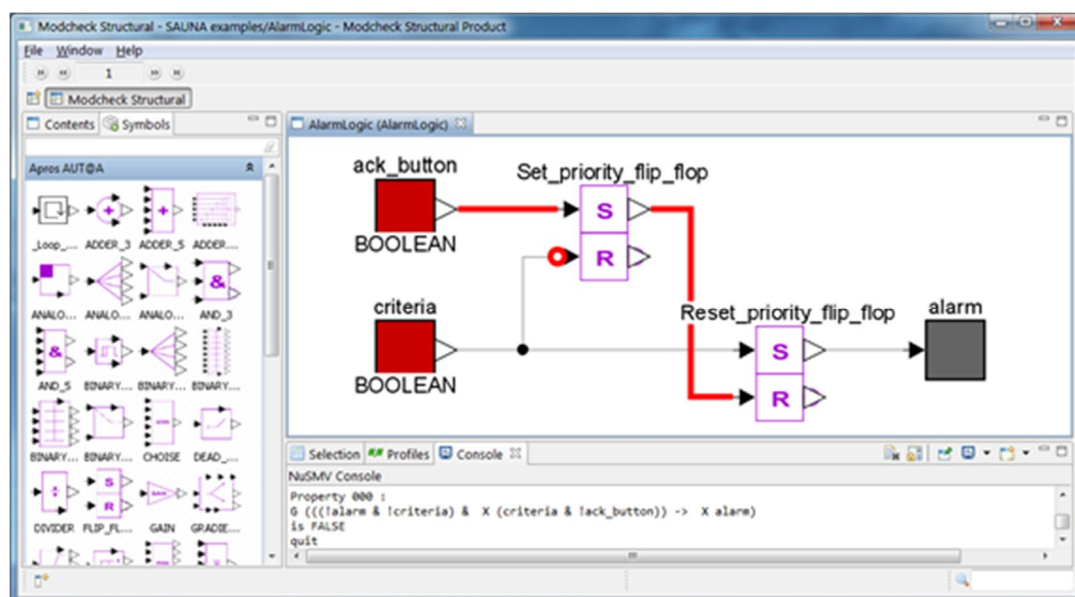


## RESEARCH REPORT

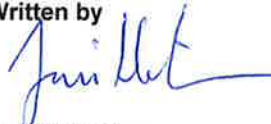


VTT-R-02454-18



# SAFIR2018 Annual Report 2017

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<b>Summary</b> <p>The mission of the National Nuclear Power Plant Safety Research programme 2015-2018 (SAFIR2018) is derived from the stipulations of the Finnish Nuclear Energy Act. The programme is continuation to a series of earlier national nuclear power plant safety research programmes that have proven their worth in maintaining and developing expertise.</p> <p>SAFIR2018 Management Board is responsible for steering and planning of the research programme and consists of the representatives of the Radiation and Nuclear Safety Authority (STUK), the Ministry of Economic Affairs and Employment (MEAE), Fennovoima Oy, Fortum, Teollisuuden Voima Oyj (TVO), Technical Research Centre of Finland Ltd (VTT), Lappeenranta University of Technology (LUT), Aalto University (Aalto), Finnish Funding Agency for Innovation (Tekes), and Swedish Radiation Safety Authority (SSM).</p> <p>The actual volume of the SAFIR2018 programme in 2017 was 6,8 M€ and 47 person years. Main funding organisations in 2017 were the Finnish State Waste Management Fund (VYR) with 4,0 M€ and VTT with 1,5 M€. The programme was divided into three research areas and in 2017 research was carried out in 29 projects.</p> <p>This report provides a summary of the results of the individual projects and overall financial and administrative issues. Summaries of project publications, international cooperation, academic degrees, travels and personnel are presented in the Appendices.</p>		
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## 1. Introduction

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In accordance with Chapter 7a of the Finnish Nuclear Energy Act enacted in 2004, the objective of the National Nuclear Power Plant Safety Research programme 2015-2018 SAFIR2018 is to ensure that should new matters related to the safe use of nuclear power plants arise, the authorities possess sufficient technical expertise and other competence required for rapidly determining the significance of the matters. High scientific quality is required of the research projects in the programme. The results must also be available for publication.

The SAFIR2018 programme's planning group, nominated by the Ministry of Economic Affairs and Employment in March 2014, stated the following mission for national nuclear safety programmes:

*National nuclear safety research develops and creates expertise, experimental facilities as well as computational and assessment methods for solving future safety issues.*

The vision of SAFIR2018 was defined as follows:

*The SAFIR2018 research community is a vigilant, internationally recognised and strongly networked competence pool that carries out research on topics relevant to the safety of Finnish nuclear power plants on a high scientific level and with modern methods and experimental facilities.*

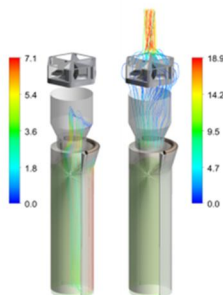
The Framework Plan [1] describes the research to be carried out in SAFIR2018. The new programme essentially covers the themes of the preceding SAFIR2014 programme [2].

SAFIR2018 management board was nominated in September 2014. It consists of representatives of the Radiation and Nuclear Safety Authority (STUK), the Ministry of Economic Affairs and Employment (MEAE), Fennovoima Oy, Fortum, Teollisuuden Voima Oyj (TVO), Technical Research Centre of Finland Ltd (VTT), Aalto University (Aalto), Lappeenranta University of Technology (LUT), and the Finnish Funding Agency for Innovation (Tekes). In 2015 the management board was completed with a representative of Swedish Radiation Safety Authority (SSM).

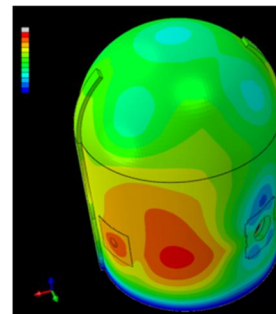
A public call for research proposals for 2017 was announced on 25 August 2017. After the closure of the call, SAFIR2018 management board, taking into account the evaluations made by the steering groups, prepared a proposal for the MEAE regarding the projects to be funded in 2017. The funding decisions were made by the Finnish State Nuclear Waste Management Fund (VYR) in March 2017. In 2017 the programme consisted of 29 research projects and a project for programme administration.



Plant safety and systems engineering



Reactor safety



Structural safety and materials

Figure 1.1. SAFIR2018 research areas.

VYR funding is collected from the Finnish utilities Fennovoima Oy, Fortum and Teollisuuden Voima Oyj based on their MWth shares in Finnish nuclear power plants (units in operation, under construction, and in planning phase according to the decisions-in-principle). In addition to VYR, other key organisations operating in the area of nuclear safety also fund the programme.

The planned [3] and actual volumes of the SAFIR2018 programme in 2017 were 6,7 M€ and 6,8 M€, and 42 and 47 person-years, respectively.

This annual report summarises the results of the individual projects (Chapter 2) and provides financial statistics of the research programme (Chapter 3). Administrative issues are summarised in Chapter 4.

Project publications are listed in Appendix 1, information on international co-operation in Appendix 2, list of Academic degrees obtained in Appendix 3, list of international travels in the projects in Appendix 4, and Appendix 5 contains list of the persons involved in the programme in the Management Board, Steering Groups, Reference Groups and in the projects.

This report has been prepared by the programme director and project co-ordinator in cooperation with the managers and staff of the individual research projects.

## **2. Main results of the research projects in 2017**

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The SAFIR2018 research programme is divided into three major research areas:

1. Plant safety and systems engineering
2. Reactor safety
3. Structural safety and materials.

The research areas are presented with more detailed descriptions of their research needs during the programme period 2015-2018 in the SAFIR2018 Framework Plan [1]. The research areas and research needs are based on the knowledge at the time of making the framework plan. The Framework Plan will be updated during the programme period, if necessary.

In 2017, the research was performed in altogether 29 research projects. The total volume of the programme was 6,8 M€ and 47 person years. The research projects in the various research areas with their planned and realised volumes are given in Table 2.1.

Summaries of research project results are given in the following subsections.

Table 2.1 SAFIR2018 projects in 2017.

Research area	Project	Acronym	Organisation(s)	Planned costs (k€)	Actual costs (k€)	Planned volume (person months)	Actual volume (person months)
1. Plant safety and systems engineering							
	Crafting operational resilience in nuclear domain	CORE	VTT, FIOH	235,0	262,6	18,6	22,1
	Extreme weather and nuclear power plants	EXWE	FMI	200,0	233,8	19,8	27,7
	Management principles and safety culture in complex projects	MAPS	VTT, Aalto, University of Oulu	199,0	197,1	15,0	13,9
	Probabilistic risk assessment method development and applications	PRAMEA	VTT, Aalto, Risk Pilot	328,0	345,8	24,2	27,3
	Integrated safety assessment and justification of nuclear power plant automation	SAUNA	VTT, Aalto, FISMA, Risk Pilot	347,0	344,7	26,2	28,6
	Safety of new reactor technologies	GENXFIN	VTT	94,0	94,0	5,3	5,9
	Electric systems and safety in Finnish NPP	ESSI	VTT, Aalto	130,0	114,0	11,0	12,6
2. Reactor safety							
	Comprehensive analysis of severe accidents	CASA	VTT	214,0	214,4	13,2	12,8
	Chemistry and transport of fission products	CATFIS	VTT	143,0	143,2	8,0	9,2
	Comprehensive and systematic validation of independent safety analysis tools	COVA	VTT	249,0	249,9	18,5	17,3
	Couplings and instabilities in reactor systems	INSTAB	LUT	162,0	167,3	13,5	15,1
	Integral and separate effects tests on thermal-hydraulic problems in reactors	INTEGRA	LUT	357,0	358,2	15,5	28,0
	Nuclear criticality and safety analyses preparedness at VTT	KATVE	VTT	200,0	199,5	11,0	17,1
	Development of a Monte Carlo based calculation sequence for reactor core safety analyses	MONSOON	VTT	146,0	146,7	11,5	11,6
	Development and validation of CFD methods for nuclear reactor safety assessment	NURESA	VTT, LUT	234,0	234,2	17,2	25,4
	Physics and chemistry of nuclear fuel	PANCHO	VTT	259,0	254,3	18,0	20,5

	Safety analyses for dynamical events	SADE	VTT	93,0	91,6	6,6	6,4
	Uncertainty and sensitivity analyses for reactor safety	USVA	VTT	115,0	108,4	9,0	9,0
3. Structural safety and materials							
	Experimental and numerical methods for external event assessment improving safety	ERNEST	VTT	115,0	115,4	6,0	5,6
	Fire risk evaluation and Defence-in-Depth	FIRED	VTT, Aalto	201,0	200,9	16,0	14,8
	Analysis of fatigue and other cumulative ageing to extend lifetime	FOUND	VTT, Aalto	325,0	326,5	20,4	22,1
	Long term operation aspects of structural integrity	LOST	VTT	285,0	285,8	16,6	17,0
	Mitigation of cracking through advanced water chemistry	MOCCA	VTT	136,0	136,1	8,4	7,4
	Thermal ageing and EAC research for plant life management	THELMA	VTT, Aalto	234,0	240,6	16,0	13,5
	Non-destructive examination of NPP primary circuit components and concrete infrastructure	WANDA	VTT, Aalto	160,1	160,4	10,1	12,5
	Condition monitoring, thermal and radiation degradation of polymers inside NPP containments	COMRADE	VTT, SP	188,0	180,7	8,2	8,7
4. Research infrastructure							
	Development of thermal-hydraulic infrastructure at LUT	INFRAL	LUT	284,0	292,6	15,0	25,9
	JHR collaboration & Melodie follow-up	JHR	VTT	29,0	29,2	1,7	2,2
	Radiological laboratory commissioning	RADLAB	VTT	703,0	737,3	46,8	45,6
0. Programme administration							
	SAFIR2018 administration	ADMIRE	VTT	355,0	354,9	10,5	10,8

The costs of ADMIRE are for period 1.1.2017-31.3.2018. The costs include two subcontracted small study projects and value-added tax 24%.

## 2.1 Plant safety and systems engineering

In 2017 the research area “Plant safety and systems engineering” consisted of seven projects:

1. Crafting operational resilience in nuclear domain (CORE)
2. Extreme weather and nuclear power plants (EXWE)
3. Management principles and safety culture in complex projects (MAPS)
4. Probabilistic risk assessment method development and applications (PRAMEA)
5. Integrated safety assessment and justification of nuclear power plant automation (SAUNA)
6. Safety of new reactor technologies (GENXFİN)
7. Electric systems and safety in Finnish NPP (ESSI).

### 2.1.1 CORE - Crafting operational resilience in nuclear domain

The aim of the CORE project is to improve safe operation of nuclear power plants by developing guidance, training interventions, and other practical solutions that promote resilience for the three general defence levels of prevention, preparation, and consequence management. Regarding prevention, the aim is to support operating personnel to succeed better in challenging work tasks by being more reflexive, engaged, and self-conscious and aware of high-level goals, instead of being solely guided by fixed and predetermined procedures. The aim is also to develop new Human Factors guidelines, models, and tools and interventions that will be tested and examined in simulated test environments and in workshops. Regarding preparation, operating personnel needs generic skills and abilities to master difficult, unfamiliar, and ‘knowledge-intensive’ operational situations. They need skills to cope with excessive acute stress in demanding operational situations. There is also need to collect operating experiences from successful actions and decisions and analyse the lessons learned from these experiences. Regarding consequence management and recovery, it is required that risk is efficiently detected, recognized, interpreted, and communicated so that a collective response is mobilized promptly. Therefore, such methods and tools are needed in crisis management that help stakeholders with different responsibilities to coordinate their actions to achieve a common operational picture.

#### **Specific goals in 2017**

Within WP1, guidelines for learning from successes have been developed, and the draft version of the guidelines has been described in a conference paper (Skjerve et al., 2017). An AcciMap variation for the analysis of successful events, or successes embedded in adverse events have been developed using the guidelines as a basis for the development. Furthermore, a modelling exercise has been provided in which staff meetings were used as an example case to identify the factors that facilitate or hinder organizational learning from successes. The main insights of the exercise are the following: Firstly, the meaning and the perceived value of success-related information differs between the actors that participate in the meeting. This directs attention to topics such as: i) the translation of the concept of success to context (e.g., explaining what types of successes there are and how they relate to a given actor’s task); ii) the identification of those to whom the success-related knowledge can be beneficial and thus should be shared to (e.g., creating generalizations and links within and outside the particular staff meeting); iii) the justification of the success-approach and the relevance of lessons learned from successes to others; and iv) the identification of those who possess relevant information. Secondly, success items in staff meetings can serve multiple functions (i.e., reinforce existing knowledge, create new knowledge, or induce socio-affective effects), and that the interrelation of these functions can have adverse consequences to safety if not properly managed.

Within WP2, the developed work-based learning method was tested with the operating organization. The method guides the operators to discuss and reflect their performance in simulator training sessions. The method includes individual and group reflection of the applied work practices – practices are, thus, evaluated. Good practices are disseminated between and within operator crews. The reflection is done in view of the established performance criteria of the plant. Overall, the feedback was shown to be positive, and there was a vivid discussion among the operator shifts encompassing relevant themes, such as work practices, collaboration, plant dynamics and stress at emergency situations. Decision on how to develop work practices were made among the shifts. Overall, we suggest that the application of the method might be beneficial for system resilience, because a significant proportion of the discussions supported reflection concerning issues that may support system resilience: collaboration, understanding of plant dynamics and the use of procedures.

Within WP3, we have outlined a draft version of a multitasking questionnaire, and prepared a slide set on multitasking modelling, including a concept analysis and a theoretical framework of multitasking and interruption management. We have analysed operator practices in simulator conditions with the Functional Situation Model (FSM) method, and the FSM method has been further developed. We have also further developed a modelling approach suitable for analysing collaborative diagnostic reasoning and troubleshooting of a NPP control room crew which is based on existing methods and tools. The approach describes the progress and evolution of a CR operator crew's knowledge states throughout the critical sections of a simulator run (Figure 2.1.1.1). We have analysed simulator data on troubleshooting in complex fault states by using the modelling approach. A review of the role of cognitive heuristics in process control work has also been prepared, and heuristics, biases and rules of thumb have been collected by analysing debriefing interview sessions that has been collected in simulator settings.

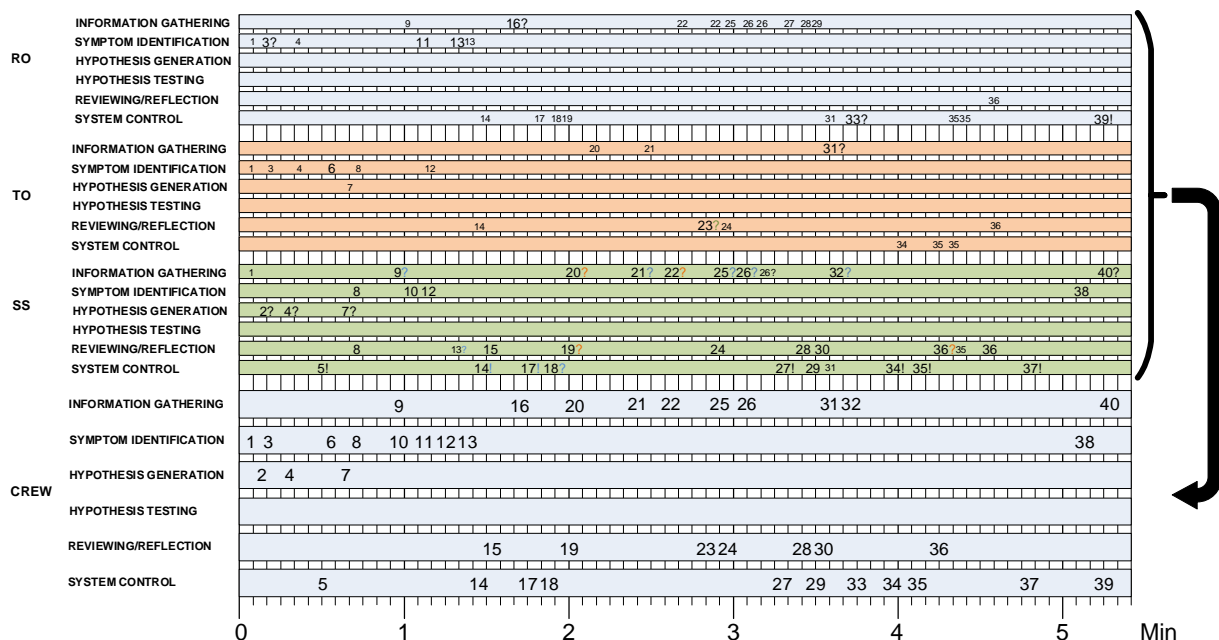


Figure 2.1.1.1. A diagram of a sequential analysis of the evolution of a CR crew's problem space in terms of critical functions in a five-minute period of time in a simulated accident scenario.

