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KYT2022 Finnish Research Programme on Nuclear Waste Management 2019–2022

Final Report

Ministry of Economic Affairs
and Employment of Finland

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Final Report

KYT2022 Management Group

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KYT2022 Finnish Research Programme on Nuclear Waste Management 2019–2022 Final Report

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Abstract

KYT2022 (Finnish Research Programme on Nuclear Waste Management 2019–2022), organised by the Ministry of Economic Affairs and Employment, was a national research programme with the objective to ensure that the authorities have sufficient levels of nuclear expertise and preparedness that are needed for safety of nuclear waste management.

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 energy, developing new know-how and participating in international collaboration.

The content of the KYT2022 research programme was composed of nationally important research topics, which are the safety, feasibility and acceptability of nuclear waste management.

KYT2022 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 helped to make use of the limited research resources. The programme aimed to develop national research infrastructure, ensure the continuing availability of expertise, produce high-level scientific research and increase general knowledge of nuclear waste management.

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Julkaisija	Työ- ja elinkeinoministeriö		
Yhteisötekijä	KYT2022 Johtoryhmä		
Kieli	englanti	**Sivumäärä**	154

Tiivistelmä

KYT2022 (Kansallinen ydinjätehuollon tutkimusohjelma) on työ- ja elinkeinoministeriön alla vuosina 2019–2022 käynnissä ollut Valtion ydinjätehuoltorahaston (VYR) rahoittama tutkimusohjelma, jonka tavoitteena on ollut varmistaa, että viranomaisilla on saatavilla riittävästi ja kattavasti sellaista ydinteknistä asiantuntemusta ja muita valmiuksia, jota tarvitaan ydinjätehuollon alalla.

Julkisten ydinturvallisuustutkimusohjelmien lähtökohtana on, että ne luovat edellytyksiä ydinenergian turvallisen ja taloudellisen käytön jatkumiseen tarvittavan osaamisen säilymiselle, kehittämiselle ja kansainväliseen yhteistyöhön osallistumiselle.

KYT2022 tutkimusohjelman sisältö koostui kansallisesti tärkeistä tutkimuskohteista, jotka liittyivät ydinjätehuollon turvallisuuteen, toteutettavuuteen ja yhteiskunnalliseen hyväksyttävyyteen.

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.

Asiasanat	energia, ydinenergia, ydinturvallisuus, ydinjätehuolto, tutkimus		
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KYT2022 Nationellt forskningsprogram om kärnavfallshantering 2019–2022 Slutrapport

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Referat

KYT2022 (Nationella forskningsprogrammet för kärnavfallshantering) är ett forskningsprogram finansierat av Statens kärnavfallshanteringsfond (VYR), som drivits av Arbets- och näringsministeriet under åren 2019–2022. Programmets syfte har varit att säkerställa att myndigheterna har tillgång till tillräcklig och heltäckande kärnteknisk expertis och annan kapacitet som behövs inom kärnavfallshanteringen.

Utgångspunkten för offentliga kärnsäkerhetsforskningsprogram är att de skapar förutsättningar för att bevara och utveckla den kompetens som behövs för ett fortsatt säkert och ekonomiskt utnyttjande av kärnenergi, samt att de befrämjar internationellt samarbete.

Innehållet i KYT2022 bestod av nationellt viktiga forskningsämnen relaterade till säkerhet, genomförbarhet och social acceptans av kärnavfallshantering. Forskningsprogrammet fungerade också som ett forum för diskussion och informationsutbyte mellan myndigheter, forskningsinstitut och organisationer som genomför kärnavfallshantering. Programmet syftade till att främja utvecklingen av nationell forskningsinfrastruktur, att säkerställa en kontinuerlig tillgång till expertis, att främja högkvalitativ vetenskaplig forskning och att öka den allmänna kunskapen inom kärnavfallshanteringen.

Nyckelord	energi, kärnenergi, kärnsäkerhet, kärnavfallshantering, forskning		
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FOREWORD

The Finnish Research Programme on Nuclear Waste Management KYT2022 ran from 2019 to 2022. 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 that the expertise in the area of nuclear waste management is available primarily for the use of authorities when evaluating different implementation methods and processes according to the objectives defined in the Nuclear Energy Act. In addition, the goal of KYT2022 research programme has been to support and complement the research programmes of the waste management organizations, and to further develop communication between authorities, waste management organizations and researchers.

The final report of the KYT2022 research programme presents the objectives set for the research programme, the attainment of the 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 July 2018, 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: Mia Ylä-Mella of STUK, the chairman of the steering group; programme head Suvi Karvonen, and project expert Aku Itälä of VTT; and Petri Jussila and Ville Koskinen of STUK, and Linda Kumpula of MEAE, the chairmen of the support groups.

Helsinki, March 2023

Ministry of Economic Affairs and Employment, Energy Department

1 Introduction

The Finnish Research Programme on Nuclear Waste Management (KYT2022) was launched in 2019 and ended at the end of January 2023.

The research programme was based on the Nuclear Energy Act (990/1987) and the research needs of the authorities. According to the Nuclear Energy Act, the purpose of the research programme is "*ensuring that the authorities have at their disposal such adequate and compre-hensive nuclear engineering expertise and other facilities as are needed to assess the various practices and methods of nuclear waste management*" (§53 b).

The research topics and objectives of KYT2022 were set in the Framework Programme[1], published by the Ministry of Economic Affairs and Employment in 2018. The aim was to focus on research topics that are essential for national competence development and important for the safety of nuclear waste management. Topics directly linked to the supervision of the use of nuclear energy, the handling of licenses or the preparation of license application were left outside the scope of the research programme.

The research programme revolved around public annual calls where proposals were made by research organisations, and the projects that are funded based on these proposals. The programme was governed by a steering group that had representation from all of the key actors in the field (STUK, Posiva, Teollisuuden Voima, Fortum, Fennovoima) as well as some of the relevant ministries (Ministry of Economic Affairs and Employment, Ministry of Social Affairs and Health, Ministry of the Environment). Of these, Fennovoima withdrew their license application from the handling of the Government in May 2022 and therefore ceased their participation in KYT2022 in 2022.

Compared to previous research programmes, KYT2022 introduced a new project type in Excellence projects. These projects received a funding recommendation from the steering group for one to four years. This was done toreduce bureaucratical load and increase stability of the research for selected projects.

1 KYT2022 Framework Programme, MEAE 2018. http://urn.fi/URN:ISBN:978-952-327-338-2

The KYT2022 research programme also served as a forum for discussion and communication between the authorities, nuclear waste organisations and research institutions. This was especially important during the research programme period and the situation created by the Covid-19 pandemic, where normal contacts between different stakeholders were reduced by necessity.

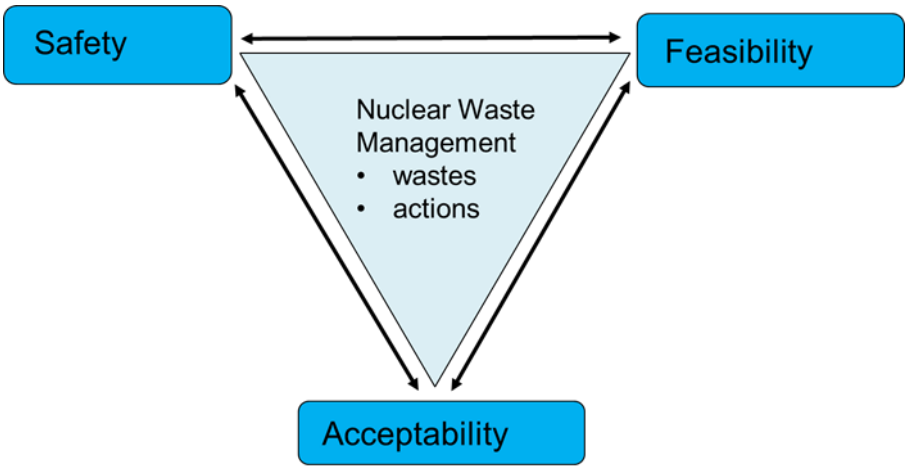
The KYT2022 research programme is the last of its kind as nuclear waste management research funded by the National Nuclear Waste Management Fund continues in the new SAFER2028 (National nuclear safety and waste management research programme 2023–2028) research programme, where nuclear waste management research is merged with nuclear safety research.

1.1 Objectives

The main objectives of the KYT2022 research programme are described in the KYT2022 Framework Programme[2]. The research topics were divided into three key areas:

1. safety in nuclear waste management,
2. feasibility of nuclear waste management, and
3. acceptability of nuclear waste management, as illustrated in Figure 1.1.

Figure 1.1. Thematic research areas of KYT2022.



2 KYT2022 Framework Programme, MEAE 2018. http://urn.fi/URN:ISBN:978-952-327-338-2

For the administration of the programme, i.e. project progress follow up and information sharing, the projects were categorised to thematic groups:

- Basic elements in safety
- Buffer/bedrock – interface
- Canister/Capsule
- Interaction between barriers/microbiology
- Host rock
- Other safety research
- Low and intermediate level waste management
- Alternative technologies
- Acceptability
- Infrastructure.

In addition to the Framework Programme, each year the Management Group of the research programme prepared a public letter containing instructions for the call for project proposals. The letter typically highlighted some research topics where new proposals are especially hoped for and described the evaluation criteria for the proposals received in the call. These have included e.g. overall safety research as well as research related to the closure of the repository.

Proposals received in the annual calls were evaluated using the following criteria:

1. relevance and usability
2. networking and integration
3. educational impact and scientific merit
4. efficiency demonstrated in KYT projects or in other context
5. realism in cost and workload estimates
6. novelty value of the research plan.

Relevance and usability has been assessed in accordance with the objectives set by the Nuclear Energy Act for granting research funding, and in relation to the annual letter published by the Management 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 required that research projects build networks among industry players and to set up joint projects and integral entities.

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.

Novelty in the assessment criteria can represent e.g. a new research topic, a new method or a new persperctive to an old topic.

1.2 Results and accomplishments

A total of 26 research projects were funded during the research period, either as separate and new projects or as continuations of previous projects. In all, 11 projects were in progress throughout the whole four year research period. The research projects were primarily linked to the assessment of the safety of nuclear waste management. During the research period, the National Nuclear Waste Management Fund funding for the research programme, including administration costs and infrastructure[3] funding, was approximately 13.5 million euro. Funding for research projects was 7.7 million euro from the National Nuclear Waste Management Fund and approximately 4 million euro from research organisations and other sources (e.g. end users, Nordic Nuclear Safety Research NKS). The distribution of the funding according to thematic areas are presented in Figures 1.2 and 1.3.

3 The financial arrangements of the VTT Centre for Nuclear Safety, commissioned in 2016, changed the calls for project proposals so that they consisted of two parts (a call open to all and an infrastructure call targeted only at VTT).

Table 1. VYR funding for the thematic research areas in the Framework Programme over the programme period 2019–2022, 7.7 million euro in total

Research area	No. of projects	Volume (VYR funding)
Engineered barrier system	4	3.3 million euro
Safety assessment and innovations	19	4.0 million euro
Society and man	3	0.4 million euro

Figure 1.2. VYR funding for different thematic research areas over the programme period 2019–2022, 7.7 million euro in total.

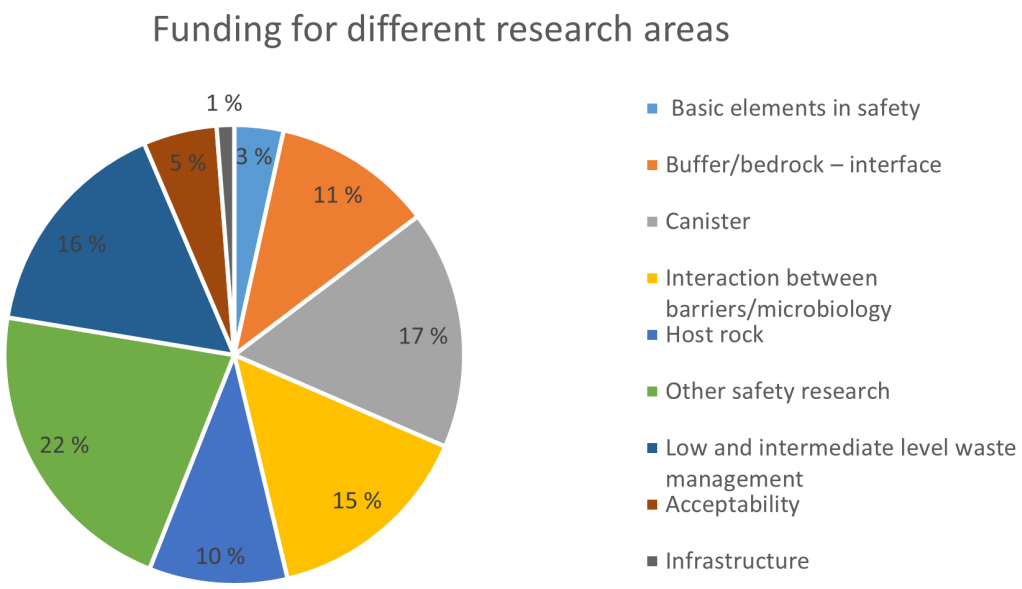
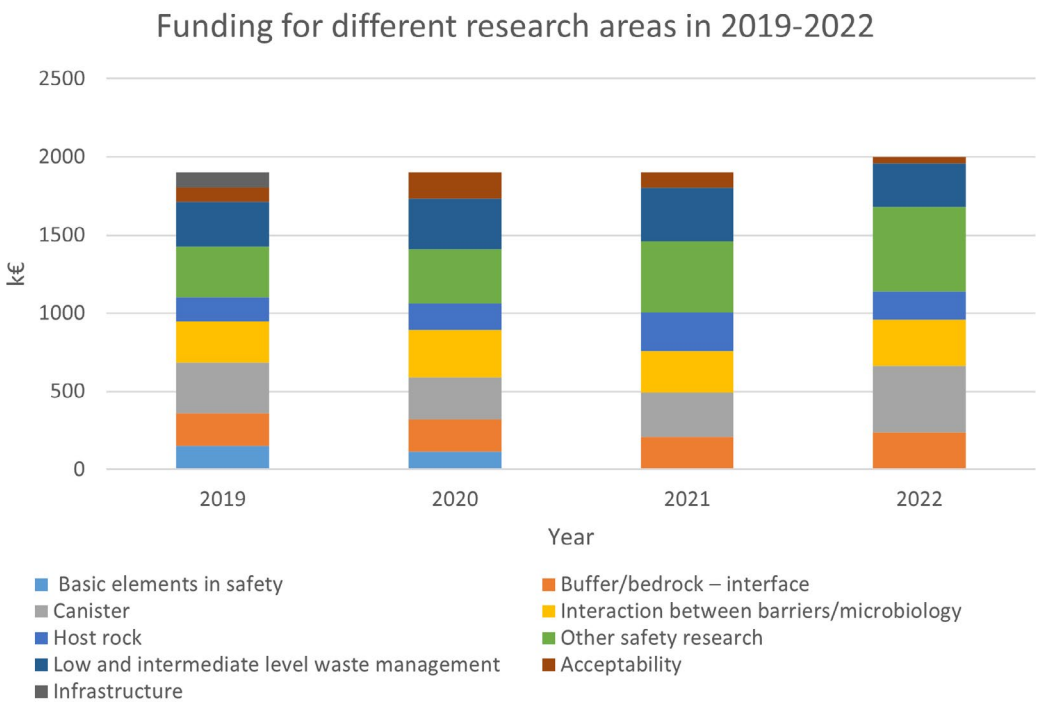


Figure 1.3. VYR funding for different thematic research areas over the programme period 2019–2022.



During the research period, the research programme projects have published a total of 64 peer reviewed articles, 150 conference papers or working reports, and 38 academic theses (see Table 1.1 below The titles of the publications have been reported in the annual reports of the research programme[4] [5] [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 KYT2022 programme that preceded KYT2022 and, correspondingly, part of the work done in the KYT2022 programme will be published in SAFER2028, which succeeds the KYT2022 and SAFIR2022 programmes.

4 KYT2022 Annual report 2019 http://kyt2022.vtt.fi/pdf/KYT2022_vuosikatsaus_2019.pdf

5 KYT2022 Annual report 2020 – http://kyt2022.vtt.fi/pdf/KYT2022_vuosikatsaus_2020_v1.pdf

6 KYT2022 Annual report 2021 – http://kyt2022.vtt.fi/pdf/KYT2022_vuosikatsaus_2021.pdf

Table 1.1. KYT2022 publications and theses in 2019–2022.

Publication	2019	2020	2021	2022	Total
Peer reviewed articles	16	16	18	14	64
Conference articles or working reports	53	31	27	39	150
Bachelor's theses	3	4	3	4	14
Master's theses	1	4	5	6	16
Doctoral theses	4	1	2	1	8

In total, 8 doctoral dissertations were completed during the research period.

- Pulkkanen (2019), topic: buffer/bedrock interface
- Kari (2020), topic: acceptability
- Forsström (2019), topic: canister
- Muuri (2019), Majlesi (2021), Li (2021) and Ho (2022), topic: other safety research
- Wiikinkoski (2019), topic: alternative technologies

Doctoral dissertations have a long time frame and at least part of the work has usually begun before the KYT2022 research period. They may also have other inputs from outside the KYT2022 programme.

The following research organisations have been involved in the KYT2022 research programme:

- VTT Technical Research Centre of Finland
- University of Helsinki
- Aalto University
- Geological Survey of Finland
- University of Jyväskylä
- University of Eastern Finland
- University of Turku
- Tampere University
- Rock Mechanics Consulting Finland

1.3 Evaluation of the research programme

The evaluation of the research programme took place in Helsinki in February 2022, jointly with the other VYR -funded research programmes (The Finnish Research Programme on Nuclear Power Plant Safety 2019 – 2022, SAFIR2022 and Framework Plan for the National Nuclear Safety Research Programme 2023–2028, SAFER2028). 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[7].

The evaluation report presented the findings, challenges and recommendations, as well as the overall conclusions. The main outcome of the evaluation was that in general, the research programme produces a remarkable level of scientific output for their limited funding. The role of the research programmes in producing new experts and competences required for the successful regulation of nuclear power and waste management activities in Finland was recognised in the report. The quality of the research products was generally considered to be of a high technical quality.

Areas for improvement were also discovered in the evaluation. In some instances, the research was seen to be aimed at mature fields of study where the value added in terms of increased knowledge or improved safety could be considered marginal, although the educational benefit in training new experts in relevant fields was acknowledged. The evaluation team recommended that research could be better directed to produce more meaningful (i.e., safety relevant) results in the future, through improved engagement between the researchers and the end-users, most notably STUK and Posiva.

The international evaluation result has recommendations related to the research areas of KYT2022. They saw that optimization and post-closure related topics should be considered in the research and that the funding balance between research projects related to the final disposal of spent fuel and research projects related to low and intermediate level waste repository should reconsidered in the future.

7 TEM 2022. SAFIR2022 Program, KYT2022 Program and SAFER2028 Draft Framework External Evaluation Report, Publications of the Ministry of Economic Affairs and Employment Energy 2022:36, 69 p.

The administration of the KYT2022 research programme was also considered in the evaluation. The structure was found to be simpler than in SAFIR2022, which lends itself to more flexibility and was considered appropriate for a smaller program (in terms of funding).

The evaluation team concluded that the program produced research of a high scientific quality, as evidenced by the number of peer-reviewed publications listed by the presenters, and by the technical content of the presentations themselves.

1.4 Administration of the research programme

The KYT2022 research programme work has been based on cooperation and the division of labour between the research programme steering group, three support groups, the directors of the programme and the research projects. The steering group has usually met five times a year (in 2022 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 National Nuclear Waste Management Fund to nuclear waste management research.

The research programme's support groups have met at least once a year every autumn. 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 administrative organisation of the research programme.

The steering group of the research programme was comprised of the 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 was chaired first by Jaakko Leino and by Mia Ylä-Mella from 2020 on (both from the Radiation and Nuclear Safety Authority). The other members were

- Linda Kumpula (Ministry of Economic Affairs and Employment), deputy Jaakko Louvanto
- Mikko Paunio (Ministry of Social Affairs and Health)
- Sami Rinne (Ministry of the Environment)
- Pasi Kelokaski (Fortum Power and Heat Oy), deputy Heidi Lampén
- Arto Kotipelto and Anne Kontula (Posiva Oy and Teollisuuden Voima Oyj), deputy Antti Tarkiainen
- Anne Kontula and Pekka Kupiainen (Posiva Oy)
- Heikki Hinkkanen (Fennovoima Oy), deputy Tuire Haavisto

The steering group 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.

1.5 Contacts

1.5.1 Seminars

A total of 13 seminars were organised for exchanging of information in the KYT2022 research programme. The themes of the research programme were discussed in 10 thematic seminars. They focused on one topic at a time and presented associated perspectives from the viewpoint of research institutions and end 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 KYT2022 programme was organised before the first call for project proposals. Similarly, a seminar for presenting the SAFER Framework Plan was organised together with the SAFIR2022 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 1.2. The materials of the seminars are archived on the website[8] of the research programme. Due to the Covid-19 pandemic during the programme many of the planned seminars were held as webinars.

Table 1.2. KYT2022 Research programe seminars in 2019–2022

Topic of the seminar	Time	Place
Presentation of the KYT2022 draft framework programme	20.8.2018	Aalto University, Espoo
SURFACE Seminar on Near Surface Repositories in Finland	26.9.2019	VTT, Espoo
SOLID-project seminar "Social licence"	7.10.2019	VTT, Espoo
Overall Safety in Nuclear Waste Disposal	7.10.2019	VTT, Espoo
Mid-term seminar of the KYT/SAFIR 2022 programmes	18–19.3.2021	Remote webinar
The first workshop on SMR Waste Management in Finland	2.6.2021	Remote webinar
The KYT Closure Workshop on respository closure related topics	23.6.2021	Remote webinar
KYT2022 SURFACE Webinar	3.11.2021	Remote webinar
KAPSELI seminar	10.11.2021	Remote webinar
Microbes and barrier material performance	23.3.2022	Remote webinar
Near field workshop by BROCTIO	13.5.2022	VTT/webinar
KYT2022 SURFACE project "Near Surface Repositories in Finland" final seminar	17.11.2022	Remote webinar
KYT2022 and SAFIR2022 final seminar	23–24.1.2023	Espoo/webinar

1.5.2 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. All projects included in follow-up groups 1–8 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 priorities of the end users in terms of project content and orientation. The project of follow-up group society and

8 http://kyt2022.vtt.fi/tapahtumat.htm

man -nuclear waste management acceptability typically organised an annual seminar 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 infrastructure projects was implemented in cooperation with the SAFIR2022 research programme. The SAFIR2022 programme has had a follow-up group specialised in monitoring infrastructure projects. The chair of the KYT2022 steering group and the coordinator of the research programme were members of this group.

1.5.3 Other contacts

The website of the research programme (kyt2022.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 had a protected intranet for use by the steering group and the support groups.

Each year, the research programme has published annual plans and annual reports. 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.

2 Research on Engineered Barrier System

2.1 Bentonite-Rock Interaction (BROCTIO)

The coordinated project Broctio was granted excellense status in the 2018 call for project proposals, therefore it has been able to plan for the whole duration of KYT2022. In the Broctio coordinated project, there have been three institutes supporting each other, VTT, University of Jyväskylä (JyU) and Finnish geological survey (GTK). Broctio is continuation from previous KYT-programs.

VTT work has focused on the model development for the rock shear movement effect on bentonite and experimental work supporting the model development. At the end of the program VTT has adequate data to begin the model development. Work will be continued in SAFER2028 program.

JyU work has focused on x-ray studies of the wetting of bentonite sample. The x-ray facility has been developed over several years and now provides unique opportunities to study bentonite wetting phenomena. During the research there was surprising result of sudden wetting in low density sample, same phenomena has not been detected in high density samples (similar density than is designed to be used in KBS-3 buffer).

GTK work has been focusing on mineralogical studies. GTK studies were effected by covid-pandemic, and it needed to be refocused. Much of the work focused on study of multispectral imaging to identify minerals in rock cracks. The method was proven to be quick, easy to use, and relatively accurate. This method might be useful also for quality inspections of bentonite in the clay-based barrier production.

Broctio has been internationally connected through EURAD projects. One doctoral thesis worker worked in BROCTIO, however there were no finalized thesis.

2.2 Canister

Canister projects were in coordinated project Kapseli. Kapseli included 6 different projects. Out of those six projects four lasted whole program, one started 2020 and one had funding only for the last year. Many of the projects were continued from the previous program KYT2018, but also new research projects were started. Research institutions involved in the Kapseli were Aalto university and VTT, both having three projects.

BECOLT – Behavior of copper under load transients (VTT). Project focused on creep behavior of copper canister and weld material under repository conditions, which impacts the safety related properties of the canister. Project has exceptionally long tests upto 20 years and therefore produced unique information on creep behavior of copper. One surprising result was that the heat treated (large grain size) sample behaved very differently that was assumed, therefore further investigation is needed if heat treatment of copper canister parts will be taken into use.

MECAN – Mechanical strength of copper canister and its cast iron insert (Aalto). Project focused on different processes and phenomena related to the canister and cast-iron insert that affect the mechanical stability. The project included design and testing of new testing samples. D-shape test samples were investigated and proven to be functional, although there are some issues with reliability. Also, X-shape specimens were studied but there are still open issues. In the second part the hydrogen loading of the copper was studied and the conclusion is that hydrogen can be accumulated in laboratory conditions into copper matrix enough to cause corrosion. Weather this is possible in repository conditions was not studied.

MECCI – Mechanical strength of cast iron insert (Aalto). The project was a spin off from MECAN, focusing on stain aging and hydrogen effect of cast iron. Project was ongoing only for 2022, and therefore the results are limited. Achieved results indicate that the hydrogen may have an effect on non-uniform deformations.

CRYCO – Validated advanced modelling and prediction of long-term deformation and damage of copper (VTT). The project is focusing on investigating the formation and evolution of cavities as a result from creep processes with a combination of scanning and transmission electron microscopy. These mechanisms are then implemented in a crystal plasticity model to evaluate the material performance during disposal time spans. The project has produced some models which are surprisingly accurate in small scale. The models need to be further developed to be practical tool for safety assessments, since currently model needs detailed SEM pictures as initial data, also computing power is limiting the scaling up to cm-scale at the moment.

OXCOR – The effect of oxide layer on copper corrosion in repository conditions (Aalto). The project focuses on answering the question whether an initial oxide film on the copper canister can increase the copper corrosion rate under relevant conditions. The results show that the impact of the initial oxide film has no measurable impact. These insights help to reduce uncertainties related to the performance of the canister for the period of consideration.

SUCCESS – Stress corrosion in copper caused by sulphide (VTT). Project was started on 2020. The project focuses on answering the questions that arose from a Japanese publication in 2008 regarding the role of sulfide species in stress corrosion cracking. As an final conclusion is that the probability of stress corrosion in copper under projected condition in disposal facility is very low.

Capsule projects have enabled several student to graduate and some of the graduated students have continued as researcher in the projects.

2.3 Microbiology

In the microbiology field there has been MoToPro coordinated project which has included interactions between different barriers (rock, clay and copper) and different test set ups. The coordinated project has involved research groups from VTT and GTK.

Due to the nature of microbiological investigations and difficulties on repeating test reliably, the results are challenging to apply to safety case work. The tests are complicated and when nutrients are added it will make the interpretation of the results even harder.

MoToPro coordinated project has enabled some students to graduate.

In addition of the coordinated project, there was one year long project (KAMU) on large scale gas generating experiment, located in Olkiluoto LILW-repository. Test has been evolving over 20 years and is planned to be dismantled. In this project the power companies invested their own money and gave steering work to get useful information as return for the investment.

3 Research on Safety Assessment and Innovations

3.1 Basic factors in safety

The projects under the title Basic factors in safety were the following:

- Overall safety, multibarrier system and transient phase (OMT) by VTT,
- Systematic scenario methods for the assessment of overall safety (SYSMET) by VTT and Aalto.

Both OMT and SYSMET were short projects: SYSMET was a 2-year Excellence project, while OMT ended after a single year.

These projects have been well suited to the Framework Programme covering the topic of overall safety. OMT seemed to be exactly tailored to the Framework Programme. However, as OMT was prematurely ended after the first year, it did not achieve all of its goals.

National collaboration and networking were one of the main goals of these projects and have in principle been at a high level.

The profitability and the usability of SYSMET could have been better if more concrete tools were constructed. The educational impact and scientific level of SYSMET have been high because of completion of one doctoral, one master's, and three candidate theses as well as publication of several articles. The cost-efficiency, novelty of the methods and new approaches of SYSMET have been reasonable. However, SYSMET could have benefitted from conducting a longer project than just two years.

3.2 Spent nuclear fuel waste management – Bedrock research

The projects under the title Bedrock research were the following:

- 3D-modelling of microstructures (MIRA-3D) by UTU,
- Bedrock fragmentation (KARIKKO) by GTK,
- Water conductivity of fractured rock mass (RAKKA) by Aalto,
- Factors affecting the chemical form of radio carbon in bedrock (C-ROCK2) by UH,
- Comparative analysis and development of modelling of earthquake fault ruptures (BEEFS) by VTT and RMCF.

C-ROCK2 ended after one year, BEEFS started in the final year of the programme, and MIRA-3D ended after three years of research. C-ROCK2 did not achieve all of its goals because of its untimely end.

All these projects have been well suited to the Framework Programme covering the topic of safety and the sub-system of bedrock.

The profitability and the usability of the results have been diverse. The short duration of C-ROCK2 and BEEFS naturally lowered the benefits of these projects as well as their chances to collaborate. The other projects in this category continued their long and succesfull history in Finnish research programs with good national collaboration and networking. All the projects could have benefitted from more international collaboration.

The projects have trained new experts and produced several scientific articles implying a good scientific level. In view of the results, the cost-efficiency has been average. Novelty of the methods and new approaches have been at a good level for all the projects.

3.3 Spent nuclear fuel waste management – Other safety research

The projects under the title of Other safety research were the following:

- Radionuclide transport on the interface of cement and bedrock (RASK) by UH,
- Better radioecology for the modelling of biosphere (RABIO) by UEF,
- Characterization and source term of spent nuclear fuel (KÄRÄHDE) by VTT,
- Microstructure of nuclear fuel and radium solubility (PORA) by VTT, and
- Using volcanic-geothermal fields as natural laboratories to investigate transfer of 14C in soils and into terrestrial food webs (NAT-LAB-14C) by UEF.

PORA and NAT-LAB-14C were only 2-year projects but despite that managed to reach notable results as all the other projects in this category.

All these projects have been well suited to the Framework Programme covering the topic of safety and the subsystems of spent fuel, concrete, bedrock, and biosphere.

Both the profitability and the usability of the results have been notable as the projects have produced both qualitative and quantitative information of safety significant parameters for the assessment of the source term (KÄRÄHDE) and radionuclide transport (RASK, RABIO, PORA, NAT-LAB-14C).

National and international collaboration and networking have mainly been good but diverse. PORA was a successful bridge between KYT and SAFIR as was called for in the Framework Programme. However, it could have collaborated more concretely with the other projects. The biosphere projects could also have benefitted from better networking.

