Midterm Seminar of the SAFER2028 Research Programme

Project Abstracts

Juhlasali Day 1 – Nuclear Waste Management

ABCRad - Alternative Buffer/Backfill Characterisation + Radionuclide Interactions, HU

ABCRad (Alternative Buffer/Backfill Characterisation and Radionuclide Interactions) investigated the suitability of alternative bentonite materials for use as buffer and backfill in the Finnish spent nuclear fuel repository at ONKALO®. The project combined physico-chemical characterisation, laboratory sorption experiments, advanced spectroscopic analyses, and thermodynamic modelling to evaluate (i) how elevated temperatures of 100 and 150 °C affect bentonite chemistry and mineralogy, and (ii) how key, risk-driving radionuclides interact with two alternative bentonites under repository-relevant conditions. ABCRad demonstrated that both bentonites were remarkably stable following heat treatment, with only minor impacts on sorption behaviour, and that while alternative bentonites can perform suitably, radionuclide retention and binding mechanisms vary between materials and radionuclides, challenging the assumption that all bentonites behave equivalently. The work provides improved justification of sorption parameters, reduces uncertainty in safety assessments, and establishes a mechanistic basis for long-term extrapolation. In addition, ABCRad trained early-career experts and established strong international research collaborations, directly informing the design and focus of the follow-on project ABCRad 2.

DEHYDSU - Defects, hydrogen and susceptibility of Cu-OFP to stress corrosion cracking in sulphide containing environment, VTT

The SCC susceptibility of phosphorus micro-alloyed copper (Cu-OFP) in sulphide environments was investigated. The effect of plastic deformation and environment on the appearance of surface microcracks on Cu-OFP was studied using tensile tests and microscopic characterization techniques. Tensile tests on specimens from three different Cu-OFP batches were performed. The tests in ambient conditions under tensile loading showed several thousand microcracks per mm2, with maximum length in the range of 15–20 µm and maximum depth of about 3 µm. Specimens exposed to water with 80 mg/l sulfide had lower microcrack density, about 6% of that in air tested specimens and showed no evidence of crack growth, indicating that sulfides do not promote stress corrosion cracking. Additionally, the interaction of copper with sulfide in saline ground water in buffered and unbuffered conditions was studied using electrochemical techniques and microscopic characterization. Results indicate that no continuous adherent barrier type layer is formed on Cu in sulfide-containing groundwater, thus precluding the possibility of the development of localized corrosion modes.

MOCRYCO - Model based on crystal plasticity for copper, VTT

OFP Copper is used for outer shell material in nuclear waste end disposal canister. The work in Mocryco project focuses on developing analysis method and deepen the understanding of deformation and ultimately damage mechanisms of OFP copper. Work consists of experimental campaign focusing deepen the understanding of material behaviour in different loading situations and on microstructural level, and micromechanical model development and utilisation in analysing the local and lifetime behaviour of the material under the loading conditions in end disposal storage conditions. During the first three years of SAFER2028 project, we have focused on generating data and understanding for developing the

micromechanical model as well as deepen the understanding of deformation mechanisms (e.g. slip banding) on microstructural level. Especially generating data for cyclic loading and developing small scale testing methods (e.g. in-situ DIC combined with EBSD characterisation) has been prioritised. Also investigation of impurities and (possible) segregation of elements in the material has been started and conducted with high-end tools (e.g. TOF-SIMS and TEM). In numerical part of the project, the we have been focusing on developing micromechanical modelling framework (i.e. crystal plasticity finite element method) for simulating the material behaviour at microstructural level ultimately aiming to deepen the understanding of damage (e.g. creep void) accumulation as well as generating understanding how material behaves around different microstructural features.

SAGE - Sensitivity analysis guided disposal barrier experiments, VTT, JyU, GTK

The Design of Experiments (DoE) statistical analysis, coupled with advanced mechanical and chemical testing, X-ray computed tomography (XCT), and electrical resistivity measurements (ERT), aims to develop experiment-based surrogate models of model parameters for swelling clays used in spent nuclear fuel repositories. These surrogate models can be used to enhance repository designs and safety. Extensive datasets have been acquired, and modelling efforts have been started. In parallel, advancements in experimental techniques, such as dual-energy XCT, μXRF combined with XCT, and ERT for water-content measurements, have been made. These methods provide hydro-mechanical-chemical information on bentonite and facilitate the upscaling of experiments from the laboratory scale to that of a spent fuel repository.

TRIMO - Triaxial tests modelling, Mitta

Ion composition of the groundwater that saturates the filling components in spent nuclear fuel repositories is a relevant uncertainty for predicting the shear behavior of the bentonite buffer due to the influence of the pore-water chemistry on the mechanical behaviour of bentonites. This article applies two different models for considering salinity in the effective stress to carry out the simulation of triaxial tests performed in Wyoming-type bentonite with saline water in saturated conditions taken from the literature. The effective stress concept is used for describing the behaviour of bentonite in shear events. This concept is usually used to describe volumetric changes related to hydration and swelling pressure development, rather than shear strains.

ECOLAB - Laboratory-based studies for radioecological modelling of 14C, HU, FMI, UI, UEF, EnviroCase

Radiocarbon (14C) is a key radionuclide in biosphere safety assessment for nuclear facilities and radioactive waste repositories due to its long half-life, high mobility, and direct incorporation into biological systems. The ECOLAB project addresses critical knowledge gaps in radioecological modelling of 14C by generating empirical data on its uptake and transfer across aquatic and terrestrial ecosystems. Laboratory-based microcosm studies were conducted to quantify sediment/soil-derived carbon uptake in aquatic plants, benthic invertebrates, fish, and soil fauna, using radiocarbon and stable isotope analyses. Results demonstrate strong species-specific and pathway-dependent differences in 14C incorporation, highlighting the importance of sediment/soil, feeding strategies, habitat structure, and organic matter quality. Floating aquatic plants, benthic invertebrates, fish and surface-dwelling soil fauna were identified as key entry points for sediment/soil-derived 14C into food webs. The project further evaluates root uptake of dissolved carbon from soils, supported by an SKB technical report, emphasizing relevance for human exposure via root vegetables and crops. Overall, ECOLAB provides mechanistic insights and quantitative data that support improved biosphere models by quantifying pathway-dependent differences in 14C incorporation across biological compartments, thereby strengthening safety case development within SAFER2028