In WP4, we have shown with electrocardiography (ECG) that during a cognitively challenging scenario simulating a sensor malfunction the operators' stress was mild to moderate and that during simulations of severe accidents of fire and radioactive steam leakage the experienced stress and cardiac activity were on a moderate to high. Furthermore, we showed that the cardiac activity was strongly linked to the experience of stress and not accountable by

operators' movement within the simulator. Thus we were able to show that cardiac measurements in naturalistic settings with free movement, such as in a full-scale NPP simulator can reveal relevant information on the level of operator's acute stress without interrupting the primary task. We have also investigated the stressfulness of the individual tasks within the scenarios. The ECG, electrodermal activity (EDA), and accelerometer data have been re-analysed with respect to the scenario events. Various statistical models have been fitted to the data. For instance, we have conducted a set of principal component analyses (PCA), with different combinations of variables, i.e., the cardiac features (e.g., mean HR), electrodermal activity, physical activity (accelometer vectors mean activity and its variance), and performance (event times and durations) included in the same model. In the main model including all aforementioned signals, the 1st principal component explained 50% from the total variance, and could be interpreted as representing the stress of the operator. The 2nd component explains 20% of the variance, with the rest of the components explanatory power remaining below 10%. Furthermore, the justifications for the use of event times and durations as performance estimates have been explored by comparing the event times and durations with the instructor's performance estimates and qualitative performance measures (e.g., errors).

Within WP5, the method for analysing verbal communication during the observed emergency exercise was refined and tested. As a result, the method was found to be easy to use as an online method (information gathering and analysis simultaneously when performing observation) and providing relevant results. Irrespective of the existence of different tools supporting communication between contact persons, communication was smooth and effective in this exercise, perhaps because the exercise (emergency scenario) did not set specific challenges to the communication between these parties.

Within WP6, we conducted workshops with Fortum, TVO, Fennovoima and STUK, to evaluate the current HF activities and needs, to further develop and implement HF tool, and to inform about the latest findings and re-modification of the HF tool. Based on users' findings, improvement needs for the HF tool have been put in practice. Furthermore, in the workshop conducted with the MAPS-project, we found that although the HF tool includes several basic items, necessary in nuclear safety, it is still missing some system and context aspects. Based on feedback, several re-modifications were added to the tool. First, we produced a HF fan, to include several interview questions to support investigation and HF data gathering at the NPPs. The HF fans were delivered to the NPPs, to support the OE analysis. We were also aware of the official guideline at the NPPs, to use Accimap as an official investigation method in OE analysis, and thus, produced a HF-MAP, which includes the best parts of both Accimap and HF-tool (Figure 2.1.1.2). In the final HF-MAP, positive factors are included, as well as the four levels of HF tool (individual-, work-, group- and organizational factors), but then added with Accimap 'society'-level.

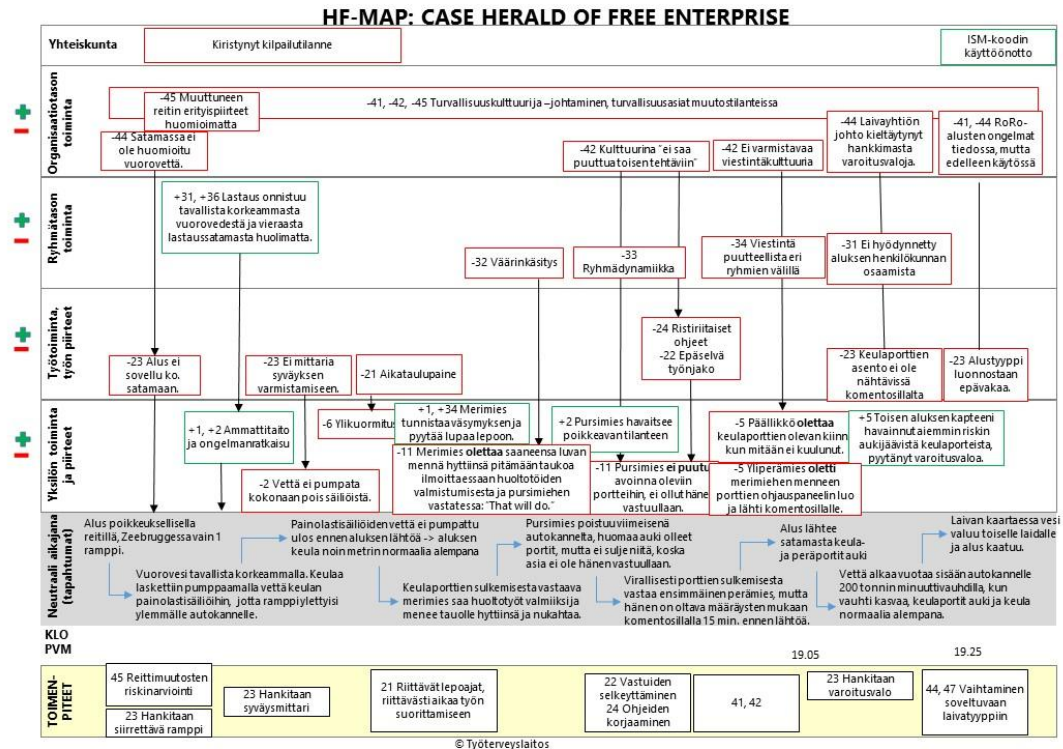


Figure 2.1.1.2. A depiction of HF-MAP in Finnish; combining the strengths of the Accimap and HF-tool; the lines are from HF-tool, except the line 'society' from Accimap. The model includes successes, the idea from HF-tool. The yellow line 'corrective actions' is new in HF-tool (obs. example is from maritime, which we used in nuclear HUMTOOL workshops, to learn the basic idea and use of the HF-MAP).

## Deliverables in 2017

- Presentation at the HUSC meeting describing principles for promoting learning from successes in the nuclear industry
- Conference article on a modelling exercise in which staff meetings were used as an example case to identify the factors that facilitate or hinder organizational learning from successes
- Finalized guideline for learning from successes
- Draft manuscript of a journal article describing the guideline and other relevant project results
- Conference article on the development of training in NPPs
- Conference article on a set of methods developed for the analysis of operator work practices
- Draft version of a multitasking questionnaire
- Slide set presenting the concept analysis of the phenomenon multitasking
- Conference article presenting a revised version of a modelling approach suitable for analyzing collaborative diagnostic reasoning and troubleshooting of a control room crew
- Conference article on cognitive heuristics and biases in operator work

- Peer-reviewed article on the operator stress during simulated incident and accident scenarios in a full scale simulator
- Outline of a research article on stressfulness of distinct events in accident simulations and relationship between stress and performance
- Workshop presentations on key findings and recent literature on stress in NPP work and training
- Conference article presenting the EAST-based communication analysis method
- Research report on collaborative resilience in emergency field exercises
- Article draft titled “Facilitating collaborative safety culture by applying Human Factors perspective with HF-tool”
- Research report presenting the theoretical basis of the HF-tool and the HF tool developments and implications
- Several workshop presentations on the HF-tool and the HUMTOOL project

#### 2.1.2 EXWE - Extreme weather and nuclear power plants

The general objective of EXWE (2015–2018) is to give better estimates of probabilities of extreme geophysical events that affect the design principles of nuclear power plants (NPPs) and may pose external threats to the plants. Three themes were covered in 2017: 1) extreme weather incidents, 2) extreme sea level events, and 3) atmospheric dispersion tool. The safety assessments of the NPPs require not only observation-based frequencies for the extreme events, but also estimates on the probabilities of such extremely rare events that have not occurred during the past 100 years of observations. Therefore, both instrumental records and model simulations are utilized in the work. The end users are the power companies designing and running NPPs as well as the nuclear safety authorities defining the safety regulations for NPP constructions and operations.

##### **Specific goals in 2017**

WP1 of EXWE focuses on extreme weather events. In 2017, the main topics were warm-season convective weather phenomena; detection and characteristics of sea-effect snowfall intense sea-effect snowfall; and severe freezing rain.

1.1) Warm-season convective weather phenomena. Extreme convective weather (hereafter called ECW) is caused by mesoscale convective systems (such as derechos, in Finnish “syöksyvirtausparvi”), detached thunderclouds or convective elements in extra-tropical cyclones. ECW materializes as heavy rain, large hail, intense lightning, strong wind gusts (i.e., downbursts) and/or tornadoes (termed as waterspouts over sea, and in Finnish “trombi” or “vesipatsas”). The number of ground flashes in Finland has been found to be correlated with several other indicators of ECW. ECW may result in flash floods and coastal flooding, including also meteotsunamis. The specific goals in 2017 were i) to test the use of a machine learning method for evaluating the past thunderstorm occurrence based on reanalysis data and ii) to clarify the synoptic and mesoscale mechanisms that contributed to the 8 August 2010 derecho case. The use of neural networks appeared to be more efficient than any simple predictors of thunderstorms. The derecho case was a linear mesoscale convective line that can be called a squall line.

1.2) Detection and characteristics of sea-effect snowfall. While summertime ECW is more likely to occur, wintertime sea-effect ECW occasionally develops over ice-free sea areas. Depending on the mean wind direction, excess coastal snowfall may occur, as happened in Merikarvia on 6 January 2016. It is not evident whether the ongoing climate change will make extreme sea-effect snowfall cases more severe and frequent or vice versa. The specific goal in 2017 was to simulate the Merikarvia case by running the HARMONIE weather prediction model with assimilation of radar reflectivities and to compare the results with outcomes of a previous simulation of the case, at that time without radar assimilation (Olsson et al., 2017). It was found that both the simulations managed to produce the Merikarvia sea-effect snowfall case quite well, although this may not be true for other intense snowfall events.

1.3) Severe freezing rain. An optimal vertical temperature profile for freezing rain consists of subzero temperatures near the ground and a melting layer aloft. Consequently, the sign of future trends in occurrences of freezing rain depends on whether such vertical temperature structures will occur more or less often during future precipitation events. The specific goal in 2017 was to estimate future changes in probabilities of freezing rain above selected intensity values at the NPP sites on the Finnish coast based on a freezing detection methodology developed earlier in EXWE (Kämäräinen et al., 2017) and 6-hourly data from six regional climate models available from the CORDEX initiative (Kotlarski, S. et al., 2014). No clear changes were projected for in the annual number and amount of severe freezing rain in the future, but the annual cycle of freezing rain may be affected.

WP2 of EXWE focuses on extreme wave and sea level events. In 2017, the four research topics included the joint effect of sea level and waves; wave model validation; the long-term occurrence of meteotsunamis in the Gulf of Finland; and simulating sea level extremes on the Finnish coast.

2.1) Joint effect of high waves and high sea level. Combined probability distributions of sea level and wind waves can be used to evaluate the maximum wave crest height on the shore and to offer improved estimates of flood probabilities. Previously in EXWE, the method was developed assuming that the two distributions are independent of each other (Leijala et al., 2018). However, the results at certain locations may be affected by a dependency between the two parameters. In 2017, the conditional probability of waves and sea level was examined using 27 years of sea level and wave data at a site near Helsinki. The effect of seasonal ice cover and wind direction on the dependence structure of sea levels and waves was also studied.

2.2) Improving wave modelling on the Finnish coast. Flooding risk estimates that combine wave and sea level statistics set higher requirements for wave data, but wave measurements are mostly conducted on the open sea and the time series are rather short. Model data is a feasible solution to fill the gap and provide the necessary data for the flooding risk estimates, but there are still challenges concerning the accuracy of the wave models. In 2017, three wave models (WAM, SWAN, and WaveWatch III™) were implemented to the Finnish archipelago and their performance was studied in comparison with coastal wave buoy observations. Despite some differences, all three models were found to be equally suitable to provide wave predictions in archipelagos.

2.3) Meteotsunamis on the Finnish coast. The objective in 2017 was to prepare a scientific manuscript documenting the occurrence of meteotsunamis in the Gulf of Finland over the past century (1922–2015) and to study correlations between the occurrence of meteotsunamis and atmospheric parameters. The results showed decadal variability in the frequency of meteotsunamis (Figure 2.1.2.1), but no apparent trend could be identified. It was discovered that the occurrence of meteotsunamis is strongly connected with thunder over the region: the number of cloud-to-ground flashes over the Gulf of Finland were over ten times as high during the days when a meteotsunami was recorded compared to other summer days.

2.4) Simulating extreme sea levels in the Baltic Sea. A two-dimensional hydrodynamic sea level model allows us to study extremely rare but physically plausible sea level events that have not occurred during the century-long observation period. In 2017, the reliability of the model was assessed by performing a simulation of sea level in the Baltic Sea 1900–2010. The simulation results had good agreement with the Finnish and Swedish tide gauge records, but the highest sea level extremes were underestimated due to the insufficient quality of the wind and air pressure data in sea areas. The work will continue in 2018.

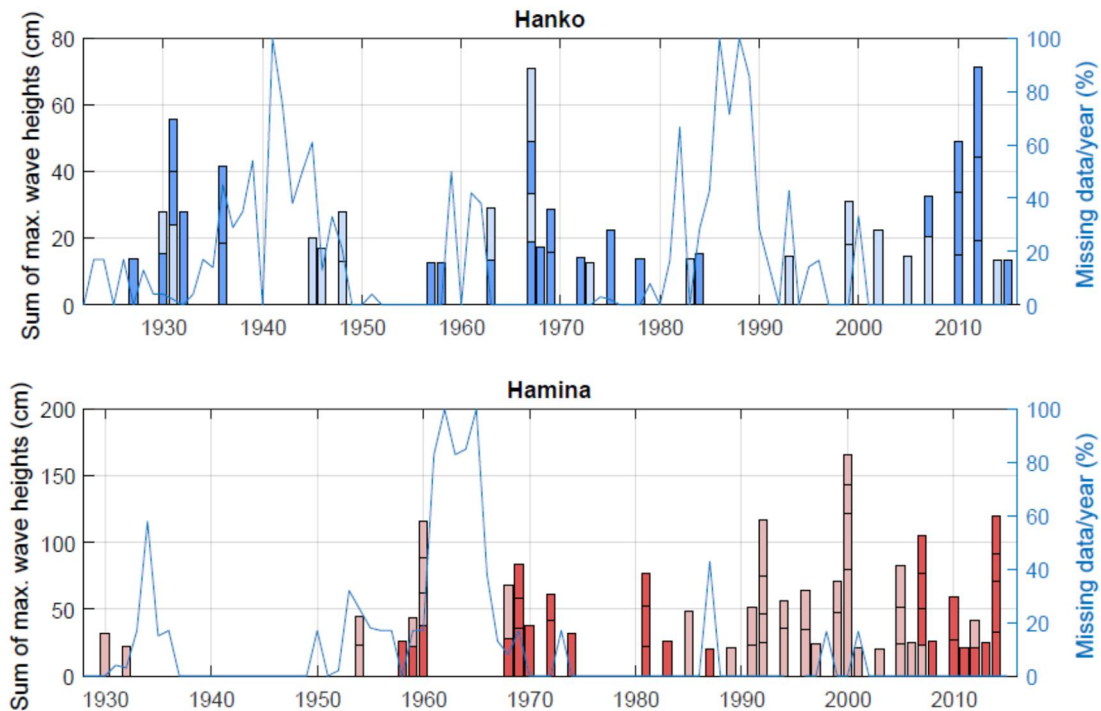


Figure 2.1.2.1. Meteotsunami occurrence in Hanko (upper panel) and Hamina (lower panel) in 1922–2015. The events are stacked so that the height of the columns correspond to the sum of maximum wave heights of the events during the given year. Confirmed meteotsunami events are plotted with darker colour; for the light-coloured events, the meteorological origin of the wave is uncertain. The blue curves show the proportion of missing sea level data per year.

WP3 of EXWE concentrated on studying the ability of the high-resolution Harmonie-SILAM modelling system to simulate atmospheric dispersion over a heterogeneous surface.

3.1) Output of the high resolution convection-permitting Harmonie-Arome model (with 0.5 km horizontal grid resolution) has been validated using measurements of temperature and wind speed near the Loviisa nuclear power plant in spring 2015. The main research subject was to evaluate ability of the meteorological model to simulate atmospheric boundary layer over a heterogeneous surface. The results show that the high resolution model is capable to simulate the contrast between sea and land surface and is also able to realistically simulate a boundary layer structure over the coastline and areas nearby. The simulated vertical structure as well as the diurnal cycle of the temperature the wind fields resembles the observations, confirming the models ability so simulate the transition from between land and sea.

The results are encouraging concerning the utility of atmospheric flow variables from a weather prediction model as input for the dispersion model SILAM, in order to improve and develop dispersion calculations over heterogeneous surfaces, like a coastline. High resolution atmospheric model simulations are the only realistic source of information about the boundary layer over a heterogeneous surface. Unlike measurements, which represent

only one location, with the high resolution Harmonie-Arome model the entire area can be described.

3.2) For nesting the SILAM-dispersion model and high resolution meteorological model some challenges were identified and most of them also solved during 2017 by updating the SILAM-dispersion model accordingly: i) Technical challenges: somewhat different GRIB coding, higher frequency of meteorological fields updates, non-SI units and non-standard features of some fields; ii) Fundamental: non-hydrostatic model with output presented as instant screenshots needs to be handled by the transport model requiring strict flow non-divergence, both locally and globally.

### **Deliverables in 2017**

- A report on past trends in warm-season convective weather phenomena using novel downscaling approaches
- Two conference presentations about synoptic environments of significant-hail producing thunderstorms in Finland.
- A report on mesoscale factors contributing to derecho formation and decay
- Two conference presentations about long-term monthly, annual and decadal variations and trends in the occurrence of thunderstorms in Finland
- Scientific paper on the Merikarvia sea-effect snowfall case
- A report about sea-effect snowfall simulations
- A report on the present-day and future annual probabilities of severe freezing rain at the NPP sites.
- A conference paper about the EXWE work, freezing rain as one of the examples.
- Scientific paper on using a conditional probability method to assess the joint effect of high sea level and waves
- A conference poster presentation on the method to assess the joint effect of high sea level and waves.
- A conference presentation about the EXWE work, high sea level together with waves as one of the examples.
- Scientific paper on validating a high-resolution wave model on the Finnish coast
- Scientific paper summarizing 100 years of meteotsunami statistics on the Finnish coast
- A conference presentation on the high-frequency sea level oscillations in the northern Baltic Sea and the Mediterranean.
- Scientific manuscript on hindcast simulation of Baltic Sea levels
- Report on the development of the high-resolution (0.5 km) NWP-model HARMONIE and its evaluation results against
- Technical report describing the integration of the SILAM dispersion model with the NWP-model HARMONIE

- Two doctoral theses

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### 2.1.3 MAPS - Management principles and safety culture in complex projects

The *ultimate goal of MAPS project* (2015-2018) is to enhance nuclear safety by advancing the knowledge on supporting high quality execution of complex nuclear industry projects, including modernizations and new builds. MAPS is an *interdisciplinary* project, which brings together expertise in safety culture and organizational factors, governance of complex projects, project alliancing/collaborative project arrangements, societal research on safety regimes and system dynamics modelling.

