Publications of the Ministry of Economic Affairs and Employment
Energy • 2019:30

KYT2018 Finnish Research Programme on Nuclear Waste Management 2015–2018

Final Report

Ministry of Economic Affairs
and Employment of Finland

Publications of the Ministry of Economic Affairs and Employment
2019:30

KYT2018
Finnish Research Programme on Nuclear Waste Management 2015–2018

Final Report

Ministry of Economic Affairs and Employment, Helsinki 2019

Ministry of Economic Affairs and Employment

ISBN PDF: 978-952-327-426-6

Layout: Taina Ståhl

Helsinki 2019

Description sheet

Published by	Ministry of Economic Affairs and Employment		1 April 2019
Authors	KYT2018 Steering Group Chairperson Jarkko Kyllönen, Secretary Kari Rasilainen		
Title of publication	KYT2018 Finnish Research Programme on Nuclear Waste Management 2015–2018 – Final Report		
Series and publication number	Publications of the Ministry of Economic Affairs and Employment 2019:30		
Register number		**Subject**	Energy
ISBN PDF	978-952-327-426-6	**ISSN (PDF)**	1797-3562
Website address (URN)	http://urn.fi/URN:ISBN: 978-952-327-426-6		
Pages	166	**Language**	English
Keywords	Nuclear energy, nuclear safety, research		

Abstract

KYT2018 was the research programme of the Ministry of Employment and the Economy (now Ministry of Economic Affairs and Employment), where the objective has been to ensure that the authorities have access to sufficient levels of such nuclear expertise and preparedness that are needed for comparison of different nuclear waste management methods and technologies. Research directly related to licensing applications belongs to other programmes by the authorities and those responsible for nuclear waste management. KYT2018 research programme was conducted 2015–2018.

The starting point for public research programs on nuclear safety is that they create the conditions for maintaining the knowledge required for the continued safe and economic use of nuclear power, developing new know how and participating in international collaboration. Nuclear research organizations in Finland have been an important asset for the ministries, Radiation and Nuclear Safety Authority (STUK), power companies and Posiva.

The content of the KYT2018 research programme was composed of nationally important research topics, which are the long-term safety of nuclear waste management, technologies in nuclear waste management and nuclear waste management and society. The research programme had 32 research and infra projects. KYT2018 research programme also functioned as a discussion and information-sharing forum for the authorities, those responsible for nuclear waste management and the research organizations, which helps to make use of the limited research resources. The programme aimed for its part to develop national research infrastructure, ensure the continuing availability of expertise, further high-level scientific research and increase general knowledge of nuclear waste management. According to the international review of the research programme, the aims were met.

The final report has been authored on behalf of the Steering Group of the research programme. MEAE contact: Energy Department/Linda Kumpula, tel. +358 29 506 0125.

Publisher	Ministry of Economic Affairs and Employment
Distributed by/ publication sales	Electronic version: julkaisut.valtioneuvosto.fi Publication sales: julkaisutilaukset.valtioneuvosto.fi

Kuvailulehti

Julkaisija	Työ- ja elinkeinoministeriö		1.4.2019
Tekijät	KYT2018 Johtoryhmä puheenjohtaja Jarkko Kyllönen, sihteeri Kari Rasilainen		
Julkaisun nimi	KYT2018 Kansallinen ydinjätehuollon tutkimusohjelma 2015–2018 Loppuraportti		
Julkaisusarjan nimi ja numero	Työ- ja elinkeinoministeriön julkaisuja 2019:30		
Diaari/ hankenumero		**Teema**	Energia
ISBN PDF	978-952-327-426-6	**ISSN PDF**	1797-3562
URN-osoite	http://urn.fi/URN:ISBN: 978-952-327-426-6		
Sivumäärä	166	**Kieli**	englanti
Asiasanat	ydinenergia, ydinturvallisuus, ydinjäte, tutkimus		

Tiivistelmä

KYT2018 oli työ- ja elinkeinoministeriön tutkimusohjelma, jossa tavoitteena on ollut varmistaa, että viranomaisilla on saatavilla riittävästi ja kattavasti sellaista ydinteknistä asiantuntemusta ja muita valmiuksia, jota tarvitaan ydinjätehuollon erilaisten toteutustapojen ja menetelmien vertailuun. Ydinjätehuollon valvontavelvollisuuteen ja lupahakemuksiin suoraan liittyvä tutkimus kuuluu viranomaisten ja jätehuoltovelvollisten muihin ohjelmiin. KYT2018-tutkimusohjelma toteutettiin vuosina 2015–2018.

Julkisten ydinturvallisuustutkimusohjelmien lähtökohtana on, että ne luovat edellytyksiä ydinvoiman turvallisen ja taloudellisen käytön jatkumiseen tarvittavan tietämyksen säilymiselle, uuden tietämyksen kehittämiselle ja kansainväliseen yhteistyöhön osallistumiselle. Alan tutkimusta Suomessa harjoittavat organisaatiot ovat olleet tärkeä voimavara, jota eri ministeriöt, Säteilyturvakeskus (STUK), voimayhtiöt ja Posiva ovat pystyneet hyödyntämään.

KYT2018 tutkimusohjelman sisältö koostui kansallisesti tärkeistä tutkimuskohteista, jotka ovat ydinjätehuollon pikäaikaisturvallisuus, ydinjätehuollon teknologiat ja ydinjätehuolto ja yhteiskunta. Tutkimusohjelmassa oli mukana 32 tutkimus- tai infrahanketta. KYT2018 tutkimusohjelma toimi myös viranomaisten, ydinjätehuoltoa toteuttavien organisaatioiden ja tutkimuslaitosten välisenä keskustelu- ja tiedonvälitysfoorumina, jossa luodaan edellytyksiä rajallisten tutkimusresurssien hyödyntämiselle. Ohjelmassa pyrittiin osaltaan edistämään kansallisen osaamisen ja tutkimusinfrastruktuurin kehitystä, varmistamaan asiantuntemuksen jatkuva saatavuus, edistämään korkealaatuista tieteellistä tutkimusta ja lisäämään yleistä tietämystä ydinjätehuollon alalla. Tutkimusohjelman kansainvälisen arvion mukaan pyrkimyksissä onnistuttiin.

Loppuraportti on laadittu tutkimusohjelman johtoryhmän puolesta. TEM:n yhdyshenkilö: Energiaosasto/Linda Kumpula, puh. +358 29 506 0125.

Kustantaja	Työ- ja elinkeinoministeriö
Julkaisun jakaja/myynti	Sähköinen versio: julkaisut.valtioneuvosto.fi Julkaisumyynti: julkaisutilaukset.valtioneuvosto.fi

Presentationsblad

Utgivare	Arbets- och näringsministeriet		1.4.2019
Författare	Ledargruppen för KYT2018 ordförande Jarkko Kyllönen, sekreterare Kari Rasilainen		
Publikationens titel	KYT2018 Nationellt forskningprogram för kärnavfallshantering 2015–2018 Slutrapport		
Publikationsseriens namn och nummer	Arbets- och näringsministeriets publikationer 2019:30		
Diarie-/ projektnummer		**Tema**	Energi
ISBN PDF	978-952-327-426-6	**ISSN PDF**	1797-3562
URN-adress	http://urn.fi/URN:ISBN: 978-952-327-426-6		
Sidantal	166	**Språk**	engelska
Nyckelord	kärnenergi, kärnsäherhet, kärnavfall, forskning		

Referat

KYT2018 var arbets- och näringsministeriets forskningsprogram, vars mål har varit att säkra, att det till myndigheters förfogande finns tillräcklig och omfattande tillgång till sådan kärnteknisk sakkunskap, som behövs för att jämföra olika tillvägagångssätt och metoder för kärnavfallshantering. Den forskning, som direkt hör till övervakningsplikten av kärnavfallshantering och till tillståndsansökningar, hör till myndigheternas och de avfallshanteringsskyldigas övriga program. Forskningprogrammet KYT2018 sträckte sig över åren 2015–2018.

Utgångspunkten för programmen inom kärnsäkerhetsforskning är att de skapar förutsättningar för upprätthållande och utveckling av sådant kunnande, samt deltagande i internationellt samarbete, som en fortsatt säker och ekonomisk användning av kärnkraft förutsätter. De organisationer, som bedriver forskning inom detta fackområde har varit en stark tillgång, som olika ministerier, Strålsäkerhetscentralen (STUK), kärnkraftsbolagen och Posiva har kunnat utnyttja.

Innehållet i forskningsprogrammet KYT2018 bestod av nationellt viktiga forskningsmål, det vill säga långtidssäkerhet för kärnavfallshantering, teknik inom kärnavfallshantering och kärnavfallshantering och samhället. Inom forskningsprogrammet fanns 32 forsknings- och infraprojekt. KYT2018 forskningsprogrammet fungerade också som ett diskussions- och informationsforum för myndigheter, de organisationer som verkställer kärnavfallshantering och forskningsinstitutionerna, varvid man skapar förutsättningar för användning av de begränsade forskningsresurserna. Strävan är att inom programmet för sin del befrämja utveckling av det nationella kunnandet, av infrastrukturen, säkra fortlöpande tillgång till sakkunskap, befrämja högklassig vetenskaplig forskning samt öka kunskapen inom kärnavfallshanteringens fackområde. Enligt den internationella utvärderingen av forskningsprogrammet lyckades man med detta.

Slutrapporten har utarbetats på uppdrag av forskningsprogrammets ledargrupp. Kontaktperson på ANM: Energiavdelningen/Linda Kumpula, tfn +358 29 506 0125.

Förläggare	Arbets- och näringsministeriet
Distribution/ beställningar	Elektronisk version: julkaisut.valtioneuvosto.fi Beställningar: julkaisutilaukset.valtioneuvosto.fi

Contents

FOREWORD

The Finnish Research Programme on Nuclear Waste Management KYT2018 ran from 2015 to 2018. The research programme was a continuation of several coordinated research programmes on nuclear waste management within public administration, the first of which started already in 1989.

The objective of the research programme has been to ensure nuclear waste management expertise primarily for use by the authorities when assessing various technologies and methods for nuclear waste management in line with the goals defined in the Nuclear Energy Act. In addition, the research programme has been designed to support and complement the programmes of organisations responsible for waste management, and to promote communication between the authorities, the organisations responsible for waste management, and researchers.

The final report of the KYT2018 research programme presents the objectives set for the research programme in 2014, the attainment of these objectives, and the research projects carried out by theme. Moreover, the final report presents the research programme's administration and evaluation as well as the seminars and follow-up meetings held.

The final report has been prepared by the steering group of the research programme, appointed by the Ministry of Economic Affairs and Employment on 4 August 2014, and the support groups assisting it. The summaries of research projects are drawn up by project managers. The Ministry wishes to thank the following people, in particular, for their editing work: Jarkko Kyllönen of STUK, the chairman of the steering group; research programme coordinator Kari Rasilainen, and Aku Itälä of VTT; and Petri Jussila and Ville Koskinen of STUK, the chairmen of the support groups. Linda Kumpula served as the contact person at the Ministry of Economic Affairs and Employment.

Helsinki, December 2018
Ministry of Economic Affairs and Employment
Energy Department

1 Introduction

The Finnish Research Programme on Nuclear Waste Management KYT2018 was launched in 2015. The research period closed at the end of 2018.

The starting points of the KYT2018 research programme are based on the Nuclear Energy Act (990/1987), which emphasises the research needs of the authorities. According to the Nuclear Energy Act, the purpose of the research is "*to ensure that the authorities have such sufficient and comprehensive nuclear engineering expertise and other facilities at their disposal that are needed for comparisons of the various ways and methods of carrying out nuclear waste management*" (§53 b).

When defining the content of the research programme, the aim was to seek research topics essential for national competence, which should be explored because of their importance. Coordinated projects covering the entire research period were outlined for the key themes. Topics directly related to the preparatory work, implementation or official inspection of nuclear waste management were left outside the scope of the research programme. The aim of this demarcation of the research field was to ensure that participation in the research programme would not jeopardise the independence expected from the nuclear waste management actors (e.g. STUK and Posiva).

An additional goal of the KYT2018 research programme has been to serve as a forum for discussion and communication between the authorities, nuclear waste organisations and research institutes. The purpose has been to create conditions for the efficient use of limited research resources in order to attain sufficiently diverse and interdisciplinary research teams for individual research projects. To reduce any duplication of research and to coordinate, for example, international projects, effective exchange of information and coordinated projects have been sought.

It has also been possible in the KYT2018 research programme to carry out projects with co-financing from the National Nuclear Waste Management Fund and other Finnish or foreign sources. For example, national co-financing is usually required for participation in EU projects. During the research period, one project of the research programme took part directly in an EU project[1].

[1] Carbon-14 project participated in the EU project CAST (CArbon-14 Source Term).

2 Organisation of the research programme

A central starting point for the organisation of the research programme and its practical work is that the project entity to be funded is selected annually on the basis of a public call for project proposals.

2.1 Objectives and their attainment

The main objectives of the KYT2018 research programme are recorded in the framework programme[2]. The main themes of the framework programme for the research programme are: 1) technologies in nuclear waste management; 2) long-term safety of nuclear waste management; and 3) nuclear waste management and society. Research on the long-term safety of nuclear waste management has five areas: safety case; buffer and backfill performance; canister performance; microbiological effects; and other safety studies. Since 2016, the research programme has included the theme of nuclear waste management infrastructure projects, which is associated with the commissioning of the VTT Centre for Nuclear Safety; infrastructure projects are not mentioned in the framework programme.

To specify the framework programme, each year the steering group of the research programme has prepared a topical guide for the call for project proposals. Above all, the guide has specified the theme of the long-term safety of nuclear waste

[2] TEM, 2014, Finnish Research Programme on Nuclear Waste Management KYT2018. Framework Programme for the Research Period 2015–2018, MEE Publications: Energy and the Climate 51/2014.

disposal and the importance of technical barriers in the nuclear waste repository. The guide has also presented general goals. For example, the call for projects of 2018 emphasised the goal of completing ongoing projects before the end of the research period.

The evaluation criteria for the research projects have been: 1) relevance and usability; 2) networking and integration; 3) educational impact and scientific merit; 4) efficiency demonstrated in KYT projects or in other contexts; and 5) realism in cost and workload estimates.

Targeting has been assessed in accordance with the objectives set by the Nuclear Energy Act for granting research funding, and in relation to the annual guide published by the steering group of the research programme. While usability has been evaluated primarily from the perspective of the safety assessment of nuclear waste management, the evaluation has also enabled the justification of other potential benefits to the end user.

Networking and integration have meant that research projects have been expected to build networks among industry players and to set up joint projects and integral entities.

The educational impact takes into account both the quantitative impact (dissertations, Master's theses) and the qualitative impact, which means the creation of expertise in the key competence areas of nuclear waste management in Finland.

Publications, posters and other such presentations have been regarded as scientific merit. Qualitative review has paid attention, among other things, to the nature of research (experimental research, basic research, modelling), innovation (new set-ups, new techniques) and extent (e.g. scope of sampling).

Efficiency has assessed the progress of the project. The results obtained in other research contexts have been taken into account when evaluating new projects.

Realism in cost and workload estimates means that the costs and workload are in balance, the workload and the time available are in balance, and the workload and human resources are in balance.

A total of 32 research projects were underway during the research period, either as separate and new projects or as continuations of previous projects. In all, 25 projects were in progress throughout the research period. The research projects were primarily linked to the assessment of the safety of nuclear waste management. The theme Nuclear waste management technologies had three projects, while the themes Nuclear waste management and society and Nuclear waste management infrastructure projects each had one project (infra project in the years 2016–2018).

Research projects were underway as follows: 29 research projects in 2015; 30 research projects in 2016; 29 research projects in 2017; and 29 research projects in 2018. For a list of projects, see Appendix 1. In 2018, the research programme had two small projects that were implemented by the decision of the steering group outside the public call for project proposals. The small projects are also covered by this final report.

During the research period, the National Nuclear Waste Management Fund channelled about EUR 11.6 million to the KYT2018 programme. The financial arrangements of the VTT Centre for Nuclear Safety, introduced in 2016, changed the calls for project proposals so that they consist of three parts (a call open to all and two infrastructure calls targeted only at VTT). A total of about EUR 7.5 million of funding was channelled to calls open to all (under the themes of research projects, infrastructure projects and further education). There were no further education projects during the research period. Approximately EUR 1.9 million was spent annually on research and infrastructure projects; Table 1 and Figure 1.

Table 1. Breakdown of financing from the Nuclear Waste Management Fund by theme in 2015–2018.

Research topic/ thousand euros	2015	2016	2017	2018
Technologies in nuclear waste management	80	63	70	70
Safety case	73	61	62	58
Buffer and backfill performance	478	341	385	401
Canister performance	351	253	255	255
Microbiological effects	297	220	230	238
Other safety studies	523	439	418	402
Nuclear waste management and society	45	40	100	100
Nuclear waste management infrastructure projects	-	143	143	136
Other activities	112	112	146	291
Total	**1959**	**1672**	**1809**	**1951**

On average, the relative distribution of funding from the Nuclear Waste Management Fund between the main themes throughout the research period was:

- Technologies in nuclear waste management 4%
- Long-term safety of nuclear waste management 78%
- Nuclear waste management and society 4%
- Nuclear waste management infrastructure projects 6%
- Other activities 8%.

Nuclear waste management infrastructure projects were started during the research period in 2016; once started, their share of the funding was around 8%. Other activities include, for example, the administration of the research programme and, in 2018, also the costs of small projects commissioned by the steering group, since small projects have in practice been implemented as subcontracts under the administration project.

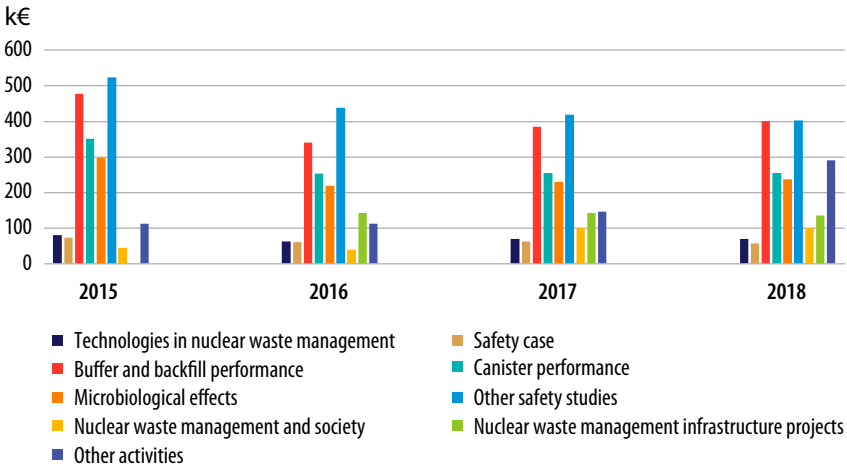

Figure 1. Breakdown of financing from the Nuclear Waste Management Fund by theme in 2015–2018.

During the research period, the research programme projects have published a total of 71 peer reviewed articles, 215 conference papers or working reports, and 36 academic theses (see Tables 2–4). The titles of the publications have been reported in the annual reviews of the research programme [3] [4] [5]. In the annual reviews, the research projects have also reported on publications at the approval stage and on ongoing theses, which have not been considered in the following tables[6]. A summary of the publications is listed in Appendix 2. Some of the publications are based on the work done in part in the KYT2014 programme that preceded KYT2018 and, correspondingly, part of the work done in the KYT2018 programme will be published in KYT2022, which succeeds the KYT2018 programme.

Table 2. Number of peer reviewed articles by theme 2015–2018.

Number of publications by theme	2015	2016	2017	2018
Technologies in nuclear waste management	-	-	1	1
Safety case	-	-	1	-
Buffer and backfill performance	3	4	1	3
Canister performance	4	3	6	4
Microbiological effects	8	2	3	3
Other safety studies	3	7	6	4
Nuclear waste management and society	-	-	3	1
Nuclear waste management infrastructure projects	-	-	-	-
Other activities	-	-	-	-
Total	**18**	**16**	**21**	**16**

3 KYT2018 Finnish Research Programme on Nuclear Waste Management 2015–2018, Annual Review 2015. (in Finnish only)

4 KYT2018 Finnish Research Programme on Nuclear Waste Management 2015–2018, Annual Review 2016. (in Finnish only)

5 KYT2018 Finnish Research Programme on Nuclear Waste Management 2015–2018, Annual Review 2017. (in Finnish only)

6 Conference presentations are often published as peer reviewed articles: in these cases, conference publications are not mentioned (i.e. a publication is recorded only once).

Table 3. Number of conference papers and working reports by theme 2015–2018.

Number of publications by theme	2015	2016	2017	2018
Technologies in nuclear waste management	1	5	5	8
Safety case	-	3	2	-
Buffer and backfill performance	9	10	4	4
Canister performance	8	9	13	8
Microbiological effects	9	8	12	8
Other safety studies	13	12	6	11
Nuclear waste management and society	6	4	10	13
Nuclear waste management infrastructure projects	-	6	5	-
Other activities	-	2	-	1
Total	**46**	**59**	**57**	**53**

Table 4. Number of academic theses by theme 2015–2018.

Number of academic theses by theme	2015	2016	2017	2018
Technologies in nuclear waste management	-	-	-	-
Safety case	-	-	-	-
Buffer and backfill performance	2	2	3	2
Canister performance	1	1	1	-
Microbiological effects	1	1	2	-
Other safety studies	8	4	4	3
Nuclear waste management and society	-	-	-	1
Nuclear waste management infrastructure projects	-	-	-	-
Other activities	-	-	-	-
Total	**12**	**8**	**10**	6

In total, 12 doctoral dissertations were completed during the research period. Four of them were under the theme Buffer and backfill performance (Itälä (2018)[7], Lavikainen (2016), Matusewicz (2018), Sun (2016)); one was under the theme Canister performance (Rajala (2017)); one under the theme Microbiological effects (Purkamo (2015)); and six under the theme Other safety studies (Ikonen (2017), Kietäväinen (2017), Kuva (2016), Markovaara-Koivisto (2017), Tuovinen (2016) and Uotinen (2018)). Doctoral dissertations have a long time frame and at least part of the work has already begun before the KYT2018 research period. They may also have other inputs from outside the KYT2018 programme.

The following research organisations have been involved in the KYT2018 research programme: VTT, Aalto University, University of Helsinki, Geological Survey of Finland, University of Jyväskylä, University of Eastern Finland, Numerola Oy, Tampere University of Technology and University of Tampere.

2.2 Evaluation of the research programme

The evaluation of the research programme took place in Helsinki on 31 May – 1 June 2017. The evaluation team reviewed research programme documents and interviewed the organisation of the research programme, project managers of research projects and other key persons. To complete their work, the evaluation team compiled an evaluation report, which has been published as a separate report in the Ministry's publication series[8].

The evaluation report presented the findings, challenges and recommendations, as well as the overall conclusions. According to the evaluation, the KYT2018 research programme has comprehensive and in-depth knowledge of nuclear waste management, and the administration of the research programme has been implemented efficiently. The research programme's support groups have created an active national research community, and the research programme promotes

7 Unless otherwise stated, references in this report refer to the list of publications in Appendix 2.

8 Pellegrini, D., Simic, E. & Salomaa, R. 2017. KYT2018 Review Report. MEAE guidelines and other publications 9/2017, 29 p.

dialogue between the authorities, the organisations responsible for nuclear waste management, and researchers. However, according to the evaluation, the research topics of the KYT2018 research programme have been limited too strictly to benefit the authorities only, and research has become too differentiated from other research carried out on nuclear waste management in Finland. The evaluation team considered it necessary to strengthen the scientific steering of the research programme and to focus the research more sharply on the challenges still open. The utilisation of the infrastructure of the VTT Centre for Nuclear Safety was seen as useful from the perspective of both research equipment and the research community. At the same time, the usability of the centre was seen as a challenge in the next few years. The evaluation team noted that cuts in funding for research projects during the research programme had made it more difficult to conduct research. It was also considered a challenge that research funding was only granted for one year at a time, and not earlier than March of the research year.

The steering group of the KYT2018 research programme reviewed the results of the evaluation in the autumn of 2017 and noted that it is appropriate to address the challenges and recommendations in the planning group of the KYT2022 research programme. The planning group began its work in autumn 2017. In summer 2018, the group submitted its proposal for the framework programme[9] and organisation of the research programme to the steering group of the KYT2022 research programme, which approved the proposal in autumn 2018. In the framework programme, the thematic area of the research programme has been expanded to benefit not only the authorities but also the nuclear waste management operators and their research on nuclear waste management. The importance of the scientific steering of research has been emphasised in order to increase the usability of research. Challenges related to the development of financing have been discussed in the Ministry of Economic Affairs and Employment, and the Ministry has set up a project to go through alternative solutions and, if necessary, to amend the Nuclear Energy Act. Assessing the impact of reforms is only possible during the KYT2022 research programme.

9 TEM 2018. Finnish Research Programme on Nuclear Waste Management KYT2022 – Framework Programme for the Research Period 2019–2022. Publications of the Ministry of Economic Affairs and Employment 25/2018, 56 p.

2.3 Administration of the research programme

Research programme work has been based on cooperation and the division of labour between the research programme steering group, three support groups, the coordinator and the research projects. The steering group has usually met five times a year (in 2018 only four times, because there was no call for project proposals in the last year of the research period).

The steering group has been responsible for the research programme's strategic policies and has acted as the body coordinating the research programme's administration and the general outlines of research. The steering group has supervised the planning of the research programme and has monitored the quality of research findings. Each year the steering group has drawn up recommendations to the Ministry on how to channel funding from the Nuclear Waste Management Fund to nuclear waste management research.

The research programme's support groups have met one or two times a year. The support groups have had the following mutual division of labour: Support group I: Buffer, backfill materials and canister; Support group II: Safety assessment and innovation and Support group III: Society and man.

Each year the support groups have assessed the project proposals in detail and, based on this assessment, they have drafted a summary report to the steering group on each project proposal they have assessed. Following an appropriate internal division of labour, the support groups have monitored the progress of the research projects. For practical monitoring work, the support groups have divided research projects by topic into follow-up groups, which have met once a year.

VTT Technical Research Centre of Finland has served as the coordinator of the research programme.

The steering group of the research programme comprised representatives of the Ministry of Economic Affairs and Employment, the Radiation and Nuclear Safety Authority, the Ministry of Social Affairs and Health, the Ministry of the Environment, and nuclear waste organisations. The steering group has been chaired by Jarkko Kyllönen (Radiation and Nuclear Safety Authority). The other members have been

Mikko Paunio (Ministry of Social Affairs and Health), Miliza Malmelin[10] (Ministry of the Environment), Sami Hautakangas (Fortum Power and Heat Oy), Pekka Viitanen[11] (Teollisuuden Voima Oyj), Marjut Vähänen[12] (Posiva Oy) and Jaana Avolahti[13] (Ministry of Economic Affairs and Employment). Mia Ylä-Mella[14] (Fennovoima Oy) has served as an expert member.

The deputy members have been Kaisa-Leena Hutri (Radiation and Nuclear Safety Authority), Jari Keinänen (Ministry of Social Affairs and Health), Magnus Nyström[15] (Ministry of the Environment), Kristiina Söderholm (Fortum Power and Heat Oy), Liisa Heikinheimo[16] (Teollisuuden Voima Oyj), Lasse Koskinen (Posiva Oy), Jorma Aurela (Ministry of Economic Affairs and Employment) and Hanna Virlander[17] (Fennovoima Oy).

The steering group has appointed members to the support groups from the Radiation and Nuclear Safety Authority, the Ministry of Economic Affairs and Employment, the Ministry of the Environment, Fennovoima Oy, Fortum Power and Heat Oy, Posiva Oy and Teollisuuden Voima Oyj.

2.4 Contacts

2.4.1 Seminars

A total of 13 seminars were organised for exchanging of information in the KYT2018 research programme. The themes of the research programme were discussed in nine thematic seminars. They focused on one topic at a time and presented associated perspectives from the viewpoint of research institutions and end

[10] Until 4 March 2016. Susanna Wähä as from 5 September 2017. Sami Rinne as from 2 January 2018.

[11] Nina Paaso as from 27 February 2015.

[12] Anne Kontula as from 4 July 2016.

[13] Linda Kumpula as from 22 January 2016.

[14] Ville Koskinen as from 10 January 2016. Heikki Hinkkanen as from 31 July 2017.

[15] Kati Vaajasaari as from 2 January 2018.

[16] Until 9 January 2017. Arto Kotipelto as from 1 September 2017.

[17] Ville Koskinen as from 17 December 2015. Heikki Hinkkanen as from 10 January 2016. Tuire Haavisto as from 31 July 2017.

users. The research programme and all its themes, as well as research projects, were discussed in seminars organised both in the middle and at the end of the programme period. There were two such seminars. The seminar for presenting the framework programme of the KYT2018 programme was organised before the first call for project proposals. Similarly, a seminar for presenting the KYT2022 draft framework programme was organised together with the KYT2022 programme.

Several stakeholders were informed of the seminars. The events were open to everyone interested. In general, 10 to 30 people attended the thematic seminars, and participants also came from outside the research programme. A list of the seminars is presented in Table 5. The materials of the seminars are archived on the website of the research programme.

Table 5. KYT2018 research programme seminars.

Topic of the seminar	Time	Place
Presentation of the KYT2018 draft framework programme	22 August 2014	Radiation and Nuclear Safety Authority, Helsinki
Modelling of fractured bedrock	3 December 2015	Geological Survey of Finland, Espoo
Copper corrosion, 1st seminar	15 December 2016	Aalto University, Espoo
Bentonite research, 2nd workshop	16 December 2016	VTT, Espoo
Mid-term seminar of the programme period	7 April 2017	Finlandia Hall, Helsinki
Social acceptability of nuclear waste management	6 October 2017	Ministry of Economic Affairs and Employment, Helsinki
Copper corrosion, 2nd seminar	2 November 2017	Aalto University, Espoo
Bentonite research, 3rd workshop	8 November 2017	Aalto University, Espoo
Numerical modelling of fractured rock mass and rock fractures	1 December 2017	Geological Survey of Finland, Espoo
Microbiology in the final disposal of nuclear waste	24 April 2018	VTT, Espoo
Presentation of the KYT2022 draft framework programme	20 August 2018	VTT, Espoo
Social licence to operate and nuclear waste management	10 October 2018	VTT, Espoo
Final seminar of the programme period	29 January 2019	Finlandia Hall, Helsinki

2.4.2 Follow-up meetings

In order to monitor the progress of research projects in the research programme, the projects were divided into follow-up groups according to their themes[18]. All projects included in follow-up groups (1) to (8) met their support group once a year. The aim has been to obtain information on the latest research findings and to hear the opinions, views and wishes of the researchers, as well as to highlight the needs and wishes of the end users in terms of project content and orientation. The project of follow-up group (9) organised two seminars in the field of social sciences; otherwise the follow-up group did not meet for project monitoring purposes.

The monitoring of the progress of the project included in the theme Infrastructure projects for nuclear waste management was implemented in cooperation with the SAFIR2018 research programme. The SAFIR2018 programme has had a follow-up group specialised in monitoring infrastructure projects. The chair of the KYT2018 steering group and the coordinator of the research programme were reserved seats at the meetings of this group.

2.4.3 Other contacts

The website of the research programme (kyt2018.vtt.fi) has been the main means of contact and communication. All material published by the research programme is available on the website. In addition to the public website, the research programme has a protected intranet for use by the steering group and the support groups.

Each year, the research programme has published annual plans and annual reviews. Interim reviews have been published twice a year. Information on decisions made at steering group meetings and on other current affairs has been published as bulletins on the website.

The steering group has also maintained direct contacts with research projects by inviting project managers to present their project's current situation at steering group meetings. Project presentations were held once a year with the exception of 2017, when the international evaluation of the research programme was carried out.

[18] There were nine follow-up groups in 2018. The follow-up groups of Support Group I were (1) buffer and backfill performance, (2) canister performance, and (3) bedrock. The follow-up groups of Support Group II were (4) safety case, (5) nuclide transport, (6) microbiological effects, (7) biosphere, and (8) nuclear waste management technologies. The follow-up group of Support Group III was (9) social sciences.

3 Studies under the theme Technologies in nuclear waste management 2015–2018

According to the framework programme, the authorities must have access to up-to-date information and expertise on the alternatives of geological disposal under research and development, as well as expertise for the comparison of different ways and methods of implementing nuclear waste management in Finland. The assessment and elaboration of different nuclear waste management options may reveal the possibility or need to explore new or alternative technical solutions. Exploration of new and alternative technologies will improve the reliability of implementing Finnish nuclear waste management if the geological disposal — the current principal option — would not be carried out as planned or if new methods would be developed, for instance, to reduce or process the amount of waste generated. According to the framework programme, research on the theme is best carried out by participating in international cooperation. However, the participation of Finnish research teams in international research programmes requires that Finns have their own expertise.

The projects implemented in the research programme focused on some key areas mentioned in the framework programme. The theme included two projects dealing with advanced nuclear fuel cycles, i.e. nuclear waste management solutions based on spent fuel reprocessing and nuclide separation. The projects Advanced fuel cycles – New adjustable separation materials (SERMAT) by University of Helsinki (HYRL) and Advanced Fuel Cycles – Scenario and Inventory Analysis (KOSKI) by VTT were both a continuation of the previous programme period.

The HYRL project covered one postgraduate student's experimental study associated with nuclide separation technology. The aim of the project was to train a doctor of radiochemistry in the field of separation and transmutation technology. The objective of the research work was the study and development of new nano-porous metal-phosphate ion exchangers for separating actinides in spent fuel or secondary waste solutions produced by new liquid extraction methods. Additional objectives included monitoring international research on advanced fuel cycles and disseminating information on new specialist techniques in collaboration with the VTT project. The aim of VTT's project was to acquire and maintain Finnish modelling expertise regarding advanced fuel cycles, and to follow international development and research in the field. VTT team made reference calculations on the dose rate of spent fuel in an international group of experts.

In line with the policy of the framework programme, the nature of the projects included in the programme was to monitor international information through one's own concrete efforts. The projects have managed to provide the authorities with expertise for the comparison of different methods and of ways of implementing nuclear waste management in Finland. The information acquired mainly deals with reducing the amount and activity of the waste generated and the impact of this on the implementation of geological disposal.

The organisations of the projects involved in the programme have a long common history within the Finnish Research Programme on Nuclear Waste Management, during which cooperation between the projects has been rather close. Owing to the follow up of research and maintenance of expertise, international networking has been the key objective of the projects.

The educational impact of the projects has been moderate. The core content of the projects has been to train experts through their own work and through the follow up of international research. The projects have produced several working reports and conference presentations. One doctoral dissertation in the field of separation technology will be completed in 2019 through the project at the Radiochemistry Laboratory of the University of Helsinki (HYRL).

Project performance and costs have been average. Both projects have suffered significant financial cuts during the programme period.

Under the theme of nuclear waste management technologies in 2018, VTT and HYRL carried out a joint small project: Measurement methods for hard to measure radionuclides (VAMMA). The project was a feasibility study by nature and explored the research capabilities of Finnish laboratories at VTT, HYRL, Fortum, Teollisuuden Voima, and STUK for measuring the most important difficult to measure radionuclides. The difficult to measure radionuclides are mainly beta-active radionuclides in decommissioning waste, which cannot be measured without a preceding demanding radiochemical separation of waste samples.

The project was compatible with the framework program and had a considerable networking by collecting the knowhow of some of the main stakeholders.
A Master's thesis on the subject was being prepared at HYRL, but its completion was postponed until 2019. Research on difficult to measure radionuclide measuring methods continues in the KYT2022 programme.

4 Studies under the theme Long-term safety of nuclear waste management 2015–2018

4.1 Safety case

According to the framework programme, the authorities must have access to sufficient high-quality information, independent of the licence applicant, on the principles for drawing up the safety case, its associated lines of thinking, and its restrictions, since it is the responsibility of the authorities to assess the applicant's safety case. The framework programme presents the need for a coordinated project on this complex and demanding theme. Its aim is to produce new experts for the drafting and assessment of the safety case, and to increase competence with respect to methods included in the safety case. According to the framework programme, on the basis of this competence, it will later be possible to examine the feasibility of various final disposal projects separately.

A coordinated project that participated in the research programme under this theme was Systematization of the Safety Case Methodology (TURMET), which consisted of subprojects at VTT and Aalto University; VTT served as the coordinator. The coordinated project explored the methods for the safety case in the final disposal of nuclear waste, in particular from the perspective of scenario analysis, assessed how the management of uncertainties affected the methods of the safety case, and developed technical tools for the assessment of uncertainties. Aalto's subproject developed and applied methods and tools based on scenario analysis and probabilistic risk analysis to support the assessment of the long-term safety for nuclear waste management.

The coordinated project was a rather small-scale project with two researchers, and thus focused only on a limited selection of possible topics covered by the framework programme. The project's literature reviews on the safety case and scenario formulation, as well as the website created, focused on the content of the framework programme, creating the basis for developing the structure and ways of presenting the safety case so as to make it understandable for broader circles. The scenario-building tool developed in the project is well-focused on the objectives of the framework programme to develop methods included in the safety case. However, the applicability and usability of the tool will probably remain more modest than expected.

The small size of the project also had a detrimental effect on other evaluation criteria, such as networking. The networking goals were considerably higher than what the actual resources eventually made possible.

The educational impacts, in view of the project size, were good. The project trained a new expert for the field of safety cases in both subprojects. The results were literary reviews associated with the safety case and scenario analysis, as well as a doctoral dissertation on the theme of scenario analysis, which will be completed in 2019. A website was also set up for the project.

Especially the Aalto University subproject produced exemplary results. Completion of a doctoral dissertation on the basis of work done over a four-year period is a worthwhile achievement.

The costs of the Aalto University subproject were exceptionally low.

4.2 Buffer and backfill performance

In the KBS-3 concept, reliable assessment of the performance of the buffer and backfill materials largely determines the reliability of the entire safety case. To this end, the authorities must have access to a sufficient amount of high-level expertise in the performance of these substances and its impact on long-term safety. The framework programme (KYT2018) identifies a stepwise need to target research

with respect to buffer and backfill materials. The priority is to develop scientifically well-founded conceptualisations for studying the buffer and backfill performance, as well as mathematical and computational models derived from them. Secondly, these models must be used to assess the long-term behaviour of bentonite. To meet this need, the programme financed one coordinated project and two individual projects.

The coordinated project THEBES (THMC Behaviour of the Swelling Clay Barriers) studied and developed the THMC model for bentonite. Aalto University was responsible for coordinating the project. Other participating organisations included the University of Jyväskylä, VTT, and Numerola Oy.

Apart from the coordinated project, the programme period included the project Bentonite swelling pressure (UEFBENT) by the University of Eastern Finland, and the project Bentonite erosion and radionuclide interaction processes (BENTO) by the University of Helsinki. The project of the University of Eastern Finland focused on the modelling of bentonite on the atomic level and on molecular dynamics. As indicated by its name, the University of Helsinki project focused on the erosion of bentonite and the transport of radionuclides.

The scope of the projects was well in line with the objective determined in the framework programme. Especially at the beginning of the programme, the projects proceeded slowly due to significant cuts in financing. After the initial problems, the projects were able to adjust their activities to their financial level, after which the projects progressed steadily towards their revised target.

The coordinated project THEBES managed to implement the THMC model on the platform of a commercial modelling tool. In the model, the coupling of chemistry is relatively limited, as the model takes into account only key salts. The experimental research needed for the development of the model has mainly been done using an arrangement based on the tomography equipment developed in the University of Jyväskylä during the KYT2014 period. On the basis of experimental research, the coordinated project has been able to develop modelling in a more reliable direction during the project. The project has thus reached its goal. In connection with the THEBES project, the participants have had international cooperation with several European universities.

The project of the University of Eastern Finland has created new understanding of the swelling behaviour of bentonite at the molecular level. Molecular modelling is a new research method in the KYT programme, although the conceptual model goes back a longer time. The project progressed steadily over the programme period and reached its target at the end of the programme period. At the end of the programme period, the project had produced a functioning model for the swelling behaviour between montmorillonite sheets in one-dimensional space.

From the point of view of the authorities' work, the results of the project can in part be utilised in evaluating Posiva's operating licence application, but owing to the stage of the licensing process, it has not been possible to utilise the results immediately. However, the results have contributed to increased expertise and understanding of bentonite materials, serving the knowledge of phenomena in final disposal, thus benefiting the entire industry in the longer term.

Several Master's degrees were completed in bentonite and backfill projects during the programme period. In addition, three of the researchers involved in the project earned a doctoral degree, and the fourth doctoral degree will be completed in 2019. In addition to academic theses, the project has produced presentations, posters and journal articles. The project has raised the level of expertise in the theme and has trained new experts in the field.

