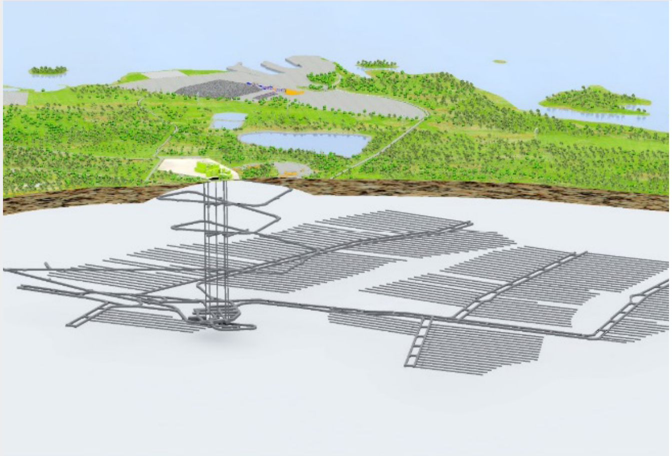
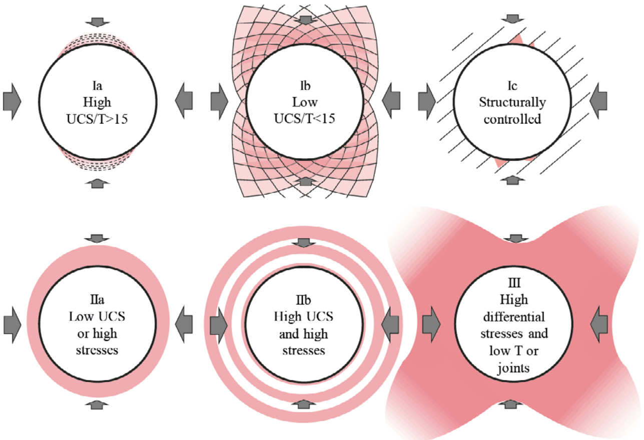
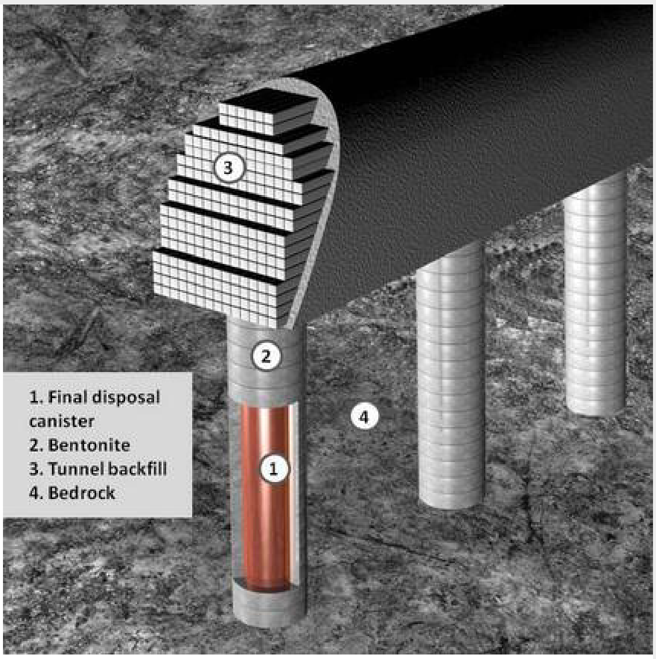


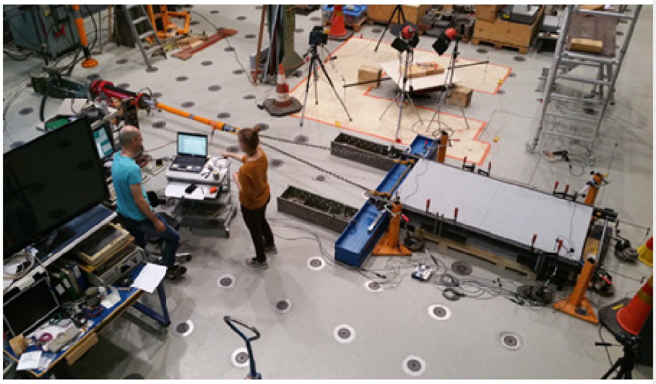
Repository for highly radioactive waste (Olkiluoto Posiva). Magnification of one horizontal tunnel with deposition holes for canisters is shown at left.



Rock mass failure potential in different types of geological conditions surrounding the canister hole (ø 1.75m) for spent nuclear fuel (Siren 2015)



KBS-3 spent nuclear fuel disposal concept. The solution is based on the multiple barriers principle: copper canister, bentonite, horizontal tunnel and bedrock.



World's largest laboratory-scale shear test for a rock fracture of 2m x 1m (Uotinen 2016). Shear movement of rock fractures poses a risk for the integrity of the copper canister.