The specific *objectives* of MAPS project are 1) to identify the generic safety principles of managing complex projects in the nuclear industry; 2) to clarify the cultural phenomena in major projects and the influence of time, scale, governance models, and the diversity of the involved actors on safety culture, and thus on safety, and 3) to facilitate management and safety culture of ongoing and planned major projects by providing practical tools and guidance on e.g. facilitating communication, organising decision-making in unexpected situations, encouraging openness, and distributing knowledge and lessons learned.

### Specific goals in 2017

First, we focused on continuation of conducting in-depth case studies on critical events in a new build and a modernization project. Critical incident approach was utilized in the case studies, and the scope of the case was determined by an unexpected event, which the project network had to handle. In a complex project environment “critical incidents” could be seen as events that involve different project partners, and that make a significant contribution to the general aim of the activity. A specific event was selected by each nuclear industry organization. The 14 interviews carried out in the new build project network were analyzed further, and results were discussed with practitioners. The aim was to contribute to improved management of project networks, regulatory project oversight practices and to bring the complex projects perspective to safety culture discussion and literature.

Second, we continued our research on safety culture in complex network organizations. We studied the role of institutional complexity and institutional logics in projects as a part of general institutional arrangements. We focused also on improving the understanding of multicultural aspects and safety management in nuclear industry projects, more specifically focusing on discussing with practitioners of safety management and exploring cross-cultural synergy in multicultural project networks. Distinctive characteristics and uncertainties of

international projects were taken into account, as well as practical strategies for managing institutional and cultural differences in global megaprojects, the role of boundary spanning competence for overcoming cultural differences and facilitating a shared understanding about safety and project objectives.

We continued our study on methods for enhancing and assuring safety culture in complex projects: we conducted three international workshops with different stakeholders to feed our practical understanding on safety culture change in projects. We provided guidance for methodical safety culture change in complex nuclear industry projects by identifying a set of twelve principles of safety culture change, based on up-to-date practical experience and theories of systems thinking, organizational management and safety science. We developed guidelines for the implementation of Safety Culture Ambassadors as a method for safety culture improvement. This method refers to involving safety-conscious individuals from different parts of an organization/project network in safety culture activities. We proposed a model of Adaptive Safety Culture: an organizational culture that recognizes qualitatively different organizational manifestations of safety management; the model is intended to support safety practitioners to better plan, implement, monitor and review safety culture activities in complex international projects.

Third, we continued the study on the applications of system dynamics modelling in complex projects. Research work focused on the document handling of complex projects, including both new build and modernization projects, and better understanding the implications on safety. Data collection to support modelling work continued as well, supported by a workshop with practitioners. The workshop provided valuable insights on initial sources of delays in complex nuclear industry projects and especially what is relevant for modernization projects in an operating NPPs, where major upgrades have been conducted. A system dynamics simulation model has been developed and the simulation model can be used to analyze different scenarios related to document handling and review in nuclear industry projects and at regulator's side.

Fourth, we aimed at internally integrating our insights and disseminating the results from the MAPS project towards practitioners and academic community. The international visibility of project results in 2017 was ensured by research participation in different events, such as international scientific conferences, international workshops, domestic industry seminars and research workshops, as follows: International Research Network on Organizing by Projects (IRNOP), Boston University, Boston, USA, June 11-14, 2017; WOSNET2017, 9th International Conference on the Prevention of Accidents at Work, October 3-6, 2017, Prague, Czech Republic; Resilience Engineering Symposium, 26-29 June, 2017, Liege, Belgium, and IAEA CS meeting to review and provide support for the IAEA Safety Culture Continuous Improvement Plan (SCCIP). MAPS interim results have also been presented and discussed during an ad-hoc meeting at STUK in relation to renewal of YVL guides relevant for safety culture and project management.

Strengthening cross-project collaboration in SAFIR2018 was one of the aims as well: a joint researchers' workshop was held with MAPS and FIOH researchers (HUMTOOL task/CORE project) and draft of a joint article was prepared. The aim was to explore the HF tool from the MAPS perspective and to discuss possibilities for incorporating a human factors view for facilitating nuclear power industry level or system-level learning and cooperation.

### **Deliverables in 2017**

- A conference paper was presented to the IRNOP conference in the USA. The article investigates how the actors in a project network make sense of a novel method introduced somewhat abruptly during the design phase of a nuclear industry project. The paper illustrates that there is a great deal of diversity of interpretations among project actors and suggests some managerial implications for dealing with issues of

ambiguity/equivocality, e.g. co-existence of multiple fragmented meanings among project participants. Manuscript of a joint scientific article, based on the IRNOP conference paper, has been prepared for submission to a journal.

- MAPS ad-hoc seminar “Multicultural aspects and safety in nuclear industry projects” was organized for researchers, authority and power companies. The seminar provided a better understanding of multicultural dynamics in international projects and insights on the relevance of this knowledge for management of safety in complex nuclear industry projects.
- Research report was written on the topic “Multicultural aspects in complex projects: Safety management implications for the nuclear power industry”. The paper provides a scoping review of pertinent studies on the topic.
- A conference paper was written on institutional complexity associated with safety requirements in a large nuclear industry project. The paper was presented to WOSNET2017, 9th International Conference on the Prevention of Accidents at Work, October 3-6, 2017, Prague, Czech Republic. The paper indicated that project actors’ responses to institutional complexity stem from different underlying logics, classified as driving, conservative and balancing.
- A conference paper was presented as a poster at the Resilience Engineering Symposium in Liege, Belgium in 26-29 June, 2017. The paper described a novel perspective to the practical development of safety culture in projects with illustrative examples from four safety culture assurance methods.
- A book chapter draft “Actionable Safety Culture” was written, which discusses the gap between safety science and safety practice. The chapter will be included in a book concerning new directions in safety science (edited by J.-C. Le Coze). The actionable safety culture idea was presented to WOSNET2017, 9<sup>th</sup> International Conference on the Prevention of Accidents at Work, October 3-6, 2017, Prague, Czech Republic.
- A workshop with the NKS research partners was held in Stockholm on the topic of the essential characteristics of safety culture and the identification of prerequisites and leverage points for safety culture change.
- The final NKS report “Safety Culture Assurance and Improvement Methods in Complex Projects” was published on NKS webpage (NKS-405, ISBN 978-87-7893-493-2).
- A paper manuscript was written on the topic of system dynamics modelling perspective on latent defects in the design of complex safety critical projects; the paper presents the system dynamics model and its development.
- Invited participation at IAEA (Vienna) meeting on safety culture - CS to Review IAEA Safety Culture Continuous Improvement Plan (SCCIP) Support.
- A joint workshop was organized with CORE project/HUMTOOL to discuss the industry or system level factors in HF tool in terms of facilitating the cooperation of different nuclear industry stakeholders.

#### 2.1.4 PRAMEA - Probabilistic risk assessment method development and applications

The general objective of the PRAMEA project is to develop methods and tools for probabilistic risk analysis (PRA) of digital systems and to utilize them in practical case studies. The project covered most of the topics relevant to the PRA of nuclear power plants. PRAMEA has provided reviews of performance shaping factors when assessing human error probability in advanced control rooms, and of the effects of digitalization of control rooms on human reliability analysis (HRA). It has participated in the preparation of an IAEA safety report for HRA. It has proposed risk metrics and developed methods for site PRA in Nordic co-operation project SITRON. It has studied solving of dynamic flowgraph models using fault tree algorithms. Further, it has developed a simplified boiling water reactor (BWR) plant PRA model with PRA levels 1 and 2 integrated, and improved level 2 analysis support and performance in FinPSA software. In level 3 PRA, it has laid groundwork for the incorporation of seasonal and contextual factors in level 3 analyses and consequence assessment. Finally, it has focused on optimizing risk-informed decisions in safety critical contexts when the setting is dynamic and the available information is incomplete.

##### **Specific goals in 2017**

The objectives of the task on HRA of digitalized control rooms were to define the characteristics and trends for computerized HSI, including computerized procedures, in modernized and new control rooms and conduct initial work on task analysis or Performance Shaping Factors.

To participate in the international expert team to prepare a guide on human reliability analysis. The work is led by the International Atomic Energy Agency.

To develop a Nordic approach for a nuclear power plant site risk analysis, driven by performance of pilot studies. 2017 work was limited to level 1 PSA.

The objective of the dynamic flowgraph methodology (DFM) task was to study solving of a DFM model using fault tree algorithms of FinPSA.

The objective on level 2 integrated deterministic and probabilistic safety analysis (IDPSA) task was to study steam explosions and level 2 modelling in the context of integration of PRA levels 1 and 2.

Level 2 method support objectives were related to FinPSA code. They included knowledge transfer to new developers, monitoring support for level 2 model analysis, functions to solve models in a goal-oriented way, and better analysis performance.

In level 3 PRA, the objective was to study the impact of seasonal and context factors in level 3 analyses and consequence assessment.

In the risk analysis of organizations and operations, the objective was extend the methodology, developed in previous years within PRAMEA, to support the selection of cost-efficient portfolios of structural safety measures for dynamic systems.

##### **Deliverables in 2017**

- A conference paper Markus Porthin, Terhi Kling, and Marja Liinasuo. New Challenges for Performance Shaping Factors in Advanced Control Rooms. Paper presented at the PSAM Topical Conference on Human Reliability, Quantitative Human Factors and Risk Management, 7-9 June 2017, Munich. The paper reviews the performance shaping factors (PSFs) commonly used in HRA methods and compares them with current

knowledge of human factors issues in ACRs. An overview of analysis approaches for establishing the effect of PSFs on human reliability is also given.

- A review paper has been submitted to *Reliability Engineering and Safety Science, Special Issue on Foundations and novel domains for Human Reliability Analysis*: Markus Porthin, Terhi Kling, Marja Liinasuo. Effects of Digitalization of Nuclear Power Plant Control Rooms on Human Reliability Analysis – a Review (currently in review process).
- Participation in an IAEA expert group to develop a Safety Report on Human Reliability Assessment for Nuclear Installations. Draft report prepared during 2017 and two meetings organised in Vienna.
- Risk metrics report for site PRA.
- Methods report for site PRA, limited to level 1 PRA.
- We have outlined preliminary requirements for site PRA model management.
- Two pilot studies on site PRA limited to level 1 PRA and multi-unit loss-of-offsite power initiating event (Forsmark 1&2 units and Ringhals 3&4 units).
- We have transformed DFM models into fault trees of FinPSA. We have developed minimal cut set solving algorithms of FinPSA to take into account non-coherent logic of DFM. We have solved a simple DFM model correctly in FinPSA.
- We have developed a simplified BWR plant PRA model that includes levels 1 and 2 as integrated and studied modelling of emergency core cooling system recovery in level 2 based on level 1 results. We have discussed possibilities to improve ex-vessel steam explosion modelling. We have also outlined a two-phase uncertainty analysis procedure to treat different types of uncertainties separately in level 2 PRA.
- Analysis performance was improved for level 2 models. Existing parallel implementation of level 1 model solving was studied and knowledge was transferred to new experts. New software interfaces were specified for parallel analysis, and a solver was implemented to simulate and analyse multiple containment event trees simultaneously. In addition, variable viewer was updated to monitor model changes in level 2 analysis and a new function to solve models in goal oriented way was implemented. User guide was updated according to changes in the software.
- Tests of level 2 parallel analysis and exception cases were planned, executed and reported.
- Groundwork was laid for the incorporation of seasonal and contextual factors in level 3 analyses and consequence assessment. Seasonal factors refer to factors that are associated with a given season(s) - for example, frost affecting the transport of radionuclides, or snow cover affecting the level of groundshine radiation. Contextual factors refer to e.g. initiating events that may have implications on accident consequences: for example, tsunami as an initiating event may imply that large areas have been depopulated or people evacuated before radionuclide release. These factors affect many important level 3 phenomena such as aquatic dispersion, transport of radionuclides in the environment and biosphere, population demography and behaviour, and the attenuation of ionizing radiation. The results were documented in a research report.
- A scientific paper on an optimization methodology for cost-efficient defense-in-depth strategies has been published by *Reliability Engineering and System Safety*.

- A conference paper on an extension of the optimization methodology accounting for imprecise information was presented by Alessandro Mancuso at the ESREL 2017 conference in June 2017.
- In 2017, we developed a methodology to support the selection of cost-efficient portfolios of structural safety measures for dynamic systems. In particular, we extended the methodology to time-dependent accident scenarios by explicitly encoding the dynamic behaviour of engineering systems. The manuscript has been submitted to *Reliability Engineering and System Safety*.

A paper on an extension of the optimization methodology accounting for imprecise information has been accepted for ESREL 2017 conference.

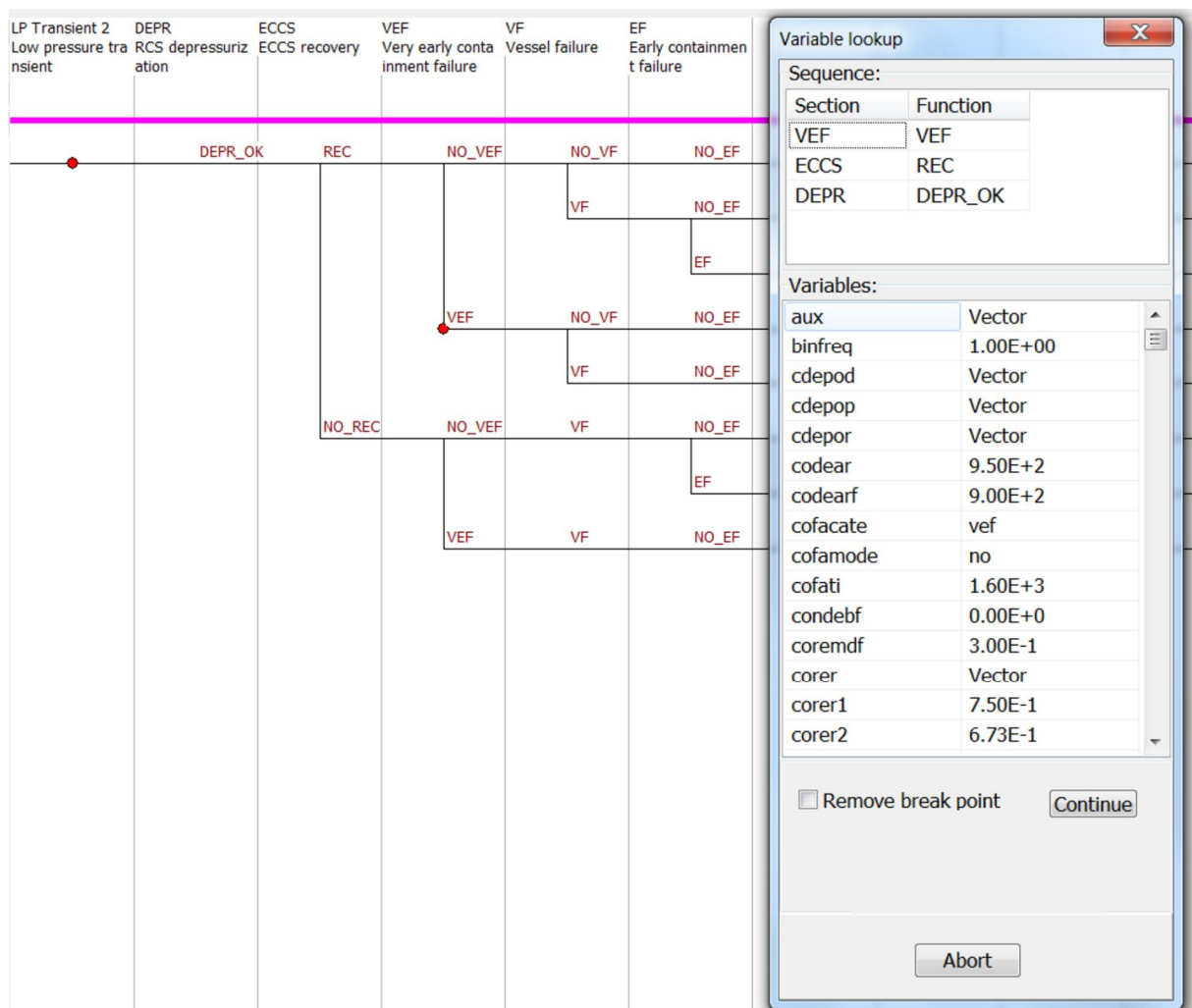


Figure 2.1.4.1. The variable viewer of FinPSA Level 2 user interface was improved to monitor changes of variable values in a containment event tree during execution. In this figure, breakpoints (red dots) have been set to the event tree so that when the execution proceeds to a breakpoint, the user may inspect values of global variables at that point.

### 2.1.5 SAUNA - Integrated safety assessment and justification of nuclear power plant automation

The general objective of SAUNA (2015-2018) is to develop an integrated framework for safety assessment and transparent safety demonstration of nuclear power plant instrumentation and control (I&C) systems. Traditionally, safety assessment tends to focus on technical issues, single faults or limited combinations, deterministic analysis and PRA, and a document-based approach (SARs). In SAUNA, the research theme is overall plant safety. A key challenge is therefore to consider (1) all types of hazards, including rare and extreme conditions, (2) all disciplines and types of system elements (technical, human, environmental...), and (3) all life-cycle phases and activities.

Through a multidisciplinary research strategy, SAUNA will look at plant operations in the context of the whole plant and investment project, while keeping the focus on I&C systems. The different work packages will (1) build a shared understanding of the underlying challenges, concepts, and Systems Engineering principles, (2) develop dedicated methods and tools for assessing the safety of systems and their development processes – particularly focusing on the efficient integration of different approaches – and (3) tie the results together into an integrated, structured, model-based approach to safety demonstration and licensing.

#### **Specific goals in 2017**

WP1 of SAUNA focuses on clarifying the terminology and Systems Engineering principles in order to provide a common basis for research activities on NPP safety. In 2017, the focus was on further developing model-based safety assessment methodologies for Defence-in-Depth.

Model driven engineering design methods like dependency and functional modelling can be utilised to provide early safety-related feedback to the system designer. Early Defence-in-Depth (DiD) is a key issue in NPP safety, during 2016 a metamodel supporting early interdisciplinary modelling for DiD assessment and a prototype tool were developed and tested in a small case study of a spent fuel cooling process (see Figure 2.1.5.1). In 2017, the objective was to further demonstrate the possibilities provided by structured system models and computer assisted analysis techniques. Specifically, a functional modelling method was presented which supports failure propagation from external events with time-varying failure probability. The case study model was also further developed to demonstrate the connection between the proposed multidisciplinary system dependency model and early safety assessment with automatic generation of fault trees. In addition, a method to identify cyber-security attack scenarios with high risk was proposed, based on genetic algorithms.