4.3 Canister performance

According to the framework programme, the authorities must have access to sufficient high-level knowledge of the long-term durability of final disposal canisters, the principal factors affecting it, and the methods used to assess long-term durability. For their part, the canister projects implemented in the KYT2018 programme have helped to meet this need.

The KBS-3 concept is based on a multibarrier system with complementary release barriers. The final disposal canister is considered to be the most important single release barrier, and its long-term performance is of great importance in the KBS-3 concept. When examining the performance of the final disposal canister,

consideration must be given to issues affecting both mechanical durability and chemical resistance.

During the KYT2018 programme period, canister projects focused on research into the chemical resistance of copper. The canister projects formed a coordinated project called KAPSELI. The coordinator was VTT, and the other participants in the coordinated project came from Aalto University and VTT. During the programme period, there were five subprojects studying the chemical resistance of the disposal canister, all of which ran throughout the entire KYT2018 period. Three of the sub-projects investigated various corrosion phenomena, while two studied the effect of microbial activity on copper corrosion.

Of the microbial research projects, the microbial research on oxic conditions came to the conclusion that further research would no longer provide significant additional information. Good results were achieved in other projects, but there was still a need for further research. High corrosion rates were detected in some of the projects, but the reason for these is assumed to lie in the test arrangements and in the short duration of the tests.

Owing to the licensing status of Posiva's project, the results cannot immediately be utilised in the authorities' work. There is still a need for further information, but the research data already obtained during the KYT2018 programme period will assist the authorities and will also help to create basis for the licence-holders' own research projects.

One of the objectives of the KYT programme is to train a new generation of experts in the field of nuclear waste management. Canister research projects gave rise to several academic theses (Master's theses) during the programme period. The aim of the projects was to encourage graduates to stay in the research field, but at least in part, the graduated researchers have moved to work for the industry. A doctoral dissertation has also been completed during the KAPSELI project. The academic theses completed during the programme period and the new researchers studying the properties and performance of the disposal canister met the goal set for the educational impact well. In addition to the academic theses, the results of the canister projects were also published at several seminars and conferences and in peer-reviewed journal articles. For example, the scientific merits of the projects

include long-term data (many years) on the creep tests of copper and its welding joints and the modelling of creep, as well as information on copper corrosion mechanisms in various environments and the impact of groundwater microbial activity on copper corrosion.

4.4 Microbiological effects

According to the framework programme, the authorities must have access to sufficient high-quality information on the impact of microbiological activity on the performance of release barriers. The framework programme calls for a coordinated project on this theme. The project would work in close cooperation with other coordinated projects, as well as in international cooperation, in order to identify the specific needs of research on the safety case and technical barriers.

There were four projects under the theme of microbiology. The coordinated project Microbiological risks of the final disposal of nuclear waste (MILORI) consisted of the following VTT's subprojects: Microbiology related to geological disposal of low- and intermediate level waste (MAKERI); Microbially induced corrosion of low and intermediate level radioactive waste (CORLINE); and Microbial sulphur cycle in final nuclear waste repository conditions (GEOBIOKERTO). In addition, the project Nutrients, energy and gases in bedrock biosphere (RENGAS) by Geological Survey of Finland was included as an independent project.

MAKERI project assessed, among other things, microbiological risks associated with the geological disposal of low and intermediate-level waste, which may lead to the weakened performance of release barriers, the release of gas and the transport of radionuclides from the repository into the biosphere. CORLINE project assessed the formation of biofilms and the risk of microbiological corrosion on metallic materials and developed a real-time in-situ monitoring technique for measuring the links between corrosion and water chemistry changes. GEOBIOKIERTO project experimentally investigated the impact that microbial communities in the repository groundwater have on the sulphur cycle and on the speed of sulphur compound formation in various circumstances, and assessed the impact that microbes in groundwater and their metabolic products have on the physical structure and performance of the bentonite buffer. RENGAS project investigated the occurrence

and movement of bio-geochemically important elements in rock groundwater, the energy sources of the deep biosphere, and the transfer of energy in redox reactions catalysed by microbes.

Microbiology projects have been focused well on the framework programme: the theme was used to construct a coordinated project, which collaborated, in particular, with coordinated projects concerning engineered release barriers and was engaged in international cooperation. Research within the theme has produced high-quality information about the impact of microbiological activity on the performance of the release barriers. The information obtained can be utilised at least in safety analyses, modelling, and in the assessment of the safety case.

Microbiology projects have conducted commendable cooperation both among themselves and with other KYT projects; domestic and international networking has been excellent.

The projects have significantly increased expertise, and their educational impact has been considerable. The studies have been a part of two doctoral dissertations and one Master's degree, all of which were completed; several international publications have come out.

The studies have produced good results considering the special features relating to the theme, such as its short research history, its multidisciplinary nature, the time-consuming development of experimental methods and the high proportion of experimental work in general.

The cost of research within the theme is fairly high, as much of it is experimental work done by seasoned experts. The share of funding obtained by the RENGAS project outside KYT has been commendably high.

4.5 Other safety studies

The framework programme outlines that when assessing the safety of nuclear waste management in general and the safety of geological disposal in particular, information is needed from a wide range of disciplines and also in addition to

the coordinated projects mentioned in the framework programme. The themes of projects outside these coordinated projects vary for natural causes. By their content, they focused on the themes mentioned in the framework programme, but did not cover everything listed separately in the framework programme.

Support Group I projects

Support Group I was responsible for the follow up of themes rock fractures, and imaging and modelling techniques for rock fractures, which were studied in the KYT2018 programme in three projects KARMO II, KARMO III and ROSA. In addition, Support Group I followed up geopolymer research.

The successive projects Mechanical properties of rock joints (KARMO II and KARMO III) by Aalto University, studied the technical properties of rock fracture surfaces. This was the first time that world-class experiments were conducted for research on a large scale. One result of the research is a spinoff project funded by TEKES, which aims to commercialise the technology developed. A doctoral dissertation was completed in the project, and new research methods were developed for studying large surfaces and modelling their technical properties. As the surface to be studied increases, the number of observation points need to be reduced in order to keep the research time reasonable and the amount of data suitable for the application. The technology also has applications outside the disposal projects, e.g. in infrastructure construction and mining. The project has met its objectives well and has produced new professionals for the field (Bachelor's, Master's and doctoral theses).

Project Fracture simulator which respects the measured fracture length and orientation distributions (ROSA) was conducted by the Geological Survey of Finland. The aim was to develop methods for predicting underground fracturing on the basis of fractures detected on the ground. In addition, on the basis of the fractures observed, effort was made to assess the geological age relations of the fractures so that the geological activity of the area under study could be anticipated better. An important part of the work is the grouping of the fractures observed so as to make the handling of observations easier. The project met its objectives in part, since the determination of the age relations proved to be more difficult than expected. A doctoral dissertation and a Master's thesis were completed in the project.

Application of geopolymers in solidification of liquid waste was studied in the project Applicability of geopolymers in nuclear waste management (GeoP-NWM) by VTT. Geopolymers are an inorganic alternative for Portland-cement and may function as environmentally friendly alternative in the solidification. The project was initiated with literature survey and proceeded into manufacturing of small-scale test samples. The project has raised awareness of an internationally interesting option for solidification. Considering the small size of the project, it has achieved good results which can be used by regulatory body as well as in the nuclear industry.

Support Group II projects

Among the themes covered by Support Group II, especially the following were emphasised in the framework programme and implemented in the programme: transport of radionuclides; uncertainties associated with C-14 isotope; and transport in the biosphere. The educational impacts of the different projects were diverse. The projects have trained new experts for the field and have together produced academic theses. Several projects have also employed more experienced researchers.

Themes pertaining to the transport of radionuclides were addressed in the projects: Behaviour of radionuclides in the geosphere; in situ studies (RAKU) by University of Helsinki (HYRL); Release of C-14 from metallic waste (HIILI-14) by VTT; Chemical forms and sorption of radiocarbon in geosphere (C14ROCK) by HYRL; and Modelling fracture flow, matrix diffusion and sorption using the lattice-Boltzmann method (JYFLKYT) by University of Jyväskylä.

Among other things, these projects did the following. RAKU project studied radionuclide retention and transport in crystalline rock using field and laboratory tests, and developed and applied reactive transport models. HIILI-14 project investigated the release of C-14 isotope present in the active metal components of reactor and decommissioning waste into groundwater in repository conditions, its release rate and the dissolved and gaseous states of carbon formed in water. C14ROCK project studied the chemical states of radiocarbon originating from spent nuclear fuel and their changes on the way through bedrock into the biosphere, studied the effects of bacteria in the transformation of methane carbon to carbonate, and studied the ability of bacteria to generate calcite in bedrock conditions. JYFLKYT project modelled radionuclide transport in bedrock fractures and the delays caused by matrix diffusion and sorption.

The study of rock transport and C-14 isotope uncertainties is well in line with the goals of the framework programme. The usability of projects associated with radionuclide transport is particularly evident in safety analysis and in the modelling needed to support it. In these topics the long-term safety implications of the studies are significant and their results may have an impact on the assessment of the assumptions and results of the safety case.

The networking of transport-related projects has been moderate. Cooperation has been visible both within the programme and in international projects.

The educational impact of the projects associated with transport has been variable. Experts have been trained for an important area. One doctoral dissertation has been completed on the theme and another one is about to be released in 2019. Unfortunately, one doctoral dissertation was left unfinished because the researcher left the programme before the end of the programme period.

The effectiveness of transport-related projects and keeping costs realistic have also been variable.

Biosphere phenomena were addressed in the projects Risk assessment of radioactive waste: development of radioecological modelling for terrestrial and aquatic ecosystems (YRMA) by University of Eastern Finland and Alternative methods for biosphere modelling and their evaluation (VABIA) by Tampere University of Technology. Among other things, these projects did the following. YRMA project developed the radioecological modelling of fresh water and its use for the assessment of potential risks of final disposal. VABIA project developed methods for studying the effects of low radiation doses in natural organisms; and created simple biosphere transport and dose models, which were applied to estimate the doses resulting from spent fuel disposal.

The topics of the biosphere projects are well in line with the framework programme, and their results are significant. The results can be utilised to assess the source data used in the safety assessment of final disposal, and its results.

The networking of biosphere projects has been modest as they did not cooperate with other KYT projects and were not linked with international projects.

On average, the educational impact of the biosphere projects has been good. The UEF project produces content for two doctoral dissertations, one of which was completed during the programme period. Both projects have generated international publications.

The effeciency of biosphere projects has been variable. The YRMA project has occasionally encountered timetable problems, and the VABIA project was not part of the programme for a year due to a belated project application.

In view of the results, the costs of the biosphere projects have been average.

5 Studies under the theme Nuclear waste management and society 2015–2018

The purpose of social research in the research programme is to support decision making and its preparation. Decisions made in nuclear waste management have a long-term impact on the future. Nuclear waste management requires not only technical expertise but also political and wider social acceptance. The licensing of nuclear waste management takes place in Finland step by step, starting with a decision in principle where nuclear waste management solutions are assessed in terms of the overall good of society. Government decisions are influenced by the values and expectations of society as a whole.

In the research programme, the views on nuclear waste management and, in particular, on the final disposal of spent nuclear fuel held by various actors and groups were considered important topics. The theme could be approached, e.g. from the perspective of the various actors' independence. Topics of interest included ethical and public debate, issues relating to the long duration of nuclear waste management, and the link with nuclear energy generation. The long duration involves issues such as intergenerational justice, possible long-term costs, and the reliability and preservation of information over the long term.

In 2015–2018, the research programme funded a social research project Governing safety in Finnish and Swedish nuclear waste regimes (SAFER) by University of Tampere that compared the public debate held in Finland and Sweden on current licensing procedures for spent nuclear fuel and the approaches to challenges arising from the ethical aspects and long duration of the projects. The project explored the views on ethical issues and the number of repositories held by

Finnish municipalities where potential repositories would be located. The project further compared the approaches of the municipalities of Eurajoki in Finland and Östhammar in Sweden in the projects dealing with the final disposal of spent nuclear fuel. In addition, the project examined the applicability of the social licence to operate in Finnish nuclear waste management by means of an international comparison.

The results of social research can be used when assessing the social acceptability of nuclear waste management and the general need for information in society. Based on the research results, it is also possible to highlight topics that require further research and to obtain new perspectives and good practices. The research will also train new experts to the social research field of nuclear waste management and will maintain networks with national and international researchers in the field. Social research on nuclear waste management is internationally important, and research findings are also published in international publications in the sector.

6 Project abstracts

6.1 Technologies in nuclear waste management

6.1.1 Advanced Fuel Cycles – New adjustable separation materials – SERMAT (Project 1)

Risto Koivula[19]**,** Elmo Wiikinkoski, Risto Harjula, University of Helsinki

About:

The meaning of advanced fuel cycles is in the maximized efficiency, safety and economic use of nuclear fuel. Here, efficiency relates to the use of Plutonium (Pu), formed in the current reactor types, in closed fuel cycles that are made possible with the 4th generation fast reactors. For the safety of final disposal of spent nuclear fuel, it is of importance to develop such methods and facilities where minor actinides (Np, Am, Cm) and some fission products (I, Tc) are separated from nuclear waste, and transmuted into less radiotoxic waste. Advanced separation techniques make it possible for different nuclides or groups of nuclides to be disposed or stored in individually best possible manner.

Partitioning and transmutation (P&T) of the long-lived radionuclides contained in nuclear waste is a part of the world-wide research on the topic of next generation nuclear technology such as closed fuel cycles. Depending on the methods used, it is estimated that with the use of P&T, the radiotoxicity of end waste can be decreased 10 to 100-fold in comparison with the direct final disposal route. The separation techniques

[19] In project abstracts the central project group is mentioned at the beginning and the project manager is bolded. If the project had multiple project managers during the programme period, all of them have been bolded. In addition, in coordinated projects the subproject managers have been bolded as well.

developed in P&T concept can be divided in hydrometallurgical and pyrometallurgical methods that usually aims on separation of uranium and transuranium elements (Np, Pu, Am, Cm) onto clean fractions ready for transmutation. The advanced methods are still done in laboratory scale and the separations have shown to be very complex since it is difficult to separate transuranium elements from similar lanthanides. The drawback on hydrometallurgical processes is often limited radiochemical stability of the used organic extracting reagents and therefore they might not be very suitable for processing of the high activity transmutation fuels. Also, hydrometallurgical processes form considerable streams of secondary active liquid waste.

SERMAT focused on developing inorganic ion exchange materials and methods for the difficult separation of actinides from lanthanides. These materials can be used in separation columns, they withstand acidic conditions and radiation, and ideally are also reusable. In addition, independent of the advances of transmutation technologies, the materials can be used to reduce the secondary waste volumes of current solvent extraction based separation processes used in nuclear industry.

Methods used, main results:

In SERMAT a series of zirconium phosphates were synthesized and characterized on their physicochemical properties (XRD, solid-phase NMR, IR, Raman, thermogravimetry, SEM, pKa-determination) and on their ion exchange properties (europium (Eu) and americium (Am) distribution coefficients, separation factors, selectivity coefficients and metal binding coefficients).

Some of the materials showed very high separation factors (max. 90 in pH 0.5 to 1.5) between Am and Eu with Eu as the preferred element. This is excellent, since it means that actinides can be eluted out to be transmuted, while most of lanthanides will remain in the material, that is directly ready for final disposal.

Our recent publication (Wiikinkoski et al, ChemistrySelect 2018, 3, 9583.) describes the relationship between materials acidity, crystallinity and ion exchange properties that is regarded as one of the significant results of the project.

The most important results of SERMAT is the successful Am/Eu separation in column experiments. In load-elution experiment (Figure 2) an extremely pure Am fraction

was collected (99.9992%) when 76 % of the loaded Am was eluted. When the experiment was continued to the point where 88% of Am was eluted, the purity of Am was still 99.6%. 7% of Am retained in the column and could not be eluted even with concentrated acids. In constant feed column separation experiment with a feed solution containing equal amounts of Am and Eu we determined that in the conditions of this experiment, 1 kg of ZrP (zirconium phosphate) is able to separate 330 L with a Am purity above 99.5% or alternatively, 630 L / 1 kg and 95% Am purity.

The most important result of SERMAT is the training of a PhD in nuclear waste management and more specifically in separation techniques. PhD candidate Wiikinkoski will have his defense in early 2019 with the preliminary title *Ion Exchange in Nuclear Fuel Reprocessing – Zirconium Phosphate Materials for the Separation of Trivalent Actinides and Lanthanides*.

Importance/Applicability:

Through the doctoral training, this project advances the expertise in this field in Finland, and helps Finnish research institutes to get involved in international P&T collaboration. The developed materials and know-how can be used in the processing of existing waste solutions, or world-wide in the spent nuclear fuel / reprocessing facilities. In long term, the results can be exploited in the fuel cycles that would use P&T concept. The results of SERMAT supplements and complete earlier P&T results related to KYT-projects, and via the doctoral thesis all the separate project results will be compiled under a concise package.

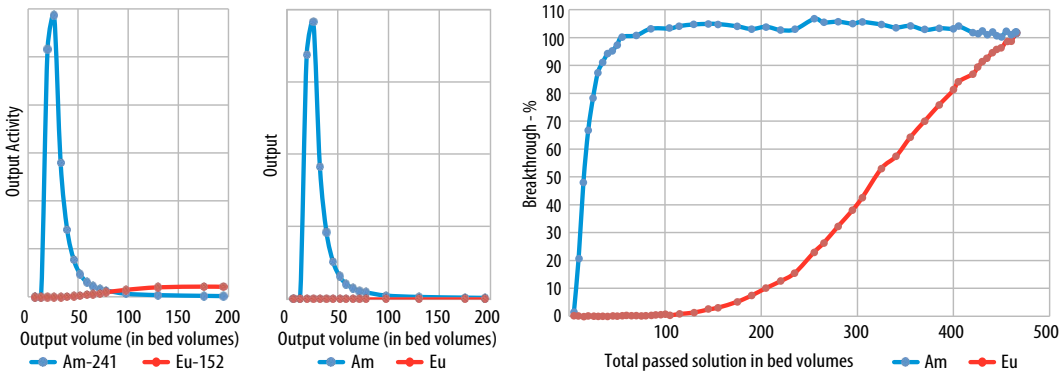

Figure 2. Left: Load-elution separation experiment with zirconium phosphate (bed volume of 1 ml). Right: Constant feed separation experiment with the same material.

6.1.2 Advanced Fuel Cycles – Scenario and Inventory Analysis – KOSKI (Project 2)

Silja Häkkinen, Tuomas Viitanen, Pauli Juutilainen, Antti Räty, VTT

In Finland, the main strategy for spent nuclear fuel management is direct disposal into a geological repository. However, in order to manage a credible waste management programme one must have knowledge and understanding about the alternatives of the chosen strategy. The theme of KOSKI project is advanced fuel cycles whose basic idea is reprocessing of the spent nuclear fuel before final disposal. The objective of advanced fuel cycles is, among other things, the minimization of the volume of nuclear waste, decay heat and radiotoxicity in the waste along with improved proliferation resistance. The volume, decay heat and radiotoxicity of spent fuel can be reduced by transmutation. Transmutation means the burning of long-lived highly radioactive and heat generating nuclides in a nuclear reactor or a subcritical system. The reactors and systems best suited for transmutation are advanced generation IV fast reactors. The goal of KOSKI project is to obtain the tools and know-how to model advanced fuel cycles and to follow-up international research on the field. Part of the project work has been realized in cooperation with KYT project SERMAT and part of the work has been realized in international cooperation in OECD/NEA expert group AFCS (Advanced Fuel Cycle Scenarios) under the guidance of WPFC (Working Party on Scientific Issues of the Fuel Cycle).

The main goal of the project is to obtain sufficient level of knowledge and tools in order to participate in international research on advanced fuel cycles scenario calculations. Scenario calculations consist of the modelling and comparison of different fuel cycle systems. The parameters to compare between different fuel cycles and reactor types can be various such as e.g. the volume of highly radioactive waste, decay heat, quantity and quality of fissile nuclides, etc. Scenario modelling at VTT was started already in the previous KYT research programme by acquiring the scenario code COSI developed at CEA France. In the beginning of KYT2018 programme, the COSI licence was discontinued due to its relatively high licence fee and a new scenario code SITON developed by Hungarian MTA EK and BME NTI was obtained. SITON, as well as COSI, is able to model large reactor fleets and track nuclide inventory in different stages of the fuel cycle. An important part of the code is reactor models that define what kind of reactors can be calculated with the

code. Each modelled reactor type requires its own reactor model. For SITON, these models are calculated applying the FITXS method developed by the Hungarians. FITXS is based on the parametrization of cross sections as a function of the detailed composition of the fuel. For the parametrization, the fuel composition and the cross sections must be calculated with a separate code which for the Hungarians is the SCALE code system. At VTT Serpent and Kraken, developed in SAFIR2018 projects MONSOON and KATVE, are used.

The SITON usage was started by comparing its performance against the previously used COSI scenario code whose licence was still valid until autumn 2016. Because SITON's development in the beginning of the KYT2018 programme was not yet very advanced, the code included only one reactor model for fast reactors, namely a model for gas cooled fast reactors (GFR). This kind of model was not available in COSI and so the comparison was done by tracking the nuclide inventory of ordinary thermal light water reactors. Plutonium and minor actinide accumulation in spent fuel was modelled and compared between the two codes. The results agreed fairly well. For plutonium, the results of the two codes differed at the most 8 % and for minor actinides somewhat more. In order for similar comparisons to be possible also after the COSI licence had expired, some extra calculations were done with COSI in the beginning of the KYT2018 programme for later validation of SITON results.

In order to realize the main goal about participating in international research work using SITON, we must be able to calculate new reactor models for SITON. The purpose of the reactor model is to determine how the nuclear fuel is burned in the reactor. Understanding the dependence of cross sections on the fuel burnup and composition is needed when developing a reactor model. To improve this understanding cross sections were studied in different fuels as a function of burnup using the reactor physics code Serpent developed at VTT. Based on this knowledge, reactor model calculation will be started for SITON.

Since 2015, VTT has participated in a benchmark calculation related to gamma dose rate from spent nuclear fuel in the NEA expert group AFCS. The purpose of the benchmark is to insure sufficient "self-protection" of spent fuel against a potential thief after 30 years of cooling and to validate modern calculation codes for dose rate calculations. IAEA and NRC consider sufficient self-protection to be

1 Sv/h one meter away from the fuel assembly. The calculation was divided in two parts: i) code-to-code comparison and self-protection verification and ii) code-to-measurement comparison. In both parts, the calculation was divided in three phases: i) fuel burnup calculation, ii) decay calculation and photon source formation and iii) photon transport and gamma dose calculation. Serpent was utilized in the VTT calculations.

In the code-to-code benchmark, a UOX and MOX assembly irradiated in a PWR reactor were calculated. The required self-protection was well satisfied and the results of the different participants agreed very well. The average of dose rates calculated by all participants using the ANSI 1977 conversion factors was 5.8 Sv/h with 0.8 Sv/h standard deviation for the UOX assembly after 30 years of cooling. VTT's result calculated with Serpent was 5.7 Sv/h. For the MOX assembly, the dose rate was higher and VTT's result deviated slightly more from the average of all participant.

In the code-to-measurement benchmark, a few different fuel assemblies irradiated in a PWR reactor were calculated. AT VTT, an assembly irradiated in USA in the Turkey Point nuclear power plant during the 1970s was calculated. The calculated dose rates remained mostly within 20% from the measurement results, but larger discrepancies were also observed depending on the measurement distance and assumed cobalt concentration of the Inconel spacer grids. Many other participants calculated also other assemblies. Especially the calculations of another assembly irradiated in the Turkey Point power plant deviated significantly from the measurement results. The calculations were not considerably improved relative to the measurement results despite of several attempts to improve the calculation models. In the end, the participants questioned the soundness of some of the measurement results. There were also several unclarities and deficiencies in the documentation of the irradiation history, assembly geometry and composition and the measurement conditions that forced the participants to make educated guesses. One of these was the concentration of cobalt impurity in the Inconel spacer grids of the fuel assemblies. It was observed that cobalt activation, depending on its original concentration, might have a significant impact in the dose rate after a short cooling time of a couple of years. However, cobalt was not mentioned in the documentation at all. The cobalt concentration was estimated from various literature sources that were also often in conflict with each other.

Within the KOSKI project, VTT has participated in the yearly meeting of NEA working group WPFC and the two yearly meetings of the expert group AFCS. The meetings and cooperation with other participants have helped the project to keep informed on the progress of international research in advanced fuel cycles. Fast reactors have a significant role in the advanced fuel cycle research. Also accelerator driven subcritical systems (ADS) have been studied in some countries. The most popular and most advanced fast reactor is the sodium cooled fast reactor (SFR). It has been developed especially in France, Russia and Japan. In the end of the KYT2018 research programme, a literature review on the current situation of advanced fuel cycles will be done together with the KYT SERMAT project.

6.1.3 Measurement methods for hard to measure radionuclides – VAMMA (Project 3)

Antti Räty, Anumaija Leskinen, VTT
Susanna Salminen-Paatero, Risto Koivula, Taneli Iso-Markku, University of Helsinki

Active waste from decommissioned nuclear reactors contain both gamma and beta active radionuclides. According to current nuclear safety guides, all waste packages need to have data on their total activity and distribution of activities between different radionuclides i.e. a nuclide vector.

Measuring gamma activities is relatively fast and easy, whereas measuring beta active radionuclides requires radiochemical separation. Many of the beta active radionuclides are very long-living and thus their characterization is especially important to ensure safe final disposal of low and intermediate level waste.

Because activation of reactor structures is a linear process as a function of neutron flux, material-wise nuclide vectors remain around constant for large amounts of waste. A common method is to characterize decommissioning waste by forming material-wise nuclide vectors from representative samples prior to start of dismantling and use this data to scale total activities from gamma activity measurements during dismantling (Figure 3).

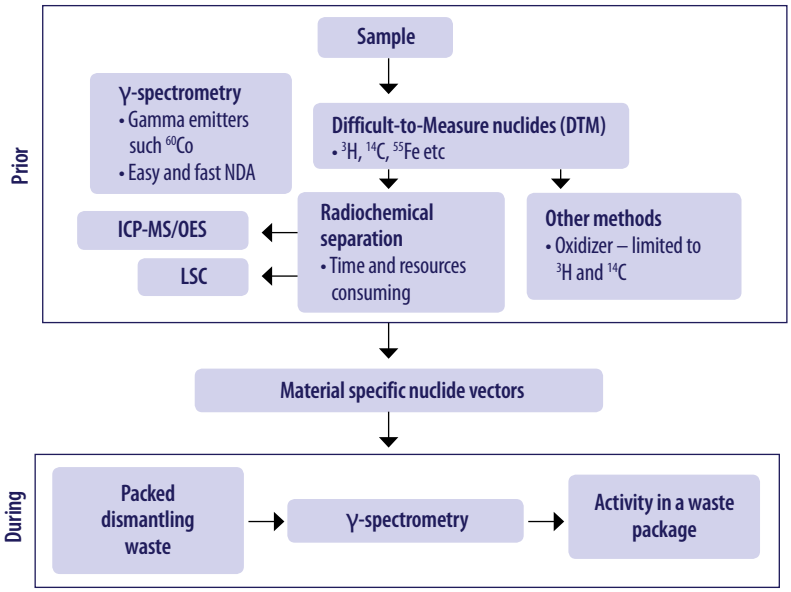

Figure 3. Formation of material specific nuclide vector and its use in characterisation of waste.

The aims of KYT2018/VAMMA small project was to study the measurement methods of hard to measure beta active nuclides for the most important radionuclides in decommissioning waste.

Some methods were studied as a literature survey utilizing e.g. the experiences from nuclear decommissioning projects in Denmark.

Most important nuclides and materials were identified from comments from the power companies and research institutes and nuclides that are considered relevant in the operating licenses of Finnish LILW final repositories.

Experimental part of the project was to test a studied method with reactor pressure vessel steel samples supplied by VTT. Activities of Fe-55, Ni-63 and Ni-59 were measured at the UH (University of Helsinki). From dissolved steel Fe and Ni were separated to their own fractions mainly by anion exchange. The activity concentrations of Fe-55 and Ni-63 were determined with LSC (liquid scintillation counting). While testing radiochemical separation method the high concentration of Co-60 in activated steel required efficient separation of Co-60 from Fe and Ni fractions before LSC to produce beta spectra without

interference from Co-60. Ni-59 was planned to be determined from Ni fractions with XRF (x-ray fluorescence spectrometer) but the XRF of UH was in fault condition during the end of year 2018. VTT assisted planning the measurements and also tested a measurement method for C-14. VTT also carried out gamma analysis of the RPV samples.

As a part of the project, a survey was conducted on technical capabilities to measure beta active nuclides at Finnish radiochemistry laboratories (VTT, UH, STUK, Fortum, TVO). Data was collected via electronic communication and visiting the laboratories at the sites. Results include used methods and experiences from recent years.

Results of the project were reported in a pro gradu thesis at the Department of Chemisty, UH and in a laboratory report of the measurements performed at the VTT laboratories. In 2018 project personnel visited two international conferences (partial funding from other projects) and two presentations on project theme were given.

VAMMA-project was the first KYT project regarding characterization of decommissioning waste and it was a good start on this field. The results on the characterization of RPV steel showed that further studies are needed and also other materials should be studied in order to establish reliable analytical methods for other materials and radionuclides.

6.2 Safety case

6.2.1 Coordinated project – TURMET – Systematization of the Safety Case Methodology (Projects 4-5)

Suvi Karvonen, VTT
Ahti Salo, Edoardo Tosoni, Aalto University

Research topic

The TURMET project addresses the safety case methodologies in nuclear waste management. By building confidence in safety, the safety case provides the basis

for promoting the dialogue between the stakeholders and licensing a nuclear waste repository. Because the evolution of the repository is uncertain, safety is typically assessed through scenario analysis. Nevertheless, it is difficult to ensure that the results effectively help build confidence on the safety of the repository. The TURMET project aimed at supporting scenario analysis through methods of probabilistic risk assessment, in which uncertainties are quantified and taken into account for assessing safety.

Main results

Literature reviews – identifying the challenges

Two literature reviews on Safety Case methodology and Scenario Analysis highlighted that scenarios are typically generated either as illustrative assumptions about the evolution of the repository (pluralistic approach) or as events in a probability space representing the future (probabilistic approach). Against this background, the specific challenges were identified in

- the evaluation of comprehensiveness, i.e., ascertaining whether the results of scenario analysis warrant conclusive statements about the safety of the repository,
- the systematic generation of scenarios as joint evolutions of the Features, Events and Processes (FEPs),
- the quantification of the knowledge gaps, also known as epistemic uncertainties, about, for instance, the FEP probabilities.

Scenario analysis model

To address these challenges, a probabilistic methodology for scenario analysis was developed in which the repository is modeled as a Bayesian network of the FEPs and their interactions (Figure 4). Scenarios are generated as combinations of states of the FEPs, which are characterized by different probabilities (obtained by computer simulations and expert judgments). The risk of the repository is assessed through the violation probability, i.e., the overall probability that the safety target (e.g., the dose rate to the public) violates a safety threshold. The model was implemented in Matlab codes. The main features and scientific contributions of the methodology are described in the following.

Comprehensiveness and residual uncertainty

Scenario analysis involves residual uncertainty about the risk of the repository. Comprehensiveness can be considered achieved if the residual uncertainty is sufficiently small to conclusively assess whether the repository is safe or not.

Residual uncertainty originates from the knowledge gaps, or epistemic uncertainties, about the FEP probabilities. These uncertainties are quantified by admitting sets of feasible probabilities, which are propagated in the Bayesian network to estimate the corresponding lower and upper bounds on risk, i.e., on the violation probability. The distance between the risk bounds is a measure of residual uncertainty.

Comprehensiveness can, therefore, be evaluated by comparing these bounds with the predefined risk limit. Then, comprehensiveness is achieved if both bounds are below or above the limit, because the repository can be conclusively deemed safe (Figure 5a) and unsafe (Figure 5c), respectively. On the other hand, when the bounds enclose the risk limit (Figure 5b), no conclusive statement is warranted and comprehensiveness is not achieved.

Risk importance measures

For purpose of risk management, it is helpful to identify the most important scenarios. To this end, risk importance measures from traditional reliability analysis (e.g., fault trees) were extended for systems, such as nuclear waste repositories, in which failure is not defined for the individual components (i.e., the FEPs).

Visualization tools were designed to help interpret and use the results from different risk measures. For instance, the *risk achievement worth* measures the relative risk increase if a given scenario were to occur, irrespective of its probability. Instead, the *contribution to risk* depends on the probability of both occurring and causing safety violations once occurred. With reference to the scenarios of *Water flux* and *Hydraulic conductivity* in Figure 4, Figure 6 shows that scenario 1 (high flux, low conductivity) implies the highest risk achievement worth (260%), but, due to its relatively low probability, contributes only 20% of risk. In summary, risk importance measures can inform the implementation of actions to prevent the most important scenarios and reduce the risk of the repository.

Dynamic scenario analysis

In order to capture the temporal evolution of risk (which is of special interest in presence of mutual interactions or feedback loops between the FEPs) a Dynamic Bayesian network can be built by representing the FEPs and the safety target at multiple time instants. However, this requires that the interactions be modeled in simplified ways to limit the number of probabilities, both cognitively and computationally. The evolution of the repository can be simulated by Monte Carlo sampling, whereby the time-dependent risk of the repository can be estimated by averaging the number of safety violations over all iterations.

Use of the methodology in nuclear waste management

A study was carried out in collaboration with the Centre of Nuclear Studies SCK•CEN to evaluate comprehensiveness in the scenario analysis of a near-surface repository. First, adopting a pluralistic approach, 13 scenarios were formulated to represent illustrative futures. Yet, the simulation of individual scenarios does not enable the quantification of residual uncertainty and, hence, the evaluation of comprehensiveness.

The analysis was repeated using the Bayesian-network methodology (Figure 4). Sets of feasible FEP probabilities were obtained from 1,000 COMSOL Multiphysics simulations and preliminary expert judgments. The corresponding interval for the violation probability was estimated to be [3.3% – 85.6%]. The selection of which combinations of FEP states (specifically defined as subscenarios) to simulate was optimized by the Adaptive Bayesian Sampling algorithm, which, compared to a random selection, granted a reduction of the interval width (i.e., of residual uncertainty) by 16.4%. Furthermore, sensitivity analysis highlighted that the elimination of the uncertainty about *Water flux* would further reduce the residual uncertainty by 4%.

Although the risk limit (to be decided by safety authorities) was not fixed, the large residual uncertainty likely corresponds to that of Figure 5b, in which comprehensiveness is not achieved. Thus, it was demonstrated that, unlike pluralistic approaches, the novel methodology quantifies the residual uncertainty about risk. This made it possible to conclude that 1,000 simulations did not lead to conclusive statements about safety, wherefore the considerably lower number of simulations of the pluralistic approach may not be sufficient to achieve comprehensiveness.

Conclusions

The methodology developed in the TURMET project enables the evaluation of comprehensiveness in scenario analysis, the identification of the most important scenarios, and time-dependent analyses. This methodology was applied to a case study inspired to a real near-surface repository, with the goal of evaluating comprehensiveness. With access to relevant data, problems of larger scale (such as deep-geological repositories) may also be addressed. Still, it was demonstrated that the quantification of the residual uncertainty about risk is fundamental for evaluating whether comprehensiveness has been achieved. Specifically, it was shown that pluralistic approaches relying on a restricted set of illustrative scenarios make it difficult to achieve comprehensiveness.

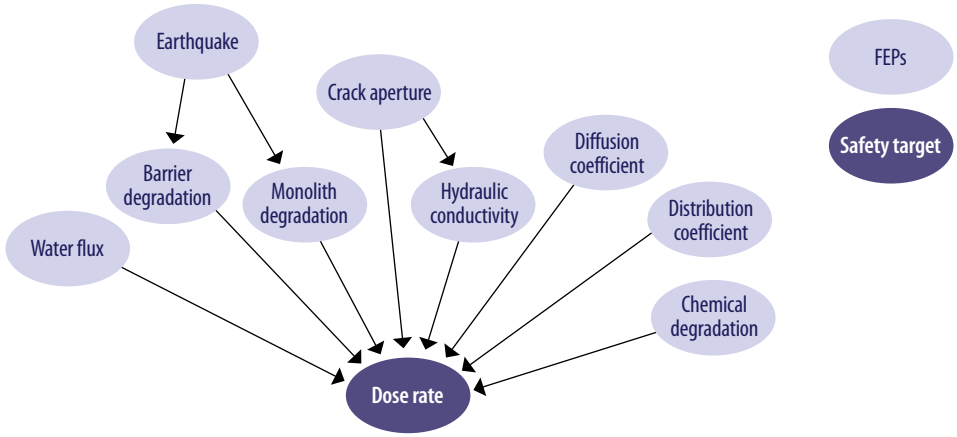

Figure 4. **Bayesian network representing a nuclear waste repository.**

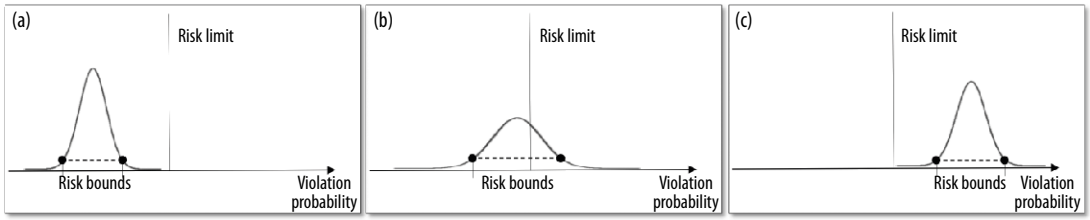

Figure 5. **Comparison of risk bounds with the risk limit for evaluating comprehensiveness.**

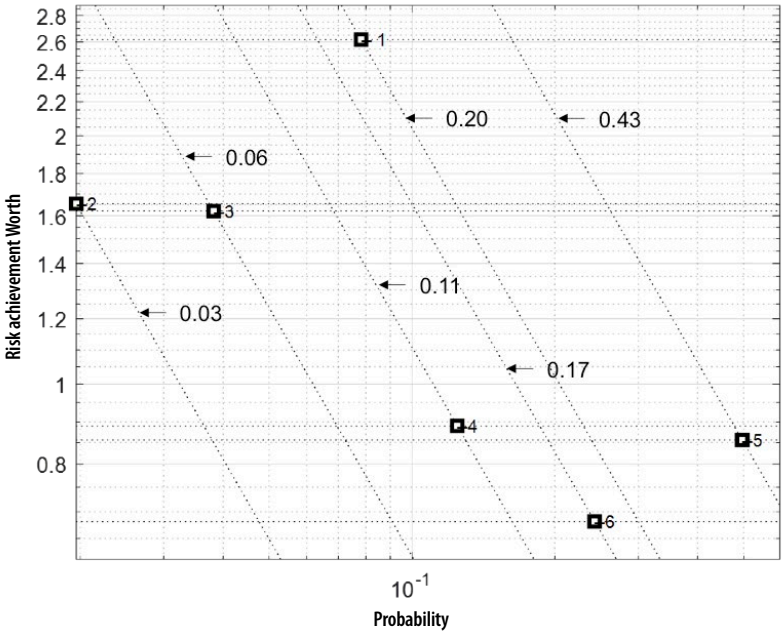

Figure 6. Scenarios (squares) of *Water flux and Hydraulic conductivity* in Figure 4, ranked by risk achievement worth (vertical axis) and contribution to risk (diagonal lines).

6.3 Buffer and backfill performance

6.3.1 Coordinated project – THEBES – THMC Behaviour of the Swelling Clay Barriers (Projects 6-9)

Wojciech Solowski, Ayman Abed, Aalto University
Veli-Matti Pulkkanen, Michal Matusewicz, Joonas Järvinen, Markus Olin, Ville Sjöblom, VTT
Markku Kataja, Tero Harjupatana, University of Jyväskylä
Kai Hiltunen, Mika Laitinen, Janne Martikainen, Antti Niemistö, Numerola Oy

Thebes consortium consists of two universities: Aalto (coordinator) and Jyväskyla University, as well as VTT Technical Research Centre of Finland Ltd and Numerola Oy. The consortium expertise span from microscale laboratory testing to chemistry and to numerical modelling of bentonite. THEBES consortium research covered all these areas, as well as used the participants expertise to create added value. In

this text, the published references refer to the Appendix 2 of the report, while the references marked with '?' are listed at the end of the text.

1. Research topic and central results of the studies

The aim of the research was to enhance the understanding of bentonite behaviour, and with the combined expertise of the participants gain insights into bentonite micro- and macro- behaviour of bentonite. These insights, as well as the obtained laboratory data acted as cornerstones in the creation of numerical frameworks, which, in the future, can be used for simulation and prediction of the bentonite barrier behaviour in the nuclear waste repositories.

