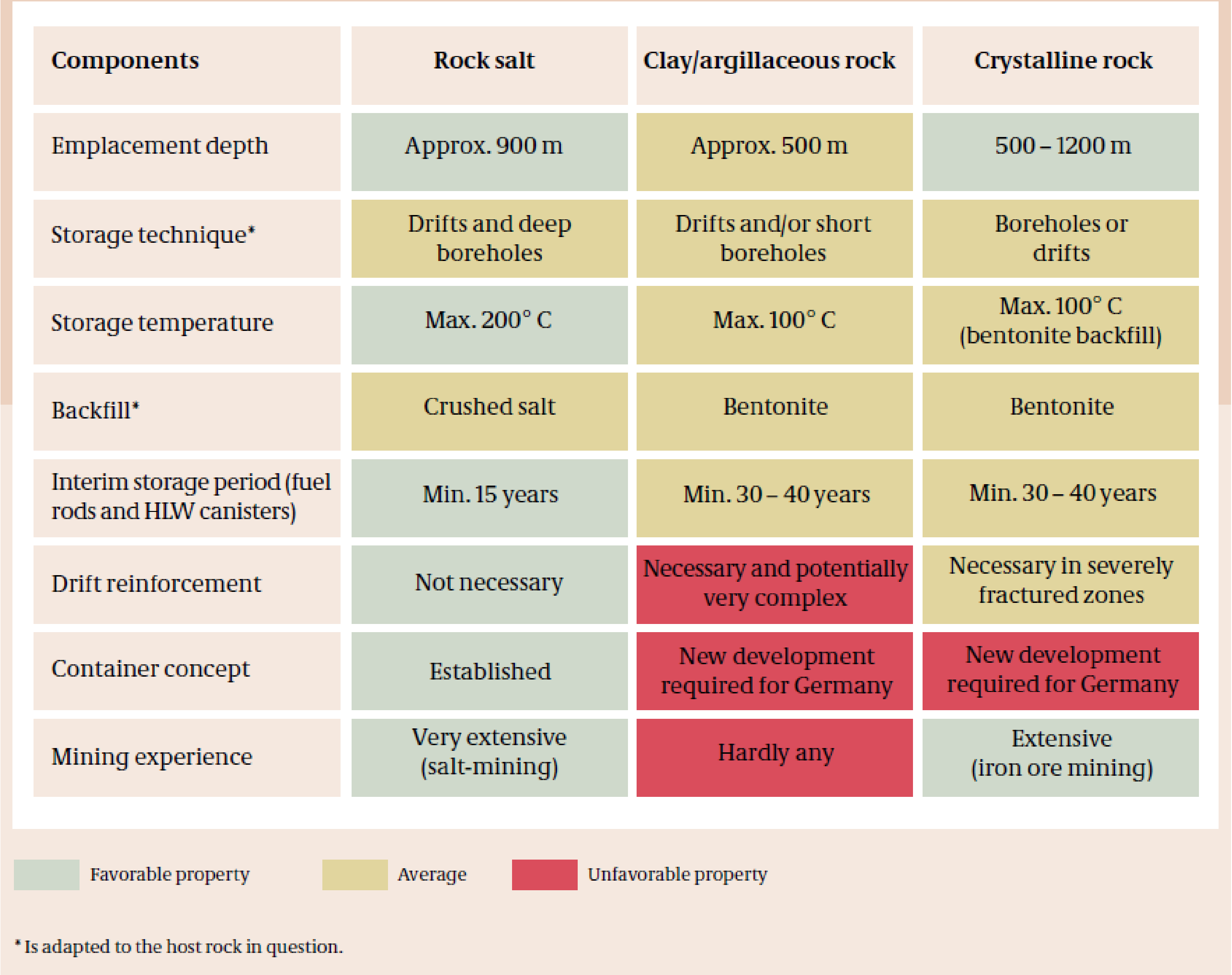


Fig. 23: Germany’s GDF Site Selection Process between 1973 - 1976 (Stage 3)

Before the 2013 Repository Site Selection Act (StandAG), crystalline rock in Germany was considered to have unfavorable properties (fractures with possibility of water intrusion) and would therefore not be considered any further. It was also observed that rock salt has considerable advantages over argillaceous rock. Additionally, from the German scientific perspective before 2013, the existing reserves of argillaceous rock in South Germany were considered less suitable than those in North Germany. Further, a comparison of the various repository concepts from the German perspective available as of 2008 is reproduced in Fig. 23 [35]. Bear in mind that this information has been scrubbed from German government sources, so as not to prejudice ongoing/current siting activities following the promulgation of the 2013 Repository Site Selection Act (StandAG).



Components	**Rock salt**	**Clay/argillaceous rock**	**Crystalline rock**
Emplacement depth	Approx. 900 m	Approx. 500 m	500 – 1200 m
Storage technique*	Drifts and deep boreholes	Drifts and/or short boreholes	Boreholes or drifts
Storage temperature	Max. 200° C	Max. 100° C	Max. 100° C (bentonite backfill)
Backfill*	Crushed salt	Bentonite	Bentonite
Interim storage period (fuel rods and HLW canisters)	Min. 15 years	Min. 30 – 40 years	Min. 30 – 40 years
Drift reinforcement	Not necessary	Necessary and potentially very complex	Necessary in severely fractured zones
Container concept	Established	New development required for Germany	New development required for Germany
Mining experience	Very extensive (salt-mining)	Hardly any	Extensive (iron ore mining)

🟩 Favorable property 🟨 Average 🟥 Unfavorable property

* Is adapted to the host rock in question.

Fig. 24: Comparison of Potential Repository Concepts in Germany Pre-2013

RWM recently explored the benefits of sharing technologies with the German programme, primarily focusing on technologies developed for evaporite geologies[35]. It concluded that while technology transfer events generally support the credibility of a national GDF programme, care must be taken as solutions are concept and site specific. The technical report remarked that technology transferred must either be fit for purpose or adapted appropriately (especially, considering differences in the regulatory systems). Option 1 in the technical report presents the straightforward transfer solution. It notes that "why [a certain] solution was chosen, why other options have been omitted and what experience and lessons have been learned during the process is not completely covered in the reports produced. Since many solutions had been developed over very long periods this problem becomes more pronounced" (pg. 115). However, as shown in Figs. 20-22, one can get a sense of the original desired siting characteristics and challenges in Germany. Additionally, Fig. 23 succinctly details the believed pros/cons of potential repository site host geology in Germany before 2013. These clearly indicate that the failures in repository siting for Germany were not technical/scientific, but because of a perceived lack of adequate consent-based protections.

4.0 Hydrology

Many modern geological applications, including the planning and safety assessment of underground nuclear waste repositories, require the determination of fluid flow pathways in rock masses[36]. A deep geological repository of spent nuclear fuel has to be safe for thousands of years. During this time, water–rock interaction on surface as well as in the rock around the repository will progress. All exogenous processes will depend on future evolution of climate [36]. It has generally been observed that a significant proportion of the conductive fractures located in the upper part of the bedrock is critically stressed, whereas at deeper levels the fractures are in a stable stress state. This change from critical to noncritical stress state is gradual and takes place within the depth interval of 300–400 m [37].

In a paper from 2014, Hökmark & Lönnqvist (2014) considered the vertical stress and horizontal stresses at all depths and during all periods of a glacial cycle at Forsmark[37]. It was determined that

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[35] *Technical Report, BGE TEC 2018-02, Technology Transfer: Identification and Quantification of Potential Benefits – Geologic Disposal Programme in Germany,* *https://rwm.nda.gov.uk/publication/technology-transfer-identification-and-quantification-of-potential-benefits-geologic-disposal-programme-in-germany/*

[36] Goncalves, et. al. (2012) developed a developed a mathematical expression for the thermo-osmotic permeability based on the physical molecular theory for thermo-osmosis. Using this theoretical expression, the thermo-osmotic permeability of argillaceous media can be estimated from their standard physical and chemical properties, providing both the sign and the order of magnitude of this permeability; this new expression substantially improves the estimation of this permeability, which varies over four orders of magnitude; *Goncalves, Julio, De Marsily, Ghislain, & Tremosa, Joachim. (2012). Importance of thermo-osmosis for fluid flow and transport in clay formations hosting a nuclear waste repository.(Report). Earth and Planetary Science Letters, 339 340, 1*; A mixing model is rated as good if coverage is high and deviation is low, *Gomez, J., Gimeno, M., Auque, L., & Acero, P. (2014). Characterisation and modelling of mixing processes in groundwaters of a potential geological repository for nuclear wastes in crystalline rocks of Sweden. Science of the Total Environment, 468-469, 791-803*

[37] "Hydraulically, the repository is drained during construction and operation. As a consequence of the rock properties at Forsmark, the times required for resaturation of the deposition tunnel backfill and of the buffer will vary considerably between different parts of the repository and are likely to range from a few tens of years to several thousand years", *Hedin, A., & Olsson, O. (2016). Crystalline rock as a repository for Swedish spent nuclear fuel.*

horizontal fractures would be the first ones to jack open, i.e., "to dilate in response to water pressures higher than the sum of the fracture normal stress and tensile strength and to lose the mechanical interaction between the fracture surfaces" and concluded that at "Forsmark, hydraulic jacking will be confined to the uppermost 200 m of rock" [38]. The proposed Yucca Mountain repository for spent nuclear fuel in the U.S. was subject to extensive geologic and hydrologic study for more than 20 years. The hydraulic conditions of the proposed repository were quite different than those at the Forsmark site. The water table is very deep beneath Yucca Mountain, where it is 500–750 m below the land surface, providing a large thickness of unsaturated rocks. The nature of unsaturated flow processes, which are important for assessing radionuclide migration, "are inferred mainly from hydrochemical or isotopic evidence, from pneumatic tests of the fracture systems, and from the results of in situ experiments" [39].