In the MODIG (MOdelling of DIGital I&C) subtask on PRA methods, work continued on three topics: DiD analysis supported by PRA, I&C software reliability modelling, and international collaboration. Specifically, (1) a paper was written to discuss the problems related to preparing a safety case for digital I&C, and how to remedy the issue by building an idealised process description together with arguments, claims and evidence (submitted to the RESS journal), (2) the earlier developed model checking methods was updated to better correspond with the DIGREL example, to continue to study the integration of PRA and model checking, and (3) the DIGREL model itself was modified in order to better focus on digital I&C modelling issues, to facilitate collaboration in the “Comparative application of DIGital I&C Modeling Approaches for PSA (DIGMAP)” task started by OECD/NEA WGRISK.

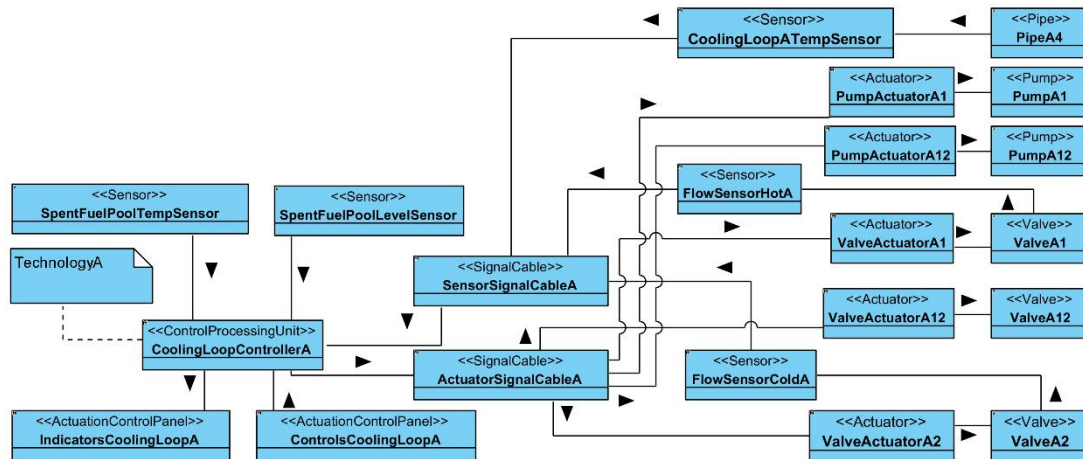


Figure 2.1.5.1. Partial view of the automation dependencies in the spent fuel pool case study. The model contains also dependencies related to process, environment (including the control room), power supply and human factors.

WP2 of SAUNA looks at the assessment methods and tools for specific technical, human, and systemic safety issues. In 2017, the focus was on increasing the reliability of model checking, making the interpretation of counterexamples (produced in model checking) more user-friendly, further developing the Nuclear SPICE process assessment method, and on structured safety demonstration of control room systems.

Model checking is a powerful formal verification method that has for the last ten years been successfully used in the Finnish nuclear industry. The modelling method used by VTT in practical customer projects depends upon a manually modelled library of elementary (or basic) function blocks. Due to the proprietary source code not being available, manual modelling by the analyst is a necessity, and introduces a source for human error. In 2017, a method was developed for the automatic synthesis of basic function blocks, based on LTL (Linear Temporal Logic) properties derived from block specifications (e.g., user manuals). The method was successfully used to detect errors in models developed manually by VTT analysts to represent Apros process simulator I&C function blocks. While somewhat laborious to use, the method can reveal errors that arise from either human errors in modelling or ambiguity in the textual block specifications.

Another practical challenge in model checking is that the counterexamples produced by model checkers can be long, making it hard to pinpoint of the root of the cause (in either the model or the verified property) for the failure scenario. The graphical model checking tool MODCHK already uses model view animation. In 2017, a complimentary feature of animating the property was developed, along with a feature that highlights the important changes of model variables, based on a causality model (see Figure 2.1.5.2). The developed prototype tool was able accurately point to the exact failure point in over 40 real-world test cases based on VTT customer projects, also pointing out in several cases the exact root cause of the failure.

Process assessment for systems and safety engineering benefits from further development of the current Nuclear SPICE assessment method. In 2017, the objective was to extend the method based on potential new sources for assessable processes, and to study novel solutions for the collection, management and reuse of evidence data. For the latter topic, two approaches were studied, one for mapping the process assessment models to domain-specific requirements based on Safety-oriented Process Line Engineering, and another for analysing the relevance of the evidence based on a binary distance metric.

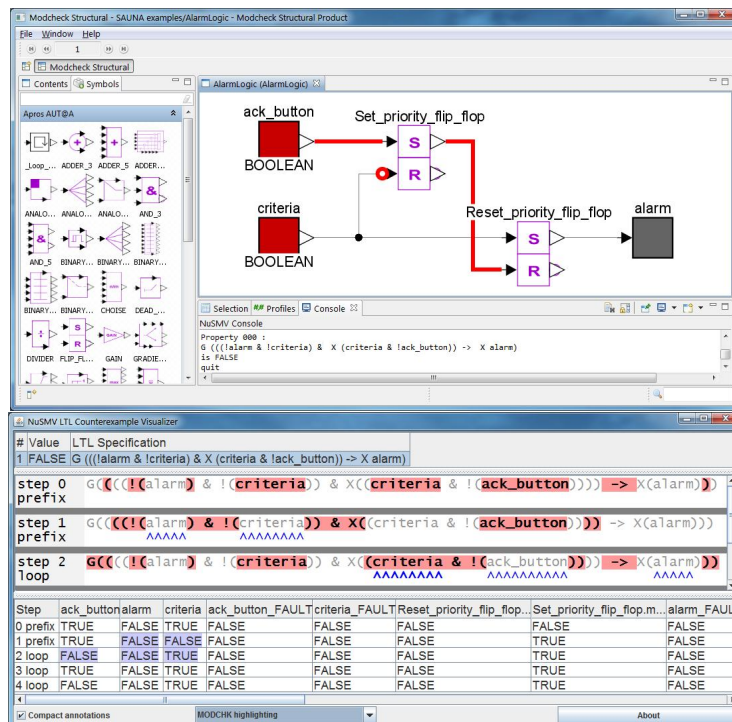


Figure 2.1.5.2. Along with the model animation feature of MODCHK (above) a tool demonstration was implemented to animate the property, and point out important variable changes (below).

Process assessment for systems and safety engineering benefits from further development of the current Nuclear SPICE assessment method. In 2017, the objective was to extend the method based on potential new sources for assessable processes, and to study novel solutions for the collection, management and reuse of evidence data. For the latter topic, two approaches were studied, one for mapping the process assessment models to domain-specific requirements based on Safety-oriented Process Line Engineering, and another for analysing the relevance of the evidence based on a binary distance metric.

For the multistage validation of control room systems, a Systems Usability Case approach was developed in the previous SAFIR programme. In SAUNA, the focus has been on creating a Safety Case based approach for organizing and assessing the fulfilment of Human Factors requirements. Practical demonstration in Fortum's ELSA project has been carried out to monitor how evaluation evidence is aggregated over variety of validation steps and how the design solution is maturing towards a tool of a good quality and usability. A conference paper from SAUNA 2016 was developed into a journal manuscript submitted to the RESS journal, aiming is to provide a complete description of the SUC approach and process including, for example, documentation formats and procedures for accumulation of evidence over different phases of control room V&V process.

WP3 of SAUNA aims to provide recommendations, insight, new viewpoints, and tools for planning, documenting and communicating the safety demonstration, and enabling the licensees to efficiently carry out the licensing process.

The objective in 2017 was to define a top-level framework for safety demonstration and assessment of I&C architecture, focusing on qualification of DiD capabilities. The systems engineering data model developed in 2016 was updated to encompass third party conformity assessment artefacts. The data model (now called "Conformity assessment data model") implements the Systems Engineering 8.0 model (see Figure 2.1.5.3) developed during the project to replace the traditional V-model to outline the life cycle of systems engineering activities from the engineering work products point of view. The data model was

demonstrated by applying it to the redundancy requirement of a spent fuel cooling system of a Nuclear Power Plant. The demonstration verified that the model provides good traceability. With a proper tool, impact analysis can also be carried out.

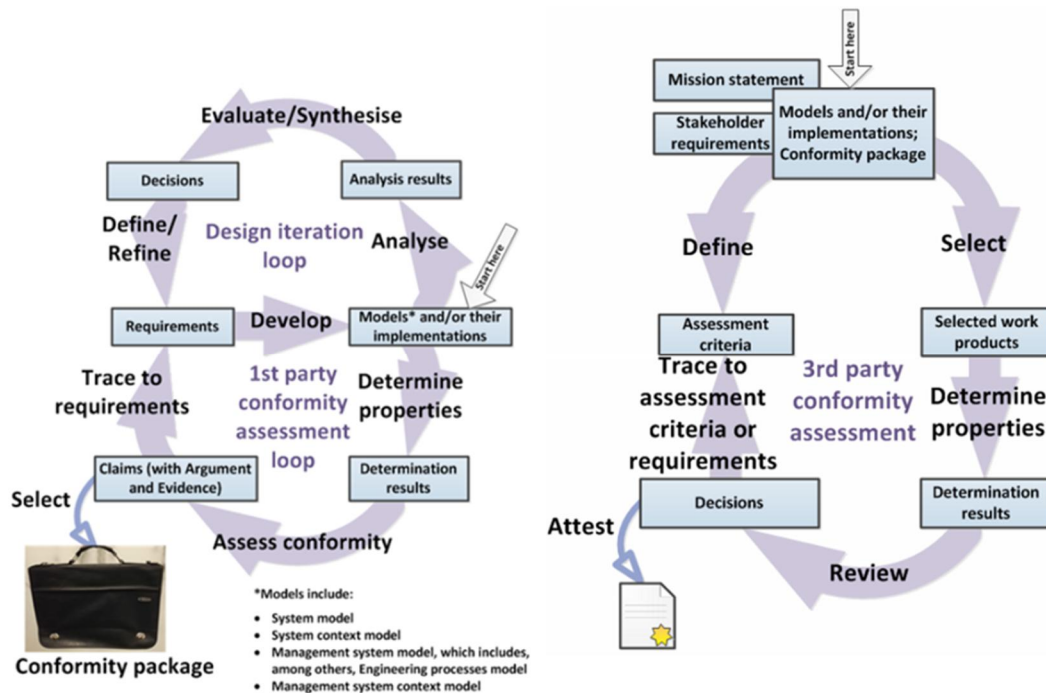


Figure 2.1.5.3. Systems Engineering 8.0 model includes the third party conformity assessment (the "zero" part to the right) in addition to the first party assessment ("eight" part to the left).

As part of Halden in-kind cooperation, SAUNA 2017 included contribution to Halden Working Report titled "Improving understanding of and supporting argumentation in safety demonstration - Status of activities". In addition to a literature study, the report is based on elicitation interviews with licensee organisations, and a small case study of a graphically presented safety case.

### Deliverables in 2017

- A conference paper in RAMS 2017 about functional modelling based early risk assessment methods including the time variation of external initiating events
- A conference paper submitted to ASME IDETC/CIE 2018 about automatic fault tree generation from multidisciplinary dependency models for early safety assessment
- A research report on dependency analysis of I&C architectures
- A conference paper submitted to IEEE INDIN 2018 about assessing the risk of cyber and physical malicious attacks during early system design
- A conference paper in INCOSE 2017 about a graph theory approach to functional failure propagation in early system design
- A journal manuscript submitted to RESS about digital I&C design aiming at the creation of believable safety cases.
- A research report on the progress in the WGRISK digital I&C benchmark study DIGMAP

- A research report on a case study of coupling of PRA and model checking
- A conference paper in IEEE IECON 2017 about the comparison of explicit-state and symbolic model checking when applied to nuclear I&C systems
- A conference paper submitted to IEEE ISIE 2017 about the synthesis of the basic function block model for model checking, and the comparison of the synthesized blocks with manual implementation
- A conference paper in ANS NPIC & HMIT 2017 about the practical applications of model checking in Finnish NPPs over the last ten years
- A conference paper in ESREL 2017 about using model checking to analyse spurious actuation of nuclear I&C application logics
- A conference paper in IEEE ETFA 2017 about modular plant model synthesis for closed-loop model checking
- A conference paper submitted to IEEE INDIN 2018 about counterexample visualisation and explanation for function block diagrams
- A conference paper in SafeComp SASSUR 2017 about process assessment in supplier selection for systems in nuclear domain
- A conference paper in EuroSPI 2017 about systematic compliance evaluation using safety-oriented process lines and evidence mapping
- A journal manuscript submitted to RESS about Systems Usability Case approach in stepwise control room validation
- A research report on a structured data model for conformity assessment
- An international research report on the status of activities related to safety demonstration

#### 2.1.6 GENXFIN – Safety of new reactor technologies

The main mission of the GENXFIN project is to improve scientific and technologic expertise in the field of new nuclear energy technologies and related processes through international collaboration. The main objective is to coordinate participation in various international working groups and information dissemination on interested parties. Essential part of the project was to get familiar with the passive safety features of innovative Small Modular Reactor (SMR) NuScale, which is interesting from a national perspective. In order to mitigate the worst effects of climate change the whole energy sector needs to be decarbonized.

##### **Specific goals in 2017**

The Finnish regulatory guides on nuclear safety define the main requirements that a new nuclear power plant must fulfil to be able to be licensed in Finland. In GENXFIN project, the main heat removal safety systems of NuScale SMR design were studied and obstacles seen in the licensing process investigated using systems engineering approaches. Recommendations of emergency preparedness zones for NuScale were evaluated and determined. The EPZ recommendations were justified by applying international safety criteria

in dose calculations. The dose calculations were done with the VALMA code using postulated source terms from Serpent calculation and real SILAM-calculated NWP-based weather data of year 2012 from the FMI. Exposure pathways include the relevant pathways: external radiation from the plume, inhalation and external radiation from the deposition on the ground.

Even with inherent safety features, severe accidents cannot be neglected. History shows that severe accidents at NPPs have happened, and by extrapolation, they can still happen in the future, regardless of all the improvements made. As a general conclusion, without referring to assessment of off-site doses, it can be said that EPR (emergency preparedness & response) will probably always be needed, however good the design of the reactor is, simply because the potential release source term is always present in the form of the core radioactive inventory. Even with a good design, military or terror action and other very low probability or beyond design events are always possible to damage the reactor. Inherently safe, passive and robust systems (leading to no need for EPR), particularly by improving levels 3 and 4 (control of DBAs / control of severe conditions) of DiD, can be a design goal, but still appropriate off-site emergency arrangements should be available. Their extent is a subject of intense debate between reactor developers and EPR people.

The DiD principle is the basis of the safety design of the reviewed SMRs and also the foundation of the Finnish regulatory guidelines of nuclear safety. The passive decay heat removal safety systems, featured in NuScale, are taken into account in Finnish regulations by giving them a reduced failure criterion (N+1) compared to (N+2) for active systems.

The main hurdle seen in the licensing of IPWR SMRs is the independency of DiD levels, and the fact that in Finland, no new-build nuclear power plant is acceptable without a feasible strategy for managing severe accidents (STUK YVL 2.2, old, and B.3 Deterministic Safety Analyses & B.6 Containment, new). Differences of SMRs from large power reactors include integrated RPVs, lower power levels and smaller reactor core radioactive inventories. The actual licensing process is very time consuming and the public information is in no way detailed enough to truly give a definitive statement on the issue.

### **Deliverables in 2017**

- Application of System Engineering Approaches to Evaluate the Heat Removal Strategies of NuScale Power Module Review report on SMR material issues
- Off-site radiological consequences from a SMR unit
- Travel reports IAEA and GIF meetings

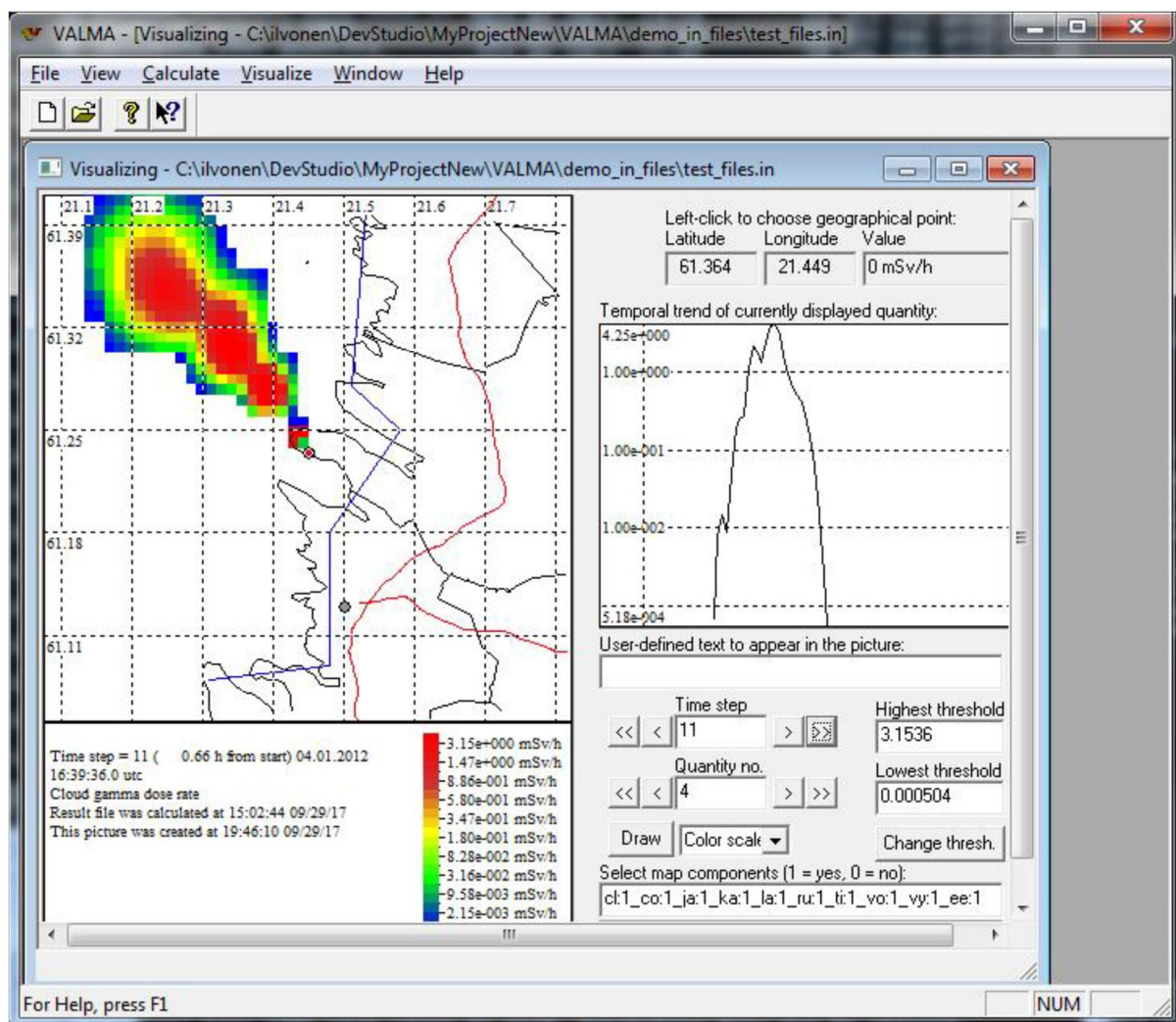


Figure 2.1.6.1. VALMA results for one single dispersion case. Cloudshine dose rate at 40 min after start of release.