POSIVA STUK TVO fortum KYT2018 BUSINESS FINLAND

Site suitability and stability of a rock mass for a nuclear waste repository

Impact case study
Department of Civil Engineering 2018

Aalto RAI 2018 Case Study

Field 3b. Engineering: Department of Civil Engineering (CE)

Site suitability and stability of a rock mass for a nuclear waste repository

1. Summary of the societal impact

'Why Finland now leads the world in nuclear waste storage; - other nations hope to learn from approval of the world's first deep repository for spent nuclear fuel' states Elizabeth Gibney in *Nature News*, 02 December 2015. Today the share of the world's electricity generated by nuclear power plants is more than 10%. Spent nuclear fuel is highly radioactive, and it poses a risk to society very long term. We need reliable knowledge of the geological and engineered environment of the repository.

The Finnish government approved the construction of such a repository to Olkiluoto, Finland. Posiva Oy is in charge of its design and construction, while the Radiation and Nuclear Safety Authority (STUK) represents the Finnish government in permitting the site. The permission for construction was based on decades of research into the long-term safety of stored nuclear waste.

Aalto University has focused on the long-term behavior of rock, swelling clay, and cementitious materials and provided knowledge for a safety assessment, which is the base tool for authorization. Our research has addressed questions related to highly and low-intermediate level radioactive waste.

The emphasis in this Case Study is on recent research related to rock mass behavior around the canister holes for storing highly radioactive waste. The construction and disposal of the spent nuclear fuel will last over one hundred years. Besides the construction license and the immediate effects of construction, our research has affected the design of the repository and regulations. The societal impact in terms of health and safety will continue for future generations for hundreds and thousands of years.

2. Underpinning research related to Aalto activities

Background*:* Research on spent nuclear fuel options already started at our university in 1970s. Since 1983, our research has focused on proving the feasibility of the geological disposal concepts and on comparing the suitability of a number of potential sites for a repository. The deep geological repository concept is called KBS-3, and its principles are represented on the cover page. The solution is based on the multiple barriers principle. The fuel is packed in corrosion-resistant canisters made of copper and cast iron, and the canister is surrounded with bentonite clay. The bedrock provides conditions where changes are slow and predictable.

Research on the host rock barrier: Over long timespans, up to 1 million years, geological conditions will change due to the increase of temperature originating from the canister's excess heat and from glacial cycles estimated to occur in the region. Consequently, research on time-dependent and thermo-hydro-mechanical (THM) effects on the fractured rock mass are extensively investigated in the Department of Civil Engineering (Uotinen 2018; Siren 2015, 2015; Rinne et al., 2013).

The canister hole locations are selected to avoid hitting natural fractures of the rock mass. A canister and its emplacement hole is shown on the cover page. Should a canister hole and a rock fracture intersect, there is risk of the canister being sheared if the rock mass moves along the fracture. We developed a testing technique that allows characterizing the mechanical parameters of rock fractures by non-destructive means (Dzugala et al. 2017; Uotinen et al. 2015). Necessary information of fractures, for example the shear strength, can be obtained in advance without traditional physical tests. This method also enables fast determination of a safe distance between two boreholes in the early stage of the design.

Multi-disciplinary research approach and research strategy: Our department encompasses many key aspects in the field of KBS-3 design and related safety assessments. Numerical modelling is one of our strengths. To verify models, we utilize our well-equipped laboratory and the unique underground test tunnel under Aalto's Otaniemi campus. The multidisciplinary Aalto Materials and Energy platforms also offer an excellent scientific framework to collaborate on issues related to nuclear waste management.

Research projects: Our major recent projects on nuclear waste disposal are the KYT funded Block-shear experiment (2012-2014), THEBES (2010-2018) and the KARMO project (2014-2018). FRACTUSCAN project is a spin-off from KARMO, funded by Business Finland TUTLI (2017-2018).

Funding and partners: Funding is mainly received from nuclear waste management companies, such as Posiva Oy (Finland) and Swedish Nuclear Fuel and Waste Management Company (SKB) and nuclear power companies (TVO and Fortum). Funding is also received from the Finnish national nuclear waste research programme KYT through STUK and TUTLI, which is a funding instrument of Business Finland. The Department of Civil Engineering is partnered with the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) in a collaborative research project called 'Understanding and predicting coupled fracturing/fluid flow/thermal processes of jointed rocks'. Our partners in this field are also: ETH (Switzerland), GFZ (Germany), KICT and KIGAM (S-Korea), LBLN (USA), SDUST (China), SNU (S-Korea).