FLOP - Flow pathways within faults and associated fracture systems in crystalline bedrock, UTU, GTK, JyU, Åbo Academi

FLOP addresses the fluid flow properties of the bedrock, which, together with the seismic stability, is among the most important engineering-geological features of the bedrock in the Fennoscandian Shield area. Fluid flow within the bedrock is controlled by the networks of mechanical discontinuities, particularly faults and fault-related fractures, and these are the focus of this project. With respect to fluid flow, we will provide realistic models about the hydrogeological behaviour of geological structures. Here we place particular focus on testing the concept of channelized flow, using structurally controlled samples in micro-scale flow modelling experiments (micro-CT) and new DFN-tools. Outcomes of the present project will provide the industry and regulatory agencies updated knowledge and parameters for assessing the risks and creating solutions for the safe underground storage of nuclear waste which - key to achieving our global decarbonisation goals while minimising environmental impacts.

MIRKA - Scale-effect in fractured rock mass, Aalto

The MIRKA research project addresses the two most important rock mechanical features of the bedrock in the Fennoscandian shield area: rock joint shear strength against secondary movements from seismic activity in the vicinity of the repository area, and fluid flow properties of displaced joints and discrete fracture network which may form an escape route for radionuclides. For repositories residing within crystalline rock, the mechanical and hydraulic behaviour of the rock mass is largely dominated by the fractures and fracture network of the rock. The safety of the repository is assessed with numerical modelling which takes input parameters from small scale laboratory tests with upscaling. It is known, there are problems in upscaling laboratory test results to site scale and there is no consensus over the validity of the various scaling laws. To study the scaling of rock joint shear strength, MIRKA conducts large scale scale series for granitic rock slab pairs. Photogrammetry provides a non-destructive method for prediction of both shear strength and fluid conductivity. The flow in rock masses occurs through discrete fracture networks, DFNs. To validate fluid flow simulations, MIRKA manufactures 25 cm x 25 cm rock sample with a fracture which is then scanned, numerically modelled and tested in laboratory. The MIRKA results can be used in numerical modelling to validate the safety of spent nuclear repositories. The results will be shared as open data and it can be used as benchmark cases when assessing the goodness of fluid flow modelling approaches by numerical modelling experts and regulatory authorities.

DODGE - Dark oxygen in the deep geobiosphere of the geological repository, HU, VTT

The DODGE project investigates the occurrence and role of dark oxygen, i.e. O2 produced without sunlight in the deep subsurface. Understanding oxygen sources and cycling in anoxic bedrock groundwater is important for predicting corrosion, microbial activity, and the mobility of uranium and other redox sensitive elements, all of which impact long-term repository safety. Groundwater from Kopparnäs (Inkoo) contained oxygen with isotopic signatures excluding direct air contamination, along with microorganisms with genes for protection against oxygen radicals and oxygen-dependent metabolisms. Laboratory experiments with 18O-labelled and substrate-amended water from Kopparnäs and the Olkiluoto repository site were conducted to further assess microbial activity in relation to oxygen dynamics. Thermodynamic calculations indicate that only some oxygen-consuming reactions are energetically feasible in the deep subsurface, potentially creating microoxic niches in the underground repository.

MICWEST - Influence of environment and microbes on corrosion behaviour of welded steels in the LILW repositories, VTT

When nuclear power plants operate, some of their structural materials and some process materials become activated through neutron absorption or are contaminated with activated substances. The MICWEST project aims to assess how steel welds perform under conditions similar to those found in low- and intermediate-level waste (LILW) repositories. The study evaluated how various steel grades, welds, and post-cleaning methods affect corrosion rates. Additionally, it examined the influence of microbial metabolism on both the environment and corrosion processes. Both localized and uniform corrosion were observed on test surfaces. Variations in groundwater chemistry, particularly chloride concentrations, significantly impacted corrosion rates. Furthermore, differences in corrosion behavior were noted between welds and base metals. Intermediate testing revealed no significant differences in the microbiological test results.

POLYDEC - POLYelectrolyte gels for DEContamination, HU

POLYDEC project develops environmentally friendly polyelectrolyte gel for the decontamination of radionuclides from nuclear facility surfaces. PDADMAC-based gels combined with suitable polyanions are being optimized to achieve high radionuclide absorption, peelability, and gel reusability. The aim is to reduce significantly low- and intermediate-level radioactive waste volumes and associated costs. Systematic studies investigated the effects of gel composition, charge ratios, mixing conditions, and reaction kinetics on absorption efficiency. PDADMAC–PSS gels demonstrated excellent uptake of 134Cs, 133Ba, and 241Am. Structural and mechanical properties of the gels are characterized using SANS, SAXS, rheometry, and optical microscopy. Ultimately, POLYDEC aims to deliver a scalable prototype for nuclear decontamination applications.

AVOCADO - Advanced Oxidation Processes with Cavitation for Decontamination Processes, HU

The objective of this project is to test and compare different Advanced Oxidation Processes (AOP) for the destruction of organic contaminants in radioactive wastewater relevant to NPP operation and their decommissioning. Particularly, the use of cavitation phenomena to produce the radicals needed in the AOP will be in the focus of the study. The successful use of AOP would contribute to itself but more profoundly allow the effective use of selective separation materials that will drastically minimize the generation of secondary waste related to normal operation and decommissioning of NPP. Ultrasound (US) device is now ready for production of radicals using cavitation and hydrodynamic device will be assembled during this year when all components have arrived. Promising US results have been obtained with methylene blue (MB) as an analogue for organic contaminants. Effective oxidation (>95%) of organic contaminants is required so that selective ion exchange can be used efficiently for wastewater treatment/waste minimization. Best practices of using AOP in different media will be studied further with more realistic solutions.