Hydrological concepts and methods are important parts of planning and permit applications for construction and operation. Specifically, such assessments provide useful guidelines for focusing monitoring and mitigation measures on a limited number of subareas. This requires the use of underlying classification and modeling tools associated with different types of assumptions and uncertainties[38]. Particularly, assumptions, parameter and model uncertainties related to water-flow models must be carefully weighed for a realistic integrated hydrological assessment. Especially, the geometries and hydraulic properties of fracture zones in crystalline rock, and hydraulic properties of rock structures are important factors that always should be accounted for in assessments of hydrological effects. Hydraulic fracturing in-situ stress measurements and acoustic image logging are tools which can assist with the characterization of a GDF. Using acoustic

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Elements (Quebec), 12(4), 247-252, "In the Forsmark case study, temporal variability of hydrometeorological parameters (including conceivable ranges of climate and sea-level changes) and uncertainties related to, e.g., the geometries and the hydraulic properties of fracture zones in the rock have been handled by comprehensive, transient model calibrations, and sensitivity analyses", *Werner, K., Collinder, P., Berglund, S., & Mårtensson, E. (2013). Ecohydrological responses to diversion of groundwater: Case study of a deep-rock repository for spent nuclear fuel in Sweden. Ambio, 42(4), 517-526*,

[38] "The study suggests that observations of hydro-mechanical property data and their spatial distribution can offer useful additional information for developing models of the regional scale hydraulic behaviour of a fractured host rock mass", *Blum, Mackay, Riley, & Blum, P. (2009). Stochastic simulations of regional scale advective transport in fractured rock masses using block upscaled hydro-mechanical rock property data. Journal of Hydrology (Amsterdam), 369(3-4), 318-325*; Chen, et. al., (2015) propose a new rock mass classification system named "QHLW" system for evaluating the suitability of the host rock for HLW disposal. In the system, the rock suitability evaluation of two different scales is considered, namely the repository and tunnel scales. The system considers both the long-term safety and constructability requirement of the host rock for disposal. Added are some additional parameters, including the fracture zone, groundwater chemistry and thermal effect because of their significant influence on the long-term safety of HLW disposal. The proposed system is thought to be a usable tool in identifying suitable rock volume of different scales for HLW disposal, *Chen, L, Wang, J, Zong, Z, Liu, J, Guo, Y, Jin, Y, . . . Zhang, M. (2015). A new rock mass classification system QHLW for high-level radioactive waste disposal. Engineering Geology, 190, 33-51*; A Coupled thermo-hydro-mechanical behaviour of the boom clay was utilized. Additionally, studies related to peak temperature, thermally induced pressurization of boom clay pore water, on the repository design was analysed. The modelling results demonstrated there exists a strong coupling between the thermal, mechanical hardening behaviour and the hydraulic response. Results showed that while the temperatures reached in this disposal concept are not of concern, the additional mechanical load should be considered. For safety assessment, a low hydraulic conductivity is favoured to reduce the possibility of advective flow, which causes an additional mechanical load on the liner, *Buragohain, P., Vardon, P.J., Hicks, M.A., & Bykov, D. (2016). Coupled thermo–hydro–mechanical processes for the Dutch radioactive waste repository. Proceedings of the 2nd Petrus-OPERA PhD and Early Stage Researcher Conference 2016, Proceedings of the 2nd Petrus-OPERA PhD and early stage researcher conference 2016, 2016.*

borehole logging data, geometric features of natural fractures can be mapped [40]. Progress in hydrology has been made over the last three decades, as research has been conducted in a number of geological formations to investigate the performance and safety of potential underground repositories for nuclear waste [41]. An overview of the key hydrologic issues involved is provided in Fig. 24.

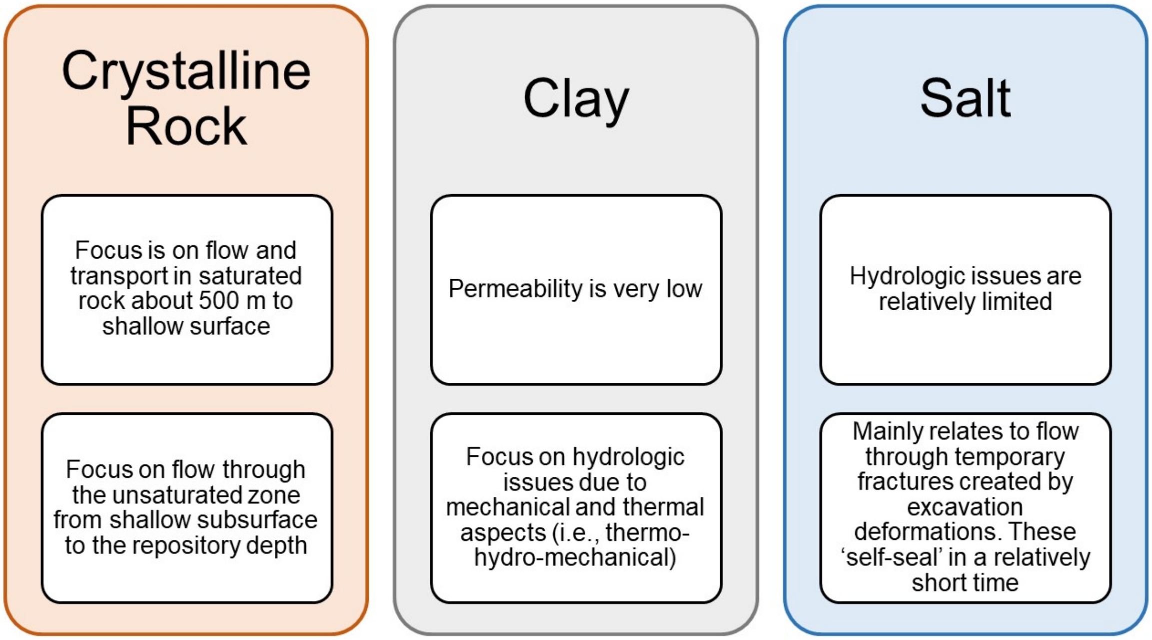

Fig. 25: Hydrological Issues Associated with Nuclear Waste Repositories

5.0 Soil Erosion

A GDF's host geology is expected to provide adequate protection throughout its lifecycle, which is likely to cover a period of thousands of years. Given the effects of a rapidly changing climate, concern may arise as to whether soil stabilization would be necessary given specific site closure alternatives[39]. As weather patterns change, minimizing spoil erosion, both by water and wind, may

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[39] Practice at the Radioactive Waste Manegement Complex (RMCW) at the Idaho National Laboratory disposed waste with a layer of soil at least 2 m thick of isolation. it is important that their isolation barrier (including the soil layer covering them) endure sufficiently long to restrict radionuclide release rates to acceptable levels. Any eventuality that could reduce the effectiveness of the waste isolation barrier requires evaluation and appropriate actions to ensure adequate barrier performance. A 1995 study considered the long-term stability and soil erosion. The report concluded that if climate shifts within the next 10,000 years are on the same order of magnitude as those experienced in the past 10,000 years, no appreciable erosion should occur at the RWCW, *Hackett, W., Tullis, J., Smith, R., & United States. Department Of Energy. (1995). Geologic processes in the RWMC area, Idaho National Engineering Laboratory: Implications for long term stability and soil erosion at the radioactive waste management complex*, https://digital.library.unt.edu/ark:/67531/metadc623925/m2/1/high_res_d/135031.pdf; Future climate scenarios influenced by human activity can be determined by: (1) the maximal cooling and drying of the climate, (2) maximal warming and moistening of the climate and (3) evolution of the future climate affected by human activities resulting in elevated concentrations of CO$_2$ in the atmosphere. Suggested time scales may be as follows: Several centuries, the

become a forward challenge when siting a geologic repository in the U.K. If stabilization is necessary, then a determination will need to be made as to which stabilization technique is the most appropriate for that specific site [42]. A diagram of soil stabilization concerns, criteria, methods and procedures is provided in Fig. 25.

In Europe, erosion by wind and water is a major cause of soil loss and soil conservation is a significant environmental concern[40]. Soil erosion is the main mechanism of landscape degradation [43]. Around 12 % of the total area of Europe is highly affected by erosion processes.

A recent study[41] (Achtley, et. al., 2019) considered the long-term environmental performance assessments of natural processes, including erosion, which are critically important for waste repository site evaluation. While challenges for any such study include assessing a site's ability to continuously function, due to parameter uncertainty and compounding nonlinear processes, the study demonstrates the utility of long-term assessments, identifies sources of erosion forecast uncertainty, and demonstrates the utility of landscape evolution model development [44]. The study accounted for parameter uncertainty by simulating high-, moderate-, and low-erosion cases. The assessments extended to 10,000 years, which resulted in large erosion uncertainties. The model analysis identified three significant methods for improving the erosion predictions by: (1) reducing initial parameter uncertainty, (2) exploring alternative reduced-order models, and (3) exploring alternative models that do not rely on the geomorphically effective runoff event assumption.