The projects have trained new experts and produced several scientific articles implying a good scientific level. Some of the projects have also used more experienced workers. In view of the results, the cost-efficiency has been average. Novelty of the methods and new approaches have been at a good level. Especially, PORA and NAT-LAB-14C have developed new kinds of approaches in the field.

3.4 Low and intermediate level waste management

The projects under the title of Low and intermediate level waste management were the following:

- Near Surface Repositories in Finland (SURFACE) by VTT and UH,
- Corrosion of low and intermediate level steel waste in in-situ conditions of final repository (TERKOR) by VTT,
- Decommisioning Material characterization and final disposal studies (DEMONI) by VTT and UH,
- Durability testing of Concrete in Long-Term Simulated Groundwater Conditions (ConLot) by Aalto.

ConLot started in the final year of the programme.

All these projects have been well suited to the framework programme covering the topics of safety, power plant waste management, management of decommissioning waste and subsystem of concrete.

The profitability and the usability of the results have generally been at a good level. National and international collaboration and networking have mainly been good. SURFACE was a joint project of VTT and UH, and there was a close collaboration between TERKOR and DEMONI. ConLot was a short and rather self-sustained project. The projects have trained new experts and produced several scientific articles implying a good scientific level. SURFACE contributed to a doctoral thesis.

The cost-efficiency has been reasonable while on the other hand the projects in this category have been slightly more expensive than average because of large proportion of experimental work and experienced workers. Novelty of the methods and new approaches have been reasonable while the areas of research in this category are rather established. Notably, SURFACE studied a new area of near surface disposal and DEMONI developed new methodologies measuring difficult nuclides.

3.5 Alternative Technologies

The projects under the title Alternative Technologies were the following:

- Separation and sorting of actinides/lanthanides (ALES) by UH,
- SMR Siting and waste management (SMRSiMa) by VTT and GTK.
- SMRSiMa started on the last year of the Programme but was a partial continuation of the previous project called SMRWaMa.

The projects have been well suited to the Framework Programme covering the topics of safety and feasibility of nuclear waste management, and the subsystem of spent fuel.

National and international collaboration and networking have mainly been good. ALES and SMRSiMa included gathering of national and international information. SMRSiMa was also an interdisciplinary project and collaborated with KÄRÄHDE. Both projects could still have benefitted from more collaboration.

The scientific level has been good. ALES has been at a high level producing a doctoral thesis as well as scientific articles. SMRSiMa has produced new knowledge and presentations but not any theses have been reported.

In view of the results, the cost-efficiency has been average. Profitability, usability, novelty of the methods and new approaches have been diverse. The results of SMRSiMa can be considered very interesting at the current technological and political situation of SMR reactors. On the other hand, the results of alternative technology studies in ALES can be considered as not directly usable.

4 Research on Acceptability and Society

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 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 the society. Government decisions are influenced by the values and expectations of society.

In the research programme, the views on nuclear waste management and, in particular, on the 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 e.g. ethical and public discussions, issues relating to the industrialisation of disposal plans, feasibility of disposal, control and monitoring of disposal facilities after closure and reliability and preservation of information over the long term.

In 2019–2020, the research programme funded a social research project Acquiring Social License for Disposal: trust and acceptance (SOLID) by University of Tampere. The project aimed to improve understanding of the Finnish nuclear waste management (NWM) and particularly its continuity and flexibility in the changing socio-technical context. The project also compared Finland and France by framing of safety in decision-making on NWM as well as potential virtues of mistrust and distrust in the countries.

In 2021–2022, the research programme funded also a research project Mapping of Closure-Related Issues in Finnish Radioactive Waste Repository Programs (CloMap) by VTT and a related research project Nuclear waste disposal and social memory (YLUMU) by University of Turku. The aim of the CloMap was to identify and describe the most critical decisions, activities, uncertainties and readiness regarding the transitions from late operational to closure and immediate post-closure phases of repository programs in Finland. The aim of the study was also select the most critical or prominent issues for which the need for further development is most acute. The aim of the YLUMU was to create a snapshot of how Finland has prepared for the preservation of information and memory about the disposal of spent nuclear fuel in the past and present, and to generate discussion on the topic, especially in the case of closure and post-closure of the repository.

In order to develop these procedures, the solutions proposed elsewhere and currently being developed were explored. The aim was also to improve the durability of the information and experience on disposal in the very long term.

In 2021, social interest in small modular reactors (SMRs) was growing in Finland. This led to a decision to fund Preliminary study of the waste management of small reactors (SRMWaMa) by VTT at first as a social research project. The aim of the study was to investigate the waste management of SMRs in Finland, including the types of SMRs relevant for Finland, the spent nuclear fuel and other radioactive wastes generated by SMRs and their differences to the wastes generated in existing nuclear power plants, as well as the organisation and implementation options for waste management. The aim was also to identify the main areas for further development in the management of waste from SMRs. The research continues in 2022 as a technical research project (see Chapter 3.5).

The results of social research can be used when assessing the social acceptability of nuclear waste management and need for information in society. The results also offer opportunity to reflect Finnish nuclear waste management in relation to international discussions, and help in anticipating new societal concerns and challenges. Based on the research results, it is also possible to highlight topics that require further research and to obtain new perspectives and good practices. Social interest on a specific topic may also generate new research projects in the programme. 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 also internationally important, and research findings are published in international publications in the sector.

5 Project Summaries

5.1 Spent nuclear fuel waste management – Buffer/Bedrock – interface

5.1.1 BROCTIO – Bentonite-rock interaction

Coordinator Markus Olin[9]; subproject managers: Veli-Matti Pulkkanen[9], Markku Kataja/ Arttu Miettinen[10], Jukka Kuva[11]; Other personnel: Olli-Pekka Rauhala[9], Tero Harjupatana[10], Joni Parkkonen[10], Heini Reijonen[11]

5.1.1.1 Research topic and key results

Bentonite-rock interaction project (BROCTIO) focused on hydraulic, mechanical and chemical interaction of the engineered clay barriers and the crystalline host rock in the KBS-3 disposal concept planned in Finland. The objective was to produce experimentally quantitative data on the hydraulic and mechanical behaviour of the clay components when they interact with the surrounding host rock. The research topics were 1) transport phenomena at the bentonite-rock interface, 2) the effect of bedrock on bentonite mechanical behaviour, and 3) rock fracture and material characterisation.

Monitoring transport phenomena at bentonite-rock interface using X-ray tomography (University of Jyväskylä)

Monitoring transport phenomena at the bentonite-rock interface using 4D X-ray tomography and image analysis revealed that water transport in high density bentonite samples resembles diffusion (negligible pressure dependence), while in low density samples advection seems to be important (significant pressure dependence). In addition, a sudden flow phenomenon through low density samples was observed in certain wetting geometries when the wetting pressure was increased at the beginning of the experiments. Bentonite transport measurements showed that only small amount of bentonite was eroded from the samples into rather small fractures used in this study. As

9 VTT Technical Research Centre
10 University of Jyväskylä
11 Geological Survey of Finland (GTK)

transport processes in the bentonite buffer and its mechanical behaviour are not yet fully understood, the detailed data set obtained here potentially helps to develop and validate better transport and material models.

Triaxial experiments for bentonite mechanical constitutive models (VTT)

An experimental process for bentonite mechanical testing covering the full cycle of bentonite sample preparation from bentonite powder to shearing the final samples was developed. In the process, batches of wetted bentonite powder were compressed and machined into standard size samples for shearing tests allowing the studying of bentonite buffer elastoplastic behaviour dependency on conditions and deformation rates. The data from the cyclic, isotropic compression were used for creating constitutive large deformation elastoplastic mechanical models.

Characterization of the bedrock fractures (GTK)

Fracture mineral investigations showed that the short wave infra-red methods can aid in clay characterization at the fracture rock interface and aid specifically in swelling clay identification. Example fracture surface with montmorillonite identified is provided in Fig. 5.1. These results have several applications related to overall safety: 1) identified fracture filling smectites can be used as natural analogues for bentonite buffer in the safety case, 2) hyperspectral methods used provide fast and efficient tool for challenging characterization tasks in underground construction where swelling minerals pose an operational safety risk 3) same tools can make fracture filling characterization much more efficient in the underground disposal facilities.

The meaning of results safety of nuclear waste management

The purpose of BROCTIO was to produce experimental data about bentonite behaviour that can be used directly in models. In this way the path to safety and performance analysis can be kept as short and clear as possible. The key results were the developed experimental research methods and processes together with detailed numerical data from the experiments, which can be used for model conceptualisation and parametrisation. The existing and developed models can be used in simulations of safety, performance and feasibility of bentonite-based materials.

Figure 5.1. Example of fracture minerals samples studied showing X-ray tomography image with details embedded from sample photography and selected hyperspectral analysis results. X-ray tomography cross-section shows how thin fracture filling clay is.

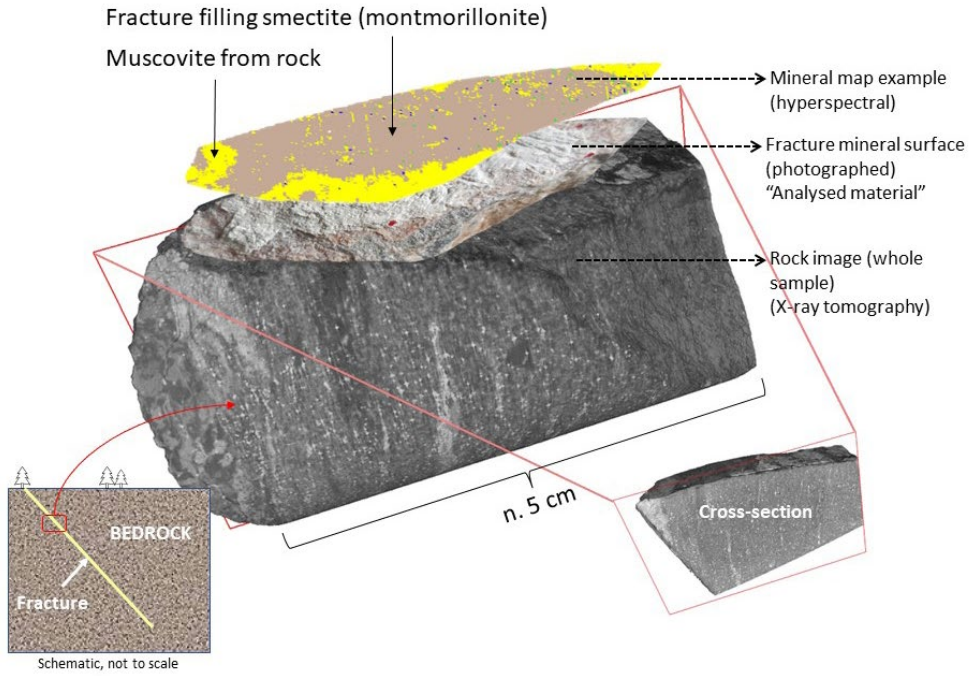
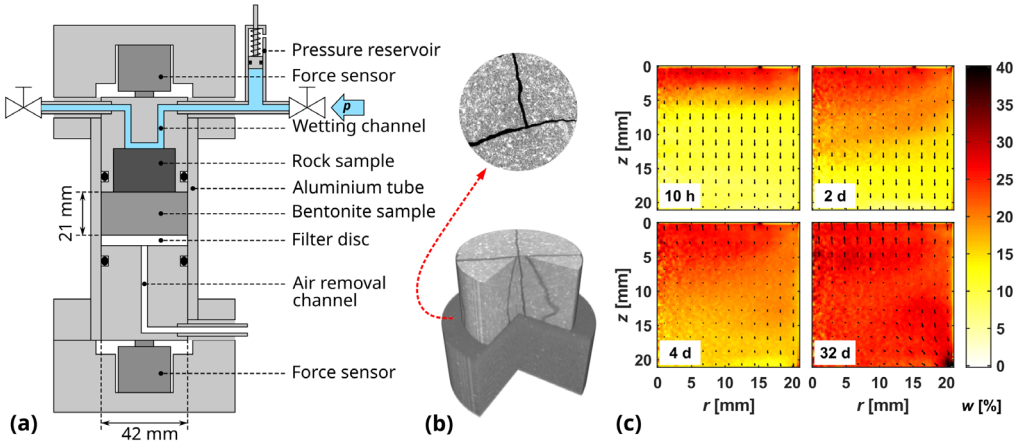


Figure 5.2. Sample chamber (a), CT image of bentonite-rock sample (b), and example of results, azimuthally averaged water content distributions and displacements in bentonite sample at four instants of time (c).



5.1.1.2 Methods

Monitoring transport phenomena at bentonite-rock interface using X-ray tomography

Transport phenomena at the bentonite-rock interface were studied using X-ray tomography (CT). Compacted cylindrical bentonite (Bara-Kade) samples (d = 42 mm and h = 21 mm) were kept in a constant volume in specific sample chambers and wetted with groundwater simulant from the upper end (Fig. 2a). The sample chamber was also equipped with force sensors to monitor the axial swelling stress at both ends. Three wetting geometries (wetting through filter disc, 3 mm hole and cracked rock), two dry densities (1.40 and 1.65 g/cm^3) and three water pressure levels (0, 2 and 4 MPa) were used in the experiments. Each sample was imaged 10–16 times during the experiment (1–4 months) using an in-house built Jtomo microtomography device, located at the X-ray tomography laboratory at the University of Jyväskylä. The obtained CT images (Fig. 2b) were analysed using the previously developed and here improved method. After careful correction and calibration procedures, the method yielded 4D (3D + time) dry density distributions, water content distributions and displacement fields in bentonite samples (Fig. 2c). The mass of bentonite in the holes and cracks was measured gravimetrically at the end of the experiment and was also monitored from CT images. Total of 19 successful full-length experiments (233 CT scans) were performed during the project.

Triaxial experiments for bentonite mechanical constitutive models

An experimental process for fully controlled mechanical testing of bentonite elastoplastic properties in altering conditions was created. The mechanical testing workflow stages are schematically presented in the Fig. 5.3.

Figure 5.3. Mechanical testing workflow.

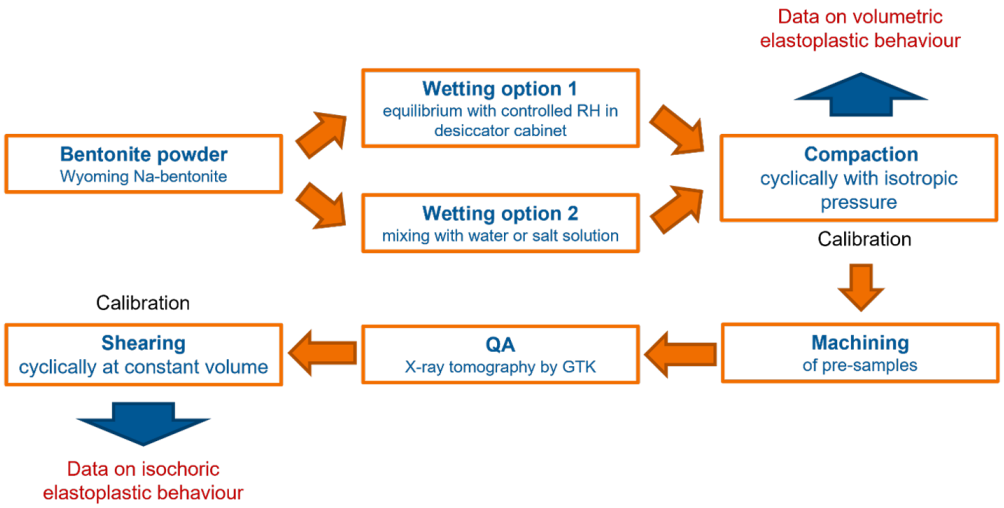


Figure 5.4. Example pressure-volumetric compaction data.

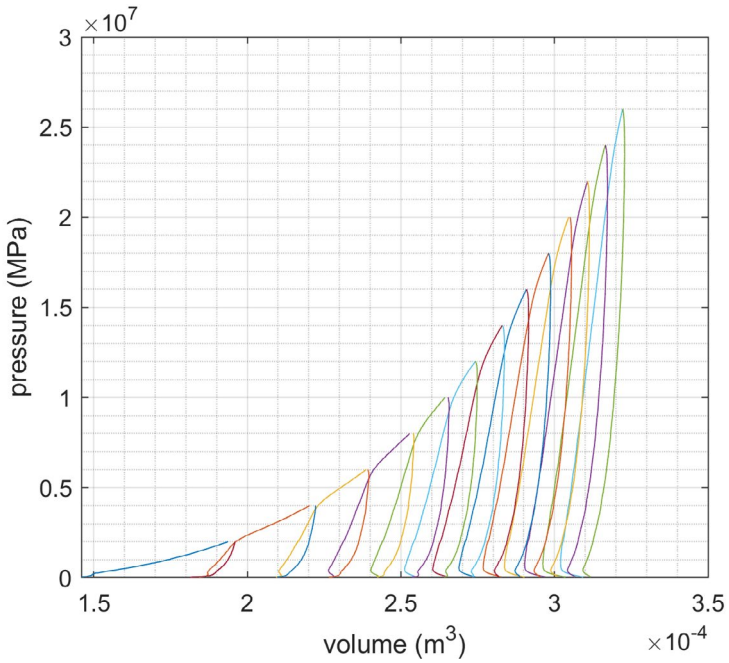
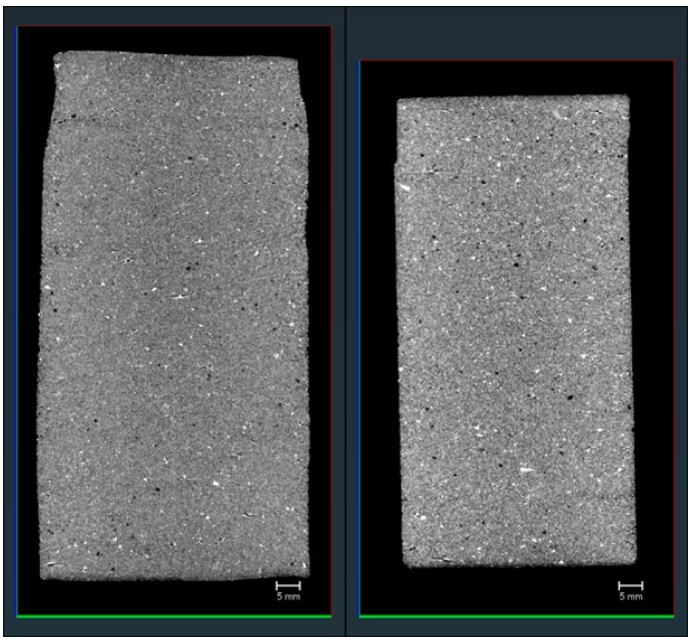


Figure 5.5. X-ray tomography image (by GTK) before and after machining.



The bentonite powder was wetted to a chosen water content either by water vapor equilibrium technique or mechanical mixing of liquid water to the powder. In the former one a controlled relative humidity was created inside a desiccator cabinet with a known supersaturated salt solution. The bentonite powder was laid insider the cabinet where it absorbs or desorbs water depending on the surrounding atmosphere and sets into equilibrium with it without mechanical or chemical distortions. Mechanical mixing of water provides a faster wetting option to smaller batches at a time with the option to control the salinity of the mixture.

Solid pre-samples were compacted from the wetted bentonite powder with isotropic pressure using a triaxial cell (GDS Instruments 32 MPa cell with silicone oil in a 250 kN hydraulically actuated load frame). The material volumetric compressibility was studied throughout the compaction with a simultaneous volume measurement and the compaction was performed cyclically to enable the separation of elastic and plastic deformations (Fig. 5.4). The system was calibrated for compaction with sample-size steel dummies to exclude the deformation of equipment from the data.

Following the compaction, the pre-samples were machined into a fixed size, 100 mm tall and 50 mm diameter cylinder, with a lathe. A quality control X-ray tomography can be run to the samples before and after this stage to verify that the machining has not affected the sample internal structure (Fig. 5.5). Finally cyclic shearing tests at constant pressure in the triaxial cell were performed on the samples with the load frame axial piston. Load-deformation data was collected, and shear strength can be demonstrated. The system was calibrated similarly for the shearing to exclude equipment deformations.

Characterization of the bedrock fractures

The XCT was performed with a GE phoenix v|tome|x s instrument. For VTT sample quality control (Fig. 5.5) the settings were always the same, with a 100 kV accelerating voltage and a 0.5 mm copper filter. The helical scans lasted for about 70 minutes per sample. For the natural clay fractures the accelerating voltages were 100 – 150 kV with a 0.5 mm copper filter, with scan times varying between 25 and 183 minutes per sample. For the clay fracture samples this was done as the first step for each sample. The 3D data was analyzed with ThermoFisher PerGeos 2020.2.

The clay fracture samples were also investigated using two types of hyperspectral instruments, X-ray diffraction (XRD), scanning micro X-ray fluorescence (μXRF), scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS) and optical microscopy with a digital camera. Hyperspectral measurements were also conducted for several clay fracture samples with a handheld Terraspec HALO spectroradiometer, that

works in the visible to shortwave infrared range (350 – 2500 nm) and a hyperspectral imaging setup located at Spectral Imaging Ltd. (SPECIM) in Oulu, Finland, working in the shortwave infrared range (1000–2500 nm).

From some clay fracture samples an area of approximately 2 cm^2 of the fracture filling was scraped off for XRD measurements, performed with a Bruker D8 Discover Bragg-Brentano powder diffractometer. The data was analysed with Bruker EVA software. Finally, four thin sections from selected clay fracture samples were prepared, and the thin section were analysed with µXRF, SEM-EDS and optical microscope to determine their mineralogy and elemental composition.

5.2 Spent nuclear fuel waste management – Canister

5.2.1 KAPSELI/BECOLT – Behaviour of copper under load transients

Project manager/Coordinator of Kapseli: Juhani Rantala[12]; Other personnel: (Jarkko Metsäjoki, Tom Andersson, Anssi Laukkanen, Kari Korhonen, Tuomo Kinnunen, Rami Pohja)[12]

5.2.1.1 Long-term uniaxial testing

During the project two long-term uniaxial creep tests for Cu-OFP were running: test y211 V1 at 120MPa 152ºC and test y303 K3 at 70MPa 200ºC. The test y211 was interrupted for inspection at 170849 hours (19.5 years) at a strain of 32.3 % and has been continued. The strain rate has reached the minimum strain rate and has already passed the expected rupture life predicted by the Wilshire equation. During the four interruptions the gauge diameter was measured. Oxide cracking has been observed during the inspections and it seems that the length of the cracks has not grown but the number of cracks is increasing with time. This single test result is valuable in the sense that it shows that creep ductility of Cu-OFP remains high to long times with a strain of over 32 % at the time of minimum strain rate.

The test y303 at 70MPa 200ºC was terminated after 117523 hours (13.4 years) at 10.0 % strain. Although the strain rate had already started to turn towards the minimum strain rate it was estimated that the test would become too long to be continued

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to rupture because the strain was currently only 10.0 %, so the test was terminated permanently. The specimen can be used in the future projects for inspection of early creep damage.

5.2.1.2 Load history dependence

A strong load history dependence in the creep behaviour of Cu-OFP was first reported in SKB R-14-31. The load was applied at 75°C in a stepwise manner by first applying only 80 % of the load for a fixed period, after which the load was increased to 90 % and held for the same period and finally the full load was applied. The main testing temperature of SKB has been 75°C, so in the KYT project VTT wanted to find out whether a similar load history dependence would appear at the main testing temperature of 175°C of the Finnish programme and at 90°C, which is the likely peak temperature the canister wall will experience. It was surprising that the stepwise loading had a strong effect at 75°C (tested by SKB) and at 175°C (tested by VTT), but not at 90°C. This behaviour cannot be predicted by the current creep models and is most likely a result of stabilised dislocation structures collapsing and new dislocations being created when the stress is increased. TEM inspections would be needed to confirm this assumption.

5.2.1.3 Effect of grain size

The original design of the canister with a pierced & drawn tube with an integrated bottom there were areas in the canister bottom where the grain size was much larger as a result of the forging process and recrystallization. Posiva Oy offered to co-fund this theme in the KYT programme and provide suitable test material for creep testing in 2020. The test material had to be produced by heat treatments, which caused long delays. Test temperatures of 175°C and 250°C were selected for grain sizes 370µm and 600µm. The rupture time of the KYT series at 175°C with 370µm and 600µm grain sizes differs by orders of magnitude from the reference data. At 250°C there is about factor of 3 to 6 difference between the KYT results and normal grain size results. TEM investigation of the dislocation density would be needed to cast light on the differences.

5.2.1.4 Relaxation

In the repository the canister will experience a forced displacement loading case where the deformation is limited by the dimensions of the canister, the insert and the air gap between those, so the copper material will experience a relaxation period at a fixed strain and decreasing stress.

In the beginning static relaxation testing was carried out where the test specimen was subjected to a fixed strain and the decreasing stress was monitored during the test period. Kohlrausch relaxation model was used for fitting the data. As next phase cyclic relaxation tests were performed for Cu-OFP. Several stress relaxation periods of 70 to 200 h under tensile stress were applied to test specimens. the new SAFER2028 framework programme the relaxation testing will serve Crystal Plasticity modelling in the MOCRYCO project.

5.2.1.5 Combined effect of creep and corrosion

Cu-OFP CT-specimens were submerged into Olkiluoto reference groundwater at 90°C and wedge loading was used for maintaining the mechanical stress of 35MPa in the specimen. The purpose of this test was to see if there is a combined effect of creep and corrosion at the tip of the notch of the CT specimen. Two tests were made with the first test duration of 1000 hours and the second of 5000 hours. No combined effect of creep and corrosion was seen. It can be argued that possibly the test arrangement was not completely successful in the sense that the wedge loading is not well controlled.

5.2.1.6 Damage behaviour

A M.Sc thesis was completed in 2021. A series of cross-weld creep tests of friction stir welded copper tested for Posiva Oy were used for the thesis work. The cavitation damage was assessed by calculating the cavity density, the cavity area fraction and grain size of the specimens. For calculating the cavity density image processing software was used to automate the cavity counting from optical images over a large surface. The automated image analysis is now available for analysing other creep tested specimens, either fractured specimens or specimens interrupted at a predefined strain or life fraction.

Furthermore, more detailed studies on the creep cavitation damage were conducted in a Ph.D project by investigating the size and shape of creep cavities using scanning electron microscope. Based on copper material creep cavitation studies (along with selected steel materials), a new material damage model based on the creep cavitation propagation was developed during the course of the project and published in a scientific journal. The life of material/component is proportional to the creep cavitation measure, such as cavitation area fraction.

5.2.2 KAPSELI/MECAN – Mechanical strentgh of copper canister and its cast iron insert

Project manager: Sven Bossuyt[13]; other personnel: (Risto Ilola, Yuriy Yagodzinskyy, Antti Forsström, Patrik Sahiluoma)[13]

5.2.2.1 Localisation of strain in copper capsules

Antti Forsström's PhD thesis on 'Localized deformation in spent nuclear fuel disposal canisters' was completed. The dissertation was accompanied by articles on improving the resolution of optical strain measurement in copper and quantification of the data published in 2019. In addition, a second article was written on the localisation of strain in new and old capsule welds and the effect of hydrogen on the mechanical properties of the welds.

A new DIC system was taken into use. Initial measurements with a D-shaped specimen designed to provide non-uniform deformation data have now been carried out. Optimized geometry and speckle pattern have been developed in order to gather wider range of strain rate dependent data that could be used in future for material model calibration through inverse methods such as the Virtual Fields Method. Recent work has focused on developing the methodology and patterning methods to make future work more efficient.

5.2.2.2 Effect of hydrogen on copper

An article on deformation and strain localisation in copper capsule friction stir welds (FSW) was published in 2019. The absorption of hydrogen in FSW welds containing oxide particles and in welds welded using shielding gas was also investigated. The oxide particles significantly increase hydrogen absorption but had no effect on the macroscopic ductility of the weld in these experiments. No hydrogen was absorbed in the weld specimens produced using shielding gas. However, it is noteworthy that the new shielded weld was inferior to the old weld in terms of mechanical properties. This is due to the inferior material used in the canister lid rather for these specimens, rather than due to any deficiency in the new welding method.

An article on hydrogen micro-voids was published in 2023. Copper samples were charged with varying electrochemical potentials and a significant change was found when potential was below -1,1V Hg/Hg_2SO_4. The hydrogen content measured with thermal desorption spectroscopy (TDS) increased markedly and the sample surface became thoroughly covered with microscopic voids. After electroless nickel-plating, the

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cross-sections of the samples were examined, and the voids were observed up to depth of 20 µm. It is unclear how these micro-voids relate to the micro-voids that develop during creep testing of copper.

5.2.2.3 Stress corrosion of copper

Sulphide stress corrosion of copper was studied in collaboration with Studsvik (Sweden). Preliminary results were published at the Eurocorr 2017 conference and were the basis for two additional 1-month experiments. The results of these trials were presented in November at the LTC2019 conference in France. A SSM report on the results was published and was the basis for an article for the LTC2019 conference. In particular, the new experiments were used to study the structure of sulphide films under different conditions and the absorption of hydrogen in sulphide-rich environments. Under stress, hydrogen accumulated in the copper, as in the previous experiments, but not under no stress. This suggests an interaction between the vacancies and hydrogen during deformation.

Intergranular stress corrosion cracking was found to occur in reducing anoxic conditions at sulphide concentration of 0.001 M. Defects on grain boundaries were found in sulphide concentrations of 0.00001 M and in FSW welded copper samples when welding was done in air and tested in high sulphide conditions. Film in low and high sulphide solutions were thin, single-layer and multilayer respectively. Both films were porous and brittle. Hydrogen uptake was increased when plastically deformed in slow strain rate testing (SSRT). A conference paper was published in summer of 2020.

These studies were then continued in co-operation with VTT. Creep experiments in sulphide environment were executed in SUCCESS-project by VTT and Aalto University measured the hydrogen content in the samples and did the microstructural analysis. The copper specimens were hydrogen charged under tensile loading in sulphide contents of 0.006 M and 0.002 M for 2 days and 2 weeks respectively. The material exhibited the three-layer sulphide film in both experiments, similarly observed in previous studies. However, cracking was found under the longer exposure with sulphide content of 0.002 M in the tensile specimen.

5.2.2.4 Hydrogen effects in ductile cast iron

It was found that hydrogen significantly affected ductile cast iron (DCI). The strain rate in both SSRT and constant load testing (CLT) increased markedly under hydrogen charging. Under the effects of hydrogen and tensile loading, the failure mode of DCI changed from ductile to brittle. Also microscopical examination of the material revealed small cracking around nodules in ferritic matrix and detachment of graphite nodules from the matrix.

Also, the trapping potential of DCI increased under tensile loading and hydrogen uptake occurred by free immersion in 0.1 N H_2SO_4. A M.Sc. thesis and a conference paper were published in spring and summer of 2020 respectively.

Criticism that these hydrogen charging conditions are too severe to be relevant to the repository conditions led to an assessment of the maximum concentration of hydrogen that could occur in the repository. The previous upper end of the estimated range of expected *average* hydrogen content in the insert was based on the calculation of 600 grams of allowed residual water accounting to 7 wt.ppm of hydrogen for the whole insert with 2 wt.ppm coming from metallurgical hydrogen. However, a maximum *local* concentration of hydrogen that could be present in the cast iron insert could not be established, because mechanical stress significantly enhances hydrogen uptake and there are local stress concentrations in the canister insert.