At the smallest scale, VTT analysed the size and shape distribution of montmorillonite platelets in the samples originating from GEOBIOKIERTO project. The research generally observed no significant change to montmorillonite was observed during the 3 years of experiment. VTT also investigated the evolution of bentonite chemistry with in situ electrodes (pH, Cl and Na) for compacted bentonite samples, leading to data on the chemical evolution. The relevant data is, or will be available in Matusewicz *et al.* (2016a[20],b[21]), Matusewicz & Olin (2018), Matusewicz (2018), Järvinen *et al.*(2019?).[22]

At sample scale, Jyväskylä University used the X-ray tomography and imaging to investigate MX-80 bentonite behaviour upon wetting. The first set of experiments led to the data consisting of constant volume water content and displacement fields data in 4D (i.e. for the 3D samples in time), with the swelling pressure measured at both sample ends. Further set of experiments investigated free swelling of bentonite, when wetted with 0.1 M NaCl solution. The measurements were carried out for 16 samples covering all the possible combinations of three initial dry densities (ρ_{b0} = 1.40 g/cm^3, 1.65 g/cm^3 and 1.90 g/cm^3) and water contents (w_0 = 12%, 17% and 24%), each measured twice, also resulting in a set of 4D measurements. As the free-swelling leads to large deformations and significant variations in the water content, the created dataset may prove to be difficult to replicate numerically, thus leading

[20] Paper associated with project financed by KYT2014 programme.

[21] Paper associated with the BELBaR project.

[22] The so far unpublished references of the project have here been indicated with question mark, they will be listed at the end of the project abstract.

to a significant differentiation between various material and transport models. The final set of experiments included measuring wetting and swelling in constant volume with a set-up similar to that used in the free swelling experiments. Altogether 12 types of samples, varying initial dry density and water content were measured (with two repetitions) with some results presented in Figure 7.

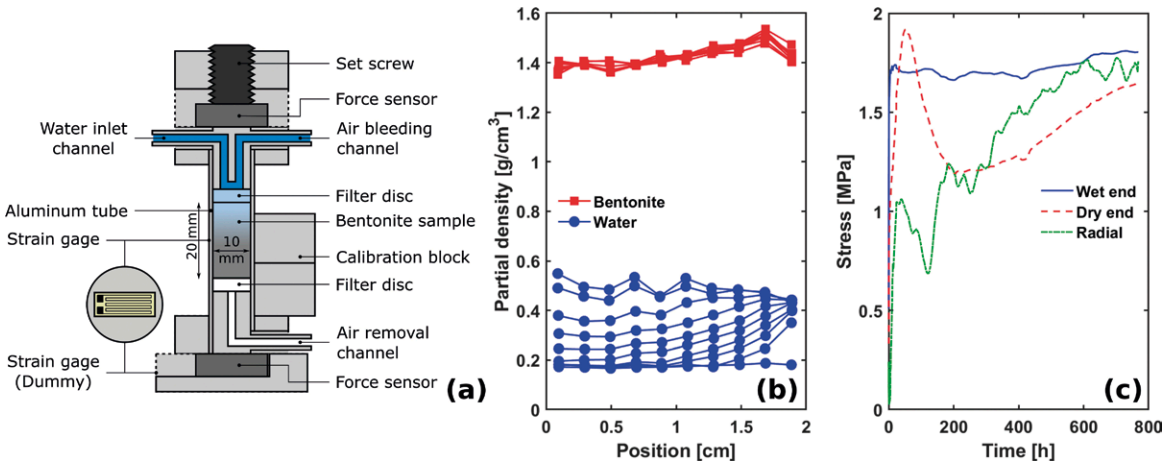

Figure 7. A schematic cross-sectional view of the sample holder used in the constant volume wetting experiments (a). An example of time series (t = 0, 2 h, 6 h, 12 h, 1 d, 2 d, 4 d, 8 d, 16 d, 32 d) of the measured partial density of bentonite and water (b), and of stresses (c).

The results are gathered in a databank (temporary link http://users.jyu.fi/~hpatana/bentonite_databank/) and in Harjupatana et al. (2015[23]), Harjupatana et al. (2019a?, 2019b?) and Abed *et al.* (2016).

Aalto performed further experiments on MX-80 bentonite, which established its water retention behaviour. The water retention curves were obtained first for distilled water, using both filter paper technique and WP4 chilled-mirror dew-point psychrometer. After the initial successful verification of the results against the literature data, Aalto obtained also the water retention curves for NaCl 1M, 2M and 4M solutions as well as for the Olkiluoto water simulants. The simulants were

[23] Paper associated with project financed by KYT2014 programme.

prepared by VTT. The results have been published in Kuusela-Lahtinen *et al*. (2016), Yang *et al.* (2018[24]), with a journal paper being prepared (Yang *et al.*, 2019?).

Finally, VTT also set up laboratory equipment, devices and procedures to study the macroscopic mechanical behaviour of bentonite in various conditions. The devices include high pressure triaxial cell, corresponding loadframe, other uniaxial cells, as well as equipment for sample preparation and associated laboratory techniques and protocols. There are some first results of the tests. VTT is also gaining now the ability to use the new equipment and has procedures to perform the tests.

Based on the experimental insights, in particular the experiments performed at Jyväskylä University and Aalto, as well as on the published data, all the network participants engaged in numerical replication of experimentally observed bentonite behaviour. Pulkkanen from VTT is preparing a PhD thesis related to chemo-elastic modelling of bentonite (Pulkkanen 2019?). The rest of the network participants used software framework *Numerrin*, a high level in-house modelling software being continuously developed and maintained by Numerola Oy. *Numerrin* is a highly flexible framework, which can be used for THMC analyses, necessary for simulation of bentonite barriers in nuclear waste repositories. Numerola, in cooperation with Jyväskylä University, also developed and coded into *Numerrin* framework a hydro-mechanical constitutive model of Kataja. The model describes the mechanical deformations of bentonite upon wetting, including predictions of swelling pressure. The model assumes bentonite to be an elasto-plastic material and has mechanical parameters depending on water content and plastic deformations. The model development is a continuation of work initiated in KYT2014 programme. Current iteration of the model was verified and validated based on the experiments performed at the Jyväskylä University.

Aalto University introduced into the *Numerrin* framework a very significant number of features, which allows for thermo-hydro-mechanical-chemical interdependent simulation of bentonite. The most significant introduced capabilities include: (i) the Extended Basic Barcelona Model, with thermal effects on the mechanical behaviour and modified elastic behaviour, (ii) the liquid water transport based

[24] Paper acknowledging KYT2018 THEBES project (Sołowski) and Chinese Research Council funding (Yang).

on the extended Darcian coupled formulation for unsaturated porous materials, including mechanical deformation effects, temperature effects on water density and viscosity, soil-water retention behaviour, salt concentration effect on water density and the alteration of permeability due to porosity variation, (iii) the water vapour flow based on Philip & De Vries theory, (iv) the gas flow based on Darcian flow, coupled to the degree of saturation and affected by porosity changes, (v) the thermodynamic consistent balance of energy, including heat flow and energy related to phase change, as well as coupling the heat flow with mechanical deformation, water flow and gas flow and (vi) the salt transport based on Fick's law and the compositional method. Each of these features has been carefully verified, including e.g. solution to rather difficult Elder problem benchmark (Abed & Sołowski 2017, 2018, 2019a?,b?, Abed *et al.* 2016, 2018). Aalto used the developed THMC framework for replication of number of experiments crucial for the nuclear waste. The Aalto simulations used the water retention data obtained from experiments. Aalto also replicated the experiments done by Jyväskylä University (Abed *et al.* 2016), as well as several other experiments, including infiltration tests on FEBEX bentonite (Abed & Sołowski 2017), large scale buffer material test (CIEMAT mock-up experiment, Abed & Sołowski 2019c?), see also Figure 8, and bentonite block-pellet laboratory scale test (Abed & Sołowski, 2019d?). The block-pellet test is of particular interest for Posiva Oy, who kindly provided all the laboratory data for the simulations. This strengthen the industrial cooperation between THEBES and the actors in Finland interested in nuclear research.

Based on THEBES experimental data, as well as the data from literature, Aalto also developed a novel model to accurately predict water retention behaviour of montmorillonite rich materials. The model is based on minerology of the clay, as well as microstructural data, e.g. mercury intrusion tests, and is the first model to use such features to predict water characteristic curve of clay materials (Abed & Sołowski 2018, Abed & Sołowski 2019a?,b?).

The final outcome of the Aalto research is a world-class THMC framework which can be used for simulation of bentonite-rich materials subjected to THMC loading, as is the case in geological repositories for nuclear waste.

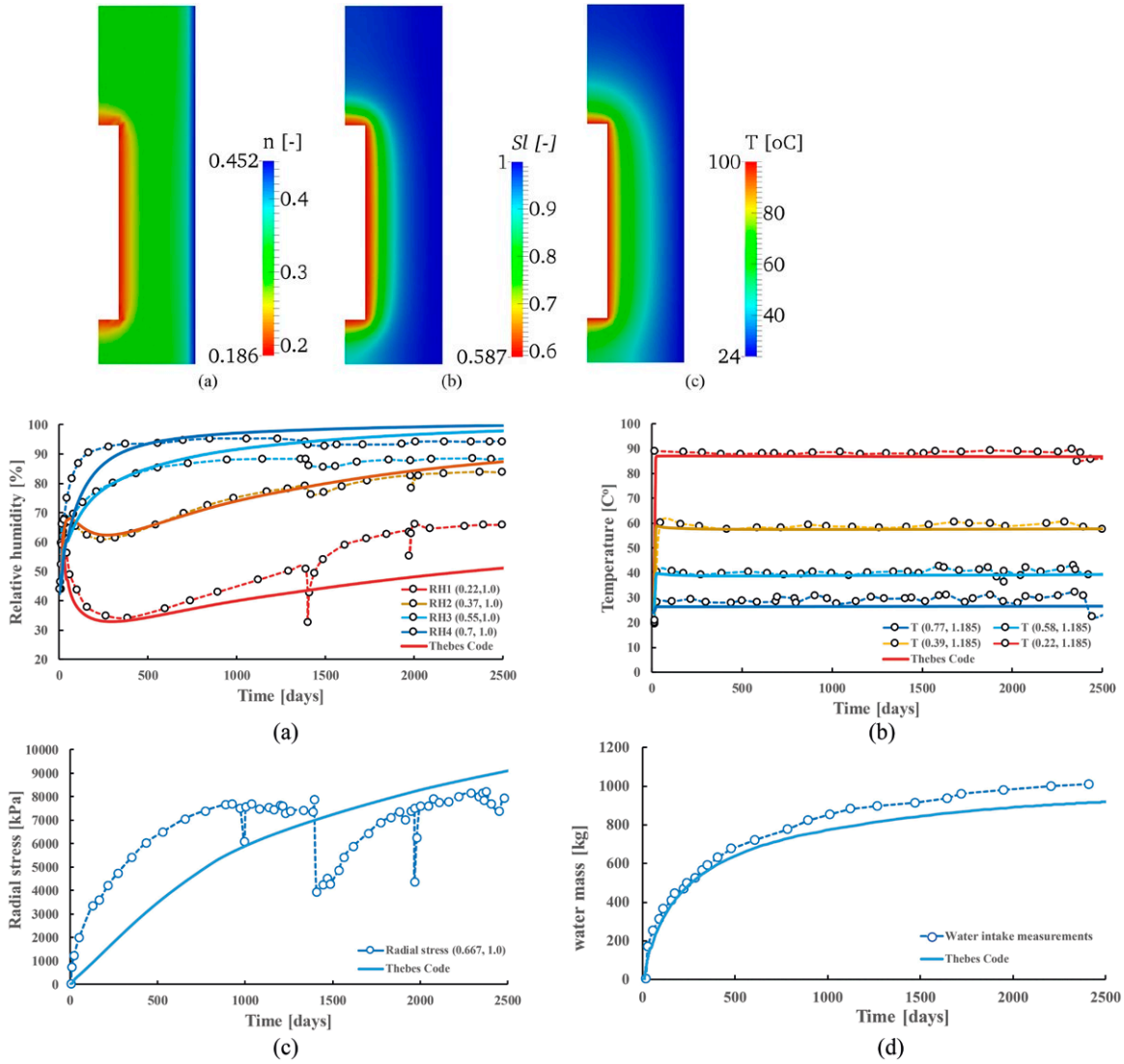

Figure 8. CIEMAT experiment simulated at Aalto. Porosity, degree of saturation and temperature evolution (topmost picture) and the evolution of humidity, temperature, swelling pressure and excess pore pressure in time (lowest 4 graphs).

The consortium also organised yearly open seminars with invited speakers. The seminars allowed for exchange of the research ideas. The seminars encouraged the participation from industry, which helped in exchange of expertise between the THEBES participants and the key entities in Finland interested in the role of bentonite swelling barriers in nuclear waste repositories. The consortium also

maintain a website, which gives some recent THEBES news, as well as serves as an easily reachable contact point.

2. The meaning of results vis-a-vis nuclear waste research, especially focussing on usability of results and connections with other research

THEBES consortium identified and investigated a wide spectrum of bentonite behaviour. The results were used to create models which were taking into account some or all aspects of bentonite behaviour affected by temperature, chemistry of the pore water, external mechanical factors, mineralogy and amount of water in the material. The experimental results can be also used directly in verification and validation of numerical models for bentonite, which, in turn, are fundamental for the assessment of clay components in nuclear waste repositories.

VTT performed microstructural studies and observed microbial influence on montmorillonite under various conditions, as well as chemical studies, based on the in-situ electrodes. Especially the latter are highly relevant for understanding the clay component behaviour, particularly in anaerobic conditions.

The experiments based on X-ray tomography and imagining at Jyväskylä University provided valuable data on water transport and bentonite swelling in a 3D sample in time. Such data is not easily obtainable and will lead to better validation examples for numerical modelling of bentonite. Such validation is most important, as the models used for prediction of bentonite behaviour in nuclear waste repositories must be as accurate as possible.

The experimental data from Aalto, related to water retention of bentonite when partially saturated with saline solutions is valuable for validation of any models which take into account chemical influence on the bentonite behaviour. As water retention behaviour is fundamental feature of partially saturated bentonite, and is directly linked to its microstructure (Abed & Sołowski, 2019a?), this data not only can be useful for chemically coupled modelling, but also for direct assessment of influence of salt on bentonite microstructure, giving extra insights on top of those obtained from other microscopic methods, such as molecular dynamics. It is also clear that the chemical coupling plays a role in bentonite behaviour significant enough that it cannot be excluded from modelling, while not being fully understood yet. The research also tested the water retention behaviour

with Olkiluoto water simulants. Those results may be directly used in the future modelling of nuclear waste repository constructed.

The numerical modelling undertaken within THEBES framework investigated different approaches towards predicting the bentonite behaviour numerically. In particular, VTT aimed at elasto-chemical approach (Pulkkanen 2019?, in pre-examination), while Numerola with Jyväskylä University, and Aalto aimed at coupled elasto-plastic framework. The model developed jointly by Jyväskylä University and Numerola directly used the Jyväskylä University experimental programme for design and calibration. This suggests that much further validation is needed before gaining enough confidence to use the framework in nuclear waste repository design, yet should such a simpler approach work, it would be a significant development.

Aalto took a different approach and constructed a fully coupled THMC framework, approaching the problem similarly to other existing frameworks, like that offered by the CODE_BRIGHT. The obtained framework is robust numerically, to some degree due to well design *Numerrin* solver, but also due to more modern coding and lessons and experience gained from the existing frameworks. This Finite Element framework (Abed & Sołowski 2017, 2019c?) combines the existing models in novel way, as well as new models (Abed & Sołowski 2019a,b?). It has been thoroughly verified and validated, with simulations of many problems directly relevant for construction and use of nuclear waste repositories. As such, this numerical tool can be directly used to simulate problem related with the nuclear waste repository, as e.g. (Abed & Sołowski, 2019b,c?). The research process also identified some shortcomings which will be investigated in the future research, as well as some features of the material which must be taken into account in more accurate way.

THEBES consortium reached out and cooperated with number of well-established international research partners, who have deep expertise related to bentonite-rich clays and their application in nuclear waste repositories. This resulted in joint publications (Abed et al. 2016, Kuusela-Lahtinen et al. 2016), as well as seminars and presentations at, among others, Université de Pau et des Pays de l'Adour (2015), Politecnico di Milano (2017) and Imperial College (Jan 2019, planned). THEBES also hosted number of international speakers during the yearly events and seminars, including Kröhn (GRS), Delage (Ecole des Ponts ParisTech), Villar (CIEMAT)

and Mendes (Northumbria University). The free-entry open yearly seminar also encouraged the connections with other researchers and industrial partners.

THEBES also contributed to publication of 3 MSc theses, a PhD thesis with another PhD thesis being in pre-examination.

In more general sense, THEBES consortium research is linked to other research activities of THEBES members, including European Union Euratom projects, cooperation with Finnish and international entities interested in safety and design of nuclear waste repositories, as well as the wider research community.

3. Methods used in the studies.

The research undertaken by THEBES member used sound and valid research methods. That is confirmed by a large number peer-reviewed scientific publications, listed in Appendix 2. The interested reader is directed towards these publications for the details on the methods used in the studies.

4. Unpublished References

Abed AA & Sołowski WT (2019a?, after second review) Estimation of water retention behaviour of bentonite based on mineralogy and mercury intrusion porosimetry tests. Geotechnique, (second round of review).

Abed AA & Sołowski WT (2019b?, in review) Numerical implementation and validation of a microstructure-based procedure to estimate the water retention curve for granular materials. International Journal of Numerical and Analytical Methods in Geomechanics, under review.

Abed, AA & Sołowski, WT (2019c?, accepted) Applications of a New THMC Coupled Code "Thebes". Accepted for publication in Environmental Geotechnics.

T. Harjupatana, J. Alaraudanjoki and M. Kataja (2019a?, in prep) A method for measuring wetting and swelling of bentonite in a narrow channel using X-ray imaging.

T. Harjupatana and M. Kataja (2019b?, in prep) One-dimensional free swelling and constant volume wetting of MX80 bentonite measured by X-ray imaging.

Järvinen, J. et al. (2019?, in prep.) Diffusion of pH in compacted bentonite under an-aerobic conditions

Matusewicz, M., Olin, M. (2018?, accepted). Comparison of microstructural features of three compacted and water saturated swelling clays: MX-80 bentonite, and Na- and Ca- montmorillonites, Clay Minerals

Yang, X, Sołowski, WT, Matusewicz M (2019?, in prep.), Experimental Study on Effects of Saline Solutions on Soil-Water Characteristic Curves of MX-80 Bentonite.

Abed, AA & Solowski, WT (2019d?, submitted), Simulation of swelling pressure evolution during infiltration in a bentonite block-pellet laboratory scale test. 7th Asia-Pacific Conference on Unsaturated Soils, Nagoya, Japan.

Veli-Matti Pulkkanen (2019?, in pre-examination), A large deformation model for chemoelastic porous media – bentonite clay in spent nuclear fuel disposal. Dr. (Tech.) Thesis. Aalto University publication series.

6.3.2 Bentonite erosion and radionuclide interaction processes (BENTO) (Project 10)

Pirkko Hölttä, Outi Elo, Valtteri Suorsa, Eini Puhakka, University of Helsinki

As a result of the chemical erosion of bentonite, the buffer loses, which may adversely affect the ability of the buffer to protect the canister and retard the release of radionuclides from the disposal site. Stable and mobile clay particles, called colloids, released from bentonite adsorb radionuclides and can act as carriers for them in the bedrock. The project aimed to experimentally investigate the erosion of bentonite, and the interactions between bentonite colloids, radionuclides and minerals, under repository relevant conditions.

In the "Bentonite erosion" subproject investigated bentonite erosion and the formation and stability of colloids, by determining the particle size distribution, concentration and zeta potentials of colloids using dynamic laser light scattering

and ICP-MS techniques. The ionic strength of the water and the cations of the solution were the main factors affecting the erosion and colloid stability of the MX-80 bentonite and Nanocor PGN (Figure 9). The MX-80 bentonite erosion and stability of colloids was followed for eight years. In dilute solutions (I = 0.001–0.01 M), the particle size distribution was narrow and the size remained below 500 nm and the zeta potential was less than -30 mV confirming stabile colloids. In the saline solutions, colloids aggregate into larger particles and sediment out of solution. In the presence of two valent calcium ions, colloids were larger and less stable than one valent sodium. After an initial increase in colloid concentration, a level was reached at which erosion slowed down and almost ended. Alkaline cement water (pH 9, pH 12) increased bentonite erosion and colloid stability (Figure 10). The montmorillonite content also clearly affected erosion, Nanocor PGN ontmorillonite (98%) eroded more than MX80 bentonite (76%).

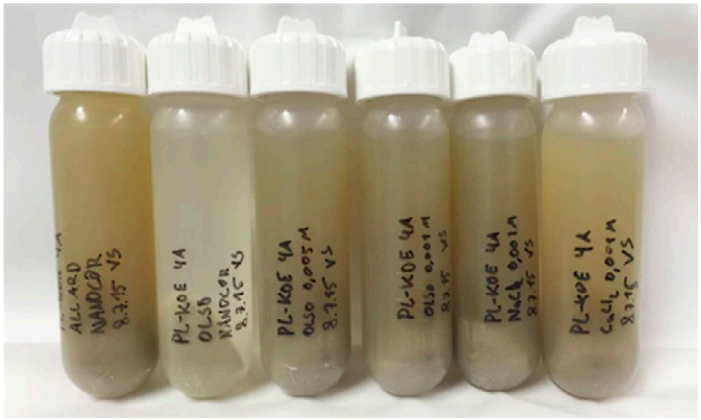

Figure 9. Nanocor PGN montmorillonite erosion experiment in different ionic strength reference ground water and electrolyte. From left: Allard (4.2 mM), Olso (0.52 M), Olso (5 mM), Olso (1 mM), NaCl (1 mM) and $CaCl_2$ (1 mM).

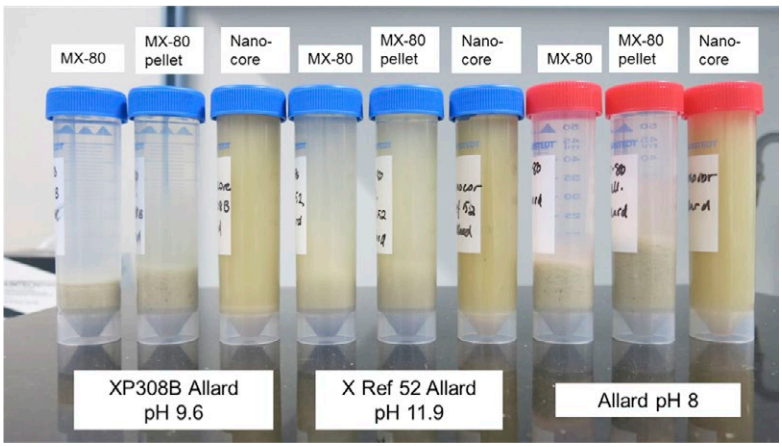

Figure 10. MX-80 bentonite and Nanocor PGN montmorillonite erosion experiment in cement water.

In the "Radionuclide Interaction" subproject the batch method was used to investigate the sorption/desorption of radionuclides (^{85}Sr, ^{134}Cs, ^{152}Eu, ^{237}Np) on two bentonites and their colloids. The effect of colloids on the transport of radionuclides was investigated by column experiments. The distribution coefficients (K_d) for radionuclides were obtained as a function of pH, ionic strength, tracer concentration and time. Desorption experiments revealed how permanently the radionuclide was attached to the colloid or mineral surface. The most important factor affecting the sorption of radionuclides was pH. The sorption to the colloids was also affected by the ionic strength, which increased the sorption when the specific surface area of the aggregated particles increased. MX-80 bentonite adsorbed more strongly radionuclides than Nanocor PGN montmorillonite. The sorption of radionuclides, was interpreted by molecular modelling to provide information on cation adsorption mechanisms. Cs^+ and Sr^{2+} bind to the basal sites of the montmorillonite 2:1 (tetrahedral- octahedral- tetrahedral) sheet structure by cation exchange, while $Eu(H_2O)_9^{3+}$ attaches to the edge sites of the structure (Figure 11), where its sorption energy is higher than that of the basal sites. Spectroscopic methods, in-situ ATR FT-IR and EXAFS in collaboration with HZDR (Helmholtz-Zentrum Dresden-Rossendorf) were used to identify neptunium(V) inner-sphere complex on montmorillonite edge sites.

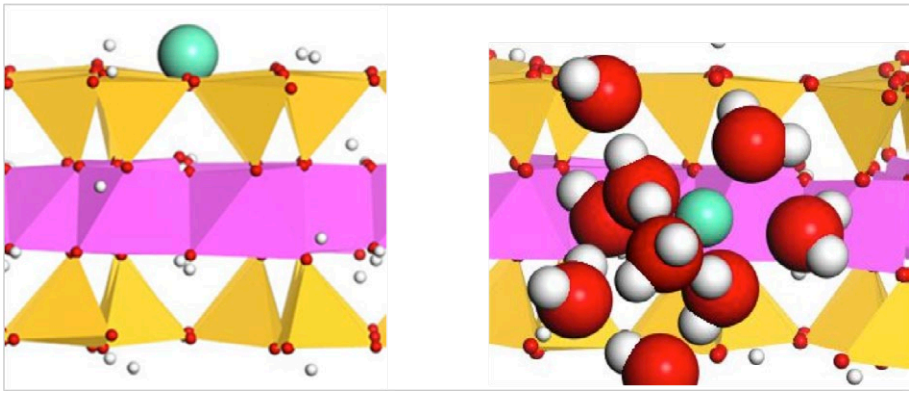

Figure 11. On the left, sorption of Cs^+ and Sr^{2+} ion onto the basal sites of the montmorillonite tetrahedral sheet. On the right, sorption of $Eu(H_2O)_9^{3+}$ onto the edge site of the montmorillonite octahedral sheet. Silicon (yellow), aluminium (pink), sodium (purple), oxygen (red), hydrogen (white) and Cs/Sr/Eu (turquoise).

The effect of the MX-80 bentonite colloids on ^{237}Np migration was studied in Kurun Gray granite crushed and drill core columns using 10 mM sodium perchlorate (pH 8 and pH 10) and flow rates of 0.8 mL/h and 0.3 mL/h. The breakthrough curves were modelled using the analytical solution of advection–matrix diffusion equation. A slight influence of the colloids was observed implying that Np(V) attached to colloids was eluted from the columns at pH 8 faster than neptunium which retarded reversibly on granite surfaces (Figure 12). For the 0.3 mL/h experiment at pH 10, colloid clogging of flow channels, resulted in an enhanced retention of colloid-associated Np(V) which was confirmed by the decreased recovery of neptunium(V) (Figure 12).

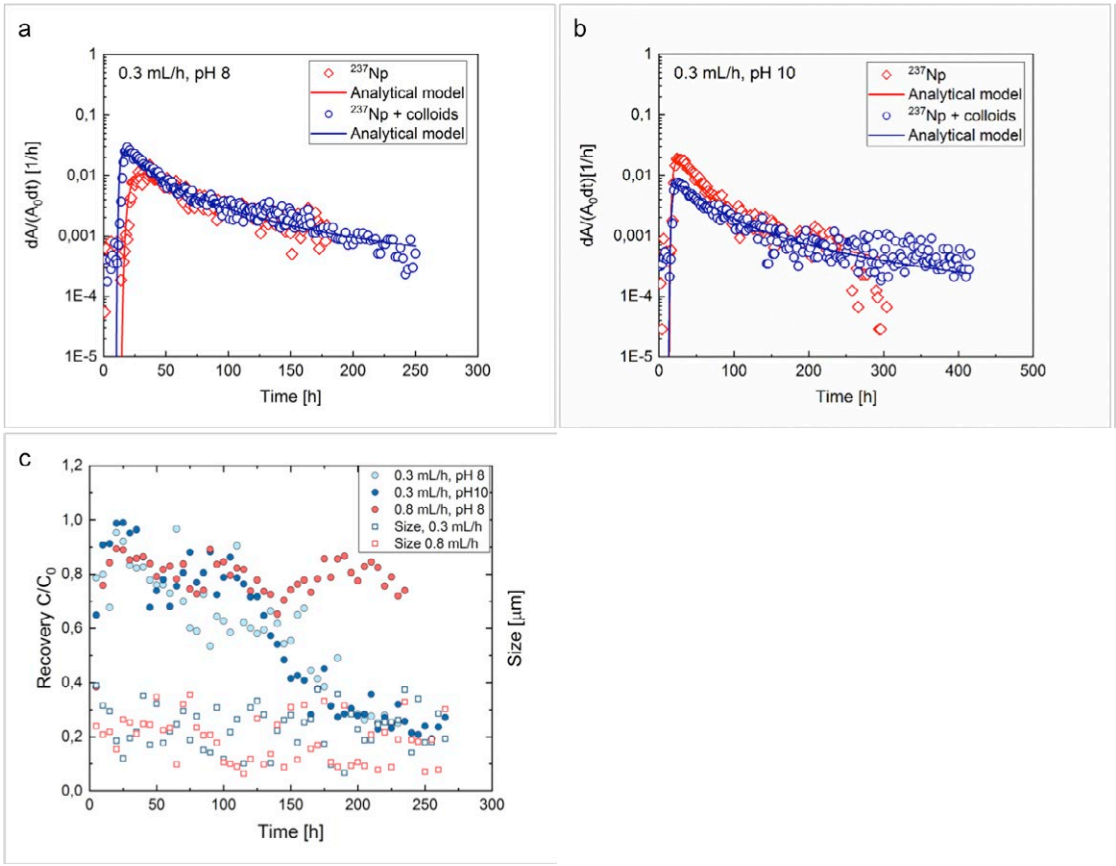

Figure 12. Measured and modelled breakthrough curves for Np(V) through the drill core column, a flow rate of 0.3 mL/h in 10 mM $NaClO_4$ pH 8 (a) and 10 (b) in the absence (red symbols) and presence of colloids (blue symbols). The recovery and mean particle size of MX-80 colloids (c) from the drill core experiments.

The suitability of the Kuru Gray granite block fracture was assessed by conducting several experiments using different non-sorbing and sorbing tracer and montmorillonite colloids. Laser-induced breakdown detection (LIBD) in Karlsruhe (KIT) in Germany, photon correlation spectroscopy (PCS) and ICP-/MP-OES were utilized in colloid detection. Batch sorption experiments in a ternary system were conducted to determine the distribution of ^{152}Eu between crushed granite and colloids. The fraction of Eu attached to colloids decreased during the experiments and correspondingly the fraction attached to the granite increased resulting in fairly even Eu distribution between the colloids and the crushed rock. No breakthrough

of colloids or ^{152}Eu was observed within two months due to the europium adsorption to the fracture surfaces, and the possible colloid filtration into uneven fracture surfaces owing to the slow flow rate.

During the KYT2018 research period, a lot of new experimental data was obtained on bentonite erosion and sorption of radionuclides. Different experimental arrangements were developed and applied during the project and advanced analytical methods were introduced. The results indicate that the salinity of water is the most important factor for the bentonite erosion and the stability of colloids. Spectroscopic methods and molecular modelling provided important information on the sorption mechanisms of radionuclides. Column experiments demonstrated the enhanced effect of colloids on the transport of radionuclides. The results were utilized in EU/BELBaR and Grimsel CFM projects. Domestic expertise was developed and new experts were trained in the field of radiochemistry, especially in the field of nuclear waste disposal. In the future, the results may possibly be used as parameters for developing models in other KYT projects.

6.3.3 Bentonite swelling pressure – UEFBENT (Project 11)

Tapani Pakkanen, Linlin Sun, Janne Hirvi, Bukunmi Akinwunmi and Aderemi Fayoyiwa, Department of Chemistry, University of Eastern Finland

Research topic and central results of the studies

The main topic of the research is the determination of swelling pressure of bentonite clay buffer material by molecular modeling techniques. The swelling pressure of bentonite is the central physical quantity, defining the usability and function of clay as a buffer between the nuclear waste canister and the rock cave. Bentonite clay and the surrounding water media have several structural and chemical variables, affecting clay swelling properties. A comprehensive experimental evaluation of the parameter space would be an enormous task, while the effect of some of the structural parameters influencing the swelling pressure is not within the reach of experiments.

A simulation model based on molecular dynamics has been developed to mimic the experimental determination of swelling pressure. It has been shown to reproduce the trends of the experimental measurements. The model comprises

of two clay layers which are immersed into a water box. In contrast to earlier theoretical models, the influx of water into the interlayer space is possible allowing the determination of swelling pressure.

The first step of the study was the consideration of the structural parameters of smectites, i.e. swelling bentonite clays. The swelling property of a smectite is due to the replacement of aluminum atoms with magnesium atoms in the octahedral sheets and the replacement of silicon atoms with aluminum atoms in the tetrahedral sheets of the smectite layers. The replacements lead to the charging of the layers and enable the swelling process. The structural changes in the aluminum silicate layers were first examined, followed by a systematic evaluation of the effect of total charge and charge distribution between the octa- and tetrahedral sheets on the swelling pressure as a function of clay dry density. The results, as shown in the Figure 13, can be used in the estimation of swelling pressure of natural clays if the structural information is available. The highest pressure is developed by a montmorillonite clay, where one eighth of the aluminum ions in the octahedral layers is replaced by magnesium ions. The result is in good agreement with experimental observations as corresponding Wyoming type bentonites have high swelling pressures.

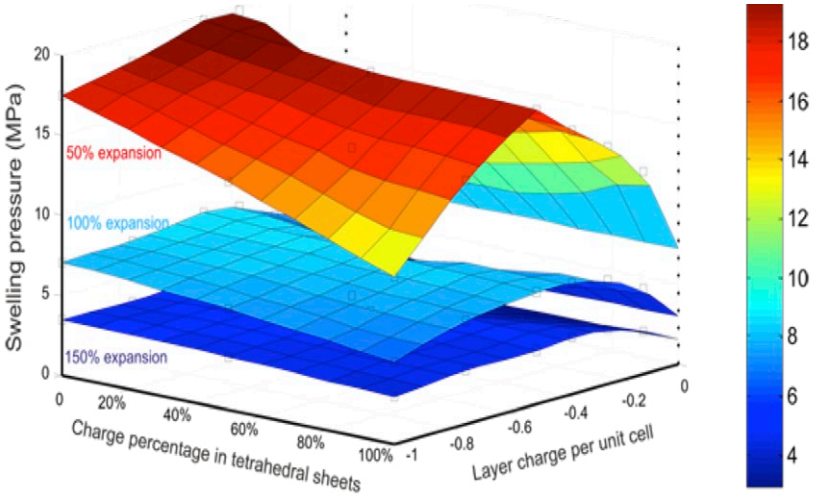

Figure 13. The swelling pressure of sodium montmorillonite at 50%, 100% and 150% swelling states corresponding dry densities of 1650 kgm^{-3}, 1240 kgm^{-3} and 990 kgm^{-3}.

In the following step of the project, the effect of smectite iron content on swelling pressure was studied. In natural clay samples, the Fe^{3+} and Fe^{2+} ions replace aluminum and magnesium ions in the octahedral sheets. The effect of Fe^{3+} replacement was studied with simulations, since it is the predominant form of iron in the samples. The outcome of the study is that the replacement of aluminum with iron lowers the swelling pressure, particularly in the montmorillonite clays. The reason for the pressure drop was traced back to the increased dry density of the clay. The result is in good accord with experimental observations and can be used to predict swelling properties of naturally occurring iron containing clays.

An important structural variable of the bentonite clays is the ion content in the interlayer water. The ion replacement builds a negative layer charge, which is compensated by cations in the interlayer water. Sodium and calcium cations are typically in the interlayer space and ion exchange is also possible due to the external water reservoir. Simulations have shown how sodium and calcium chloride solutions influence the swelling. The swelling pressure decreases as the ionic strength increases and sodium ions in the interlayer are exchanged to calcium ions if the calcium chloride concentration is high enough in the surrounding water media. The interlayer and external water space studies have been extended also to potassium and cesium chloride solutions. The result has practical significance, when the behaviour of the bentonite buffer is considered in the varying solution conditions of the deposition of nuclear waste.

The final step of the study was to inspect the influence of temperature on the montmorillonite swelling pressure. The simulations were initiated from a state at –120 °C and continued by slow warming. The frozen smectite does not expectedly to swell, but when the temperature approached ambient conditions, a slow emergence of swelling pressure was observed. At higher temperatures the swelling pressure increases slowly as the function of temperature. The temperature dependence of swelling properties of bentonite in important information, since the canister containing nuclear waste emits heat to the bentonite buffer in the initial phases of the final disposal.

Molecular modeling techniques have been shown to produce important information of the influence of structural and environmental factors on the swelling pressure of bentonite materials.

The meaning of results vis-à-vis nuclear waste research

The importance of the results is connected to the bentonite buffer materials selections, control of swelling and long term behaviour at varying conditions. In the selection of the bentonite for buffer, it is vital to know the swelling pressure and hydraulic conductivity as function of dry density. Bentonites are natural materials, where structural and composition variations are commonplace. The present study enables a systematic evaluation and prediction of swelling properties in variable solutions and temperatures. The results can be used in the selection of bentonite materials and in the forecasts of the behaviour of the buffer in the final deposition. The results have an intimate link to the experimental clay studies and can be integrated into common THMC models by supplying detailed atomic level information.

Methods used in the studies

The central tool in the study is molecular dynamics simulation. It is based on the description of the interactions of atoms in a chemical system by classical molecular mechanics force fields. The atoms move in the simulation according to Newton's Laws and reach equilibrium in the simulation process. In bentonite modeling, all atoms are described explicitly; their number is typically in ten thousands. In the dynamics simulations the bentonite swelling pressure is determined for each combination of parameters, where the bentonite dry density is the common variable.

6.4 Canister performance

6.4.1 Coordinated project – KAPSELI (Projects 12-16)

Juhani Rantala, Jarkko Metsäjoki, Tom Andersson, Anssi Laukkanen, Kari Korhonen, Tuomo Kinnunen, Rami Pohja, Pertti Auerkari, VTT
Sven Bossuyt, **Hannu Hänninen**, Yuriy Yagodzinskyy, Antti Forsström, Aalto University
Jari Aromaa, Atte Tenitz, Aalto University
Leena Carpen, Pauliina Rajala, Maija Marja-aho, Elina Huttunen-Saarivirta, Malin Bomberg, Elisa Isotahdon, VTT
Pauliina Rajala, Leena Carpen, Maija Marja-aho, Elina Huttunen-Saarivirta, Malin Bomberg, Elisa Isotahdon, VTT

This project includes five sub-projects which all deal with the copper canister from either mechanical strength or corrosion point of view. The PRECO project studied the creep behaviour of the copper material while the MECHACOP project looked at the localisation of damage in FSW welds and various effects of hydrogen on copper and cast iron. The REPCOR project studied general corrosion of copper and characterised the oxide layers and the corrosion products. The microbiological corrosion during aerobic period was studied in the MICOR projects and during the anaerobic phase in the BASUCA project.

In the KAPSELI coordinated project two copper corrosion seminars have been organised in 2016 and 2017 with contributions from STUK, Aalto university, VTT, Posiva and SKB.

Experimentally verified model based predictions for integrity of copper overpack (PRECO)

The PRECO project has concentrated on studying the creep properties of Cu-OFP. The loading which copper overpack will experience in the repository is a combination of uneven load increases followed by periods of relaxation. Eventually the copper overpack will come into contact with the insert and then creep and relaxation will be concentrated on the FSW root area. Therefore, both the creep and relaxation behaviour of copper have been studied experimentally and modelled. The models

have been applied in the FE analysis of the copper overpack to calculate the stress and strain distribution in various parts of the canister.

The relaxation behaviour of copper at 80°C, 60°C and 40°C has been tested and the results have been fitted with a relaxation model. Also repeated relaxation tests have been carried out where after the first relaxation test the strain is brought back to zero and then re-loaded to the same initial strain.

Two very long-term uniaxial tests, which have been started during the previous programmes, are still running. A systematic study of the loading history effect in copper is in progress at 175°C and at 90°C to study the effect of step-wise application of load on rupture time. Rather surprisingly the rupture time becomes much shorter when cu-OFP is loaded in steps. The effect is possibly caused by formation of new dislocation when the stress is increased. The same mechanism causes also the phenomena of repeated primary creep when the stress is removed and put back on, which leads to consumption of creep strain and thus shortening of rupture time. Step-wise loading is what the canister will experience when the external pressure increases unevenly.