DENSE: SurePhD - Increasing surety in the performance of present and future VLLW disposal – HU

SUREPhD project conducted at University of Helsinki aims to inform the safety assessment of the planned Finnish surface disposal site for very low level waste which features a landfill-type design. The research investigates the source term of key risk driving radionuclides 14C (Co, Ni, Sr, Cs) arising from degradation of mock waste forms representative of Finnish very low level waste under environmental conditions. Preliminary results show slow but continuous release of 14C from the wastes to the aqueous and gaseous phases as $^{14}CO_2$ and $^{14}CH_4$, rapid initial release of Co, Ni, Sr, Cs from soft wastes, and steady sorption of metals and 14C in the barrier materials. Early results from future looking parts of this project: co-disposal of decommissioning concrete and geopolymers show formation of highly alkaline conditions of pH ~12.5 with the activity of 14C in solution dropping in concrete mesocosms and remaining steady in the geopolymer mesocosms.

These findings provide insight into the source term, barrier performance, and potential of new waste management strategies of very low level waste in Finland.

DENSE: MOXSEAL - Metal Oxides for Group Separation of Actinides and Lantanides, HU

The aim of the MOXSEAL project is to develop an inorganic ion exchanger that can handle radiation and acidic conditions for efficient actinide/lanthanide ‘group separation’ in relation to separation and transmutation processes. Zirconia materials have been synthesized with and without phosphate functionalization increasing actinide and lanthanide sorption efficiency up to >99%. The materials were characterized using XRD, IR, TG, and BET, while sorption performances were tested through batch experiments under conditions relevant to nuclear waste separations.

Karl Lindahl Day 1 – Mechanical and Structural Safety of Nuclear Power Plants & Cementitious materials

AMANE - Additively Manufactured Materials in Nuclear Environments, VTT

The aim of AMANE project is to increase the understanding on the material behaviour of Additively manufactured materials under conditions typically found in Nuclear Power Plants, advancing the safe adoption of AM for nuclear power plant applications in Finland. It builds on previous work on AM 316L stainless steel, expanding into nickel-based alloys such as Alloy 718 to address high-temperature and corrosion-critical environments. Key research focuses include stress corrosion cracking (SCC), fatigue assessment using novel miniature methods, and thorough mechanical testing and material characterization for comparing AM material to conventionally manufactured counterparts. The key project outcomes are the following: mechanical and corrosion properties of LPBF processed materials are greatly influenced by the performed thermal post-processing and surface treatments and there is often a tradeoff between corrosion resistance and mechanical properties. Proper surface treatment and heat treatment are essential to obtain desired performance in NPP relevant environment. With proper control of the manufacturing and post-processing steps, AM materials are comparable or outperform conventional materials studied in the project.

BRIGHT - Barsebäck RPV investigation through thickness, VTT

The BRIGHT project examines the mechanical and microstructural properties of reactor pressure vessel (RPV) materials from the decommissioned Barsebäck 2 nuclear power plant (NPP). Ensuring RPV safety is critical for NPPs, with radiation-induced embrittlement as a key aging issue, monitored via surveillance programs and mechanical tests. Mechanical testing of A533B base material included impact toughness, fracture toughness, and tensile strength. The beltline, RPV head (RPVH), and surveillance specimens were assessed. Findings indicate surveillance specimens effectively track RPV aging; the RPVH is tougher and stronger than the beltline. Fracture toughness is lower closer to the beltline surface, likely due to fluence attenuation. These results support the reliability of surveillance programs and enhance understanding of attenuation effects. Analysis of fracture surfaces from miniature-C(T) specimens showed that brittle fracture typically originates at Mn-rich carbides at grain boundaries in the base material. TEM confirmed these initiators as M23C6 carbides.

CHAOS - Characterization of NPP structural integrity, VTT

The goal of the chaos project was to develop more accurate structural integrity assessment methods allowing for better transferability between laboratory specimens and target components. As the reference material used in surveillance programs is diminishing, a secondary objective of the project was to explore miniaturization techniques for fracture toughness testing. The design of low-constraint miniature specimens was accompanied by modelling and Digital image correlation (DIC) measurement. The project produced new data on low constraint and miniature specimen fracture toughness, demonstrated the measurement of J-integral from DIC images and proposed best practices for low-constraint testing. The results have been disseminated in several peer reviewed articles and conferences, and are expected to be valuable in the development of a new low constraint testing standard suitable for the ductile to brittle transition region. The knowledge gained though the project culminated in the comparison of three advanced toughness assessment methods for a real component, which can be used by researchers and utilities alike in their service life management efforts.

MINERVA - Mitigation of corrosion and novel water chemistries in light water reactors, VTT

The MINERVA project aims to provide solutions for chemistry- and corrosion-related issues that the currently operating plants in Finland have:

- Determination of the effect of alternative oxygen scavenger chemicals on water chemistry and long-term corrosion behaviour of 22K, 08X18H10T and A690
- Develop a zeta potential measurement setup to assess the role of surface charge of colloidal corrosion particles in fouling of steam generators
- Study online water chemistry monitoring methods and demonstrate the use of turbidity measurement in colloidal corrosion particle determination
- Update the state of the art of the transition from LiOH to KOH in primary circuit pH adjustment
- Update the knowledge available on SMR water chemistries
- Summarise different water chemistry guidelines

PRANCS - Practical solutions for sealant performance issues in nuclear power plants, VTT

The PRANCS project aims to provide solutions for sealant related issues that the currently operating plants in Finland have:

- Develop hardness measurement to monitor joint sealant condition on site
- Assess the lifetime of a polyurethane-based elastomer sealant
- Study the effect of compression on sealant ageing
- Develop a test method and assess the performance of graphite sealants under compression and high temperature

AI4NDE - Advanced and Intelligent Nondestructive Evaluation, VTT, Aalto

This project advances the use of Artificial Intelligence (AI) in ultrasonic Non-Destructive Evaluation (NDE), enhancing crack detection, characterisation, and sizing in nuclear components. Ultrasonic datasets from a Reactor Pressure Vessel mock-up, acquired using Plane Wave Imaging (PWI) and reconstructed with the Total Focusing Method (TFM) and a novel hybrid technique integrating TFM with the Synthetic Aperture Focusing Technique, enabled the development of transformer-based and other AI models with improved flaw identification ability and sizing accuracy. Comparative studies of TFM, implemented with two beamforming methods, and Phase Coherence Imaging (PCI) revealed clear trade-offs between image clarity, flaw characterisation capability, and computational efficiency. These results show that AI and advanced imaging can provide safer, more reliable ultrasonic inspections.