Another 2019 study considered the Opalinus Clay shale that has been selected as the host formation for radioactive waste disposal in Switzerland. The minimum required depth of the repository is related to the long-lasting isolation required for the disposal (1 million years). During this period, possible erosion scenarios affecting the repository need to be analyzed. Opalinus Clay from shallow depths (< 70 m) was sourced from a borehole in Northern Switzerland, where the formation was affected by a considerable exhumation process. The results revealed a limited impact of the erosion phenomenon on the analyzed aspects of Opalinus Clay at the laboratory scale. The compressibility and swelling indexes were shown to strongly depend on the clay-mineral content of the specimens [45]. Whilst soil erosion will most likely not have a great impact on the host repository given the depth of these systems, it is still a subject that is becoming more important given the UK's changing climate[42].

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next 10 thousand years and the next 100 thousand years, *Pačes, T., Dobrovolný, P., Holeček, J., Nývlt, D., & Rukavičková, L. (2017). Future Water-rock Interaction in Deep Repository of Spent Nuclear Fuel. Procedia Earth and Planetary Science, 17, 100-103.*

[40] "The mean soil loss rate in the European Union's erosion-prone lands (agricultural, forests and semi-natural areas) was found to be 2.46 t ha^{-1} yr^{-1}, resulting in a total soil loss of 970 Mt annually; equal to an area the size of Berlin at 1 metre deep", European Commission, EU Science Hub, *Soil erosion in Europe: Current status, challenges and future developments*, https://ec.europa.eu/jrc/en/publication/soil-erosion-europe-current-status-challenges-and-future-developments; See also *UK Soil Degradation*, https://www.parliament.uk/documents/post/postpn265.pdf; More recent information can be found at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/805926/State_of_the_environment_soil_report.pdf, though this covers concerns from an agricultural perspective.

[41] The study's focus was for low-level waste repository on mesas in Los Alamos National Laboratory in New Mexico.

[42] *How much flooding is in the UK's future? A look at the IPCC report, https://www.carbonbrief.org/how-much-flooding-is-in-the-uks-future-a-look-at-the-ipcc-report, Committee on Climate Change, Preparing for Climate Change, https://www.theccc.org.uk/tackling-climate-change/preparing-for-climate-change/, UK Met Office, Effects*

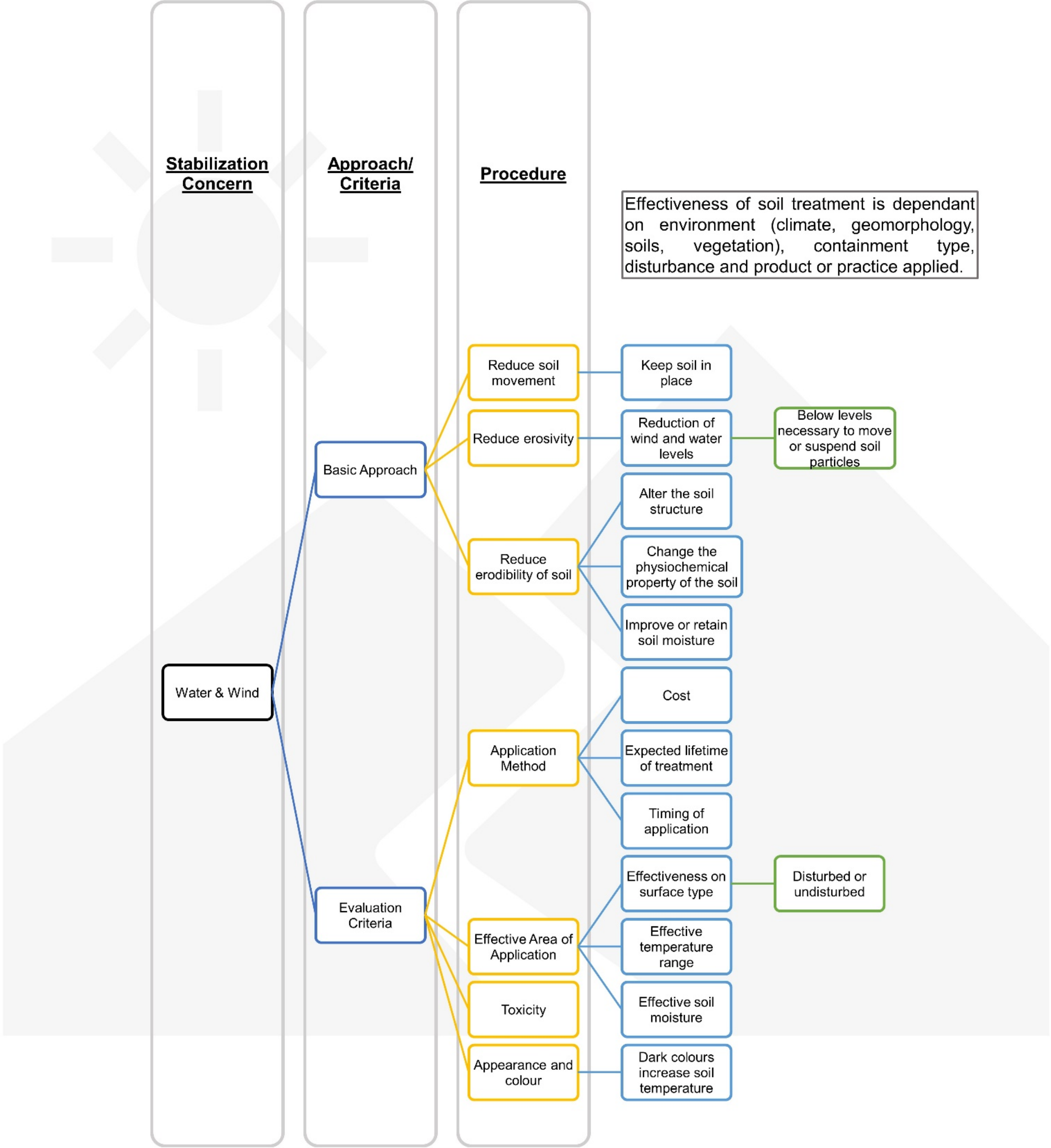

Fig. 26: Soil Stabilization Concerns, Criteria, Methods and Procedures

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of Climate Change, https://www.metoffice.gov.uk/weather/climate-change/effects-of-climate-change, According to the Met Office the UK can expect an increased change in the intensity and /or frequency of heavy rain. However, an increased in wind storm trends is not detected, as yet.

6.0 Multi-purpose or Dual-purpose Canister

The UK has undertaken numerous studies previously on the multi-purpose[43] (MPC) or dual-purpose canister[44] (DPC) system for the storage of spent nuclear fuel. Therefore, this concept will only be briefly mentioned here. This approach is to establish a dry cask system to hold several spent fuel assemblies, and be part of the transport, storage, and possibly geological disposal systems of an integrated spent fuel management system[45] [46]. A dedicated DPC or MCP can be simultaneously used to transport fuels from spent fuel pools from nuclear power plants to off-site interim storage or final disposal sites [47]. The flexible use of such a dry cask system accelerates the release of space spent fuel pools, and increases the forward momentum of decommissioning activities in some nuclear facilities [48]. Direct disposal is technically feasible in the generally sought-after disposal concepts, including “the salt concept, and emplacement in hard rock (i.e., crystalline) or argillaceous sedimentary rock, with or without backfill, and others” [49].

7.0 Modelling/Validation

The use of research tools to model and validate a proposed technical system or siting characteristics has grown exponentially in the past half-century[46]. However, the ability to mesh quality, model validation and the reporting of these metrics has not kept equal pace [50]. To ensure that the qualitative information to host communities is provided during the siting process, an ability to expeditiously evaluate the “goodness” of every set of tested parameters needs to be formulated. These validation methods and techniques form a crucial part of the holistic nuclear waste

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[43] Multi-purpose casks are intended for storage, transportation, and disposal in a geologic repository. *See also: Sanders, C. (2013). Review of the development of the transportation, aging, and disposal (TAD) waste disposal system for the proposed Yucca Mountain geologic repository. Progress in Nuclear Energy, 62, 8-15.* A 2005 study considered the design calculation revisions and updates of previous criticality evaluations for the canister handling, transfer and staging operations to be performed in the Canister Handling Facility (CHF) at the proposed Yucca Mountain Repository. It considered spent nuclear fuel (SNF) and high-level radioactive waste (HLW) canisters, defense high-level radioactive waste (DHLW), naval canisters, multicanister overpacks (MCOs), vertical dualpurpose canisters (DPCs), and multipurpose canisters (MPCs) (if and when they become available). normal operations in CHF prove to be criticality safe for all Department of Energy (DOE) SNF types considered in the calculation. The DOE SNF canisters can be placed in an infinite array size as long as the spacing between the surfaces of the canisters is 30 cm or greater, *Sanders, C., & United States. Department Of Energy. (2005). CANISTER HANDLING FACILITY CRITICALITY SAFETY CALCULATIONS.*

[44] Dual-purpose casks are licensed for both storage and transportation. See *Hardin, et. al, (2015), Investigations of Dual-Purpose Canister Direct Disposal Feasibility – 15106, WM2015 Conference, March 15 – 19, 2015, Phoenix, Arizona, USA, https://www.osti.gov/servlets/purl/1367651*.