A long series of tests to study the life shortening effect of stress multiaxiality on copper is nearing completion. The results suggest that at low stresses the creep life of copper is shortened by multiaxiality. The weld root area is not only the most highly stressed location in the canister but there the stress state is also highly multiaxial due to geometrical constraint.

Testing and a metallography study a FSW lid welded in argon have been completed. Hydrogen annealing was applied to make the oxide particle zone visible. The results show that there are less oxide particles in the FSW when the welding is carried out in a protective atmosphere instead of air and as a result the oxide particle did not crack when it was loaded by a CT specimen.

Mechanical strength of copper canister (MECHACOP)

Cooperation with KTH was started in 2014 with a joint study on absorption of hydrogen in copper under γ radiation. The conditions mimic the repository conditions during the first 1000 years of disposal. γ radiation enhances the corrosion reactions, as well as hydrogen absorption in copper. Under γ radiation

a two-layer oxide film is formed, which was shown to initiate stress-corrosion cracking (SCC) of copper.

The macroscopic deformation of electron beam welded (EBW) and friction stir welded (FSW) copper was studied by digital image correlation. The measurements indicate that strain localization in the welds is enhanced by low strain rates. Welding defects were shown to markedly enhance the localization of deformation in the EBW copper, whereas FSW copper exhibits similar mechanical properties to those of the base materials. A new FSW canister weld, which was welded in argon shielding gas environment, was received from Posiva. Similar tensile tests were performed, but for some reason the new weld deformed less than the old one. The studies were continued at Kyushu University by hydrogen charging oxide containing FSW canister welds to study the effect of absorbed hydrogen on the deformation of the welds.

The effect of absorbed hydrogen on single crystal copper was studied. Hydrogen activates more slip planes in copper, which leads to formation of thick slip bands. Positron annihilation measurements show that at the same time hydrogen enhances vacancy formation and that the vacancies form clusters and nano-voids in copper. The same phenomenon was observed in a simulation study. The nano-voids enhance the creep and fracture of copper.

The stress-corrosion cracking (SCC) of copper in sulphide containing environment is under investigation in a joint study with Studsvik, Sweden. Preliminary results were published in Eurocorr 2017 conference. SCC initiates and propagates on the grain boundaries of copper. Similar small surface defects were found on the grain boundaries even with low sulphide contents, similar to those in the repository conditions. In addition, it was observed that hydrogen was absorbed in copper during SCC testing. The hydrogen content was doubled when compared to the initial state. Unloaded specimens did not experience similar hydrogen absorption. The sulphide induced SCC mechanism and the role of hydrogen is currently under investigation. It is expected, that the oxide/sulphide film is the key to the initiation of SCC of copper in sulphide containing environment.

The effect of hydrogen on deformation of the cast iron insert was studied. Hydrogen is absorbed greatly in the cast iron and it was observed that loading enhances markedly the hydrogen uptake. The fracture mechanism turns into

brittle cleavage fracture, the ductility is compromised, and creep is enhanced. It is possible, that in the repository conditions hydrogen is absorbed in the cast iron insert due to corrosion reactions and neutron radiation, which may drastically affect the mechanical properties. Therefore, it is important to continue the studies on the cast iron insert to understand the fracture mechanism and the role of absorbed hydrogen and especially the role of the graphite nodules in brittle crack initiation.

The author took part in the 50th anniversary book of EFC by writing a chapter about properties of copper in the repository conditions. The author also took part in the actions of the Swedish National Council for Nuclear Waste (Kunskapslägesrapporter 2014-2018, for example chapter Teknisk och vetenskaplig osäkerhet – osäkerheter med avseende på kapsel och insats) for the whole duration of the KYT2018 project, and the evaluation of the SKB FUD program (SOU 2017:62), as well as activities of the IGD-TP council (SOU 2018:8).

The effect of reaction product layers on copper corrosion in repository conditions (REPCOR)

The aim of the REPCOR project was to determine the effects of copper corrosion product films on copper corrosion. The research covered different stages of the repository process starting from temporary storage after loading the canister to corrosion in the gaseous phase, then to corrosion when immersed in oxic conditions and finally immersion in oxygen-deficient conditions. The corrosion product films can be protective, or they can increase corrosion. Generally, sound and continuous oxide films are protective whereas damaged films can lead to accelerated and often localized corrosion on exposed areas of copper. Considering the large outer surface area of the copper canister, damages in the oxide films are likely.

The research tasks of the REPCOR project were formation and characterization of corrosion product films and the effect of the films on copper corrosion rate. Oxidation of copper in air at $T \approx 100\ ^{o}C$ produced in couple of days oxide films that were tens or hundreds of nanometres thick. This is the currently estimated oxide film thickness before emplacement. The air-formed oxide films contained mainly Cu2O with some CuO. The oxide films formed in immersion contained Cu2O. Pre-oxidized films continued to grow in thickness during immersion in air-saturated waters but dissolved in oxygen-deficient waters.

The corrosion rate of unoxidized copper in oxygen-deficient water was from few µm/year to few tens of µm/year depending on water composition. In air-saturated waters the corrosion rates were hundreds of µm/year. The factors of environment have complex interactions, but general trends were following: Change from oxygen-deficient to oxygen-saturated water increased corrosion rate by up to two orders of magnitude. Water with low pH of 4 can show 20 times higher corrosion rate than in near neutral waters. Increasing the total dissolved solids indicated up to 5 times higher and increase in temperature up to 7 times higher corrosion rates.

Weight loss of pre-oxidized sample measured by Quartz Crystal Microbalance showed usually first rapid decrease that evened out in tens of minutes. After the initial weight loss of the oxide-covered samples the calculated corrosion rates were 2–5 times higher than for non-oxidized copper. This indicates that the remaining oxide films increase corrosion rate of the exposed copper.

The oxide films produced in air show thickness and composition that correspond with current reported estimates. During immersion in saline groundwater the corrosion product films are more complex, but the other possible compounds could not be identified using the selected analysis method. The behavior of the pre-oxidized copper during immersion indicates that the oxide films can increase copper corrosion rate. This means that damages in oxide film during emplacement may cause temporarily localized corrosion. The effect of environment changes followed known trends. The corrosion rate changes in short-term tests of the REPCOR project were high, but based on reported long-term tests the corrosion rates will decrease over months or years.

Microbially induced corrosion during the oxic stage of repository (MICOR)

The objective of the MICOR-project was to evaluate the impact of microbiological activity on the behaviour of copper capsule material in the final disposal during the aerobic warm phase in final repository conditions in Finland. When examining the behaviour of the copper capsule in the repository, the conditions can be divided into an aerobic and anoxic phase with the main corrosion mechanisms depending on the phase. Microbiological processes also differ during these stages. MICOR focused on the evaluation of corrosion of copper and the effect of the microbiological activity near the capsule in the aerobic phase aiming to evaluate the overall corrosion performance of capsule. The simultaneous KYT project

BASUCA focused on assessing the microbiological corrosion effects of the later anoxic phase.

Experiments were conducted both in the absence of microbes (under abiotic conditions) and in the presence of microbes (biotic conditions). The enrichment of microbes were made from the groundwater of Olkiluoto to create realistic conditions for tests. Bentonite was added to the test solution to assess the synergistic effects of bentonite and water. Generally, under abiotic conditions, the average corrosion rates were lower than in the presence of microbes. Temperature affected the corrosion rate and corrosion product formation. The highest average corrosion rates, ca. 25 µm/a, based on weight losses were observed at 60 °C test with microbes and at the lowest in the 24 °C test (3.5 µm/a). Immersion of samples in bentonite clearly affected the corrosion behaviour of the samples and resulted in a deviation of the results between parallel samples. Based on the test results, bentonite was a bigger source of microbes than the groundwater of the repository.

The results of the project can be utilized when evaluating the long-term safety of nuclear waste management in assessing the corrosion rates in the aerobic phase. In addition, the results support the validitation of the previously made models. In the MICOR and BASUCA projects parallel measurements were carried out, so the construction and development of the experimental arrangement was made in co-operation between the projects. In addition, the results of the projects combined will increase the understanding of the corrosion effects of the various stages in the copper capsule.

Long laboratory experiments of the project were carried out at three temperatures of 24°C, 37°C and 60°C. Water collected from Onkalo was used in the experiments. The test vessels were partially filled with MX-80 bentonite either in as received state or sterilized. In biotic experiments, microbial enrichments made of Onkalo water were added. Abiotic experiments were performed using glutaraldehyde as a biocide. The sample material was Cu-OFP from which weight loss samples, biofilm samples and electrochemical samples were prepared. In the biotic experiments, U-bend samples were also prepared to investigate the risk of stress corrosion cracking. In the electrochemical tests, the corrosion rate and surface phenomena of the samples were measured by determining the linear polarization resistance (LPR), Tafel curves, EFM measurements, ER resistance film measurements and impedance measurements (EIS). Laboratory experiments lasted for 3, 5, 9 and 10 months. After

the experiment, corroded samples were studied with scanning electron microscope (SEM) and an elemental analyzer (EDS) in order to identify corrosion product layers. Corrosion products were also characterized by X-ray diffractometer (XRD). The water used in the experiments was analyzed before and after the experiments to detect changes in water chemistry.

The quantitative PCR method (qPCR) was used to determine the number of bacteria, archeons, 16 rRNA gene copies, sulphate reducing dsrB gene copies and methanogens mcrA gene copies in order to estimate the relative amount of microbes in biofilm and in water. Overall, the amount of microbes found were very small in biofilms and in water. Sequencing was made to identify the compositions of biofilm and water microbial communities. Sequencing analysis is currently going on.

The effect of microbial activity on corrosion of copper in anoxic state of repository (BASUCA)

The aim of the BASUCA project was to evaluate the impact of microbiological activity on the behavior of copper canister material and to develop competence and a reliable experimental arrangement to evaluate the microbiological corrosion of copper in the final disposal during the anoxic phase during Finland's final repository conditions. The goals were achieved by creating a suitable laboratory environment where the corrosion of copper canisters can be studied reliably and versatile in the presence and absence of microbes. New methods were used to investigate the properties of the biofilm accumulated on the surfaces, the properties of the corrosion product and the microbe - metal interactions.

The project focused on the later stages of the repository period, when all oxygen is consumed and the temperature has gradually decreased to the surrounding bedrock temperature (temperatures used in tests were 10 and 37 °C). It is also assumed that copper is in contact with groundwater, that is simulating the worst possible situation, when the bentonite buffer no longer protects the copper capsule. The effects of the bentonite layer on groundwater chemistry have been taken into account in the experimental environment used (simulated water). One set of experiments was also carried out using Onkalo borehole water.

During the research program, several laboratory test sets were carried out to evaluate the corrosion behaviour. Test material was OFP-copper supplied by Posiva.

Results on the corrosion behaviour were obtained from one 4 months and two 12 months test series. Several sample types were used: electrochemical samples, weight loss samples and samples for microbiological assays, and U-bend samples for the detection of stress corrosion susceptibility. Part of copper samples for weight loss analysis were oxidized (90 °C, 7 days) prior to insertion into an anaerobic test. Similar type of pretreatment simulating the oxic phase was achieved when samples from oxic test (water+bentonite environment, MICOR project test) were transferred to this anoxic test (MICOR-BASUCA test). The results were compared to those obtained with fresh copper samples without a similar oxidation layer.

In addition, a verification test was carried out on the potential effect of the culture medium used in biotic environments on corrosion results. In the first experiments, the corrosion effects of sulphate-reducing bacteria and methanogenic archeons were studied compared to those conducted in similar environments with no microbes. At these low temperature experiments, it was found that both copper sulphide and copper oxides were formed on the copper surface in the biotic environment, whereas in the sterile (abiotic) environment only copper oxides were formed. Corrosion rate results (general corrosion) were small with all the analytical methods used (weight loss and electrochemical measurements). Based on the weight losses, the average corrosion rate of copper in the sterile environment was slightly higher (1.2 µm/a vs. 0.2 µm/a) after the 4 months exposure than in the biotic environment, suggesting that the biofilm generated in this case protects rather than contributes (general) corrosion. However, in both environments, small corrosion pits were found in SEM studies (localized corrosion). There were also indications of initiation of stress corrosion cracking in the biotic environment. In the sterile environment, there was also mild crevice corrosion detected. Based on the LPR-results and weight loss studies in longer test (12 months) corrosion rates in both environment were similar – in biotic environment 1.18 µm/a, being only slightly higher than that in abiotic, 0.95 µm/a. At higher temperatures in the presence of sulphate reducing bacteria and/or acetogens, the average corrosion rates calculated on the basis of weight losses were all of the same class, except for the previously oxidized sample with a corrosion rate significantly higher than others. In environment with enriched sulphate-reducing bacteria, corrosion pits and the largest number of sulphate-reducing bacteria were found on the surfaces of these samples. What was remarkable was also the fact that the pre-oxidized samples had higher corrosion rates than the so-called fresh samples. It is thus emphasized, that it is important to examine the corrosion phenomena taking into account the entire repository period.

The results of the research project are utilized in the long-term safety of nuclear waste management in the area of capsule performance in assessing the corrosion rates and the validation of the corrosion models. A test arrangement that allows corrosion of copper to be studied at different temperatures in an oxygen-free environment both in the presence and absence of microbes was development in the project. The work in co-ordinated Kapseli project included co-operation with the MICOR and REPCOR projects to simulate the environment of the final disposal and the effect of the change of the conditions on the surface layers.

The online measurement methods used in the project to investigate copper corrosion and molecular biological microbial methods can be utilized widely in a variety of application environments. The project involved a bachelor's thesis co-ordinated with the consortium projects of co-ordinated MILORI. The thesis increased synergy between the projects and offered the student a multidisciplinary support group for the thesis work.

6.5 Microbiological effects

6.5.1 Coordinated project – Microbiological risks of the final disposal of nuclear waste – MILORI (Projects 17-19)

Minna Vikman, Mirva Pyrhönen, VTT
Leena Carpen, Pauliina Rajala, Maija Marja-aho, Elina Huttunen-Saarivirta, Malin Bomberg, Elisa Isotahdon, VTT
Hanna Miettinen, Atte Mikkelson, VTT

Microbiological risks in the final disposal of high-level nuclear waste are related to the durability and deteriorating performance of the release barriers, which could lead to the mobility of radionuclides from the repository to the biosphere. Microbes and their metabolites can enhance corrosion of the copper capsule and influence the properties of the bentonite buffer. In the final disposal of low- (LLW) and intermediate level waste (ILW), biodegradation of organic components of the waste can enhance gas generation, which can influence the mobility of gaseous radionuclides (e.g. ^{14}C) and cause pressurization of the repository. In addition, corrosion of the decommissioning waste can also influence the safety of the

disposal and mobility of the radionuclides. The aim of the coordinated MILORI project was to obtain knowledge on these topics and to continue research that has started in the KYT2010- and in the KYT 2014-research programmes. The results of the three subprojects GEOBIOKIERTO, CORLINE and MAKERI, are presented in the following chapters. The results of the coordinated MILORI-project were also presented in the workshop in the spring 2018 and the presentations are available at the KYT2018-website.

Microbial sulphur cycle in final nuclear waste repository conditions, GEOBIOKIERTO, Hanna Miettinen, VTT

The primary objective of the project has been to study the biological sulphide formation and different sulphur cycling reactions in the deep subsurface groundwater microbial communities by utilising and developing a sulphate label ($^{35}SO_4$) method. During the project a very sensitive method was developed for the biological sulphide formation rate measurements. Olkiluoto and Outokumpu deep drillhole groundwaters showed wide range of sulphate reduction rates from different water types. In a groundwater with no previous measurable sulphate reduction, it was initiated with an electron donor, such as acetate, addition. This indicated that a shortage of a suitable electron donor was limiting the microbiological sulphate reduction in part of the groundwaters. Sulphate, acetate and possible methane were found to increase the sulphate reduction rate in some studied groundwaters. On the other hand, in some groundwaters the sulphate reduction rate was decreased by acetate and nitrate additions. With the help of the sulphate-label method a cryptic sulphur cycling was found. In the cryptic sulphur cycle the reduced sulphide was further microbiologically oxidised, which is not detectable with the traditional methods and thus, the real extent of the sulphate reduction can be missed. Microbiological sulphate reduction is a complex process affected by the microbial species present as well as the availability of different electron donors and acceptors and their amounts. Microorganisms most actively metabolising are those that can most effectively utilise the energy sources available. The project results showed and confirmed the biological sulphide formation and its large variation in different groundwaters and additionally, the effects of electron donor and acceptor concentrations on the sulphide formation rate.

The results from the sulphate reduction experiments can be utilised when assessing the risk of microbiological sulphide formation in relation to the copper capsule

corrosion in different conditions. Based on the obtained results, sulphide amounts forming can be evaluated and the risks of microbial activity caused to the capsule long-term safety can be modelled. The research has produced a lot of information about the method that can be utilised in the monitoring of the sulphide formation in the deep groundwaters of the nuclear waste final disposal sites.

The second aim of the project has been to assess the influence of the deep subsurface groundwater microorganisms on the bentonite structure and ability to function in long-term. The experiments were planned to study the microbial effects in so-called "worst case" conditions, which can occur locally in the interfaces of the final disposal site bedrock, water and bentonite, where the bentonite is not yet operational. The experiments have been carried out in cooperation with the KYT GEOBIOKIERTO and the EURATOM MIND projects. After a year of storage, there was no significant structural changes detectable in the bentonites. However, cation exchange capacity (CEC) increased slightly in the microbiological anaerobic bentonites. In addition, the microbial activity consumed oxygen in few months from the bentonite bottles started from oxic conditions. In the anaerobic bentonite bottles (Figure 14), hydrogen gas was consumed in few weeks from the start. In addition, there were clear changes in the chemistry and in the microbiology of the bentonite samples after one year of storage. Microbiological sulphate reduction was ongoing in the bentonite bottles started from the anaerobic conditions, whereas it was not detected in the control samples or in the samples started from the aerobic conditions. After two years of storage, there was no significant changes detected in the bentonite samples compared to one-year samples analysed with atomic force microscopy and CEC. With the help of a DNA extraction method developed for the bentonite samples, the amounts of bacteria, archaea, fungi and sulphate reducers were quantified with quantitative PCR (qPCR). More bacteria, archaea and especially sulphate reducers were detected in the bentonite samples started from the anaerobic conditions than from the bentonite samples started with oxygen. The amounts of microorganisms remained at the same level or their amount decreased a little as a function of storage time. Based on the results it is likely that a shortage of energy sources in the samples with liquid volume of only 80 mL, started to limit the microbiological activity after one-year of storage. The results from the bentonite experiments do not provide enough information so far, to assess the effects of the microbial activity on the bentonite structure, stability and ability to functioning in long-term. The levelling out of the microbial activity due to the decrease of energy sources and also the short storage time regarding to microbial perspective leave the question of microbial

effects on the bentonite structure unanswered. The sample bottles still remaining offer a possibility to continue the experiment together with energy source additions to accelerate the microbial activity again.

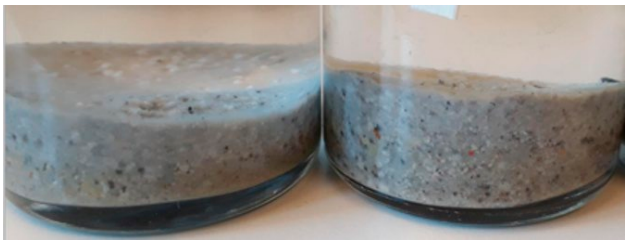

Figure 14. Bentonite bottles started from anaerobic conditions.

Microbially induced corrosion of low and intermediate level radioactive waste, CORLINE, Leena Carpén, Malin Bomberg, Elisa Isotahdon, Pauliina Rajala, VTT

The aim of the CORLINE project plan was to study the formation of biofilm and assess the risk of microbially induced corrosion (MIC) of decommissioning waste in the Finnish final repository concept. In addition, the aim was to monitor corrosion and water chemistry and their combined nature also in situ. To achieve this, a large laboratory test set-up was built and simultaneously an in situ tests with a novel field measurement system was set up in the final repository cave. In this study, several corrosion measurement methods were used together with microbiological and material characterization techniques to study the properties of biofilms, corrosion products and microbe - metal interactions.

Adding microbe enrichments (SRB, metanogens, acetogens) accelerated the corrosion of steels in all tests. In the abiotic environment, the corrosion rates of the studied steels were relatively small. The highest weight losses indicating highest average corrosion rates (12.2 µm/a) were recorded for carbon steels in the acetogen environment. The electrochemical measurements agreed with this finding, since also the highest momentary corrosion rates were recorded in the same environment. The average corrosion rate of carbon steel in the anoxic abiotic environment (bioside/sterilized) was 1.1 µm/a/0.4 µm/a, which was higher than any of the recorded value for corrosion rate of stainless steel. They did not suffer any weight losses during the test. According to electrochemical measurements, both

steel types were prone to localized corrosion, especially in the SRB environment. Steel samples were further characterized with scanning electron microscopy (SEM). Corrosion product formation and microbes were found as seen in the example in Figure 15 left.

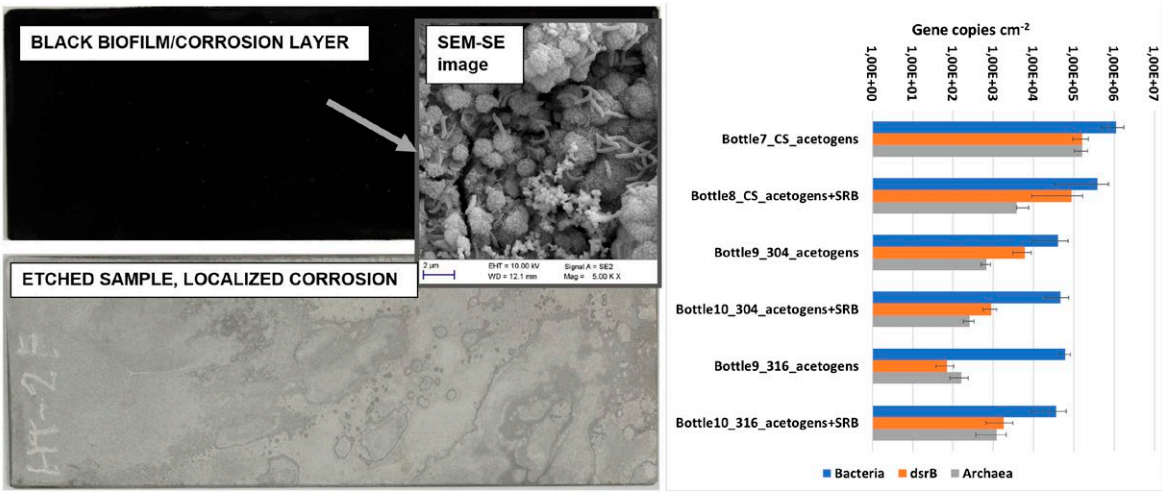

Figure 15. Microbes and corrosion product on surface of carbon steel exposed to groundwater with sulphate reducers and acetogen amendment (left). The number of bacterial 16S rRNA and *dsr*B genes and archaeal 16S rRNA genes per cm^2 or mL estimated by qPCR (right).

According to the sequencing results, different methanogenic archaea adhered on to the carbon steel and stainless steel surfaces, depending on the steel type (Methanobacteria on the carbon steel surface, Methanomicrobia on the stainless steel surface). A similar trend in the selection of bacterial taxa was also seen. Relevant metabolic reactions in the investigated groundwater of the VLJ cave include methanogenesis, sulphate reduction and sulphide formation as well as nitrogen metabolism and acetogenesis.

The gases formed in the experiment were analyzed and their composition was different in the presence of steels compared with mere groundwater. Gas composition was also dependent on the steel grade. Carbon dioxide was detected when steel was absent. In the presence of carbon steel, carbon dioxide was consumed and the amount of methane increased indicating that autotrophic methanogenic archaea were present. A small amount of carbon dioxide was consumed when stainless steel was present, compared to groundwater without stainless steel, and

only a small amount of methane was observed. The amount of hydrogen sulphide in the water increased more in the presence of stainless steel compared to carbon steel.

Commonly used carbon steel and stainless steel grades were studied in this project. Therefore, the results of the research can be applied extensively in the assessment of corrosion risks of in-use and decommissioning waste. The results of this project are valuable for the producers of steel waste, i.e. the power plants, but also for the authority. In addition to the measurements carried out in the laboratory, in-situ measurement systems were developed to be used in drillholes in the repository cave. The feasibility of reliable corrosion monitoring in actual field conditions is important for assessing long-term safety. However, such equipment has not been previously available. As part of the co-ordinated MILORI project, the CORLINE project co-operated with other projects under MILORI, increasing the overall knowledge of microbiological corrosion. In addition, long-term electrochemical tests similar to CORLINE's laboratory experiments were carried out in the same laboratory for different KYT projects for copper, allowing the development of measuring instruments to be used for all projects.

During the project, several different series of tests were carried out to evaluate microbially induced corrosion in the laboratory. The carbon steels (AISI 1005 or cold rolled DC01AmO) as well as the austenitic stainless steel grades (AISI 304 and AISI 316) were used as sample materials for laboratory testing and VLJ cave experiments. Information on corrosion rates was obtained by performing two long-term electrochemical laboratory tests, in which samples were regularly measured to define Tafel curves, linear polarization resistance (LPR), impedance measurements (EIS) and open circuit potentials. In addition, localized corrosion was monitored using MASS sensors. The results were compared with corrosion rates determined by weight losses. In addition, the gas formation was monitored. In addition, control experiments with the culture medium and control experiments in abiotic (both sterile and biocide treated) environments as well as electron transfer experiments were performed. The amount of microbes on the steel surfaces was estimated with qPCR (Figure 15 right) and high-throughput sequencing.

In the laboratory experiments, the water from drillhole VLJ-KR9 of the Olkiluoto VLJ cave was used. Water was enriched with sulphate reducing bacteria (SRB), methanogenic archaea and acetogenic populations. Field trials were performed in the Olkiluoto VLJ cave drillholes VLJ-KR19 and VLJ-KR21 during a two-year experiment. The

measuring equipment was installed in the spring of 2016 and included a corrosion measurement unit (electrochemical and weight loss samples) and an OsmoSampler water sampler collecting 5-14 ml of water sample per month. The potential of the samples and the linear polarization resistance was monitored and thereby the instantaneous corrosion rate could be calculated. The exposed samples from both laboratory and in situ test were analyzed using microbiological methods (DNA and qPCR), weight loss analysis and FE-SEM imaging combined to EDS analysis of surface layers.

Microbiology related to geological disposal of low- and intermediate level waste, MAKERI, Minna Vikman, VTT

The aim of the Makeri-project was to evaluate the microbiological degradation of low (LLW) and intermediate level waste (ILW) and factors influencing gas generation in the repository conditions. The Makeri project produced new information about microbiological degradation of LLW and about factors affecting the gas generation. The results of the project can be utilized in modelling and to evaluate microbiological risks in the final disposal of LLW and ILW. Both laboratory-scale simulation experiments and *in-situ* Gas Generation Experiment (GGE) in the TVO's final disposal repository were performed in Makeri-project. The research related to the GGE have been carried out in cooperation with the EURATOM MIND project.

In Finland, LLW is composed of e.g. protective clothing, fire fabrics, plastics and metallic waste. Currently LLW and ILW are packed into carbon steel drums and concrete boxes which are then disposed into silos or repositories at the depth of 60–110 metres inside the bedrock. Because LLW contains considerable amount of cellulose and hemicellulose-based material, it is easily utilized by microbes. The degradation of organic components is a complex multi-step process, which leads to formation of carbon dioxide and methane. Concrete structures creating alkaline conditions are expected to limit microbial processes in the repository conditions, which was also observed in this project. One of the main results, however, was that the heterogeneous chemical conditions created optimal niches for the microbial functioning and for the gas generation. In addition, microbial metabolites can reduce pH in the repository, which was seen both in simulation tests and in the GGE. The most important microbial groups influencing the gas generation were microbes degrading cellulose and hemicellulose, methanogens and microbes competing with methanogens, such as the sulphate reducers. Molecular biological methods (qPCR, sequencing) were used to study the composition of microbial

populations. The activation of methanogens and the formation of methane require e.g. pH within certain limit values and a low sulphate concentration. Experiments with labelled sulphate in water from the GGE demonstrated that sulphate reduction could initiate quite rapidly, if sulphate-containing groundwater flows to the repository. This could reduce the gas generation at least in short term. In addition, it was observed that hydrogen formed as a result of corrosion of metals and in biodegradation was utilized in microbial *in situ* processes, and hydrogen was not detected in the gas phase.

Also, corrosion of steel as well as the microbial growth on the surface of the LLW were studied using capsules loaded to the GGE. The corrosion rate of steel was highest inside the drum containing the highest amount of cellulose-based waste and where the microbial activity was the highest. Because it was not possible to analyze chemical parameters from the same drum, it cannot be concluded whether the high corrosion rates are related to the microbial activity or the chemical conditions favoring the corrosion. The main corrosion product in the steel plates detected by the X-ray diffraction method, was siderite $FeCO_3$, which is typically formed under methanogenic conditions. Although a small amount of sulphur was detected in elemental analysis, no iron sulphide was observed. Iron sulphide is typically associated with microbial corrosion. Microbial clusters were observed by field emission scanning electron microscopy (FESEM) on the surface of the waste materials and sequencing analysis showed that same microbial groups were found in the waste materials than in the water samples taken from the GGE.

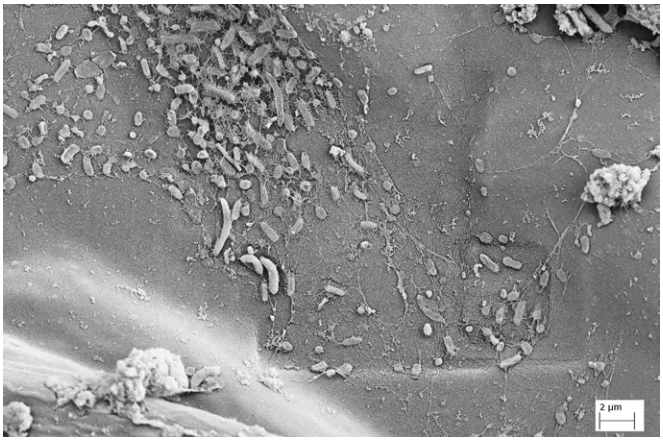

Figure 16. Microbes on the surface of plastic sample taken from the GGE. Analysis with FESEM by Irina Tsitko.

According to the literature review made in this project, the most relevant organic components in ILW in Finland are ion exchange resins and bitumen used for encapsulation. Organic part of ILW can degrade microbiologically, chemically, by radiation, or by combination of them. Components formed as a result of the degradation can enhance the microbial activity, promote corrosion of metals and/or form complexes with radionuclides increasing their solubility and mobility. In the Makeri-project microbiological degradation of bitumen was studied in the repository conditions in Finland. Bitumen contains aliphatic, aromatic and heterocyclic hydrocarbons, which are shown to be biodegradable at least in certain environmental conditions. Groundwater from the final repository and sulphate reducers enriched from the groundwater were used in the experiments. In anaerobic conditions, sulphate reducers are believed to be a significant microbial group that degrades bitumen, in which case sulphate in the groundwater could act as an electron acceptor. After one year of experiment, no significant microbiological degradation of bitumen was observed but it can be pointed out that the observation period of one year is quite short.

6.5.2 Nutrients, energy and gases in bedrock biosphere – RENGAS (Project 20)

Riikka Kietäväinen, Lasse Ahonen, Nina Heikkinen, Leena Järvinen, Jenni Keränen, Yann Lahaye, Irmeli Mänttäri, Arto Pullinen and Lotta Purkamo, Geological Survey of Finland (GTK)

The theme and key findings of the research

The RENGAS project (2015-2018) aimed to study the reactions and movements of biogeochemically important elements in bedrock groundwaters, sources of energy in the deep biosphere and energy transitions in microbially catalysed oxidation/reduction reactions, as well as their time scales and importance for the safety of the geological disposal of nuclear waste. The project consisted of five sub-projects: 1) Methods and infrastructures of deep borehole research, 2) Residence times and origin of saline fluids in bedrock, 3) Sulphur speciation and biogeochemical importance in bedrock, 4) Carbon speciation and presence in crystalline bedrock, and 5) Biogeochemical factors in the safety assessment. The key findings of the project have been published in international scientific journals. In addition, one PhD thesis on the origin and evolution of bedrock groundwaters (Kietäväinen, 2017) as

well as a master's thesis on the solubility of gases (Heikkinen, 2016) was completed. Methods were developed for groundwater and gas sampling and monitoring, as well as for sulphur isotope analysis of saline water samples.

The evolution of deep bedrock groundwaters can be described with a model, which includes infiltration of meteoric water, separation from the hydrological cycle up to hundreds of millions of years ago, and development of salinity, gas composition and water stable isotopes as a result of water-rock interaction. However, the results show that the geochemical and microbiological characteristics of bedrock groundwaters are strongly dependent on the local hydrological and lithological conditions and closely connected. With regard to migration processes, the project focused on gases, which were demonstrated to occur mainly dissolved in groundwater, but gas separation takes place relatively close to the ground (<150 m) especially in methane rich groundwaters. In the most methane rich areas, the amount of gas flux from a single borehole can be up to tens of thousands of litres per day. Solid Earth tides, i.e. the movement of the crust by the gravitational fields of the Moon and the Sun, was found to affect migration of crustal gases, especially helium and methane.

The sulphur isotope fractionation measured between sulphate and sulphide phases is compatible with the isotope fractionation caused by sulphate reducing bacteria. The differences in the amount of fractionation observed between the different sites can be due to variation between the oxidation of organic matter and the use of hydrogen. Thermodynamic calculations show that when the sulphate content is the limiting factor, the removal of sulphide either by oxidation or precipitation favours methane as an electron acceptor compared to hydrogen.

Hydrocarbons, methane in particular, is formed *in situ* in the bedrock both in microbial and geochemical (abiotic) processes. The presence of methane was discovered especially in the graphite containing metasediments, and graphite was found to be thermodynamically likely carbon source for methane. The proportion of ^{13}C-rich, possibly abiotic, methane was found to increase deeper (>1.5 km) in the bedrock, as well as in granitic and volcanic environments, although microbial methanogenesis is possible at least to 2.2 km depth either via hydrogenotrophic, aceticlastic or metylotrophic pathway. Methane oxidation is most significant at depths less than 1 km below the surface. Concentrations of inorganic carbon compounds are low, but addition of carbon dioxide in the system will activate microbes especially in the long term, allowing activation of methanogenic

microbes and change in carbon speciation from carbonate to hydrocarbons. In addition, acetate can be an important source of carbon, and possibly also energy, in the bedrock biosphere and it has proved to be a key link between the sulphur and carbon cycles.

Significance and applicability of the results, connections to other research

The biogeochemical reactions examined in the RENGAS project, and the results obtained, are mainly related to the release and migration of radioactive or corrosive compounds and elements in the bedrock-groundwater system, which forms the outermost, natural barrier of the spent nuclear fuel repository. The results considering the gas formation and migration in particular can also be potentially applied in the safety assessment of low and intermediate level waste disposal.

Understanding of the time scales in the bedrock groundwater environment is necessary in order to predict changes. On one hand, residence times of tens to hundreds of millions of years imply the slow pace of the reactions and isolation of the system, but, on the other hand, the results show that the bedrock biosphere can respond quickly to changes caused e.g. by the construction of the repository. Long residence times have also enabled the accumulation of significant methane concentrations in groundwater. The mobilisation of carbon can affect the disposal safety by changing pressure conditions, enabling ^{14}C migration outside the repository and by providing energy sources to microorganisms. No clear link between the isotopic composition of methane and various microbial communities could be revealed, which highlights the need for the use of different research methods and a multidisciplinary approach in order to achieve a complete view. The importance of sulphur compounds in the repository is mainly related to the corrosion to metals, caused by sulphide, and formation of sulphide minerals, which may affect the buffering capacity of the bentonite. The role of microbial sulphate reduction on sulphide formation is important. The methods used in the project allow for factors controlling the reactions, such as solubility, oxidation/reduction conditions and the availability of electron donors and acceptors to be considered in support of the risk assessment.

The methods developed and comparisons done during the project can be used in bedrock groundwater studies related to site selection and site characterisation for the final disposal of nuclear waste, and error estimations associated with such

investigations. Based on the results, it is recommended that e.g. gas sampling is done using pressurised methods. The solid Earth tides are seen as a tool to monitor fracture formation and changes in the engineered and natural barriers. The results of the project will also benefit the future KYT and EURAD programs.

The implementation of the study included networking and cooperation between several research institutes and universities. The project took place in close dialogue with VTT's microbiology themed KYT2018 projects, including also collective sampling. The main international collaborators were GFZ Potsdam, for the measurement of noble gas isotopes, and INGV Rome as well as the International Continental Scientific Drilling Program (ICDP) for the measurements of gas flux.

Research methods

Water and gas sampling and monitoring in deep bedrock boreholes formed the basis of the RENGAS project. Methane flux was measured in the Outokumpu and Juuka areas using a gas collection chamber combined with TDLAS + IR equipment and compositional changes in the gas phase were monitored at the well head of the Outokumpu Deep Drill Hole using a quadrupole mass spectrometer. Variation in the composition of gas with time was compared to the level of the water table and the atmospheric pressure changes, as well as the calculated solid Earth tides. Tube sampling was carried out in Pori (down to 440 m), Outokumpu (down to 2100 m), and in Åre (down to 2500 m), and pumping experiments were done in Outokumpu at 1500 m and 1000 m depths. Furthermore, samples were taken directly from the pressurised boreholes at the 1430 m level of the Pyhäsalmi mine. In addition to geochemistry, the samplings in Åre, Outokumpu and Pyhäsalmi included microbiological sampling for collaborators (VTT, Lawrence Berkeley National Laboratory and Uni. St Andrews). Material gathered in the former KYT2014 project, SALAMI, was also used.

Alkalinity, pH and electrical conductivity (EC) of the samples was determined in the field. The chemical composition of the water (cations and anions, including sulphide concentration) and gas composition was analysed in laboratory (Labtium, Eurofins Environment Testing and Isotech Laboratories). Oxidation-reduction potential, speciation of alkalinity and ion activities were determined from the analysis results using PHREEQC software and wateq4f database (USGS). Furthermore, the concentration of acetate in water in the Outokumpu tube samples

was measured by ion chromatography at TVO Nuclear Services and the isotopic composition of noble gases in the Pyhäsalmi samples by mass spectrometry at GFZ Potsdam. Isotope composition of hydrocarbons (methane, ethane) was analysed from some gas samples at Isotech Laboratories. Water stable isotopes were determined using cavity ring down spectroscopy and sulphur isotopes using high resolution MC-ICP-MS at GTK. The project also included testing and development of sulphur separation methods for saline groundwaters. Thermodynamic calculations were done using concentrations, pH, alkalinity determined from water and gas samples and *in situ* temperature of the specified depths, and the results used to determine Gibbs free energies and energy densities of the key biogeochemical reactions related to the carbon and sulphur cycles.

6.6 Other safety studies

6.6.1 Behaviour of radionuclides in the geosphere; in situ studies – RAKU (Project 21)

Marja Siitari-Kauppi, Eveliina Muuri, Mikko Voutilainen, Jussi Ikonen
Chemistry Department, University of Helsinki

Retention of radionuclides in the bedrock surrounding the repository for the final disposal of spent nuclear fuel has been studied in this project in the Department of Chemistry in the University of Helsinki. Aim of the project was to estimate the migration properties of radionuclides in the bedrock in in-situ conditions compared to laboratory conditions, where migration properties have been commonly determined for the safety analysis. Chemical retardation was aimed to be combined with matrix diffusion and a reactive transport model taking into account the mineral and structural heterogeneity of rock matrix was developed. An additional aim of the project has been to decrease the uncertainty in the retardation parameters that are used in the safety analysis. The project has been conducted in close collaboration with the international Long Term Diffusion (LTD) project within the Grimsel Test Site (GTS) Phase VI program.

The development of a reactive transport modelling tool that was started during KYT2014 was continued and the TDRW model regarding the transport of cesium in Grimsel granodiorite was published (Voutilainen et al. 2017). The first in-situ

experiment was reported (Ikonen et al 2016a, 2016b, 2017) and the second in-situ diffusion experiment (LTD Monople2) was continued in the GTS in Switzerland. Tritiated water (HTO), Cl-36, Na-22, Cs-134, Ba-133 and stable selenium were used as tracers in the in-situ experiment. The concentration changes of the tracers were measured in the experiment: the concentration decrease of the tracers was measured in the inlet hole and the concentration increase was measured in the observation hole. Instant information about tracer retardation and migration was obtained from the inlet hole and increased concentrations of tritiated water were measured from the observation hole six months after the beginning of the experiment.