In addition, a Bayesian Belief Network (BBN) method was developed to quantify sizing uncertainty in dissimilar metal welds. The proposed approach quantified the probabilities of flaw depth measurement variations. It gives the results in interactive Directed Acyclic Graphs (DAGs), which enables a user-friendly interface for examining various scenarios of sizing uncertainty.

LOAD - Long-term Operation on Aging and environmental Degradation of nuclear reactor materials, VTT

Safe long-term operation of nuclear power plants requires a detailed understanding of materials aging and degradation. The LOAD project addresses these challenges, with WP1 focusing on stress corrosion cracking (SCC) of stainless steel 316L welds following extensive SCC findings in the French fleet. A representative OL3 weld was characterized using advanced microscopy and tested under slow strain-rate conditions in oxygenated PWR water. Weld regions—especially the weld root—showed clearly higher SCC susceptibility than 15% cold-worked material, exhibiting multiple SCC initiation sites. Additional high-constraint weld mock-ups and repair scenarios provided key insights into the thermal and mechanical factors influencing weld integrity. WP2 examined thermal aging of 22K carbon steel, showing minor changes in hardness but modest softening in small punch tests and a slight increase in SCC susceptibility associated with precipitate coarsening. Together, these results strengthen the understanding of environmentally assisted degradation mechanisms essential for reliable long-term operation of Finnish NPPs.

TOFFEE - Total fatigue life in plant environment, VTT, Aalto

The SAFER2028 TOFFEE project focuses on advancing the understanding and modeling of total fatigue life in nuclear power plant (NPP) piping under realistic environmental conditions. The project has developed the FaVite test facility at VTT, enabling precise, programmable, and repeatable environmental fatigue (EAF) experiments, particularly for primary circuit pipes in pressurized water reactors (PWRs). Key achievements include the commissioning of FaVite, initial air tests, and the development of new EAF models that integrate both crack initiation and growth phases, supported by extensive material characterization and experimental data. The project also addresses thermally induced stress corrosion cracking (SCC) through dedicated experiments and metallographic analysis. Despite technical challenges, the project has made significant progress, with international collaboration and dissemination through conferences and ASME working groups. Next steps involve EAF testing and further total life model refinement, aiming to improve the reliability of NPP piping assessments.

FN-CAMP - Finnish Nuclear Concrete Ageing Management Project, VTT

The Finnish Nuclear Concrete Ageing Management Project (FN CAMP) strengthens the long term safety of concrete structures in Finnish nuclear power plants and radioactive waste repositories. As these facilities move toward extended operation, understanding how concrete degrades under decades of chemical, mechanical, thermal, and environmental exposure becomes essential. FN CAMP addresses this need by combining advanced modelling, experimental research, and monitoring data interpretation.

The project focuses on four areas: • Ageing management and long term operation (WP1): A comprehensive review of ageing mechanisms in reinforced concrete structures and identification of critical knowledge gaps relevant to Finnish facilities. • Concrete degradation mechanisms (WP2): Development of physics based tools to predict alkali silica reaction (ASR) expansion and aggressive aqueous attack (AAA), enabling long term assessment of structural performance. • Containment and pool liner performance (WP3): Investigation of corrosion mechanisms, analysis of degraded liners from Finnish NPPs, and evaluation of monitoring methods to ensure leak tightness and structural integrity. • Monitoring data interpretation (WP4): Creation of inverse modelling and shape sensing methods to extract meaningful insights from large datasets collected in pre stressed containment structures.

FN CAMP’s achievements include improved understanding of key degradation processes, new assessment tools for predicting long term behaviour, enhanced insight into liner corrosion, and advanced methodologies for interpreting

structural monitoring data. Together, these outcomes support safer long term operation of nuclear facilities and strengthen national expertise in nuclear concrete ageing.

PERCO2 - Long-term Performance Modelling of Concrete in Final Repositories of LILW Nuclear Waste, Aalto

The PERCO2 project addresses the research needs related to specific deterioration mechanism of reinforced concrete that have a significant contribution and influence on the long-term durability performance and to service-life estimations of reinforced concrete in low- and intermediate-level radioactive waste repositories.

Various testing methods were implemented in the PERCO2 project, including: (i) assessing the mechanical properties of both aged and young concrete, (ii) evaluating the durability performance of the concrete, and (iii) utilizing Artificial Intelligence (AI) to predict the concrete's durability.

The results of the PERCO2 research project enhance our understanding of the long-term performance of concrete used in underground repositories by specifically focusing on the deterioration mechanisms that can impact reinforced concrete, thereby affecting its mechanical properties and durability.

RACEMAT - Radionuclide transport in cementitious materials, HU, GTK

The three-year RACEMAT project (University of Helsinki and GTK, 2023-2026) investigated radionuclide transport, retention, and spatial distribution in cementitious materials relevant to Finnish low- and intermediate-level radioactive waste repositories. The study covered three engineered barrier system materials: repository basin concrete, basin-fill concrete, and solidified radioactive waste material. Through-diffusion experiments combined with radioactivity-based imaging (autoradiography) and microstructural analyses (SEM-EDS and XCT) quantified diffusion behavior, material porosity and characteristics, and radionuclide spatial distribution. Results showed slow transport and strong retention in dense basin concrete, faster diffusion in higher-porosity basin-fill concrete, and nuclide-specific retention in solidified waste matrices. Overall, the findings strengthen safety-case parameterization and increase confidence in current nuclear waste management processes and methods.