## 2.1.7 ESSI – Electric systems and safety in Finnish NPP.

The objective of ESSI (2017-2018) is to examine the possible common cause fault impacts of open phase conditions (OPC) and large lightning strikes in Finnish NPP electrical systems. Also the risks of adaptive operation of NPP in load following mode will be examined.

The severity of unbalance in different possible open phase situations is analysed. The consequences of possible voltage unbalances are assessed from different electrical system components point of view. Criticality of different OPC cases is analysed with regard the possible risks and time required from mitigation actions. An expected result will be how the operating plants have been prepared to OPC.

Voltage stresses caused by large lightning currents in Finnish NPP electric systems is analysed for both surges entering via transmission grid and through lightning strikes into the grounding system. The adequacy of overvoltage protection is assessed and possible improvements are suggested for the surge arrester sizing and location, as well as for the grounding arrangements of the electrical, automation and instrumentation systems.

Concerning the adaptive operation of NPP, the objective is to estimate requirements, technological limits and risks of adaptive control in today's nuclear power plants with regard to electrical systems in order to avoid the increase of disturbances in power plant. The objective is to obtain the minimum requirements for the manoeuvrability capabilities of Finnish nuclear power plants.

### Specific goals in 2017

OPC is a possible source of a severe common cause failure in a NPP. The WP1 starts by making a survey how the operating plants have been prepared to OPC and by a review of the existing literature. The WP1 should take into account work already done e.g. by GRS (Gesellschaft für Anlagen- und Reaktorsicherheit) and continue from that.

The survey how the operating plants have been prepared to OPC covers the protections against unbalance voltages in the case of disconnection of one or two phases of the transmission grid in the following two cases: Generator connected in the grid and generator disconnected. It is likely, that in case of severe unbalance in the grid, the generator is tripped by negative sequence voltage relay, which leads to the situation that NPP house load is supplied by the grid solely. This is probably the worst scenario from house load components point of view.

The literature review analyses also how possible locations of lost phases affect different alternative power supply sources (like 400 kV and 110 kV) and the unbalance in them (simultaneous OPC in both 400 kV and 110 kV). The impacts of OPC on various NPP loads and components are investigated. The goal is to assess the severity and time criticality of various unbalance cases and different components. It will be investigated impacts of OPC on the generator, with regard to an analysis of the operation of the unbalance protection and tripping of the generator in different OPC cases. Impact of OPC on house load and electrical components is focused on behaviour of protection, hazard of damage, and urgency of mitigation actions in terms of time. The loads studied are: direct connected motor drives, transformers, cables and rectifiers of AC/DC systems.

In directly connected motors, the negative sequence component of supply voltage causes torque which opposes the direction of rotation. At the same time, the positive direction voltage is reduced, and the machine takes correspondingly larger current in order to produce the mechanical power required. Sustained operation with unbalanced supply voltage may lead to either tripping of the motor protection, and hence disconnection of the motor from power supply, or in the worst case, damaging of the machine due to overheating. Laboratory measurements are conducted to investigate the motor voltages and currents and the temperature behaviour in an induction motor under OPC using the measurement setup presented in Figure 2.1.7.1.

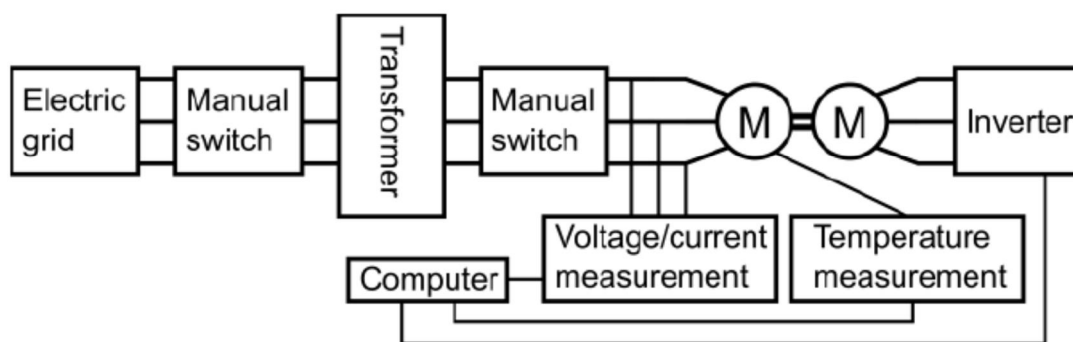


Figure 2.1.7.1. The basic structure of the measurement setup.

In WP2, the lightning overvoltages coming from the national grid to the NPP electric systems are investigated. In the case of direct lightning strike, it should be examined which kind of overvoltages are able to cause extremely high lightning currents (over 200 kA) in different parts of NPP electrical system. The capacity of the surge arresters should be assessed and the probabilities of common cause faults on different voltage levels analyzed. One topic of interest, too, is the grading and coordination of overvoltage protection at different system levels. For instance, if at the high voltage side of a transformer there is flashover from phase to ground, the steep change of voltage is strongly connected through transformer capacitances to the secondary side.

The research is focused on extremely high current surges. The data of the magnitude and probability for the surges are available in Fennovoima's internal report collected from FMI's statistics (FMI= Finnish Meteorological Institute). The modelling of NPP electrical system is done for lightning strikes coming from the 400 kV national grid. The cases analysed are overvoltage due to direct lightning to the phase and back-flashovers close to the grid transformer. The latter case produces very steep overvoltages which may have a strong capacitive coupling through the transformer.

In addition to the modeling of overvoltages, the work comprises analysis of the present capacity of surge arresters and analysis of overvoltages created in lower system levels if flashover at the high voltage side of grid transformer. The result is possible recommendations for the coordination of overvoltage protection at different electrical system levels.

WP3 of ESSI focuses on adaptive operation of NPPs which are normally not operating in manoeuvring regimes in Finland. However, the more we get stochastic generation and in the future also stochastic or movable consumption and energy storages in the form of cars, the more important this issue becomes. In fact, majority of the currently operating NPPs were designed to have strong manoeuvring capabilities (NEA, 2011). However, operating an NPP at a constant power level is simpler and less demanding on the plant's equipment and fuel. Usually three types of manoeuvring are defined: primary and secondary frequency regulation (which depend on current grid demand) and predefined variable load programmes (i.e. reductions or increases in power output agreed in advance with the grid operator). Planned reductions or increases in power output allow initial balancing of electricity supply and demand. These variations can be significant.

Adaptive operation of NPP may have risks for electric systems and control inside NPP and for stabilization of national grid. It is expected that the disturbance sensitivity of the electrical components and ICT systems can increase. Load following operation has some influence on the ageing of certain operational components and thus one can expect an increase in maintenance.

The objective is to estimate the technological limits and risks of adaptive control in Finnish nuclear power plants with regard to electrical systems in order to avoid the increase of disturbances in power plant. In the year 2017, the minimum requirements for the manoeuvrability capabilities of Finnish nuclear power plants are mapped and clarified. The mapping will base on the utility requirements from the safety point of view. This includes also the manoeuvring capabilities of Finnish NPPs in different types of frequency and balancing control of the national grid. During this task information will be exchanged with the GINO – Grid Interference on Nuclear power plant Operation- project, Energiforsk in Sweden

### **Deliverables in 2017**

- Unbalances caused by different OPC cases in NPP electric systems and preparedness of operating plants against OPC. The technical report introduces the OPC phenomena and its impact on different NPP components. Also different alternatives for protection against OPCs are briefly described.

- Analysis of Open Phase Condition Influence on an Induction Motor. The conference paper investigates different open phase conditions (OPCs) and their influence on an induction motor. The considered conditions include single and double line OPCs on the primary-side of a transformer supplying the motor. Several different transformer connections are investigated. The OPCs are first analyzed analytically with symmetrical components, after which the results are compared with simulated values. Measurements are performed to showcase the stator temperature evolution under OPC and to validate the numerical results. The results indicate that in the case of single OPC, only moderate unbalance is observed with YNd and YNyn transformer connection, whereas the highest phase current occurs with Dyn connection.
- Lightning Overvoltages in Electrical Power System of a Power Plant. The conference paper presents the impacts of lightning strokes to NPP power system. Direct stroke to the phase conductor of the connected line and back flashover resulting from the lightning stroke to the transmission tower or shield wire injects wave current with high amplitude to the phase conductors and eventually through the transformer. In this paper the voltage rise at the secondary of each connected transformer at different voltage levels in a house load network of a power generation plant is analyzed. Protective measures are analyzed in the study to mitigate the transferred overvoltage at the far end and ensure the overvoltage is within the basic insulation level (BIL) of the connected equipment. Simulations using different combination of protective surge arrestors have been done with EMTP-ATPDraw and the results have been presented.
- Perspectives for flexible nuclear power plant operation. The technical report presents the results of a literature survey and interviews of the Finnish NPP plant operators, STUK and the information received from the Swedish Centre for Nuclear. The focus of the report is in the impacts of the flexible operation on the electric system but some other issues were also included because they were mentioned in discussions.

## 2.2 Reactor safety

In 2017 the research area “Reactor safety” consisted of eleven projects:

1. Comprehensive analysis of severe accidents (CASA)
2. Chemistry and transport of fission products (CATFIS)
3. Comprehensive and systematic validation of independent safety analysis tools (COVA)
4. Couplings and instabilities in reactor systems (INSTAB)
5. Integral and separate effects tests on thermal-hydraulic problems in reactors (INTEGRA)
6. Nuclear criticality and safety analyses preparedness at VTT (KATVE)
7. Development of a Monte Carlo based calculation sequence for reactor core safety analyses (MONSOON)
8. Development and validation of CFD methods for nuclear reactor safety assessment (NURESA)
9. Physics and chemistry of nuclear fuel (PANCHO)
10. Safety analyses for dynamical events (SADE)
11. Uncertainty and sensitivity analyses for reactor safety (USVA).

### 2.2.1 CASA - Comprehensive analysis of severe accidents

This project brings together a large spectrum of phenomena related to the thermal hydraulics of severe Nuclear Power Plant (NPP) accidents. The objective is to decrease uncertainties in defining the possible radioactive release to the environment. Analyses also include evaluating the environmental consequences of a hypothetical severe accident. These topics are of high importance in the severe accident management of the Finnish NPPs.

#### **Specific goals in 2017**

Fukushima accident provides a unique opportunity for gaining more information on the progress of severe accidents and their prevention and mitigation. In 2017, the third version of VTT's MELCOR model of the Fukushima unit 1 accident was developed. Compared to the second version, detailed plant data from the OECD BSAF-2 project was utilized, and now it was possible to eliminate most of the uncertainties that were related to unknown dimensions of the plant. Most of the remaining uncertainties are related to physical models and nodalization in MELCOR, and uncertain boundary conditions, for example water injection rate with the fire engines and locations of various leaks.

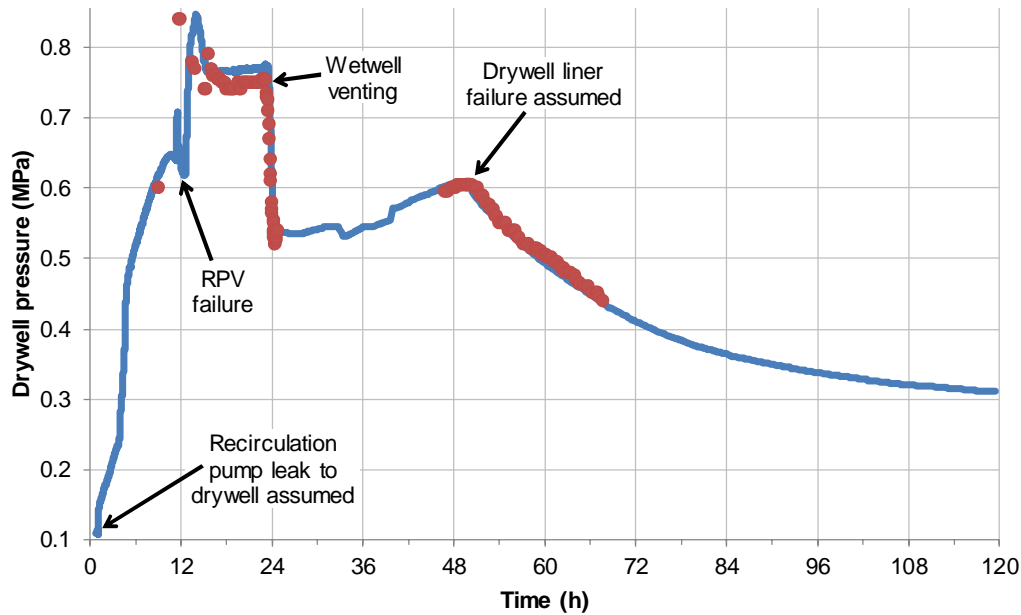


Figure 2.2.1.1. Fukushima unit 1 pressure in the containment drywell during the accident. Red dots are measured values and blue curve is the result from the MELCOR simulation.

The calculation reproduces the measured pressures well as indicated for containment drywell in Figure 2.2.1.1. Leaks from the recirculation pump seals were assumed because otherwise the measured containment pressure would have been underestimated. It was assumed that the seawater injections during the calculated time period (five days) failed because starting and stopping of the injection would have caused large changes to the reactor and containment pressures, but such changes do not exist in the measured pressures. The earlier freshwater injections were assumed successful. Reactor Pressure Vessel (RPV) lower head penetration failure and debris ejection to the containment was calculated to occur at around 12 h.

Coolability of corium should be ensured in all of its locations and forms. Previously the effect of debris bed geometry and flooding mode on dryout heat flux have been analysed experimentally and analytically to evaluate the coolability of an ex-vessel debris bed. However, the coolability limit based on the minimum dryout heat flux might be overly conservative, since the temperature may remain on an acceptable level even in the dry zone. Instead of the dryout heat flux, it has been proposed that the coolability limit should be based on the increase of the particle temperature.

To analyse this, the behaviour of conical debris beds was studied by performing MEWA simulations. The effect of heat transfer models available in MEWA did not explain the differences compared to the KTH's DECOSIM results and therefore the influence of the friction model in post-dryout conditions was analysed. As MEWA does not feature the same friction model used in DECOSIM, it was added into the Fluent implementation of the debris bed coolability models. The usage of the same friction model improved the agreement. The comparison is in Figure 2.2.1.2. However, the convection and viscous term in the full multiphase flow equations solved by Fluent modify the flow field especially close to the tip of the conical bed hampering quantitative comparisons with the MEWA and DECOSIM results. On the other hand, in case of a conical debris bed, the simplified momentum equations might not predict flows satisfactory enough to be used in quantifying the temperature-based coolability limit.

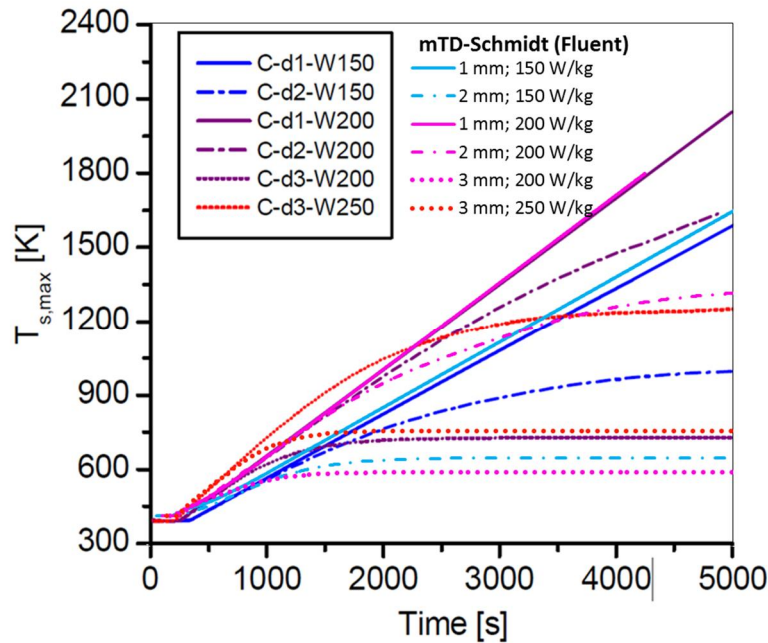


Figure 2.2.1.2. Comparison of the time evolution of the maximum solid particle temperature in the Fluent simulations of this study and in the DECOSIM simulations.

Some of the small- and medium-scale pool scrubbing experiments with non-soluble aerosols performed in the SAFIR2018 CATFIS project were analysed with ASTEC V2.0, ASTEC V2.1 and MELCOR. The analytical results from medium-scale experiments are compared to experimental values in Figure 2.2.1.3. In general, integral codes result smaller Decontamination Factors (DF) than recorded in the experiment. This is conservative what comes to the potential source term.

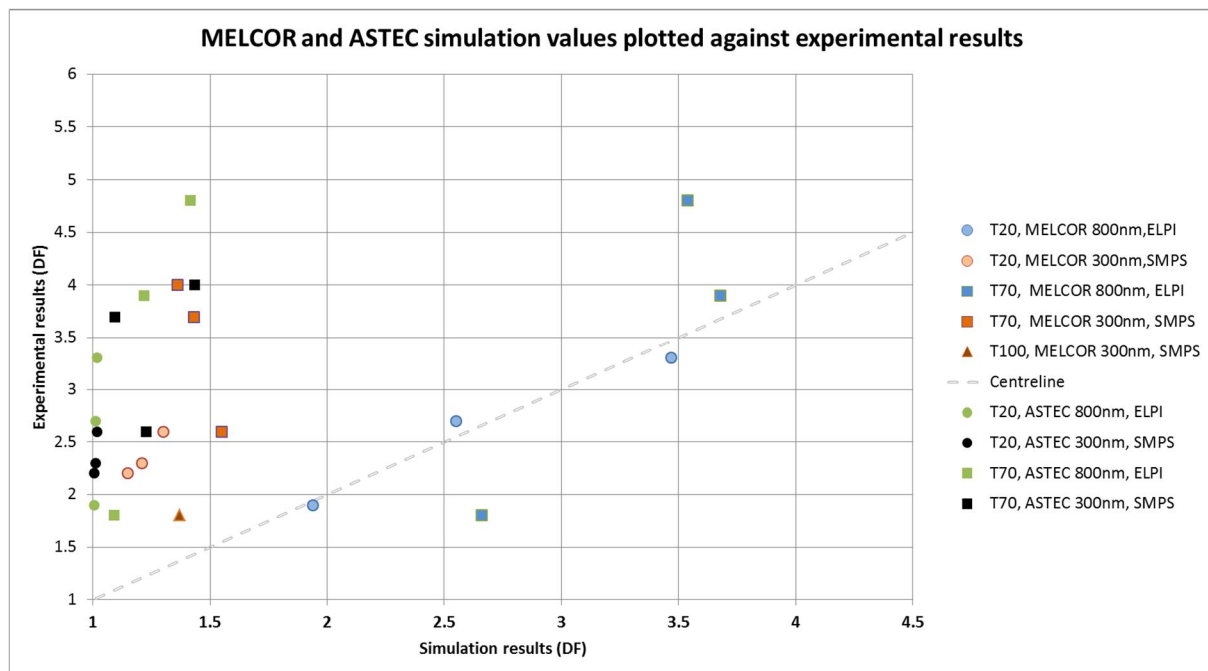


Figure 2.2.1.3. Comparison of simulated and experimental result for medium-scale pool scrubbing experiments with non-soluble aerosols.