5.2.3 KAPSELI/CRYCO – Validated advanced modelling and prediction of long term deformation and damage of copper

Project manager: Tom Andersson[14]; other personnel: (Rami Pohja, Anssi Laukkanen, Pertti Auerkari, Juhani Rantala, Asta Nurmela)[14]

Regarding the spent nuclear fuel repository in Finland, the copper overpack of the canister will be an important barrier against release in the repository. As the hydrostatic and bentonite swelling pressure will develop in the environment of final repository, the copper overpack will be pressed against the insert, affecting the stress state in the overpack. Depending on location, stress-strain history from manufacturing, transport and assembly, defect structures, and possible rock movement, the resulting deformation and damage is challenging to predict and assess in detail. A particular challenge will arise from these changes being time-dependent and very slow in comparison to most technical applications that are designed for relevant deformation and damage mechanisms (creep, stress relaxation and cyclic loads). Oxygen-free phosphorus-doped (OFP) copper is the intended material for the overpack that will protect the spent fuel canisters against corrosion in the underground final disposal repository in the Olkiluoto Onkalo site. Because the canister will experience internal heating by residual nuclear fuel activity, with loads or strains from thermal, handling or other sources the shell may creep to some extent. Additionally, the shell may experience stress relaxation, when such loading is

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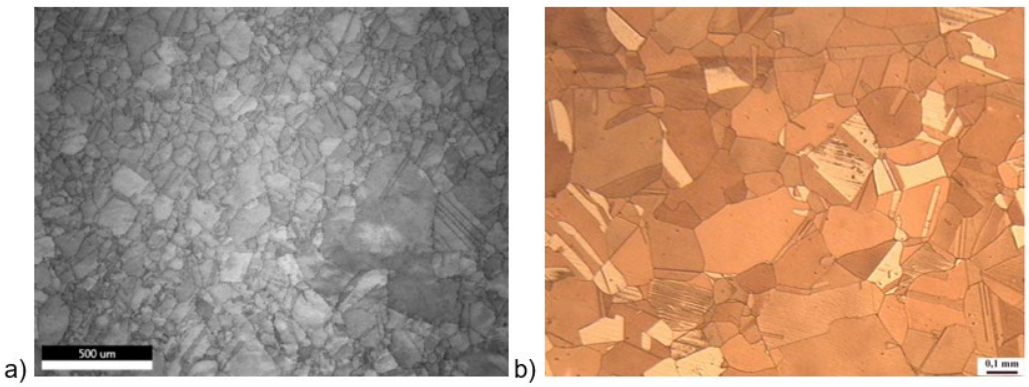
first peaking and then followed by steadier periods under constraint. Relaxation refers to material response where the stress under structural constraint is decreased (relaxed) by mechanism of creep.

Examined OFP copper material was delivered to VTT for the studies by Posiva. The nominal chemical composition of the test material (OFP copper) is shown in Table 5.1 and in Figure 5.6.

Table 5.1. Chemical composition of the tested material.

Element	Cu	P	Ag	S	O	H
ppm	bal.	50–55	10.6	5.1–5.2	1.3–1.8	0.38–0.5

Figure 5.6. The OFP copper microstructure; a) a SEM image, b) a light optical microscopy image.

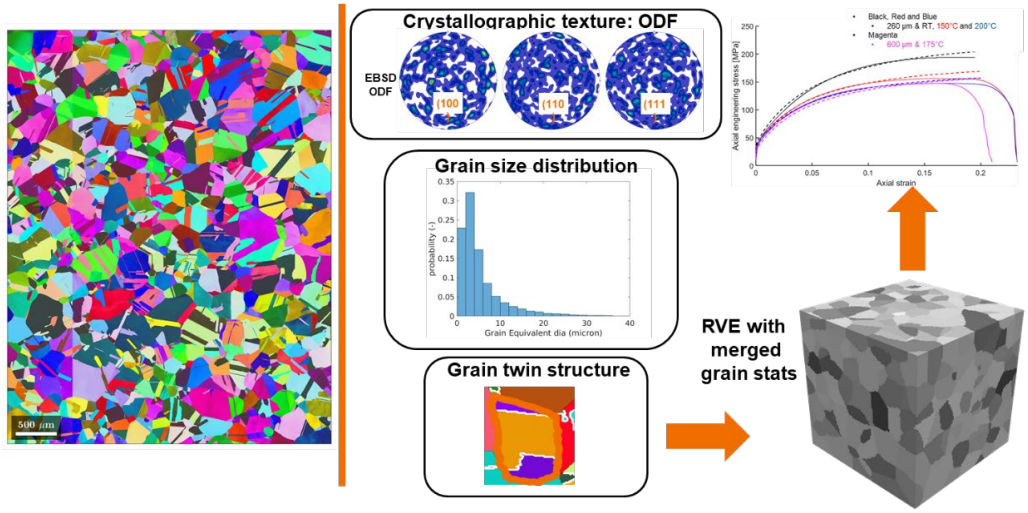


The objective of the research was to gain further understanding of the mechanical behavior of the copper canister under repository conditions. The project consist of 3 part:

1. To characterize the relevant OFP-copper material and gain insight of the damage mechanisms at play during the lifetime of the material in relevant conditions.
2. To perform stress relaxation testing for the OFP copper material and developing an engineering stress relaxation model for the OFP copper material to assess and verify the performance of the material. Both tests with single relaxation period and tests with multiple relaxation periods were performed.
3. And finally to develop FE-based crystal plasticity copper material model that is able to take into account and estimate the deformation mechanisms at microstructural level to gain insight of the critical (to creep behavior) features of the material.

Figure 5.7 shows the shows the EBSD mapping revealing the orientation of the crystal planes in the microstructure. The measured hardness of the material (HV5) was between 40 and 42.

Figure 5.7. Workflow from SEM EBSD IPF image of copper microstructure to finite element mesh with EBSD based grain structure and finally to stress-strain comparison with experimental data (solid curve experiments and dashed simulation).



5.2.3.1 Key results

Dislocation density based formulation of crystal plasticity modeling was used to describe dislocation slip deviated plasticity. A model extension was proposed to include crystalline level damage that can cause material loss of strength and ultimately failure. Demonstrations were presented using a finite element solver. Project results are summarized in following 3 point:

1. Regarding SEM characterization of creep exposed copper material, different level of creep cavitation damage, including small single cavities, large single cavities, chains of large cavities and coalesced large cavities/microcracks, were discovered from the inspected samples. Additionally, microstructural characterization for determining grain boundary chemistry and deformation microstructures in creep tested OFP-Cu was initiated using STEM. The results indicated that electrolytic sample preparation is challenging for OFP-Cu as the creep voids tended to cause difficulties in the process and residuals from the electrolyte impair the reliability of the elemental grain boundary analyses. The deformation microstructures were successfully imaged and will be further analysed when results from reference material are available. In addition, small point-like defects were observed in the proximity of dislocations and assigned to strain effects.
2. Based on the results from tests with single relaxation period, increasing the temperature and strain (and stress) seems to increase the amount of the relaxed stress. This assumption was utilized in the stress relaxation modelling approach. In the tests with multiple relaxation periods, the amount of relaxed stress seemed to decrease in the later relaxation periods. The underlying substructure scale mechanism for the reduced stress relaxation is yet, however, to be confirmed. The developed stress relaxation model gave reasonable predictions with relation to the results of the single relaxation period tests. However, the model at its current formulation does not take possible additional substructure effects caused by cycling into account. The future objectives are to perform more stress relaxation tests to validate and refine the stress relaxation model and to learn more about cyclic stress relaxation behavior of OFP copper and possible other relevant phenomena.
3. A coupled plasticity-damage crystal plasticity model was formulated. It was shown that the model is able to describe some of the most important damage phenomena in the material, such as grain boundary type damage and shear localization related damage growth in the polycrystalline material. Micromorphic strain gradient model was used to investigate the effects of non-uniform grain size in the material and heterogeneous strain hardening and strain localization behaviour. Both modelling approaches are found feasible to represent material behaviour, however, they require further development and validation to derive effective parameter set and damage regularization for the model frameworks.

5.2.4 KAPSELI/OXCOR – The effect of oxide layer on copper corrosion in repository conditions

Project manager: Jari Aromaa[15]; other personnel: (Mika Sahlman, Petteri Halli, Alexander Chernyaev, Muhammad Kamran Khalid, Anssi Karppinen)[15]

5.2.4.1 Research topic

The processing of the final disposal copper canister causes oxidation of canister surface as the spent fuel will increase its temperature. The maximum surface temperature can be close to 100 ºC. In the literature the oxide film has been stated both to increase corrosion rate and to protect from corrosion. The task of the OXCOR project was to verify if the oxide film can cause increased corrosion in the initial phase of final deposition. The research tasks were to produce oxide films on the surface of clean copper simulating the oxidation in air when canister surface is hot, characterize the oxide film composition and thickness and measure the effect of oxide film on corrosion rate in different groundwater and porewater environments. The research was done by comparing corrosion rates of oxidized and non-oxidized samples in synthetic waters.

5.2.4.2 Key results

The oxidation tests in air showed that oxidation rate increases above 80°C. The maximum oxide film thickness was slightly over 100 nm after almost three months at 100°C. The oxide film growth starts as islands that grow together and the resulting oxide film was cracked. The oxide film consisted mainly of Cu_2O with some CuO detected at longer times and higher temperatures. The thickness range of tens or hundreds of nanometres that has been estimated earlier was confirmed.

The corrosion rates were measured using weight loss tests and electrochemical monitoring. The weight loss tests at room temperature showed that the corrosion rate decreases with time and remains steady after 8–10 months. In the short-term electrochemical corrosion monitoring tests, the corrosion rates were steady after a couple of weeks. The long-term weight loss tests at room temperature showed that the corrosion rate in pH = 8 air-purged synthetic ground water decreases from 20 µm/a after 2 months to 5 µm/a after 40 months. In nitrogen-purged ground water the corrosion rate decreased from 8 µm/a after 2 months to 4 µm/a after 40 months. In long-term tests in pH = 10 air-purged pore water the corrosion rates decreased from 5 µm/a after 2 months to less than one µm/a after 40 months. In nitrogen-purged pore water the corrosion rates were less than one µm/a all the time. In short-term immersion tests at elevated temperatures the

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corrosion rates increased with increasing temperature. The highest corrosion rates at 80°C were 45–55 µm/a in air-purged ground water and 35–45 µm/a in nitrogen-purged ground water. In pore water the highest corrosion rates at 80°C were 6–8 µm/a both in air-purged and nitrogen purged waters.

The electrochemical corrosion monitoring tests were done in same environments as the weight loss tests. The electrochemical measurements were done to get more information from the change of corrosion rates during the first weeks. The corrosion rates increased with increasing temperature. The corrosion rates in ground water ranged from 7 µm/a at 20°C to 30–40 µm/a at 80°C. In pore water the corrosion rates were from about one µm/a at 20°C to 3–7 µm/a at 80°C. The corrosion rates measured in short-term weight loss tests and electrochemical tests were similar.

Comparison of corrosion rates between oxidized and non-oxidized samples in long-term weight loss tests showed that the corrosion rates of non-oxidized samples were usually higher than those of oxidized ones. The differences were small but statistically significant. The largest difference was in air-purged ground water at the beginning, about 4 µm/a. After 40 months of immersion the corrosion rate differences were only 0.2–0.7 µm/a. In short term immersion tests, both in weight loss tests and corrosion monitoring tests, the corrosion rates were usually not significantly different. This is due to larger scatter in short-term tests, especially at highest temperatures. The oxidized samples showed in some cases higher and some cases lower corrosion rates that the non-oxidized ones. In air-purged ground water the average corrosion rates of oxidized samples at 60°C and 80°C were 8–10 µm/a higher than those of the non-oxidized ones. In nitrogen-purged ground waters the corrosion rate differences were 3–5 µm/a, and in some cases the oxidized samples corroded faster, in some cases the non-oxidized ones. In pore water the differences were less than one µm/a, and in some cases the oxidized samples corroded faster in some cases the non-oxidized ones.

5.2.4.3 The significance of the results

The corrosion rates in weight loss tests varied from less than one µm/a in cool high pH pore water to 45–55 µm/a in air-purged ground water at 80°C. The corrosion rates in electrochemical tests varied from about one µm/a in cool high pH pore water to 30–40 µm/a in air-purged ground water at 80°C. These results are in line with previous corrosion rate measurements done using different measurement methods. The most significant factor affecting corrosion rate was pH. In pH = 10 synthetic bentonite clay pore water the corrosion rates were clearly lower than in pH = 8 synthetic ground water. The effect of oxide film on corrosion rate was clear only in long-term weight loss tests at room temperature. In these measurements the corrosion rates of oxidized samples were slightly lower than those of the non-oxidized ones. In short-term measurements neither weight

loss tests nor electrochemical monitoring tests showed any clear trends between oxidized and non-oxidized samples. The air-formed oxide film will not increase corrosion rate in the first phase of final disposal.

5.2.4.4 Test methods

The oxidation tests were done using a thermobalance and an oven. The oxide film growth rates were measured using weight change in the thermobalance and Quartz Crystal Microbalance samples in the oven. Oxide film thicknesses were measured using ellipsometry and electrochemical reduction. Oxide film compositions were analysed using XRD and SEM. Corrosion tests included weight loss test and electrochemical monitoring using Linear Polarization resistance. In all corrosion tests the environment was either synthetic ground water or bentonite clay pore water under air or nitrogen purging. The ground water contained 5340 mg/l Cl^- and 580 mg/l SO_4^{2-}, with total dissolved solid 10070 mg/l and pH = 8. The pore water contained 80 mg/l Cl^- and 1300 mg/l SO_4^{2-}, with total dissolved solid 3360 mg/l and pH = 10. Weight loss tests included long interval tests at room temperature and short tests at elevated temperatures up to 80°C. The long-term tests were 8 months and 40 months, and the 8-month test was done three times. The time intervals were 2, 4 and 8 months or 10, 20 and 40 months. The short-term lasted 3–4 weeks without intermediate sample sets. The samples were cut from a 1 mm thick plate, sample size was 30 mm by 30 mm, and weight approximately 1 g. The corrosion rates were calculated from weight loss divided by sample area and immersion time. The electrochemical corrosion tests were done at temperatures 20, 40, 60 and 80°C. The samples were cut from rod or bar and mounted in epoxy. The sample areas were approximately 0.7 to 3 cm^2. The corrosion rate was measured as polarization resistance as it is a non-destructive method. The polarization resistances were converted to corrosion rates in final analysis. The effect of oxide film on corrosion were estimated by comparing the corrosion rates oxidized and non-oxidized samples using two-tailed t-test with test hypothesis that the corrosion rate difference is zero, also that the oxide film has no effect on corrosion rate.

5.2.5 KAPSELI/SUCCESS – Stress corrosion in copper caused by sulphide

Project Manger: Timo Saario[16]; other personnel: (Konsta Sipilä, Essi Jäppinen)[16], Patrik Sahiluoma[17]

The nuclear fuel disposal technology in Finland and Sweden (both based on the KBS-3 concept) is slowly maturing. Some issues regarding the main corrosion protection offered by the copper canister still remain to be further studied, among them the possibility of stress corrosion cracking (SCC) of Cu-OFP induced by sulphides in the ground water. The early Japanese study by Taniguchi and Kawasaki in 2008, using slow strain rate method, SSRT, (a standard method used to reveal SCC susceptibility) claimed SCC is possible for copper in presence of sulphide, but later investigations have failed to unequivocally support the claim. In Canada, in a study using electrochemical methods instead of SSRT and reaching over ten years in time, the main conclusion was that localized corrosion induced by sulphides is not possible in Cu-OFP at sulphide concentrations below 16 mg/l.

In the SUCCESS-project, a set of three separate electrochemical methods (electrochemical impedance spectroscopy (EIS), current-voltage curves (CV) and re-passivation rate measurement) were used in combination with scanning electron microscopy (SEM) to study the issue further in the sulphide concentration range of 10 to 100 mg/l. Starting from 2021, the possibility of hydrogen entering friction stir welded (FSW) Cu-OFP, during exposure to sulphide containing environment, in sufficient amounts to induce hydrogen cracking or other hydrogen related degradation was studied in co-operation with Aalto University.

A set of three research questions was set forth: 1) Does Cu-OFP passivate sufficiently in sulphide containing environments to allow SCC to take place?, 2) Is the passivation rate of fresh Cu-OFP surface in sulphide containing environments in such a range that SCC can occur? and 3) Does hydrogen enter Cu-OFP to a detectable degree during exposure to sulphide containing environment and induce SCC?

The key results from the project are as follows. Based on the results, no continuous adherent barrier-type layer is formed on Cu in sulfide solutions, thus precluding the possibility of the development of localized corrosion modes. The current-voltage measurements showed that the current density in presence of sulphides is very high, corresponding to a corrosion rate of about 1 mm/y. Such a high corrosion rate indicates that the film forming on Cu-OFP in presence of sulphides is not protective (passivating),

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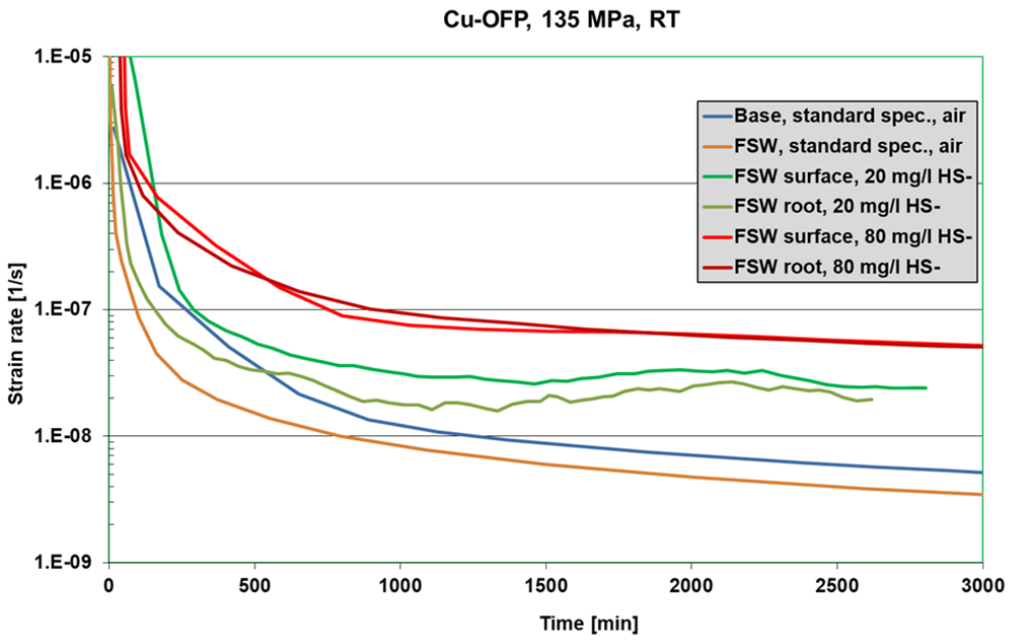
and since passivity is a pre-condition for SCC to take place, no SCC (or pitting) can occur. SEM-studies revealed that the sulphide film forming is porous and highly defective, and that the film is poorly adhering to the Cu-OFP base material. The re-passivation rate and EIS measurements corroborated the same conclusion, that *Cu-OFP is not susceptible to SCC in presence of 10 to 100 mg/l sulphide*.

The FSW Cu-OFP samples were tested under creep condition, and were exposed to sulphide containing environment with either 20 mg/l (up to 48 hrs) or 80 mg/l (up to 240 hrs) sulphide, two repetitive tests were made at each sulphide concentration. The hydrogen concentration in the material was measured with hot melt extraction (HME-MS) technique for total hydrogen content and with thermal desorption spectroscopy (TDS) for identification of different hydrogen traps. The main result from the studies was that the hydrogen content in FSW Cu-OFP does not increase due to sulphide exposure, but decreases by a factor of about two. Thus, *sulphide exposure does not increase the risk of hydrogen related degradation in FSW Cu-OFP*.

The creep test results, Figure 5.8, revealed that the creep rate of FSW Cu-OFP increases as a function of sulphide concentration. This is a new finding, which may be worth of additional investigation.

Figure 5.8. Strain rate of FSW Cu-OFP at T = 25oC in borate buffer solution of pH = 8.0 and 20 or 80 mg/l HS-.



5.2.6 KAPSELI/MECCI – Mechanical strength of cast iron insert

Project manager: Sven Bossuyt[18]; other personnel: (Ville Björklund, Yuriy Yagodzinskyy)[18]

5.2.6.1 Hydrogen kinetics and degassing in DCI

The investigations of the cast iron inserts that were started in MECAN were split off into a separate project MECCI in 2022. The hydrogen embrittlement (HE) in the material shows that hydrogen may collect in cracks and voids in the material and local elevated hydrogen content in the material, caused by residual stresses and triaxial loads imposed from the repository, may reach much higher levels than the average concentration. Also, the amount of hydrogen that may enter the canister through the zirconium found in the fuel is undetermined.

5.2.6.2 Static strain aging

The M.Sc. thesis of Ville Björklund (not funded in the KYT programme) showed that static strain aging (SSA) does occur already after 1 % plastic strain when aged at room temperature (RT). A paper summarizing this work and expanding the discussion and interpretation, has been written as part of the MECCI project and is planned to be published soon. The SSA manifests as pronounced and elevated yield point and reduced elongation to fracture. Additionally, the SSA increases the strain localization in the material based on our full field strain measurements with digital image correlation. The lower boundary conditions for plastic strain or temperature where the SSA occurs has yet to be determined and based on our results it is likely that plastic strains lower than 1 % and temperatures under 20°C could cause SSA to occur. Thus far the findings suggests that the static strain aging is possible in repository conditions, and even very likely in any events where the cast iron insert undergoes any plastic deformation. This should be further considered in the safety analysis of the canister.

Future work should focus on determining the lower boundary conditions mainly regarding the pre-strain that are needed for SSA to occur in this material. SSA was already observed at the lowest pre-strains included in the experiments. Further experiments were designed (but not yet carried out) to make use of non-uniform specimen geometry to create a gradient of pre-strain in the specimen and make use of DIC to evaluate the resulting deformation behaviour across the specimen. Thus, these experiments will allow much more efficient characterization of the SSA in the material, with a single specimen accessing a continuous range of pre-strains from zero to a chosen value.

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5.2.6.3 Dynamic strain aging

Strain aging also manifests as a negative strain rate sensitivity at certain temperatures and strain rates. Experimental and numerical work for the identification of temperature-dependent material parameters allowing to model strain aging of DCI was carried out with the principal contributions made by Malo Valmalle. The mechanical response of the ductile cast iron was studied when subjected to uniaxial tension at temperatures ranging from 20°C up to 300°C and strain rates of 10^{-2} and 10^{-4}. To account for the strain localization patterns due to dynamic strain aging the kinematic fields were measured via Digital Image Correlation (DIC). A constitutive law based on the Kubin-Estrin-McCormick model (KEMC) was used to model the behavior of the ductile cast iron across the range of the experimental conditions. The displacement fields were successfully measured and the strain localization patterns were observed. These measurements were then used to calibrate the parameters of the constitutive law. Numerical simulations are shown to be in agreement with experimental measurements at the macroscopic scale. These results have been written up in a paper which will be published after the project ended.

The theory and the modelling results indicate that at lower temperatures dynamic strain aging (DSA) will occur at lower strain rates, making it very likely that at the very low strain rates relevant for the repository conditions, DSA must be taken into account to accurately predict the deformation behaviour of the DCI. In particular, DSA results in increased tendency for localized deformation and earlier onset of deformation damage. Additionally, it should be noted that the underlying mechanisms of strain aging and other embrittlement phenomena have much in common: the mobility of dislocations is affected by diffusion of atoms like carbon and hydrogen, or Frenkel pairs created by neutron bombardment. Therefore, increased strain localization could work synergistically with HE as well as radiation embrittlement, and experiments on the possible synergistic effects of all these phenomena, along with residual stresses and casting defects, should be done in future.

5.3 Spent nuclear fuel waste management – Interactions of release barriers/microbiology

5.3.1 MoToPro/VaVu – Interactions of release barriers

Coordinator: Minna Vikman[19]; Subproject managers: Hanna Miettinen[19], Malin Bomberg[19], Thomas Ohligschläger[19], Leena Carpén[19], Riikka Kietäväinen[20]; other personnel: Maija Nuppunen-Puputti[19], Tuomo Kinnunen[19], Mia Tiljander[20], Lasse Ahonen[20], Yann Lahaye[20], Minna Myllyperkiö[20]

The aim of the MoToPro project was to gain new knowledge on the microbial influence on the multi-barrier system performance in the geological disposal of high-level nuclear waste. Microbiological activity is closely connected to bio- and geochemical processes, which were also an essential part of this multidisciplinary project. MoToPro included five sub-projects dealing with various aspects of barrier performance in the final repository conditions. The MiBe studied bentonite performance while KUKO evaluated factors influencing corrosion of copper canister. BIKES and MIMOSA examined sulfate and hydrogen accumulation using natural analogues. In addition, MIMOSA focused on the influence of *in-situ* pressure on microbial communities. All sub-project participated to perform a unique multi-barrier experiment, which was co-ordinated by VaVu.

The MoToPro organized a webinar in 2022 with contributions from VTT and GTK.

5.3.1.1 Interactions between different release barriers and their role in copper canister corrosion (KUKO)

The copper cannister in the KBS-3 multi-barrier system has the task to separate the spent nuclear fuel from the deep geological environment, which is populated by a variety of microbes like sulphate reducing bacteria (STB), nitrate reducing bacteria and acetogenic and methanogenic archaea. The KUKO project studied the influence of these microbes on the performance of copper (Cu-OFP) in simulated saline groundwater in the absence and presence of graphite-rich mica schist rock found at some parts in the Finnish repository site in Olkiluoto. Graphite-rich mica schist has not only the potential to act as crevice former in corrosion processes but may also have the ability to promote microbial activity and to act as an electrode for corrosion reactions when in galvanic contact with copper.

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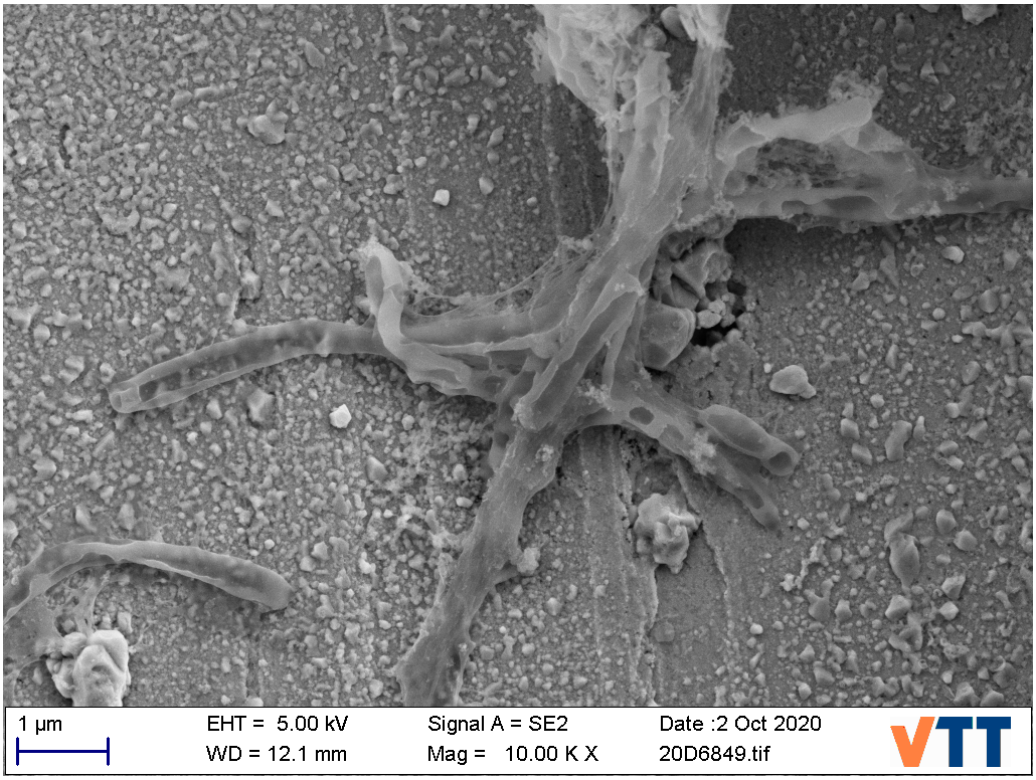
Two long-term immersion experiments were performed under anoxic conditions in artificial groundwater at room temperature. Microbe enrichments extracted from Olkiluoto groundwater were added to the test solution. The copper samples had been pre-oxidized considering the influence of the oxic phase early in the repository evolution. Corrosion rates were determined by weight loss measurements and regular corrosion rate monitoring using electrochemical methods. Changes on the copper samples and on the added rocks were documented by optical and electron microscopy. The composition of the surface films on copper and present corrosion products were characterized by energy-dispersive X-ray analyzed in the electron microscope. The microbial population in the solution and the formed biofilms were analyzed by DNA-based microbiological methods.

The addition of microbes to the simulated groundwater modified the surface films formed on copper. When SRB's were added to the test solutions, thinner copper sulfide films were observed instead of thicker copper oxide films. The highest corrosion rates were found when no microbes were added to the artificial groundwater indicating that microbes in the deep groundwater may have an inhibiting effect on the corrosion of the copper cannister. On the bare copper coupons, only minor corrosion pits and shallow surface etchings, especially when in contact with the rocks, were remarked. The specimens containing parts of the friction stir weldments showed the same corrosion behavior as the bare specimens. The U-bend specimens did not suffer from stress corrosion cracking during the experiments. Besides the long-term immersion tests, a master's thesis proved that microelectrodes are suitable to study biofilms on copper even under anoxic conditions.

The results of the KUKO experiments show that different microbe groups influence the corrosion behavior of copper in deep saline groundwater in different ways. Direct contact of bedrock with the copper cannister can lead to increased localized corrosion. As the corrosion tests were performed in the absence of bentonite, the selected test conditions represent worst-case scenarios that are unlikely but not completely impossible during the evolution of the repository.

Figure 5.9. Microbes on the surface of a copper specimen imaged by scanning electron microscopy.



5.3.1.2 Microbial actions in bentonite (MiBe)

Bentonite as an engineered barrier has many important features to protect the highly radioactive nuclear waste, one of them being the reduction of microbiological activity. The main aim of the MiBe project was to find out if microorganisms are able to harm bentonite structure and performance in conditions that simulate Finnish disposal site in so called worst-case scenario. After a five-year experiment it can be concluded that extensive sulfate and iron reduction was supported by bentonite slurry and low concentration of simple carbon compounds (formate and acetate) to speed up the microbial processes to occur within the project duration. At the end of the experiment, all structural iron in bentonite was reduced, which was not detected in the abiotic bentonite controls. Moreover, the bentonite swelling ability of the microbe-affected bentonites was clearly lower than that of the original bentonite. The microbial effects happened regardless of where the active microorganisms originated, bentonite, anoxic Olkiluoto groundwater or Olkiluoto oxic surface water (Korvensuo pool).