VOLA - Accurate, precise and sensitive chlorine (Cl) analysis method development and analysis in steel and concrete, VTT

Characterisation of chlorine (Cl) in different reactor materials is needed due to its neutron activation to long-lived 36Cl. The objective of VOLA was to i) develop microwave-assisted acid digestion methods for steel and concrete, ii) Cl detection method development using mass spectrometry (namely, QQQ-ICP-MS), and iii) analysis of end-user materials. The acid digestion method needed to be free of Cl containing acids (e.g., HCl) and controlled in order not to volatilise Cl. Acid mixture and detection parameters needed to be suitable for optimal detection of Cl. Several different acid mixtures, acid digestion programs, and detection parameters were tested for optimal analysis results

Juhlasali Day 2 – Infrastructure & Reactor Safety and Fuel

JHR2028 - Participation in the Jules Horowitz Reactor project, VTT

The JHR2028 project promotes Finland's continued involvement in the development and early planning of the utilisation of the Jules Horowitz Reactor (JHR). Work in 2023–2025 covered active participation in Fuel, Materials and Technology Working Groups, and the JHR Technical Seminar. The project advanced the development of the MeLoDIE II bi-axial creep testing device. The project also promoted VTT contribution and involvement in international programmes such as OECD/NEA FIDES-II and the Halden Programme Group, ensuring Finland remains integrated in global nuclear materials research. The JHR Archive Material project progressed with cold characterisation of 304L reference material. These activities strengthen harmonised testing practices across Europe and support preparation for future JHR irradiation campaigns. The project builds experimental readiness, enhances collaboration, and supports long-term national expertise in nuclear fuel and materials research.

RADCNS - Radiological laboratory facility costs of the Centre for Nuclear Safety, VTT

The RADCNS project was the means of delivering facility cost support for the radiological infrastructure renewal project triad that also included RADINFRA (equipment procurement investment aid) and the RADLAB suit of projects supporting the execution of the infrastructure renewal process. The radiological laboratory and hot cells embodied in the VTT Centre for Nuclear Safety were designed, constructed, and equipped over the period 2010 through 2017. The RADCNS project lasted almost a decade, from when the radiological laboratory was completed in June 2016, through the end of 2025. During this period, the RADCNS project made an important financial contribution to the start-up phase of the new infrastructure, and its early operation phase, during which the project portfolio has grown significantly in volume. The ending of the RADCNS project brings to an conclusion contribution made by VYR towards this important national nuclear sector infrastructure renewal.

DEMAIN - Development and maintenance of LUT thermal hydraulic infrastructure, LUT

The objective of the DEMAIN project is to develop and maintain the experimental thermal hydraulic infrastructure at LUT University nuclear safety research laboratory in Lappeenranta. The project is divided into four work packages. WP1 includes activities related to purchase, implementation and development of advanced thermal hydraulic measurement techniques. The work has focused on testing of optic fibers, and procurement and implementation of gamma densitometry measurement system. WP2 focuses on continuous maintenance of test facilities, and procurements of materials and components. Instrumentation calibrations are done annually during summer, and pressure vessel inspections are carried out according to the pressure equipment legislation. WP3 continued the data management work started in the previous project, aiming to begin the archival of the large data sets from advanced measurement techniques. WP4 includes project management work and international co-operation in the form of participation in the SILENCE network for operators of large test facilities.

GRAF - Gravity driven flow experiments & NEXT – NEA experiments, LUT

LUT participated in the NEA ETHARINUS project. The project included the PKL III J and PWR PACTEL test programs and was implemented between October 2020 and September 2024. In response to the Russian Federation's aggression against Ukraine in February 2022, Russia has been suspended from NEA operations as of May 11, 2022. In the SAFER2028 GRAF project, LUT also conducted experiments at the MOTEL and PASI test facilities. The range of stable operating conditions for the helical coil steam generators at the MOTEL test facility was investigated in four experiments.

The stable operating conditions of the open loop passive containment heat removal system were determined in experiments at the PASI test facility. The effect of nitrogen on core cooling during Loss of Coolant Accidents was experimentally investigated using the PWR PACTEL facility.

The NEA SYSTHER project is a joint effort between Framatome GmbH, LUT University and CEA for the years 2025–2028. Finland participates in the project with the PASI, PWR PACTEL, and MOTEL test facilities. The PASI experiment in 2025 aims to expand the existing database and search for mechanisms that can degrade the system performance by focusing on riser throttling. Of particular interest is the damping of flow oscillations due to the CCFL phenomenon in the riser. In cooperation with TVO, a preliminary test plan has been prepared for the PWR PACTEL experiment (OL3 commissioning experiment) for 2026. The experiment will test the scalability and representativeness of the PWR PACTEL test facility for the OL3 EPR plant. The NEA SYSTHER project also includes two open PWR PACTEL and/or MOTEL experiments in 2027 and 2028. It has been agreed that at least one will be a MOTEL test.

DECAPOD - Deterministic safety analyses with Kraken, VTT

DECAPOD advances the development and validation of the Kraken computational reactor analysis framework, a next-generation toolset designed to support the safety analyses of Finnish nuclear power plants. The overarching objective of this work is to ensure that the Finnish regulatory authority, nuclear industry, and research organizations have access to an independent, state-of-the-art reactor analysis framework, together with the technical expertise required for its sustained and effective use. Specific targets for development and validation in DECAPOD are the VVER-440 reactors of Loviisa and the boiling water reactors (BWRs) of Olkiluoto, as previous efforts have concentrated more on pressurized water reactor (PWR) and VVER-1000 systems. The effort of the project is divided between developing the nodal neutronics program Ants, developing capabilities for VVER-440 and BWR specific modeling including the validation of Kraken, and strengthening the Kraken community with non-commercial distribution of Kraken, workshop hosting, and other knowledge-sharing collaboration.