[45] Allows for the spent fuel of nuclear power plants including highly radioactive isotopes be managed economically and safely, *Rezaeian, M., & Kamali, J. (2017). Effect of a dual-purpose cask payload increment of spent fuel assemblies from VVER 1000 Bushehr Nuclear Power Plant on basket criticality. Applied Radiation and Isotopes, 119, 80-85*.

[46] “is concerned with checking whether or not a chosen statistical model is in agreement with observed data”, *Al-Labadi, L., & Evans, M. (2018). Prior-based model checking. Canadian Journal of Statistics, 46(3), 380-398*; “Model checking is an automatic technique to formally verify that a given specification of a concurrent system meets given functional properties”, *Bošnački, D., & Wijs, A. (2018). Model checking: Recent improvements and applications. International Journal on Software Tools for Technology Transfer, 20(5), 493-497*; “Checking that models adequately present data is an essential component of applied statistical inference”, *Wang, N., & Alomond, R. (2019). Bayesian model checking in cognitive diagnostic models. Behaviormetrika, 46(2), 371-388*.

repository siting and development activities. A given validation method must select the best values, as a wrong evaluation could produce poor results and confusion among the potential host communities [51].

Computational models enable us to explore the impact of distinct causal factors, and to manipulate parameters that cannot be accessed experimentally[47] [52]. Interestingly, validation methods are used among a variety of industries and for various purposes. In agriculture, cropping systems have studies using a variety of modeling approaches, focusing on the quality of crop predictions. These activities inter-correlate many different variables such as agricultural production systems, digital agriculture, and effects of climate change. In all of these models, an important step is validation of the model [53]. For the proposed Yucca Mountain Repository, a geologic framework model was developed as one component of the integrated site model which has been developed to provide a consistent volumetric portrayal of the rock layers, rock properties, and mineralogy. The integrated site model scope consisted of three components, found in Fig.26 [54]. The integrated site model framework used at Yucca Mountain is presented in Fig. 27 [54]. These models and validation methods may be useful as a template for developing an integrated framework with the U.K.'s siting and design applications.

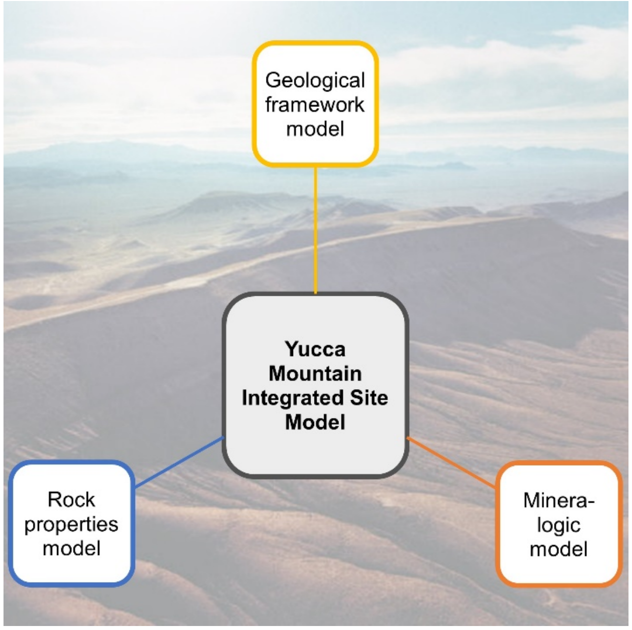

Fig. 27: Yucca Mountain Integrated Site Model

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[47] "The ideas of program verification date back to Turing and von Neumann, who introduced the concept of an assertion as the specification of an interface between parts of a program", *C. A. R. Hoare. 2005. The verifying compiler, a grand challenge for computing research. In Proceedings of the 6th international conference on Verification, Model Checking, and Abstract Interpretation (VMCAI'05). Springer-Verlag, Berlin, Heidelberg, 78*; "Model checking is one of the most important approaches to program verification. Model checking has achieved spectacular success in the context of finite state systems, where the behavior can be captured by a finite graph", *Abdulla, P. (2012). Regular model checking. International Journal on Software Tools for Technology Transfer, 14(2), 109-118*, "The term hybrid logic refers to a family of logics which enrich modal logics with certain first-order constructs. This takes their expressiveness beyond the limitations of bisimulation invariance", *Kernberger, D., & Lange, M. (2020). Model checking for hybrid branching-time logics. Journal of Logical and Algebraic Methods in Programming, 110, Journal of Logical and Algebraic Methods in Programming, January 2020, Vol.110.*

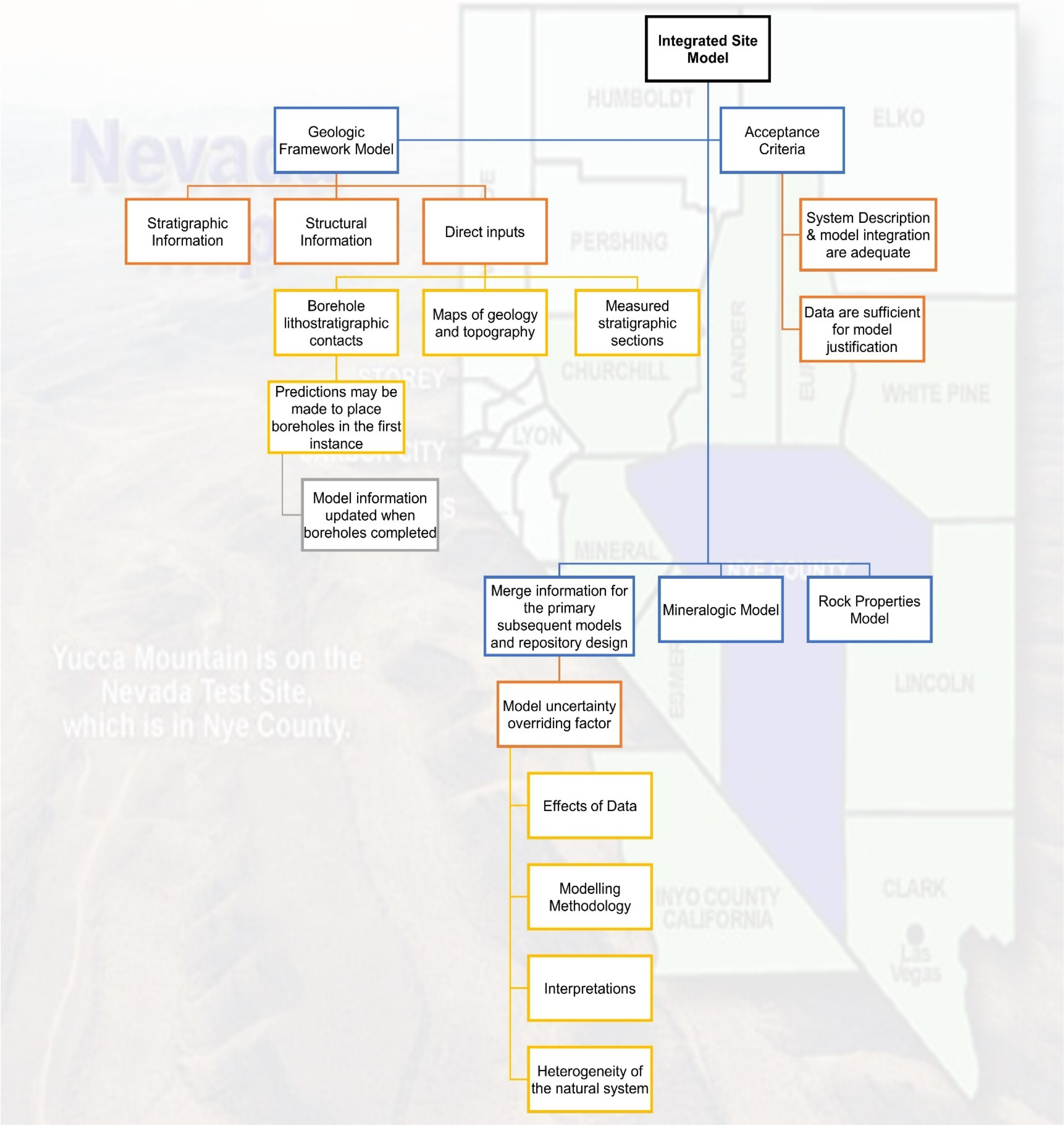

Fig. 28: Yucca Mountain Integrated Site Model Framework

8.0 Summary and Conclusions

The decision-making processes for the siting of a GDF in many states have shown that these processes are a dichotomy of politics and science, with politics at times displaying the dominating factor. While these are essentially political processes, the risk of instability in decision-making for the final disposal of radioactive waste can be managed to provide for informative transparent decision-making initiatives in host communities. This is, of course, well demonstrated in site selection processes in Sweden and Finland. The ability of the State to successfully process legitimate change between and within each milestone determines the ability to maintain project legitimacy from the initial site selection through to the closure of a GDF.

In Section 1.2, mention was made to the core influencers impacting a radioactive waste management program. Each influencer has the ability to exert pulling influences moving a programme into opposing directions. Each influencer must be carefully weighed and acted upon to ensure that each are moving a programme in a similar direction. These influencers govern the site selection processes (see Section 2.0). A holistic approach to site selection expresses the economic benefit, sustainability, reputation and longevity of the siting activities, as well as the nuclear industry.