The fact that microbial iron and sulfate reduction is able to affect bentonite swelling ability and performance, should be kept in mind considering the safety case by disposal organizations, supervising authorities and the research community. Only after bentonite wet density exceeds 1800 to 2000 kg/m^3, the microbial activity is insignificant and microbial aspects can be ignored in case of bentonite. The project approach was multidisciplinary to be able to study bentonite microbial, chemical and mineralogical aspects. The most important methods included DNA-based microbiological methods so that the amount of different microbial groups based on their gene counts and their diversity could be followed. Another key methodology was the bentonite iron speciation measurement with x-ray absorption near edge structure, XANES, in cooperation with the University of Helsinki.

5.3.1.3 Biogeochemical scenarios (BIKES)

Molecular hydrogen (H_2) and sulfide are recognized as potential risks for the long-term safety of nuclear waste disposal as their accumulation may change pressure conditions in the repository and promote corrosion of copper. Formation of hydrogen and sulfide are interlinked and related to microbial processes in the subsurface, such as bacterial sulfate reduction and fermentation. The BIKES project investigated effects of varying environmental conditions and elemental concentrations on the formation and accumulation of hydrogen and sulfide.

Accumulation of hydrogen was strongest in bedrock groundwater environments where, in addition to radiolytic production, iron hydration reactions are present, and weakest in the presence of high sulfate concentrations. Isotope fractionation between water and H_2 indicated formation of the detected H_2 within the upper 7 km of the crust and within temperature limit for life. Comparison of concentrations and isotopic compositions of different sulfur phases showed that sulfide formation rate increases with increasing sulfate concentration, but sulfide accumulation requires continuous sulfate supply for example from sea water or dissolution of sulfate minerals, in the presence of sulfate reducing microbes. In these conditions, sulfide oversaturation can take place after sulfide sinks, such as precipitation into iron sulfides, are used up.

The results are based on geochemical and isotope analysis of groundwater and gas samples collected from four sites (Pori, Loviisa, Liminka and Inkoo), and complemented with previous data from additional three sites (Outokumpu, Juuka and Pyhäsalmi). All samplings were accompanied with microbiological sampling carried out within the MIMOSA project. Analytical method for determining isotopic composition of sulfur in different sulfur compounds in saline bedrock groundwater was developed, which significantly reduced and simplified the steps needed in the sample preparation without compromising analytical precision.

5.3.1.4 Diverse metabolic strategies of the pressurized deep biosphere (MIMOSA)

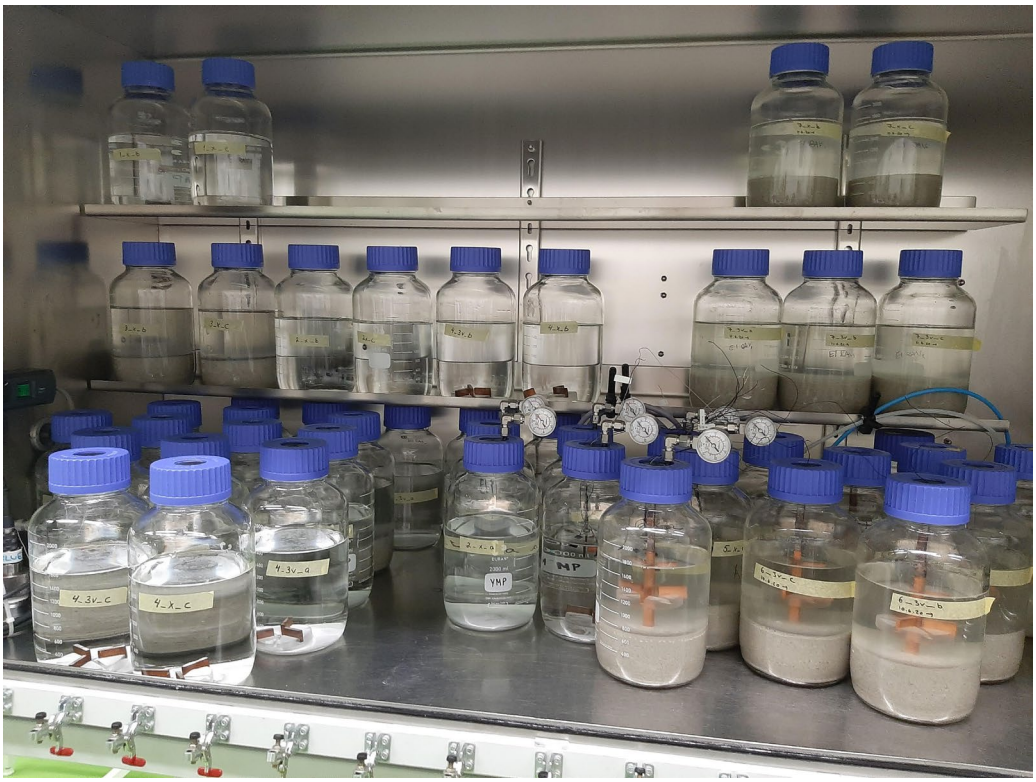
The microbial communities in different parts of the Finnish bedrock deep subsurface differ both in size and composition between sites with a general decline in microbial numbers with depth. However, when comparing 9 different sites, the communities at depths below 400 m in Liminka had generally higher microbial numbers (up to 10^6 bacterial 16S rRNA gene or *dsr*B gene copies mL^{-1}), which is higher than generally detected at shallower depths. In addition, the community composition varied between the different sites. The MIMOSA project also detected a population of ultra-small (between 0.1–0.2 µm cell size) microorganisms in Liminka, Loviisa and Pori deep subsurface, contributing with approximately 10^1-10^2 bacterial 16S rRNA gene copies mL^{-1} independent of depth. Sample water from the ONKALO-PVA8 borehole situated at 276 m depth was tested in pressure experiments, where microbial communities were incubated with or without different carbon sources, anaerobically, under 40 bar pressure or at atmospheric pressure for 13 and 33 weeks at 12°C. The experiment showed that bacterial growth was initially slower in incubations at atmospheric pressure compared to those incubated at 40 bars but was eventually equalled after 33 weeks of incubation. However, at 40 bar the microbial population contained more spore-forming sulphate and iron reducers compared to the incubations kept at atmospheric pressure, demonstrating the importance of *in situ* pressure for evaluating microbiological scenarios.

5.3.1.5 Interactions in multibarrier system (VaVu)

VaVu coordinated the MoToPro and a joint multibarrier experiment in the final repository conditions. Experimental set-up included Wyoming bentonite, copper specimens, ground water from Olkiluoto and gas atmosphere simulating real conditions in Olkiluoto. To enhance microbial activity, energy sources were added to the some of the reactors at regular intervals. In addition to bentonite slurry, reactors with compacted bentonite were also included in the test set-up (Fig. 2).

Energy addition and low compaction degree of bentonite (to speed up experiments) had major impact on microbial activity, and therefore also on bentonite performance. The number of microorganisms in the water phase was more strongly affected by the presence of bentonite in the system than by the added organic energy sources, showing stronger increase in microbial numbers in the presence of bentonite. The bentonite also increased the relative abundance of spore forming bacteria in the water containing bentonite compared to water without bentonite. The presence of bentonite also reduced the risk for corrosion of copper. When present, bentonite associated bacteria dominate in biofilms on copper. Compacted bentonite has less microorganisms as expected, but sulfate reducer activity was detected in the surface layer and 40 to 50 % of bentonite structural iron was reduced.

Figure 5.10. Multibarrier experiment simulating final repository conditions. On the left: Glass mesocosms with bentonite slurry, copper specimens and Olkiluoto groundwater. On the right: Reactors with compacted bentonite.



5.3.2 KaMu – Effects of circumstances to gas formation in the final repository of low activity maintenance waste

Project manager: Vikman Minna[21]; other personnel: Sohlberg, E[21].

In Finland, low level radioactive waste (LLW) originated in nuclear power plants contains considerable amounts of biodegradable, cellulose-based material. LLW is disposed of in the repositories situated ca.60 – 100 meters below the sea-level. A large-scale Gas Generation Experiment (GGE) was established in 1997 in Olkiluoto, Finland, to simulate

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the gas generation from LLW under repository conditions. The experiment is operated by Teollisuuden Voima Oyj (TVO) and it has been regularly analysed for chemistry, gas generation, composition of gas and microbiology.

The gas generation started already during the first year of the GGE resulting from microbial degradation of waste and steel corrosion. A significant observation from the GGE has been that the pH conditions were heterogeneous (pH 11 to 6), providing optimal neutral pH niches for microbial activity from the outset of the experiment. Over the extended time scale of the experiment, chemical conditions were stabilized and differences in the microbial abundances and community structure in various GGE compartments have become less significant.

The aim of the KaMu project was to induce disturbances to the GGE and study the impacts on gas generation and gas composition. The addition of sulphate simulated sulphate-rich flow of groundwater through the repository and the higher pH value the influence of concrete in the repository. The obtained results can be used to improve the understanding of gas generation processes and thus support the safety cases of the final disposal of low-level radioactive waste in Finland.

5.3.2.1 Methods

Because tank water already contained considerable amount potassium-ions, K_2SO_4 and KOH were selected to induce disturbances in the GGE. Tank water samples were regularly taken from several locations in the GGE to analyse water chemistry (TVO laboratory), gas composition (TVO) and microbiology (VTT). The total number of microbial cells in tank water was determined by fluorescent staining with 4,6-diamidino-2-phenylindole (DAPI). The microbial community sizes and the abundance of sulphate reducers and methanogens were estimated using quantitative PCR. Archaeal and bacterial community analysis was performed with Illumina Miseq next generation sequencing. The sequence reads obtained from Illumina Miseq sequencing were subjected to sequence analysis using the DADA2 software package and DADA2 Pipeline Tutorial 1.16 with some modifications.

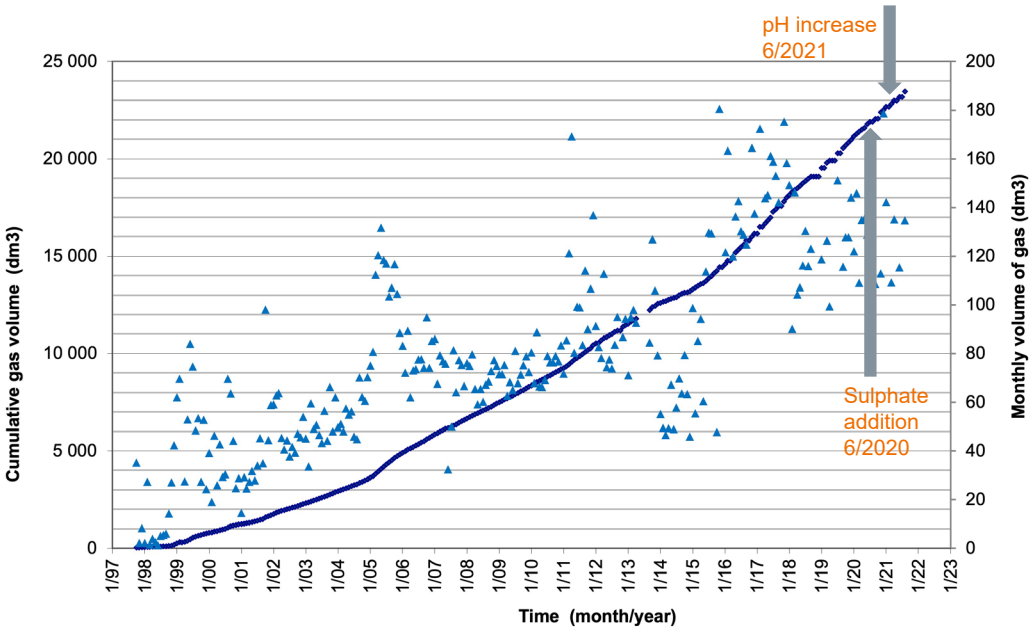
5.3.2.2 Results

Methane producing microbes and sulphate reducing bacteria compete for same electron donors, e.g. acetate and hydrogen. As sulphate concentration in the GGE has been below detection limit, the addition of sulphate was expected to enhance activity of sulphate reducing bacteria and thus potentially decrease activity of methane producing microbes and gas generation. After sulphate addition, microbiological analyses showed a moderate increase in the number of sulphate reducers and a decrease in the number of

methanogens. The diversity of methanogens stayed similar during the disturbance but certain sulphate reducing bacteria emerged in the microbial population in the tank water. Despite of these microbial changes the sulphate reduction was not enhanced significantly and no changes in gas generation or gas composition were detected.

Similarly, the increase of pH can potentially induce changes in microbial population and influence gas generation. After the increase of tank water pH from 6.7 to 8.1 some changes in gas composition were detected. CO_2 concentration in the released gas was reduced because CO_2 was partly absorbed into the more alkaline tank water. In addition, the concentration of soluble iron in the tank water was decreased indicating precipitation of iron. However, no change in gas generation was detected.

Figure 5.11. Gas generation during the GGE. Induced disturbances are marked by arrows.



5.3.2.3 Conclusions

The main conclusion from KaMu project was that gas generation in the GGE remained stable and neither the addition of sulphate nor the increased pH did influence gas generation rate. The obtained results can be used to verify modelling and to improve safety assessment related to the final disposal of low-level radioactive waste in Finland.

5.3.2.4 Acknowledgements

The research project was funded by the KYT, VTT, Teollisuuden Voima, Fortum and Fennovoima. The authors would like to thank the members of the project steering group for fruitful discussions and active participation in the project meetings. Sauli Tenlén and Kalle Kesonen are thanked for their valuable help in the samplings in Olkiluoto and Mikko Nykyri for reviewing the report. The work of Malin Bomberg (VTT) with bioinformatics tools is greatly appreciated. The skilful assistance of Mirva Pyrhönen is also acknowledged.

5.4 Basic Factors in Safety

5.4.1 OMT – Overall safety, multibarrier system and transient phase

Project manager: Heidar Gharbieh[22]; other personnel: (Marja Ylönen, Kari Rasilainen)[22]

The OMT project was in operation in 2019.

A literature study on safety culture and the safety case concept has been carried out and aspects deemed relevant for overall safety of nuclear waste disposal have been discussed. Overlaps between safety cultural aspects and the safety case methodology have been identified. In this regard, the importance and usefulness of management systems and, in particular, knowledge management systems has been discussed. The discussions about the applicability of existing holistic approaches on evaluating the safety of nuclear waste disposal have been deepened, particularly with regard to the defence-in-depth (DiD) philosophy. After outlining the concept of overall safety based on the literature review, structured interviews with experts of several different topics relevant for nuclear waste disposal have been conducted in order to build a basic understanding of overall safety and its different facets in the Finnish context. To this end, a questionnaire covering the themes overall safety, safety culture, collaboration and information flow, integrity as well as assumption and uncertainty management has been developed. Main findings

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concern the organisation of research in Finland related to nuclear waste disposal, the compartmentalization of knowledge, competence management and knowledge transfer as well as commercial considerations.

5.4.2 SYSMET – Systematic scenario methods for the assessment of overall safety

Project coordinator/subproject manager: Raija Koivisto[23]; subproject manager: Ahti Salo[24]; other personnel: (Anna Leinonen, Kari Rasilainen, Nadezhda Gotcheva)[23], (Edoardo Tosoni, Alessandro Mancuso)[24]

VTT's subproject produced information on the use of the scenario method in different fields of application by conducting an extensive qualitative literature review and developing an epistemic scenario framework based on epistemic analysis. In the second phase of the project, the final disposal system of nuclear waste was analysed as an application of the scenario method, applying the epistemic framework developed in the project. These entities were related to the first and second objectives of the project. The development of the conceptual model, which was the goal of the project, was realized in the form of an epistemic scenario framework.

The framework examines scenario approaches as data generation processes and identifies different scenario approaches by specifying the purpose of data generation (normative or exploratory) and the alignment of scenarios (focus in a system or system environment). The literature study identified four scenario approaches that represent different epistemic emphases in scenario formation typical of different fields (including the purpose, methodological means and substantive targeting of scenario information).

The analysis of the nuclear waste disposal system found that scenario formation requires a systematic approach, and the requirements set for scenario work include both normative and exploratory information needs. For this reason, the scenarios related to the final disposal of nuclear waste can be compared with the scenario analysis and safety analysis approaches identified in the literature study. In them, scenarios are linked to modelling-based impact assessment methods, and scenarios are formed using systematic and partly mathematical methods. However, in order to strengthen the exploratory dimension, the formation of scenarios is also accompanied by qualitative approaches, such as the use of expert assessments, various workshops or other ideation methods. It is typical of such

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scenario analysis that the formation of scenarios and the study of their effects are closely interlinked in the process of data production. This link forms a kind of paradox in scenario work.

In order to ensure exploratory nature and for the transparency of the data generation process, it is important to distinguish between the three phases of the analysis (scenario formation, quantification of scenarios for impact assessment and impact assessment calculation), but on the other hand, the result of the entire scenario analysis is obtained only as a common result of these work phases. The subproject's objectives were achieved, but there was a deviation from the scope of reporting the results within the project schedule. The literature study produced in the project and the information-theoretic framework of the scenario methods based on it are the basis for the article manuscript, which will be finalized after the end of the project. In this respect, the results are not tied exclusively to the nuclear waste context, but have a more general interest in the production of future information. Also, the conference presentation related to the results of the project will not be realized until after the end of the project due to changes in the conference schedule due to the corona pandemic.

Aalto University's subproject in 2020 focused primarily on the development of a probabilistic cross-effect method. The method is based on the fact that consistency and causality estimates determined either by statistical methods or by means of expert judgements can be computationally combined in such a way that either the most likely scenarios or those with the highest safety significance can be determined. In particular, the applicability of the method was developed by producing research data on how expert data should be collected and processed as a basis for analysis. Secondly, the subproject has continued research into generalized probabilistic risk assessment importance measures, which can be used to identify the most safety-relevant scenarios by describing uncertainties and the various outcomes and the consequences of these as a Bagy network. The measurements can be used to assess the impact on safety of cause-and-effect factors between uncertainties. Thirdly, further research has been carried out on the comprehensivness of scenario reviews. The aim is to support the selection of the initial parameters of computational models so that justified assessments of the overall safety of the nuclear waste facility can be produced efficiently.

5.5 Spent nuclear fuel waste management – Bedrock research

5.5.1 MIRA-3D – 3D-modelling of microstructures

Project manager: Pietari Skyttä[25]

The MIRA-3D project was in operation in 2019–2021. It was originally planned as a four year project, but was cancelled by the responsible organisation before the last year and results are thus incomplete.

The goal of the MIRA-3D project was to identify and characterize gap systems on a cm-scale. The project utilized the new 3D-grinder equipment developed at the University of Turku (an attachment for an automated sander machine), in which accurate 3D models can be created from samples up to 50x60 mm in size. The project produced information on the 3D geometry and properties of the gap at the micro level, assesses the relationship between the transitions and the related secondary gaps and the kinematics of the transitions, evaluates the properties of litology at the micro level, and the orientation and orientation of the stone to the tension field that caused the crevice.

5.5.2 KARIKKO – Bedrock fragmentation

Project manager :Nicklas Nordbäck[26]; other personnel: **(**Nikolas Ovaskainen, Jon Engström, Jussi Mattila, Mira-Markovaara Koivisto, Riikka Kietäväinen, Markku Paananen, Eevaliisa laine, Antti Ojala)[26]

The coordinated KYT KARIKKO-project (2019–2022), managed by the Geological Survey of Finland, examined the multiscale characterization and modelling of brittle structures (fractures and faults) of the Finnish bedrock. The MIRA3D project (2019–2021), managed by University of Turku, was a subproject to the coordinated KARIKKO project and focused on three-dimensional (3D) fracture networks within microscopic scales.

The main motivation for this research was the inherent uncertainty related to multiscale datasets and current assumptions regarding the scalability of brittle structures in 3D and discrete fracture network (DFN) modelling. The properties and type of occurrence (frequency, spatial distribution) of individual brittle structures in a fractured rock mass

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cannot be deterministically modelled, and, therefore, they must be modelled using statistical distributions that are sampled from multiple scales of observation. Thereby, modelling is highly dependent on the availability of high-quality multiscale data. In Finnish conditions, however, field investigations and remote mapping are limited by the availability of large and representative outcrops between 10 m and 1 km scale range and by the resolution of available remote sensing data, respectively. Thus, since geological structures cannot be studied in all scales, fracture models need to be constructed based on incomplete datasets.

5.5.2.1 Key results of the project

KARIKKO has provided new regional perspectives for understanding the inherent uncertainties related to the multiscale datasets used in DFN and 3D modelling in Olkiluoto. In addition, the project enabled a better understanding regarding the complex brittle tectonic development and the associated brittle properties of the Finnish bedrock. The key findings have been published in international per reviewed journals, as five Master's Thesis and in numerous conference papers. In addition, two PhD projects at the University of Turku have been enabled as part of this project.

The key results of KARIKKO and MIRA-3D include the development and optimisation of:

1. new methods for interpreting lineaments at different scales, based on LiDAR integrated with aerogeophysical data,
2. new methods for mapping outcrop fracture networks at different scales, using UAV-photogrammetric methods,
3. new methods for investigating micro-scale fracture networks,
4. and automated mapping of bedrock-fractures traces from UAV-acquired images using U-NET convolutional neural networks. In addition, the project has resulted in
5. significant new multiscale brittle structure datasets, publicly available for further research,
6. the development of *fractopo*, an open-source Python toolkit for analyzing two-dimensional lineament and fracture trace maps,
7. an enhanced understanding on the scalability of brittle structures and
8. and improved understanding of the brittle tectonic evolution within southern Finland.

5.5.2.2 The meaning of results for nuclear waste research

The newly developed methods for mapping multiscale datasets can be applied in the characterization of nuclear waste repositories. For example, photogrammetric semi-automatic methods for digitizing fractures in outcrops and tunnel walls offer possibilities for more efficient and detailed mapping of fracture trace data, compared to manual mapping. Fully automatic fracture mapping using shape recognition algorithms or artificial intelligence, as developed as part of KYT KARIKKO, need further development but could offer possibilities in the future.

The new methods for analyzing topological relationships between fractures within a fractured rock mass provide useful and new information on both the connectivity and age relationships within a fracture network, which has a significant impact on the permeability of fractured bedrock volumes. Our scalability results indicate uncertainties with regards to the accuracy of both the smallest-scale and largest-scale lineaments, while lineaments (with sizes primarily in the range of 10 km to 100 km) mapped at 1:200 000 scale of observation are least affected by various biases and censoring effects of the source data. In addition, comparisons between the outcrop scales and lineament scales indicate that most fractured bedrock volumes (including e.g. both joints and fault zones) cannot be accurately modelled with only a single length distribution for fractures. For example, based on our results, joints shorter than 2–5 metre seems to follow lognormal length distributions while the longer joints can be accurately modelled using a power law length distribution. However, the lineaments, interpreted as large fault zones, seem to follow a different power law length distribution compared to joints. Thus, our results highlight uncertainties associated to bedrock models where the outcrop scale data and lineament data have been used to interpolate length properties for the intermediate scales lacking in data, as e.g. the tectonic continuum size model used in the DFN modelling in Olkiluoto. However, the limited maximum lengths we observed for joints (< 200 m) strengthens previous modelling of Full Perimeter Intersection fractures in ONKALOTM. Furthermore, new information on the tectonic evolution of fault structures and later formed joints provide new information that is useful for further constraining the current conceptual geological models of southern Finland. Altogether, the KYT KARIKKO project contributed towards more reliable modelling of fractured bedrock volumes and, thus, a better safety for the primary barrier for nuclear waste, the bedrock.

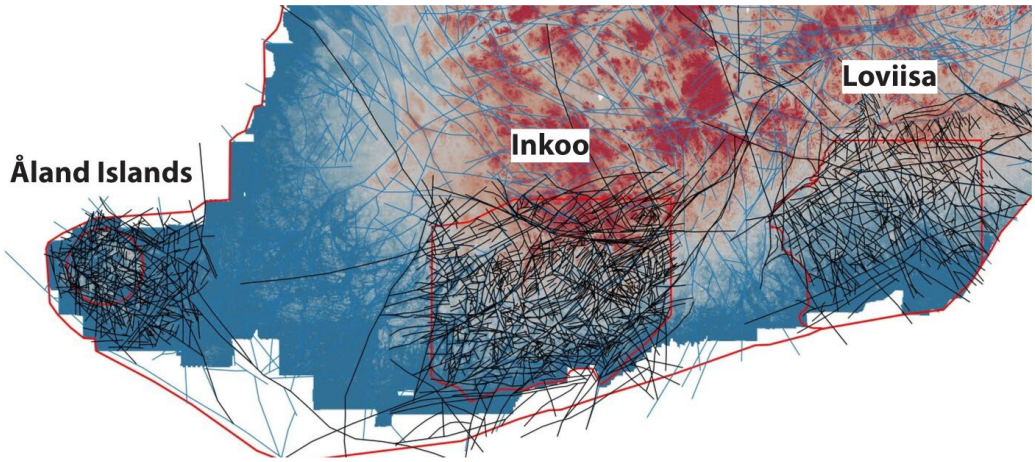
5.5.2.3 Methods used in the studies

We approached the research aims by developing novel methods for collecting and analysing representative multiscale datasets from large areas of southern Finland, including: 1) bedrock samples from distinct faults and surrounding damage zones, further analysed in the microscopic scales, 2) remote sensing of bedrock outcrops using

UAV-photogrammetric methods in up to three different resolutions and 3) from new LiDAR remote sensing data combined with aerogeophysical datasets in three different resolutions.

We collected large lineament datasets based on LiDAR and aerogeophysical source data in 1:500 000 resolution from the entire southern Finland, and in 1:200 000 from the Åland Islands, Inkoo and Loviisa study areas (Fig. 5.12). To characterize the brittle properties within the finer scales, we also studied brittle structures at the resolution of LiDAR and UAV-acquired photogrammetric source data. Furthermore, we performed extensive and detailed structural outcrop investigations in all three study areas, including validation and characterization of the remotely mapped features. Field observations were integrated with the digital UAV-acquired remote sensing datasets which enabled mapping of relatively large outcrop areas in high resolution. For calculating length distributions, we used the newly developed fractopo toolkit.

Figure 5.12. Lineament datasets from southern Finland. The 1:500 000 lineaments, covering the entire southern Finland, in blue and the 1:200 000 lineaments, covering the three study areas (Loviisa, Inkoo and Åland Islands), in black.



5.5.3 RAKKA – Water conductivity of fractured rock mass

Project Manager: Mikael Rinne[27]; other personnel: (Lauri Uotinen, Masoud Torkan, Pertti Alho)[27]

5.5.3.1 Introduction

Understanding the fluid flow characteristics of fractured rock masses is crucial for the design and safe operation of geological spent nuclear fuel storage and disposal facilities. This research project investigated the fluid flow behavior of fractured rock masses in the context of spent nuclear fuel management. The goal was to produce a new method for contactless determination of fluid flow characteristics of individual rock joints. A new photogrammetric method was developed to capture the fracture geometry. The captured geometries were then used in numerical modelling to predict the fluid flow characteristics. Laboratory scale fluid flow tests were used to validate the results from the numerical modelling predictions. The resulting methodology may be used to assess the safety of the geological spent nuclear fuel repository by creating initial data for site-scale simulations of fluid flow to estimate the risk of radionuclide escape.

5.5.3.2 Photogrammetric method

RAKKA utilized a new photogrammetric method to obtain the fracture aperture at high detail. First a pattern of automatically detectable markers is applied on all sides of the slab pair (Fig. 5.13a) and then the slab pair is photographed together and each slab individually (Fig. 5.13b). This results in three models which can be placed in shared coordinate system with known predetermined marker distances. For fracture surfaces of 25 x 25 cm the method is assessed to reach the accuracy of 20…30 µm RMSE.

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Fig. 5.13a. Markers with predetermined distances on all sides.

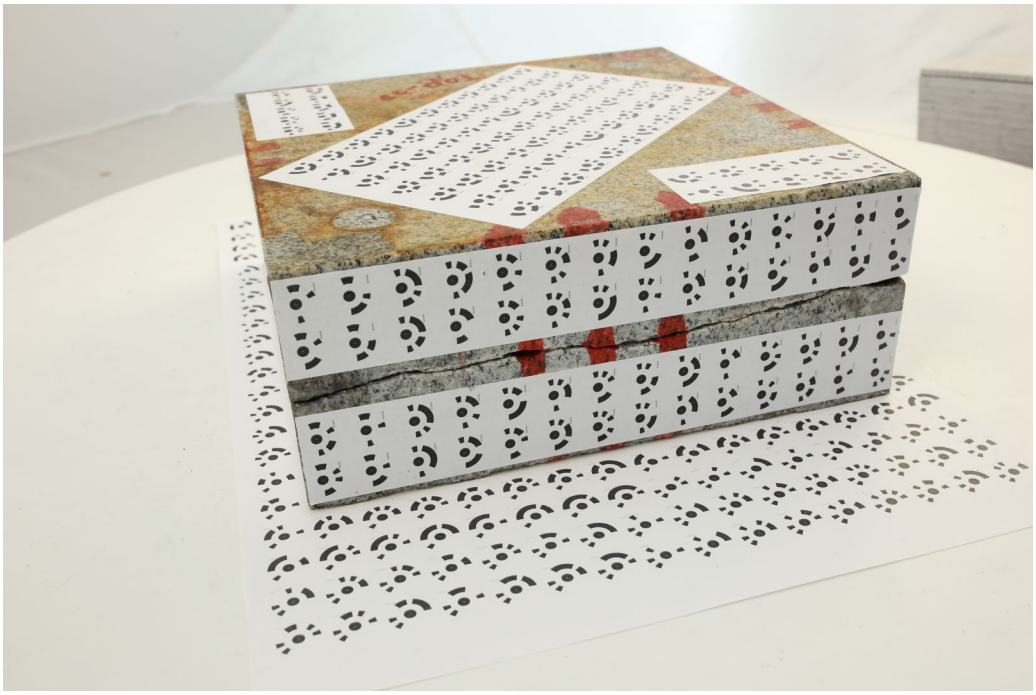
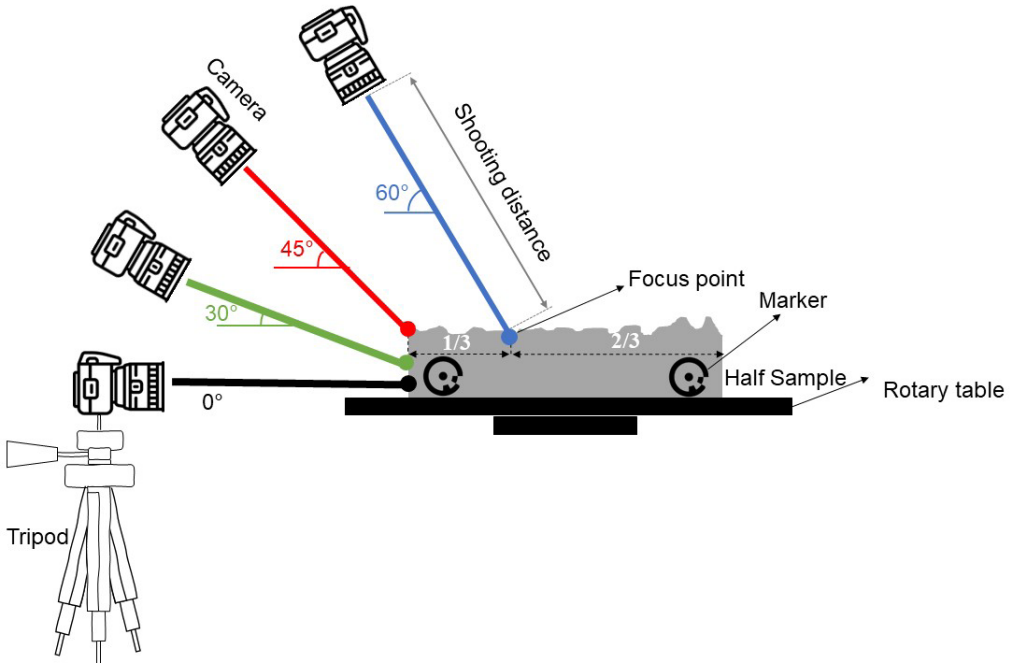


Fig. 5.13b. Four rings of photographs using a revolving table.