MATFINE - Methods for current and accident tolerant fuels modelling, VTT

Topic of the MATFINE project was nuclear fuel behaviour, with focus on Accident Tolerant Fuels (ATF). Two approaches were used: modelling and experimental studies. In modelling part, methods and tools for integral fuel behaviour were developed, and in experimental part, studies on coated ATF cladding samples were conducted. Reviews and simulations on machine learning, as well as low temperature, low pressure Small Modular Reactor (SMR) fuel behaviour were done. Design basis accidents LOCA and RIA were considered in code development, coated cladding behaviour, and by participating simulation benchmarks organized within the FIDES-II and CABRI International Project. In experimental side, cladding thermal creep tests on Cr coated cladding were conducted. Methodology for steam oxidation testing was developed further.

NOTCO- Neutronics for fuel outside the reactor core, VTT

The NOTCO project develops advanced computational tools and expertise for spent nuclear fuel (SNF) characterization to support safety analyses in storage, transport, and disposal. The work focuses on two main themes: (1) uncertainty propagation in burnup calculations, and (2) enabling realistic full-core SNF characterization within VTT's Kraken framework. Key objectives include expanding the stochastic uncertainty propagation tool set and developing a novel deterministic method, improving validation for criticality safety and decay heat analyses, and enabling inventory calculations with nodal code Ants. The results enhance the reliability of SNF source term predictions, reduce conservatism

in safety assessments, and strengthen Finland's capabilities in nuclear waste management. International collaboration through OECD/NEA benchmarks ensures alignment with global best practices.

DENSE: REST - The reduction of large source term during severe nuclear accidents, UEF

In the event of severe accidents at nuclear power plants, the mitigation of hydrogen explosion risk and the release of radioactive aerosols, particularly iodine, remains a critical safety concern. This study investigates the reduction of fission product aerosols through the development and evaluation of advanced filtration technologies based on highly efficient electrostatic precipitators (ESP) designed for radioactive aerosol capture. The work also examines the interaction of these systems with hydrogen mitigation strategies to ensure safe hydrogen management.

Experimental results demonstrate that the lab-scale ESP achieved particle filtration efficiencies exceeding 90% under standard operating conditions, with further optimization increasing the efficiency to more than 99.5%. Hydrogen mitigation experiments showed no measurable influence of ESP operation on hydrogen concentration under typical conditions (5 % vol), indicating compatibility with existing nuclear power plant safety protocols. These findings confirm that ESP-based filtration systems can provide effective aerosol removal without increasing hydrogen-related risks, supporting their potential application in severe accident management strategies.

DENSE: NCGDENSE- The measuring, modelling and development of non-condensable gas models for nuclear safety research, LUT

Understanding how non-condensable gases (NCGs) behave in the coolant systems of light water reactors (LWRs) is essential because their presence can make accidents and transients severe by hindering heat transfer and flow routes, particularly during long-term post-accident reactor cooling. The reactor coolant system's possible sources of NCGs have been carefully examined. Nevertheless, there are few published studies that discuss the specifics of NCG release and dissolution, despite their significant role in the reactor coolant system. The NCG release and dissolution are complex phenomena. It is essential to consider several physical factors while modeling the dissolution and release of NCGs. These include the equations of state for a mixture of two components, where one of the components is water that can exist in liquid and vapor forms, the transport equation for dissolved gas concentration, release and dissolution rates, and the conservation equations for the gas phase. The inadequacies in modeling NCG release and dissolution are covered in this work. The study offers information about the LUT University of Finland's ongoing NCGDENSE project, which is supported by SAFER2028 (National Nuclear Safety and Waste Management Research Program 2023-2028). Under the NCGDENSE, a Separate-Effect-Test (SET) facility will be constructed to provide a platform for measuring direct NCG release and dissolution

ALISA - Analytical and experimental investigation of severe accident phenomena, VTT

The ALISA project (2023–2025) was aimed to strengthen the connection between experimental and analytical research on severe accidents (SA). The experiments performed were used to study and validate the capabilities of computer code in modelling SA phenomena. ALISA was also closely linked to the international SA research community by facilitating Finland's participation in OECD/NEA and U.S. CSARP projects and by disseminating the key project results to Finnish stakeholders. These actions provided the basis for improving understanding of SA phenomena and, consequently, enhance nuclear safety in Finland.

Experimental work was focused on the formation of volatile organic compounds (VOCs) from painted surfaces representative for Finnish NPPs and their reactions with fission products under the containment building conditions. It was

observed that VOC release increases with temperature, and the release is higher from floor than from wall paint. There was also an indication of methane formation from concrete samples. Another experimental task involved pool scrubbing of fission products (FP's). Result indicated that the studied aerosol overall decontamination factor (DF) increases from approximately 4 to 24 with increasing gas flow rate and particle size, although even higher DF can be observed for specific particle sizes. Tentative results show no significant evidence that flow direction affects the decontamination factor, but further experimental verification is required.

Modelling work was focused on studying and validating the MELCOR code capabilities to model SA phenomena, such as Passive Autocatalytic Recombiners, steel oxidation, and dose rates during the Fukushima accident. Related uncertainty and sensitivity analyses were also conducted.

CeReSa - CFD for Reactor Safety, VTT

The goal of the CeReSa project was to develop and validate Computational Fluid Dynamics (CFD) methods for nuclear safety assessments. Research topics, where CFD can provide added value to the safety assessments, were in the scope of the project. The main focus was on containment modelling for which various sub-models were developed on top of the open-source CFD framework OpenFOAM. For example, surface condensation model was implemented and validated against CONAN experiments and ice condenser model was developed. In addition, capabilities of OpenFOAM's XiFluid solver were tested for modelling hydrogen deflagration in the THAI experiments and studying the sensitivity of the solution to various modelling parameters. Furthermore, bubble dispersion modelling was studied with the goal of addressing previously noticed shortcomings in benchmark calculations.

C-FLOW - Critical Flow Separate-Effect-Test Facility & Experiments, LUT

C-FLOW has been active through 2023-2025. C-FLOW is devoted to investigating the complex phenomenon of two-phase critical flow. Within C-FLOW a new separate-test-facility called CRAFTY (CRiticAl Flow Test facilitY) has been designed, build, and commissioned. CRAFTY utilizes very large L/D ratio test sections that resemble the L/D ratio that are faced in double-ended primary-to-secondary guillotine breaks in pressurized water reactors. TPCF experiment work prior has lacked TPCF experiments with test sections this large. In addition, most experiment work on TPCF is decades old. There are still very large prediction errors with SYS-TH codes even in simple geometries. The ultimate goal of C-FLOW is to contribute meaningful TPCF experiment data and eventually resolve the underlying physics that control the TPCF rate.