ASTEC V2.0 and MELCOR simulations were in a good agreement with the experiments about the DFs for non-soluble aerosols. ASTEC V2.1 resulted the smallest DF values. With pool temperature near to the boiling point, ASTEC V2.1 overestimated the DF values notably. These results are not included in Figure 2.2.1.3 and this behaviour is not yet explained. DF decreasing with the decreasing pool depth and increasing flow rate was confirmed in most of the analysed cases. DF dependence on the pool temperature seems to be a bit more complicating issue. At temperatures clearly below boiling point, DFs increase with the increasing temperature also in the simulations.

Ensuring the integrity of the containment during a hypothetical severe accident is extremely important since the containment is the last safety barrier preventing radioactive release to the environment. In addition to core melt also highly energetic events steam and hydrogen explosions may threaten the containment integrity. To achieve reliable results specific know-how related not only to the phenomena but also to specialised and well-validated codes is needed.

The effect of RPV breaking location on dynamic pressure load on cavity wall induced by a steam explosion has been analysed with MC3D. During the analysis of the results, it became clear that the simulations suffer from stability issues that were in the explosion part and caused the simulations to stop before the defined end time. This in turn makes analysing the pressure peaks at the wall difficult as it becomes uncertain if the maximum is reached before the calculations end. However, the resulting explosions were stronger in comparison to the previous 2D central break cases.

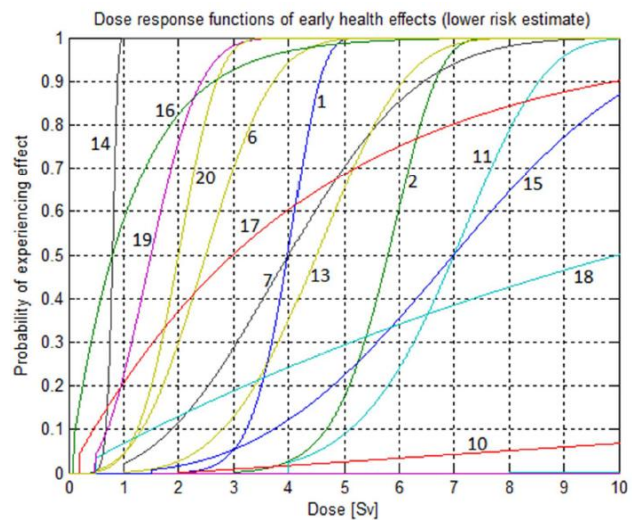
Hydrogen combustion was studied by simulating three experiments as a double-blind validation study on flame propagation in the new ENACCEF2 facility that includes obstacles accelerating the flame propagation as real containment rooms. The applicability of alternative modelling approaches was tested by computing the first experiment and the most promising ones were chosen. The uncertainties of model parameters are commonly significant in terms of the flame propagation speed. The flame speed was also found to be sensitive especially to the modelling approach for the flame-front propagation and to some extent to the mesh density as well as time step. However, the maximum pressure is less influenced by the computational parameters.

There are two primary models at VTT available to assess the environmental consequences for emergency preparedness purposes and level 3 PSA. ARANO is a straight line Gaussian type dispersion model for probabilistic consequence assessments where weather remains the same until the plume exits the computation area. VALMA is a dispersion and dose assessment code purposed to serve as an emergency preparedness tool that is able to use many kinds of weather data.

VALMA was augmented with the calculation of acute and late health effects of radiation doses to increase also its competence to assist in radiation protection and in level 3 PSA. Fortran-coded functions returning the probabilities of certain health effects when the corresponding radiation dose is given, have been incorporated in the VALMA code. Dose response parameter data from NUREG CR-4214 report from 1993 was used since it was readily available in digital format. The functions contain a total of 42 effect types, divided between acute, late and genetic health effects. Implemented acute health effects and their dose response functions are in Figure 2.2.1.4.

1	mortality / hematopoietic syndrome / minimal treatment
2	mortality / hematopoietic syndrome / supportive treatment
3	mortality / pulmonary syndrome
4	mortality / gastrointestinal syndrome
5	pulmonary morbidity
6	prodromal syndrome / vomiting
7	prodromal syndrome / diarrhea
8	thyroiditis
9	hypothyroidism / internal exposure to I-131
10	hypothyroidism / all other exposures
11	erythema
12	transepidermal injury
13	reproductive effects / ovulation suppression
14	reproductive effects / suppression of sperm count
15	cataracts
16	in utero / microencephaly / 0 - 17 weeks
17	in utero / severe mental retardation / 8 - 15 weeks
18	in utero / severe mental retardation / 16 - 25 weeks
19	in utero / death of embryo or fetus / 0 - 18 days
20	in utero / death of embryo or fetus / 18 - 150 days

(a)



(b)

Figure 2.2.1.4. Radiation-induced early health effects implemented in VALMA (a) and dose response functions (probability of health effect as a function of dose) as a graphical representation in the interval 0...10 Sv of the appropriate organ-specific dose (to be chosen appropriately for each effect) (b). These functions are for the lower estimate of risk.

VALMA calculations were performed with a severe accident radioactive source term using one year of Oikiluoto real weather data. Only early (acute) health effects were included, as the risk of various cancers is usually taken as linearly proportional to dose. All acute health effects contained in the models were successfully computed in all dispersion cases. Results are individual risks of experiencing the effect at distances of 1, 2, 3, 5, 8 and 12 km. It must be emphasized that the situation is highly hypothetical (big release and population remaining), and it mainly serves to test the health effects models.

Corresponding analyses were done with the simpler but also much faster ARANO code, generating results for radiation sickness and early fatalities, and including also optionally the effect of countermeasures. It must be noted that in the near range, the simple description of weather used in ARANO is usually well sufficient.

## Deliverables in 2017

- Updates to the Fukushima Unit 1 model were described in a research report. Now it was possible to eliminate most of the uncertainties that were related to unknown dimensions of the plant.
- A conference poster about the Fukushima calculations performed during the recent years was presented in the ERMSAR conference.
- A travel report from the CSARP/MCAP meeting did summarize the most interesting presentations.
- The effect of heat transfer models and friction model on debris bed post-dryout temperature behaviour was tested and results compared to KTH's DECOSIM results in a research report.

- The effect of RPV breaking location on dynamic pressure load on cavity wall induced by a steam explosion has been analysed with MC3D. The results were presented in a research report.
- Some of the small- and medium-scale pool scrubbing experiments with non-soluble aerosols performed in the SAFIR2018 CATFIS project were analysed with ASTEC V2.0, ASTEC V2.1 and MELCOR
- A conference paper on the effect of post-accident pH control on iodine behaviour in the Nordic BWR containment was written and results were presented in the ERMSAR conference.
- Three hydrogen combustion experiments were simulated as a double-blind validation study on flame propagation. An abstract of a common MITHYGENE ETSON benchmark paper has been submitted
- VALMA was augmented with the calculation of acute and late health effects of radiation doses. The new models were tested and the results were presented in a research report.

### 2.2.2 CATFIS - Chemistry and transport of fission products

The objective of the project (2015-2018) is to study the behaviour of fission products in severe accident conditions. In particular, the aim is to increase understanding of revaporisation and transport of iodine in primary circuit and containment of a nuclear power plant. The primary circuit study has been conducted in close co-operation with IRSN Cadarache research centre for the determination of iodine chemistry. The objective of the primary circuit study at VTT is to determine iodine compounds released due to the reactions on the surface of primary circuit piping. At the same time IRSN is focused on the gas phase chemistry of iodine in similar experimental conditions. The measurements with EXSI-PC provide information on high temperature chemistry and facilitate validation of for example iodine chemistry codes. The second aim is to find out the effect of primary circuit conditions on the transport and speciation of ruthenium. These experiments are conducted with VTT's Ru transport facility in collaboration with Chalmers University of Technology as part of NKS-R activity. As a third aim, radiolytical reactions by various radiation sources in containment conditions is studied using EXSI-CONT and BESSEL facilities. The objective is to verify the possible oxidation of iodine into particles and also the formation of nitric acid. The fourth aim is to study the "pool scrubbing" of fission products in the water pools of containment building. The objective is to widen the knowledge towards conditions which are not well-known and to enhance source term calculations. In addition, the gathered data in all experiments is used to derive models for the studied reactions, which can eventually be implemented in severe accident analysis codes.

International collaboration is also conducted by participation in the work of OECD/NEA STEM-2, OECD/NEA BIP-3 (both started in 2016) and NUGENIA programmes. The data of experiments performed as part of SAFIR2018 will also be shared within these forums, as well as information related to the progress of programmes will be distributed to SAFIR2018 members.

#### **Specific goals in 2017**

The main goal in 2017 was to study the effect of reactions of iodine containing deposits on primary circuit surfaces on the release and transport of iodine. Fission product deposits on

primary circuit surfaces can act as a source of gaseous iodine even in the late phase of a severe accident. However, that is not considered in the severe accident analysis codes currently. The primary circuit experiments were conducted using the updated EXSI-PC facility.

The second goal was to study the formation of nitric acid ( $\text{HNO}_3$ ) by radiation. The aim was to verify the capability of beta radiation to produce nitric acid in humid air simulating containment conditions in a severe accident. The objective was to compare the results with the previous gamma radiation results. The third goal was to study the effect of  $\text{HNO}_3$  generated by beta radiation on the pH of containment pools. This was performed utilizing the data of experiments (in the above task) in ChemPool calculations. The effect of beta radiation e.g. on the formation of nitric acid is currently poorly known, although beta decay corresponds for a significant fraction of the accumulated radiation dose in the containment atmosphere. As a fourth goal the retention of aerosols and gaseous organic iodine in the containment pool was studied. The experiments were performed at pool temperatures up to boiling point, since the existing data is mainly limited to studies at 20 °C. The performed aerosol experiments were simulated with ASTEC and MELCOR codes in collaboration with CASA project and the experimentally and analytically obtained decontamination factors were compared. This task also takes part to the NUGENIA TA2.4 area IPRESKA project dedicated to pool scrubbing research internationally.

Another goal was to continue the follow-up of the OECD/NEA STEM-2 and OECD/NEA BIP-3 programmes. The durations of programmes are four years and three years, respectively. The programmes will e.g. verify the findings of the CATFIS project in ruthenium chemistry, and also produce complementary and new data on ruthenium transport in the RCS and on iodine behaviour in the gas phase of containment building and on the painted containment walls. A significant part of the programmes is to compare the performance of various severe accident analysis codes and the user effect.

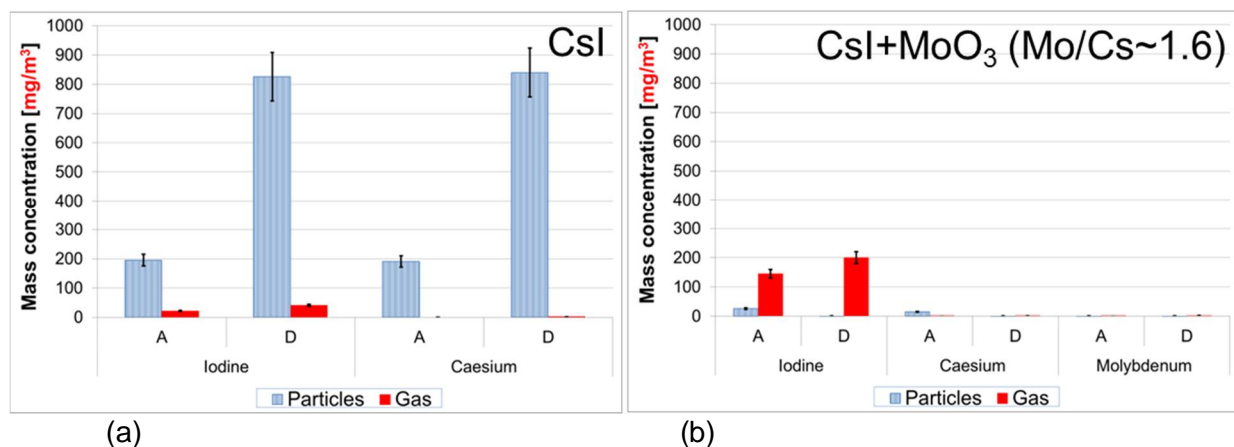


Figure 2.2.2.1. The transported mass concentrations [ $\text{mg}/\text{m}^3$ ] of iodine, caesium and molybdenum in gaseous and aerosol forms under A: Ar/ $\text{H}_2\text{O}$  and D: Ar/Air atmospheres. When the Csl precursor was heated to 650 °C (a), iodine was mainly transported as aerosol. With the addition of molybdenum (b) the release of iodine in aerosol form decreased notably, at the same time the amount of iodine in gaseous form became significant.

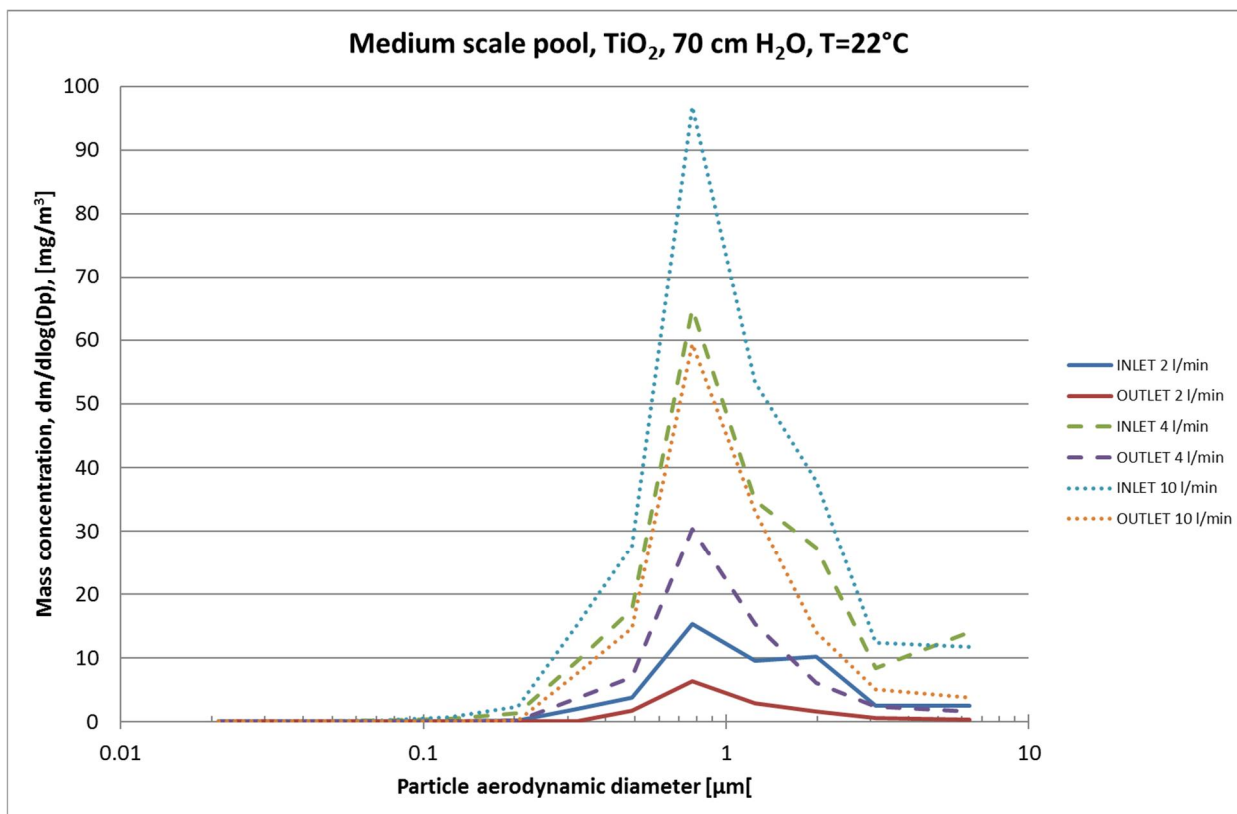


Figure 2.2.2.2. The retention of insoluble aerosol ( $\text{TiO}_2$  in this experiment) in containment pool was examined with the medium scale pool facility. The pool depth was 70 cm and the temperature of water pool and air entering the pool was 22 °C. The air flow rate transporting the particles into the pool was varied from 2, 4 to 10 l/min. The mass size distributions of  $\text{TiO}_2$  particles at the inlet and outlet the pool were measured with ELPI. The mass median aerodynamic diameter (MMAD) of particles at the inlet of pool was 800 nm. On the basis of ELPI measurements, the decontamination factor (DF) for particles decreased from 3.3, 2.7 to 1.9 when the flow rate was increased. MELCOR simulations resulted in comparable DF results with the experimental ones, whereas ASTEC simulations resulted in lower DFs.

## Deliverables in 2017

- In the primary circuit studies the source of iodine was CsI powder which was evaporated at 650 °C on ceramic surface under Ar/ $\text{H}_2\text{O}$  and Ar/Air atmospheres. The surface of the reaction furnace tube, made of stainless steel, was pre-oxidized before the experiments. Two mixtures of CsI with  $\text{MoO}_3$  (molar ratios Mo/Cs = 1.6 and Mo/Cs = 5) have been tested for each atmosphere composition. To summarize the main outcome of experiments, a notable release of gaseous iodine from CsI powder was observed at 650 °C when molybdenum was added to caesium iodide as precursor, whereas in the experiment with CsI only the aerosol fraction was dominating the release, see Figure 1. The release of gaseous iodine was higher when the oxygen partial pressure was higher (i.e. for Ar/Air atmosphere). The formation of caesium molybdates was identified in the crucible after the experiments, confirming that the reaction between caesium and molybdenum was the reason for the observed formation of gaseous iodine. In addition, the gaseous iodine fraction, experimentally assessed to be higher than 84.9 %, was mainly under molecular iodine form ( $\text{I}_2$ ). A conference paper for the International Congress on Advances in Nuclear Power Plants (ICAPP 2018) was written and reviewers selected it as a candidate for the best paper.
- Two scientific publications concerning the studies of boron effect on the iodine chemistry in primary circuit were accepted for publication in Nuclear Technology.