Site selection of a GDF begins with initial characterization using indispensable applications. Having an ability to work with numerous unavoidable variabilities and uncertainties during the initial stage of site characterization provides the foundational cornerstone for host communities to make necessary informative decisions, within certain time constraints. A Geotechnical site characterization program serves to develop the base qualitative and quantitative knowledge below the subsurface at a given site, as shown in Fig. 7. A basic model for developing information desired for the characterization of a particular site of interest was shown in Fig. 8. Such a model can be indispensable in developing quantitative and qualitative information, without incurring greater expense in the first instance. Of course, one must carefully assess the value of any information collected and presented at a certain stage in the siting process (see Fig. 9).

In Section 2.2, CO_2 siting experiences were considered. These experiences show that there are similar processes for siting this type of facility, comparable to a GDF. What can be gleamed from this section, is that these particular siting activities use available knowledge obtained from oil and gas exploration, which is why it is often more desirable to use a former oil/gas site. Using this knowledge, and a pre-use site, will more likely than not help to accelerate siting for CO_2 capture and sequestration. One lesson that may be learned here is that using an acceptable site where nuclear activities are ongoing, or have previously occurred, may help to accelerate the siting of a GDF. However, a note of caution may be advisable that this could also lead to feelings of burden by the local communities, and could bring about greater risk to the siting process.

In Section 3, various potential host geology was considered (rock, clay, salt). The chosen geology of a DGF is a central factor as engineered barriers must perform in the chosen natural environment over geologic time periods. Thus, the engineered barriers become part of the natural system. In choosing the host geology, experience with each of these geological formation types may be a deciding factor, as the developed learning is already present. Before 2013, this was a significant weighting factor for the German selection of Gorleben as the country's potential host repository. Section 4, discussed the hydrological concepts and methods important to planning and permit applications for construction and operation of a GDF. Specifically, such assessments provide useful guidelines for focusing monitoring and mitigation measures on a limited number of subareas. This requires the use of underlying classification and modeling tools associated with different types of assumptions and uncertainties. An overview of the key hydrologic issues involved is provided in Fig. 24. In this vein, soil erosion was briefly discussed in Section 5. Whilst it may not pose a great impact to the host engineered geologic barrier system, given the proposed depth, the changing climate may cause additional necessary investigations to be made to ensure these systems are maintained over the course of thousands of years.

Lastly, the ability to mesh quality, model validation and the reporting of desired metrics, depends on the accurate portrayal of presented information. To ensure that good qualitative information is provided to host communities during the siting process, an ability to expeditiously evaluate the "goodness" of every set of tested parameters needs to be formulated. These validation methods and techniques form a crucial part of the holistic nuclear waste repository siting and development activities. What can be taken from these investigations is that the largest impact and ability to accelerate a GDF does not necessarily depend on technical solutions, but on optimized processes.

8.1 Recommendations

A characteristic and vital concern with GDF siting programs internationally is that as more knowledge and experience is gained, historical practices continue to evolve. It would be presumptuous to assume that impacts to the outlined processes will not require some alteration or amendments to final conclusions and/or recommendations. It may be that the mechanisms of implementation subtly require a shifting of priorities, as the tension between flexibility and process delineations balance out.

Robust stepwise site selection and scientific screening processes should be developed and implemented to ensure that willing host communities are informed in a timely manner during site selection activities. Having access to good qualitative information, where the "goodness" of critical tested parameters is well formulated, allows the needs of individual communities to be addressed with maximum room for a change of course, where warranted, during the initial/early siting phases. Optimizing GDF siting in the pre-planning phase, or during pre-site investigation, develops the required competences and inputs that will inform overall project implementation. Such actions create a higher degree of certainty for decision-making and provide the added bonus of directing and focusing more expensive invasive site-specific subsequent investigation methods later in the siting process. Recommendations for these initial stages are divided into three phases – 'Initial Investigation', 'Depiction Phase', and 'Site Specific Activities'. Each phase is more fully described in Figs. 28 through 30.

The Initial Investigation phase consists of three lines of discovery. The focus during the Initial Investigation phase seeks as much input as possible from waste producers and interested non-government organizations (NGOs) on recommended host geology and on sustainable development of a GDF. This particular effort builds on experience from the Swiss siting strategy.

There are two major milestones that characterize this phase – (1) develop potential suitable areas of interest based on desktop studies to help inform potential host communities, and (2) determine the suitable host geology for a GDF. As displayed in Fig. 28, the determination of suitable areas for site selection is built on desktop studies using existing information from reports, guides, and publications, etc. Assessing a suitable host geology requires justification of desired characteristics and needed requirements for proceeding with a recommended host geology. These two milestones, and the input from waste producers and NGOs, are integrated into the next stage - the Depiction Phase.

Building on knowledge and experiences developed during the Initial Investigation phase, the Depiction phase involves the description of a fuller picture of the desired GDF concept. During this phase, one considers geotechnical problems utilizing available site information at volunteered sites, such as topographical maps and other relevant records, as well as collecting and assembling accessible soil and rock property data. Also, the wider GDF project is developed, including further definition of site/GDF characteristics and concepts (see Fig. 29).

As detailed in Fig. 30, the final phase is site specific. Once a final site or sites have been winnowed down and selected, detailed invasive exploratory investigations need to be conducted. Site specific investigations include site description modeling development, in-situ investigations (e.g., borehole drilling) and laboratory testing. Importantly, the development of the site-specific safety assessments and the site-specific environmental impact assessment are conducted during this final phase. Using dedicated stepwise phases to develop the wider GDF siting initiatives, will help to focus resources and funding more appropriately, while providing relevant information to host communities in a timely manner and sustaining decision-making processes and practices.

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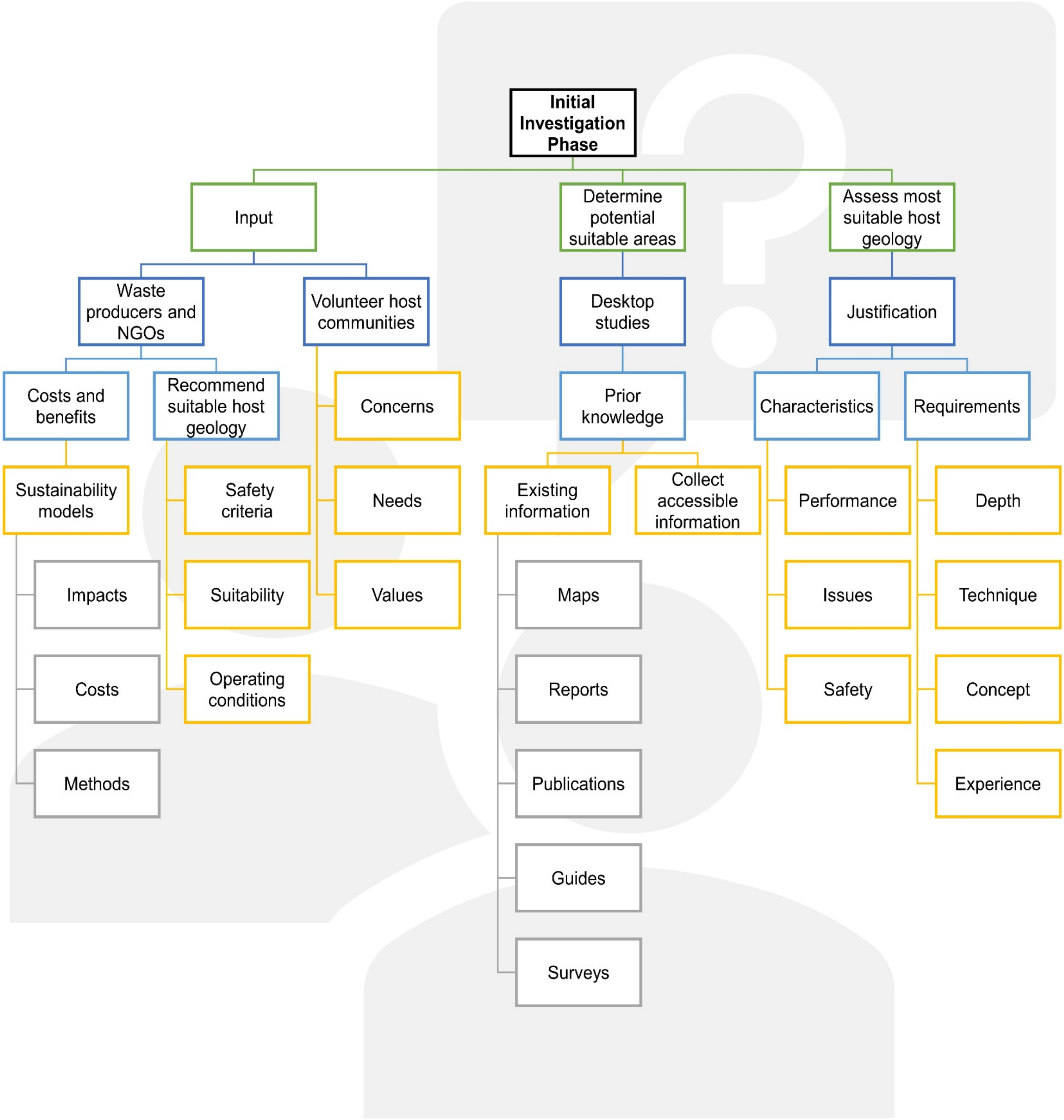