ESPO - Analysis of Passive Safety Systems' Operations and Modelling, VTT

The ESPO project, Analysis of Passive Safety Systems' Operations and Modelling, was a three-year research project under the SAFER2028 program that aimed to advance nuclear safety through enhanced understanding and analysis of passive safety systems. Its core objectives included the development and validation of computational tools, the improvement of modelling approaches, and the investigation of phenomena critical to Small Modular Reactors and large Nuclear Power Plants in general. The project emphasized experimental benchmarking, including the International Standard Problem (ISP-52) and additional experimental tests from OECD/NEA international projects, alongside code-to-code comparisons and code-to-data validation using the Apros system code and OpenFOAM. ESPO coordinated national participation in international collaborative activities with OECD/NEA programs and the U.S. NRC CAMP agreement, ensuring effective knowledge exchange and harmonization of safety practices. In addition, ESPO supported human capacity building through collaboration between senior and junior researchers and by supporting graduate thesis work. By addressing key uncertainties in safety analysis tools, the ESPO project has contributed to improving the methodologies of

accident scenario evaluation and passive system performance assessment, which reinforces Finland's expertise in nuclear safety research.

THEME - Computational Modeling of Thermal-Hydraulic Phenomena, VTT

THEME combines VTT's modelling and LUT's experimental know-hows in a true cooperation project to develop deep understanding of relevant light water reactor thermal-hydraulic phenomena and how they can be modelled. Experiments are carried out at LUT University, and they are related to NCG behaviour, gravitational and critical flows. Modelling of experiments is carried out at VTT, with selection of computational tools, in pre-test phase to support experimentation, as well as post-test phase to assess the accuracy of modelling, and to develop new physical models, or to calibrating or validating existing models. More used tools perform well in computational tasks but are lacking adaptability in new methods. Use of new tools teach more about the phenomena and modelling know how, but experts need time and practise to utilize them more efficiently

Karl Lindahl Day 2 – Overall Safety and Organisation

RESPECT - Residents' Gendered Safety and Risk Expectations - The Case of SMRs in the urban area, LUT

RESPECT – Residents' Gendered Safety and Risk Expectations – the Case of SMRs in the urban area, was a project of LUT University1 which took place from April of 2023 to January of 2024. The RESPECT project analysed Finnish residents' views and expectations on the safety and risks of small modular reactors (SMRs), with special attention to the gender perspective. RESPECT aimed to enhance practical implications and theoretical understanding of SMR attitudes, given that women's and men's views on nuclear technologies have previously known to significantly differ from each other. To expand on the social understanding of the SMRs, project conducted online web panel resident survey in 2022, reaching total of 3200 respondents. Later 2025 published projects' research article2 analysed Helsinki metropolitan area residents' expectations concerning perceived safety and acceptability of SMRs (see Kiviluoma et al. 2025). Key findings from ordinary least squares linear regression modelling suggest that gender is the strongest indicator on both acceptability and perceived safety of SMRs. Although public attitudes towards SMRs were mostly positive among residents, these levels of acceptability and perceived safety of SMRs were highly gender-specific. In both analysed surveys (from 2021 and 2022), women tend to a greater extent than men perceive SMRs as unsafe, while more often opposing the siting of possible SMRs in their own residential area. Hence, future SMR decision-making should not overlook these differences in attitudes but seek better understanding of the underlying reasons and social implications, and integrate these insights into decision-making on nuclear energy policy.

SCALA - Safety Culture and Leadership in Sociotechnical Changes and Transitions, VTT, Lilikoi

SCALA examined the sociotechnical characteristics of major changes and identified ways of managing, leading, overseeing, and assessing them. The project, implemented by VTT (lead) and Lilikoi, studied sociotechnical change during nuclear new build commissioning, safety system modernization project, decommissioning, and in the introduction of internal independent nuclear safety oversight (INSO). Through interviews, document reviews, and analysis of significant events, the project identified key challenges and lessons learned regarding leadership, culture, and organizational development. Notable lessons learned include the importance of treating major transitions as sociotechnical, building shared ways of working across licensee and supplier organizations, organizing changes as knowledge creation processes, not only knowledge transfer, and actively counteracting "turnkey mentality" through early ownership and involvement. The project also developed three practical tools for assessing and developing INSO.

TONUS - Towards Nuclear Human Systems Integration, VTT, FIOH

The TONUS project advanced the integration of human, technical, and organizational (HTO) factors to strengthen the capabilities of key stakeholders—nuclear power plants, regulators, and technical support organizations—in managing severe accidents and other failure situations. The project consisted of five work packages. First, we developed methods and tools for evaluating the impact of Human Factors Engineering (HFE) and for assessing the readiness and capability of HFE organizations to implement HFE interventions. Second, we conducted a simulator study and found, for example, that automation failures and multitasking scenarios increased operator workload, although the magnitude of this effect varied considerably between individuals. Third, we evaluated new methods and tools for operator work and for training cognitive readiness skills, including part-task training in a part-scope simulator and field-operator training using virtual reality. Fourth, we investigated field operators' visual inspection practices through interviews, workshops, and a survey, and produced recommendations to support their inspection rounds. Finally, we organized an annual HOF seminar in collaboration with the SCALA project.

SEAMLES - Systems Engineering approaches for managing the life cycle of I&C systems, VTT, Aalto

Over the past three years, the SEAMLES project's Multidisciplinary Design Assessment work package has advanced deterministic safety assessment methods for nuclear I&C systems. In 2023, the team applied the Systems-Theoretic Process Analysis (STPA) methodology on the Olkiluoto 1&2 feedwater control system, identifying over 400 loss scenarios. Consequently, we tested the Risk Priority Number approach to prioritize most important results. In 2024, the work focused on improving STPA's applicability across I&C system engineering lifecycle phases. We identified barriers limiting its broader application beyond safety analysis and proposed corresponding solutions. Interviews with STPA experts led to defining 32 requirements for efficient STPA software tools, after which six tools were evaluated. In 2025, we tested H-STPA, an extension of STPA that enhances the identification of safety hazards stemming from human information processing and human–system interactions.