- The formation of nitric acid by beta irradiation in humid air simulating containment conditions in a severe accident was experimentally verified. The experimental results were used to determine a G-value (radiolytic-yield value, molecules formed per 100 eV of energy absorbed) for the formation of  $\text{HNO}_3$  by beta radiation. As a result, the  $G(\text{HNO}_3)$ -value was determined for the first time considering beta radiation in the containment gas phase. The result was compared with gamma radiation in similar conditions, it seemed that beta radiation resulted in a slightly higher G-value, although considering the uncertainties of experiments both values are practically the same. The obtained new G-value was utilized in the ChemPool code analysis on the containment pool pH evolution in a severe accident. The investigated accident scenario was a total blackout and a big break LOCA in the cold leg of a PWR. Specific estimation on the evolution of pH in pools was given for pools with relatively large water content ( $> 10000 \text{ kg}$ ): “CV304 Upper compartment” and “CV310 Annular compartment”. In both cases, the obtained new  $G(\text{HNO}_3)$ -value resulted in a significant decrease of pH to a level of pH 2 to 3. As pH drops the formation of molecular iodine ( $\text{I}_2$ ) begins in the pools. For  $\text{pH} < 3$ ,  $\text{I}_2$  is the dominant form of iodine. In acidic conditions volatile form of radioactive iodine could be formed and released into atmosphere. This result was significant and the potential release of iodine from the pools was indicated.
- Two experimental setups simulating small and medium scale pools were built to study NPP containment pool efficiency in the retention of fission products as aerosol particles and gaseous compounds. The experimentally determined decontamination factor (DF) increased with the increasing pool depth (up to 70 cm pool depth used in the experiments) and decreased with the increasing air flow rate through the pool (see an example in Figure 2.2.2.2). In general, integral codes resulted smaller DFs than recorded in the experiment. This is conservative what comes to the potential source term. ASTEC V2.0 and MELCOR simulations were in a good agreement with the experiments about the DFs for non-soluble aerosols. ASTEC V2.1 resulted the smallest DF values. With pool temperature near to the boiling point, ASTEC V2.1 overestimated the DF values notably. This behaviour is not yet explained. DF decreasing with the decreasing pool depth and increasing flow rate was confirmed in most of the analysed cases. DF dependence on the pool temperature seems to be a bit more complicated issue. At temperatures clearly below the boiling point, the DFs increase with increasing temperature also in the simulations (as in the experiments).
- The “kick-off” meeting of NUGENIA TA2.4 area IPRESKA project dedicated to pool scrubbing research internationally was participated.
- The results of ruthenium studies obtained in the SAFIR2014/SAFIR2018 programs, partly in NKS collaboration with Chalmers, have been presented in the NENE2017 conference.

### 2.2.3 COVA - Comprehensive and systematic validation of independent safety analysis tools

The COVA project aims at developing and promoting a rigorous and systematic approach to the procedures utilized in validation of independent nuclear safety analysis tools. The process enhances the expertise in thermal hydraulic area of Generation II and III LWR reactors and includes as an essential part training of new experts to this relevant area of reactor safety. Main part of the work is carried out with the system-scale safety analysis tool Apros that has been developed in Finland in cooperation between VTT and Fortum and that is currently used in safety analysis work both at the regulatory side and by Finnish utilities Fortum and TVO. The U.S. NRC's TRACE code that is currently used by VTT for the Finnish regulatory body STUK provides suitable benchmark in the validation process as an independent, widely used and well validated safety analysis tool. Participation in international

research projects related to nuclear safety research in the field of thermal hydraulics forms an essential part of the project: experimental data produced in these activities is directly utilized in the validation work carried out within COVA, and on the other hand, these validation activities support conduction of the experiments, in addition to promoting international cooperation and networking in the field of nuclear safety research.

COVA is divided into four work packages: Validation matrices, Analyses of new experiments, Management and international cooperation and Participation fees. The actual research work dealing with analysis tool validation is carried out in the first two work packages, with the first one concentrating on the fundamental aspects of the validation work with Apros, and the second in application of Apros and TRACE to validation using primarily integral-scale experiments. Third work package contains all the administrative work in the project and all costs arising from participating in the international projects and reporting of their results to the Finnish research community, with the exception of the participation fees. The fourth work package includes the participation fees of international research projects and nothing else.

### **Specific goals in 2017**

Assessment of Apros' validation base was performed in the first year of COVA and in 2017 analyses were performed in order to fill the validation gaps identified in the TH and containment model's assessment reports.

Christensen subcooled boiling experiments have been calculated in a master's thesis work that started in 2017 and will be finished in the 2018 project. In this work a subcooled boiling for Apros is being developed.

The ISP-47 was conducted to assess the capabilities of Lumped Parameter (LP) and Computational Fluid Dynamics (CFD) codes in containment thermal-hydraulic simulations and the experiments were done in three separate test facilities: TOSQAN, MISTRA and ThAi. TOSQAN experiment involving wall condensation, steam injection in air/helium atmospheres and buoyancy was simulated using the Apros containment package. Major differences were noticed using different calculation options. The effect of the convection correlation used in the heat transfer calculation was also studied.

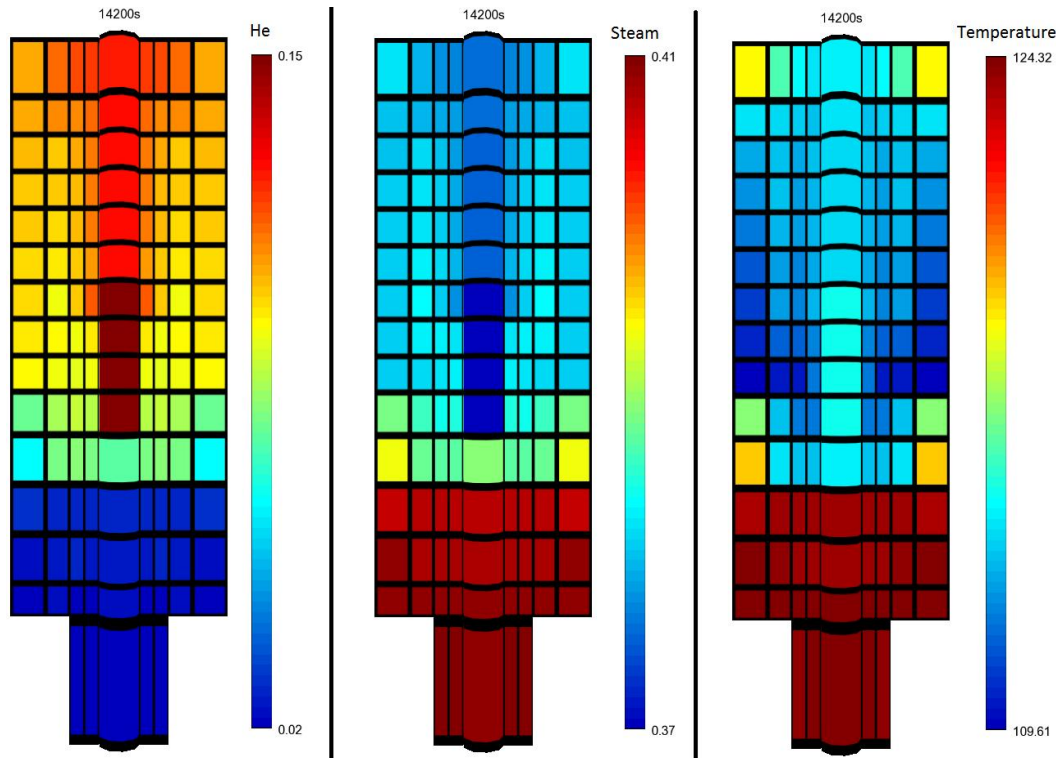


Figure 2.2.3.1. Visualization of ISP-47: Helium and steam concentrations & gas temperature.

A natural circulation flowmap test (PKLIII NC-flowmap) was performed at PKL facility as part of the OECD/PKL4 project. The Apros model of the facility was updated in Apros 6.07 environment and tuned with initial boundary conditions of the test. Comparing experimental and calculation results one can conclude that SG behaviour was predicted well by calculation considering primary levels and reverse flows in certain U-tube groups.

HYMERES/PANDA HP6\_2 test was calculated with Apros containment. The general objectives of the HP6 series tests were to investigate gas transport and related natural circulation flow with consequent homogenization of the hydrogen stratification (simulated with helium) in a multi-compartment containment. The goal of the work was to study the capability of a LP approach used in the Apros containment library to model the steam and helium stratification and homogenisation of stratified gas mixture in a multi-room geometry due to natural circulation flow. Two different nodalisations were made for Apros model. The final conclusions of the work are that the pressure history and natural circulation flow pattern could be simulated qualitatively well with Apros.

NEPTUN reflooding experiments 5050 and 5052 were calculated with TRACE V5.0 Patch 5. The work was an in-kind contribution to USNRC CAMP program and was reported in NUREG-IA format. Calculation results were compared to experiment data received from OECD/NEA databank.

In FONESYS program the FO-02 critical flow benchmark, originally started in 2015 and extended in 2016, was further extended in 2017. A subset of this quite extensive benchmark has been calculated COVA.

Five international cooperation programmes were followed in COVA project. These were OECD/NEA PKL-4, HYMERES and WGAMA, USNRC CAMP and FONESYS network.

Participation fees were paid for OECD/NEA HYMERES Phase 2 and USNRC CAMP.

**Deliverables in 2017**

- A presentation of the master's thesis work was given in RG4 meeting 3/2017.
- A research report on PKLIII NC-flowmap test.
- A research report on ISP-47 TOSQAN experiment.
- A research report on HYMERES/PANDA natural circulation test HP6\_1.
- NUREG-IA series publication on NEPTUN reflooding experiments.
- A research report on Boivin critical flow experiments.
- FONESYS paper on hyperbolicity and numerics in SYS-TH codes was accepted as an extra deliverable in RG4 meeting 3/2017. The paper is co-authored by Markku Hänninen (retired), the former VTT's representative in FONESYS network.

**2.2.4 INSTAB - Couplings and instabilities in reactor systems**

The INSTAB project aims to increase understanding of the phenomena related to BWR pressure suppression function to enhance capabilities to analyse Nordic BWR containments under transient and accident conditions. Particularly, additional information is needed on the effect of Safety Relief Valve (SRV) spargers, residual heat removal (RHR) system nozzles, strainers and blowdown pipes on mixing and stratification of the pool as well as feedbacks between wetwell water pool and spray i.e. formation and mixing of thermally stratified water layers in the suppression pool due to spray operation. A combined experimental/analytical/computational program is carried out where Lappeenranta University of Technology (LUT) is responsible for developing an experimental database on pool operation related phenomena in the PPOOLEX test facility with the help of sophisticated, high frequency measurement instrumentation and high-speed video cameras. LUT, VTT and KTH will use the gathered experimental database for the development, improvement and validation of numerical simulation models. The project outcome will allow the end users to analyse the risks related to different scenarios of safety importance in the drywell and wetwell compartments of a Nordic BWR.

**Specific goals in 2017**

Specific goals in 2017 included a test with the SRV sparger in the PPOOLEX facility after the sparger first had been moved to the center position in the pool. SRV sparger studies were also conducted with a small-scale separate effect test facility enabling a direct measurement of force induced by steam injection. In addition, wetwell spray injection tests, where mixing of a stratified wetwell pool by spray injection from above was studied, were carried out. The main motivation for all these tests was to support the development and validation work of the Effective Heat Source (EHS) and Effective Momentum Source (EMS) models being done at KTH. Experiment results obtained in the INSTAB project are extensively utilized also by LUT and VTT in parallel SAFIR2018 projects for the development/validation work of direct contact condensation (DCC) models to be used in CFD codes such as NEPTUNE\_CFD and OpenFoam.

The pressure suppression pool in a BWR serves as a primary heat sink during a loss of coolant accident (LOCA) or in case the reactor is isolated from the main heat sink. The pool

surface temperature defines the saturation steam pressure in the containment. Steam condensation creates a source of heat in the pool. In case of small steam flow rates, thermal stratification could develop and significantly impede the pressure suppression capacity of the condensation pool. Experimental studies have shown that once steam flow rate increases significantly, momentum introduced by the steam injection and/or periodic expansion and collapse of large steam bubbles due to DCC can destroy stratified layers and lead to mixing of the pool water. Accurate and computationally efficient prediction of the pool thermal-hydraulics with thermal stratification, mixing, and transition between them, presents a computational challenge.

KTH is developing the EHS and EMS models and implementing them in GOTHIC code. The models aim to capture thermal stratification and mixing phenomena in a large pool of water. They can be implemented also in system codes, such as APROS. The models have already been validated against PPOOLEX experiments where the dynamics of free water surface in the blowdown pipe with different steam mass flow rates and transient times was studied. KTH is now extending the validity of the EHS and EMS models to spargers, RHR nozzles and sprays.

In 2017, the SRV sparger in the PPOOLEX test facility was moved to a centre position in the pool. Originally, it was about 0.42 m away from the pool centre axis. A characterizing sparger test was then done to find out how the change in the sparger position affects stratification/erosion/mixing behaviour during steam discharge via the sparger pipe. Particularly, the effect on the elevation and thickness of the thermocline between the cold and warm water volumes and on the temperature profile of the pool were of interest.

The general behaviour during the stratification/erosion/mixing phases is almost identical in the new sparger test and in the earlier reference test. The initial uniform temperature profile first changes to a stratified situation and eventually back to an almost uniform and mixed situation at the end of the final mixing phase (Figure 2.2.4.1). During the erosion phase the thermocline moves slowly downwards and the thickness of the transition region seems to be almost the same as in the reference test. The moving of the sparger pipe to the centre axis of the pool, however, seems to have a slight effect on the elevation of the thermocline as well as on the temperature profile in the pool. The thermocline settles at the end of the stratification phase about 150-250 mm deeper if the sparger pipe is in the centre of the pool compared to the situation where the sparger was about 420 mm away from the centre axis.

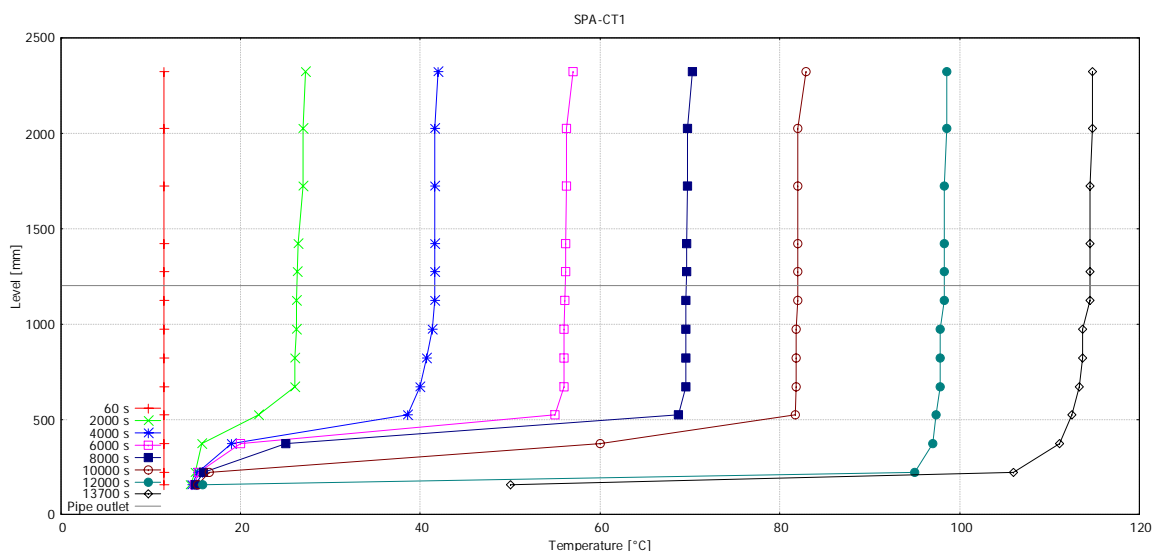


Figure 2.2.4.1. Development of vertical temperature profile in suppression pool in a PPOOLEX sparger test.

The separate effect test facility, SEF-POOL, was designed together by KTH and LUT. It was constructed by the nuclear engineering research group at LUT and it is aimed to be used for the validation of the EMS model proposed by KTH for simulation of steam injection into a pool filled with sub-cooled water. The model have been validated against the PPOOLEX experiments with blowdown pipes and are now being extended to SRV spargers.

The main parts of the separate effect test rig are the sparger piping and condensation pool (Figure 2.2.4.2). The sparger pipe is pivoted on a vertical axis with low friction bearings in order to allow direct force measurement. The lower end of the sparger pipe mounts a flow plate with injection holes and a polycarbonate (PC) pipe. Steam is discharged through the injection holes and it condenses inside the PC pipe. The purpose of the PC pipe is to act as a propulsion volume and thus create a parallel flow pattern so that the amount of momentum transferred from the steam to the liquid at the outlet of the PC pipe can be estimated.

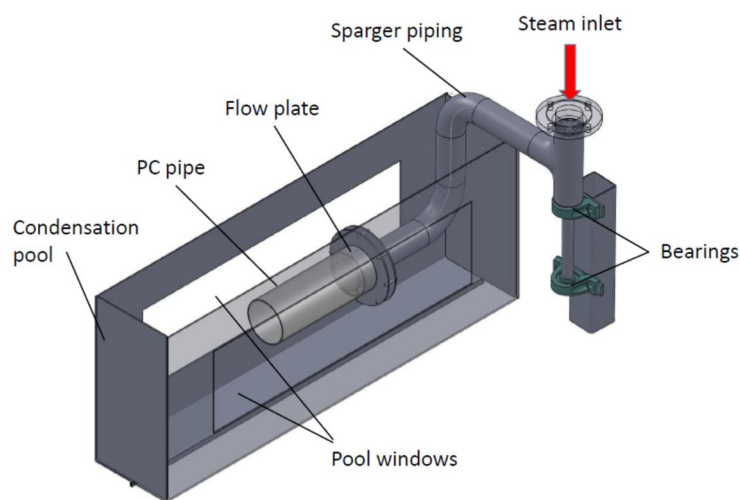


Figure 2.2.4.2. General view of the SEF-POOL test facility.

Preliminary/characterizing tests were conducted with the SEF-POOL facility during the latter part of 2017. Steam-to-water and water-to-water injections were done. One test was done with water injection into an empty pool (Figure 2.2.4.3). The main goal was to test different options for the force measurement and to provide data for KTH for preliminary comparison of theoretical effective momentum with values calculated based on directly measured force.