5.5.3.3 Numerical modelling predictions

The top and bottom flat surfaces of the assembly can be cut away. This exposes top and bottom fracture surfaces near to each other. The thin gap in between the surfaces is meshed and used as the geometry in numerical modelling. Negative volumes are deleted and interpreted as areas where the fracture surfaces are in contact.

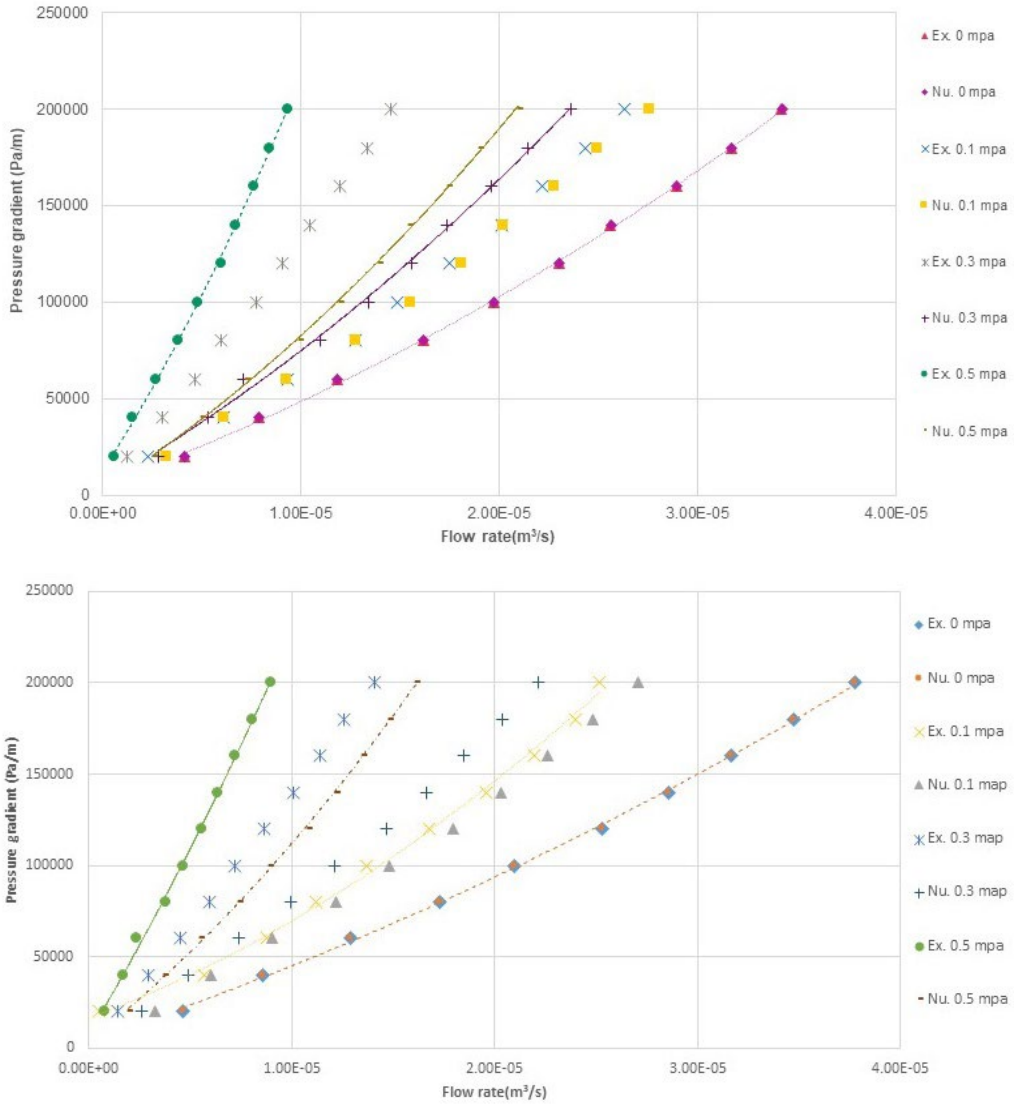
5.5.3.4 Experimental validation

The predictions were validated with a new laboratory testing arrangement. The slab pair is laid on a flat plate, one edge is used as the inlet and the opposite edge is the outlet. The amount of water over a period is measured. The two remaining sides are sealed with rubber gaskets. The experimental arrangement allows to change the water pressure, water flow rate and normal pressure perpendicular to the fracture surface.

5.5.3.5 Main results

The comparison of the laboratory measurements ("Ex" in Fig. 5.14) vs. photogrammetric predictions ("Nu" in Fig. 2) shows a very good agreement at low confinement pressures. Several device options were tested ranging from professional DSLR to typical mobile phones. The results show that even mobile phones can be used to produce high resolution photogrammetry.

Fig. 5.14. Experimental and numerical data analyzed with polynomial regression analysis of measured pressure gradient as a function of flow rate using the Forchheimer equation for the fracture under different normal stresses.



5.5.3.6 Utilization of results

Fluid flow characteristics can be predicted from an exposed single surface or a pair of surfaces (preferred). In addition, the aperture and its distribution over the fracture can be determined. The methods can be used to create site specific initial data for site-wide fluid flow analyses. The results support the safety assessment of geological disposal of spent nuclear fuel. The results are applicable to individual rock joints. To describe the connectivity of fractures, some other approach such as KARIKKO (GTK) could be used. More work is needed to describe the scaling more accurately. The scaling will be studied more closely in the continuation project MIRKA (SAFER2028).

5.5.4 C-ROCK2 – Factors affecting the chemical form of radio carbon in bedrock

Project manager: Merja Lusa[28]; other personnel: Gareth Law[28]

C-ROCK2 -project ran in 2021 and was discontinued afterwards due to research organisation's own initiative.

The project examined changes in the chemical form of radiocarbon in bedrock conditions, and in particular the effect of microbial activity on the chemical form of radiocarbon (14C) from nuclear fuel and on possible changes in shape and precipitation as carbon passes through bedrock into the biosphere.

The first part provides new information on carbon specialization and the conversion of methane to carbon dioxide under conditions similar to the sulphate-methane zone of the Olkiluoto bedrock under the influence of bedrock bacteria. In addition, information is obtained on the associated bacterial metabolism and its possible changes/changes on carbon specialization, which further affects the transport of carbon through bedrock to the surface biosphere.

Preliminary preparations were made in the project during spring 2021 by acquiring the bacteria and bacterial mixtures used in the study (Desulfovibrio pure culture as a control, as well as bacterial mixtures from deep bedrock (400–700 m)), as well as with the preparation of GC-MS measurements. The actual experimental work began in August 2021 with bacterial breeding and the preparation of experimental growing conditions. The samples were balanced under redox conditions corresponding to the bedrock conditions,

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using four different growing media based on the nutrient and salinity concentrations of the Olkiluoto bedrock (OL-SR and ALL-MR bedrock groundwater simulants with varying carbon sources + post gate medium as controls).

At the end of the balancing, CO2/CH4, sulphate, and other small carbon molecules resulting from bacterial metabolism were determined from the samples. In addition, the bacterial mixtures used have been sequenced (NGS) to determine bacterial populations and the size of bacterial populations has been determined using the qPCR method.

5.5.5 BEEFS – Comparative analysis and development of modelling of earthquake fault ruptures

Project Manager: Ludovic Fülöp/Juha Kortelainen[29], Jussi Mattila[30]; other personnel: (Paula Keto, Vilho Jussila)[29], (Outi Kaisko, Jouni Valli)[30]

5.5.5.1 The research topic

Finland is located on the seismically quiet Fennoscandian shield, with no modern-time observations of large earthquakes. Therefore, seismic hazard analysis is conducted with very limited observations of surface ground motions caused by earthquakes. The underground repository suffers from even lesser data availability, as no observation on underground movements caused by earthquakes exists. With developments in earthquake fault-rupture simulations, advanced software applications became available, and many publications were dedicated to simulating the rupture of earthquake faults, leading to large benchmarking exercises to compare predictions of different software. In this work we propose an agile simulation methodology, by benchmarking suitable FEM/DEM codes FLAC3D and SEISOL. We confirm that these software codes are simulating the rupture of earthquake faults identically, and we compare the model preparation, run-times etc., to select the agile modeling technique for the future. Detailed reporting of the work is in Fülöp et al. (2023)[31].

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30 RMCF Rock Mechanics Consulting Finland

31 Fülöp, L., Jussila, V., Kaisko, O., 2023. Benchmarking and evolving earthquake fault-rupture simulations (Research Report No. VTT-R-00102-23). VTT Technical Research Centre of Finland, Espoo.

5.5.5.2 Methods and key results

The main source of benchmarking cases has been Harris et al (2009)[32]. The selection criteria for Fennoscandia were based on the geological conditions, seismicity, and targeted hazard outputs. An earlier attempt was made to model strike-slip and dip-slip faults in 3DEC and derive generated ground motions. The modelled moment magnitude was M_w5.5, with a fault size of 5×5km and a stress drop of 5MPa. Oblique fault-ruptures were modelled. The range of moment magnitudes was M_w4 to M_w5.5; the fault sizes 1×1km to 3.5×3.5km and the stress drops of 10MPa and 50MPa (Jussila et al. 2021)[33].

The magnitudes were chosen to correspond to high contributors of hazard for nuclear power plants (NPPs). In different probabilistic seismic hazard analysis studies, the assumed largest magnitude ranges were between M_w5.5…7.7. Given the design lifetime of the underground repository, the modelled moment magnitudes should be in the range of the largest magnitudes. The following selection logic was applied to choose a benchmark. First, strike-slip, or gently dipping faults are relevant for Finnish NPPs and the repository. Second, in this stage it was no need to use sophisticated initial stress distribution (e.g., random heterogeneities) for the benchmarking, but the modelling should be able to accommodate it later. Third, a case with very-hard rock condition had to be chosen. Fourth, moment magnitude of the earthquake had to be in the range of maximum magnitude. With M_w6…7, relevant for both NPPs and the repository, the approximate fault area was estimated between 100–1000km^2.

The benchmarking case TPV5 was used from Harris et al. (2009)[32]. The velocity model is homogeneous with shear wave velocity of V_s=3464m/s. The fault was a vertical right-lateral strike-slip planar fault within the half-space, reaching the Earth's surface. The rupture may occur within a rectangular area of 30×15km. The boundaries of the potential rupture area were defined as high-friction barriers. The nucleation of the earthquake rupture was located 15km along-strike and at 7.5km depth, occurring in a 3×3km nucleation patch. Failure extended on the entire fault plane, following a linear slip-weakening friction law.

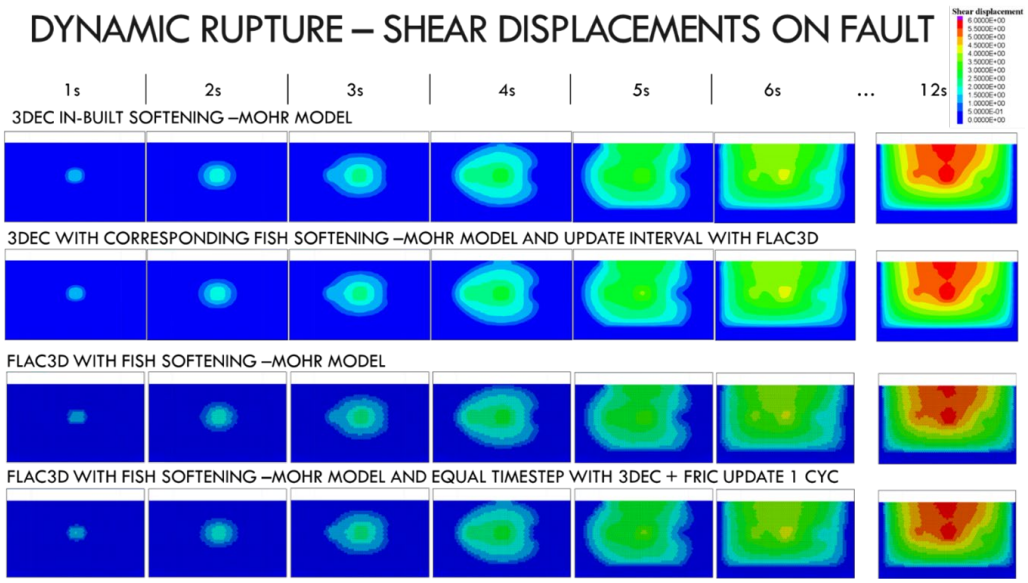
32 Harris, R.A., M. Barall, R. Archuleta, B. Aagaard, J.-P. Ampuero, H. Bhat, V. Cruz-Atienza, L. Dalguer, P. Dawson, S. Day, B. Duan, E. Dunham, G. Ely, Y. Kaneko, Y. Kase, N. Lapusta, Y. Liu, S. Ma, D. Oglesby, Olsen, K. and Pitarka, A. and Song, S. and Templeton, E. (2009) The SCEC/USGS Dynamic Earthquake Rupture Code Verifi-cation Exercise. Seismological Research Letters, 80 (1). pp. 119–126. ISSN 0895-0695. doi:10.1785/gssrl.80.1.119.

33 Jussila, V., B. Fälth, P. Mäntyniemi, P.H. Voss, B. Lund, L. Fülöp, 2021, Application of a Hybrid Modeling Method for Generating Synthetic Ground Motions in Fennoscandia, Northern Europe, Bull. Seism. Soc. of Am. https://doi.org/10.1785/0120210081

In this study, two modeling paths were explored. The first was using the commercial software family of ITASCA (i.e., 3DEC, FLAC3D, PFC, etc.), the other was using the free SEISSOL software specialized in earthquake fault-rupture modeling. We assessed the capabilities of these modeling paths, the level of difficulty to prepare inputs, the run-time performances, and the efficiency of result extraction.

The first modeling path was using a novel method combining FLAC3D and PFC, developed in order to run models more quickly and easily. A new contact logic for discrete joints within a FLAC3D continuum model utilizing PFC contacts was introduced by Itasca. The logic fully combines the codes describing the model domain as a FLAC3D continuum and the joints as PFC discontinua. The joint constitutive models used in 3DEC are introduced for the so-called zone joints. The new FLAC3D zone joint simulation method was first studied by comparing the performance to published results gained with 3DEC. The aim was to demonstrate that the new zone joint logic is performing equally well as the 3DEC code, since no previous experience of the dynamic behavior of such simulations exists. The comparative plots of the fault rupture evolution with different modeling methods are shown in Figure 5.15.

Figure 5.15. Example of shear displacement evolution of the fault with comparative runs with a coarse mesh. Same model was run with four different set-ups: in 3DEC with the in-built and .FISH scripted softening-Mohr joint model and in FLAC3D with two differently updating .FISH scripted softening-Mohr models.



The second modeling path used the SEISSOL software, which is capable to simulate fault rupturing, wave propagation and ground motion. The discontinuous Galerikin method is the core of SEISSOL. The mass and stiffness matrices are defined for each element separately, resulting in high efficiency by parallelizing runs, when powerful multi-core computers are available. Computational efficiency is improved because the inversion of large system level mass and stiffness matrices are not required. The results obtained with SEISSOL are compatible with the results of the benchmark. Quantitative comparisons show that both modeling paths can perform the required tasks of simulating the rupture propagation in the primary fault, and the transport of the stress waves in the surrounding solid rock mass.

5.5.5.3 Use of the results for safety analysis

The explored modeling paths can be used to carry out parametric studies for ground-motion and secondary rupture modeling, relevant for the NPPs and the underground repository. Both have distinct advantages, and a decision to continue with both, or choose a single path, will be taken with the stakeholders in the upcoming SAFER project. Both modeling paths have significant performance advantages, compared to the modelling methods used thus far in Finland. Significant building of know-how was achieved in the project.

5.6 Spent nuclear fuel waste management – Other safety research

5.6.1 RASK – Radionuclide transport on the interface of cement and bedrock

Project manager: Marja Siita-Kauppi[34]; other personnel: (Juuso Sammaljärvi, Eveliina Muuri, Xiaodong Li, Jaakko Hietava)[34]

In geological disposal of spent nuclear fuel matrix diffusion into the rock, sorption onto mineral surfaces and solubility control is generally believed to be the most significant processes that retard the transport of radionuclides from the spent nuclear fuel in the geosphere. Radionuclides are transported by advective flow in water-conducting fractures of the rock and by diffusion into the surrounding rock. In nuclear waste repositories that will contain concrete structures in contact with the bedrock (e.g. claystone or granitic host rock), the large uncertainties in the repository safety assessments are also related to the

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behaviour of radionuclides with small or poorly known retention, such as C-14, Cl-36 and I-129. In addition, the long-term performance of a cement-based barrier may be affected by interactions with its surroundings, driven by chemical gradients in the pore water composition at the interfaces.

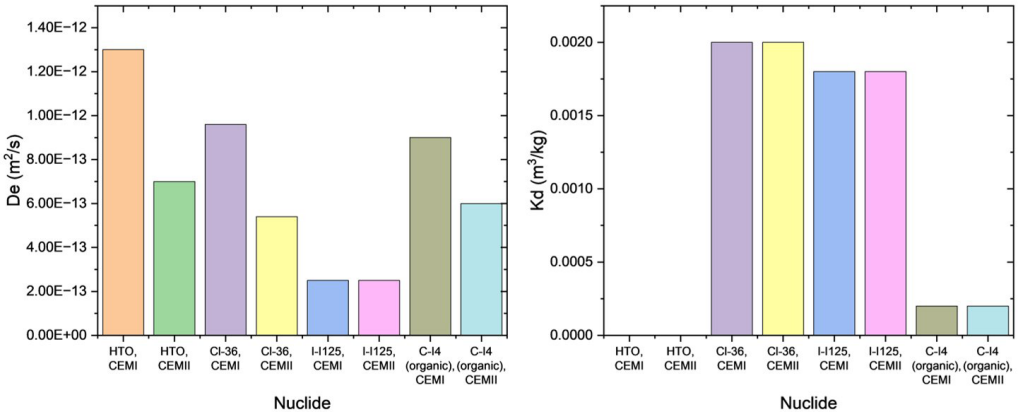
Radionuclide mobility in the cement-rock interface (RASK) project was initiated to investigate these topics. At the beginning of this project, radionuclides' transport was studied by in-situ experiments in the Grimsel Test Site in the Swiss Alps in the Long Term Diffusion project (LTD). Diffusion and sorption behavior of barium and cesium were determined and the spatial distribution of radioactivity in granitic rocks was measured with autoradiography techniques that were developed.

We set out also to characterise the retention and diffusion behaviour of radionuclides of small or poorly known retention and investigate possible structural and mineralogical changes caused by long contact time between rock and concrete.. The study involved the characterization of changes in structure and mineralogy on samples from in situ-diffusion experiment at Grimsel Test Site (Switzerland) as part of a Carbon and Iodine Migration (CIM) project. Parallel to the structural studies, laboratory experiments were conducted.

Laboratory experiments were performed to investigate the retention behavior of several radionuclides (HTO, organic C-14, Cl-36 and I-125) in different cementitious materials. The distribution and effective diffusion coefficients were determined by through-diffusion experiments. The mobility of radionuclides in *in situ* samples of mylonitic granodiorite were also characterised using autoradiographic methods. Methods were developed to measure diffusion profiles of the retarded part of RN via autoradiography. Quantification and distribution of porosity were studied in a mortar and mylonitic granodiorite interface sample by C-14-PMMA autoradioradiography to identify any changes/zoning towards the mortar-granite interface at the sub-mm scale. In addition, mineral-chemical information was provided by element mapping by SEM/EDS.

The results from laboratory diffusion experiments on different concrete samples are summarized in Figure 5.16. It can be seen from these results that the diffusion coefficients were mostly smaller in the CEM2-based concrete. Cl-36 and organic C-14 had larger diffusion coefficients than I-125. In terms of distribution coefficients, the Cl-36 and I-125 had quite similar values, while organic C-14 was one decade smaller. There was no significant difference in the distribution coefficients between different cementitious materials.

Figure 5.16. Summary of the diffusion coefficients and distribution coefficients.



The characterisation of an in situ rock-concrete interface showed that crystalline rock had not experienced any notable amount of alteration, while concrete is slightly degraded during 15 years of contact. This was seen as increased porosity near the interface area with autoradiography. Electron microscopy analysis showed that degradation had produced an interface region with a width of 200–400 µm that was partially filled with porous material and partially empty. Elemental and morphological analysis indicated that the porous material originated from the cement phase and its origin probably involved the leaching and dissolution of the cement matrix.

During the course of this work, we determined the effective diffusion coefficients and distribution coefficients of several radionuclides with small or poorly known retention. The analysis on in situ- interface samples showed the rock appears to be stable against the alkaline conditions but the concrete phase is slightly degraded. We also developed methods and optimized methods to image pore space and to image the retention of radionuclides. The in situ diffusion experiment is planned to be overcored in 2024, and the methods developed here will help to analyse samples from the upcoming overcoring campaign. The increased understanding produced by this work will lessen the conservatism in the safety assessment of the multi-barrier system and help to assess suitable cementitious materials. Methodologies developed during this project can be fully applied to the study of near-surface repository systems for LLW.

5.6.2 RABIO – Better radioecology for the modelling of biosphere

Project manager: Jarkko Akkanen[35]; other personnel: (Marko Ylönen, Jukka Juutilainen, Christina Biasi, Soroush Majlesi, Päivi Roivainen, Jonne Naarala, Jouni Sorvari, Tiina tuovinen, Mikko Kolehmainen)[35]

5.6.2.1 Research topic and key results

The overall the focus of the project was to study the source and transfer of elements relevant to the nuclear waste management from the environment to the aquatic food chain. The project was divided into smaller subprojects including studies on the sediment as a potential source for radionuclides in the aquatic food chains, including a separate subproject on ^{14}C-transfer from organic matter to terrestrial and aquatic food chains. Third subproject was dedicated to study the implications of the empirical observations for the current practices and outcomes of the radioecological modelling. In addition, emphasis was placed on training of experts for the field of radioecology.

The main aims were: 1) To study the importance of sediments as a source of radionuclides compared to porewater and water. 2) To study if the concentration ratios of elements between the organism and their environment independent of the environmental concentrations. 3) To study if sedimentary organic matter act as a source for 14C into aquatic food chains. 4) To train of experts for the field of radioecology.

The main results: 1) The distribution of elements in the study lakes and laboratory experiments emphasized the role of the sediment. The sediment concentrations were much higher compared to that of in the porewater or overlying water. The concentration ratios calculated using porewater and water concentrations were much higher than expected. 2) Depending on the element the increasing environmental concentration resulted in either constant or decreasing concentration ratios (e.g. Majlesi et al. 2021). In some, occasions lower concentration ratios were observed with increasing environmental concentration, but this was noticed only in the cases with quite small differences between the environmental concentrations. 3) It was shown that the benthic organisms can take up and assimilate 14C from the sedimentary organic matter in the aquatic environment. Assimilation was species dependent. 4) One PhD degree and one Master's degree was achieved during the project. In addition, another PhD project and Master thesis was started during the project and will be finalized later.

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We have still field experiment data under investigation (questions 1 and 2) and manuscript under way to be submitted on the uptake of 14C from sedimentary organic matter into benthic organisms. In addition, we will still analyze the meaning of our results for the radioecological modelling.

5.6.2.2 Meaning for nuclear waste management and safety

The project connects to the topic "Safety" in the KYT2022 framework program that includes the chapter 3.1.2. and in there, section "biosphere". The purpose was to study transfer of elements in boreal aquatic food chains. This included sources of radionuclides to the aquatic food chains, concentration ratios between organisms and their environment that are important in radioecological modelling in safety analyses. The project contributes to the rare data that we have on the topic in boreal aquatic environments and improves radioecological modelling.

5.6.2.3 Methods

The methods that have been applied include field sampling, laboratory experiments and chemical analyses. The peat samples for both terrestrial and aquatic environment studies of the transfer of 14C to food chains were obtained from cut-away peatland Linnansuo (Joensuu). Accelerator mass spectrometer (AMS) were used to analyze 14C in different samples through commercial services (Poznan Radiocarbon Dating Laboratory, Poland) except gas samples, which were analyzed in in the Laboratory of Chronology (University of Helsinki). In the transfer of 14C a two-pool mixed model was used to contributions of two carbon sources in organisms (Majlesi et al. 2019).

For other elements, total element concentrations were used as a proxy for the corresponding radionuclides. The samples to study the transfer of the elements were all obtained from small lakes downstream from or nearby a former uranium mine (Paukkajanvaara, Joensuu). Common benthic organisms *Chironomus riparius* and *Lumbriculus variegatus* were used to study the effects and uptake of elements from sedimentary materials in the aquatic environment. Concentration ratios were also measured from field collected benthic organisms (Chironomidae) and fish (*Perca fluviatilis* and *Rutilus rutilus*) (e.g. Majlesi et al. 2021). All samples were analyzed in commercial laboratory (SGS Finland Oy). In addition, samples to study the distribution of elements among sediment, porewater and overlying water was taken using Rhizon samplers (Rhizosphere Research Products B.V., Wageningen, The Netherlands).

5.6.3 KÄRÄHDE – Characterization and source term of spent nuclear fuel

Project Manager: Pauli Juutilainen/Silja Häkkinen[36]; other personnel: (Antti Rintala, Riku Tuominen, Jaakko Leppänen, Ville Valtavirta, Ana Jambrina, Lauri Vaara, Topias Kähkönen)[36]

Safe and economic spent nuclear fuel (SNF) management requires profound knowledge of the nuclide concentrations in SNF. The concentrations as such and the resulting properties, such as decay heat and neutron and photon emission rates, affect the safety margins related to storage, transportation and final disposal of SNF. Such knowledge practically relies on computational analyses whose accuracy is affected by various uncertainties as well as modelling assumptions and approximations. The significance of these factors was studied in KÄRÄHDE from various perspectives, mostly using the Serpent Monte Carlo code as the reference computing tool.

The uncertainties in computational spent fuel characterization, or burnup calculation, were divided into following main components:

- Nuclear data (cross-sections, fission yield, decay)
- Impurities in fuel and structural materials in the reactor core
- Choice of computational parameters for burnup calculation
- Simplifications in irradiation history

The uncertainty propagation of the cross-section data through the burnup calculation comprises probably the most demanding topic out of the above-listed components. It was chosen as one of the main objectives of KÄRÄHDE to identify applicable tools and start building expertise on the topic, as the computing tools of VTT were not able to evaluate the impact of the cross-section data uncertainties. For that purpose, the T6/TALYS package based on the Total Monte Carlo (TMC) approach was tested and set up for use on VTT's computing cluster. In TMC, a very large number of randomized cross-section data sets is created, and a Monte Carlo burnup calculation is performed with every one of them to obtain the predicted uncertainty range for each nuclide concentration in spent fuel.

The T6 package is currently developed and administered by the Swiss Paul Scherrer Institute. It creates the TENDL nuclear data library starting from the fundamental nuclear physics models and utilizing the available experimental data. It creates the randomized data sets based on the evaluated cross-section uncertainties and correlations between

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reactions and nuclides. The resulting data is processed to Serpent-compatible ACE-format with the NJOY processing code. The same package can be also used to produce fission yield data variations.

As a result of work in KÄRÄHDE (and partly funded together with SAFIR2022/RACSA), 500 randomized cross-section data sets have been constructed for 88 nuclides at temperatures of 0 K, 300 K, 600 K, 900 K and 1200 K. Random fission yield data files have been obtained directly from the TENDL website. Several scripts for file processing, data visualization and other required actions have been written to facilitate the TMC calculations. Thus, an environment has been established to VTT's computing cluster to enable predicting the impact of nuclear data uncertainties in burnup calculation with Serpent. One should bear in mind that the quality of the underlying uncertainty estimates for each nuclide and data item define the credibility of the obtained uncertainty ranges. Preliminarily, the ranges seemed somewhat large.

The TMC with Serpent has been tested and demonstrated with two burnup benchmark cases. First, the Gundremmingen-1 BWR with 6x6 assembly was calculated and, in the second phase, the Novovoronezh-4 benchmark with a VVER-400 assembly was calculated. The latter of these was run with the full above-listed coverage of randomized data, whilst the former was based on reduced extent of data variations. Both benchmarks are documented in SFCOMPO database, whose main purpose is to provide data that is needed for criticality safety analyses utilizing burnup credit.

The decay data uncertainty treatment is somewhat more straightforward as it does not contain correlations between nuclides. The uncertainty sampling feature was implemented to Serpent in the early phase of the project. With the feature activated, Serpent samples varied decay data for each nuclide in the beginning of the burnup calculation. Similarly to TMC, multiple repeated burnup calculations with varied data will yield an uncertainty estimate for the nuclide concentrations.

The minute contents of various impurities in fuel and other materials accommodated in the reactor core may cause significant trouble in spent fuel management after getting activated under irradiation. At first, a literature review was conducted to survey the impurity concentrations evaluated in previous studies. The largest concentration found for each nuclide was applied in the subsequent Serpent calculations, so the results are strongly conservative. The activation was calculated with a 2D assembly model, followed by a 3D assembly and full-core models. The 2D calculation suggested that the impurities caused up to 2.5 % increase to fuel activity, whereas for the cladding as much as 800 % increase was observed at highest, compared to completely pure materials.

The irradiation history of a fuel assembly usually needs to be simplified for a burnup calculation. Practically, the power, boron concentration (in PWRs), fuel and coolant temperatures and coolant density are the varying features that affect the neutronics environment and thus the calculated SNF composition. The significance of these variations were studied using two VVER-440 assemblies with real operating data as the reference and calculating the same history with averaged parameters. The calculations suggested that the power history averaging caused major overestimation – more than 70 % – to the decay heating power immediately after the end of irradiation, but the difference mostly disappeared in less than 10 years. The averaging of other parameters did not affect any of the studied properties much, as the relative difference was mostly kept below 1 % all the time when decay heat, photon emission, spontaneous fission rates and concentrations of a few selected key nuclides were considered.