3. References to research related to KBS-3

Three doctoral projects dealing with the KBS-3 concept were completed within the past three years, and three doctoral theses are in progress. Tens of journal articles addressing this concept were published in the past five years. The five most important rock-mass-related publications include the following:

1. Uotinen, L. 2018. *Prediction of stress driven rock mass damage in spent nuclear fuel repositories in hard crystalline rock* (PhD thesis. Thesis defense May 2018).
2. Markovaara-Koivisto, M. 2017. *Visualization modelling of rock fractures and quality parameters in 1-3 dimensions in crystalline bedrock*. (PhD thesis) ISBN: 978-952-60-7754-3.
3. Dzugala, Magdalena; Sirkiä, Joni; Uotinen, Lauri; Rinne, Mikael. 2017. 'Pull Experiment to Validate Photogrammetrically Predicted Friction Angle of Rock Discontinuities'. Elsevier. *Procedia Engineering*. ISSN 1877-7058 (online). DOI 10.1016/j.proeng.2017.05.194.
4. Siren, T. 2015. *Excavation damage zones, fracture mechanics simulation and in situ strength of migmatitic gneiss and pegmatitic granite at the nuclear waste disposal site in Olkiluoto, Western Finland*. (PhD thesis) ISBN: 978-952-60-6518-2.
5. Rinne, M; Shen, B; Backers, T. 2013. 'Modelling fracture propagation and failure in a rock pillar under mechanical and thermal loadings'. *Journal of rock mechanics and geotechnical engineering*. 5(1). DOI 10.1016/j.jrmge.2012.10.001.

Awarded Prizes: The International Society for Rock Mechanic's Rocha Medal runner up-award 2017 was granted to Topias Siren for his 2015 doctoral dissertation (see item 4 above) https://www.isrm.net/noticias/detalhes.php?id=414.

Invention disclosures, patents and startups. Research on rock mass characterization and rock mechanics have initiated several inventions and startups. The laser scanning based LADIMO project studied characterization of underground facilities. The invention based on this project was patented, and a Business Finland TUTLI supported startup company was launched. Another TUTLI startup is FRACTUSCAN, which has its background in the KYT-funded KARMO project. One of the founders of the Stress Measurement Company Oy is Dr. Siren.

4. Societal Impact, activities and roadmap for the case

Main Impacts for society: In 2016, construction of the repository started at the Olkiluoto site. Our research is part of the safety assessment, one of most crucial documents in the licensing process. Our credible research and design allowed authorities to permit the construction of the repository. The closure of the repository is planned to occur in 2120, hence the effects of construction and disposal will extend over a time span of one hundred years. The main impact, however, will become tangible in the next hundreds and thousands of years once it is recognized as a safe, viable, and socially accepted way to dispose of spent nuclear fuel.

Impacts on industry: Being the forerunners in the implementation of the KBS-3 concept is an asset for the entire Finnish nuclear power industry, and this status increases its visibility worldwide. Besides the safety assessment, our research contributed to the creation of principles for site selection and design of the facilities. The repository is unique, and the detailed design is yet to be made; the effect of our research on detailed design is hence difficult to point out explicitly for the time being. An example of the impact on construction costs is the fracture characterization tool developed in the KARMO project (Uotinen 2018; Dzugala et al. 2017). The pillar width between two deposition holes can be optimized in the early stages of design. Specifically, the mechanical properties of fractures can already be determined from cores from exploration drilling.

International impacts: Our research is of great interest worldwide, especially for nations considering geological disposal in crystalline bedrock like Sweden, Canada, and South Korea. The results also accumulate efforts to improve global standards for design.

5. Sources to support the impact case

1. Business Finland TUTLI funding: https://innovation.aalto.fi/researchers-r/business-finland-tutl/
2. Fractuscan start up – in progress: http://fractuscan.com/
3. KYT: http://kyt2018.vtt.fi/en/
4. Ladimo start up –in progress; http://www.ladimo.fi/
5. Posiva and final disposal: http://www.posiva.fi/en/final_disposal#.WsTGlohuY2w
6. STUK: http://www.stuk.fi/web/en/topics/nuclear-waste
7. Stress Measurement Company Oy: https://www.smcoy.fi/

6. Future goals

Construction of the repository and disposal of waste in Olkiluoto will last, most likely, over one hundred years. The related research will continue with increased focus on detailed design and construction. This acquired knowledge will be utilized in new applications. Geothermal energy and underground energy storage are prime examples of applications where rock mass THM-behavior is studied using the means of previous studies. The ongoing project 'Technical and economic aspects of storage and extraction of heat in crystalline bedrock' by PhD student Mateusz Janiszewski is a good example of a new research area.

The department has invested in research infrastructure for nuclear waste application, and these facilities are suitable also for renewable energy studies. The joint research infrastructure within the School of Engineering will further solidify cooperation with other departments.

Research related to this Case Study has improved our visibility. Today our department is internationally well known and a respected research partner in applied geosciences, which is a great asset to continue international collaboration in the future.