Fig. 29: The Initial GDF Investigation Phase

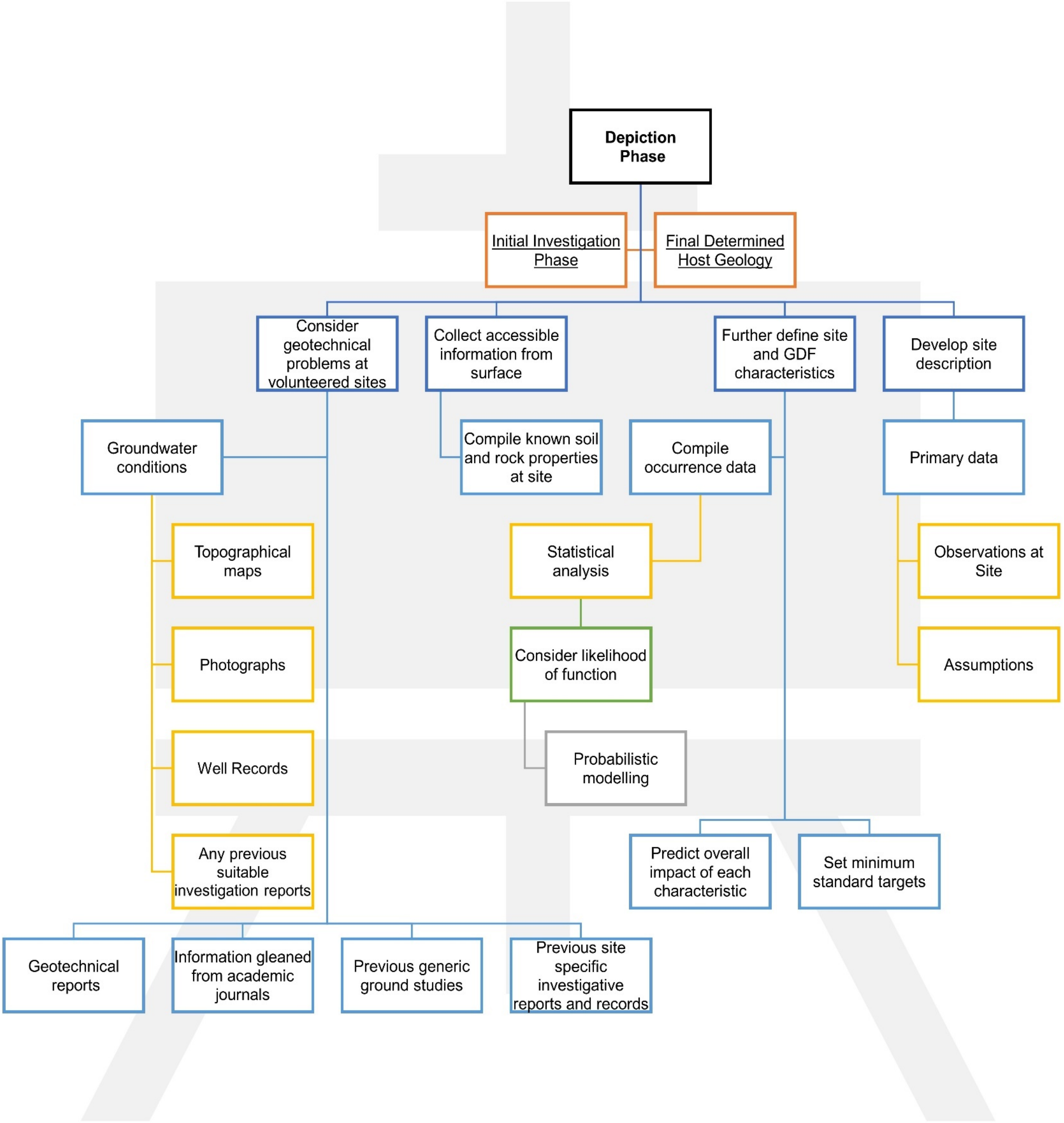

Fig. 30: The GDF Depiction Phase

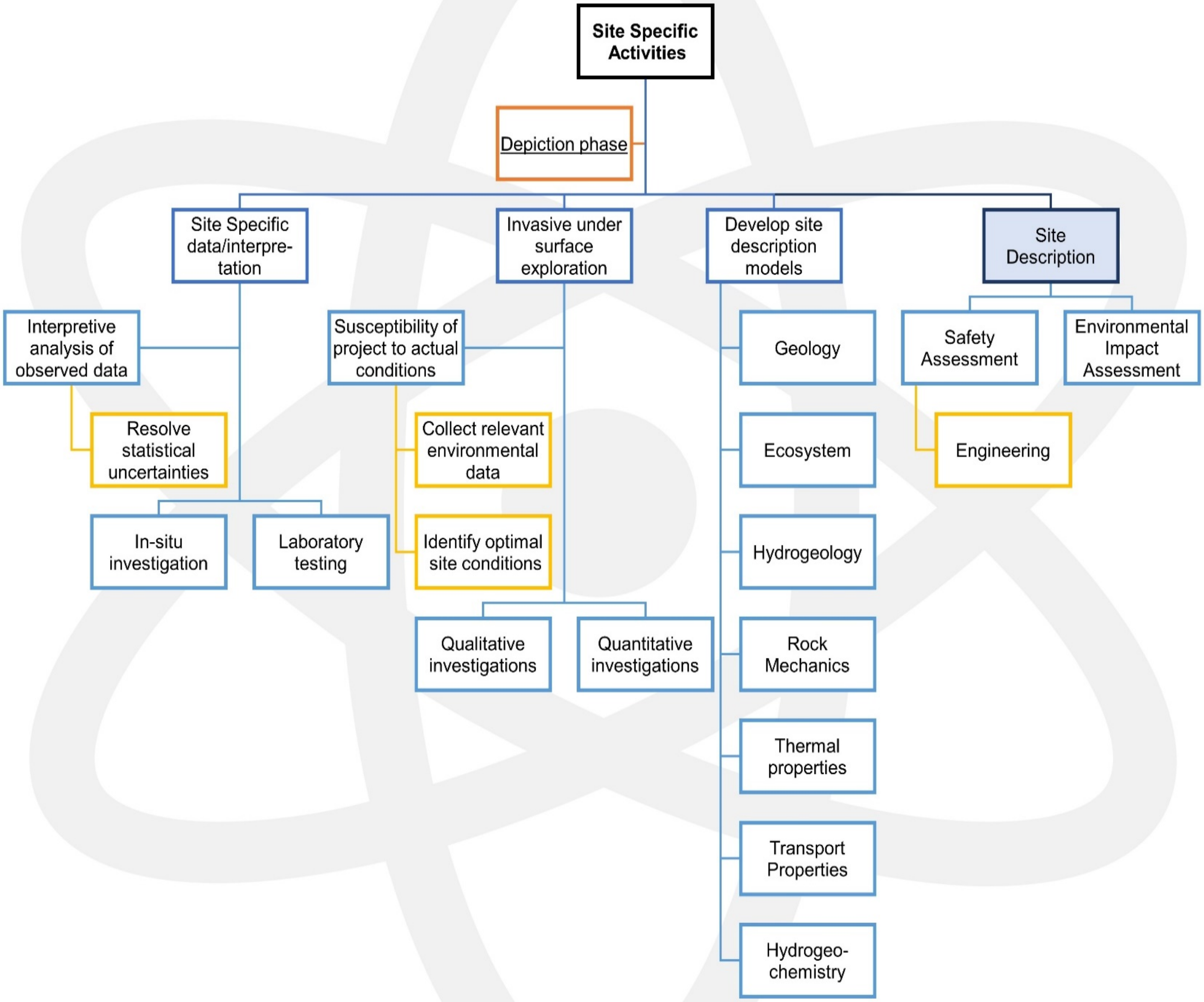

Fig. 31: The GDF Site Specific Activities

9.0 References

[1] Sanders, Mark Callis, & Sanders, Charlotta E. (2019). A world's dilemma 'upon which the sun never sets': The nuclear waste management strategy (part II): Russia, Asia and the Southern Hemisphere. Progress in Nuclear Energy, 110, 148-169.

[2] Sanders, Mark Callis, & Sanders, Charlotta E. (2016). A world's dilemma 'upon which the sun never sets' – The nuclear waste management strategy (part I): Western European Nation States and the United States of America. Progress in Nuclear Energy, 90(C), 69-97.

[3] Falconer, L., Telfer, T., & Ross, L. (2016). Investigation of a novel approach for aquaculture site selection. Journal of Environmental Management, 181, 791.

[4] De, A 2015, Geotechnical Site Characterization, Momentum Press, New York. Available from: ProQuest Ebook Central.

[5] Sharma M., Inti S., Tandon V. (2019) Impact Assessment of Climate Change in Texas Pavements and Resiliency Strategy. In: Weng MC., Lee J., Liu Y. (eds) Current Geotechnical Engineering Aspects of Civil Infrastructures. GeoChina 2018. Sustainable Civil Infrastructures. Springer, Cham.