The in-situ experiment was stopped in summer 2017 after over three years of monitoring. The test area was overcored and, in addition, three far-field samples were cored approximately 50 cm from the inlet hole. A part of the core samples were sent to the University of Helsinki to be analyzed within the KYT2018 project. Non-sorbing nuclides (HTO and Cl-36) and stable selenium were determined from the samples through out-leaching. Tritium and chlorine were observed in clearly measurable amounts in the far-field samples, hence tritium had been transported over 50 cm from the inlet hole during the experiment. This means that the connected porosity of the rock is continuous at least in this scale. Clear effect of foliation was also observed in the out-leaching results of the far-field samples, based on which an estimation of the transport direction of the non-sorbing nuclides was made (Figure 17). Selenium was not observed in the studied samples.

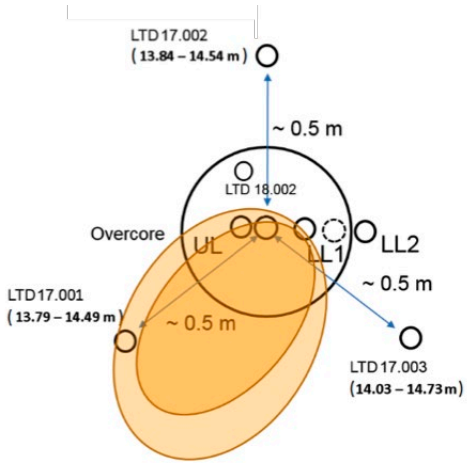

Figure 17. The transport of tritiated water in the LTD Monopole2 in-situ experiment after three and a half years based on the out-leaching results from the overcore samples.

Sorbing radionuclides (Ba-133, Cs-134 and Na-22) were determined through gamma spectrometry and autoradiography from the samples near the inlet hole. Most of the activity of the sorbing nuclides was found from approximately one cm from the inlet hole in the rock matrix in the analyses (Figure 18). It was also discovered with autoradiography methods that the foliation of the rock, which is dependent on the distribution of biotite and mica minerals in the rock, had a clear effect also on the results of the sorbing nuclides (Figure 19).

It was discovered during the in-situ experiment that barium was retarded in the rock more than initially suggested, which is why the retardation of barium was studied more closely in laboratory conditions in this project (Muuri et al. 2017, 2018a). The sorption of barium was studied in the laboratory in batch sorption experiments and sorption experiments on thin sections. It was discovered in the experiments that barium is strongly sorbing especially on biotite and that the laboratory sorption experiments overestimate the sorption of radionuclides in in-situ conditions. The distribution coefficient of Ba-133 determined in the laboratory was 0.184 m^3/kg whereas the value obtained from the COMSOL Multiphysics modelling of the in-situ results was 0.009 m^3/kg. The sorption mechanisms of barium on biotite were estimated with molecular modelling and it was discovered that barium is attached on the mineral surfaces of biotite through ion exchange. The sorption results of barium were modelled with PhreeqC using an ion exchange model.

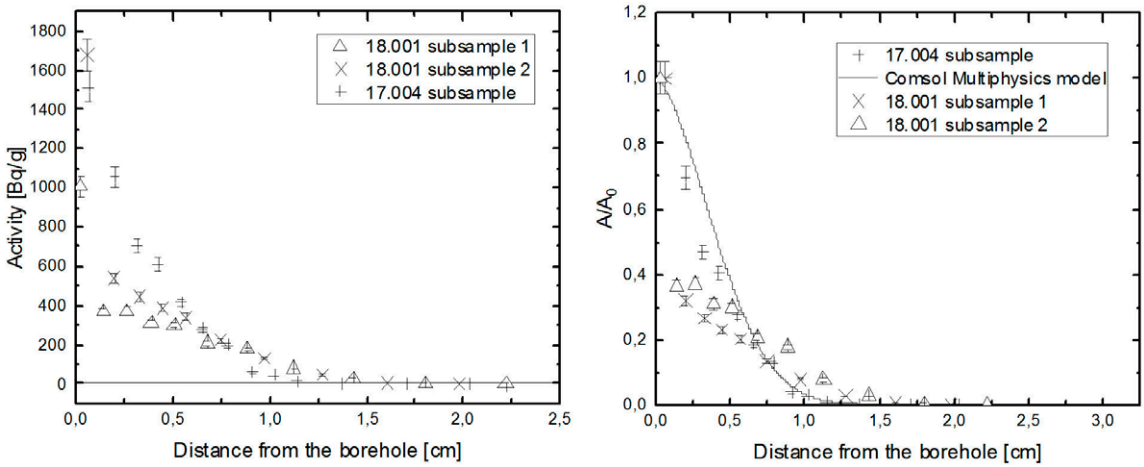

Figure 18. The diffusion profiles of Ba-133 in Grimsel rock after the in-situ experiment. The COMSOL Multiphysics diffusion model fitted to the experimental results is presented on the right (effective diffusion coefficient $1.8 \cdot 10^{-12}$ m^2 s^{-1}, distribution coefficient 0.009 m^3 kg^{-1} and porosity 0.7 %).

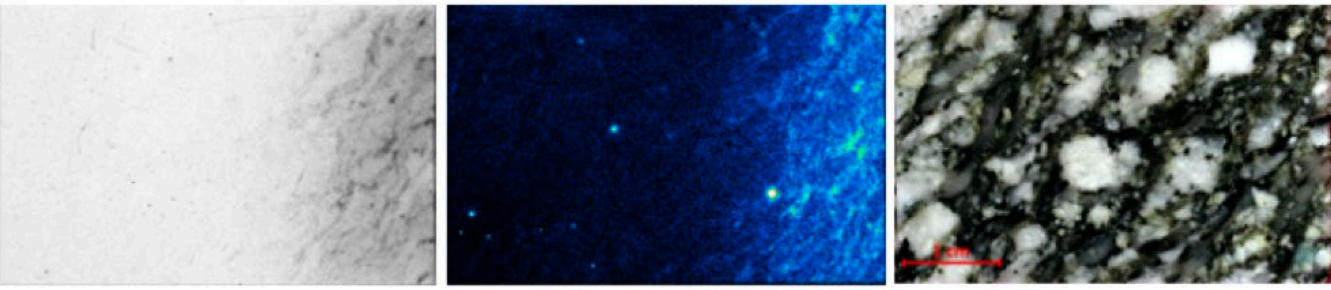

Figure 19. Film autoradiogram (left), electronic autoradiogram (middle) and the scanned rock surface (right) show the distribution of Ba-133 in rock (right side of the images is the surface of the inlet hole). In film autoradiograms the darkest areas and in electronic autoradiograms the lightest areas are the most active. The effect of the foliation of the rock on the transport of sorbing nuclides can be seen clearly on the autoradiograms.

The diffusion of barium was also studied in different laboratory experiments and the results were modelled using COMSOL Multiphysics (Muuri et al. 2018b). Laboratory diffusion results were very similar to the in-situ diffusion results. In order to examine the intrusion depth and spatial distribution of barium in different minerals, electronic autoradiography method was developed in the project (Figure 3) where the spatial distribution of radioactivity is determined quantitatively straight forward from the surface of the sample using MPGD technology (Micro Pattern Gas Detector, BeaQuant®). The laboratory and modelling methods developed in the project were used in the analysis of the in-situ samples and results.

6.6.2 Release of C-14 from metallic waste – HIILI-14 (Project 22)

Tiina Heikola, Kaija Ollila, Tiina Lavonen, Kirsti Helosuo, VTT

The objectives of the project was to gain understanding of the potential release mechanism and rate of the release of carbon-14 from the activated metallic waste materials as well as speciation of carbon in geological disposal conditions. When assessing the mobility of carbon it is especially crucial weather, carbon is in organic or inorganic form. The project was also involved in the CAST (CArbon-14 Source Term) EU project (WP: Steels) which started in 2013 and ended in March 2018. Besides that, the project was continuum from the earlier C-14 release in repository conditions that ran in KYT2014 program.

There are some uncertainties concerning the form of carbon-14 in irradiated steel structure. It has been suggested by Johnson and Schwyn (2004) that carbon-14 arising from nitrogen is present in the form of carbide in the steel lattice. In order to investigate the influence of the initial speciation of carbon, the solid phases chosen for the experiment were non-irradiated AISI 316Ti type stainless steel and Fe(III)carbide (Fe_3C) powders, in which carbon is in interstitial atom and carbide form respectively. The AISI 316Ti type stainless steel powder was prepared at VTT in Material modelling and eco design team. A small batch of iron carbide powder was received from a component manufacturer from USA. The microstructure and composition of both materials was checked before starting the experiments (optical microscopy, SEM/EDS, XRD, OES). Groundwater samples from Loviisa site were analyzed and the composition of simulated leaching solutions were modelled according to those results. Two pH values were chosen, pH 12.5 (CA125) to simulate the effect of cement in the repository conditions and pH 8.5 (CA85) was selected as reference.

The batch type experiments for liquid and gas phase analysis were started in glass bottles under anaerobic conditions inside a glove box. The samplings were performed according to schedule. The total amounts of dissolved inorganic carbon (DIC) and organic carbon (DOC) were analyzed with TOC analyzer (Analytika Jena N/C UV HS). The results from the liquid phase samples are presented Figure 20 and suggested that majority of carbon was released in organic form from both materials. According to Vuorinen (2012), the presence of carbides in metals seems to increase the formation of organic species at high pH. AISI316Ti steel powder had much lower carbon content, but relatively more carbon was released from AISI316Ti stainless steel powder compared to Fe_3C powder. The composition of the organic carbon compounds in liquid phases were determined by means of different gas and liquid chromatographic techniques as well as by capillary electrophoresis (CE) instrument equipped with a photodiode array UV-Vis detector. The volatile organic alcohols, methanol, ethanol and 1-propanol, were detected from the carbide powders samples although the concentrations were close to the detection limit. In the steel powder sample all the concentration were below the detection limit. The gas phase analyses were performed in collaboration with the University of Helsinki. Additional gas phase analyses were performed later at VTT. Hydrocarbon compounds were analyzed by gas chromatograph Agilent 6890N with Pulsed Discharge Helium Ionization Detector (PD-HID) with CP-Molsieve 5A column. No organic compounds were detected in steel powder samples (AIAI316Ti). Instead, rather high methane and ethane concentrations were detected in the gas samples taken from Fe_3C

experiments. Tentative results suggested around 1100-1900 ppm content of CO in the Fe_3C gas phase and minor concentration of CO_2 (10 ppm). In the course of the gas analyses, we observed clear overpressure inside the sample vessels.

The experiments with irradiated specimens were started in June 2016 inside an under-pressure glove box in anaerobic conditions. The two specimens were cut from the surveillance capsule chain material from the Loviisa nuclear reactor inside a hot cell at VTT. From the initial composition and irradiation history, the theoretical maximum ^{14}C content after exposure was calculated to be 2 x 10^3 Bq ^{14}C/g. Detailed description of the experimental set-up is given in Table 6. The first samples from the irradiated experiments were taken after 133 days from the start. Liquid scintillation counter (LSC) Wallac 1415, Protocol 81 was used to measure beta activity of the leaching solution. Gamma-emitting radionuclide activities in the solutions were determined with gamma spectrometry. Some precipitates were found in the solutions before the analyses. The activity measurements were performed without any pre-treatment of the solutions (e.g. ion exchange). Without the chemical separation it is impossible to identify present radionuclides, but it was suspected that they could be ^{55}Fe and ^{63}Ni or ^{14}C. The measured activities are presented in Table 7. Clearly higher activities were detected in the lower pH solution (CA85). The results from the latest sampling and analyses are still incomplete while this abstract was written, but will be published early in the year 2019. Due to the removal to the new laboratory facilities there has been a delay in the experiments. This delayed and prevented us from continuing according to initial plan.

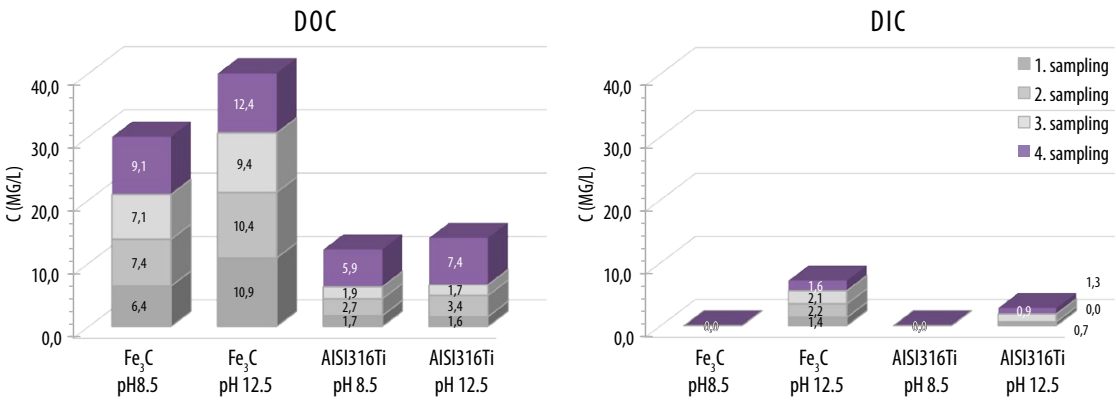

Figure 20. The concentration of carbon released to liquid phase (DOC = organic form, DIC = inorganic form, as carbonate).

Table 6. The sample info and experiment set-up details for irradiated steel specimens.

	Sample 1	Sample 2
Activity (MBq 60Co)	227.27	619.23
Mass (g)	2.975	9.211
Leaching solutions / Vol.	CA85 / 120 mL	0.01M NaOH / 120 mL
Sampling	liquid phase	

Table 7. Activities of the measured radionuclides in sample solutions.

Bq/g	$^{63}Ni/^{14}C$?	^{55}Fe	^{54}Mn	^{58}Co	^{60}Co	^{125}Sb	^{124}Sb	^{110m}Ag
Sample 1	131.9	1053.1	23.0	2.2	328.9	16.0	4.9	
Sample 2	4.6	11.1	0.4		1.2	2.0	0.7	0.4

References

JOHNSON L and SCHWYN B. 2004. Behaviour of ^{14}C in the safety assessment of a repository for spent fuel, high-level waste and long-lived intermediate level waste in Opalinus Clay. In: Johnson LH and Schwyn B (eds). Proceedings of a workshop on the release and transport of C-14 in repository environments. Nationale Genossenschaft für die Lagerung radioaktiver Abfälle NAGRA Interner Ber-icht 04-03.

VUORINEN, U. 2012. ^{14}C in irradiated metallic waste – Literature survey. VTT Research report, VTT-R-05446-12 (in Finnish).

6.6.3 Modelling fracture flow, matrix diffusion and sorption using the lattice-Boltzmann method – JYFLKYT (Project 23)

Keijo Mattila, Jukka Kuva, University of Jyväskylä

In this project, the migration of radionuclides in water conducting fracture and in the bedrock surrounding it, is studied. The project is focused on computational modeling, in other words the migration is investigated through computer simulations.

Motivation

In Finland, the high-level spent nuclear fuel is planned to be disposed of in deep crystalline bedrock so knowing the bedrock phenomena forms the basis for assessing the safety of final disposal. The safety of such disposal site includes, for

example, the ability of the bedrock to retard the transport of radioactive isotopes that have possibly been released to the groundwater. Because of the uncertainties associated with groundwater transport pathways and bedrock properties, the role of geosphere in retarding the radionuclides has been deliberately underestimated in current safety analyses. The uncertainties related to the pore volume and heterogeneity of the rock matrix have also led to changes in the modelling principles of radionuclide migration.

Background

In the bedrock, the transport of radionuclides occurs mainly in water conducting fractures and in fracture zones, where their transport can be slowed down by matrix diffusion and sorption. Matrix diffusion is a process in which radionuclides diffuse into porous rock material around the migration pathway and possibly return to the flow only after a random diffusion time.

The chemical process, that allows the radionuclides to chemically attach themselves (sorb) on the surfaces of minerals along the transport pathways, in turn, is called sorption. These minerals can be located either on the fracture surfaces or inside the porous rock material, into which the nuclides have migrated via diffusion. These phenomena are believed to be significant retarding mechanisms in the flow occurring in crystalline bedrock. In practice, the available porosity of the bedrock close to transport pathway, the sorption capacity and the specific surface area, and the radionuclide in question, affect the significance of the retardation. These properties vary greatly between the minerals in the bedrock and, therefore, the heterogeneous properties of the material typically need to be taken into account.

Computational modelling

In recent years, new methods have been developed for the computational modelling of radionuclide transport phenomena. One of these is the Lattice-Boltzmann simulation method (LBM), which is based on solving the discrete Boltzmann equation. The method is based on statistical mechanics and kinetic theory, which makes it possible to easily consider multiple microscopic mechanisms in modelling. In addition, the advantage of this method is its numerical efficiency, especially in parallel computing, and easy applicability in complex structures (such

as porous materials). The method is particularly suitable for simulating flows but also for diffusion and sorption.

Another effective method for simulating the transport of radionuclides is Time-Domain Random Walk (TDRW) method, which is based on the random migration of tracer particles and statistical behavior. The method is ideally suited for parallel computation and enables the modeling of multiple physical and chemical phenomena, including diffusion and sorption. The weakness of the method has been that it has not been able to take into account the transport caused by water flow and is has, therefore, not been suitable as such for simulating the fracture flow.

Results

During the first two years of this project, the TDRW method has been further-developed and it is now possible to simulate the transport of tracer in flowing water in a known flow field.

In addition, a simulation tool that is based on parallel computation and capable of high performance computing was built in the project. This enables computational modelling using e.g. the super computer of CSC – IT Center for Science Ltd.

The simulation tool utilizes both LBM and TDRW method simultaneously. LBM-method takes care of modelling the fracture flow and TDRW-method is used to model radionuclide transport through advection, diffusion and sorption. The hybrid method utilizes the best properties of both methods: LBM-method has established itself as one of the most effective tools for flow simulation in porous material and TDRW-method, in turn, is capable of modelling transport in highly heterogeneous materials, even when modelling with more traditional methods is difficult or even impossible (e.g. when material parameters are discontinuous or vary greatly).

The method development and the implemented simulation tool enable the computational modelling of radionuclide transport in a realistic water conducting fracture and in the heterogenous rock matrix surrounding it. Such modelling can be used, for example, to evaluate relevant migration scenarios.

In addition, combining realistic fracture geometry, mineral and pore structure, and chemical properties of minerals into diffusion modelling promotes the

interpretation of laboratory experiments as well as the evaluation of transport concepts. Modelling can also be used to increase understanding of how the transport in realistic natural fractures often differs from the simplified cases used in modelling.

The information obtained in the project contributes to the long-term safety assessment capability of the authorities and benefits the actors in nuclear waste disposal projects.

6.6.4 Chemical forms and sorption of radiocarbon in geosphere – C14ROCK (Project 24)

Merja Lusa, **Jukka Lehto,** Janne Lempinen, University of Helsinki

1. Research topic and relevance of the project for the nuclear waste research

C14ROCK project investigated the sorption behavior of radiocarbon (^{14}C) originating from spent nuclear fuel (SNF) in the deep bedrock and the changes of ^{14}C chemical forms, i.e. speciation, as carbon passes through the bedrock to the surface biosphere. ^{14}C is produced through neutron activation of nitrogen with the reaction $^{14}N(n,p)^{14}C$ and is found in the fuel material, Zircaloy cladding and steel structures in approximately equal portions, and is assumed to be present as insoluble carbides or graphite. However, these sparingly soluble species may be oxidized into more soluble species, like carbon dioxide (CO_2) e.g. by radiation induced radiolysis. The speciation strongly affects radionuclide migration and retardation in the environment, but previous knowledge on radiocarbon behavior in deep bedrock anaerobic environment is very limited. ^{14}C is one of the high priority radionuclides in the biosphere safety assessment of the disposal of SNF. Nuclides belonging to this category are expected to account for the majority of the possible future radiation doses to humans ensuing from the disposal of SNF. Compared with other high priority ($^{36}C1$, ^{129}I) and lower priority class radionuclides, radiocarbon behavior has been studied only marginally in Finland, as well as worldwide. However, in the safety analysis of the disposal of SNF, the greatest uncertainty relates to the speciation of radiocarbon, and the possible changes in the speciation, caused both by abiotic and biotic (i.e. microbiological) factors. As a result, in the safety analysis it is conservatively presumed that ^{14}C is not retained at all in the bedrock, but is transported at the velocity of the groundwater flow.

Hence, research on factors influencing its possible retardation and speciation behavior is very important. There is no previous research done in Finland such as in this project, and no information similar to the project is available internationally.

In the first part of the C14ROCK project the retardation of ^{14}C (as carbonate, HCO_3^-) in the deep bedrock mineral phase was investigate. This included the studies of the effect of isotope exchange as well as sorption of ^{14}C-carbonate on iron hydroxides (goethite (α-FeOOH), hematite (α-Fe_2O_3) and magnetite (Fe_3O_4,)). In the second part, the biotic effects of in particular sulphate reducing bacteria (SRB) found in the sulphate-methane mixing zone of deep bedrock at approximately 250 – 350 m depth on the radiocarbon retardation and on the changes of speciation between methane (CH_4) and carbonate were studied.

2. Methods and central results

The isotope exchange was investigated using batch experiments with synthetic powdered calcite, $NaH^{14}CO_3$ tracer and 0.0002M – 0.1M calcium chloride ($CaCl_2$) solutions with 0.01M sodium chloride (NaCl) or 0.0001M bicarbonate ($NaHCO_3$) + 0.005M NaCl solution. In addition, two synthetic reference groundwaters, ALL-MO (fresh water) and OL-SO (saline water), mimicking conditions at the Olkiluoto site, were used. These groundwater model solutions represent the Olkiluoto groundwaters under oxic conditions in equilibrium with calcite, talc and apatite. In this part of the study, inorganic radiocarbon was found to rapidly retain onto calcite by isotope exchange with half-lives of isotope exchange ranging from 3.6 d to 70 d. High calcium concentration and low bicarbonate ion concentration increased the rate of retention. However, the concentration of magnesium in solution should also be considered in assessing the rate of the isotope exchange as it can inhibit calcite dissolution and the isotope exchange. The rate of radiocarbon retention by isotope exchange can be expressed with mathematical functions of either the Ca^{2+} or HCO_3^- ion activity and therefore calcium and bicarbonate deep bedrock concentrations provide a tool for assessing the rate of radiocarbon retention by isotope exchange.

In addition, batch sorption experiments were used to determine the sorption isotherms of radiocarbon and the effect of pH and ionic strength on radiocarbon sorption on goethite, hematite and magnetite. For sorption isotherms, samples with various concentrations of $NaHCO_3$ and 0.01 M TRIS buffer (tris(hydroxymehthyl) aminomethane) (pH 8.2) were prepared and radiolabeled with $NaH^{14}CO_3$. In order

to study the effect of pH and ionic strength on the sorption, sets of samples were prepared at three different ionic strengths (0M, 0.01M and 0.1M) using NaCl as the background electrolyte and HCl and NaOH for pH adjustment. Carbonate was found to considerably sorb on goethite and hematite depending on pH (Figure 21A, 1B), but the sorption on magnetite was negligible in all studied conditions. Sorption on goethite and hematite was largest in the neutral pH-range and it decreased with increasing pH. This is caused by the decreasing positive charge of the mineral surfaces as the pH increases. Carbonate sorption was also observed to slightly decrease with increasing ionic strength (Figure 21), which can be due to the saturation of sorption sites caused by the interactions of chloride ions on the plane typically occupied by electrolyte outer-sphere complexes. The batch sorption results were modelled with the generalized double-layer surface complexation model and the model was able to reproduce rather well the experimental sorption results.

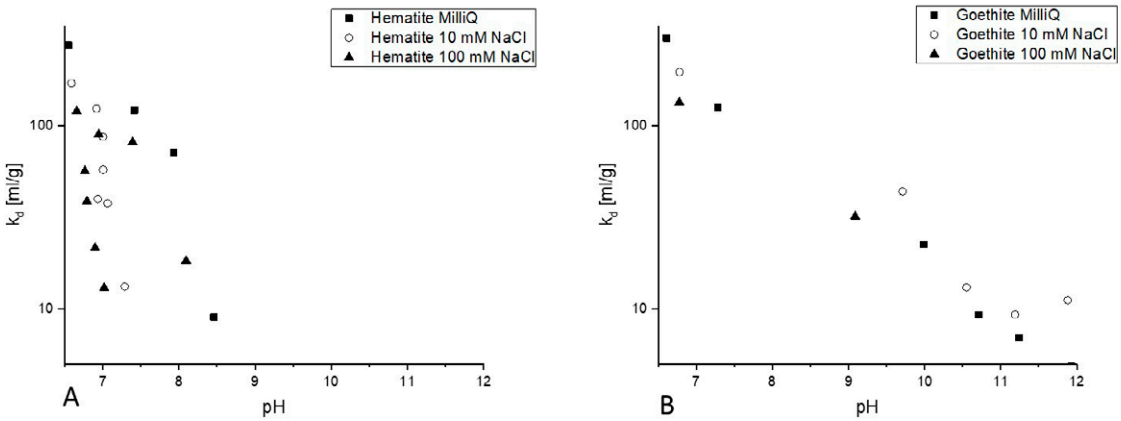

Figure 21. Distribution coefficients (K_d [ml/g]) of radiocarbon (14C) as carbonate on hematite (A) and goethite (B) as a function of pH.

Isotope exchange and sorption on iron hydroxides, applies only to inorganic radiocarbon but not organic species, such as methane. In order to predict radiocarbon migration in bedrock, also further studies on its speciation and the biotic factors affecting its retardation and speciation, were required. In the C14ROCK project, the effect of sulphate reducing bacteria (SRB) on radiocarbon removal and speciation was investigated using Desulfovibrio desulfuricans strain, obtained from DSMZ collection (Deutsche Sammlung von Mikroorganismen und

Zellkulturen GmbH). The cells were cultivated in three different growth solution conditions (A-C), with varying salt and nutrient concentrations. One solution (A) consisted of typical growth broth used generally for D. desulfuricans including salts, Na-DL-lactate and Yeast extract as the sources of carbon and other nutrients. The other two were based on OL-SR groundwater simulant, mimicking conditions at the Olkiluoto site under anoxic conditions. Na-thioglycolate was used as a reducing agent. The solution B included Na-DL-lactate and Yeast extract, which were omitted in the solution C. C only contained OL-SR, reducing agent, ascorbic acid and redox indicator (included also in A and B). Cells were incubated for 7 – 21 days under low redox conditions (-200 – (-) 400 mV) with $NaH^{14}CO_3$ for radiocarbon uptake studies or with added $NaHCO_3$ (0 – 41 µM) or CH_4 (510 mM) for speciation studies. In these studies change (□) in CO_2, CH_4, lactate ($CH_3CH(OH)CO_2H$) and acetate (CH_3COOH) concentrations were recorded in connection to sulphate reduction. In addition, the formation of SRB induced calcite crystals was examined using electron microscopy (TEM). Cell numbers were estimated using sulphate reducing gene (dsrB) and 3.9×10^3 copies/sample were used in the experiments. In above-mentioned studies, SRB bacteria were observed to efficiently remove 40 – 98 % of radiocarbon (as carbonate) from the solution, depending on nutrient conditions (solutions A, B and C). Incubation time had no clear effect on removal and highest removal was observed in OL-SR as Na-DL-Lactate and Yeast extract were present as nutrient and carbon sources. However, also under very low nutrient conditions (solution C), considerable removal of 53 – 72% was observed. In the microscopic studies, crystal formations (likely calcite) in the SRB containing samples were observed (Figure 22). Concurrently, weak, though statistically significant, positive correlation (R=0.419, p=0.02) between □CO_2 and the decrease of ^{14}C activity of the solution was observed. In addition, statistically significant positive correlation between lactate consumption and acetate production (R=0.844, p=0.002) and strong positive correlation with SO_4^{2-} reduction and lactate consumption (R= 0.952, $p = 2.2\times10^{-5}$) and acetate production (R=0.882, $p=7.5\times10^{-4}$) were recorded. In the CH_4 supplemented samples an increased conversion of CH_4 to CO_2 in samples with SRB, compared to samples without bacteria was observed. In these samples CH_4 concentrations were on average 30% lower, than in the samples without bacteria addition. Similarly, CO_2 concentrations were on average 53% higher in SRB containing samples. Positive statistically significant correlation between CH_4 consumption and CO_2 production was recorded (R=0.859, $p<0.05$). Average CH_4 consumption decreased exponentially with free sulphate concentration. However,

no statistically significant correlation was proved between CH_4 consumption and free sulphate concentrations in methane inoculated samples.

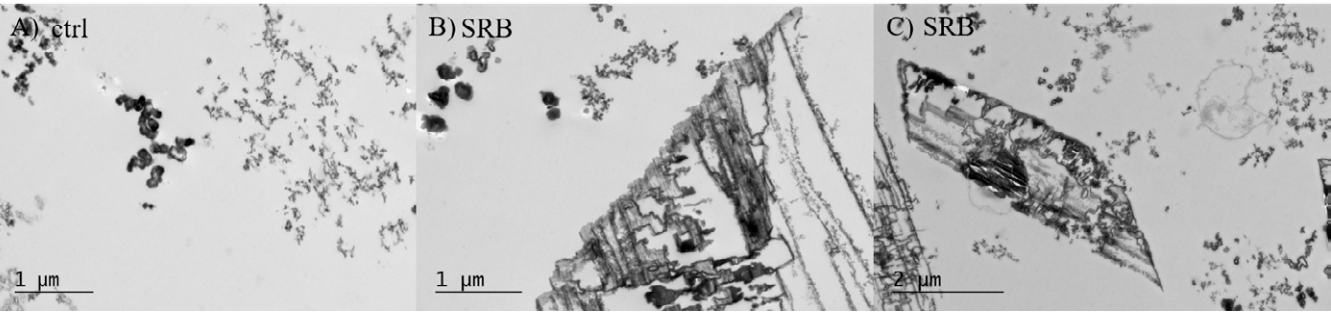

Figure 22. In B) and C) crystals (presumably calcite) formed in connection to carbonate removal on 41 µM carbonate solutions containing SRB bacteria. In control 41 µM carbonate solutions A) without bacteria addition, crystals were not formed.

Considering the long-term consequences of the final disposal of SNF, it may be concluded that radiocarbon as carbonate is not completely non-sorbing as presently is assumed in conservative safety analyses. In addition to isotopic exchange reactions of carbonate with calcite, the sorption on iron oxides may prevent rapid migration of radiocarbon into the biosphere. In addition, microbiota present in the deep bedrock, may affect both radiocarbon speciation, as well as its retardation in the bedrock due to speciation changes from CH_4 to CO_2 under low redox conditions, uptake of carbonate by bacterial cells and ultimately the formation of biogenic calcite.

6.6.5 Applicability of Geopolymers in Nuclear Waste Management – GeoP-NWM (Project 25)

Tarja Laitinen, **Eila Lehmus**, Tapio Vehmas, Markku Leivo, Kalle Loimula, Markus Olin, VTT

The goal of the project was to study applicability of geopolymer-based matrixes for solidification and encapsulation of low- and intermediate level nuclear waste. Studies were performed for three binder types: fly ash, iron blast furnace slag and metakaolin. Reference material in the studies was Portland cement, which is widely used material for solidification and encapsulation.

In industrial-level processes, some compatibility problems is observed between organic waste materials and Portland cement. Certain organic materials disturb natural hydration process of Portland cement. As a consequence, hydration retardation, even infinitely, has been observed. With Portland cement, solidification and encapsulation are mainly based physical encapsulation.

The studies were divided to three topics. First topic was literature surveys related to general properties of geopolymers and more specific on geopolymer application on nuclear deposition of low- and intermediate level nuclear waste. Second topic of the studies was an experimental research related to mix designs of various geopolymers. A method to formulate geopolymer mix design was created. Third topic was a study related to diffusion and dissolution of Cs-ion from the geopolymers. According to calculations, Cs is mainly responsible for radioactive ion-exchange resins activity during the first 300 years.

According to literature surveys, geopolymers and Portland cement are very different materials. Both are alkaline cements, which solidify under alkaline conditions. Both have also aluminium and silicon in the elemental composition. The biggest difference between Portland cements and geopolymers is the amount of calcium in the elemental composition. Portland cement contains a significant amount of calcium and the main reaction products are calcium-silicate-hydrates. In calcium-silicate-hydrate structure, short silicon chains are surround with calcium oxide layers. Main reaction product of geopolymers is three dimensional silicon/aluminium network. Due to nature of main reaction product, geopolymers are sometimes called polysialates which is a more accurate name compared to geopolymers.

Due to different main reaction products, also the strength determining process varies between geopolymers and Portland cement. Hardening process of Portland cement is a hydration process, where high temperature treated instable materials hydrate into hydration products. Hardening process of geopolymers is a nucleophilic addition process. In Nucleophilic addition process, electron defect silicates prefers to form a covalent bond between electron-rich aluminium. The process is a polymerization process, where the polymer -part in the geopolymer name originates. Because the main hardening mechanism are different, also the harmful factors to the processes differs. Hydration process is susceptible to organic

materials whereas geopolymerisation is susceptible to temperature and alkali content.

According to literature surveys, solidification and encapsulation of low- and intermediate level radioactive waste with geopolymers is an excellent option. Geopolymers tend to bind permanently most of the multivalent cations into the crystalline structure. It is also possible to remove water from geopolymers by heating, to avoid potential autoprotolysis of water. Geopolymers are also fireproof and for example, fly ash -based geopolymers tends harden in elevated temperatures.

Mix design of the geopolymers is a problematic part according to literature surveys. In the second step of the study, mix design of geopolymers was studied with the standard practices of concrete technology. Water demand of various binders were determined by producing a constant workability mortars. Workability of the mortars were determined with a standardized method. Water demand of blast furnace slag and fly ash was low, compared to water demand of metakaolin. According to results, implementation of standard practices of concrete technology was possible for fly ash and blast furnace slag -based geopolymers. Various methods to decrease the water demand of metakaolin was studied without success. Commercially available dispersants were not able to reduce water demand of metakaolin. Only applicable method to decrease the water demand of metakaolin-based mix design was to incorporate some of the silicates as alkali silicates into the mixture. Strength development of geopolymers were observed to originate from to factors: water/binder -ratio of the mix design and alkali content. The effect of water/binder -ratio and alkali content was presented as a 3D plane. Mix designs with 3D plane enable geopolymer proportioning to a constant strength by constant water/binder -ratio or constant alkali content.

At the third phase of the study, the effect of binder composition to Cs-ion diffusion and leaching were studied. On the basis of the developed mix design methodology, geopolymers-based mortars were manufactured using various binders. Distribution coefficient and diffusion coefficient between the mortars and ion-exchanged water was experimentally determined. Coefficients were determined by adding a known Cs content either to the mortar or to the ion-exchanged water. Hardened mortar samples were grind to particle size below 1mm. Ground mortar and water was shaken throughout the exposure time. After 14 day of exposure, samples were

filtered and Cs concentration of the solution phase determined with ICP. Diffusion and distribution coefficient were calculated from the results, assuming reversible Fick's diffusion between the sample and solution. Results are presented in Table 8.

According to results, metakaolin-based geopolymers had the best capability to bound Cs chemically. Worst capability was observed with Portland cement. Smallest relative diffusion coefficient was observed with blast furnace slag and the highest with metakaolin. Diffusion coefficient is depended on the physical properties of the mortar and could be adjusted by tuning mix design. In the studied mortars, the tightness was not optimized because high accuracy of the distribution coefficient was affiliated. Distribution coefficient is likely related only to chemical properties of the binding matrix. According to results, appropriately designed metakaolin based geopolymers is a good alternative for solidification and encapsulation if the process enables use of alkali silicates. Blending Portland cement with blast furnace slag and/or fly ash is an alternative to increase the Cs binding capacity of cement.

Table 8. Distribution coefficients and relative diffusion coefficients of the studied mortars.

Binder	Distribution coefficient	Relative diffusion coefficient
Portland cement	0,75	1
Blast furnace slag	0,58	0.2
Fly ash	0,24	1.7
Metakaolin	0,16	11.6

6.6.6 Risk assessment of radioactive waste: development of radioecological modelling for terrestrial and aquatic ecosystems – YRMA (Project 26)

Jukka Juutilainen, Jarkko Akkanen, Jouni Sorvari, Tiina Tuovinen, Soroush Majlesi, Jonne Naarala, University of Eastern Finland

1. Research topic and central results of the project

The general aim of the project was to produce improved radioecological modelling suitable for Finnish forest and aquatic ecosystems and its use for assessing possible risks of final disposal of nuclear waste. The objectives were

- to study transfer of radionuclides to such freshwater food chains key species, for which little previous data was available,
- to develop radioecological modes so that they are based on improved theoretical and empirical knowledge on transfer of elements into organisms,
- to develop methods for studying the effects of low radiation doses on organisms.

The sediment U concentrations of ponds located in our research area in Paukkajanvaara were about 500-fold and 90-fold higher than the concentrations found in a nearby reference pond. Considerable differences were found also in the concentrations of many other elements that are important for this study (elements having radionuclides with potential relevance to the risks of nuclear waste). The results fit with earlier results from terrestrial ecosystems, and indicate that transfer of elements into organisms is nonlinear also in aquatic ecosystems. This observation is important for the development of radioecological models. Another finding important for further studies was the observation that the concentration of uranium and many other elements was high in the organic sediments; for example, the concentration of U was about 105 fold higher in sediment than in water. This indicates that, contrary to the assumption generally used in radioecological models, organic sediment rather than water is the principal source of radionclides in the food chains of Finnish lakes and ponds (in which decaying organic matter is usually a more important source of matter and energy than photosynthesis). Studies on biologial effects with chironomid midge (Chironomidae) larvae did not support the hypothesis that fluctuating asymmetry is a particularly sensitive indicator of adverse effects: although

emergence of adults was delayed when larvae were grown in sediments from the research area, these sediments did not cause changes in wing symmetry.

2. The meaning of results vis-a-vis nuclear waste research, and connections with other research

Knowledge of the transfer of radionuclides from water to organisms is needed for the biosphere modelling done as a part of the safety case of final disposal of spent nuclear fuel. Data from Finnish environmental conditions and better radioecological modelling will improve the reliability of model predictions. Potential users of the results include licensees responsible for nuclear waste management, authorities, and all those who need biosphere modelling for assessing the possible risks of nuclear waste. The results can also be utilized in assessment of environmental risks of, e.g., prospecting of uranium ore, possible uranium mines and mines utilizing uranium-rich ores, and for development of radioecological models in general.

Previous KYT projects of the University of Eastern Finland focused on radioecology of terrestrial forest ecosystems. Open questions that remain after these projects (e.g., uptake of elements into key species of forest ecosystems, transfer of 14C from soil to biosphere) will be investigated in further studies with other funding (including funding from foundations). Experimental research with microcosms on effects on aquatic ecosystems has been conducted in the NKS-funded NORCO and NORCO2 projects, together with Stockholm University, Norwegian University of Life Sciences, Norwegian Radiation Protection Authority and the Finnish Radiation and Nuclear Safety Authority STUK. The first experiments, completed in November 2016, were done with external radiation. Further studies include investigations on the feasibility of experiments with radionuclides.

3. Methods

The research area was the Paukkajanvaara abandoned and restored uranium mine area in Eno. Samples of water, sediment, chironomid larvae (and other aquatic organisms that were found in the samples), and two fish species (roach and perch) were obtained from two ponds (Iso Hiislampi and Pieni Hiislampi) located in the study area and from a nearby reference pond. Element concentrations of the samples were determined by ICP-MS, and these concentrations were used for studying transfer of elements from water/sediment to organisms.

Biological effects were studied in laboratory by growing chironomid larvae in sediments from the three selected ponds. Developmental instability was assessed by measuring wing asymmetry of the emerged adult midges. Time to emergence of adults was studied as another indicator of adverse effects.

6.6.7 Alternative methods for biosphere modelling and their evaluation – VABIA (Project 27)

Tarmo Lipping, Jari Pohjola, Jari Turunen, Tampere University of Technology

Research topic and central results of the studies

The research focus of the VABIA project was to evaluate and simplify the compartments of the biosphere model that simulates radionuclide migration so that, for example, a certain compartment could be replaced either by a constant value or by being integrated into another compartment. Moreover, the overall impact of the radionuclides in the biosphere model should remain within the same order of magnitude compared to the more complex models. The biosphere model considered is a relatively simple and self-contained lake-farm model where the household water is taken directly from the lake (to avoid groundwater control parameters in the well). Household water is used for washing and as irrigation water for vegetables and berries, as well as for drinking water for animals.