The impact of computational parameter definitions for Serpent burnup calculation was studied with a 10x10 BWR assembly. The following parameters were studied: depletion zone division, burnup step length, unresolved resonance probability table sampling (on/off for U-234, U-235, U-238, Pu-239 and Pu-240.), Doppler-Broadening Rejection Correction (DBRC, on/off) and energy-dependent branching ratios (vs. built-in default constants). The impact of these on decay heating power, photon emission and spontaneous fission rates was studied and found to be mostly small or negligible. However, it was found that the unresolved resonance probability table sampling and DBRC should be switched on. A commonly used burnup step length is sufficient, as well as the automatic depletion zone division pin-wise for ordinary fuel pins and with 10 subrings for Gd fuel.

The inventory calculations for the reactor and fuel types interesting in the Finnish scope with various discharge burnup levels were updated in terms of calculation code and reactor types, compared to the previously published results. The SNF properties as such were rather similar between fuel types, but the further steps in the waste management analysis chain would reveal, how significant the obtained differences are. Such sensitivity analyses were not performed in KÄRÄHDE.

The project also participated an international decay heat benchmark organized by SKB. Five 17x17 PWR assemblies were calculated, and the results were compared between participants and against measurements. The code-to-code agreement was rather good, but the calculations generally underestimated the heating power with respect to the measured values. However, most of the calculated values were within the uncertainty range of the experiments. It is expected that similar exercises will be included in the agenda of the decay heat subgroup under the OECD/NEA Working Party on Nuclear Criticality Safety, which raise opportunities to obtain better knowledge on the reasons of discrepancies between the calculated and measured decay heating power.

Serpent was also tested and slightly developed to model the Passive Gamma Emission Tomography (PGET) system for safeguard applications. The work served as an educational project for a new expert, along with which the variance reduction methodology of Serpent was improved to perform more efficiently in collimated detector problems.

Most of the described calculations were performed with Serpent in 2D assembly geometry in infinite lattice. For further accuracy, it would be beneficial to run the calculations with the realistic 3D full-core models. An attempt to do it with Serpent was performed using an SMR core as a test case. The Monte Carlo calculation, however, is extremely time-consuming for a full-core model. Therefore, a deterministic core calculation with a micro-depletion feature is a more realistic approach for practical applications. For that purpose, it is a near-future target to make the Serpent – Ants sequence capable of performing that with reasonable user effort. The target was promoted in a joint M.Sc. thesis task with a few other VYR and EU projects, as the micro-depletion feature of Ants was demonstrated against Serpent reference calculations with 2D assembly and 3D full-core models. These results suggest that the Serpent – Ants chain can be used for SNF characterization with operating cycle modelling, but it will require considerable effort to make the chain fluent and reliable.

5.6.4 PORA – Microstructure of nuclear fuel and radium solubility

Project manager: Janne Heikinheimo[37]; other personnel: (Tom Andersson, Jussi Peltonen, Emmi Myllykylä, Anniina Seppälä)[37]

5.6.4.1 Fuel pellet mechanical modelling

The parabolic temperature profile in the fuel pellet causes tensile stresses at the outer region of the pellet. On the other hand, the inner parts of the pellet experience compressing forces. At the pellet edges, the mechanical behaviour is close to brittle. However, with the elevated temperatures at the central parts of the pellet, the behaviour is more plastic. Stress over the fuel pellet can result diverging local stresses and microcracking due to strain incompatibilities between the grains. Also, porosity, location of pores in grains or at grain boundaries, their size and shape have a strong effect on the UO_2 mechanical behaviour.

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A crystal plasticity model was introduced to enable investigation of UO_2 deformation behaviour. Both single crystal and polycrystal compression tests were applied in the parametrization of crystal plasticity model. Special attention was placed on the effect of porosity on stress and strain localization. The porosity and grain structure were based on the 2D SEM-EBSD image of a real UO_2 fuel pellet. Also, comparisons were carried out for 3D simple-element- based approach and explicit 3D porosity structure. All structures were addressed to similar uniaxial compression tests up to 6.8 % of nominal strain. The results have been published in Journal of Nuclear Materials [1].

Microstructural mechanical performance was compared to macroscopic BISON simulation for OECD/NEA/WGFS RIA Fuel Codes Benchmark Case 5. For now, the von Mises stresses in the pellet were not realistic for higher temperatures. Discussion and modelling development of nuclear fuel pellet mechanical performance will continue under collaborative EU project OperaHPC (OPEn HPC theRmomechanical tools for the development of eAtf fuels).

5.6.4.2 Radium transport

The objective of this project was to analyse the Ra-226 release from SIMFUEL (Simulated Irradiated Fuel) pellets to natural ground water in anaerobic conditions. Another objective was to study the sorption of Ra-226 to bentonite and bentonite-zeolite mixed matrix in anaerobic conditions. In support of the experimental work, molecular dynamics simulations were conducted to investigate Ra adsorption onto the surfaces of montmorillonite (the main and functional component of bentonite) and zeolite.

Measured concentrations from the SIMFUEL dissolution tests to natural ground water in anaerobic conditions where at the same level as in the background sample, so it is possible that detected Ra-226 originates from the ground water. Nevertheless, measured Ra-226 concentrations were very low (~1 ·10–12 mol/L).

Reaction experiments of bentonite and bentonite – zeolite mixed materials showed that even 5 % zeolite addition increases the material's sorption capacity, especially for Ba2+. Due to the demanding and time-consuming nature of Ra-226 analysis, only few samples were analysed. However, significantly better sorption capacity of 20 % zeolite – 80 % bentonite mixture could be seen in comparison with pure bentonite.

Molecular dynamics simulations showed clear differences in the adsorption properties of montmorillonite and zeolite A. Simulations suggested that the partition coefficient KD depends on the initial concentration in water. Although the Ra concentrations considered

here were much higher than is feasible to study experimentally, the results indicated a significantly higher adsorption capacity for zeolite than montmorillonite, which is in line with the experimental results.

5.6.4.3 Meaning of the results for safety of nuclear waste management

Fuel cracking is strongly related to FGR as cracks within the fuel can immediately release the fission gas trapped at grain boundaries or within grains. Macroscopic models have been developed to account for micro-cracking of the fuel, which is generally assumed to explain some observed FGR in transient (such as fast power increases) conditions. However, the micro-cracking phenomenon itself is quite poorly understood. The PORA project laid foundation for modelling of the pellet microstructural behaviour. FGR during the in-pile operation of the fuel is also relevant regarding spent fuel disposal. The FGR is assumed to correlate with the instant release fraction (IRF) of certain nuclides, such as the fission products ^{129}I and $^{135/137}$Cs, in spent fuel disposal. The IRF is defined in the literature as the inventory of nuclides at the grain boundaries and the gas gap. It is instant in the sense that it is thought to leach out from damaged final disposal canisters immediately, at least at geological timescales. As FGR is routinely calculated by fuel performance codes, such as FRAPCON, ENIGMA or FINIX in use or under development at VTT, these codes can be easily used to also estimate the instant release fraction regarding the relevant nuclides. However, there is uncertainty in the relationship between FGR and IRF in the experimental data. For example, the relationship between FGR and IRF of caesium has been determined to be from 1:1 to 1:3.

Radium is a radioactive alkaline earth metal found naturally in the environment. Its two longest-lived isotopes, ^{226}Ra and ^{228}Ra occur in the uranium and thorium decay chains, respectively. Radium exhibits high radiotoxicity as it has multiple alpha-emitting daughter isotopes and when ingested by animals it concentrates in bones. ^{226}Ra is an important nuclide for spent fuel disposal as it is produced in the decay chain of uranium, of which most of the spent fuel pellets consist of. In the long-lived natural chain ^{238}U produces ^{234}U which produces ^{230}Th and further ^{226}Ra. In addition, in spent nuclear fuel there is excess of ^{234}U in activity (about 10 times in Bq) due to isotopic enrichment, and ^{234}U is also produced from decay of ^{238}Pu that forms by neutron activation of the actinides in the fuel. Also, radium can be quite mobile in groundwater, depending on water quality. Especially in high-salt wells drilled into bedrock in the Finnish coastal areas radium can typically be found in the well water. There are certain important phenomena regarding important nuclides like ^{226}Ra and the KBS-3 repository concept. An important aspect is the release rate of ^{226}Ra from precipitated uranium and especially amount of ^{234}U in precipitate inside canister.

5.6.4.4 References

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5.6.5 NAT-LAB-14C – Using volcanic-geothermal fields as natural laboratories to investigate transfer of 14C in soils and into terrestrial food webs

Project manager: Jukka Pumpanen/replaced Christina Biasi[38]; other personnel: (Mpamah Promise, Tatiana Trubnikova, Dan Kou, Soroush Majlesi)[38]

5.6.5.1 The research topic and key results of the project

Radiocarbon (^{14}C) has been recognized, both at national and international level, as an important radionuclide for safety assessment studies associated with operational discharges as well as radioactive waste. Radiocarbon is a key contributor to the doses in many assessments, and it is particularly important with respect to low and intermediate-level waste material and spent fuel. The topic is particularly challenging due to the ubiquitous nature of carbon in the nature and its intimate involvement of physiology and metabolism of all living organisms; that is, also radiocarbon exhibits elaborate and complicated biogeochemical behaviour. In addition to knowledge gaps in the validation and other scrutiny of the modelling of radiocarbon behaviour, there are also still major knowledge gaps in basic carbon cycling. For example, considerable uncertainty remains in predicting the fate of ^{14}C derived from belowground sources into plants and the terrestrial food web. The degree of uncertainty starts from the chemical form in which ^{14}C would enter the biosphere. Currently, it is cautiously assumed in the long-term safety assessments that all of ^{14}C released from a repository will be transformed to CO_2 and enter the food chain through plant uptake. The assumption that CH_4 is completely oxidized to CO_2 likely results in considerable pessimisms in current model assessments.

A particular challenge in ^{14}C biosphere assessments is of methodological nature, as it is very difficult to separate natural and anthropogenic atmospheric input from that relevant to potential releases from geological repositories. This research contributes particularly to

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addressing the sub-surface carbon signal and transfer of ^{14}C into the biosphere, through utilising the volcanic carbon isotopic (^{13}C) signature as a substitute for ^{14}C potentially released from nuclear waste disposal in gaseous forms.

By using this approach for the first time, we aimed at 1) determining the uptake of $^{14}CO_2$ from below ground sources into different plant species characteristic for forests and grasslands 2) reducing the pessimism in current ^{14}C assessment models by quantifying ^{14}C release in form of CH_4 and 3) enhancing assessment-level models on the fate of gaseous ^{14}C from belowground sources.

Our results showed that in the plant samples including trees, herbs, grasses and lower plants, the portion of belowground source of carbon differed between 0 to 15 % depending on the plant species and plant part. The maximum portions found (15 % in *Ranunculus* sp.) were higher than the previously assumed transfer rates, but some plants showed also no signs of carbon from belowground sources. The ^{13}C signature of the plants were not predicted well with any of the environmental drivers measured, thus we could not identify controlling factors of soil-C incorporation. There was also no clear difference between different plant parts, but some indication that uptake occurs primarily via roots exists. Since also trees were enriched with carbon stemming from belowground sources, though to a lower level (5–7 %) contamination of forest vegetations could be significant in case of accidental or operational release of ^{14}C from nuclear waste deposits.

Our results further showed CH_4 is oxidized to CO_2 completely in nearly all plots expect for the warmest plot, where high CH_4 emissions were observed. The isotope signal of CH_4 from the warmest plots, where CH_4 emissions were observed, indicate a deep geological CH_4 source. Not all the CH_4 which is emitted at these sites is oxidized, indicating that also in arable soils CH_4 oxidation may be not complete.

With regards to the modelling tasks, the number of soil compartments increased from one to three to match with site properties. Quality controls (benchmarking, verification) were performed to develop model for this project. However, there has been some delay in the start of the modelling work because a) it took longer than anticipated to produce the quality-checked field data due to COVID-related delays in analysis, b) additional information recent field work seems useful to fit the model into the full-system field data, and c) a mathematical model which is simultaneously developed in the ^{14}C project of the Bioprota Forum, which would considerably help to develop our Ecolego model more realistic and was expected for early summer 2022, is still in progress. At the time of writing this report, the modelling work is still ongoing. Plans were made that the models created with Ecolego can be run with different input data for free to reach wider use in the researcher community and in education/training.

The meaning of results safety of nuclear waste management, especially focusing on usability of results and connections with other research

We confirmed previous studies conducted by us and also others, that the proportion of ^{14}C derived from belowground sources can be higher than commonly assumed in the literature on general carbon cycling (e.g., 1–2 %) in terrestrial plants. However, assessment-level ^{14}C transport models used by most radioactive waste management organisations and regulators typically assume pessimistically high ^{14}C capture into the plants, and thus likely overestimate the transfer of C from belowground sources into plants even if the direct root uptake would be somewhat higher than assumed. We could not identify the influencing factors on the highly variable proportion of soil-derived C into plants, and suggest that more studies are needed. As a direct outcome of our research, we were invited by SKB to write an extensive literature review on the proportion of ^{14}C or soil-derived C in plants, an undertaking which is ongoing and which will reveal more information on the uptake of C from belowground sources in plants and thus risks related to radioactive waste disposal. In general, the assumption that all CH_4 is oxidized to CO_2 holds true for natural CH_4 concentrations in arable soils, but not necessarily when CH_4 concentrations raise relatively quickly (as it could be the case for a gas release event from a repository). There is thus a possibility that assumptions in the models (particularly, that of complete CH_4 oxidation to CO_2) are too pessimistic.

Even though there was a delay in data collection and processing in this project (partly due to COVID), and the modelling work could thus not be finished within the current time frame of the project, we are positive that the parameterization of ^{14}C transfer models, implemented in Ecolego, will be completed utilising the data derived from the project in near future. Since UEF is now academic member of the BIOPROTA Forum, there are plans to compare the model outcome with models used by other BIOPROTA members (great interest already expressed) and ultimately this will help to improve also other models (e.g., SSPAM^{14}C used by SSM). We anticipate that the pessimism of most current assessment models will subsequently be reduced. A follow-up project was granted within the SAFIR program network (project leader: Soroush Majlesi), and thus research on radiocarbon transport and fate in the surface environment will continue.

5.6.5.2 Methods used in the studies

The study was carried out at the ForHOT study site in Western Iceland, within volcanic areas influenced by geothermal activity. Plant and soil samples were taken, and gas analysis were collected. We analysed mainly the C and ^{13}C content in the soil, plant and gaseous material, by using stable isotope ratio mass spectrometer connected to elemental analyser, and laser spectrophotometric methods. Fluxes of CO_2 and CH_4 were measured with a modern, transportable CO_2/CH_4 gas analyser was brought from Finland to Iceland,

which allowed for flexible and abundant in-situ gas flux measurements. Root samples were additionally taken, and environmental parameters (e.g., soil temperature, water content, plant biomass, normalised difference vegetation index) were either measured or retrieved from existing data repositories.

5.7 Low and intermediate level waste management

5.7.1 SURFACE – Near Surface Repositories in Finland

Project manager: Paula Keto[39] and Gareth Law[40]; other personnel: (Laura Wendling, Heidar Gharbieh, Shila Jafari, Minna Vikman, Pauliina Rajala, Melany Gouello, Suvi Lamminmäki, Ville Rinta-Hiiro, Timothy Schatz)[39], Gianni Vettese[40]

5.7.1.1 Research topic and key results of the project

The first year of the SURFACE project was performed as a literature study published in Keto et al. (2019) focusing on regulatory framework, different near surface disposal concepts and barrier options, safety case considerations and monitoring. The work continued in cooperation with University of Helsinki in 2020 focusing on performance of a landfill-type of a near surface disposal facility. This selection was made based on TVO's decision to adapt the design used in Sweden with similar type of geological conditions and waste. During 2020–2022 the work performed in the KYT2022 SURFACE project (2019–2022), was divided into three work packages (WPs), each addressing a different theme:

- WP1: Radionuclide transport behaviour in barrier materials;
- WP2: Biodegradation of waste and steel corrosion;
- WP3: Performance of engineered barriers.

WP1 of the SURFACE project started in year 2022 and involved UH and VTT. Tasks focused on developing robust laboratory-based methodologies at each partner institute that permitted long-term radionuclide transport studies in dynamic, heterogeneous systems representative of shallow subsurface radioactive waste disposal, complete with flowing water / leachate and solid phase sampling. In consultation with TVO, UH was tasked with using their system to evaluate ^{90}Sr behaviour and transport in scenarios representative of TVO's surface disposal barrier / backfill material. VTT were to study ^{36}Cl. At UH, a column system was designed and tested during 2020 using a simpler experimental matrix

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(disaggregated sandstone) and a non-active tracer (Se). The system was found to be capable of reliably studying radionuclide behaviour and the evolution of environmental / barrier systems, across timescales of >1 year (Ho et al., 2022). Further scoping work with a radiotracer indicated the system did not leak and could be easily decontaminated after use (Ho, 2022). Finally, we demonstrated that all of the possible barrier / backfill materials considered in TVO's near-surface disposal concept could be included in the column system. Therein, radionuclide transport and uptake to solids / removal from infiltrating water could also be monitored with time, and the co-evolution of the barrier materials and speciation / binding mechanism(s) of radionuclides retained on the solids could be tracked. The column system also permitted perturbation experiments where inflowing leachate compositions could be changed to represent surface disposal disturbance scenarios (e.g., flooding, sea-water ingress etc.). Combined, this permits evaluation of radionuclide retention under best and worst-case release scenarios, which informs safety case needs. After testing of the UH column system was complete, it was successfully used in year 3 to study ^{90}Sr behaviour and transport. A combination of outer-sphere (weak) and inner-sphere (strong) Sr binding to barrier / backfill materials were observed. Interestingly, the addition of bentonite and steel to the rock flour matrix appeared to offer little-to-no enhanced Sr removal from leachates and reactive sites in the column volumes became saturated over 1 year. In year 4, Sr reversibility from the barrier materials was then tested under climate change scenarios (flooding and seawater intrusion). Significant remobilisation was apparent from all scenarios and from all barrier materials, although Sr binding to the rock flour was strongest (i.e., least reversible). The Sr work was recently submitted to the journal *Minerals* (Vettese et al., in review). Data outputs from the UH experiments will provide parameters for disposal safety case modelling and highlight potential future risks to the disposal scenario from climate change. The column design work and the Sr study were successfully defended in a UH PhD in September 2022 (Ho, 2022). The UH column system is now a legacy of the project to be used in future experimentation. VTT's column system unfortunately suffered from repeatability problems and provides very slow flow-through times. It is not optimal for surface repository type studies and its use is not continued. Also, the VTT work planned for 2022 suffered some drawbacks one reason being the poor condition of the samples stored from 2019 and failure in preparation of good quality subsamples. The funds allocated for this work were used in scientific article writing instead to support dissemination of both WP1 and WP2.

WP2 also started in year 2022 of the SURFACE project. Here, the importance of water inflow to the disposal system's behaviour was seen in biodegradation and steel corrosion studies. In WP2, two simulated microbiological experiments were conducted under controlled conditions, after which the gas generation, corrosion of the steel coupons, microbes present, and leachates were analysed. The experiments had different combinations of carbon steel coupons, simulated rainwater, simulated waste, aged concrete, and microbes added to bentonite, crushed rock, and rock flour. The importance

of the possible ingress of water was highlighted, as it was found that if no water was in contact with the waste, there was no generation of gas. Gas, in turn, was mostly formed as a result of microbial degradation of waste; steel corrosion did generate gas, but to a much lesser extent in the simulated laboratory experiments. The main component of the released gas was found to be methane and no hydrogen was detected. The same observation on gas composition has been made in on-going large-scale gas generation experiment at Olkiluoto (; Vikman et al., 2019), indicating that hydrogen is rapidly consumed by microbial activity. Water also plays a role in waste material corrosion because it is an essential factor for microbial activity and steel corrosion. In addition to these changes driven by the presence water, Keto et al. (2019) found, based on preliminary numerical modelling, that there is a relatively high probability for disposed wastes to be in contact with the water during a Finnish surface repository's lifetime.

In WP3 of SURFACE (2020–2022), we considered the design of the surface disposal facility and focused on establishing safety functions, the design basis, and on performance assessment through laboratory studies, case studies, monitoring needs, and numerical modelling (Keto et al., 2019, 2020, 2021, and summary report from 2022). Based on the study, the critical engineered barriers are likely to be relatively robust under near surface conditions, also considering extreme weather conditions (e.g., freezing and thawing). However, considering the expected service life of the repository (up to 300 years), some recommendations were made in the summary report (Keto et al. 2022) for increasing the safety of the system (barrier layer thicknesses and compositions.

5.7.1.2 Meaning of the results to safety of nuclear waste management (usability of the results and connections with other research)

The results give basis for the design of a near surface disposal facility in Finland and basic information on the performance of a landfill-type near surface disposal facility in Finnish site conditions. The experimental column system used in radionuclide behaviour studies is also important legacy of the SURFACE project and it has now been adapted for safe use with radioisotopes (e.g., Tc-99).

5.7.1.3 Methods used in the studies

The methods used in SURFACE include:

- Literature review (Keto et al. 2019–2022)
- Numerical modelling methods used for studying the infiltration of water through the barriers and formation of ground frost (Keto et al. 2020, 2021)
- Laboratory methods:
  - Column tests for radionuclide transport, retention and re-mobilisation (see Ho et al. 2022, Vettese et al. 2023)
  - Test method for studying corrosion, biodegradation of the waste and gas generation (Vikman et al. 2023)
  - Geotechnical laboratory studies (Keto et al. 2020, 2021, 2022).
- Risk analysis (Keto et al. 2022)

5.7.2 TERKOR – Corrosion of low and intermediate level steel waste in in-situ conditions of final repository

Project Manager: Pauliina Rajala/Leena Carpen/Vilma Ratia-Hanby[41]; other personnel: (Elisa Isotahdon, Thomas Ohligschläger, Malin Bomberg, Shila Jafari)[41]

5.7.2.1 The research topic

The aim of the project was to assess the corrosion properties of nuclear power plant (NPP) and decommissioning steels in natural or simulated groundwater conditions considering the possibility for microbially influenced corrosion (MIC) and to assess the impact of activation on corrosion. The decommissioning phase of the NPPs produces activated waste, and a large part of this waste is steel, such as carbon steel (CS), pressure vessel steel (PVS) and stainless steel. Contaminated waste is also generated already during the operation of the NPP. Knowledge of steel durability and its corrosion behavior is essential when planning the final repository conditions, and information on the corrosion of steels in the varied final repository conditions in Finland as well as the influence of radioactive activation on corrosion is needed. As corrosion is dependent on the surrounding conditions, these studies were conducted in conditions mimicking the ones in the actual repository. In addition to water chemistry, microbes can influence corrosion and their role on steel corrosion was evaluated in these studies. Microorganisms are known to

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affect corrosion both directly and indirectly, creating localized conditions underneath the biofilm and changing the chemistry of the surroundings through their metabolic cycles (use and production of compounds).

5.7.2.2 The key results of the project

The effect of microorganisms on corrosion of steels was studied through adding different microbial enrichments to the groundwater laboratory setups, and it was revealed that the corrosion outcome of steels in repository simulating conditions was affected by the presence of microorganisms and varying microbial community composition. For the CS, the addition of sulphate reducing bacteria (SRB) led to highest general corrosion in the first long-term (11 months) experiment. Corrosion rates obtained gravimetrically from environment including SRB and iron reducing bacteria (IRB) showed that the PVS suffered higher corrosion rate when compared to the CS, and the electrochemical results further indicated that there was no similar kind of a protective corrosion product/biofilm layer on PVS than on the CS in this environment. The corrosion rate obtained gravimetrically for the stainless steel was determined to be low overall. The amounts of bacteria in general, SRB and methanogenic archaea were determined by bacterial 16S rRNA gene, *dsr*B gene and *mcr*A gene targeted quantitative polymerase chain reaction (qPCR), respectively. The qPCR indicated that PVS supported the highest number of bacteria, SRB and methanogens in the water phase (SRB+IRB inoculated), whereas the highest sessile bacterial, SRB and methanogen marker gene copy counts were detected on the stainless-steel surfaces (SRB+iron oxidizing bacteria inoculated). Different sample conditions hosted unique microbial communities both in the water phase and on metal surfaces, and dissimilarities in microbial community structure between experiments were detected.

In the second long-term experiment (9–10 months) a microbial enrichment was added to natural groundwater for a range of steels. Based on gravimetry and electrochemical methods, the corrosion rate of CS was lower in the environment with microbial addition in this time scale in comparison to one without (treated with biocide). However, there was also difference in oxygen level detected after the test between these CS environments. For stainless steels, the corrosion rate was practically immeasurably small with gravimetry. Electrochemical methods showed similar low corrosion rates for 304 and 316 steels in environments both without (treated with biocide) and with microbial addition, but more pit forming for 316 steels in the biotic environment. Momentary localized corrosion was observed in the electrochemical measurements for all the studied environments, and it is important to consider both general and localized phenomena. The bacterial 16S rRNA gene qPCR indicated that all tested steel grades hosted high levels of bacteria in both the biofilms on the steels and in the water phase in the mesocosms. Based on the qPCR, SRB attached especially to stainless steel 321. Bacterial communities were more diverse on 321 steels compared to CS, whereas observed richness remained on equal levels

in all sample types. The water phase in the CS experiments hosted a unique microbial community compared to the waters incubated with other steel types, which shared more similarities in their bacterial community structure. Fungal community differences between sample types remained small. Archaea remained mostly below the detection limit of the qPCR, whereas the hybridization chain reaction-fluorescence in situ hybridization (HCR-FISH) method applied to a smaller-scale TERKOR experiment suggested that archaea could also be part of the steel surface biofilms. This HCR-FISH protocol for biofilm morphology analysis on stainless steel was developed during the project. Generally clear and high-contrast epifluorescence microscopy images were obtained for the groundwater exposed surfaces, enabling the *in-situ* detection of the microorganisms (bacteria, archaea and SRB) on the surfaces, which will be useful also in the future studies.

The importance of assessing the material corrosion performance in all repository sites was highlighted by the study of corrosion behaviour with short term electrochemical tests in groundwaters from ca. 100 m depth from three different sites, Olkiluoto, Loviisa and Hanhikivi, and simulated groundwater. The microbiological and chemical composition of the groundwaters varied markedly between different sites, resulting in differences in the corrosion of steels. The higher corrosion rate in simulated water in comparison to the natural groundwater with similar concentration of sulphates and chlorides indicated that natural groundwater may have properties that might inhibit corrosion at least short term compared to the simulated solution (containing only chlorides and sulphates). The corrosion was also localized for both stainless and CS in all of the tested natural and simulated groundwaters.

The influence of radioactive activation on corrosion was studied by exposing activated and non-activated PVS to the natural and simulated groundwaters in collaboration with project DEMONI. After one year of exposure, scatter of the corrosion rate was large especially in the activated samples. This may indicate that localized corrosion was more intense for the activated than non-activated steel. The composition of the corrosion products was found to vary between the activated and non-activated samples. After one-year exposure, sessile bacterial communities on surfaces of both active and non-active steels showed high similarities. However, after three-year exposure the bacterial community in activated samples resembled the earlier time point, whereas the non-activated samples showed a clear change in the bacterial community structure. Bacteria were able to attach to steel surfaces during the experiment indicating that activation did not hinder biofilm formation on steel surfaces. Biofilms hosted abundant microbial communities with bacteria as main domain, and SRB from the Desulfobacterota phylum dominated all active steel and water samples. In activated samples, fungi were detected solely from the steel surfaces and not in the water phase. These results suggest that

microbial communities in the activated samples need to be studied in more detail in the future to estimate their cellular activity and the functional potential residing in these radiotolerant microbial communities.

5.7.2.3 The meaning of results for the safety of nuclear waste management

TERKOR project expanded the knowledge on corrosion behaviour of steels in different geological settings. The project mainly used natural groundwater obtained from Loviisa, whereas previous project CORLINE studied corrosion of steel with the Olkiluoto site groundwaters. The corrosion results for a range of steels (PVS, CS and stainless steels) and activated steel can be used in planning the repositories for both the decommissioning phase waste and the maintenance material waste containment. The project enabled the training of new experts and promoting the continuance of the research area. The TERKOR project worked in continuance with the previously conducted research as well as future studies. It utilized results and methods obtained in projects of previous KYT programmes, such as REMIC (KYT2014) and CORLINE (KYT2018). Within the KYT2022 programme, TERKOR had a close collaboration with DEMONI project. TERKOR results will be used in the MICWEST project (SAFER2028) and ACED project (EURAD).

5.7.2.4 The methods used in the studies

The experiments were conducted in controlled laboratory environments aiming to mimic anoxic repository conditions, and the majority of the tests were conducted in natural groundwaters and performed at ~ 10 °C temperature. Microbial enrichments originating from the repository site groundwaters were used in simulating microbial activity in the environment. Corrosion was studied from the materials as well as the microbiological aspects. Corrosion behaviour of the materials were determined with electrochemical methods (such as linear polarization resistance, anodic and cathodic polarization, electrochemical impedance spectroscopy). Continuous monitoring was conducted using open circuit potential logging and logging with multielectrode array sensors. Corrosion rates were also determined gravimetrically. Optical microscopy and scanning electron microscopy (SEM), also with a specific method allowing the SEM imaging of the microorganisms attached on the surfaces, were used for imaging the samples. Moreover, the corroded surfaces were studied with energy dispersive X-ray spectroscopy and X-ray diffraction. Analyses for the water compositions were conducted through standardized methods such as inductive coupled plasma. Microbiological methods focused on microscopy (SEM, HCR-FISH) and molecular biological methods. Planktic microbial communities residing in the water phase and sessile biofilm communities on the steel surfaces were compared in all long-term experiments. Microbial community sizes were estimated with the qPCR for bacteria, archaea, fungi, SRB and methanogens, and microbial communities were characterized with the amplicon sequencing.

5.7.3 DEMONI – Decommisioning Material characterization and final disposal studies

Project manager Antti Räty[142] and Susanna Salminen Paatero[43]; other personnel: (Anumaija Leskinen, Tandre Oey, Tiina Lavonen, Jari Lydman, Miguel Ferreira, Tapio Vehmas, Tiina Heikola)[42]

5.7.3.1 Introduction

DEMONI is a coordinated project between VTT and Helsinki University radiochemistry unit. The aim of the project is to develop and validate activity measurement methods and to perform leaching rate tests to study different long-term phenomena in low- and intermediate level decommissioning waste. Main focus was on activated concrete and steel, which correspond to major part of decommissioning waste (excluding spend nuclear fuel).

Four different tasks are interconnected by same sample materials so that the measurement activity data can be utilized in the final disposal simulation tests. Samples have been collected from the FiR1 research reactor under decommissioning and partially from Finnish nuclear power plants. Having samples from real nuclear facilities has been extremely important to be able to take into account practical problems, which are not typically present when using only laboratory standards.

DEMONI project was planned to be part of KYT2022 framework program section 3.1.4. "decommissioning waste management". Methods developed at DEMONI project provide data on activity characterisation both for power companies and radiation safety authorities to ensure safety in future decommissioning projects.

DEMONI is a coordinated project with four tasks. Main outcomes of each task are described in following subsections.