[6] Algreen, M., Kalisz, M., Stalder, M., Martac, E., Krupanek, J., Trapp, S., & Bartke, S. (2015). Using pre-screening methods for an effective and reliable site characterization at megasites. Environmental Science and Pollution Research, 22(19), 14673-14686.

[7] Wang, Y., Cao, Z., & Li, D. (2016). Bayesian perspective on geotechnical variability and site characterization. Engineering Geology, 203(C), 117-125.

[8] De, A 2015, Geotechnical Site Characterization, Momentum Press, New York. Available from ProQuest Ebook Central.

[9] Nordstrom, DK, & Nicholson, A (eds) 2017, Geochemical Modeling for Mine Site Characterization and Remediation, Society for Mining Metallurgy and Exploration, Littleton, CO. Available from: ProQuest Ebook Central.

[10] Carvalho, S., Gonçalves, J., Guisan, A., & Honrado, J. (2016). Systematic site selection for multispecies monitoring networks. Journal of Applied Ecology, 53(5), 1305-1316.

[11] Dai, Z., Stauffer, P., Carey, J., Middleton, R., Lu, Z., Jacobs, J., . . . Spangler, L. (2014). Pre-site characterization risk analysis for commercial-scale carbon sequestration. Environmental Science & Technology, 48(7), 3908-3915.

[12] Offei-Nyako, K., Tham, L., Bediako, M., Adobor, C., & Asamoah, R. (2016). Deviations between Contract Sums and Final Accounts: The Case of Capital Projects in Ghana. Journal of Construction Engineering, 2016, 1-8.

[13] Conroy, G. (1997). ConSERV: A Methodology for the Management of Capital Projects and Concurrent Engineering Design Using Knowledge Based Technology, PQDT – Global.

[14] Arqué Armengol, Anna, Universitat Politècnica De Catalunya. Departament D'Enginyeria Del Terreny, Cartogràfica I Geofísica, Gens Solé, Antonio, Fernlund, Joanne, & Morfeldt, Daniel. (n.d.). Comparison between pre-investigations and geotechnical site characterization of City Link, Stockholm.

[15] Eskerod, P. (2010). Action learning for further developing project management competencies: A case study from an engineering consultancy company. International Journal of Project Management, 28(4), 352-360.

[16] Sanders, M.C. and Sanders, C.E., Nuclear Waste Management Strategies: An International Perspective, Elsevier (Academic Press), 2020, ISBN 978-0-12-813738-3, https://www.elsevier.com/books/nuclear-waste-management-strategies/sanders/978-0-12-813738-3.

[17] Prades, A., Espluga, J., Real, M., & Solá, R. (2009). The siting of a research centre on clean coal combustion and CO2 capture in Spain: Some notes on the relationship between trust and lack of public information. Journal of Risk Research, 12(5), 709-723.

[18] Morgan, M. Granger, and Sean T. McCoy. *Carbon Capture and Sequestration: Removing the Legal and Regulatory Barriers*, Routledge, 2012.

[19] Library of Congress. Congressional Research Service. (2008). Community Acceptance of Carbon Capture and Sequestration Infrastructure Siting Challenges. S.l]: [s.n.].

[20] Parfomak, E.C. 2012, Geologic Sequestration of Carbon Dioxide: Socioeconomic Characteristics and Landowner Acceptance of Carbon Sequestration Sites, George Mason University.

[21] Lehmann, P., Creutzig, F., Ehlers, M., Friedrichsen, N., Heuson, C., Hirth, L., & Pietzcker, R. (2012). Carbon Lock-Out: Advancing Renewable Energy Policy in Europe. Energies, 5(2), 323-354.

[22] Cantucci B., Buttinelli M., Procesi M., Sciarra A., Anselmi M. (2016) Algorithms for CO2 Storage Capacity Estimation: Review and Case Study. In: Vishal V., Singh T. (eds) Geologic Carbon Sequestration. Springer, Cham.

[23] Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste, edited by Allison MacFarlane, et al., MIT Press, 2006. ProQuest Ebook Central.

[24] Laverov, N., Omel'yanenko, P., & Yudintsev, B. (2011). Crystalline rocks as a medium for nuclear waste disposal. Russian Journal of General Chemistry, 81(9), 1980-1993.

[25] Petersson, J., Stephens, M., Mattsson, H., & Möller, C. (2012). Albitization and quartz dissolution in Paleoproterozoic metagranite, central Sweden — Implications for the disposal of spent nuclear fuel in a deep geological repository. LITHOS, 148, 10-26.

[26] Hedin, A., & Olsson, O. (2016). Crystalline rock as a repository for Swedish spent nuclear fuel. Elements (Quebec), 12(4), 247-252.

[27] Wersin, P., Kiczka, M., & Koskinen, K. (2016). Porewater chemistry in compacted bentonite: Application to the engineered buffer barrier at the Olkiluoto site. Applied Geochemistry, 74, 165-175.

[28] Bossart P. et al. (2018) Mont Terri rock laboratory, 20 years of research: introduction, site characteristics and overview of experiments. In: Bossart P., Milnes A. (eds) Mont Terri Rock Laboratory, 20 Years. Swiss Journal of Geosciences Supplement, vol 5. Birkhäuser, Cham.

[29] Mon, A., Samper, J., Montenegro, L., Naves, A., & Fernández, J. (2017). Long-term non-isothermal reactive transport model of compacted bentonite, concrete and corrosion products in a HLW repository in clay. Journal of Contaminant Hydrology, 197, 1-16.

[30] Briggs, S., Mckelvie, J., Sleep, B., & Krol, M. (2017). Multi-dimensional transport modelling of corrosive agents through a bentonite buffer in a Canadian deep geological repository. Science of the Total Environment, 599-600, 348-354.

[31] Kim, Min-Jun, Lee, Seung-Rae, Yoon, Seok, Jeon, Jun-Seo, & Kim, Min-Seop. (2018). Optimal initial condition of a bentonite buffer with regard to thermal behavior in a high-level radioactive waste repository. Computers and Geotechnics, 104, 109-117.

[32] Swiss Federal Office of Energy, Legal Services and Safety Division, *Sectoral Plan for Deep Geological Repositories*, 2 April 2008, https://www.nagra.ch/display.cfm/id/100691/disp_type/display/filename/e_sachplan.pdf, Accessed April 1, 2020.

[33] Blanco Martín, L., Rutqvist, J., & Birkholzer, J. (2015). Long-term modeling of the thermal–hydraulic–mechanical response of a generic salt repository for heat-generating nuclear waste. Engineering Geology, 193(C), 198-211.

[34] Waste Isolation Pilot Plant Disposal Phase Final Supplemental Environmental Impact Statement, Volume I, Chapters 1-6, https://www.wipp.energy.gov/library/seisii/Volume%20I.PDF, Accessed April 01, 2020.

[35] Federal Ministry of Economics and Technology, *Final Disposal of High-level Radioactive Waste in Germany – The Gorleben Repository Project*, October 2008.

[36] Pačes, T., Dobrovolný, P., Holeček, J., Nývlt, D., & Rukavičková, L. (2017). Future Water-rock Interaction in Deep Repository of Spent Nuclear Fuel. Procedia Earth and Planetary Science, 17, 100-103.

[37] Stress-controlled fluid flow in fractures at the site of a potential nuclear waste repository, Finland. (2014). Geology, 40(4), 82.

[38] Hökmark, H., & Lönnqvist, Margareta. (2014). Reply to comment by Christopher Talbot on "Approach to estimating the maximum depth for glacially induced hydraulic jacking in fractured crystalline rock at Forsmark, Sweden". Journal Of Geophysical Research-Earth Surface, 119(4), 955-959.

[39] Stuckless, J., & Dudley, W. (2002). The geohydrologic setting of Yucca Mountain, Nevada. Applied Geochemistry, 17(6), 659-682.

[40] Zhang, Chongyuan, Chen, Qunce, Qin, Xianghui, Hong, Bo, Meng, Wen, & Zhang, Quanfeng. (2017). In-situ stress and fracture characterization of a candidate repository for spent nuclear fuel in Gansu, northwestern China. Engineering Geology, 231, 218-229.

[41] Tsang, Chin-Fu, Neretnieks, Ivars, & Tsang, Yvonne. (2015). Hydrologic issues associated with nuclear waste repositories. Water Resources Research, 51(9), 6923-6972.

[42] Shillito, R., Fenstermaker, L., Nevada System of Higher Education. Desert Research Institute, & Nevada State Publications Repository. (2014). Soil stabilization methods with potential for application at the Nevada National Security Site: A literature review (Desert Research Institute publication; no. 45255). Nevada: Desert Research Institute.

[43] Zupanc, V., & Mabit, L. (2010). Nuclear techniques support to assess erosion and sedimentation processes: Preliminary results of the use of 137Cs as soil tracer in Slovenia. Dela, 0(33), 21.

[44] Adam L. Atchley, Kay H. Birdsell, Kelly Crowell, Richard S. Middleton, & Philip H. Stauffer. (2019). Simulating 10,000 Years of Erosion to Assess Nuclear Waste Repository Performance. Geosciences, 9(3), 120.

[45] Crisci, E., Ferrari, A., Giger, S., & Laloui, L. (2019). Hydro-mechanical behaviour of shallow Opalinus Clay shale. Engineering Geology, 251, 214-227.