The model considers the lake evolving at about 3000 AP near the Olkiluoto nuclear waste disposal district as a result of postglacial land uplift. The lake is called Liponjärvi after the nearby Liponsaari island. It is assumed that there is a leak in the radionuclide repository of 1 Bq / year. The leak passes through the groundwater streams into the lake from which the radionuclides ^{36}Cl, ^{135}Cs, ^{129}I, ^{237}Np, ^{90}Sr, ^{99}Tc and ^{238}U are transferred to the farm along with the household water. The 2015 model also included surface and middle sediments of the lake with which the lake water reacted from above. The people are assumed to catch fish from the lake in a self-sustaining farm scenario. Jari Pohjola, postdoctoral researcher, studied the uncertainty and fluctuation of the volume of the lake in his doctoral thesis in 2014, and this uncertainty was included in the study. The time span of the study was 3000-10000 AP, whereby saturation and possible long-term accumulation and equilibration are included in the assessment.

Input parameters to the model were generated using Monte Carlo simulation from averages and standard deviations of the distributions, as well as other statistical data, available in the literature. Consumption of food by humans was evaluated using the tables of Findiet 2012 research. As a result, sensitivity analysis was performed between the parameters affecting the model.

The most significant results from the 2015 survey were that the size of the lake had no effect on the radionuclide doses to humans. Instead, the outflow of the lake was much more significant compared to the volume of the lake. Also the K_d values, i.e., the distribution factors between the solid and liquid substances in the soil and the bottom sediment of the lake, played a significant role.

During 2016, the model was changed so that groundwater penetrated through sediments into lake water, and the ^{94}Nb radionuclide migrating into the air as dust was added to the model. Since the area of the future Lake Liponjärvi has been scanned by acoustic-seismic measurements by Posiva Oy to the base rock, these data could be used for the estimation of the distributions of the thicknesses.

The results showed that the bottom sediments dampened the radionuclide flow, partly also buffering the radionuclides before getting into the lake water. In the sensitivity analysis, it was found that the parameters of bottom sedimentation, such as the K_d values of different sediment layers, were most significant for most of the nuclides. For the ^{36}Cl and ^{99}Tc nuclides, which are less dependent on bottom sediments, the parameters relating to the absorption of irrigation water into the field soil and thus to the roots of the plants were in the greatest role.

The 2017 call was missed.

In the 2018 research, the sediment-farm model was expanded to include the nutrition portion of the forest, namely game, berries and mushrooms. The forest is assumed to be located next to Lake Liponjärvi and the radionuclides are transported to the overburden through sediments. The model takes into account, among other things, the shifting of radionuclides from soil to trees, decomposition of wood and leaves and the transfer of radionuclides to fungus. The Erica tool can be used to estimate the amount of radiation emitted by berries and game animals. Based on the results, the addition of the forest model appears to have the greatest

incremental effect on the amount of radiation received by humans for nuclides ^{36}Cl, ^{129}I and ^{237}Np. The increase in irradiation is the least for nuclides ^{90}Sr and ^{99}Tc.

The meaning of results vis-a-vis nuclear waste research, especially focusing on usability of results and connections with other research

Scenario-based VABIA study is part of the "Other Safety Studies" section that focuses on what happens if the worst-case scenarios are realized. The VABIA scenarios are implemented at 1Bq / year; as the considered models are linear, the model outputs can be scaled to correspond to different levels of contamination. Long-term (~ 10000 years) review is always risky as there are many uncertainties. For this reason, considering various scenarios using sensitivity analysis is the appropriate way to model future risks of the nuclear waste repository.

During the review period 2015-2018, cooperation opportunities were considered with professor Jukka Juutilainen (University of Eastern Finland). Professor Juutilainen's research topic, i.e., the transfer of radionuclides from organic surface of the pond bottom through the larvae to, for example, perches, would have been a good reference to the sediment model but it was abandoned due to lack of time.

Methods used in the studies

The starting point for the study was scenario-based sensitivity analysis. Uncertainties were utilized for all parameters for which they were available, i.e., for K_d values, food consumption by humans and bottom sediment thicknesses, for example. The uncertainty distributions were evaluated using Monte Carlo simulation for the compartment models created using Facilia's EcoLego modeling software. In connection with forest models, the K_d values were evaluated using the Norwegian Radiation Protection Authority's Erica tool.

In the sensitivity analysis, pre-screening was performed using the Morris method, which is part of the EcoLego Sensitivity analysis Toolkit. Subsequently, the results were analyzed by the Sobol method, and later on by the Fourier Amplitude Sensitivity Test (FAST), the Extended Fourier Amplitude Sensitivity Test (EFAST) and the Random Balance Design (RBD) methods.

The Mathworks Matlab tool was used to combine and visualize the results.

6.6.8 Mechanical Properties of Rock Joints – KARMO II-III (Projects 28-29)

Mikael Rinne, Lauri Uotinen, Enrique Caballero, Jukka Piironen, Veli-Antti Hakala, Juha Antikainen, Joni Sirkiä, Magdalena Dzugala, Aalto University, Civil Engineering

The goal of the KARMO research continuum (KARMO I 2014, KARMO II 2015–2016, KARMO III 2017–2018) was to produce a method for obtaining the mechanical parameters of rock joints using a laboratory scale test series. The research topic was the reduction of shear strength of rock joints with increasing scale. For materials, the research used Kuru grey granite rock slabs with a mechanically induced tensile rock joint. The joints were digitized using the photogrammetric method developed during the research project. The digitized rock joints were rescaled and 3D printed into plastic casting molds. Finally, mortar casted replica molds with size of 17 cm x 6 cm were cast to study the scale effect. In the later stages of the research project, large scale (2 m x 1 m and 0.50 m x 0.25 m) rock slab pair shear tests were carried out to study the validity of the research results at larger sample sizes. All surfaces were measured subjectively using profilometer and objectively using digital directional roughness. As result, the project developed a new nondestructive method to capture rock joint roughness, advanced the mechanical laboratory testing of large rock joints and produced a method to obtain mechanical properties of rock joints from digitized surfaces. The project produced three invention disclosures, leading to one patent application, one preparation of commercialization project (Fractuscan TUTL) and to one startup company.

Research Topic

The shear strength of rock joints depend on the testing scale (Figure 23). Laboratory samples are 50…200 mm long and the naturally occurring joints may be up to tens of meters long. Natural, undisturbed rock joints are expensive to test and the results are spatially poorly representative. The goal of KARMO was to develop a method how small scale laboratory tests can be used to derive the mechanical parameters of natural joints for numerical modelling. Modelling is used to estimate the displacement potential of rock joints in the repositories.

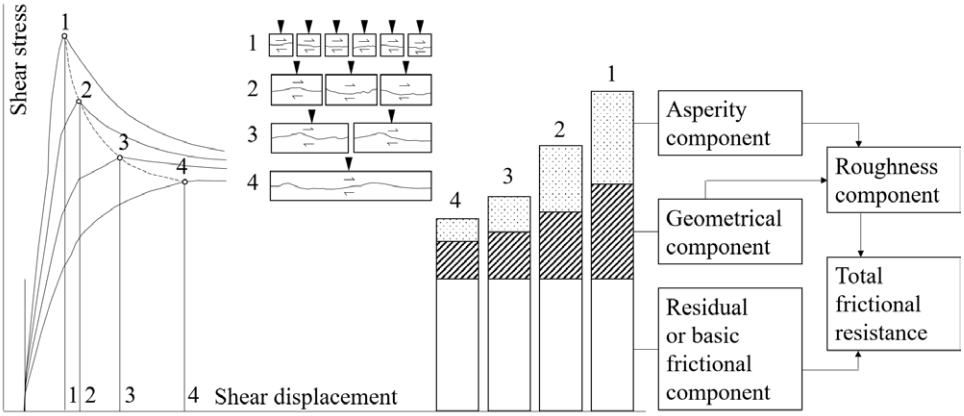

Figure 23. Scale (left) effect to shear strength (middle) three components (right) asperity, geometry and basic friction after Bandis et al. (1981).

Central results of the studies

Replication process development and validation task: In spring 2015, Laura Tolvanen executed an experimental bachelor's thesis to develop a self compacting mortar to replace the current commercial ready-mix product (Tolvanen 2015). The KARMO I method description was presented in the ISRM 2015 conference in Canada. The presentation attracted great international interest regarding the used 3D-printing materials and the achieved replication accuracy. Additionally, the usage of plastic materials as replica materials was discussed (Uotinen et al. 2015).

Photogrammetry development task: Bachelor thesis worker Pauliina Kallio photographed the casting molds of the replica series and the already tested replicas for photogrammetric measurements. The research allowed to increase the resolution and some discrepancy between the top and bottom molds were detected (Kallio 2015). Master's thesis worker Joni Sirkiä made digital roughness measurements and showed that some replicas retained the original geometry well. In most experiments too much geometry was lost during the process (Sirkiä 2015). In spring 2016, Joni Sirkiä did complementary research and established potential error sources for the method. The first publication compared the hand measured and digitally measured joint roughness and concluded the method to overestimate roughness (Iakovlev et al. 2016). In the second publication similar results were obtained and the digital method overestimated roughness by 2-3 JRC units (Sirkiä et al. 2016).

Modelling of continuous rock joint: In the spring 2016 in the Master's thesis by Magdalena Dzugala two fresh split granite slabs were obtained containing both halves of the fracture. The rock joints were scanned using the photogrammetric method developed in the course of the research. The samples were then tested by pull shear experiment and push shear experiment. (Dzugala 2016) The larger 2 m x 0.95 m slab experiment exhibited stick-slip phenomenon which did not occur in the small 0.50 m x 0.25 m slab push shear experiment. Therefore, the large 2 m x 1 m slab test was executed again as push shear test in February 2018 and the medium scale slab was executed again 0.50 m x 0.25 m in October 2018. The new test pair allows scale effect research using numerical modelling (Kivivirta 2017). For the earlier slab tests, the result comparison is shown in the doctoral dissertation *Prediction of stress-driven rock mass damage in spent nuclear fuel repositories in hard crystalline rock and in deep underground mines* (Uotinen 2018).

Significance and utilization of the results

The photogrammetric method developed in KARMO can be used as a non-destructive method to document the mechanical properties of rock joints and to predict the mechanical properties of long rock joints. The predicted properties may be entered into software modelling large volume behavior to improve the accuracy of the predictions. One important utilization field is the fluid transmissivity of rock mass, where the method can be utilized to predict rock joint transmissivity and storativity. The project produced three invention disclosures, leading to one patent application, one preparation of commercialization project (Fractuscan TUTL) and to one startup company, which aims to use the method in stability analysis for open pit mines.

The usage of this photogrammetric method to create online virtual learning environments was successfully tested in 2018 using the underground training tunnel of Aalto University. Based on the pilot experiment the MIEDU pilot (Mining Education and Virtual Underground Rock Laboratory) and KAVI pilot (Rock quality visualization in underground rock construction) were launched. Based on the initial results, the method is also suitable for the professional development in nuclear waste management and a training pilot is suggested in 2019.

Research group

Prof. Mikael Rinne (Rock Mechanics, Aalto University) acted as the Project Owner. Postdoctoral researcher Lauri Uotinen acted as the Project Manager and the Research Team Leader and carried out the analyses of the results and acted as the main author in the scientific publications and as the main instructor of the academic theses. Alireza Baghbanan participated in the writing of the scientific publications. The research project was academic theses based and as thesis workers or research aids worked Eero Korpi, Joni Sirkiä, Magdalena Dzugala, Martyna Szydlowska, Enrique Caballero, Raphaël Yorke, Antoni Kopaly, Daniil Iakovlev, Pauliina Kallio, Laura Tolvanen, Sivi Kivivirta and Henri Munukka. As laboratory staff worked Veli-Antti Hakala, Otto Hedström, Jukka Piironen, Pertti Alho and Janne Hostikka.

6.6.9 Fracture simulator which respects the measured fracture length and orientation distributions – ROSA (Project 30)

Eevaliisa Laine, Mira Markovaara-Koivisto, Geological Survey of Finland

The research was done at the Bedrock construction and site investigation unit of the Geological Survey of Finland. The project was divided into four work packages:

WP 1: Fracture simulation using R programming language

In this work package, a new fracture network simulator was created with R programming language. The simulator creates discrete fractures into a defined 3D space using statistical distributions. Input data can be in the form of scanline measurements, drill core logging or outcrop mapping. The simulator consists of several scripts which guide the user to provide input data, tests automatically which of several different type of distributions would fit the best to the input data and chooses the best fit. Distributions are fit to the azimuth, dip, fracture length and surface property data. Centre points of the simulated fractures are defined randomly within the simulation space and the corner points of the rectangular fracture surfaces are calculated based on the fracture orientation and length data. Number of fractures within the simulation space is calculated from their perpendicular fracture frequency and fracture lengths or a fracture number defined by the user. The scripts print into the working directory a text file which contains one fracture per row including its orientation, length, coordinates of the corner

points and surface properties. Age relations of the different fracture sets are taken into account by cutting the younger fractures with the older ones. Cutting the fractures is carried out with Octave, which can cut the fractures accurately and produce cut fractures with 4-5 corner points. The produced discrete fractures can be imported as text files into other modelling programs for further utilization.

WP 2: Spatial fracture distribution and validation of the fracture networks

In the second work package the geological and geomechanical validation of fracture networks were studied. The used software were Julia scripts, ISATIS, GOCAD and FEMDEM. Fracture networks for Kopparnäs and Palmottu study sites were built using these software and the codes developed within the ROSA project.

WP 3: Summer practicant

Summer practicant Riikka Valtonen (University of Helsinki) tested R codes and participated into the field work at Kopparnäs study site during summers 2017 and 2018, in addition to the other fracture related tasks at GTK.

WP 4: 3D-visualization

In the fourth work package, Julia and R scripts were built in order to write point and polygon vtk files for Paraview visualization software.

The ROSA codes and scripts make it possible to build fracture networks by using free software. Using Julia and R scripts helps also to understand the theoretical background of the whole fracture modelling process because all the calculations and operations appear on the screen. In addition, Palmottu and Kopparnäs fracture studies, linear and circular scanline observations and their interpretations gave additional information about the fracturing of the Finnish bedrock, which is useful for nuclear waste studies and, in general, for bedrock engineering in southern Finland.

6.7 Nuclear Waste Management and Society

6.7.1 Governing Safety in Finnish and Swedish Nuclear Waste Regimes – SAFER (Project 31)

Matti Kojo, Markku Lehtonen, Mika Kari, Tuija Jartti, Tuuli Vilhunen, Anna-Riikka Aarnio, Anna Oksa, University of Tampere

(1) The role of Civil Society Organisations in the licensing

This subtask explored citizen participation in the Swedish and Finnish regulatory processes for final disposal of spent nuclear fuel, applying a civil regulation perspective. The analysis targeted institutional waste management frameworks, focusing on the role of civil society organizations (CSO) in these countries, considered as frontrunners in final disposal of spent nuclear fuel. Data consisted of the official documents of the waste management companies and safety authorities, as well as, information from civil society organizations and laypeople were reviewed. The analysis concluded that there is no unified Nordic model for SNF disposal, but civil regulation differs between the two countries. Civil regulation was better established in Sweden, where the design of institutional arrangements is more complex and more open to civil society actors, and where nuclear power generates greater controversy than in Finland. As a result, the Swedish civil regulation resembled more closely a liberal approach, whereas in Finland CSOs were predominantly forced to operate outside the rather technocratic regulatory processes. The study produced information regarding the state of civil regulation in Finland, to support future decision-making. Civil regulation can provide a useful contribution to the activities of the regulated entities, to practices and management of regulatory agencies, and to meta-regulation, which governs the entire regulatory setting.

(2) Debate on the licensing procedures in print media

In this subtask, similarities and differences in media attention to the licensing of the final disposal of spent nuclear fuel in the Finnish and Swedish print media were compared in the period 2008–2015. A longitudinal approach, combined with a content analysis, formed the basis for the analysis of topics, tones of argumentation, and speakers appearing in *Helsingin Sanomat, Aamulehti*, *Dagens Nyheter* and *Svenska Dagbladet*. The main finding of our comparative study is that in terms

of speakers, the Swedish nuclear waste regime gave rise to more multifaceted discussion in the print media than the Finnish regime. Diversity of speakers in public debate can be seen as an advantage for robust political decision-making on a controversial technology project. Particularly interesting are the differences in the roles and visibility of experts and NGOs as speakers between these countries. In Sweden, the above-mentioned actor groups attracted media attention more frequently than in Finland. These findings indicate that the societal pressure from actors critical of nuclear power and geological disposal is weaker in the Finnish pro-nuclear policy context, and helps in part to understand the smooth progress of the final disposal project in the Finnish licensing process. In Sweden, by contrast, media attention seems to amplify critical handling of the final disposal issue.

(3) The ethical issues related to final disposal of SNF in print media

The objective of the subtask was to compare the Finnish and Swedish print media discussions on final disposal of SNF from a justice perspective. Drawing on existing literature, the study developed a classification system, which was used in content analysis of the media items (i.e. news and letters to the editor). This longitudinal study covers the period from 2008 to 2015. Data was collected from four of the leading newspapers in Sweden and Finland: *Dagens Nyheter, Svenska Dagbladet, Helsingin Sanomat* and *Aamulehti*. Analysis revealed that attention to justice issues fluctuated with events of the licensing process, and even with related processes bringing attention to disposal issues outside of the formal licensing process. Thematically, distributive and procedural justice were the most frequent categories in news items, where the industry was setting the agenda, stressing safety, knowledge issues and process issues. Issues related to intergenerational justice were raised by the public through letters to the editor particularly in Finland. We argue that ethical considerations regarding nuclear waste management should not rest on experts only, and it is unrealistic to assume that industry addresses, and technical specialists represent, sufficiently the values of a society, without a wider societal debate on ethical issues related to final disposal of spent nuclear fuel.

(4) Ethical aspects of final disposal at the host community level: Resident survey in Pyhäjoki and Eurajoki

The aim of the subtask was to investigate how residents of two Finnish 'nuclear communities' perceive ethical issues related to the second SNF repository in Finland

that the power company Fennovoima may have to implement. The data (N= 454) was gathered in Pyhäjoki and Eurajoki (incl. Luvia) via a telephone survey. In Pyhäjoki, the survey was conducted between 30 December 2016 and 6 January 2017 and in Eurajoki between 29 November 2016 and 5 January 2017. The study revealed that citizens emphasised perceived procedural justice and distrust in Eurajoki, while in Pyhäjoki concerns for intragenerational distributive injustice had greater priority. Surprisingly, intergenerational justice was perceived similarly in both communities, suggesting that no particular understanding towards future generations had developed over the decades despite all the information dissemination efforts undertaken in Eurajoki. Moreover, the fact that the municipality had previous experience of SNF management did not enhance local acceptance of the second repository in Eurajoki. We claim that these Finnish nuclear communities perceive concerns over environmental, political and social injustice regarding the Fennovoima SNF repository siting. We argue that the community's wishes should be considered earlier in the planning of an extension to support a fair siting process and to avoid perceptions of injustice and mistrust.

(5) Social license to operate (SLO) in nuclear waste management

This subtask examined the usefulness of the emerging concept of social license to operate (SLO) for nuclear waste management (NWM) in Finland, France and Sweden. The research was based in the first hand on a survey of existing literature on SLO and community benefits especially in nuclear waste area. We also draw on earlier SLO work conducted by some of the authors, primarily in the mining sector, and on research carried out by all authors on various aspects nuclear waste management and nuclear energy. None of the three examined countries has explicitly applied the concept of SLO in their NWM policy.

However, the term can usefully be applied to understanding the conditions of success in the three cases. While the French project has struggled to reach even the lowest levels of SLO, the two Nordic projects have clearly reached "institutionalised trust", described in the applied SLO framework as the indicator of the highest level of SLO. In consequence, also the community benefit schemes have diversely received in the three countries: in France, benefits are largely seen as measure designed to ensure local acceptance and ensure SLO, and as such often described as 'bribery', albeit a justified one, especially according to many local actors. In Finland and Sweden, accusations of 'bribery' have been few and far

between. Especially the comparison between the Finnish and Swedish cases draws attention to the potential dangers of "overtrust", and possible virtues of mistrust as a foundation of constructive "civic vigilance". In doing so, our research calls for further refinement of the SLO framework to accommodate the multiple dimensions of trust as well as the potential positive functions of mistrust and distrust. Further work on SLO and nuclear waste management should also give greater attention to the country-specific background conditions. These include the nature of the host community as a 'nuclear community' (Finland and Sweden) or an area without earlier experience of nuclear industry (France); and citizens' trust in public and private institutions, including what we call 'ideological trust' in broader meta-institutions of society, such as state, market, community, and distinct models of democracy. For example, in the French state-centred political culture, the Nordic-style locally negotiated benefit schemes would have been considered illegitimate. To render the conceptual framework of SLO useful for NWM, the framework should accommodate two issues in particular: 1) the relationships between SLO and the legal licence, and 2) the interaction between local-level dynamics and national-level policy and licencing processes.

(6) Host municipality approaches to final disposal of SNF in Eurajoki and Östhammar

The objective of the task was to compare host municipality approaches to final disposal of SNF in Eurajoki and Östhammar. Comparative case study was used as the research method. Data consisted of the documents (minutes and memos) produced by groups established in the municipalities to oversee issues related to the site selection and repository design/planning. The results indicate that the approaches adopted in Eurajoki and Östhammar differ greatly from each other. In Sweden, the municipality of Östhammar has adopted the role of a 'stretching partner' that creates a demanding environment for the implementer and the authorities, by challenging policies and actions, and actively seeking to engage public and local actors in the planning of the project. In the Finnish Eurajoki, the municipality has taken the role of a 'mostly silent partner' that holds a high level of trust in safety authorities and primarily tends to its economic interests. The study provides useful information for choices concerning the further development of the relationship between the host municipality and the nuclear waste regime. It also helps to critically re-examine current interaction activities in the host municipalities.

6.8 Nuclear waste management infrastructure projects

6.8.1 Radiological Laboratory Commissioning – RADLAB (Project 32)

Wade Karlsen, Seppo Tähtinen, Kimmo Rämö, Ilkka Palosuo, Mika Jokipii, Tommi Kekki, Petri Hakulinen, Jarmo Siivinen, Tuomo Lyytikäinen, Risto Pitkäinen, Aku Itälä, Pekka Moilanen, Marko Paasila, Anumaija Leskinen, Emmi Myllykylä, Tiina Heikola, Tiina Lavonen, Jari Lydman, Marke Mattila, Johanna Lukin, Jaana Rantanen, Joonas Järvinen, Kirsti Helosuo, Jori Helin, Merja Tanhua-Tyrkkö, Pasi Väisänen, Unto Tapper, Aki Toivonen, VTT

The safe research and testing of radioactive and contaminated materials of the nuclear sector requires radiological facilities, and for highly radioactive materials, full hot cells for remotely handling the materials inside of heavy gamma shielding. The objective of the RADLAB project (REHOT in 2015), was to plan and execute the hot cell and hot laboratory portion of the radiological research infrastructure renewal, including the planning and making of critical equipment investments for the facility, and training of the technical personnel that will be staffing the facility, carried out in tandem with the completion and commissioning of the new VTT Centre for Nuclear Safety (CNS). During the KYT/SAFIR 2018 programs the infrastructure renewal has been funded jointly by both KYT and SAFIR, reflecting the fact that the renewed infrastructure supports research activities for both safe waste management solutions and safe operation of nuclear power plants.

The design and construction of the hot laboratory facility involved defining and guiding the technical aspects of the hot laboratory portion of the new building in tandem with the engineering design of the CNS. In 2015 the construction of the VTT CNS building climaxed, requiring finalization of the smallest details of the systems, fixtures and furnishings, while preparing for moving into the new office wing. In 2016 the construction of the VTT CNS concluded, and so the move-in of equipment commenced and the application submitted for radiological commissioning of the laboratory. In tandem to this work the engineering design of the hot cells and their subsequent fabrication and installation was carried out as a subcontract with Isotope Technologies Dresden, GmbH (ITD). Installation of the hot cells was completed in 2017, including incorporation of VTT's large equipment. The hot cell operators were then trained by ITD, and STUK granted approval for

operation of the hot cells in 2018, as an expansion of the operating licence that was granted for the other laboratories in early 2017.

In parallel with the hot cell design and construction, nuclearization and remote operation methods of in-cell devices were developed, building skills important for effective utilization of the new infrastructure. This was done by utilizing 3-D models of key in-cell devices to model their remote operation (manipulator reach, window visibility, etc.). Efforts included an assessment of the applicability of semi-automatic robotic manipulation, and included an extended visit by a hot cell engineer to the Paul Scherrer Institute (PSI) in Switzerland to learn hot cell skills. Particular efforts were also made to assess robotic versus conventional CNC remote machining operations for opening reactor pressure vessel surveillance capsules, to evaluate different semi-automatic dimensioning microscope candidates, and to compare candidates for semi-automatic in-cell fracture toughness specimen pre-fatiguing equipment.

Procurement of research equipment for installation in the hot facilities is an important area of effort in the infrastructure renewal. The purchase cost of each piece of equipment supported by the investment aid mechanism was financed through the complementary RADINFRA project. The new devices all provide the capability to test the mechanical performance of all kinds of radioactive structural materials, or to characterize the materials compositionally and microstructurally. In that manner the safe performance of structural materials of operating power plants and nuclear waste management systems can be comprehensively evaluated, and models of material performance can be informed and validated. Over the course of the program, detailed reports of the devices and their capabilities were written, and can be referred to for more information.

Over the four year program period, the following equipment were procured for installation inside the hot cells: a semi-automatic hardness testing device, an instrumented impact test hammer with semi-automatic specimen feeding, an universal mechanical testing system (UTS) with an environmental chamber, a hot-cell-ready pre-fatigue device, a multi-axial CNC milling machine, a semi-automatic optical and contact precision dimensioning device, metallographic specimen preparation devices, and a light optical microscope. Also purchased, but for installation in the laboratory with only local shielding, was a large instrumented impact test hammer with semi-automatic specimen feeding. Procured for

installation directly in the new building as the laboratory wing was completed, were the radiation monitoring systems for the CNS, machines for the mechanical support workshop, and an analytical scanning electron microscope (SEM). With the laboratories completed, several more new devices were purchased for upgrading the radiochemistry and nuclear waste management research capabilities. These included a triaxial compression mechanical testing device for bentonite, a liquid scintillation counter, an inductionally-coupled plasma (ICP) optical emission spectrometer (OES), an alpha spectrometer, a high-efficiency specimen digester, and a high-resolution aerosol counter.

Some research and testing devices are not readily available on the market, but rather, require custom design. Development and construction of those research devices was carried out with the experts involved in utilizing the equipment for producing research results, and were then fabricated by in-house assembly of parts bought from component suppliers, or made by in-house or outside workshops. During the four-year program this included the design and fabrication of a new hot autoclave and water circuit for testing materials in reactor water conditions. The design of localized shielding for some large mechanical testing devices was also carried out, and a prototype was fabricated. At the same time, device nuclearization needs were identified and solved for equipment installation into the hot cells, including modifications to the electron beam welder and electric-discharge machining device. Both devices are essential for cutting and joining of a wide range of metallic materials for fabricating test specimens. Finally, starting from 2018, renewal was begun on the specially-designed iodine filter testing set-up, which facilitates evaluating the efficacy of the radioactive gas filtering systems of the containment exhaust stacks of operating plants.

The VTT CNS requires a number of supporting facilities for its research and testing operations. During the program facilities were develop for three main areas: laboratory radioactive waste handling, radioactive research material logistics, and orderly storage of radioactive specimens. These systems are located in the basement of the CNS. Dry waste is mainly in the form of contaminated trash or unusable metal piece, so in both cases the materials are sorted according to owner, packed into containers for interim storage, and regularly returned to the owner for subsequent handling. For sorting and short-term interim storage on-site, an area in the basement has been walled off and equipped with a remotely-operable crane with a specially-designed barrel grasper for 200l waste barrels.

For dealing with liquid and wet waste, a dedicated glove box was designed and fabricated on a contract with Platom Oy for evaporation of large quantities of volatiles, cementation/bituminization for sludges, or ion exchange resin filtering for contaminated liquids. For orderly storage of radioactive research materials, a special shielded matrix of alphanumerically organized storage boxes was designed and built on a contract with ITD. To maintain a record of material inventory, a dedicated database software named Pergament was designed and realized on a subcontract. The system includes the possibility to link all electronic data affiliated with a specific samples, including associating it with any daughter specimens that may be produced as a part of specimen reconstitution.

At the conclusion of 2018 it can be said that most aspects of the new laboratories and hot cell facilities are now operational, offering a wide portfolio of research devices. In-cell equipment is available for preparing various kinds of specimens from radioactive materials. An array of mechanical testing devices enable determining the fracture toughness, impact energy, tensile properties and hardness of materials. A portfolio of light optical and analytical electron microscopes enable examination of materials and their microstructures and compositional distributions from macro through nanoscale resolutions. A variety of spectrometers make it possible to analyze alpha, beta and gamma emissions from radionuclides and also atomic/isotopic compositions over a wide elemental range, down to very low concentrations. Such a diverse portfolio of modern research devices are essential for a broad range of applications in support of safe nuclear waste management and safe operation of nuclear power plants. Already during the last two years of the 2018 program, several SAFIR and KYT projects have carried out experimental research utilizing the new laboratories, including THELMA and BRUTE studying the structural performance of nuclear power plant materials, CAFIS studying the chemistry and transport of fission products, HIILI-14 focused on C-14 release from metallic decommissioning waste, and THEBES, studying the behavior of swelling clay barriers for nuclear waste management.

Appendix 1 KYT2018 research projects 2015–2018

	Time	Project	Organisation[25]
Technologies in nuclear waste management			
1	2015–2018	Advanced Fuel Cycles – New adjustable separation materials (SERMAT)	HYRL
2	2015–2018	Advanced Fuel Cycles – Scenario and Inventory Analysis (KOSKI)	VTT
3	2018	Measurement methods for hard to measure radionuclides (VAMMA)	VTT
Safety case			
4	2015–2018	TURMET[26] – Systematization of the Safety Case Methodology part 1	VTT
5	2015–2018	TURMET – Systematization of the Safety Case Methodology part 2	Aalto
Buffer and backfill performance			
6	2015–2018	THEBES[27] – THMC Behaviour of the Swelling Clay Barriers	Aalto
7	2015–2018	THEBES – THMC Behaviour of the Swelling Clay Barriers	VTT
8	2015–2018	THEBES – THMC Behaviour of the Swelling Clay Barriers), X-ray tomography and modelling	JYFL
9	2015–2018	THEBES – THMC Behaviour of the Swelling Clay Barriers	Numerola
10	2015–2018	Bentonite erosion and radionuclide interaction processes (BENTO)	HYRL
11	2015–2018	Bentonite swelling pressure (UEFBENT)	UEF
Canister performance			
12	2015–2018	KAPSELI[28] – Experimentally verified model based predictions for the integrity of the copper overpack (PRECO)	VTT
13	2015–2018	KAPSELI – Mechanical strength of copper canister (MECHACOP)	Aalto
14	2015–2018	KAPSELI – The effect of reaction product layers on copper corrosion in repository conditions (REPCOR)	Aalto
15	2015–2018	KAPSELI – The effect of microbial activity on corrosion of copper in anoxic state of repository (BASUCA)	VTT
16	2015–2018	KAPSELI – Microbially induced corrosion during the oxic stage of repository (MICOR)	VTT

[25] Aalto = Aalto University, GTK = Geological Survey of Finland, HYRL = University of Helsinki, Unit of Radiochemistry, JYFL = University of Jyväskylä, Department of Physics, Numerola = Numerola Oy, TTY = Tampere University of Technology, TY = University of Tampere, UEF = University of Eastern Finland, VTT = VTT Technical Research Centre of Finland Ltd

[26] Coordinated project TURMET

[27] Coordinated project THEBES

[28] Coordinated project KAPSELI

Microbiological effects			
17	2015–2018	MILORI[29] – Microbiology related to geological disposal of low- and intermediate level waste (MAKERI)	VTT
18	2015–2018	MILORI – Microbially induced corrosion of low and intermediate level radioactive waste (CORLINE)	VTT
19	2015–2018	MILORI – Microbial sulphur cycle in final nuclear waste repository conditions (GEOBIOKIERTO)	VTT
20	2015–2018	Nutrients, energy and gases in bedrock biosphere (RENGAS)	GTK
Other safety studies			
21	2015–2018	Behaviour of radionuclides in the geosphere; in situ studies (RAKU)	HYRL
22	2015–2018	Release of C-14 from metallic waste (HIILI-14)	VTT
23	2015–2017	Modelling fracture flow, matrix diffusion and sorption using the lattice-Boltzmann method (JYFLKYT)	JYFL
24	2015–2018	Chemical forms and sorption of radiocarbon in geosphere (C14ROCK)	HYRL
25	2015–2017	Applicability of Geopolymers in Nuclear Waste Management (GeoP-NWM)	VTT
26	2015–2018	Risk assessment of radioactive waste: development of radioecological modelling for terrestrial and aquatic ecosystems (YRMA)	UEF
27	2015–2016, 2018	Alternative methods for biosphere modelling and their evaluation (VABIA)	TTY
28	2015–2016	Mechanical Properties of Rock Joints (KARMO II)	Aalto
29	2017–2018	Mechanical Properties of Rock Joints (KARMO III)	Aalto
30	2015–2018	Fracture simulator which respects the measured fracture length and orientation distributions (ROSA)	GTK
Nuclear waste management and society			
31	2015–2018	Governing Safety in Finnish and Swedish Nuclear Waste Regimes (SAFER)	TY
Nuclear waste management infrastructure projects			
32	2016–2018	Radiological Laboratory Commissioning (RADLAB)	VTT

[29] Coordinated project MILORI

Appendix 2
KYT2018 Publications and academic theses 2015–2018

Articles in peer reviewed journals[30]

Aaltonen, P., Yagodzinskyy, Y., Saukkonen, T., Kilpeläinen, S., Tuomisto, F., & Hänninen, H. 2015. Role of excessive vacancies in transgranular stress corrosion cracking of pure copper. Corrosion Reviews, 33(2015)6, 487-500. Article available online: https://doi.org/10.1515/corrrev-2015-0047.

Abed, A.A. & Sołowski, W.T. 2017. A study on how to couple thermo-hydro-mechanical behaviour of unsaturated soils: Physical equations, numerical implementation and examples Computers and Geotechnics, vol. 92, pp. 132-155. https://doi.org/10.1016/j.compgeo.2017.07.021.

Abed, A.A. & Sołowski, W.T. 2019. Applications of a New THMC Coupled Code "Thebes". Published in Environmental Geotechnics 1.3.2019. https://doi.org/10.1680/jenge.18.00083.

Akinwunmi, B., Sun, L., Hirvi, J.T., Kasa, S. & Pakkanen, T.A. 2019. Influence of temperature on the swelling pressure of bentonite clay, Chem. Phys 516 (2019) 177.

Bomberg, M., Lamminmäki, T. & Itävaara, M. 2015. Estimation of microbial metabolism and co-occurrence patterns in fracture groundwaters of deep crystalline bedrock at Olkiluoto, Finland –Biogeosciences Discuss., 12, 13819-13857, 2015.

Bomberg, M., Raulio, M., Jylhä, S., Mueller, C. W., Höschen, C., Rajala, P., Purkamo, L., Kietäväinen, R., Ahonen, L. & Itävaara, M. 2017. CO_2 and carbonate as substrate for the activation of the microbial community in 180 m deep bedrock fracture fluid of Outokumpu Deep Drill Hole, Finland. AIMS Microbiology, 2017, 3(4): 846-871.

[30] Classification of publications to different categories (Articles in peer reviewed journals, Conference papers and working reports, and Academic theses) according to project managers.

Carpén, L., Rajala, P. & Bomberg, M. 2015. Microbially Induced Corrosion in Deep Bedrock. Advanced Materials Research Vol. 1130 (2015) pp 75-78.

Carpén, L., Rajala, P. & Bomberg, M. 2018. Corrosion of copper in anoxic ground water in the presence of SRB. Corrosion Science and Technology, 17 2018(4), 147-153.

Dzugala, M., Sirkiä, J., Uotinen, L. & Rinne, M. 2017. Pull Experiment to Validate Photogrammetrically Predicted Friction Angle of Rock Discontinuities. In Symposium of the International Society for Rock Mechanics (pp. 378-385). (Procedia engineering; Vol. 191). Elsevier. Procedia Engineering, https://doi.org/10.1016/j.proeng.2017.05.194.

Elo, O., Müller, K., Ikeda-Ohno, A., Bok, F., Scheinost, A. C., Hölttä, P. & Huittinen, N. 2017. Batch sorption and spectroscopic speciation studies of neptunium uptake by montmorillonite and corundum. Geochimica and Cosmochimica Acta 198 (2017) 168-181.

Elo, O., Hölttä, P., Kekäläinen, P., Voutilainen, M. & Huittinen, N. 2019. Neptunium(V) transport in granitic rock: A laboratory scale study on the influence of bentonite colloids, Applied Geochemistry 103, 2019, 31-39.

Forsström, A., Luumi, L., Bossuyt, S. & Hänninen, H. 2017. Localisation of plastic deformation in friction stir and electron beam copper welds, Materials Science and Technology, (2017) Article available online: http://dx.doi.org/10.1080/02670836.2016.1243337.

Harjupatana, T., Alaraudanjoki, J. & Kataja, M. 2015. X-ray tomographic method for measuring three-dimensional deformation and water content distribution in swelling clays. Appl. Clay Sci. 114, 386-394.

Huttunen-Saarivirta, E., Ghanbari, E., Mao, F., Rajala, P., Carpen, L. & Macdonald, D.D. 2018. Kinetic properties of the passive film on copper in the presence of Sulfate-Reducing Bacteria. Journal of The Electrochemical Society, J. Electrochem. Soc. 165(9): C450-C460.

Huttunen-Saarivirta, E., Rajala, P. & Carpén, L. 2016. Corrosion behaviour of copper under biotic and abiotic conditions in anoxic ground water: electrochemical study. Electrochimica Acta, Vol. 203, pp. 350-365.

Huttunen-Saarivirta, E., Rajala, P., Bomberg, M. & Carpén, L. 2017. Corrosion of copper in oxygen-deficient groundwater with and without deep bedrock micro-organisms: characterisation of microbial communities and surface processes, Applied Surface Science, 396: 1044-1057.

Huttunen-Saarivirta, E., Rajala, P., Bomberg, M. & Carpén, L. 2017. EIS study on aerobic corrosion of copper in ground water: influence of micro-organisms. Electrochimica Acta 240: 163–174.

Huttunen-Saarivirta, E., Rajala, P., Bomberg, M. & Carpén, L. 2017. Laboratory study of interactions between copper and the micro-organisms in oxic ground water environment. Environmental Geotechnics. In Press.

Huttunen-Saarivirta, E., Rajala, P., Bomberg, M. & Carpén, L. 2018. Copper micro-organism interactions in oxic groundwater. Environmental Geotechnics, Accepted – in press 2018.

Ikonen, J., Sardini, P., Siitari-Kauppi, M. & Martin, A. 2017. In situ migration of tritiated water and iodine in Grimsel granodiorite, part II: assessment of the diffusion coefficients by TDD modelling, J Radioanal Nucl Chem 2017, 311, 339-348.

Ikonen, J., Voutilainen, M., Söderlund, M., Jokelainen, L., Siitari-Kauppi, M. & Martin, A. 2016b. Sorption and diffusion of selenium oxyanions in granitic rocks. Journal of Contaminant Hydrology 192 203–211.

Ikonen, J., Sardini, P., Siitari-Kauppi, M., Martin, A. & Eichenberg, J. 2016a. The tritiated water and iodine migration in situ in Grimsel granodiorite. Part I: determination of the diffusion profiles. J Radioanal Nucl Chem, 310, pages 1041-1048.

Itävaara, M., Salavirta, H., Marjamaa, K. & Ruskeeniemi, T. 2016. Geomicrobiology and metagenomics of terrestrial deep subsurface microbiomes. In: Sariaslani, S. & Gadd, G.M. (eds.), Advances in applied microbiology. Elsevier. 94:1-77. https://doi.org/10.1016/bs.aambs.2015.12.001.

Järvinen, J., Matusewicz, M. & Itälä, A. 2016. Methodology for studying the composition of non-interlamellar pore water in compacted bentonite. Clay Minerals Vol 51:2, pp. 173-187.

Kietäväinen, R., Ahonen, L., Niinikoski, P., Nykänen, H. & Kukkonen, I.T. 2017. Abiotic and biotic controls on methane formation down to 2.5 km depth within the Precambrian Fennoscandian Shield. Geochimica et Cosmochimica Acta 202, 124-145.

Kietäväinen, R. & Purkamo, L. 2015. The origin, source and cycling of methane in deep crystalline rock biosphere. Frontiers in Microbiology 6, 725.