5.7.3.2 Task 1: Developing activity measurement methods

Radionuclides in decommissioning waste are often divided to easy-to-measure (ETM) and difficult-to-measure (DTM) radionuclides. The ETMs are gamma emitters which can be measured using gamma spectrometry which is a non-destructive detection method. The DTMs are beta or alpha emitters which determinations require destructive methods. Formation of scaling factors is a fundamental task in characterisation of decommissioning

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waste as analysis of both ETMs and DTMs in all waste would be laboursome and costly. Therefore, the scaling factor, which forms a link between a key ETM and DTMs, are formed prior to dismantling during which only ETMs are measured and DTMs are calculated using the scaling factor.

Task 1 aimed at method development and validation of DTM radionuclide analyses in activated steel, activated concrete and spent ion exchange resin. The analysis methods of DTM's often consist of several analysis steps with material, radionuclide and measurement technique specific challenges, such as low solubility (e.g. concrete), volatility (e.g. ^{14}C, ^{3}H), spectral interferences (e.g. ^{60}Co in ^{63}Ni spectrum), quenching in liquid scintillation counting (e.g. ^{55}Fe which decays via electron capture and is easily quenched), and measurement of low energy X-rays (e.g. ^{59}Ni). Therefore, method validation is especially important. However unfortunately, there are no commercially available DTM reference materials and therefore, the method validation needs to be carried out in some other way. Therefore, international intercomparison exercises were organized in co-operation with Nordic Nuclear Research (NKS) projects DTM Decom I, II, III and RESINA [Leskinen et al. 2020, 2021, 2022, 2023][4445]. Both Nordic radiochemistry laboratories, namely VTT (coordinator, FI), University of Helsinki (FI), Fortum Power and Heat (FI), Danish Technical University (DK), Institute for Energy Technology in Halden and Kjeller (NO), Norwegian University of Life Sciences (NO), Cyclife Sweden (SWE) and non-Nordic laboratories, namely CEA (FR), Taiwan power company (TW), and National Nuclear Laboratory (UK), participated during the four years of intercomparison exercises. The intercomparison exercises were executed according to the ISO 13528:2015 standard [International Standard 2015][46].

Task 1 studied different materials in different years such that each the work started with method development and the methods were validated with international intercomparison exercises.

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In 2019, activated reactor pressure vessel steel was studied. Results were published in NKS report DTM Decom I [Leskinen et al. 2020][47] and further compared with activation calculation results in a peer-reviewed article [Leskinen et al. 2020c][48].

In 2020 activated concrete from FiR1 research reactor was studied. Work included method development for both volatile (^{3}H, ^{14}C, ^{36}Cl) and non-volatile (^{55}Fe, ^{63}Ni, ^{41}Ca) nuclides. Results were published in NKS project report [Leskinen et al. 2021][49] and further compared with activation calculation results in a peer-reviewed article [Leskinen et al. 2021b][50]. A Metropolia (university of applied sciences) student also carried out experimental studies in both University of Helsinki and VTT 2020. [Laurila 2021][51]

In 2021 spent ion exchange resin provided by Finnish power companies were studied. Work included method development for both volatile (^{3}H, ^{14}C) and non-volatile (^{55}Fe, ^{63}Ni, ^{90}Sr, ^{99}Tc) DTM's. Results were published inan NKS report and in a peer-reviewed article [Leskinen et al. 2022b][52].

47 Leskinen, A., Tanhua-Tyrkkö, M., Kekki, T., Salminen-Paatero, S., Zhang, W., Hou, X., Stenberg Bruzell, F., Suutari, T., Kangas, S., Rautio, S., Wendel, C., Bourgeaux-Goget, M., Stordal, S., Isdahl, I., Fichet, P., Gautier, C., Brennetot, R., Lambrot, G., Laporte, E. 2020. Intercomparison exercise in analysis of DTM in decommissioning waste. NKS-429, Roskilde, Denmark

48 Leskinen, A., Salminen-Paatero, S., Gautier, C., Räty, A., Tanhua-Tyrkkö, M., Fichet, P., Kekki, T., Zhang, W., Bubendorff, J., Laporte, E., Lambrot, G., Brennetot, R. 2020c. Intercomparison exercise on difficult to measure radionuclides in activated steel: statistical analysis of radioanalytical results and activation calculations. Journal of Radioanalytical and Nuclear Chemistry 324:1303-1316

49 Leskinen, A., Tanhua-Tyrkkö, M., Salminen-Paatero, S., Laurila, J., Kurhela, K., Hou, X., Stenberg Bruzell, F., Suutari, T., Kangas, S., Rautio, S., Wendel, C., Bourgeaux-Goget, M., Moussa, J., Stordal, S., Isdahl, I., Gautier, C., Laporte, E., Guiliani, M., Bubendorff, J., Fichet, P. 2021. DTM-Decom II – Intercomparison exercise in analysis of DTM in decommissioning waste. NKS-441, Roskilde, Denmark

50 Leskinen, A., Gautier, C., Räty, A., Kekki, T., Laporte, E., Giuliani, M., Bubendorff, J., Lautila, J., Kurhela, K., Fichet, P., Salminen-Paatero, S. 2021b. Intercomparison exercise on difficult to measure radionuclides in activated concrete – statistical analysis and comparison with activation calculations. Journal of Radioanalytical and Nuclear Chemistry 329:945-958

51 Laurila, J. 2021. Vaikeasti mitattavien radionuklidien määrittäminen aktivoidusta betonista ja ioninvaihtomateriaalista, AMK Metropolia

52 Leskinen, A., Dorval, E., Baudat, E., Gautier, C., Stordal, S., Salminen-Paatero, S. 2022b. Intercomparison exercise on difficult to measure radionuclides in spent ion exchange resin. Journal of Radioanalytical and Nuclear Chemistry, published online, https://doi.org/10.1007/s10967-022-08687-2

The fourth and final year of the KYT-DEMONI focused on implementation of capabilities acquired during the first years in characterisation of highly activated stainless-steel sample. The work was carried out in VTT's centre of nuclear safety hot cells during a researcher visit from University of Helsinki to VTT. An international intercomparison exercise was also organised. Results will be published in a peer-reviewed article in 2023. The fourth year also included an intercomparison exercise for analysis of alpha emitters in the spent ion exchange resin, which had already been studied for betas and gammas [Leskinen et al. 2023][53]. The results will be further analysed in a peer-reviewed article in early 2023.

In addition to NKS contribution in KYT-DEMONI, method development of ^{59}Ni analysis was carried out partly funded by EU-PREDIS. The measurement method was developed in DEMONI project, but method validation is pending. Method validation is especially important because the measurements were carried out using broad energy detector, which has not been dedicated for very low energy measurements. The method validation is foreseen to be carried out bilaterally with a Czech laboratory within the EU-PREDIS project in 2023 and reported in a peer reviewed article latest in 2024.

5.7.3.3 Task 2: Effects of radiation on mechanical properties of concrete

Over the lifetime of a concrete structure, radiation is also known to influence many of the deterioration and ageing mechanisms typical for concrete as a material, as well as potentially introducing novel damage mechanisms unique to irradiated concrete [Rosseel et al. 2016][54]. This has implications for the long-term operation (LTO) of nuclear power plants (NPPs) as well as for the safety of concrete encapsulation designs for radioactive waste. Especially in the latter case, the effect of lower levels of radiation remains poorly understood, and therefore there is an increasing need to better establish what impact, if any, this type of exposure environment for concrete may have on its safety as a barrier material. Though concrete is a quite heterogenous and variable composite material, decommissioning waste concrete from the FiR1 research reactor presents has been an ideal opportunity to obtain preliminary data on safety aspects relating to deterioration under low-to-moderate levels of radiation exposure (up to 3.9×10^{18} n/cm^2).

53 Leskinen, A., Lavonen, T., Dorval, E., Salminen-Paatero, S., Meriläinen, V., Hou, X., Jerome, S., Jensen, K.A., Skipperud, L., Rawcliffe, J., Bourgeaux-Goget, M., Wendel, C., Stordal, S., Isdahl, I., Gautier, C., Taing, Y., Colin, C., Bubendorff, J., Wu, S.-S., Ku, Y.H., Li, Y.C., Luo, Q.T. 2023. RESINA – intercomparison exercise on alpha radionuclide analysis in spent ion exchange resin. NKS-466, Roskilde, Denmark

54 Rosseel, T. M., Maruyama, I., Le Pape, Y., Kontani, O., Giorla, A. B., Remec, I., ... & Ordonez, M. (2016). Review of the Current State of Knowledge on the Effects of Radiation on Concrete. Journal of Advanced Concrete Technology, 14(7), 368-383.

A literature survey of the relevant phenomena was completed in 2019 (research report VTT-R-00114-20). A critical gap in understanding with regard to damage mechanisms characteristic of lower radiation doses was identified. Specifically, the more heavily studied mechanisms relating to heating, drying, and amorphization of aggregate rocks were noted to be of limited applicability for the low intensity, sustained radiation exposure expected of, for example, concrete waste immobilization packages. The work continued with ultrasonic tests and SEM analyses. The results provide novel experimental evidence for radiation-induced alkali-silica reaction (ASR) that was not previously expected to be caused by only relatively low radiation doses.

A limited set of ongoing residual expansion and ultrasonic tests was planned for 2020–2022 as part of Task 3, and alongside comparable work in the EU-ACES and SAFFIR-CONAGE projects, to verify if mechanical changes had occurred that would impact radionuclide leaching. Results from the first year's limited mechanical tests show consistent properties typical of concrete, with porosity of about 2–3 %. These align with results from non-destructive tests and provide a basis for ongoing work regarding leaching. The outcome of the limited mechanical test program was presented by VTT at the 2022 meeting of the International Committee on Irradiated Concrete (ICIC), a closed specialist group dealing with the topic of irradiated concrete with members from R&D institutes, universities, utilities, and regulators from around the world.

5.7.3.4 Task 3: Radionuclide leaching rates in activated concrete

Concrete is not a stable material in aqueous environment, as hydration products are relatively soluble compared to aggregates and the degradation of concrete proceeds by dissolution of hydration products. Depending on the leachate composition and flow, the dissolution could be very rapid or negligibly slow. Concrete dissolution is an incongruent process and the composition of the hardened matrix changes throughout dissolution. While the dissolution process of main hydration phases is well understood, the impact of irradiation on such dissolution, as well as the combined effect of dissolution and adsorption on leaching of radionuclides within or through the concrete, is not yet understood.

Dissolution and leaching tests were performed in Task 3, in cooperation with Task 1 for measurement of the relevant radionuclides (^{3}H, ^{14}C, ^{55}Fe, ^{63}Ni, ^{41}Ca, ^{36}Cl, ^{152}Eu, and ^{60}Co). These experiments were designed with the initial goal of comparing the leaching behaviour of active and inactive samples, with differentiation for specific radionuclides. However, over the course of the long-term leaching experiments conduced during 2020–2022, no measurable quantities of any radionuclide were detected to be released to solution, making such comparisons impossible. This provides a useful indication that the

radionuclides present in the FiR1 reactor concrete, i.e., those formed within the concrete over the course of its service life prior to decommissioning, are effectively immobilized by the parent concrete by binding or adsorption to its constituent phases.

It should be noted though, that although the low levels of radiation to which the studied concretes were exposed may not be high enough within the timescale of this study to induce measurable changes, higher levels of radiation as present in full-scale NPPs, longer times of exposure to radiation as present in waste repositories, or simply longer durations of leaching may all still result in further or more significant alterations to leaching behaviour. This is especially true in cases where concrete acts as a barrier material for other radionuclide-bearing wastes, wherein more mobile nuclides are present compared to those generated within concrete itself during irradiation.

5.7.3.5 Task 4: Radionuclide leaching rates in activated steel

Task 4 aimed to study the leaching rates of radionuclides in steel in simulated final disposal conditions. Similarly with concrete, inactive and activated steel have different isotope distributions due to activation and they behave differently in dissolution, chemical separations, etc. Inactive steel with radioactive spike has often been used as a simulant while studying radiochemical properties of activated steel, but that doesn't give a realistic view of real material. In this project, the dissolution behavior of inactive and activated steels in anoxic conditions were compared. The dissolution of the steel to the water is monitored by analyzing (radio)nuclide concentrations in the water as a function of time. Research work of VTT focused on release of C-14 organic/inorganic speciation and of HU on measuring the leaching rates of ^{60}Co, ^{55}Fe and ^{63}Ni, and corrosion of steel samples. Long-term experiments were started in 2019 and finished in 2022.

Water samples from earlier EU/CAST project (finished in 2018) were also studied in 2020, but due to unstable storage conditions, these samples were not considered optimal for further studies. Based on Co-60 measurements 0,001–0,003 % of the total Co-60 inventory was released during the leaching experiments in alkaline conditions.

C-14 release experiments to liquid and gas phase from reactor pressure vessel (RPV) steel were conducted at VTT during 2019 – 2022. Experiments were conducted in anaerobic glove box and real Loviisa groundwater and two different simulant waters were used as leaching solutions. Total released C-14 was analysed. Later, also TOC-14 fraction in the leaching solution was measured with LSC after acidification and Ar gas purging. For comparison same water samples were send to commercial laboratory for TIC/TOC analysis. TOC analysis results from commercial laboratory and VTT's UV-Vis analysis gave comparable results, but TIC results were incongruent. Reason for this was not understood. During the leaching experiments the total released C-14 concentration was very low

which made all analysis very difficult and resulted in high uncertainties. In general, it must be stated that analysis of the release and speciation of C-14 from activated steel is rather demanding, since high original activation of steel is required to be able to measure the C-14 concentrations reliably. VTT's C-14 leaching results from the solution phase experiments show very low corrosion rate about 0.00001 mm/a in Loviisa groundwater and about 0.00002 mm/a in groundwater simulant, which result in respectively about 0.02 % and 0.01 % release of the total C-14 inventory from the irradiated RPV steel piece. As stated previously, due to the low activity concentration of C-14 in solution, uncertainties are high.

SEM and semiquantitative EDS (Zeiss CrossBeam 540 scanning electron microscope) analysis was also done to the leached RPV steel samples. The main oxide layer can be seen in all RPV steel samples, and its composition has only small differences. The oxide layer composes mainly of O, Fe and S. The sample leached in Loviisa groundwater contains also fan shaped surface features mainly composing of CaO, these particles were not detected on the surface of the simulant water leached RPV steel samples. Most of the detected elements originate from the RPV material or the leaching water. However, some Ni and Al was also detected in the simulant water leached RPV steel samples which could not be explained.

Sampling and gas chromatography (GC, Agilent 6890N, equipped with VICI Valco Pulsed Discharge Helium Ionization Detector) analysis for gas phase release experiments were conducted only twice, since the composition of the gas phase remained the same during the experiments. Main component of the gas phase was CH_4. C-14 analysis from the gas phase was not conducted, since it was assumed to be impossible due to the low original C-14 activity of the RPV steel samples. However, it has been recently reported by *Guillemot et al* that over 80 % of the C-14 bearing species in the gas phase is CH_4 [Guillemot et al., 2022][55].

Dissolution test for activated steel in contact with two different waters (Loviisa groundwater and a simulant water) was started at HU in 2019. Water samples from the experiment vessels have been taken after every three months and later two times a year. Eh, pH and ^{60}Co (by gamma spectrometry) have been measured from the samples. Beta emitting radionuclides ^{55}Fe and ^{63}Ni have been separated radiochemically from the solution samples and their activity was determined with liquid scintillation counting.

55 Guillemot, T., Salazar, G., Rauber, M., Kunz, D., Szidat, S., & Wieland, E. (2022). Carbon-14 release and speciation during corrosion of irradiated steel under radioactive

Dissolved radionuclides have had mainly low but highly variable concentrations in water subsamples, and much higher concentrations of ^{60}Co have been found from the synthetic ground water, compared to Loviisa ground water.

During the last months of the project, a Master thesis has been supervised [Tuna 2023][56], focusing on corroded steel sample characterisation after terminating the long-term dissolution experiment. Also, the last water sample batches have been analysed and the results for leaching of ^{55}Fe and ^{63}Ni from steel will be included in the Master thesis and a forthcoming article [Salminen-Paatero et al. 2023][57].

In addition to long-term dissolution test, the determination of ^{59}Ni was also investigated in Task 4 at HU. After consideration between µXAS (micro x-ray absorption spectrometry) and LEGe (low-energy germanium detector), it was decided to test LEGe due to its lower detection limit for ^{59}Ni. Due to general unavailability of a commercial ^{59}Ni standard, ^{55}Fe was selected as a test radionuclide, as it has sufficiently similar decay energy as the x-rays of ^{59}Ni. A test sample containing ^{55}Fe was prepared from a standard solution by $Fe(OH)_3$ precipitation. The precipitate was filtered onto a membrane filter, which was then measured with LEGe detector. Preliminary measurements gave a resolvable combination spectrum of x-rays and Auger electrons of ^{55}Fe. The counting efficiency of the detector was very low for the low-energy x-rays, <0.001 % for 5.9 keV energy. However, the measurement and sample preparation methods could be further developed to improve the counting efficiency and to decrease the detection limit for ^{55}Fe and ^{59}Ni.

5.7.3.6 Summary

DEMONI project studied LLIW waste activities, activated concrete mechanical properties and nuclide leaching rates in final disposal conditions for years 2019–2022.

Activities in Task 1 have enhanced the national capabilities in DTM analyses as both method developments and validations have been carried out for characterisation of activated steel, activated concrete and spent ion exchange resin. Three Finnish radiochemistry laboratories, namely from VTT, Helsinki University and Fortum Power and Heat, have been collaborating internationally via intercomparison exercises gaining

56 Tuna, Y. 2023. Corrosion products and dissolution of 55Fe and 63Ni from activated RPV steel samples in a long-term dissolution experiment. Master thesis, will be published in spring 2023.

57 Salminen-Paatero, S., Tuna, Y., Fabritius, O., Heikkilä, M., Tomberg, T., Ratia-Hanby, V., Bomberg, M., Huttunen-Saarivirta, E., Leskinen, A. Räty, A. 2023. Corrosion of activated RPV steel samples in ground water. Manuscript.

valuable contacts and confidence on their characterisation efforts. Students have been involved in the Task 1 via laboratory work (2 bachelor students and 1 master student at Helsinki University) and 1 bachelor thesis [Laurila 2021].

Activities in Task 2 and 3 have provided an improved foundation for future study of concrete under increasingly high doses of radiation, longer exposure times to low-level radiation, and as a barrier material for containing other types of waste with more mobile nuclides such as ion exchange resin. Results of complementary long-term mechanical tests also confirm the relative volumetric stability of the concrete material, indicating that for low radiation doses it does not introduce additional porosity, preferred leaching pathways via forming cracks, or otherwise impact the leaching of dissolved elements from the concrete. This provides a good foundation for future study to establish performance of concrete in more demanding environments, under higher levels of radiation, or in contact with more mobile radionuclides, as outlined in a manuscript in review [Oey et al. 2023][58]. Key insights across work done in collaboration with EU-ACES and SAFIR-CONAGE projects. This has particularly helped to better focus appropriate measurement techniques and methods, as to which are most applicable for a given exposure environment, while now incorporating considerations for the effects of irradiation and subsequent leaching. Such understandings are additionally expected to contribute to development of more realistic modelling and simulations of the dissolution and transport of nuclides in the near-field environment of waste repositories.

An interdisciplinary scientific network was formed between VTT and HU around corrosion product analyses and material characterization in Task 4, covering experts from radiochemistry, inorganic chemistry, mineralogy, corrosion science, physical chemistry, microbiology, nuclear physics, and many others. Certain instruments of the Helsinki University hadn't been previously utilized in corrosion product research, or only in a less extent. New measurement protocols for analyzing corrosion products in steel were successfully developed during this study in HU. Task 4 has also produced two theses [Kurhela 2021, Tuna 2023][59]. Co-operation with KYT-TERKOR project was effective in this task, especially during the last steps of terminating the experiments and last sample analyses.

58 Oey, T., Räty, A., Lavonen, T., Leskinen, A., Ferreira, M. 2023. The influence of low dose of radiation on the chemical and mechanical stability of concrete decommissioning waste. Manuscript.

59 Kurhela, K. 2021. Menetelmän kehittäminen radioaktiivisten vesinäytteiden rauta- ja nikkelipitoisuuksien määrittämiseksi, AMK Metropolia

5.7.4 ConLot – Durability testing of Concrete in Long-Term Simulated Groundwater Conditions

Project Manager: Jouni Punkki[60]; other personnel: (Fahim Al-Neshawy, Abobaker Ba Ragaa, Esko Sistonen)[60]

5.7.4.1 Introduction

The long-term behaviour of reinforced concrete structures under disposal conditions is an essential research topic in the final disposal of used fuel, nuclear power plant waste and decommissioning waste, as reinforced concrete structures must be used when closing tunnels and facilities. Long-term durability of reinforced concrete for nuclear waste disposal applications is a safety-related research topic within the KYT2022 programme. The motivation for this project lies in the need to understand how reinforced concrete performs over long periods of time in aggressive underground conditions, providing critical input for assessing the safety of the geological final disposal.

The main objectives of the ConLoT research project were to gain knowledge on the long-term performance on reinforced concrete in underground repository conditions. To achieve the objectives, we (i) investigated the mechanisms of reinforcement concrete deterioration in underground repository conditions, (ii) experimentally assessed the long-term behaviour of concrete specimens under the final disposal conditions and (iii) investigated the corrosion of reinforcing steel bars due to chloride ions (25 % sodium chloride solution) ingress by considering the storage temperature (13°C) on the corrosion phenomenon.

5.7.4.2 Experimental testing program

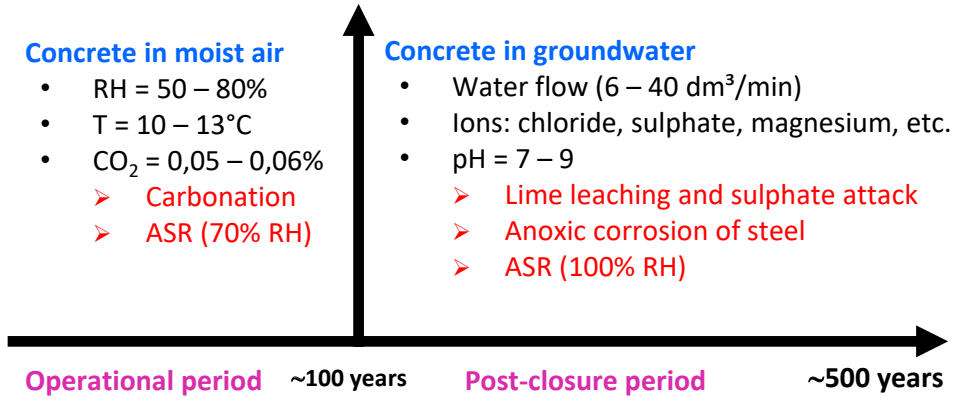
The research topics in the ConLoT during the year 2022 were divided into two work packages, addressing i) WP1 – literature review about the identification of concrete structure behaviour in repository conditions and ii) WP2 – field and laboratory testing program for assessing the long-term performance of concrete structures.

The WP1 produced a literature survey about identification of the following topics: a) the behaviour of reinforced concrete structures under LILW disposal conditions, b) understating the timescales for concrete structures in LILW nuclear waste repositories, c) investigation of the factors affecting the behaviour of concrete structures in final

60 Aalto University

disposal condition, d) studying the degradation mechanisms of concrete structures in final disposal condition and e) presenting the influence of cracks on the durability of concrete structures.

Figure 5.17. Typical concrete degradation in relation to timescale of the concrete structures.



The WP2 – included two tasks: (i) field testing program that was carried on for inspection of concrete specimens that are stored in different solutions in the Olkiluoto nuclear waste repository and (ii) laboratory testing program for measuring of the reinforcement steel corrosion in concrete stored in a condition of 25 % sodium chloride solution at about 10°C.

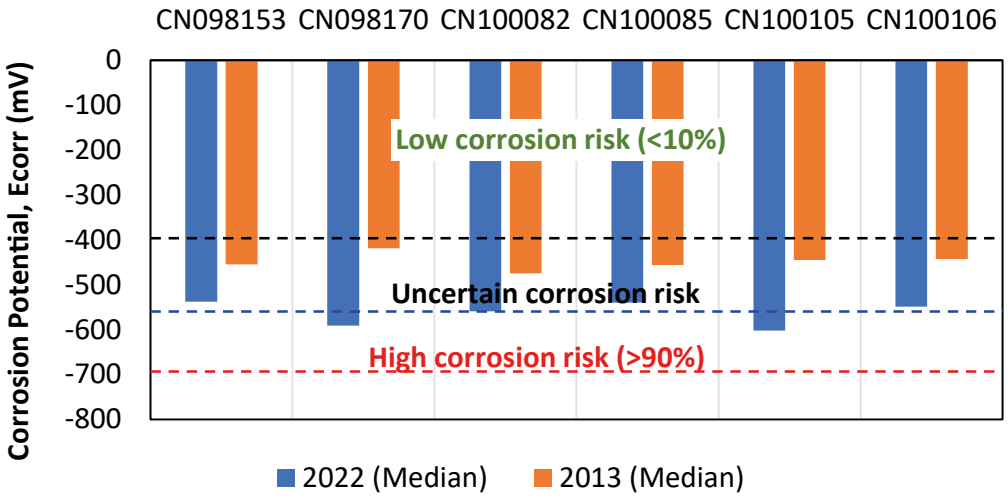
The field-testing results show that the mechanical properties of concrete (compressive strength and modulus of elasticity) were relatively high, a mesh-like micro cracking was detected in the petrographic thin-section analysis (normal occurrence for dense concrete mixtures), the chloride content in specimens stored in groundwater was very low, and no corrosion risks were expected in that scenario and the pattern of the sulfate and magnesium content with the depth is sporadic.

Figure 5.18. Petrographic thin-section analysis showing vertical crack extends through the sample depth, along the edge of the aggregates.



The results of the laboratory measurement of the reinforcement steel corrosion in concrete stored in a condition of 25 % sodium chloride solution at about 10°C show that a pitting corrosion of the reinforcement steel occurred due to the bleeding of concrete and the corrosion potential measurement results after 10 years agree with the visual inspection of the corrosion status.

Figure 5.19. Median values of corrosion potential for different steel rebar samples measured in 2013 and 2022.



5.7.4.3 Summary

The ConLoT project was a one-year project implemented during the year 2022. The project includes two work packages that (i) investigated the recent literatures dealing with the degradation of reinforced concrete structures in the Low and Intermediate Level nuclear Wastes (LILW) repositories and (ii) assessed the long-term performance of exists concrete specimens stored in condition similar to the LILW repositories.

The results show that low chloride penetration in the concrete after 25 years in underground water, while the ingress of sulphate and magnesium was somehow sporadic and no carbonation after 25 years. Pitting corrosion was presented in the reinforcement steel bars after 10 years storage at 25 % sodium chloride solution at temperature of about 10°C.

Based on the results from the one-year ConLoT project, a continuation of the assessment of the performance of the concrete specimens and a new concrete specimens series using modern cement technology will be performed through the SAFER 2028 project – PERCO2 "Long-term Performance Modelling of Concrete in Final Repositories of LILW Nuclear Waste".

5.8 Alternative Technologies

5.8.1 ALES – Separation and sorting of actinides/lanthanides

Project manager: Risto Kulmala[61]; other personnel: (Otto-Matti Hiltunen)[61]

The ALES (Actinide Lanthanide Separation) has been run under KYT 2022 Framework Programme 3.2.1 (Nuclear Waste Management Technology) and it is a project where solid phase extraction (SPE) materials were developed for Ln / Ac separation as part of partitioning and transmutation research relevant to the advanced nuclear fuel cycle. The hypothesis of the project was met as clear evidence on the effect of tunnel size and electron acidity/basicity of the hybrids' different counterparts was observed. The possibility of tailoring the hybrids was shown and material with a higher affinity to Am than Eu was synthesized based on their different Lewis acidity/basicity properties. This is the first time such behavior is reported with SPE materials. Beside the SPE-material development, one of the main goals of the project has been to train an expert in the field of the advanced nuclear fuel cycle.

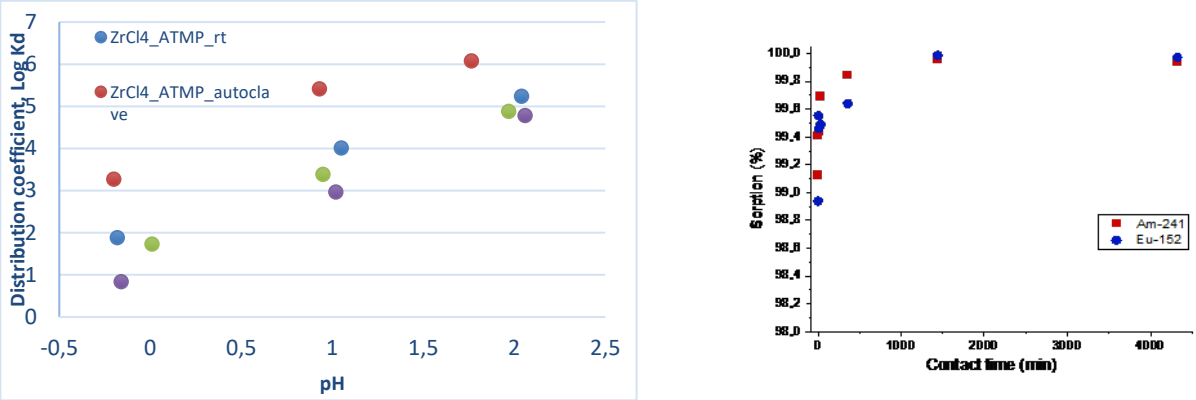
The obtained knowledge on transferring the available extractants and ideas from solvent extraction separation technique (that is at the moment the best available technique (BAT)) to solid phase extraction (SPE) technique may prove valuable not only with possible transmutation process of advanced nuclear fuel cycle but also with current nuclear waste management and waste minimization in particular. Lots of molecules targeted to specific ions can now be used in solid form, as typical ion exchangers, instead of using solvent extraction which has huge benefits considering the nuclear industry and its special needs and requirements.

Metal oxides (Sn, Zr, Ti) were synthesized as a backbone for hybrid SPE materials. Their tunnel size/porosity was adjusted by soft and hard templates. Organic molecules as soft templates were used to produce micelles into the synthesis solution that in turn guided the formation of pores inside the oxide material. Hard templates of silicon were also used for this purpose that was etched to produce the pores after synthesis. Metal oxides with pore sizes ranging from 0.8 to 16.7 nm and surface areas of 20 to 188 m^2/g were synthesized. The obtained metal oxides of different porosity showed clear differences in the lanthanide (Ln) and actinide (Ac) uptake properties when used as the backbone of the hybrid separation material. The crystallinity of the metal oxides was also examined. Increasing the crystallinity by using hydrothermal synthesis and addition of fluoride chemicals had a positive effect on the hybrid's metal uptake properties. The most plausible explanation for this is the increase in the ordered porous structure of the hybrid

61 University of Helsinki

material and better access to sorption sites inside the structure. In previous studies, the less ordered material had higher metal uptake properties which have been explained by higher surface area.