[46] IAEA-TECDOC-1192, Multi-purpose container technologies for spent fuel management, https://www-pub.iaea.org/MTCD/publications/PDF/te_1192_prn.pdf.

[47] Lee, Dong-Gyu, Park, Jea-Ho, Lee, Yong-Hoon, Baeg, Chang-Yeal, & Kim, Hyung-Jin. (2013). NATURAL CONVECTION HEAT TRANSFER CHARACTERISTICS IN A CANISTER WITH HORIZONTAL INSTALLATION OF DUAL PURPOSE CASK FOR SPENT NUCLEAR FUEL. Nuclear Engineering and Technology, 45(7), 969-978.

[48] Palacio, A. (2017). Design Process for Dual-Purpose Nuclear Spent Fuel Casks. Energy Procedia, 127, 398-406.

[49] Energy.gov, Preliminary Report on Dual-Purpose Canister Disposal Alternatives (FY13), https://www.energy.gov/ne/downloads/preliminary-report-dual-purpose-canister-disposal-alternatives-fy13.

[50] Burkhart, T., Andrews, D., & Dunning, C. (2013). Finite element modeling mesh quality, energy balance and validation methods: A review with recommendations associated with the modeling of bone tissue. Journal of Biomechanics, 46(9), 1477-1488.

[51] Gascón-Moreno, J., Salcedo-Sanz, Ortiz-Garcı´a, Acevedo-Rodrı´Guez, & Portilla-Figueras. (2012). New validation methods for improving standard and multi-parametric support vector regression training time. Expert Systems With Applications, 39(9), 8220-8227.

[52] Shankarjee Krishnamoorthi, Luigi E Perotti, Nils P Borgstrom, Olujimi A Ajijola, Anna Frid, Aditya V Ponnaluri, . . . Alan Garfinkel. (2014). Simulation Methods and Validation Criteria for Modeling Cardiac Ventricular Electrophysiology. PLoS ONE, 9(12), E114494.

[53] CAO Hong-xin, Jim Scott Hanan, LIUYan , LIU Yong-xia, YUE Yan-bin, ZHU Da-wei, LU Jian-fei, SUN. (2012). Comparison of Crop Model Validation Methods. Journal of Integrative Agriculture, (8), 1274-1285.

[54] Vogt, T., & United States. Department Of Energy. (2004). Geologic Framework Model (GFM2000).

9.1 Additional Resources

Birkholzer, J., Houseworth, J., & Tsang, C. (2012). Geologic Disposal of High-Level Radioactive Waste: Status, Key Issues, and Trends. Annual Review of Environment and Resources, 37, 79-106.

Briggs, S. et al. (2017) ‘Transient modelling of sulphide diffusion under conditions typical of a deep geological repository’, Corrosion Engineering, Science & Technology, 52, pp. 200–203. doi: 10.1080/1478422X.2017.1288336.

Buscheck, T., & United States. Department Of Energy. (2005). MULTISCALE THERMOHYDROLOGIC MODEL.

F. Huertas, F. Jullien et Al., & J. L. Fuentes-Cantillana. (2000). Full-scale engineered barriers experiment for a deep geological repository for high-level radioactive waste in crystalline host rock (FEBEX project). Luxembourg: OPOCE.

Fairhurst, C. (2004). Nuclear waste disposal and rock mechanics: Contributions of the Underground Research Laboratory (URL), Pinawa, Manitoba, Canada. International Journal of Rock Mechanics and Mining Sciences, 41(8), 1221-1227.

Faybishenko, B., Birkholzer, J., Sassani, D., & Swift, P. (2016). International Approaches for Nuclear Waste Disposal in Geological Formations: Geological Challenges in Radioactive Waste Isolation—Fifth Worldwide Review:.

Finsterle, S., Muller, R., Baltzer, R., Payer, J., & Rector, J. (2019). Thermal Evolution near Heat-Generating Nuclear Waste Canisters Disposed in Horizontal Drillholes. Energies, 12(4), Energies, Feb 2019, Vol.12(4).

Hadgu, T., Karra, S., Kalinina, E., Makedonska, N., Hyman, J., Klise, K., . . . Wang, Y. (2017). A comparative study of discrete fracture network and equivalent continuum models for simulating flow and transport in the far field of a hypothetical nuclear waste repository in crystalline host rock. Journal of Hydrology, 553, 59-70.

Howard, R., Dupont, M., Blink, J., Fratoni, M., Greenberg, H., Carter, J., . . . United States. Department Of Energy. (2011). Generic repository design concepts and thermal analysis (FY11).

Hsu, C., Wei, Y., Chuang, J., Tseng, C., Yang, J., Ke, C., . . . Teng, S. (2002). Sorption of several safety relevant radionuclides on granite and diorite – a potential repository host rock in the Taiwan area. Radiochimica Acta, 90(9-11), 659-664.

Hudson, J., Cosgrove, J., Kemppainen, K., & Johansson, E. (2011). Faults in crystalline rock and the estimation of their mechanical properties at the Olkiluoto site, western Finland. Engineering Geology, 117(3-4), 246-258.

Hökmark, H., & Claesson, J. (2005). Use of an analytical solution for calculating temperatures in repository host rock. Engineering Geology, 81(3), 353-364.

Keefer, W., Whitney, J., Buesch, D., & United States. Department Of Energy. (2006). Geologyy of the Yucca Mountain Site Area, Southwestern Nevada, Chapter in Stuckless, J.S., ED., Yucca Mountain, Nevada - A Proposed Geologic Repository for High-Level Radioactive Waste (Volume 1).

Kojo, M., Kari, M., & Litmanen, T. (2010). The socio-economic and communication challenges of spent nuclear fuel management in Finland. Progress in Nuclear Energy, 52(2), 168-176.

Leupin, O., Bernier-Latmani, R., Bagnoud, A., Moors, H., Leys, N., Wouters, K., & Stroes-Gascoyne, S. (2017). Fifteen Years of Microbiological Investigation in Opalinus Clay: A Potential Host Rock for Geologic Radioactive Waste Depository, 110(1), 343-354.

Lin, W., Roberts, J., Glassley, W., Ruddle, D., & United States. Department Of Energy. (1995). The effect of rock-water interaction on permeability. International Congress on Rock Mechanics, 1995.

Liu, X. (2016). Criticality Safety Study for the Disposal of Spent Nuclear Fuel in Water-Saturated Geologic Repository. 117.

Montazer, P., & Wilson, W. (1985). Hydrogeology of the unsaturated zone, Yucca Mountain, Nevada. Conference on Characterization and Monitoring of the Vadose Zone, Denver, Conference on characterization and monitoring of the vadose zone, Denver, 19-21 Nov 1985.

Moyce, Elizabeth B. A. (2015). Herbert's Quarry, South Wales – an analogue for host-rock alteration at a cementitious radioactive waste repository? Mineralogical Magazine, 79(6), 1407-1418.

Mukhopadhyay, S., Sonnenthal, E., & Spycher, N. (2006). Modeling coupled thermal-hydrological-chemical processes in the unsaturated fractured rock of Yucca Mountain, Nevada: Heterogeneity and seepage. Physics and Chemistry of the Earth, Parts A/B/C, 31(10-14), 626-633.

Ocelík, P., Osička, J., Zapletalová, V., Černoch, F., & Dančák, B. (2017). Local opposition and acceptance of a deep geological repository of radioactive waste in the Czech Republic: A frame analysis. Energy Policy, 105, 458-466.

Paleologos, E., Mohamed, A., & Pavlopoulos, K. (2017). Geologic environments for nuclear waste repositories. MATEC Web of Conferences, 120, MATEC Web of Conferences, Vol.120.

Pang, B., Saurí Suárez, H., & Becker, F. (2017). Monte Carlo based study of radiation field in a deep geological repository for high-level nuclear waste with different host rock types. Nuclear Engineering and Design, 325, 44-48.

Radulescu, H., & United States. Department Of Energy. (2002). EXTERNAL CRITICALITY CALCULATION FOR DOE SNF CODISPOSAL WASTE PACKAGES.

Rodosta, T., Litynski, Plasynski, Hickman, Frailey, & Myer. (2011). U.S. Department of energy's site screening, site selection, and initial characterization for storage of CO2 in deep geological formations. Energy Procedia, 4, 4664-4671.

Ström, A., Andersson, Skagius, & Winberg. (2008). Site descriptive modelling during characterization for a geological repository for nuclear waste in Sweden. Applied Geochemistry, 23(7), 1747-1760.

Stuckless, J., & Dudley, W. (2002). The geohydrologic setting of Yucca Mountain, Nevada. Applied Geochemistry, 17(6), 659-682.

Tsai, S., & United States. Department Of Energy. (2005). PRECLOSURE CONSEQUENCE ANALYSES FOR LICENSE APPLICATION.

Van Geet, M., Bastiaens, Volckaert, Weetjens, Sillen, Maes, . . . Vallejan. (2009). RESEAL II a large-scale in situ demonstration test for repository sealing in an argillaceous host rock: Phase II. Luxembourg: Publications Office.

Želimir Veinović, Gala Uroić, Dubravko Domitrović, & Leon Kegel. (2020). THERMO-HYDRO-MECHANICAL EFFECTS ON HOST ROCK FOR A GENERIC SPENT NUCLEAR FUEL REPOSITORY. Rudarsko-geološko-naftni Zbornik, 35(1), 65-80.