Kinnunen, P., Bomberg, M., Rajala, P. & Carpén, L. 2015. Industrial Views to Microbe-Metal Interactions in Sub-Arctic Conditions. 2015. Advanced Materials Research Vol. 1130 (2015) pp 114-117.

Kutvonen, H., Rajala, P. Carpén, L. & Bomberg, M. 2015. Nitrate and ammonia as nitrogen sources for deep subsurface microorganisms. Frontiers in Microbiology. Frontiers Research Foundation, vol. 6, pp. 1079.

Kuva, J., Hellmuth, K.-H., Sardini, P. & Siitari-Kauppi, M. 2015. Verification of a simulation approach for estimating crack aperture using 14C-PMMA method J. Coupled Syst. Multiscale Dyn. 3 (4): 333-340 (2015).

Lavikainen, L.P., Hirvi, J.T., Kasa, S. & Pakkanen, T.A. 2016. Interaction of octahedral Mg(II) and tetrahedral Al(III) substitutions in aluminum-rich dioctahedral smectites, Theor. Chem. Acc. 135 (2016) 85.

Lehtonen, M., Kojo, M. & Litmanen, T. 2017. The Finnish success story in the governance of a megaproject: the (minimal) role of socioeconomic evaluation in the final disposal of spent nuclear fuel. In: Lehtonen, M., Joly, P.-B. & Aparicio, L. (Eds.) Socioeconomic Evaluation of Megaprojects. Dealing with uncertainties. Routledge. p. 83–110.

Lempinen, J. & Lehto, J. 2016. Rate of Radiocarbon Retention onto Calcite by Isotope Exchange, Radiochimica Acta 104, 2016, 663–671.

Lempinen, J., Muuri, E., Lusa, M. & Lehto, J. 2018. Sorption of inorganic radiocarbon on iron oxides, Journal of Radioanalytical and Nuclear Chemistry 316(2)(2018)717-723.

Litmanen, T., Kari, M., Kojo, M., & Solomon, B. 2017. Is There a Nordic Model of Final Disposal of Spent Nuclear Fuel? Governance Insights from Finland and Sweden. Energy Research & Social Science. Vol. 25, pages 19–30, http://dx.doi.org/10.1016/j.erss.2016.10.009.

Litmanen, T., Kojo, M., Kari, M., & Vesalainen, J. 2017. Does technical risk dialogue entail socioeconomic valuation? The case of scientific dispute over copper corrosion in a spent nuclear fuel disposal project. In: Lehtonen, M., Joly, P.-B. & Aparicio, L. (Eds.) Socioeconomic Evaluation of Megaprojects. Dealing with uncertainties. Routledge. p. 134–158.

Lousada, C., Soroka, I., Yagodzinskyy, Y., Tarakina, N., Todoshcenko, O., Hänninen, H., Korzhaviy, P. & Jonsson, M. 2016. Gamma radiation induces hydrogen absorption by copper in water. Scientific Reports 6, Article number: 24234 (2016), 8 p.

Marja-Aho, M., Rajala, P., Huttunen-Saarivirta, E., Legat, A., Kranjc, A., Kosec, T. & Carpén, L. 2018. Copper corrosion monitoring by electrical resistance probes in anoxic groundwater environment in the presence and absence of sulfate reducing bacteria. Sensors and Actuators A: Physical Vol 274, pp. 252-261. https://doi.org/10.1016/j.sna.2018.03.018.

Matusewicz, M., Järvinen, J., Olin, M. & Muurinen, A. 2016. Microstructural features of compacted MX-80 bentonite after the long-time experiment. MRS Advances, 1(61), 4069-4074. https://doi.org/10.1557/adv.2017.191.

Matusewicz, M., Pulkkanen, V.-M. & Olin, M. 2016. Influence of sample preparation on MX-80 bentonite microstructure. Clay Minerals, 51(2), 189-195.

Matusewicz, M. & Olin, M. 2018. Comparison of microstructural features of three compacted and water saturated swelling clays: MX-80 bentonite, and Na- Ca-montmorillonite., Clay Minerals, (accepted).

Miettinen, H., Kietäväinen, R., Sohlberg, E., Numminen, M., Ahonen, L. & Itävaara, M. 2015. Microbiome composition and geochemical characteristics of deep subsurface high-pressure environment, Pyhäsalmi mine Finland. Frontiers in Microbiology. 6:1203. https://doi.org/10.3389/fmicb.2015.01203.

Miettinen, H., Bomberg, M. & Vikman, M. 2018. Acetate activates deep subsurface fracture fluid microbial communities in Olkiluoto, Finland. Geosciences. 8(11), 399. doi.org/10.3390/geosciences8110399.

Muuri, E., Ikonen, J., Matara-aho, M., Lindberg, A., Holgersson, S., Voutilainen, M., Siitari-Kauppi, M. & Martin, A. 2016. Behavior of Cs in Grimsel granodiorite: sorption on main minerals and crushed rock. Radiochimica Acta, Volume 104, Issue 8, Pages 575–582.

Muuri, E., Siitari-Kauppi, M., Matara-aho, M., Ikonen, J., Lindberg, A., Qian, L. & Koskinen, L. 2017. Cesium sorption and diffusion on crystalline rock: Olkiluoto case study, Journal of Radioanalytical and Nuclear Chemistry. 311, 1, pp. 439-446.

Muuri, E., Matara-aho, M., Puhakka, E., Ikonen, J., Martin, A., Koskinen, L. & Siitari-Kauppi, M. 2018. The sorption and diffusion of 133Ba in granitic rocks. Applied Geochemistry, Volume 89, February 2018, Pages 138-149.

Muuri, E., Sorokina, T., García, D., Grivé, M., Bruno, J., Koskinen, L., Martin, A. & Siitari-Kauppi, M. 2018. The in-diffusion of 133Ba in granitic rock cubes from the Olkiluoto and Grimsel in-situ test sites. Applied Geochemistry, 92, 188-195.

Nuppunen-Puputti, M., Purkamo, L., Kietäväinen, R., Nyyssönen, M., Itävaara, M., Ahonen, L., Kukkonen, I. & Bomberg, M. 2018. Rare biosphere archaea assimilate acetate in Precambrian terrestrial subsurface at 2.2 km depth. Geosciences 8, 418, https://doi.org/10.3390/geosciences8110418.

Padovani, C., King, F., Lilja, C., Féron, D., Necib, S., Crusset, D., Deydier, V., Diomidis, N., Gaggiano, R., Ahn, T., Keech, P.G., Macdonald, D.D., Asano, H., Smart, N., Hall, D.S., Hänninen, H., Engelberg, D., Noel, J.J. & Shoesmith, D.W. 2017. The corrosion behavior of candidate container materials for the disposal of high level waste and spent fuel – A summary of the state of the art and opportunities for synergies in future R&D. Corrosion Engineering Science and Technology, 2017, 227-231.

Pohjola, J., Turunen, J., Lipping, T. & Ikonen, A.T.K. 2016. Probabilistic assessment of the influence of lake properties in long-term radiation doses to humans. Journal of Environmental Radioactivity, 164, November 2016, pp. 258-267.

Purkamo, L., Bomberg, M., Nyyssönen, M., Kukkonen, I., Ahonen, L. & Itävaara, M. 2015. Heterotrophic communities supplied by ancient organic carbon predominate in deep Fennoscandian bedrock fluids. Microbial Ecology 69, 319-332.

Purkamo, L., Kietäväinen, R., Miettinen, H., Sohlberg, E., Kukkonen, I., Itävaara, M. & Bomberg, M. 2018. Diversity and functionality of archaeal, bacterial and fungal communities in deep Archaean bedrock groundwater. FEMS Microbiology Ecology 94, https://doi.org/10.1093/femsec/fiy116.

Purkamo, L., Bomberg, M., Kietäväinen, R., Salavirta, H., Nyyssönen, M., Nuppunen-Puputti, M., Ahonen, L., Kukkonen, I. & Itävaara M. 2016. Microbial co-occurrence patterns in deep Precambrian fracture fluids. Biogeosciences 13, 3091-3108.

Purkamo, L., Bomberg, M., Nyyssönen, M., Ahonen, L., Kukkonen, I. & Itävaara, M. 2017. Response of deep subsurface microbial community to different carbon sources and electron acceptors during ~2 months incubation in microcosms. Frontiers in Microbiology 8, 232.

Rajala, P. & Bomberg, M. 2017. Reactivation of deep subsurface microbial community in response to methane or methanol amendment. Front. Microbiol. 8:431.

Rajala, P., Bomberg, M., Kietäväinen, R., Kukkonen, I., Ahonen, L., Nyyssönen, M. & Itävaara, M. 2015. Rapid reactivation of deep subsurface microbes in the presence of C-1 compounds. Microorganisms 3, 17-33.

Rajala, P., Bomberg, M., Vepsäläinen, M. & Carpén, L. 2017. Microbial fouling and corrosion of carbon steel in alkaline deep groundwater, Biofouling, 33(2): 195-209.

Rajala, P., Carpén, L., Vepsäläinen, M., Raulio, M., Huttunen-Saarivirta, E. & Bomberg, M. 2016. Influence of carbon sources and concrete on microbiologically influenced corrosion of carbon steel in subterranean ground-water environment: Corrosion, Vol. 72, No. 12, pp. 1565-1579, https://doi.org/10.5006/2118.

Rajala, P., Carpén, L., Vepsäläinen, M., Raulio, M., Sohlberg, E. & Bomberg, M. 2015. Microbially induced corrosion of carbon steel in deep groundwater environment: Frontiers. Frontiers in Microbiology, Vol. 6, pp. Article number 647.

Sardini, P., Caner, L., Mossler, P., Mazurier, A., Hellmuth, K.-H., Graham, R.C., Rossi, A.M. & Siitari-Kauppi, M. 2015. Calibration of digital autoradiograph technique for quantifying rock porosity using 14C-PMMA method, Journal of Radioanalytical and Nuclear Chemistry 303(1), 2015, 11-23.

Small, J., Nykyri, M., Vikman, M., Itävaara, M. & Heikinheimo, L. 2017. The biogeochemistry of gas generation from low-level nuclear waste: Modelling after 18 years study under in situ conditions, Applied Geochemistry. Elsevier. Vol. 84 (2017), 360-372.

Sohlberg, E., Bomberg, M., Miettinen, H., Nyyssönen, M., Salavirta, H., Vikman, M, Pitkänen, P., Lamminmäki, T. & Itävaara, M. 2015. Revealing the unexplored fungal communities in deep groundwater of crystalline rock fracture zones in Olkiluoto, Finland, Frontiers in Microbiology. 6;573, https://doi.org/10.3389/fmicb.2015.00573.

Soler, J.M., Landa, J., Havlova, V., Tachi, Y., Ebina, T., Sardini, P., Siitari-Kauppi, M., Eikenberg, J. & Martin, A.J. 2015. Comparative modeling of an in-situ diffusion experiment in granite at the Grimsel Test Site, Journal of Contaminant Hydrology 179, 2015, 89-101.

Sun, L., Hirvi, J.T., Schatz, T., Kasa, S. & Pakkanen, T.A. 2015. Estimation of Montmorillonite Swelling Pressure: a Molecular Dynamics Approach, J. Phys. Chem. C2015, 119, 19863.

Sun, L., Ling, C.Y., Lavikainen, L.P., Hirvi, J., Kasa, S. & Pakkanen, T.A., 2016. Influence of Layer Charge and Charge Location on the Swelling Pressure of Dioctahedral Smectites. Chem. Phys 473 (2016) 40.

Tosoni, E., Salo, A. & Zio, E. 2017 Scenario analysis for the safety assessment of nuclear waste repositories: a critical review, Risk Analysis. 38(4): 755-776, 2018.

Tuovinen, T., Kasurinen, A., Häikiö, E., Tervahauta, A., Makkonen, S., Holopainen, T. & Juutilainen, J. 2016. Transfer of elements relevant to nuclear fuel cycle from soil to boreal plants and animals in experimental meso- and microcosms. Sci Total Environ 2016; 539:252-261.

Tuovinen, T., Makkonen. S., Holopainen, T., Kolehmainen, M. & Juutilainen, J. 2016. Non-linear transfer of elements from soil to plants: impacts on radioecological modelling. Radiat Environ Biophys 2016;55:393-400.

Uurtio, V., Bomberg, M., Nybo, K., Itävaara, M. & Rousu, J. 2015. Canonical Correlation Methods for Exploring Microbe-Environment Interactions in Deep Subsurface. – Conference: Discovery Science 2015, At Banff, Alberta, Canada DS-2015.

Vilhunen, T., Kojo, M., Litmanen, T. & Taebi, B. 2019. Perceptions of justice influencing community acceptance of spent nuclear fuel disposal. A case study in two Finnish nuclear communities, The article will be published in Journal of Risk Research in 2019 (Accepted in November 2018). https://doi.org/10.1080/13669877.2019.1569094.

Voutilainen, M., Kekäläinen, P., Siitari-Kauppi, M., Sardini, P., Muuri, E., Timonen, J. & Martin, A. 2017. Modeling Transport of Cesium in Grimsel Granodiorite With Micrometer Scale Heterogeneities and Dynamic Update of Kd. Water Resources Research, October 2017, 53, 9245–9265.

Wiikinkoski, E.W., Harjula, R.O., Lehto, J.K., Kemell, M.L. & Koivula, R.T. 2017. Effects of synthesis conditions on ion exchange properties of α-zirconium phosphate for Eu and Am, Radiochimica Acta, Vol 105, p. 1033, doi:10.1515/ract-2016-2740.

Wiikinkoski, E.W., Junhua, X., Wenzhong, Z., Hietala, S. & Koivula, R.T. 2018. Modification of α-Zirconium Phosphate Synthesis – Effects of Crystallinity and Acidity on Eu(III) and Am(III) Ion Exchange, ChemistrySelect 2018, 3(33), 9583-9588.

Yagodzinskyy, Y., Malitckii, E., Tuomisto, F. & Hänninen, H. 2018. Hydrogen-induced strain localization in oxygen-free copper in the initial stage of plastic deformation, Philosophical Magazine, 98 (2018)9, pp. 727-740.

Conference papers and working reports

Aarnio, A.-R., Kojo, M. & Litmanen, T. 2017. Fennovoiman loppusijoituslaitoksen yhteiskunnallinen hyväksyttävyys: miten suomalaiset suhtautuvat vaihtoehtoisiin paikkoihin? ATS Ydintekniikka 46(3), 16–20. (in Finnish)

Aarnio, A.-R., Kojo, M. & Litmanen, T. 2018. Ydinjätteen loppusijoituksen turvallisuuteen suhtaudutaan nykyään kriittisemmin. ATS Ydintekniikka, 47 (1), 14–21. (in Finnish)

Abed, A.A., Laitinen, M., Lämsä, J., Harjupatana, T., Sołowski, W.T. & Kataja, M. 2016. Hydro-mechanical modelling of MX-80 bentonite: one dimensional study. In 3rd European Conference on Unsaturated Soils – E-UNSAT 2016., 18005, E3S Web of Conferences, vol. 9, EDP Sciences, European Conference on Unsaturated Soils, Paris, France, 12/09/2016. https://doi.org/10.1051/e3sconf/20160918005.

Abed, A.A. & Sołowski. W.T. 2018. Invited publication of the paper in ICE proceedings from 2017 IACMAG conference in Wuhan, China.

Abed, A.A. & Solowski, W.T. 2018. Material Microstructure Effects in Thermo-Hydro-Mechanical Modelling of Bentonite. In: Hoyos, L.R., McCartney, J.S., Houston, S.L. & Likos, W.J. (eds.), PANAM UNSATURATED SOILS 2017: FUNDAMENTALS. Geotechnical Special Publication, no. 301, pp. 330-339, Pan-American Conference on Unsaturated Soils, Dallas, United States, 12/11/2017. https://doi.org/10.1061/9780784481684.034.

Abed, A., Sołowski, W.T., Romero, E. & Gens, A. 2018. Inclusion of chemical effect in a fully coupled THM finite element code. In: Ng, C., Leung, A., Chiu, A. & Zhou, C. (eds.), Unsaturated Soils. vol. 2, The Hong Kong University of Science and Technology, Hong Kong, pp. 827-832, International Conference on Unsaturated Soils, Hong Kong, 03/08/2018.

Ahonen, L., Kietäväinen, R. & Ruskeeniemi, T. 2015. Estimating the past from deep groundwaters in Finland. In: Pärn, J., Raidla, V., Vaikmäe, R., Raukas, A. & Bauert, H. (eds.): 4th Annual Meeting of G@GPS IGCP 618 Project, Estonia, 5–9 July 2015. Abstracts and Field guide. Tallinn University of Technology, Tallinn, p. 7.

Aromaa, J., Chernyaev, A., Tenitz, A. & Lundström, M. 2018. The effect of reaction product layers on copper corrosion in repository conditions. Eurocorr 2018, 9.–13.9.2018, Krakow, Poland.

Auerkari, P., Rantala, J., Tuurna, S. & Pohjanne, P. 2017. Creep ductility: appearance and requirements, 4th Intl. ECCC Creep & Fracture Conference, 10–14 September 2017, Düsseldorf, Germany.

Bomberg, M., Carpén, L. & Rajala, P. 2018. Acetate is an important carbon source for the Fennoscandian deep biosphere, DCO Shanghai.

Carpén, L. 2017. Corrosion phenomena in microbially induced corrosion of copper in repository environment. 2nd Copper Corrosion Seminar, 2 November 2017, Otaniemi, Espoo, Finland: KYT2018-seminar presentation.

Carpén, L., Rajala, P. & Bomberg, M. 2015. Real-Time Electrochemical Measurements of Carbon Steel in Ground Water with Sulfate Reducing Bacteria Enrichment. Proceedings, vol. 15604. The Annual Waste Management Conference 2015, WM Proceedings, 15–19 March 2015, Phoenix, Arizona, USA.

Carpén, L., Rajala, P. & Bomberg, M. 2015. Microbially Induced Corrosion in Deep Bedrock. Presentation in IBS 2015 (International Biohydrometallurgy Symposium), Sanur, Bali 5.–9.10.2015.

Carpén, L., Rajala, P. &, Bomberg, M. 2016. Microbially induced corrosion of copper in simulated anoxic ground-water. The annual event of the European Federation of Corrosion, EUROCORR 2016, 11–15 September 2016, Montpellier, France: EFC, No. Paper 62882.

Carpén, L., Rajala, P., Bomberg, M. & Huttunen-Saarivirta, E. 2016. Matala- ja keskiaktiivisen jätteen mikrobiologinen korroosio (CORLINE) – Vuosiraportti 2015. Research report: VTT-R-00868-16, VTT. (in Finnish)

Carpén, L., Rajala, P., Bomberg, M. & Huttunen-Saarivirta, E. 2017. Matala- ja keskiaktiivisen jätteen mikrobiologinen korroosio (CORLINE) – Vuosiraportti 2016. Research report: VTT-R-01118-17, VTT, 45 p. (in Finnish)

Carpén, L., Rajala, P., Bomberg, M. & Huttunen-Saarivirta, E. 2018. Matala- ja keskiaktiivisen jätteen mikrobiologinen korroosio (CORLINE) – Vuosiraportti 2017. Research report: VTT- R-01739-18, VTT. (in Finnish)

Carpén, L., Rajala, P., Bomberg, M., Raunio, M. & Huttunen-Saarivirta, E. 2016. Mikrobiologisen toiminnan vaikutus kuparin korroosioon loppusijoituksen hapettomissa olosuhteissa (BASUCA) – Vuosiraportti 2015. Tutkimusraportti: VTT-R-00867-16, VTT, 32 p. (in Finnish)

Carpén, L., Rajala, P., Bomberg, M., Raunio, M. & Huttunen-Saarivirta, E. 2017. Mikrobiologisen toiminnan vaikutus kuparin korroosioon loppusijoituksen hapettomissa olosuhteissa (BASUCA) – Vuosiraportti 2016. Research report: VTT-R-00992-17, VTT, 46 p. (in Finnish)

Carpén, L., Rajala, P., Huttunen-Saarivirta, E. & Bomberg, M. 2017. Corrosion Behavior of Copper in Simulated Anoxic Groundwater Inoculated with Sulfate Reducing Bacteria and Methanogens, Corrosion 2017, C2017-9355. Presentation and publication.

Carpén, L., Rajala, P. & Kinnunen, T. 2018. Real-time corrosion monitoring system under in situ conditions of crystalline groundwater. Eurocorr2018-114552, 9-13 September, Krakow, Poland.

Dobson, P., Tsang, C.-F., Doughty, C., Ahonen, L., Kietäväinen, R., Juhlin, C., Rosberg, J.-E., Borglin, S., Kneafsey, T., Rutqvist, J., Zheng, L., Xu, H., Nakagawa, S. & Nihei, K. 2017. Deep Borehole Field Test Research Activities at LBNL 2017, Report prepared for US Department of Energy, Spent Fuel and Waste Science and Technology, 118 p.

Dzugala, M., Sirkiä, J., Uotinen, L.K.T, & Rinne, M. 2017. Pull Experiment to Validate Photogrammetrically Predicted Friction Angle of Rock Discontinuities, ISRM European Rock Mechanics Symposium – Ostrava, Czech Republic, 20 Jun – 22 Jun 2017, Symposium of the International Society for Rock Mechanics, Publisher Elsevier, Pages 378-385.

Elo, O., Huittinen, N., Müller, K., Ikeda-Ohno, A., Scheinost, A.C. & Hölttä, P. 2015. A macroscopic and spectroscopic investigation of neptunium(V) adsorption on montmorillonite and corundum. Poster: 3rd BELBaR annual workshop, Madrid, Spain, March 5–6, 2015.

Elo, O., Hölttä, P., Huittinen, N. & Lehto, J. 2015. Neptunium (V) sorption onto montmorillonite and bentonite colloids and the influence of colloids on Np(V) transport. Poster: Migration 2015 conference, Santa Fe, NM, USA September 13–18, 2015.

Elo, O., Huittinen, N. & Hölttä, P. 2016. Neptunium(V) sorption onto montmorillonite and bentonite colloids and the influence of colloids on Np(V) transport. Poster: BELBaR Final Workshop, Berlin, Germany, February 3–4, 2016.

Elo, O., Huittinen, N. & Hölttä, P. 2016. Neptunium(V) uptake by granitic rock and bentonite colloids and the influence of colloids on Np(V) transport. Poster: International Conference on Nuclear and Radiochemistry (NRC9), Helsinki, Finland August 29 – September 2, 2016.

Elo, O., Hölttä, P. & Huittinen, N. 2017. The influence of bentonite colloids on neptunium(V) migration in granitic rock. Poster: Migration 2017 conference, Barcelona, Spain, September 10–15, 2017.

Eschbach, R., Feng, B., Vezzoni, B., Gabrielli, F., Alvarez-Velarde, F., Léger, V., Rocchi, F., Edwards, G., Dixon, B., Pénéliau, Y., Girieud, R., Häkkinen, S., Viitanen, T., Räty, A., Malambu, E.M. & Cornet, S. 2017. Verification of Dose Rate Calculations for PWR Spent Fuel Assemblies, Proceedings of GLOBAL 2017, September 24–29, 2017 – Seoul (Korea).

Forsström, A., Becker, R., Öijerholm, J., Yagodzinskyy, Y., Hänninen, H. & Linder, J. 2017. Hydrogen absorption in copper as a result of corrosion reactions in sulphide and chloride containing deoxygenated water at 90°C in simulated spent nuclear fuel repository conditions, Proceedings of the EUROCORR 2017 & 20th International Corrosion Congress ICC. 13 p.

Harjupatana, T., Alaraudanjoki, J. & Kataja, M. 2015. X-ray tomographic method for measuring 3D deformation and liquid content in swelling materials. Proceedings of the XII Finnish Mechanics Days: Suomen XXII mekaniikkapäivien esitelmät.

Harjupatana, T., Lämsä, J., Alaraudanjoki J. & Kataja, M. 2016. Monitoring free swelling of MX80 bentonite in a narrow channel using X-ray imaging. BelBar Final Workshop, 3.–4.2.2016. Berlin, Germany.

Heikola, T. & Ollila, K. 2017. Carbon-14 Source Term, CAST, Final Report (D2.9).

Heikola, T. & Ollila, K. 2018. Release and speciation of carbon from stainless steel under mildly and highly alkaline, reducing conditions (D2.9). CAST final report.

Heinonen, S., Ahonen, L., Kietäväinen, R. & Kukkonen, I. 2017. The Outokumpu Deep Drill Hole: window to the Precambrian bedrock of Finland. Geophysical Research Abstracts, EGU General Assembly, Vienna, Austria, 23.–28.4. (abstract and poster).

Huttunen-Saarivirta, E. 2016. EIS study on aerobic corrosion of copper in ground water: influence of micro-organisms. EIS2016 conference, A Toxa, Espanja 19.–24.6. 2016.

Huttunen-Saarivirta, E., Rajala, P. & Carpén. L. 2015. Corrosion behaviour of copper under biotic and abiotic conditions in anoxic ground water: electrochemical study EMCR 2015 Tróia, 24–29 May.

Huttunen-Saarivirta, E., Rajala, P. & Carpén, L. 2017. Microbially induced corrosion (MIC) of carbon steel and stainless steels grades EN 1.4301 and EN 1.4432 in deep bedrock environment, Eurocorr2017-86186. September 3–7, Prague, Czech Republic.

Häkkinen, S. 2016. AFCS kokous 6.-7.10.16, Matkaraportti. (in Finnish)

Häkkinen, S. 2017. Matkaraportti AFCS:n kokouksesta, 5.-6.10.2017, Paris. (in Finnish)

Häkkinen, S. 2017. Matkaraportti WPFC:n ja AFCS:n kokouksista, 6.–8.2.2017, Paris. (in Finnish)

Häkkinen, S. 2018. Matkaraportti WPFC:n ja AFCS:n kokouksista, 7.–9.2.2018 Paris. (in Finnish)

Häkkinen, S. 2018. Matkaraportti AFCS:n kokouksesta, 27.–28.9.2018, Paris. (in Finnish)

Häkkinen, S. & Wiikinkoski, E. 2015. Kehittyneiden polttoainekiertojen tutkimus maailmalla, VTT-R-00431-15. (in Finnish)

Hänninen, H. & Yagodzinskyy, Y. 2016. Hydrogen absorption and behavior in copper as a result of corrosion reactions and γ-radiation in spent nuclear fuel repository conditions. 6th International Workshop on Long-Term Prediction of Corrosion Damage in Nuclear Waste Systems, May 9-12, 2016, Toronto, Ontario, Canada, pp. 26-27.

Hänninen, H., Forsström, A. & Yagodzinskyy, Y. 2017. Copper behavior in geological nuclear waste disposal. EUROCORR 2017, 20th International Corrosion Congress & Process Safety Congress 2017, September 3-7, 2017, Prague, Czech Republic. 10 p.

Hänninen, H., Yagodzinskyy, Y. & Forsström, A. 2018. Hydrogen effects on mechanical performance of nodular cast iron. Stress-Assisted Corrosion Damage V, July 15-20, 2018, Sloss Hernstein, Austria, ECI Engineering Conferences International.

Hänninen, H., Forsström, A. & Yagodzinskyy, Y. 2018. Copper behavior in geological nuclear waste disposal. EFC "Green book" 50 Years of Nuclear Corrosion – a Review. EFC, 2018, 12 p.

Hänninen, H. 2018. Kärnavfallsrådet, Kunskapsläget på kärnavfallsområdet 2018 – Beslut under osäkerhet, SOU 2018:8, pp. 83-94 (in Swedish).

Hölttä, P., Elo, O., Suorsa, V. & Niemiaho, S. 2015. Radionuclide/colloid interaction and transport – Update of laboratory experiments. Poster: 3rd BELBaR annual workshop, Madrid, Spain, March 5–6, 2015.

Hölttä, P., Suorsa, V., Niemiaho, S. & Lehto, J. 2015. Bentonite erosion and stability of formed colloids, 2015. Poster: Clays in Natural and Engineered Barriers for Radioactive Waste Confinement conference, Brussels, Belgium, March 23–26, 2015.

Hölttä, P., Suorsa, V., Elo, O. & Lehto, J. 2015. Macroscopic interaction of radionuclides with montmorillonite and bentonite colloids. Poster: Migration 2015 conference, Santa Fe, NM, USA September 13–18, 2015.

Hölttä, P., Elo, O., Suorsa, V., Honkaniemi, E. & Niemiaho, S. 2015. Radionuclide/colloid interaction and transport – Summary of laboratory experiments. Oral presentation: BELBaR WP Progress Workshop, Karlsruhe, Germany October 12–13, 2015.

Hölttä, P., Elo, O., Suorsa, V., Honkaniemi, E. & Niemiaho, S. 2016. Effects of bentonite colloids on the radionuclide migration in granitic rock. Poster: BELBaR Final Workshop, Berlin, Germany, February 3–4, 2016.

Hölttä, P., Elo, O., Suorsa, V., Honkaniemi, E. & Niemiaho, S. 2016. Effects of bentonite colloids on the radionuclide migration in granitic rock. Poster: International Conference on Nuclear and Radiochemistry (NRC9), Helsinki, Finland August 29 –September 2, 2016.

Iakovlev, D., Sirkiä, J., Kallio, P. & Uotinen, L. 2016. Determination of joint mechanical parameters for stability analysis in low stress open pit mines. In: Johansson, E. & Raasakka, V. (Eds.), 7th International Symposium on In-Situ Rock Stress: Symposium Proceedings (RIL). Tampere, Finland: Suomen Rakennusinsinöörien Liitto RIL ry. http://urn.fi/URN:NBN:fi:aalto-201701191164.

Iso-Markku, T. 2018. 55Fe, 63Ni and 59Ni in old nuclear reactor pressure vessel steel samples. Oral presentation in seminar NKS-B RADWORKSHOP, 8.–12.10. 2018 Risö, Roskilde, Denmark.

Juutilainen, J. 2018. Non-linear transfer of elements into organisms. Cores Symposium on Radiation in the Environment Scientific Achievements and Challenges for the Society, July 2018, Helsinki, Finland, STUK-A261, p 71-73.

Juutilainen, P. 2016. SITON-polttoainekiertokoodin käyttöönotto, VTT-R-00903-16, 2016. (in Finnish)

Juutilainen, P. 2017. COSI6-laskuja SITON-ohjelman validointia varten, VTT-R-01108-17, 2017. (in Finnish)

Juutilainen, P. & Häkkinen, S. 2017. EPR fuel assembly calculations to determine homogenized one-group cross-sections for various MOX compositions, VTT-R-01082-18, 2018.

Kari, M. 2018. Host Municipality Approaches to Final disposal of Spent Nuclear Fuel in Finland and Sweden. Presentation in 22nd REFORM group meeting, Energy Democracy and Climate Change Policy. August 26 – August 31, 2018. Salzburg, Austria.

Kari, M. 2015. Civil Regulation of Final Disposal of Spent Nuclear Fuel. Comparison of Finnish and Swedish Risk Regulation Regimes, Seminar on Governance of Nuclear Safety and Nuclear Risks, University of Jyväskylä, Finland, 8 May 2015.

Kari, M. 2015. Civil Regulation of Final Disposal of Spent Nuclear Fuel. Comparison of Finnish and Swedish Risk Regulation Regimes, ESA2015 Prague, Czech Republic 25–28 August 2015.

Karlsen, W. 2016. The VTT Centre for Nuclear Safety, up-grading Finnish nuclear safety research, ATS Ydintekniikka, vol. 3, 2016, pg. 42.

Karlsen, W. 2016. The new VTT Centre for Nuclear Safety, Suomalaisen Ydintekniikan Päivät 2016 – SYP2016. https://ats-fns.fi/fi/14-syp2016.

Karlsen, W. & Paasila, M. 2016. Description of radioactive specimen storage database system, VTT Report VTT-R-00252-16.

Karlsen, W. & Rahnfeld, C. 2017. Fabrication and Installation of VTT's new hot cells, In: Proceedings of the 54th Annual Meeting of the Hot Laboratories and Remote Handling Working Group, HOTLAB 2017, September 17–22, 2017, Mito, Japan, 14 p. http://hotlab.sckcen.be/en/Proceedings.

Karvonen, S. & Peura, J. 2016. Literature review on safety case in nuclear waste deposition. 33 p. (https://www.vtt.fi/sites/turmet/).

Kataja, M., Harjupatana, T. & Riikilä, T. 2017. X-ray imaging/tomographic measurements of water transport and swelling deformation in bentonite. Beacon kick-off seminar. Kaunas, Lithuania, 19.–20.6.2017.

Kataja, M., Lämsä, J. & Harjupatana, T. 2015. Measurement of water transport and swelling of bentonite clay using X-ray imaging. An update. BelBar Workshop, 12.–13.10.2015. Karlsruhe, Germany.

Kieft, T.L., Onstott, T.C., Ahonen, L., Aloisi, V., Colwell, F.S., Engelen, B., Fendrihan, S., Gaidos, E., Harms, U., Head, I., Kallmeyer, J., Kiel Reese, B., Lin, L.-H., Long, P.E., Moser, D.P., Mills, H., Sar, P., Schulze-Makuch, D., Stan-Lotter, H., Wagner, D., Wang, P.-L., Westall, F. & Wilkins, M.J. 2015. Workshop to develop deep-life continental scientific drilling projects. Scientific Drilling 3, 1-11.

Kietäväinen, R. & Ahonen, L. 2017. Gases in bedrock groundwater: Geochemical potential for sustaining deep life. Goldschmidt Conference, Paris, France, 13.–18.8. (abstract and poster).

Kietäväinen, R. & Ahonen, L. 2018. Carbon cycling and nuclear waste disposal: Evidence for methanogenesis at low temperature bedrock setting. Goldschmidt Conference, Boston, MA, USA, 12.–17.8.2018.

Kietäväinen, R., Ahonen, L., Hendriksson, N., Kukkonen, I.T., Niedermann, S. & Wiersberg, T. 2016. Deep groundwater evolution in Outokumpu, eastern Finland –from meteoric water to saline gas rich fluid. Bulletin of the Geological Society of Finland, Special volume: Abstracts of the 32nd Nordic Geological Winter Meeting, 13–15th January 2016, Helsinki, Finland, p. 93.

Kietäväinen, R., Ahonen, L., Niinikoski, P., Nykänen, H. & Kukkonen, I.T. 2017. At the interface of geology and biology: Occurrence of methane down to 2.5 km depth within the Precambrian Fennoscandian Shield. Deep Carbon Observatory (DCO) Early Career Scientist Workshop, Sicily, Italy 28.8.–2.9. (abstract and poster).

Kietäväinen, R., Ahonen, L. & Purkamo, L. 2015. Thermodynamic constraints on methane production and consumption in deep crystalline rock biosphere. 22nd International Symposium on Environmental Biogeochemistry, Piran, Slovenia, 27.9.–2.10.2015.

Kietäväinen, R., Ahonen, L., Wiersberg, T., Korhonen, K., Pullinen, A. & Kukkonen, I.T. 2017. Deep Breath: Earth Tide Controlled Gas Flux from the Outokumpu Deep Drill Hole. 3rd Finnish National Colloquium of Geosciences, Espoo, 15–16 March 2017, abstract book p. 50. (abstract and presentation).

Kietäväinen, R., Ahonen, L., Wiersberg, T., Korhonen, K. & Pullinen, A. 2017. Tidal control on gas flux from the Precambrian continental bedrock revealed by gas monitoring at the Outokumpu Deep Drill Hole, Finland. Geophysical Research Abstracts Vol. 19, EGU2017-12348, EGU General Assembly, Vienna, Austria, 23.–28.4. (abstract and poster).

Kietäväinen, R., Etiope, G., Ahonen, L. & Kukkonen, I.T. 2015. Crustal methane in Finland – an oddity or commonplace? In: Kultti, S., Rämö, O.T., Koivisto, E. & Luoto M. (eds.), 2nd Finnish National Colloquium of Geosciences, Helsinki, Finland, 3.–5.3.2015, Program and Abstracts, Department of Geosciences and Geography C10, p. 23 (oral presentation).

Kietäväinen, R., Etiope, G., Ahonen, L. & Kukkonen, I.T. 2015. Crustal methane in Finland. 2nd DCO Early Career Scientist Workshop, Ponta Delgada, Azores, 31.8.–5.9.2015 (oral presentation and poster)

Kietäväinen, R., Etiope, G. & Ahonen, L. 2018. Occurrence and flux of crustal methane in the Fennoscandian Shield. Geophysical Research Abstracts Vol. 20, EGU2018-6115, European Geosciences Union (EGU) General Assembly, Vienna, Austria, 8.–13.4.2018.

Kojo, M. & Litmanen, T. 2018. Hallinnan keinot YVA-menettelyn yleisötilaisuudessa: Puheenjohtajan roolit vuorovaikutuksen edistämisessä. Teoksessa Kestilä-Kekkonen, E. & Raunio, T. (toim.) Valta ja politiikka. Juhlakirja Ilkka Ruostesaarelle hänen 60-vuotispäivänään. Valtiotieteellinen yhdistys ry. 101–130. (in Finnish)

Kojo, M. 2018. Is there a Nordic model of final disposal of spent nuclear fuel? Governance insights from Finland and Sweden (invited speaker). NUCLEAR FUTURES: Re-making sociotechnical research agendas. Seminar 6, 10.–11.9.2018, Sheffield, United Kingdom.

Kojo, M. 2017. Participation in the Finnish final disposal facility development process**,** NUCLEAR FUTURES: Re-making sociotechnical research agendas. Seminar 3, 8.–10 January 2017, Norwich, United Kingdom (invited speaker).

Kojo, M. 2016. Finnish and Swedish site selection programmes – different dialogue styles? Ethical Perspectives on the Nuclear Fuel Cycle, Swedish Nuclear Waste Council seminar, June 13, 2016 Stockholm, (invited speaker).

Kojo, M. 2015. Print media attention to licensing procedures for spent nuclear fuel repositories in Finland and Sweden, SENIX conference, Stockholm, Sweden, 25–27 May 2015.

Kojo, M. 2015. Print media attention to licensing procedures for spent nuclear fuel repositories in Finland and Sweden, Seminar on Governance of Nuclear Safety and Nuclear Risks, University of Jyväskylä, Finland, 8 May 2015.

Kojo, M., Kari, M., Litmanen, T. & Oksa, A. 2016. Comparison of print media attention to final disposal of spent nuclear fuel in Finland and Sweden. SENIX Conference, 13–15 June 2016, Stockholm, Sweden.

Kojo, M., Oksa, A., Vilhunen, T., Kari, M. & Litmanen, T. 2016. The Final Decision – Ethical Views on Final Disposal in Finland and Sweden, Nuclear Science and Technology Symposium, 2.11.2016, Helsinki.

Kojo, M., Kari, M. & Litmanen, T. 2016. Print media attention to licensing processes for spent nuclear fuel repositories in Finland and Sweden**,** Nordic-Asia energy and climate policy research seminar, 18 November 2016, Jyväskylä.

Kojo, M., Kari, M., Litmanen, T. & Vilhunen, T. (Presenter Litmanen, T.) 2017. High profile risk cases in the media. Print media attention to licensing procedures for spent nuclear fuel repositories in Finland and Sweden. Paper presented at the hopefulNESS 2017, The 13th Nordic Environmental Social Science Conference, 6–8th June 2017, University of Tampere, Finland.

Kojo, M., Kari, M., Oksa, A., Vilhunen, T. & Litmanen, T. 2017. Käytetyn ydinpolttoaineen loppusijoitusta koskeva mediahuomio Suomessa ja Ruotsissa 2008–2015. Poster. KYT midterm seminar, Helsinki, 7 April 2017. (in Finnish)

Kojo, M., Litmanen, T., Kari, M., Oksa, A. & Vilhunen, T. 2017. Governing Safety in Finnish and Swedish Nuclear Waste Regimes (SAFER). KYT midterm seminar, Helsinki, 7 April 2017.

Kojo, M., Oksa, A., Vilhunen, T. & Litmanen, T. (Presenter Kojo, M.) 2017. Ethical discussion on final disposal of Spent nuclear fuel in Finland and Sweden. Final ENTRIA Conference Research on Radioactive Waste Management. Ethics – Society – Technology, Braunschweig, Germany, 27 September 2017.

Kojo, M., Vilhunen, T. & Litmanen, T. (Presenters Kojo, M. & Vilhunen, T.) 2017. Ethical aspects of final disposal of spent nuclear fuel at the host community level: The resident survey in Pyhäjoki and Eurajoki in Finland. 13th Conference of the European Sociological Association, Athens, Greece, 31 August 2017.

Kojo, M., Lehtonen, M., Jartti, T., Litmanen, T. & Kari, M. 2018. Social License to Operate in Nuclear Waste Management. The annual meeting of the Society for Social Studies of Science (4S) Open panel 142. Environmental Risks in Transnational Contexts II, 29.8.–1.9.2018 Sydney.