SMRSiMa - SMR Siting and Waste Management, VTT, GTK, LUT

Small Modular Reactor (SMR) Waste Management and Siting (SMRSiMa) project prepared Finland for SMR deployment by adopting a multidisciplinary lens, characterising SMR spent nuclear fuel (SNF), assessing waste management, geological siting, regulatory and organisational aspects, and societal engagement. SNF characterisation results indicate that, for typical LWR SMR designs, SNF properties are similar to those from conventional reactors, and the KBS-3 disposal concept is likely applicable. Waste management options for SNF and other radioactive waste were assessed, including centralized, local, and hybrid strategies, with responsibility assigned to the waste producer under Finnish law. Regulatory and organizational aspects were reviewed, noting ongoing updates to the Nuclear Energy Act that will affect licensing and waste management obligations. Potential future models for organising SMR activities were also explored. Geological investigations and required geological data are introduced for site characterization of SMR facilities, and strategies for site survey and site characterization processes for deep borehole disposal sites are reviewed. Resident surveys showed generally positive attitudes toward SMRs, but residents expressing concerns regarding waste management being carried out close to their residencies.

FASAANI - Fire behaviour and safety of nuclear infrastructure, VTT, Aalto

The first topic, which addresses smoke compartmentation in nuclear facilities, a systematic method has been developed to model the complex ventilation systems of nuclear power plants and their interaction with fire. The method enables reduced-scope modelling of ventilation networks and minimises uncertainties arising from the full system and unknown parameters. Using such method, the risk of fire-induced pressure in a compartment and unintended ventilation flows can be examined through CFD simulations. The second topic focuses on the aging of polymeric materials. Under this topic, the fire behaviour of cross-linked polyethylene (XLPE), widely used as cable insulation, has been investigated through various fire-behaviour tests conducted on both virgin and aged XLPE samples. The resulting data support further research and material modelling of XLPE for large-scale fire simulations. The final topic concerns fire barrier systems. Under this topic, polymeric firestop materials used in nuclear power plants have been evaluated for experimental characterisation and performance assessment under thermal loading. The evaluation has indicated notable differences in degradation behaviour among firestops. Their thermal degradation when heated is not necessarily expected from a fire-protection product. Furthermore, some firestops have also shown notable differences in mass loss between aged and virgin samples, warranting further check on their barrier performance.

MAWECLI - Marine and Weather Events in the Changing Climate as Potential External Hazards to Nuclear Safety, FMI

MAWECLI project studied external natural hazards in the changing climate. Sea level studies showed that i) most of the high sea level events in the Baltic Sea are connected to periods when several storms pass the region, ii) the highest sea levels occur in the northern and eastern bays of the Baltic Sea, iii) hierarchical models provide narrower uncertainty ranges, and iv) meteotsunami studies require the use of multi-datasets. Ten derechos identified in Finland in 2002-2022 had wind damage track lengths of 400 km-1300 km. A few prolonged and severe joint snowfall and high wind events were detected at the NPP sites during a 65-year study period. Sea-effect snowfall was found to be more common near the southern than the western coast of Finland. The changing climate will substantially alter the probabilities of extreme air temperatures. A literature review illustrated that major weather and climate-related catastrophes are caused by compound effects of multiple drivers.

PRALINE - Probabilistic Risk Assessment Labour, Improvements aNd Extensions, VTT

PRALINE is a project, conducted by VTT, where two subfields of probabilistic risk assessment (PRA) have been treated. One is seismic human reliability analysis (HRA). A literature review of seismic HRA considered the topic from many angles (special features of earthquakes, effects of earthquakes on human psyche and performance, human actions after earthquakes, seismic HRA data sources, methods, HRA modelling in the seismic context). A scenario provided by Fortum, concerning residual heat removal after an earthquake, has been treated; special features of the scenario were identified and modelling solutions were proposed. A study of human failure event identification in the scenario has been conducted, comparing two general HRA methods (THERP and PHOENIX). The other subfield is reliability and PRA of systems containing digital subsystems. The main contribution has been participation in the OECD/NEA WGRISK project DIGMORE. In this, five approaches to reliability assessment and PRA of such systems have been benchmarked. Special attention has been given to large common cause failure groups, complexity and spurious signals. The VTT approach was based on a simple fault tree model with extensive background calculations implemented with spreadsheets and scripts programmed for the purpose; the approach also takes fault tolerant techniques into account.

SERIOUS - Sensitivity and risk informed seismic hazard updates, VTT, RMCF, AFRY, HU

The SERIOUS project, a collaborative effort between VTT, Helsinki University, AFRY Finland Oy and Rock Mechanics Consulting Finland Oy, focuses on reducing modeling uncertainties in probabilistic seismic hazard analysis (PSHA) in Finland, addressing nuclear related requirements and international collaborative research. The focus of SERIOUS has been defined from the STUK conducted sensitivity study SENSEI. SENSEI pointed to Gutenberg Richter (GRs) parameters and ground motion prediction models (GMPEs) to control the seismic hazard at Finnish NPP sites. This project addresses these two areas, looking into synthetic seismicity modelling, ground motion and fracture slip simulations, and studies on the kappa attenuation parameter in the Finnish crust The project targets updated and scientifically robust hazard calculations by PSHA, relevant for nuclear power plants and the geological repository for spent fuel. SERIOUS produced several scientific journal papers, datasets and calculation tools in use by all stakeholders in Finland. It also sponsored a PhD thesis (to be defended at Aalto University in 2026). In addition, deliverables are the Finnish input for the international SIGMA3 project, with participation from EDF, PG&E, CEA, SWISSNUCLEAR, CEZ and CRIEPI.