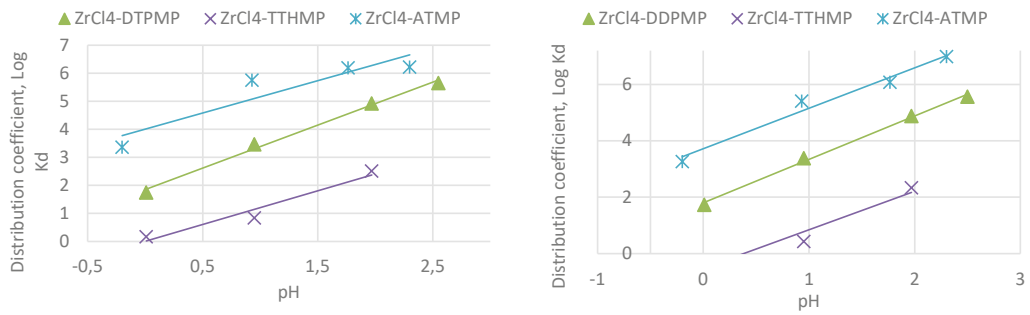
Figure 5.20. On left the effect of increased crystallinity (autoclave) on the SPE hybrids Am-241 uptake and on right the kinetics of Am-241 and Eu-152 uptake by hybrid material.



The uptake kinetics are a crucial part of successful and practical uptake material. Particularly when porous materials are used and the uptake process is suspected to happen inside the pores/tunnels of the material. The hybrids showed a fast uptake process suitable for practical SPE material.

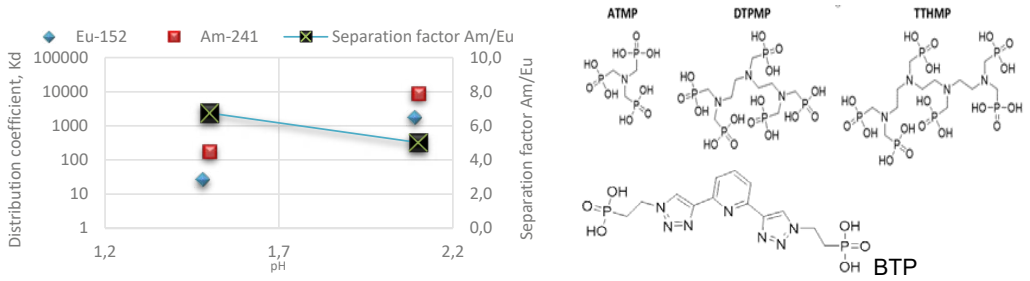
Different types of organic ligands were attached to the metal oxide backbone when making the hybrid materials. Typically, the ligand was attached to the hydroxyl group at the metal oxide surface and there a phosphonate linkage was used in order to make a strong connection between the organic and inorganic counterparts. The organic ligands were adapted from solvent extraction processes where data on their separation efficiency has been well established. Also, the initial idea of utilizing the Ac's affinity for soft and Ln's for hard Lewis acid elements of the ligand was followed throughout the project when selecting and synthesizing the organic counterparts of the hybrids. Apart from the active molecules of the ligand also the anchoring and the length of the anchoring chain to the metal oxide were the subjects of study in order to allow different levels of free movement of the ligand and produce so-called 'uptake pockets' for the target ions.

Figure 5.21. A variation on the ligands length and its effect on the Eu-152 (right) and Am-241 (left) uptake properties of zirconia-based hybrid SPE separation material.



Tailoring the hybrid's selectivity from Ln to Ac favored material was accomplished by changing the ligand's Lewis acid/base properties. A hybrid favoring Ac over Ln was made with nitrogen-rich ligand ((BTP) Bistriazolylpyridine phosphonate).

Figure 5.22. Tailoring SPE material's actinide selectivity by increasing the ligand's nitrogen content. On right some of the ligand molecules used in the project and here reported.



5.8.2 LABWAST – Pre-emptive reduction of radiological laboratory legacy waste

Project Manager: Wade Karlsen[62]; other personnel: (Marko Paasila, Teemu Kärkelä, Seppo Tähtinen, Tiina Lavonen, Petri Hakulinen, Jarmo Saaarinen, Kimmo Rämö, Mika Jokipii, Pentti Arffman)[62]

LABWAST -project ran in 2019 and was discontinued by the Management Group's decision in 2020.

The goal of the LABWAST project was to carry out the renewal of the radiological research infrastructure in VTT's new Center for Nuclear Safety as continuation to previous KYT2018 and SAFIR2018 programmes.

The commissioning of hot chambers continued in 2019 with the installation of bulk equipment and improving the usability of various devices. Devices were acquired for installation in the hot cells. In addition to the hot-chamber capabilities, the capabilities of radiochemistry and nuclear material studies were improved by acquiring a furnace for sintering alpha-active samples.

The construction of special equipment for testing iodine gas filtration continued in 2019. The equipment is used to assess the functionality of the radioactive gas filtration system of nuclear power plants in operation.

In 2019, the biggest task was the ordering of a large transport container approved for international road transport. The tendering of the procurement finally led to the order at the end of the year. The development of radioactive waste treatment tools and methods was continued in 2019 by Platom Oy through subcontracting.

5.8.3 SMRSiMa – SMR Siting and waste management

Project manager: Paula Keto[63] and Taina Karvonen[64]; other personnel: (Pauli Juutilainen, Nadezhda Gotcheva, Merja Airola, Timothy Schatz, Silja Häkkinen and Ville Tulkki)[63], (Heini Reijonen, Ismo Aaltonen and Jaakko Hietava)[64]

62 VTT Technical Research Centre of Finland Ltd

63 VTT Technical Research Centre of Finland Ltd

64 GTK Geological survey of Finland

5.8.3.1 Research topic and key results of the project

SMR Siting and Waste Management (SMR) -project performed between 1.4.2022 and 30.1.2023 was a coordinated project between VTT and Geological Survey of Finland. The project was coordinated by VTT. The work was partly continuation of the SMR Waste Management in Finland (SMRWaMa) project reported in Keto et al. (2022). In 2022, the research focused on following topics:

Siting of a SMR plant, repository for SMR waste and borehole disposal as an option for waste management reported in Hietava et al. (2023) by GTK.

Regulatory framework, spent nuclear fuel characteristics and their effect on disposal and on societal acceptability of SMR plants and their siting reported in Keto et al. (2023) by VTT.

GTK studied SMR power plant siting and SMR spent fuel repository from geological suitability perspective. The main conclusions from this work is that the same requirements that are applicable for current standard size NPPs are applicable also for SMR power plants. For example, the bedrock underlying the NPP shall be relatively intact. The possible difference in the surface area or size of the SMR plant in comparison to typical NPPs however may help in siting of the plant. The siting of a SMR plant used for district heating purposes will be affected also by other factors such as location with respect to district heating network and emergency planning zone required around the facility. Considering siting requirements for a repository of nuclear waste there are no differences in the requirements set for a SMR waste. In addition, initial observations were made concerning applicability of the borehole disposal method in Finnish bedrock conditions.

VTT studied the current regulatory framework, mainly Nuclear Energy Act (1987/990), from the perspective of SMR plant siting and SMR waste management. One question that has been discussed in this connection is adapting the centralized waste management strategy assuming several license holders with across Finland. In this case, the waste management obligation and financial provision obligation should possibly be transferred to another party (e.g. operator). This is already possible based on current legislation, but requires cooperation between the parties and further discussion considering the business models. In addition, guidelines should be given e.g. on what type of waste can be placed into the same repository and what not. Decision-in-principle is needed for SMR plants with capacity >50 MW and for waste repositories with total activity higher than 100,000 TBq or alpha activity higher than 1000 TBq. Support of municipality is needed in all of these cases, either through the decision-in-principle process or through regional and town planning processes.

VTT compared six different commercial reactor types based on light-water technology with UO_2 fuel including VOYGR (NuScale), Rolls-Royce SMR (Rolls-Royce), BWRX-300 (GE Hitachi), Nuward (EDF) and SMART (KAERI and Saudi Arabia) and their basic characteristics from the disposal point of view. In addition, conceptual design of the LDR-50 district heating reactor (VTT) was included in the study. There were some variance with the discharge burnups between the reactors commercial reactors (45–60 Gwd/ton) and a large difference between the commercial reactors and the district heating reactors (6–18 GWd/ton). Considering a centralized interim storage or a repository for SNF from various different LWR-SMRs the aspects to be considered are linked to variances in decay heating power, fission products and in risks linked to criticality safety.

Spent nuclear fuel characteristics were studied by VTT with Serpent 2D and 3D modelling focusing on the comparison of the results gained with 2D and 3D models. In addition, Serpent-Ants sequence was also under construction in a separate project. Based on the 2D results (Keto et al. 2022) the lower discharge burnup typical for SMR lead to lower decay heating power, photon emission rates (gamma radiation) and concentrations of mobile nuclides. This may have some effect on the final disposal, e.g. through canister spacing or repository layout. However, increased post-irradiation reactivity (per initial U-235 enrichment) remains as a potential criticality safety issue requiring further work. In addition, aspects such as larger neutron leakage fraction requires further full core calculations. Preliminary data shows some difference between the 2D and 3D cases, but no final results cannot be confirmed yet, due to difficulties linked with the heavy calculation process. These calculations are continued within the next phase of the project.

Finally, VTT studied societal acceptability considering importance of stakeholder, political and public opinions for SMR deployment. Municipalities have veto right in relation to siting of the plant in their area and their role in addressing the social acceptability topics in their communities is important. Insights of experiences about informing and engaging residents in climate and energy policy projects and expectations of the municipalities related to SMR plants and social acceptability were studied via municipality interviews. Results highlight the need for objective, transparent information and internal, regional co-ordination and communication and collaboration between the cities and the stakeholders. In addition, efficient and inclusive early phase information sharing, and resident engagement methods are needed in order to address the social acceptability of the SMR plants in a proactive manner.

5.8.3.2 Meaning of the results to safety of nuclear waste management (usability of the results and connections with other research)

The results can be applied in further SMR plant and repository siting related studies, in further attempts to define spent nuclear fuel characteristics for SMR reactor relevant in the Finnish markets, in further plans in organizing waste management for SMR plants and further studies on societal acceptability factors linked to SMRs.

5.8.3.3 Methods used in the studies

- Literature studies
- Interviews (societal acceptability)
- Numerical modelling, Serpent 2D, 3D and Serpent-Ants conversion

5.9 Acceptability

5.9.1 SOLID – Acquiring Social License for Disposal: trust and acceptance

Project manager: Matti Kojo[65]; other personnel: (Markku Lehtonen, Mika Kari, Tuija Jartti)[65], Tapio Litmanen[66]

The SOLID project ran in 2019–2020 and was discontinued at the Manangement Group's decision for 2021 and 2022.

The objective of the SOLID project was to increase understanding of building trust and social acceptability in nuclear waste management by comparing Finland and France.

Subtask 1 collected data from Finland in 2001 and 2015 and France in 2006 and 2016. Based on the preliminary results, the safety frameworks in Finland emphasise a long-term and high-quality preparation and research process. The frames highlight continuity and progression. The frameworks are depoliticizing. In France, on the other hand, the frameworks emphasise the requirement of reversibility and keeping alternatives open, and call for exceptional measures, thereby politicising the debate.

65 Tampere University

66 University of Jyväskylä

Subtask 2 looked at weaknesses in the ways in which social license is attained. The assessment methods for the social licence to operate (SLO) address trust as a key condition. These weaknesses and their remedies were examined using the nuclear waste projects of Finland, France and Sweden as examples. In the further development of SLO analyses, attention should be paid to the multiple dimensions of trust and mistrust, to forms of mistrust that are beneficial to society, and to relationships of trust (e.g. institutional and ideological) that go beyond the relationship between the local community and the operator.

Subtask 3 has communicated the results of the SOLID project by participating in international conferences and seminars and finalising the project's article manuscripts into publications.

5.9.2 CloMap – Mapping of Closure-Related Issues in Finnish Radioactive Waste Repository Programs

Project Manager: Timothy Schatz[67]; other personnel: (Sami Naumer, Edgar Bohner, Paula Keto, Heidar Gharbieh, Markku Leivo, Ville Rinta-Hiiro, Arto Laikari)[67]

The KYT CloMap project was conducted in two phases to evaluate the management of nuclear waste repository closure-related obligations in Finland. In the first phase of the project, national, EU and international regulations and requirements for repository closure were identified. The handling of these requirements by responsible organisations was assessed. The responsible organisations were the waste management license holders (Posiva, TVO and Fortum), the Finnish regulator STUK, and the Finnish State represented by TEM. The first phase identified thirteen gap areas related to the handling of the requirements. The Gap areas were classified into four main domains: post-closure monitoring, knowledge preservation, transfer of ownership, and post-closure responsibilities and stakeholder engagement.

In the second phase of the project, discussions were held with the responsible organizations to determine whether more detailed information regarding the handling of the identified closure-related obligations was available. In addition, a stakeholder survey was conducted to engage the public on the same topics. The responsible organizations were successfully contacted and were aware of the obligations and provided preliminary ideas which provided at least partial resolution to the identified areas regarding closure- and post-closure responsibilities.

67 VTT Technical Research Centre of Finland Ltd

The discussions showed that although a quite limited amount of planning has been carried out to date with respect to the identified closure and post-closure expectations, the responsible organisations generally take the position that detailed planning can wait until much closer (within ten years) to actual repository closing schedules. However, it can be questioned whether leaving such planning until so near to facility closure may limit planning options and leave insufficient implementation times.

As mentioned, a stakeholder survey was carried out in the second phase of the CloMap project to engage the public on the same closure-related topics. The survey was distributed primarily to residents of Eurajoki and Loviisa and was publicized in the Länsi Suomi -newspaper. Although ultimately the reach of the stakeholder survey was limited, the respondents showed interest in the topics and a desire for more information.

Also, during its second phase, the CloMap project was represented in a workshop held by the NEA EGAP working group. The purpose of the workshop was to discuss long-term knowledge preservation strategies for nuclear waste repositories. Finland's participation in the workshop was very well received. Workshop participants were rather surprised that post-closure knowledge preservation has not been a key-question amongst stakeholders in Finland. Furthermore, the records, knowledge and memory (RK&M) initiative (NEA, 2019) was suggested as a starting point for developing a knowledge preservation strategy in Finland. Such work could be started already before a decision on whether or at what level long-term knowledge preservation is required or not. The results of such work would allow the State to make a more informed decision on the topic, if sufficient background-information, tailored for Finnish needs would be available.

5.9.3 YLUMU – Final disposal of spent nuclear fuel and societal memory

Project manager: Petri Paju[68]

5.9.3.1 The research topic and key results

This research project focused on knowledge and memory preservation especially for the post-closure phase of final disposal repositories in the Finnish context. In the field of nuclear waste management, there has long been an international discussion about how to best transfer information about the repositories over extended periods, thousands of years, and whether they should warn future generations against the locations of nuclear waste repositories.

68 University of Turku

While the ONKALO spent nuclear fuel repository is nearing operational phase as first of its kind, this study explored the views of Finnish nuclear waste management experts on preserving knowledge and memory of the final disposal facility, as well as previous discussions on the topic in Finland.

Results of this study indicate that Finnish nuclear waste experts have documented few earlier discussions about knowledge preservation although they say such discussions have been ongoing especially concerning markers. Nevertheless, Nuclear Energy Agency (NEA) made a thorough literature review in their research project "Preservation of Records, Knowledge and Memory Across Generations," and from Finland only included in their final report (2019) the movie *Into Eternity* (2010). Compared with NEA's findings, this study identified some more, early Finnish debate on whether remembering the repository is necessary or not, including the possible use of markers and safeguarding nuclear materials. This study also highlighted more recent, critical contributions by artists who found preserving the memory more important and topical than the nuclear waste experts did.

Current experts saw the theme of knowledge preservation as important in principle but becoming more broadly relevant as the closure of the final disposal facilities approaches, which will take place after many decades or in the case of ONKALO even a century from now. The licensee Posiva Oy archives information at present, and considers that it is sufficient to landscape the site of the final disposal repository while the State preserves the knowledge permanently. Some of the experts say that it is impossible even to work on such questions nowadays, while a few of them admit more attention should be paid already to knowledge preservation. Some, such as the licensee, perceive that the passive system concept is safe without remembering the repository in the distant future, while others discuss where to place possible markers. Most of the experts were open to decisions that the future generation (of experts) might take to preserve knowledge and memory of the final repositories.

Overall, the recent studies by Nuclear Energy Agency suggest that knowledge preservation should be considered more urgent than most Finnish experts and actors recognize at present. Since the question has received limited attention in Finland, the solutions proposed by the NEA should prove valuable for Finnish stakeholders.

5.9.3.2 Relevance of the results

Results of this research project can increase the safety of nuclear waste management by improving understanding nationally of the importance of knowledge preservation. In relatively short term, this includes planning how to avoid losing important information and knowledge during the repository's operational time. Results can also help raise the

question of remembering, that is how to build societal or cultural memory of our long-lasting nuclear legacy. Preservation of knowledge and memory could support the long-term acceptability of final disposal, site security and safeguards.

Many actors from journalists to decision-makers could use the research results in further discussing these questions in Finland. The results could assist Finnish experts joining and contributing to NEA's work on preservation, for instance developing Key Information Files of the repositories for a broad audience. Recommended steps forward are to follow and discuss knowledge preservation in ONKALO's Periodic Safety Review process as well as to consider knowledge preservation while evaluating the operating license application for ONKALO.

Memory and heritage organizations, and artists and historians as well, are actors that focus on knowledge and memory preservation. Collaboration and perhaps partnership with them would help nuclear waste organizations to better understand and find ways of preserving their nuclear heritage for the future generations.

There are clear connections with this project and research done abroad connected to Nuclear Energy Agency's work on the preservation of knowledge and memory, for instance in the Expert Group on Awareness Preservation or EGAP group, and probably with IAEA's safeguards and other related research. Further, it links to scholarly research in Sweden where they conduct a study funded by SKB on creating a Key Information File at the University of Linköping. There is also useful overlap with closure-related research such as that in KYT's CloMap-project. When considering markers, there are potential connections to on-site research at Paukkajanvaara (Eno) where an old uranium mine is currently hardly marked.

5.9.3.3 Methods used in the study

The study consisted of searching for relevant publications and identifying related public discussions since the 1970s as well as collecting knowledge from a broad range of experts. The researcher interviewed a selection of experts. Interviewees represented actors from regulators to researchers and the licensee (Posiva Oy), and former associates of the licensee, the national archives of Finland as well as a local museum in Pori. With another KYT project CloMap, we also tested a web-based questionnaire to reach local stakeholders around the repositories in Eurajoki and Loviisa. Interviews, published sources and other information were used in conducting qualitative research, including a case study on the historical reception of nuclear semiotics and related international discussion in Finland.

Appendices

APPENDIX 1 – KYT2022 Projects in 2019–2022

Buffer, backfill and capsule

Spent nuclear fuel waste management – Buffer/Bedrock – interface

	Research Projects	Project Manager	Years	Full period
1	BROCTIO – Bentonite-rock interaction	**Veli-Matti Pulkkanen, VTT**	2019–2022	1
2	BROCTIO – Bentonite-rock interaction	Markku Kataja/Arttu Miettinen, Ujy	2019–2022	2
3	BROCTIO – Bentonite-rock interaction	Jukka Kuva/Heini Reijonen, GTK	2019–2022	3

Spent nuclear fuel waste management – Capsule

	Research Projects	Project Manager	Years	Full period
4	KAPSELI/BECOLT – Behaviour of copper under load transients	**Juhani Rantala, VTT**	2019–2022	4
5	KAPSELI/MECAN – Mechanical strentgh of copper canister and its cast iron insert	Sven Bossuyt, Aalto	2019–2022	5
6	KAPSELI/CRYCO – Validated advanced modelling and prediction of long term deformation and damage of copper	Tom Andersson, VTT	2019–2022	6
7	KAPSELI/OXCOR – The effect of oxide layer on copper corrosion in repository conditions	Jari Aromaa, Aalto	2019–2022	7
8	KAPSELI/SUCCESS – Stress corrosion in copper caused by sulphide	Timo Saario, VTT	2020–2022	
9	CAPSULE/MECCI – Mechanical strength of cast iron insert	Sven Bossuyt, Aalto	2022	

Spent nuclear fuel waste management – Interactions of release barriers/microbiology

	Research Projects	Project Manager	Years	Full period
10	MoToPro/VaVu – Interactions of release barriers	**Minna Vikman, VTT**	2019–2022	8
11	MoToPro/KUKO – Interactions of release barriers and their relevance to copper corrosion	Leena Carpén/Thomas Ohligschläger, VTT	2019–2022	9
12	MoToPro/MiBe – Effects of microbes in bentonite	Hanna Miettinen, VTT	2019–2022	10
13	MoToPro/BIKES – Biochemical scenarios	Riikka Kietäväinen, GTK	2019–2022	11
14	MoToPro/MIMOSA – Metabolical routes of microbial colonies in deep pressurised bedrock	Malin Bomberg, VTT	2019–2022	12
15	KaMu – Effects of circumstances to gas formation in the final repository of low activity maintenance waste	Minna Vikman, VTT	2020–2021	

Safety assessment and innovations

Basic factors in safety

	Research Projects	Project Manager	Years	Full period
16	OMT – Overall safety, multibarrier system and transient phase	Heidar Gharbieh, VTT	2019	
17	SYSMET – Systematic scenario methods for the assessment of overall safety	**Raija Koivisto, VTT**	2019–2020	
18	SYSMET – Systematic scenario methods for the assessment of overall safety	Ahti Salo, VTT	2019–2020	

Spent nuclear fuel waste management – Bedrock research

	Research Projects	Project Manager	Years	Full period
19	MIRA-3D – 3D-modelling of microstructures	Pietari Skyttä, Utu	2019–2021	
20	KARIKKO – Bedrock fragmentation	Nicklas Nordbäck, GTK	2019–2022	13
21	RAKKA – Water conductivity of fractured rock mass	Mikael Rinne, Aalto	2019–2022	14
22	C-ROCK2 – Factors affecting the chemical form of radio carbon in bedrock	Merja Lusa, UH	2021	
23	BEEFS – Comparative analysis and development of modelling of earthquake fault ruptures	Juha Kortelainen/ Ludovic Fülöp, VTT	2022	
24	BEEFS – Comparative analysis and development of modelling of earthquake fault ruptures	Jussi Mattila, RMCF	2022	

Spent nuclear fuel waste management – Other safety research

	Research Projects	Project Manager	Years	Full period
25	RASK – Radionuclide transport on the interface of cement and bedrock	Marja Siitari-Kauppi, UH	2019–2022	15
26	RABIO – Better radioecology for the modelling of biosphere	Jarkko Akkanen, UEF	2019–2022	16
27	KÄRÄHDE – Characterization and source term of spent nuclear fuel	Silja Häkkinen/Pauli Juutilainen, VTT	2019–2022	17
28	PORA – Microstructure of nuclear fuel and radium solubility	Janne Heikinheimo, VTT	2020–2021	
29	NAT-LAB-14C – Using volcanic-geothermal fields as natural laboratories to investigate transfer of 14C in soils and into terrestrial food webs	Christina Biasi, UEF	2021–2022	

Low and intermediate level waste management

	Research Projects	Project Manager	Years	Full period
30	SURFACE – Near Surface Repositories in Finland, phase 1–4	Paula Keto, VTT	2019–2022	18
31	SURFACE – Near Surface Repositories in Finland, phase 2–4	Gareth Law, UH	2020–2022	
32	TERKOR – Corrosion of low and intermediate level steel waste in in-situ conditions of final repository	Leena Carpén/Pauliina Rajala/Vilma Ratia-Hanby, VTT	2019–2022	19
33	DEMONI – Decommisioning Material characterization and final disposal studies	Antti Räty, VTT	2019–2022	20
34	DEMONI – Decommisioning Material characterization and final disposal studies	Susanna Salminen-Paatero, UH	2019–2022	21
35	ConLot – Durability testing of Concrete in Long-Term Simulated Groundwater Conditions	Jouni Punkki, Aalto	2022	

Alternative Technologies

	Research Projects	Project Manager	Years	Full period
36	ALES – Separation and sorting of actinides/lanthanides	Risto Koivula, UH	2019–2022	22
37	LABWAST – Pre-emptive reduction of radiological laboratory legacy waste	Wade Karlsen, VTT	2019	
38	SMRSiMa – SMR Siting and waste management	Paula Keto, VTT	2022	
39	SMRSiMa – SMR Siting and waste management	Taina Karvonen, GTK	2022	

Society and man

Acceptability

	Research Projects	Project Manager	Years	Full period
40	SOLID – Acquiring Social License for Disposal: trust and acceptance	Matti Kojo – UTa	2019–2020	
41	CloMap – Mapping of Closure-Related Issues in Finnish Radioactive Waste Repository Programs	Timothy Schatz, VTT	2021–2022	
42	YLUMU – Nuclear waste disposal and social memory	Petri Paju, Utu	2021–2022	
43	SRMWaMa – Preliminary study of the waste management of small reactors	Paula Keto, VTT	2021	

APPENDIX 2 – KYT2022 Publications and academic theses 2019–2022

Articles in peer revieved journals[69]:

Aromaa, J., Kekkonen, M., Mousapour, M., Jokilaakso, A. & Lundström, M., The Oxidation of Copper in Air at Temperatures up to 100 °C, Corrosion and Materials Degradation. 2(2021), 4, p. 625-640. https://doi.org/10.3390/cmd2040033

Aromaa, J., Khalid, M. K., Aji, A. T. & Lundström, M., Corrosion rate of copper canisters used for final disposal of nuclear waste, in synthetic ground water and bentonite clay pore water. Current Topics in Electrochemistry. 23(2021), p. 81-96. http://www.researchtrends.net/tia/article_pdf.asp?in=0&vn=23&tid=19&aid=6881

Aromaa, J. Vu, H.L. & Lundström, M. 2022. The effect of air-formed oxide film on copper corrosion during the initial phase of final deposition of nuclear waste. Current Topics in Electrochemistry 24(2022), s. 109-122. http://www.researchtrends.net/tia/article_pdf.asp?in=0&vn=24&tid=19&aid=7092

Bojinov Martin, Ikäläinen Tiina, Saario Timo, "Re-passivation rate and conduction mechanism of surface film on copper in nitrite solutions", Corrosion Science. 205, 9 p., 110447, 2022. https://doi.org/10.1016/j.corsci.2022.110447

Bomberg, M., Miettinen, H., Kietäväinen, R., Purkamo, L., Ahonen, L., & Vikman, M. (2021). Microbial metabolic potential in deep crystalline bedrock. In The Microbiology of Nuclear Waste Disposal (pp. 41-70). Elsevier. https://www.sciencedirect.com/science/article/pii/B9780128186954000034

Delayre, C., J. Sammaljärvi, S. Billon, E. Muuri, P. Sardini & M. Siitari-Kauppi. 2020. Comparison of phosphor screen autoradiography and micropattern gas detector based autoradiography for the porosity of altered rocks. Scientific Reports, (2020) 10:9455. https://doi.org/10.1038/s41598-020-65791-7

Forsström A., Bossuyt S., Scotti G., Hänninen H., 2020. Quantifying the Effectiveness of Patterning,Test Conditions, and DIC Parameters for Characterization of Plastic Strain Localization,Experimental Mechanics, https://doi.org/10.1007/s11340-019-00510-6

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

Forsström A., Bossuyt S., Yagodzinskyy Y., Tsuzaki K., Hänninen, H. 2019. Strain localization incopper canister FSW welds for spent nuclear fuel disposal, Journal of Nuclear Materials, https://doi.org/10.1016/j.jnucmat.2019.06.024.

Forsström A., Hänninen H., Yagodzinskyy Y. 2019. Hydrogen effects on mechanical performance of nodular cast iron'. Corrosion Reviews, https://doi.org/10.1515/corrrev-2019-0085

Fülöp, L., Jussila, V., Kaisko, O., 2023. Benchmarking and evolving earthquake fault-rupture simulations (Research Report No. VTT-R-00102-23). VTT Technical Research Centre of Finland, Espoo.

Hellmuth, K-H., Sammaljärvi, J., Siitari-Kauppi, M., Robinet, J-C., Sardini, P. 2021. STED nanoscopy: A novel way to image the pore space of geological materials. Journal Of Microscopy, 283(2), 151-165. DOI: 10.1111/jmi.13016

Ho, M. Vettese, G., Morris, K., Lloyd, J. Boothman, C., Bower, W., Shaw, S. & Law, G. 2022. Retention of immobile Se(0) in flow-through aquifer column systems during bioreduction and oxic-remobilization. Elservier. Science of The Total Environment. Volume 834, 15 August 2022, 155332. https://doi.org/10.1016/j.scitotenv.2022.155332

Huttunen-Saarivirta, E., Rajala, P., Bomberg, M., Carpén, L. (2020). Laboratory study of interactions between copper and microorganisms in oxic groundwater. Environmental Geotechnics, Vol.7(2). pp.110-120. https://doi.org/10.1680/jenge.17.00077

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Jussila, V., B. Fälth, P. Mäntyniemi, P.H. Voss, B. Lund, L. Fülöp, 2021, Application of a Hybrid Modeling Method for Generating Synthetic Ground Motions in Fennoscandia, Northern Europe, Bull. Seism. Soc. of Am. https://doi.org/10.1785/0120210081

Kari, M., Kojo, M., Lehtonen, M. 2021. "Role of the host communities in final disposal of spent nuclear fuel in Finland and Sweden", Progress in Nuclear Energy, 133 (2021) 103632 https://doi.org/10.1016/j.pnucene.2021.103632

Kojo, M., Kari, M., Litmanen, T., Vilhunen, T., Lehtonen, M. 2020. The critical Swedes and the consensual Finns: Leading newspapers as watchdogs or lapdogs of nuclear waste repository licensing? Energy Research and Social Science. 61, article 101354, https://doi.org/10.1016/j.erss.2019.101354.

Lalan, P., A. Dauzères, L.De Windt, J. Sammaljärvi, D. Bartier, I. Techer, V. Detilleux, M. Siitari-Kauppi. Mineralogical and microstructural evolution of Portland cement paste/ argillite interfaces at 70 °C – Considerations for diffusion and porosity. Cement and Concrete Research 115 (2019) 414- 425. https://doi.org/10.1016/j.cemconres.2018.09.018

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Leskinen, A., Dorval, E., Baudat, E., Gautier, C., Stordal, S., Salminen-Paatero, S. 2022b. Intercomparison exercise on difficult to measure radionuclides in spent ion exchange resin. Journal of Radioanalytical and Nuclear Chemistry, published online, https://doi.org/10.1007/s10967-022-08687-2

Leskinen A, Salminen-Paatero S (2022) Development of 3H, 14C, 41Ca, 55Fe, 63Ni radiochemical analysis methods in activated concrete samples. J Radioanal Nucl Chem 331:31-41. https://link.springer.com/article/10.1007/s10967-021-08073-4

Leskinen, A, Salminen-Paatero, S, Gautier, C, Räty, A, Tanhua-Tyrkkö, M, Fichet, P, Kekki, T, Zhang, W, Bubendorff, J, Laporte, E, Lambrot, G, Brennetot, R. 2020. Intercomparison exercise on difficult to measure radionuclides in activated steel - statistical analysis of radioanalytical results and activation calculations. Journal of Radioanalytical and Nuclear Chemistry, Volume 324, 1303-1316. https://doi.org/10.1007/s10967-020-07181-x.

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