Kuusela-Lahtinen, A., Sinnathamby, G., Mendez, J., Sołowski, W.T., Gallipoli, D., Pintado, X. & Korkiala-Tanttu, L.K. 2016. Estimation of water retention behaviour of MX-80 bentonite partially saturated with saline solution. In 3rd European Conference on Unsaturated Soils – E-UNSAT 2016., 11006, E3S Web of Conferences, vol. 9, EDP Sciences, European Conference on Unsaturated Soils, Paris, France, 12/09/2016. https://doi.org/10.1051/e3sconf/20160911006.

Kuva, J., Voutilainen, M., Lindberg, A., Parkkonen, J., Siitari-Kauppi, M. & Timonen, J. 2015. Pore and mineral structure of rock using nano-tomographic imaging MRS Proceedings 1744: 235-240 (2015).

Kuva, J., Voutilainen, M., Parkkonen, J., Turpeinen, T., Siitari-Kaupi, M. & Timonen, J. 2015. Tomographic investigation of cesium migration in Olkiluoto veined gneiss and Grimsel granodiorite, oral presentation, Physics Days, the Finnish Physical Society.

Kuva, J., Parkkonen, J., Turpeinen, T., Timonen, J., Voutilainen, M., Siitari-Kauppi, M., Sammaljärvi, J. & Lehtonen, M. 2015. Tomographic investigation of caesium migration in Olkiluoto veined gneiss and Grimsel granodiorite, poster presentation, Migration2015 conference.

Laine, E. 2017. Rakoverkkomallinnus, menetelmät ja ohjelmistot. GTK work report 17/2017 (31.3.2017). (in Finnish)

Laine, E. 2019. Julia scripts for fracture analysis. GTK work report 2019.

Laine, E. & Markovaara-Koivisto, M. 2015. 3D visualization and analysis of fracturing in the Precambrian bedrock characterized by complicated structures, two case studies from southern Finland. (extended abstract 10 p.) IAMG2015, Freiberg, 5th–13th September 2015.

Laine, E. & Markovaara-Koivisto, M. 2015. Rakoverkkomallinnus. KYT2018-seminaari, Kallioperän rikkonaisuuden mallinnus Suomessa. Esitelmä. http://kyt2018.vtt.fi/seminaari_03122015/Laine.pdf. (in Finnish)

Laine, E. & Markovaara-Koivisto, M. 2016. New 3D modeling approaches in the study of Palmottu fracture patterns. Bulletin of The Geological Society of Finland, Special Volume. Abstracts of the 32nd Nordic Geological Winter Meeting 13th–15th January 2016, Helsinki, Finland. pp. 94.

Laine, E. & Markovaara-Koivisto, M. 2016. The 3D visualization and analysis of Laser scanning data together with geological and geophysical data applied for fracture network modeling – examples studies from southern and eastern Finland. The 2nd Virtual Geoscience Conference (VGC 2016), Bergen, Norway 20.–23.9.2016.

Laine, E. & Markovaara-Koivisto, M. 2016 Rakoverkkomallinnuksen (DFN) lähtötiedot. Louhinta- ja kalliomekaniikan päivät 13.–14.10., Hotel Haaga, Helsinki, poster presentation. (in Finnish)

Laine, E. & Markovaara-Koivisto, M. 2018. A workflow for fracture network modelling – Palmottu and Kopparnäs study sites from southern Finland. Abstract. GeoEnv-meeting at Belfast 4.–5.6.

Lavonen, T. & Ollila, K. 2015. C-12 release during corrosion of unirradiated steels in simulated groundwaters (in: CAST – First Annual Report). VTT Research Report, VTT-R-00596-15. 2015.

Lehmus, E. & Leivo, M. 2016. Applicability of Geopolymers to Nuclear Waste Management, Presentation in NUCCON 2016 – Betoni ydinvoimarakenteissa -seminar. Nordic Concrete Research Seminar 31.10.–1.11.2016 Espoo.

Lehtonen, M. 2018. Trust in radioactive waste management policies: a historical analysis of four forerunner countries, Presentation at the European Consortium for Political Research (ECPR) General Conference, panel People, States, Power: Analyzing Energy Justice Regimes?, 25 August, 2018, Hamburg.

Lehtonen, M. 2018. Should nuclear waste policy adopt the concept of Social License to Operate? Presentation at the 22nd REFORM group meeting, Energy Democracy and Climate Change Policy, 26–31 August, 2018, Salzburg.

Lehtonen, M., Kojo, M. & Litmanen, T. 2017. The Finnish success story in the governance of a megaproject: the (minimal) role of socioeconomic evaluation in the final disposal of spent nuclear fuel. In: Lehtonen, M., Joly, P.-B. & Aparicio, L. (Eds.) Socioeconomic Evaluation of Megaprojects. Dealing with uncertainties. Routledge. pp. 83–110.

Lempinen, J., Apter, D. & Lehto, J. 2015. Retention of Radiocarbon by Isotope Exchange between Groundwater and Calcite, poster presentation, Migration 2015, Santa Fe, NM, USA, 13.–18.9.2015.

Lempinen, J. & Lehto, J. 2016. Sorption of dissolved inorganic radiocarbon on goethite, hematite and magnetite, Ninth International Conference on Nuclear and Radiochemistry (NRC9) 2016, Helsinki.

Leskinen, A. 2018. RPV steel activity measurement in KYT2018/VAMMA project, laboratory report, 2018.

Leskinen, A. 2018. Characterisation of Fir1 Triga Mark II Research Reactor – A Combination of Modelling and Experimental. Oral presentation in 13th International Symposium on Nuclear and Environmental Radiochemical Analysis (ERA13), 17.–20.9. 2018 Cambridge, UK.

Leskinen, A. 2018. Decommissioning of FiR 1 research reactor: status, challenges and solutions". Oral presentation in NKS-B RADWORKSHOP, 8.–12.10. 2018 Risö, Roskilde, Denmark.

Litmanen, T. 2017. Ethical aspects of final disposal of spent nuclear fuel at the host community level: The resident survey in Pyhäjoki and Eurajoki in Finland. The Cambridge Risk and Uncertainty (RUC) Conference, Session 2: Risk Communication and Ethics, June 12–14th, 2017, Cambridge, UK.

Litmanen, T. 2015. Socio-technical risk governance through dyadic risk dialogue: Copper corrosion as a safety challenge in the geological disposal of spent nuclear fuel, Seminar on Governance of Nuclear Safety and Nuclear Risks, University of Jyväskylä, Finland, 8 May 2015.

Litmanen, T., Vilhunen, T., Kojo, M. & Taebi, B. (presenter Litmanen, T.) 2018. Perceptions of Justice influencing Community Acceptance of Spent Nuclear Fuel Disposal. A Case Study in Two Finnish Nuclear Communities, International Conference and Workshop Regional Risks and Risks to the Regions, Vilnius, Lithuania, 30–31 January 2018.

Litmanen, T., Vilhunen, T., Kojo, M. & Taebi, B. (presenterLitmanen, T.) 2018. Perceptions of justice influencing community acceptance of spent nuclear fuel disposal. A case study in two Finnish nuclear communities, SRA E 2018, Risk and Inequality, part II, The 27th Annual Conference of the Society for Risk Analysis Europe in Östersund, Sweden, June 18–20 2018.

Litmanen, T. 2018. Understanding the Finnish model of final disposal of spent nuclear fuel: The multi-level analysis on Finnish nuclear waste policy. Lecture at NUMO (Nuclear Waste Management Organization of Japan), 14th March 2018. Organized by NUMO & Shizuoka University.

Litmanen, T. 2018. Understanding the Finnish model of final disposal of spent nuclear fuel: The multi-level analysis on Finnish nuclear waste policy. Lecture at the International Symposium: High level radioactive waste disposal and social consensus: Comparing the cases of Finland and Japan, 15th March 2018. Organized by Shizuoka University, the Faculty of Informatics, Department of Socio-Information Studies, Associate professor Takashi Nakazawa.

Litmanen, T. 2018. Nuclear power and nuclear waste policy in Finland: Policy arrangement approach. Lecture at the Forum Political Culture and Nuclear Waste in Finland, Germany and Japan. Organized by Society for Contemporary German History, University of Osaka. Venue: Campus Plaza Kyoto 1st Conference Room, Kyoto, March 18, 2018.

Litmanen, T. 2018. Understanding the Finnish model of final disposal of spent nuclear fuel: The multi-level analysis on Finnish nuclear waste policy. Lecture at the Osaka School of International Public Policy, 20th March 2018. Organized by Osaka University, the Osaka School of International Public Policy, Senior Researcher Nagako Sato.

Lydman, J. 2016. A three month visit at PSI, VTT Report VTT-R-03046-16.

Majlesi, S., Juutilainen, J., Kasurinen, A., Martikainen, P., Mpamah, P., Trubnikova, T. & Biasi, C. 2018. Fate of radionuclide 14C in soil-plant-atmosphere continuum: on the potential uptake of soil 14C into plants. Cores Symposium on Radiation in the Environment Scientific Achievements and Challenges for the Society, July 2018, Helsinki, Finland. STUK-A261, P 131-132.

Majlesi, S., Juutilainen, J., Kasurinen, A., Martikainen, P., Mpamah, P., Trubnikova, T. & Biasi, C. 2018. Fate of radionuclide 14C in soil-plant-atmosphere continuum: on the potential uptake of soil 14C into plants. 5th European IRPA (International Radiation Protection Association) congress, July 2018, The Hague, The Netherlands. IRPA 2018 Book of Abstracts, P 265.

Marjamaa, K., Vikman, M., Storgårds, E., Salavirta, H. & Itävaara, M. 2015. Genome and in-lab analysis of cold-tolerant Paenibacillus spp isolated from low level radioactive waste repository, 11th Carbohydrate Bioengineering Meeting, poster presentation.

Markovaara-Koivisto, M., Uotinen, L. & Rasilainen, K. 2017. Kalliomassan ja rakojen numeerinen mallinnus (KYT2018 Rakoiluseminaarin 5.12.2017 yhteenveto), Materia 1, 2018, pp. 47-49. (in Finnish)

Markovaara-Koivisto, M., Laine, E. & Rasilainen, K. 2016. Kallioperän rikkonaisuuden mallinnus Suomessa. ATS Ydintekniikka, Vol. 45. No 1, pp. 12-14. (in Finnish)

Matusewicz, M., Järvinen, J., Olin, M., & Muurinen, A. 2017. Microstructural features of compacted MX-80 bentonite after the long-time experiment. MRS Advances, 1(61), 4069-4074. https://doi.org/10.1557/adv.2017.191.

Mibus, J., Swanton, S., Suzuki-Muresan, T., Rodríguez Alcalá, M., Leganés Nieto, J.L., Bottomley, D., Herm, M., De Visser-Tynova, E., Cvetković, B.Z., Sakuragi, T., Jobbágy, V. & Lavonen, T. 2015. Carbon-14 Source Term (CAST) WP2 Annual Progress Report – Year 1 (D2.2). p. 87.

Mibus, J., Swanton, S., Suzuki-Muresan, T., Rodríguez Alcalá, M., Leganés Nieto, J.L., Bottomley, D., Herm, M., De Visser-Tynova, E., Cvetković, B.Z., Sakuragi, T., Jobbágy, V. & Heikola, T. 2015. Carbon-14 Source Term (CAST) WP2 Annual Progress Report – Year 2 (D2.5). p. 98.

Mibus, J., Swanton, S., Suzuki-Muresan, T., Rodríguez Alcalá, M., Leganés Nieto, J.L., Bottomley, D., Herm, M., De Visser-Tynova, E., Cvetković, B.Z., Sakuragi, T., Druyts, F. & Heikola, T. 2017. Carbon-14 Source Term (CAST) WP2 Annual Progress Report – Year 3, October 2015- September 2016 (D2.6). p. 91.

Miettinen, H. 2015. The sulfur cycling and sulfide formation in deep groundwater bedrock. EMBO Workshop on Microbial Sulfur Metabolism, Poster presentation, 12.–15.4.2015. Helsingör, Denmark.

Miettinen, H. 2016. 35S-tracer method for analyzing microbial sulfur compound cycling in oligotrophic anoxic groundwater habitat. VTT Technology 249. www.vtt.fi/inf/pdf/technology/2016/T249.pdf.

Miettinen, H. & Itävaara, M. 2016. Geobiokierto Research Report 2015. VTT-R-00387-16. (in Finnish)

Miettinen, H. & Itävaara, M. 2017. Geobiokierto Research Report 2016, VTT-R-00727-17. (in Finnish)

Miettinen, H. 2018. Geobiokierto Research Report 2017, VTT-R-00688-18. (in Finnish)

Miettinen, H., Bomberg, M., Merroun, M., Povedano-Priego, C., Jroundi, F. & Vikman, M. 2018. Comparison of three DNA extraction methods for MX-80 bentonite. MIND Project Annual Meeting 3. Lausanne, 7-9.5. 2018. Switzerland.

Miettinen, H., Vikman, M. & Itävaara, M. 2017. Activation of deep subsurface ground water microorganism by electron acceptors and donors. MIND Project Annual Meeting 2017. 3.–5.5. 2018. Prague, Czech Republic.

Miettinen, H., Vikman, M., Matusewicz, M. & Itävaara, M. 2017. Long-term lab-scale microbial bentonite storage experiment. MIND Project Annual Meeting 2017. 3.–5.5. 2018. Prague, Czech Republic.

Miettinen, H., Vikman, M., Matusewicz, M., Merroun, M. & Itävaara, M. 2018. Bentonite characteristics after one year of storage with indigenous bentonite and water microbes. MIND Project Annual Meeting 3. Lausanne, 7.–9.5.2018. Switzerland.

Moilanen, P., Lappalainen, P., Planman, T. & Lyytikäinen, T. 2016. Remote opening of an irradiated surveillance capsule by robot, VTT-R-03965-16, 20 p.

Muuri, E. 2015. Cesium sorption on main minerals of crystalline rock; Olkiluoto case study, Migration 2015, 09/2015, Santa Fe, United States, Poster presentation.

Muuri, E. 2016. The sorption and diffusion of 133Ba in granitic rocks, The 9th International conference on Nuclear and Radiochemistry, 08/2016, Helsinki, Finland, Poster presentation.

Muuri, E. 2016. Upscaling laboratory data towards in situ conditions, Nuclear Science and Technology Symposium, 11/2016, Helsinki, Finland, Oral presentation.

Muuri, E. 2017. The in-diffusion of 133Ba in granitic rocks, Migration 2017, 09/2017, Barcelona, Spain, Oral presentation.

Muuri, E. 2018. Determination of mineral-specific distribution coefficients of 133Ba from thin sections of granitic rock using filmless electronic autoradiography, The 18th Radiochemical Conference – RadChem 2018, 05/2018, Mariánské Lázně, Czech Republic. Oral presentation.

Muuri, E. 2018. Method development for electronic autoradiography with geological samples; Applications in nuclear waste management, 13th International Symposium on Nuclear and Environmental Radiochemical Analysis: ERA13, 09/2018, Cambridge, United Kingdom, Oral and poster presentation.

Myllykylä, M., Heikola, T. & Lavonen, T. 2017. Vertailumittaukseen valmistavat alkuaineanalyysit – RADLAB, VTT Report VTT-R-00697-18, 2018, 35 p. (in Finnish)

Ollila, K. & Heikola, T. 2018. Predicting release of carbon-14 nuclide from metallic radioactive waste. In: Holt, E., Kinnunen, P. & Sevelev, D. (Eds.). Impacts from VTT Nuclear Safety and Radioactive Waste Management Research. VTT Technical Research Centre of Finland, Espoo, Finland, ISBN 978-951-38-8705-6, pp. 80-81.

Pohjola, J., Turunen, J., Lipping, T. & Ikonen, A.T.K. 2016. The influence of foodstuff grouping on doses in safety assessments. Abstracts Book, Ninth International Conference on Nuclear and Radiochemistry – NRC9, Helsinki, 29 August – 2 September 2016 (pp. 499-500).

Pohjola, J., Turunen, J. & Lipping, T. 2017. The Effect of Lake Bottom Sediment Layers on Radionuclide Transport from Bedrock to Biosphere and Doses to Humans. 4th International Conference on Radioecology & Environmental Radioactivity (ICRER), Berlin, 3rd – 8th September 2017.

Pohjola, J., Turunen, J., Lipping, T. & Ikonen, A. 2016. Probabilistic Framework for Modelling the Evolution of Geomorphic Features in 10,000-Year Time Scale: The Eurajoki River Case. Geospatial Data in a Changing World, In: Sarjakoski, T., Yasmina Santos, M. & Sarjakoski, L.T. (eds.) Selected papers of the 19th AGILE Conference. Springer, Swizerland. pp. 369-382.

Purkamo, L. & Kietäväinen, R. 2015. The biological origin, source and cycling of methane in deep crystalline biosphere of Outokumpu, Finland. Geophysical Research Abstracts, Vol. 17, EGU2015-389, EGU General Assembly 2015, Vienna, Austria 12.-1.4.2015.

Purkamo, L., Bomberg, M., Kietäväinen, R., Salavirta, H., Nyyssönen, M., Nuppunen-Puputti, M., Ahonen, L., Kukkonen, I. & Itävaara, M. 2015. Microbial community structure, activity and functionality from six different depths of deep crystalline bedrock fracture zones from Fennoscandian shield. ASB6 – The Origin, Distribution & Detection of Life in the Universe, London, UK 2.-4.9.2015 Programme and abstracts, p. 36.

Purkamo, L., Bomberg, M., Kietäväinen, R., Salavirta, H., Nyyssönen, M., Nuppunen-Puputti, M., Ahonen, L., Kukkonen, I. & Itävaara, M. 2016. Ancient ecosystems in crystalline bedrock fractures. Bulletin of the Geological Society of Finland, Special volume: Abstracts of the 32nd Nordic Geological Winter Meeting, 13- 15th January 2016, Helsinki, Finland, p. 200.

Rajala, P. 2017. The microbial processes affecting the integrity of copper canister in repository. 2nd Copper Corrosion Seminar, 2 November 2017, Otaniemi, Espoo, Finland: KYT2018-seminar presentation.

Rajala, P., Bomberg, M., Huttunen-Saarivirta, E. & Carpén, L. 2017. Corrosion of stainless steels AISI 304 and AISI 316 induced by sulfate reducing bacteria in anoxic groundwater. Corrosion2017, C2017-9359. Presentation and publication.

Rajala, P. & Carpén, L. 2017. Loppusijoituksen aerobisen vaiheen korroosio. Poster. KYT2018 midtime seminar, 7.4. Finlandia Hall, Helsinki.

Rajala, P., Carpén, L., Huttunen-Saarivirta, E., Tsitko, I. & Bomberg, M. 2015. Loppusijoituksen aerobisen vaiheen mikrobiologinen korroosio (MICOR) – Research Report 2015. VTT-R-00882-16. (in Finnish)

Rajala, P., Carpén, L., Huttunen-Saarivirta, E., Tsitko, I. & Bomberg, M. 2016. Loppusijoituksen aerobisen vaiheen mikrobiologinen korroosio (MICOR) – Research Report 2016. VTT-R-01612-17. (in Finnish)

Rajala, P., Carpén, L., Huttunen-Saarivirta, E. & Bomberg, M. 2017. Loppusijoituksen aerobisen vaiheen mikrobiologinen korroosio (MICOR) – Research Report 2017. VTT-R-02763-18. (in Finnish)

Rajala, P., Isotahdon, E., Bomberg, M. & Carpén, L. 2019. The microbial processes affecting the integrity of copper canister in geological repository of nuclear waste. Paper accepted to be presented in NACE CORROSION 2019.

Rantala, J., Auerkari, P., Laukkanen, A., Andersson, T. & Pohja, R. 2015. Experimentally verified model based predictions for integrity of copper overpack – Annual report 2015, VTT-R-00832-16.

Rantala, J., Auerkari, P., Laukkanen, A. & Andersson, T. 2016. Experimentally verified model based predictions for integrity of copper overpack – Annual report 2016, VTT-R-01253-17.

Rantala, J., Pohja, R. & Auerkari, P. 2017. Experimentally verified model based predictions for integrity of copper overpack – Annual report 2017, VTT-R-01499-18.

Rantala, J., Hänninen, H., Aromaa, J., Carpén, L., & Rajala. P. 2015. Ydinjätteen kuparivaippa: kestääkö, syökö korroosio, murtaako vety? ATS Ydintekniikka vol. 44, 4/2015. pp. 25-27. (in Finnish)

Rantala, J., Pohja, R., Auerkari, P., Laukkanen, A. & Andersson, T. 2016. Relaxation behaviour of copper in disposal canisters, BALTICA X, Intl Conf on Life Management and Maintenance for Power Plants, 7–9 June 2016, Helsinki.

Rasilainen, K. (ed.) 2015. KYT2014 Finnish Research Programme on Nuclear Waste Management 2011-2014. Final Report, Publications of the Ministry of Employment and the Economy, Energy and the climate 60/2015. http://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/74994/TEMjul_60_2015_web_19112015.pdf?sequence=1&isAllowed=y.

Rasilainen, K. & Itälä, A. 2016. KYT2018-tutkimusohjelma – kyllä ydinjäte tunnetaan, ATS Ydintekniikka, 3/2016, Vol. 45. pp. 51-54. (in Finnish)

Rasilainen, K. 2018. VTT's contribution to the Finnish Nuclear Waste Management Research Programme (KYT2018). In: Holt, E., Kinnunen, P. & Sevelev, D. (Eds.). Impacts from VTT Nuclear Safety and Radioactive Waste Management Research. VTT Technical Research Centre of Finland, Espoo, Finland, ISBN 978-951-38-8705-6, pp. 114-115.

Raunio, M., Rajala, P. & Carpén, L. 2015. Corrosion of stainless steel in low oxygen groundwater environment. 16th Nordic Corrosion Congress. 20-22nd May 2015, Stavanger, Norway.

Räty, A. 2016. WPFC/AFCS Expert Group Benchmark on Dose Rate Calculations with Serpent VTT Research Report VTT-R-01661-16.

Räty, A. & Häkkinen, S. 2018. WPFC/AFCS Expert Group Benchmark on Dose Rate Calculations with Serpent, VTT-R-02506-18.

Salminen-Paatero, S. 2018. A pilot study for determining 55Fe, 63Ni and 59Ni from nuclear reactor pressure vessel steel in Finland. Poster presentation in 13th International Symposium on Nuclear and Environmental Radiochemical Analysis (ERA13), 17.-20.9. 2018 Cambridge, UK.

Siivinen, J. 2017. VTT:n Ydinturvallisuustalon jätteiden käsittely, VTT Report VTT-R-06888-17, 2018, 23 p. (in Finnish)

Sirkiä, J., Kallio, P., Iakovlev, D. & Uotinen, L. 2016. Photogrammetric calculation of JRC for rock slope support design. In: Nordlund, E., Jones, T.H. & Eitzenberger, A. (Eds.), Proceedings of the Eighth International Symposium on Ground Support in Mining and Underground Construction: Ground Support 2016 Luleå. http://urn.fi/URN:NBN:fi:aalto-201701191147.

Sirkiä, J., Uotinen, L. & Rinne, M. 2015. Kallion rakopintojen mekaaniset ominaisuudet. KYT2018-seminaari, Kallioperän rikkonaisuuden mallinnus Suomessa. Presentation, http://kyt2018.vtt.fi/seminaari_03122015/Sirkia.pdf. (in Finnish)

Sun, L., Hirvi, J.T., Ling, C.Y., Akinwunmi, B., Kasa, S. & Pakkanen, T.A. 2017. Influence of structural and environmental factors on the swelling pressure of bentonite, 7th international Conference on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Davos, September 2017, poster presentation.

Sun, L., Ling, C., Lavikainen, L., Hirvi, J., Kasa, S. & Pakkanen, T.A. 2016. Prediction of Swelling Pressure in Smectites: A Molecular Dynamics Study, 53rd Annual Meeting of the Clay Minerals Society, Atlanta, June 7, 2016, oral presentation.

Suorsa, V., Hölttä, P., Elo, O. & Lehto, J. 2015. Generation and stability of bentonite colloids. Poster: Migration 2015 conference, Santa Fe, NM, USA September 13–18, 2015.

Suorsa, V. & Hölttä, P. 2016. Generation and stability of bentonite colloids. Poster: BELBaR Final Workshop, Berlin, Germany, February 3–4, 2016.

Suorsa, V. & Hölttä, P. 2016. Block-scale experiment on bentonite colloid – radionuclide interaction. Poster: International Conference on Nuclear and Radiochemistry (NRC9), Helsinki, Finland August 29 – September 2, 2016.

Suorsa, V., Hölttä, P., Huber, F. & Schäfer, T. 2017. Block-scale study on radionuclide, montmorillonite colloid and granite interaction. Poster: Migration 2017 conference, Barcelona, Spain September 10–15, 2017.

Syrjämäki, E., Kojo, M. & Litmanen, T. 2015. Muuttunut hanke: Fennovoiman ydinvoimalahankkeen YVA-yleisötilaisuudet Pyhäjoella vuosina 2013-2014. YFI julkaisuja 2. University of Jyväksylä, Jyväskylä. Saatavissa: http://urn.fi/URN:ISBN:978-951-39-6246-3 (in Finnish).

Tosoni, E. & Salo, A. 2016. Literature Review on Scenario Analysis for Nuclear Waste Repositories. 64 p. (https://www.vtt.fi/sites/turmet/).

Tosoni, E., Salo, A. & Aio, E. 2016. A prospective review of scenario analysis of nuclear waste repositories, Society for Risk Analysis Europe Conference, June 20–22, 2016, Bath, UK.

Tosoni, E., Salo, A. & Zio, E. 2017. Bayesian networks for comprehensive scenario analysis of nuclear waste repositories. Oral presentation at the Society for Risk Analysis – Europe Conference, held in June 19–21 in Lisbon, Portugal.

Tosoni, E., Salo, A. & Zio, E. 2017. Bayesian networks for scenario analysis of nuclear waste repositories. Oral presentation at the Society for Risk Analysis – Nordic Chapter Conference, held in November 2–3 in Espoo, Finland.

Tsang, C.-F., Rosberg, J.-E., Ahonen, L. & Juhlin, C. 2016. Hydrogeological testing and sampling at the COSC-1 borehole. Bulletin of the Geological Society of Finland,

Special volume: Abstracts of the 32nd Nordic Geological Winter Meeting, 13–15th January 2016, Helsinki, Finland, p. 148.

Turunen, J., Pohjola, J. & Lipping, T. 2018. Sensitivity analysis of radionuclide transport in biosphere analysis. STUK-A261 In: Salomaa, S., Lusa, M. & Vaaramaa, K. (eds.). Cores Symposium on Radiation in the Environment – Scientific Achievements and Challenges for the Society, 16.–17.4.2018, Helsinki, Finland.

Tähtinen, S. 2016. VTT Hot Cell Design and Manufacturing by ITD – Project Quality Plan – Manufacturing, VTT Report, VTT-R-04150-16, 29 p.

Tähtinen, S. 2017. Background study on machining options in the VTT hot cells, VTT Report VTT-R-03878-17, 2017, 26 p.

Tähtinen, S. 2017. VTT Ydinturvallisuustalon kuumakammioiden toimintaperiaate, VTT Report VTT-R-00485-18, 2018, 18 p. (in Finnish)

Uotinen, L.K.T., Korpi, E., Hartikainen, A., Yorke, R., Antikainen, J., Johansson, F., & Rinne, M. 2015. A Method to Downscale Joint Surface Roughness and to Create Replica Series using 3D Printed Molds. In 13th ISRM International Congress of Rock Mechanics, Montréal, Quebec, Canada, 10–13 May 2015. International Society for Rock Mechanics. https://doi.org/10.13140/RG.2.1.4123.7848.

Vehmas, T. 2015. Introduction to Geopolymers. Research Report VTT-R-04953-15, 21 p.

Viitanen, T. 2016. WPFC ja AFCS kokoukset 1.–3.2.16, Matkaraportti. (in Finnish)

Vikman, M., Itävaara, M. & Carpén, L. 2016. Matala- ja keskiaktiivisen ydinjätteen loppusijoituksen mikrobiologisen riskit Suomessa, VTT Technology 273. VTT, 41 p. ISBN 978-951-38-8457-4. http://www.vtt.fi/inf/pdf/technology/2016/T273.pdf. (in Finnish)

Vikman, M., Marjamaa, K., Miettinen, H. & Itävaara, M. 2016. Matala- ja keskiaktiivisen jätteen loppusijoituksen mikrobiologia, Research report 2015. VTT-R-00694-16. (in Finnish)

Vikman, M. & Itävaara, M. 2017. Matala- ja keskiaktiivisen jätteen loppusijoituksen mikrobiologia, Research report 2016, VTT-R-00786-17. (in Finnish)

Vikman, M. 2018. Matala- ja keskiaktiivisen jätteen loppusijoituksen mikrobiologia, Research report 2017, VTT-R-00601-18. (in Finnish)

Vikman, M., Marjamaa, K. & Itävaara, M. 2016. Microbiological degradation of LLW under repository conditions – Case TVO, MIND Project Annual Meeting 1, Extended Abstracts, Granada May 2–4, 2016. http://www.mind15.eu.

Vikman, M., Marjamaa, K., Itävaara, M., Nykyri, M., Small, J. & Paaso, N. 2017. Microbial degradation of low-level radioactive waste in repository conditions, Presentation, Goldschmidt 2017, 13–18 August 2017, Paris, France 2017. European Association of Geochemistry.

Vikman, M., Matusewicz M., Sohlberg, E., Miettinen, H., Järvinen, J., Itälä, A., Rajala, P., Raulio, M., Muurinen, A., Tiljander, M. & Olin, M. 2018. Long-term experiment with compacted bentonite. VTT Technology, 332. https://cris.vtt.fi/ws/portalfiles/portal/19390120/T332.pdf.

Vikman, M., Miettinen, H., Itävaara, M. & Weckman, K. 2017. Microbiological degradation of LLW under in situ conditions, MIND Project Annual Meeting 2017. 3.–5.5. 2018. Prague, Czech Republic.

Vikman, M., Miettinen, H. &. Itävaara, M. 2018. Large-scale gas generation experiment with low-level radioactive waste. MIND Project Annual Meeting 3. Lausanne, 7.–9.5.2018. Switzerland.

Vilhunen, T., Kojo, M. & Litmanen, T. 2017. (Presenters Kojo, M. & Vilhunen, T.) Ethical perceptions and community acceptance of the repository for spent nuclear fuel: Comparing residents' opinions in two Finnish nuclear communities. University of Tampere, school of management, research seminar of policitical science, 16.10.2017, Tampere.

Wiikinkoski, E.W., Koivula, R.T. & Harjula, R.O. 2016. Effects of synthesis conditions on trace level ion exchange properties of α-zirconium phosphate variants for 152Eu3+ and 241Am3+. Poster abstract in abstract book. The Ninth Nuclear and Radiochemistry Conference (NRC9), Helsinki, 29.8.–2.9.2016.

Yagodzinskyy, Y., Malitckii, E. & Hänninen, H. 2015. Hydrogen-induced strain localization in oxygen-free copper at the initial stage of plastic deformation. EUROMAT 2015, Warsaw, September 19.–24., 2015.

Yagodzinskyy, Y., Malitckii, E. & Hänninen, H. 2016. Hydrogen effects on strain localization in FCC metals at the initial stage of plastic deformation. 2016 International Hydrogen Conference, September 11–14, 2016, Moran, Wyoming, USA, 8 p.

Yagodzinskyy, Y., Forsström, A. &. Hänninen, H. 2018. Hydrogen uptake and its effects on mechanical performance of nodular cast iron. EUROCORR 2018, Krakow, Poland, 9–13 September, 2018.

Yang, X, Sołowski, W.T., Fan, H. & Dang, J. 2018. Experimental Study on Effects of NaCl Solutions on Soil-Water Characteristic Curves of Expansive Soil. In: Proceedings of China-Europe Conference on Geotechnical Engineering: Volume 2. vol. 2, Springer Series in Geomechanics and Geoengineering, pp. 1328-1331, China-Europe Conference on Geotechnical Engineering, Vienna, Austria, 13/08/2018. https://link.springer.com/chapter/10.1007%2F978-3-319-97115-5_94.

Academic theses

Bachelor's theses

Heczko, V. 2018. Bariumin jakautuminen kiven pääminеraaleihin. Bachelor's thesis, University of Helsinki, (21.8.2018). (in Finnish)

Honkaniemi, E. 2015. Radionuklidien sorptio/desorptio bentoniittiin partikkelikoon mukaan. Bachelor's thesis, University of Helsinki. (in Finnish)

Kallio, P. 2015. Rakopinnan karkeuden mittaaminen fotogrammetrisesti. Bachelor's thesis. Aalto University. 31 p. http://urn.fi/URN:NBN:fi:aalto-201506033095. (in Finnish)

Kivivirta, S. 2017. Kiven leikkauskokeen numeerinen mallintaminen ydinjätteen loppusijoitusta varten, Bachelor's thesis, Aalto University. (in Finnish)

Matara-aho, M. 2015. 134 Cesiumin konsentraatioisotermien määritys kiteisen kiven päämineraaleille. Bachelor's thesis, University of Helsinki (28.5.2015). (in Finnish)

Pakkanen, N.2018. 134Cs sorptio bentoniittiin ja kolloideihin. Bachelor's thesis, University of Helsinki. (in Finnish)

Tolvanen, L. 2015. Itsetiivistyvä betoninen jäljennysmateriaali rakopinnoille. Bachelor's thesis. Aalto University. 15 p. http://urn.fi/URN:NBN:fi:aalto-201506033137. (in Finnish)

Suorsa, V. 2015. 137Cs:n konsentrointi CsTreat®-ioninvaihtimella Grimselin kolloidien in situ -kulkeutumiskokeessa. Bachelor's thesis, University of Helsinki. (in Finnish)

Master's theses

Akinwunmi, B. 2017. Swelling Behavior of Na- montmorillonite as a function of temperature: A computational study, MSc Thesis, Department of Chemistry, University of Eastern Finland, 547 (2017).

Dzugala, M. 2016. Pull experiment to validate photogrammetrically predicted friction angle of rock discontinuities. MSc thesis. Aalto University. 116+6 p. http://urn.fi/URN:NBN:fi:aalto-201609224184.

Fayoyiwa, A. 2017. Molecular dynamics study of iron-rich clay, MSc Thesis, Department of Chemistry, University of Eastern Finland, 583 (2017).

Heikkinen N. 2016. Kaasujen liukoisuus Outokummun syväkairareiän suolaisessa pohjavedessä. Master's thesis, University of Helsinki 77 p. (in Finnish)

Iakovlev, D. 2015. Comparison of Barton-Bandis and Mohr-Coulomb models for use in discontinuity shear stability analysis. Master of science thesis 62 + 4 p. Aalto University. https://aaltodoc.aalto.fi/handle/123456789/18656.

Korpi, E. 2016. Quantifying loss of geometrical features in downscaling of rock joint surfaces using shear box replica series (Kalliorakopintojen alaspäinskaalauksessa tapahtuvan geometrisen informaation katoamisen määrittäminen rasialeikkaus-koetta replikoidulle näytesarjalle käyttäen). Master of Science thesis. Aalto University. 90+15 p. http://urn.fi/URN:NBN:fi:aalto-201605262266.

Kuisma, P. 2018. Sanomalehtikeskustelu ydinjätteen KBS-3-loppusijoitusmenetelmän riskeistä Suomessa ja Ruotsissa. University of Jyväskylä. Master's thesis. Sosiology. (in Finnish)

Kääriäinen, T. 2015. Bentoniitin elastoplastisten ominaisuuksien määrittäminen. Master's thesis, University of Jyväskylä. (in Finnish)

Lindroos, V. 2015. Corrosion of copper in synthetic oxygen-free ground water. Master of Science thesis, Aalto University, School of chemical engineering, 73 p.

Lämsä, J. 2015. Veden kulkeutumisen ja muodonmuutosten mittaaminen MX-80 -tyyppisessä bentoniitissa röntgenmikrotomografisin menetelmin. Master's thesis, University of Jyväskylä. (in Finnish)

Manninen, A. 2017. Microbiological sulphate reduction in deep groundwater environment, Master's thesis, University of Helsinki.

Muuri, E. 2015. The sorption and diffusion of 133Ba in granitic rocks. Master's thesis, University of Helsinki (13.11.2015).

Porté, R. 2017. Calibration of parameters for constitutive modelling of MX-80 bentonite. Politecnico di Torino MSc thesis & Aalto University final project. Thesis has not been funded by KYT2018 programme, though done under supervision of Abed and Sołowski.

Sirkiä, J. 2015. Requirements for initial data in photogrammetric recording of rock joint surfaces (Vaatimukset lähtötiedoille kallion rakopintojen fotogrammetrisesta tallennusta varten). Master of Science thesis. Aalto University. 83+14 p. http://urn.fi/URN:NBN:fi:aalto-201512165744.

Suorsa, V. 2017. Radionuclide transport on the block-scale –effect of clay colloids on RN mobility. Master's thesis, University of Helsinki.

Tenitz, A. 2016. Kuparin korroosio ydinjätteen loppusijoitusolosuhteissa (Corrosion of copper in deep geological repository conditions). Master of science thesis, Aalto university, 2016, 64 p. (in Finnish)

Dissertations

Ikonen, J. 2017. Sorption and matrix diffusion in crystalline rocks – In-situ and laboratory approach. University of Helsinki, Doctoral thesis in Radiochemistry 36 (8.9.2017), 64 p.

Itälä, A. 2018. Chemical behaviour of bentonite in the near field of the KBS-3V concept. Dissertation, University of Helsinki, VTT Science 183 (20.11.2018), 60 p.

Kietäväinen, R. 2017. Deep Groundwater Evolution at Outokumpu, Eastern Finland: From Meteoric Water to Saline Gas-Rich Fluid. Dissertation, University of Helsinki, GTK special publication nr. 97, 54 p.

Kuva, J. 2016. Tracer Migration in Crystalline Rock – Application to Geological Barriers of Nuclear Waste Storage. Dissertation (20.1.2016), University of Jyväskylä, 72 p.

Lavikainen, L. 2016. The Structure and surfaces of 2:1 phyllosilicate clay minerals. PhD Thesis, Department of Chemistry, University of Eastern Finland, 137 (2016).

Markovaara-Koivisto, M. 2017: Visualization and modelling of rock fractures and rock quality parameters in 1-3 dimensions in crystalline bedrock, Dissertation, Aalto University, 14.12.2017, p. 63.

Matusewicz, M. 2018. The Microstructure Of Bentonite Clay, PhD thesis, Department of Physics Research Report No. 9/2018, University of Jyväskylä, Jyväskylä 2018, 61 p., ISBN 978-951-39-7604-0 (print), ISBN 978-951-39-7605-7 (electronic)

Purkamo, L. 2015. Microbial ecology and functionality in deep Fennoscandian crystalline bedrock biosphere, Doctoral Thesis, VTT Science 116, 86 p. + app. 82 p.

Rajala, P. 2017. Microbially induced corrosion of carbon steel in a geological repository environment, Academic Dissertation, VTT Science S155.

Sun, L. 2016. The Effects of Structural and Environmental Factors on the Swelling Behavior of Montmorillonite – Beidellite Smectites: a Molecular Dynamics Approach. PhD thesis, Department of Chemistry, University of Eastern Finland, 135 (2016).

Tuovinen, T. 2016. Transfer of elements related to the nuclear fuel cycle – Evaluation of linearity in boreal ecosystems. Publications of the University of Eastern Finland. Dissertation in Forestry and Natural Sciences. 2016.

Uotinen, L. 2018. Prediction of stress-driven rock mass damage in spent nuclear fuel repositories in hard crystalline rock and in deep underground. Dissertation. Aalto University. 63 + 105 p. http://urn.fi/URN:ISBN:978-952-60-8005-5.

KYT2018

Finnish Research Programme on Nuclear Waste Management 2015–2018

Final Report

KYT2018 was conducted 2015–2018. Its objective has been to ensure that the authorities have access to such nuclear expertise that is needed for comparison of different nuclear waste management methods and technologies.

The content of KYT2018 was composed of nationally important research topics, which are the long-term safety of nuclear waste management, technologies in nuclear waste management and nuclear waste management and society. The research programme had 32 research and infra projects; most projects were focused on long-term safety. The programme aimed to contribute to the development of national know-how and research infrastructure, ensure the continuing availability of expertise, promote high-level scientific research and increase general knowledge of nuclear waste management.

This final report presents KYT2018 research programme's objectives, organization and results.

Electronic publications
ISSN 1797-3562
ISBN 978-952-327-426-6

Electronic version: julkaisut.valtioneuvosto.fi
Publication sales: julkaisutilaukset.valtioneuvosto.fi