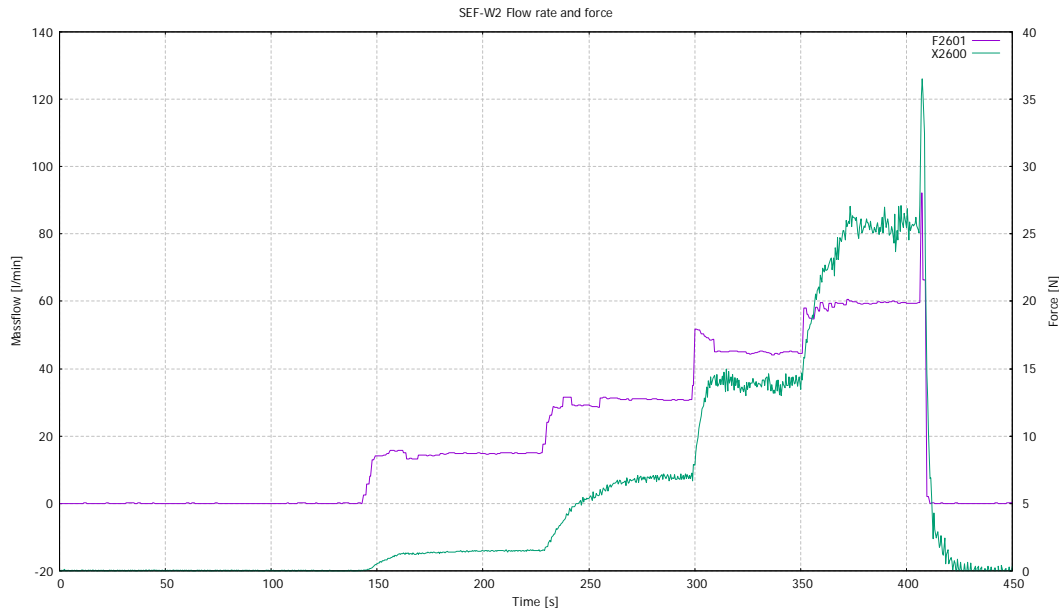


Figure 2.2.4.3. Water flow rate (F2601) and corresponding force (X2600) in a water-to-water injection test in the SEF-POOL facility.

Analysis of the tests by KTH showed that the steam momentum can be roughly predicted by the theoretical estimate and the frequencies obtained with the fast pressure transducer correlate well with the correlations proposed in the literature. A strong temperature dependence, i.e. larger momentum as the pool temperature increases, was noticed. Some deviations between theoretical and experimental momentum values, however, were encountered. Proper design for the test facility needs to be found before the actual tests to be used for the validation of the EMS model can be carried out in 2018.

Mixing of a thermally stratified pool with the help of spray injection from above was studied in four PPOOLEX experiments. An effort to characterize developing flow fields in the mixing region with the help of the PIV measurement system was made although it was known that setting up the PIV system inside the PPOOLEX test facility is challenging in many ways.

The tests revealed that cold spray water first penetrated the water surface causing mixing in the top layers. Then an internal circulation process took place in the pool at the elevation of the thermocline between the cold and warm water as the cold and therefore more dense sprayed water pushed its way downwards. Most of the pool water volume mixed during the tests as the downwards penetrating mixing process continued.

For the analysis of the PIV results, all the tests could be separated to three phases. In first phase, the movement of the particles is minor and thus the velocities are very small. The whole particle ensemble moves in unison and there are indications that there is no mixing involved. The second phase covers the time period when the optical environment does not suit the PIV measurement at all. The last phase starts after the mixing has occurred in the PIV measurement area and the optical environment enables PIV to be executed to some extent in a normal manner by averaging velocity fields. Figure 2.2.4.4 presents an averaged velocity vector field from the latter part of a spray test when the mixing region has already passed the PIV measurement area. Figure 2.2.4.5 shows the magnitude of turbulence intensity from the same period.

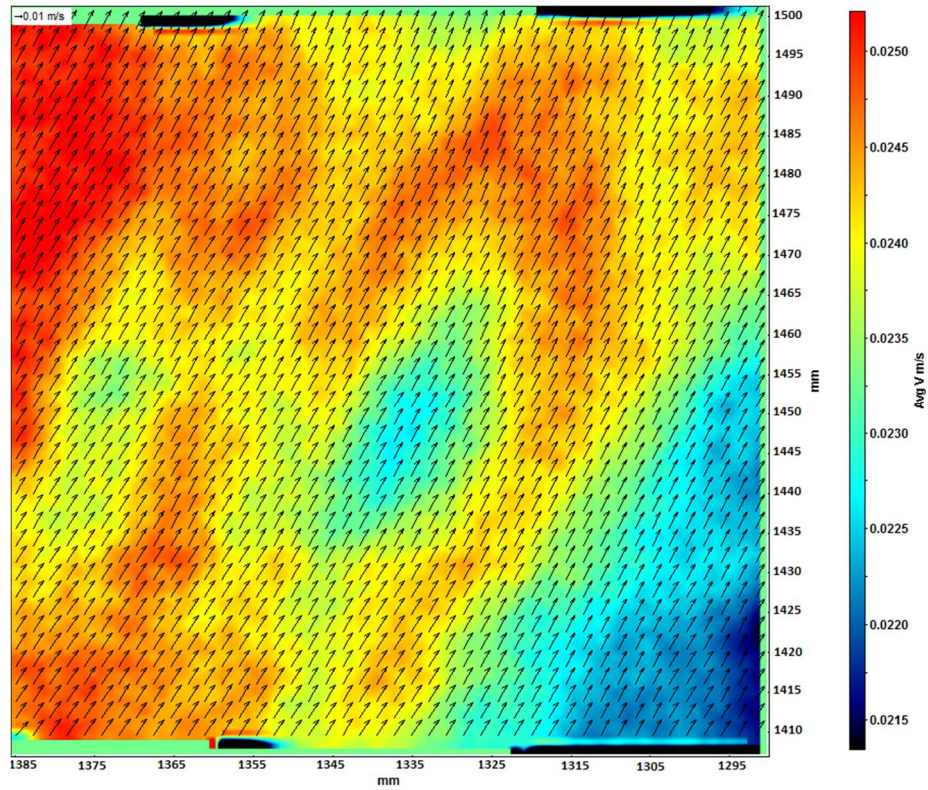


Figure 2.2.4.4. Averaged velocity vector field of PIV measurement from a spray test in PPOOLEX.

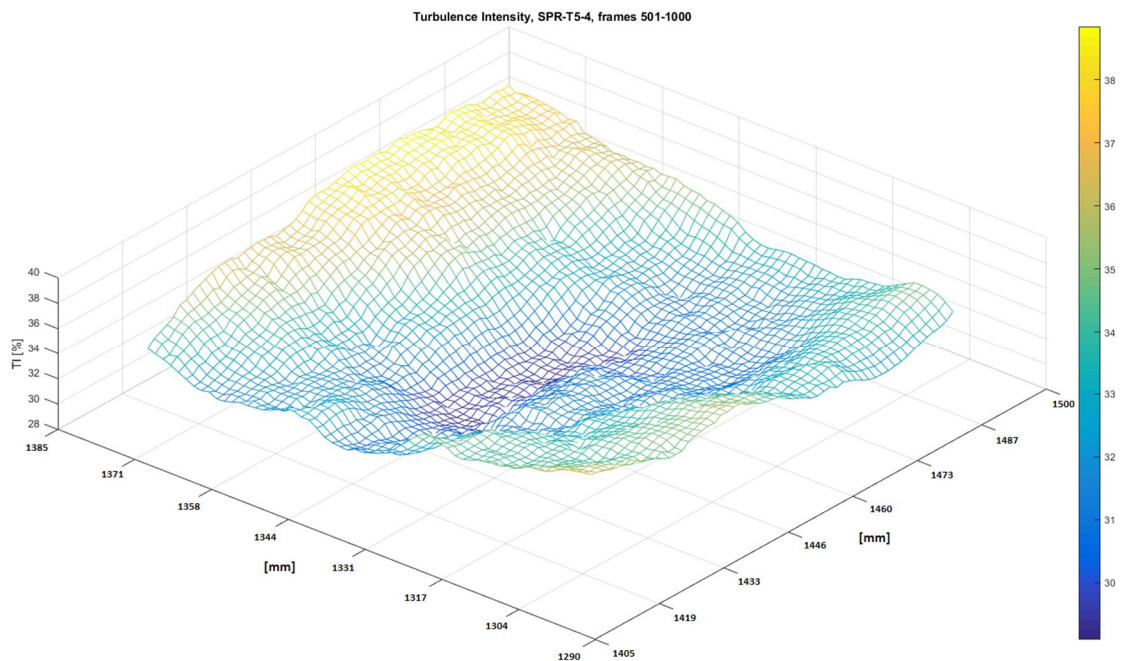


Figure 2.2.5.5. Turbulence intensity field of PIV measurement from a spray test in PPOOLEX.

## Deliverables in 2017

- The SRV sparger in the PPOOLEX test facility has been moved to a centre position in the pool. The effect of the change in the sparger position on stratification/erosion/mixing behaviour during steam discharge via the sparger pipe has been studied in a characterizing test and compared to a reference test done with the sparger away from the pool centre.
- A separate effect test facility, SEF-POOL, has been constructed at LUT. It will be used for the validation of the EMS model proposed by KTH. A series of preliminary/characterizing tests including steam and water injection cases has been conducted with the SEF-POOL facility.
- Mixing of a stratified pool by spray injection from above has been studied in test series in PPOOLEX. An effort to characterize developing flow fields in the mixing region with the help of the PIV measurement system has been made. Difficult optical environment enabled PIV to be executed in a normal manner only outside of the mixing region i.e. before or after the mixing region had passed through the PIV measurement area.
- A literature survey of existing experiment data and models for noncondensable dissolution/release dynamics has been done.
- Master's thesis on steam sparger modelling for boiling water reactor suppression pool has been published at Lappeenranta University of Technology.
- Journal article on thermal stratification and mixing in a condensation pool induced by direct steam injection has been published in Annals of Nuclear Energy.

### 2.2.5 INTEGRA - Integral and separate effects tests on thermal-hydraulic problems in reactors

The objective of the project is to improve the understanding of thermal-hydraulic system behavior by performing integral and separate effects tests, in particular regarding the impact of non-condensable gases on core cooling and reliability of natural circulation loop decay heat removal. Carefully designed experiments are the most reliable way to obtain fundamental understanding and reliable data of the phenomena. This data will be used in the development and validation of computer codes for the safety analyses of nuclear power plants. Computer analyses with system and CFD codes are needed in the planning of the experiments as well as in post analyses to help understanding the physics in the experiments.

LUT participates in the OECD/NEA PKL Phase 4 project (2016-2020) with PWR PACTEL experiments. The OECD/NEA PKL Phase 4 project is performed with the financial support of the Finnish Research Programme on Nuclear Power Plant Safety (SAFIR2018), the Finnish power company Teollisuuden Voima Oy (TVO), and the partners participating in the OECD/NEA PKL Phase 4 project. The authors are grateful for their support to OECD Nuclear Energy Agency (NEA), the members of the SAFIR2018 Reference Group 4 and the members of the Program Review Group and the Management Board of the OECD/NEA PKL Phase 4 project. The data from the experiments in the OECD/NEA PKL Phase 4 project will be available to the NEA member countries via their CSNI representative organizations three years after the end of the project.

## Specific goals in 2017

Specific goals in 2017 were to perform tests studying the flow reversal due to a pump trip and to construct a test system to investigate the fundamentals of the open natural circulation heat removal system.

Tripping of a reactor coolant pumps causes asymmetric flow conditions in primary loops as well as in a reactor core. A flow reversal occurs in the affected loop due to the reversal of the pressure distribution in the loop caused by the other running pumps. The final flow conditions are characterized by a slight overflow in the intact loops and a backflow in the loop with the idle reactor coolant pump. In the INTEGRA project, the phenomenon was studied experimentally with the PWR PACTEL facility. The plans were done in cooperation with TVO and with help of pretest calculations using APROS and TRACE codes. Two experiments were carried out in 2017. The experiments were otherwise similar to each other but the core power level after the pump trip was different. The analyses and reporting of the experiment results are planned to year 2018.

At LUT a model of an open type passive heat removal loop (PASI), with open pipeline connections to the water pool, was constructed according to the reference passive containment heat removal system. This type of passive system is designed also for the planned Hanhikivi unit in Finland, i.e. for the AES-2006 type nuclear power plant design. The functioning of the PASI facility is based on natural circulation. With the PASI facility, the goal is to make tests to measure system performance characteristics, and to detect issues that could disturb the operation of a passive system or prevent it from functioning as designed. The PASI test facility consists of a pressure vessel simulating containment conditions, a heat exchanger, a water pool and interconnecting riser and downcomer pipelines. Additional systems are included to provide steam, collect condensate water, remove heat and inject feed water. An aerosol injection system can be added to the system in future. The facility is ready for characterizing tests in 2018.

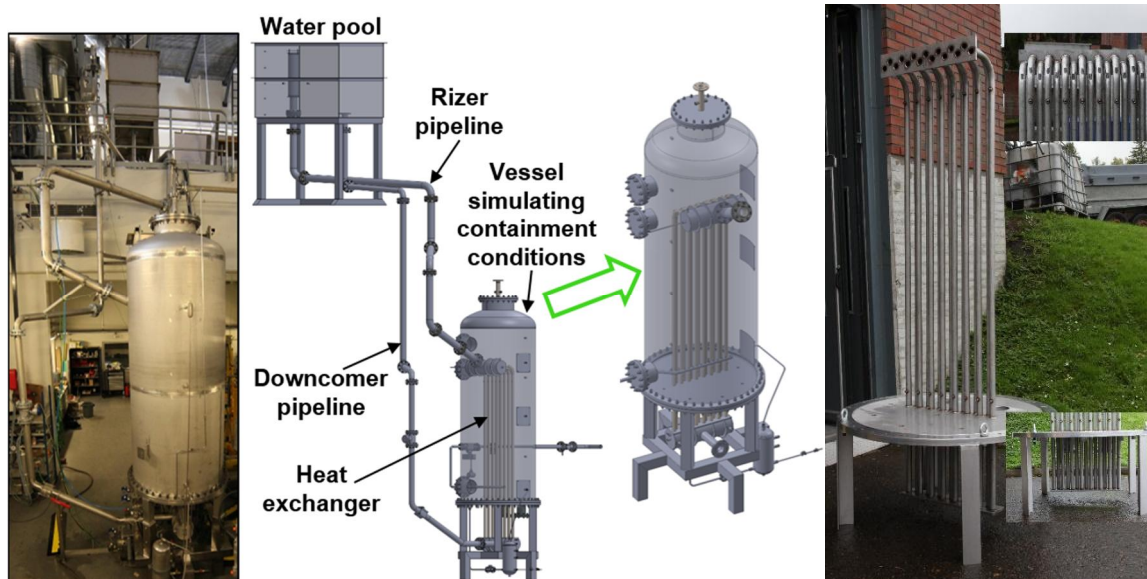


Figure 2.2.5.1. PASI test facility.

The PWR PACTEL experiments in the OECD/NEA PKL Phase 4 project have been planned with assist from the pretest calculations using APROS and TRACE codes. The first experiment will be in 2018 and the other experiment in 2019.

## **Deliverables in 2017**

- Participating in the OECD/NEA PKL Phase 4 project
- Experiment results of the flow reversal due to a pump trip
- Facility description of the system designed for studies on passive heat removal system operation (published in January 2018)
- Journal article “Experimental observation of adverse and beneficial effects of nitrogen on reactor core cooling” (under review process in Nuclear Engineering and Design)

### **2.2.6 KATVE - Nuclear criticality and safety analyses preparedness at VTT**

The general objective of the KATVE project is to maintain and develop the domestic competence in various nuclear safety analyses that may be required by the authority or the utilities. The safety analyses covered in the project are mainly related to reactor physics and radiation transport, but also heat transfer and fuel integrity analyses are included in a comprehensive safety study of a dry storage cask, which will be completed during the four-year project. In practice, the KATVE project involves development and validation of calculation tools required for safety analyses, studying the domestic and international standards and requirements, and performing practical safety analyses which provide valuable experience for the research personnel.

#### **Specific goals in 2017**

One of the main objectives in the project is the development of radiation shielding functionalities in the Serpent Monte Carlo code. The first code version supporting photon transport and thus allowing gamma shielding calculations was released in 2015. The photon interaction physics was thoroughly tested and the compared against MCNP6 with good results. The work has continued and extended to the transport physics related to severe accident management conditions when the separately proposed new RADICAL project was partly funded and merged with KATVE, effective from the beginning of 2017.

Neutron-rich radioisotopes found in spent fuel decay predominantly through beta decay. As beta particles slow down in matter, they emit bremsstrahlung, which often needs to be taken into account in radiation shielding calculations. The radioactive decay source mode in Serpent was extended to include the beta bremsstrahlung component. A theoretical model for the energy spectrum of beta decay was implemented, as beta spectrum data is not available for all the relevant nuclides. An option for user-defined beta spectrum data was also included. The built-in thick-target bremsstrahlung routine is used for creating the bremsstrahlung photons without simulating electron transport. The beta bremsstrahlung model was compared to Geant4 Monte Carlo code in a simple fuel pin geometry for Sr-90 and Y-90. A good agreement was obtained in the peak regions of the bremsstrahlung spectra. Serpent underestimated the spectra in the high-energy regions, which is most likely due to the limitations of the thick-target bremsstrahlung approximation. The beta bremsstrahlung model was also compared to available beta spectrum data for a few nuclides by calculating effective dose rates around a fuel pin. The dose rates calculated with the Serpent beta spectrum model were a couple of percent higher on average.

To enable a straightforward calculation of effective dose rates with Serpent, built-in ANSI/ANS 6.1.1-1977, ICRP-21 (1971), ICRP-74 (1996) and ICRP-116 (2010) flux-to-effective dose rate conversion factors were added in Serpent. Comparisons with MCNP6

were performed by calculating effective dose rates inside a simple maze geometry using monoenergetic point sources between 100 keV and 10 MeV. Good agreement was obtained in all cases.

Some of the photon physics routines in Serpent were slightly updated. The Compton scattering model was improved by implementing a new interpolation and extrapolation scheme for Compton profiles, which are needed for sampling the energy of a Compton-scattered photon. A new efficient sampling method for the direction of photoelectrons was also developed. These and the other photon physics models and methods used in Serpent will be described in a journal article which is expected to be finished in the first quarter of 2018. The work on photonuclear reactions was also started in 2017 by implementing relativistic collision kinematics for discrete inelastic ( $\gamma, n$ ) reactions. Other ( $\gamma, xn$ ) reactions and photofission will be added in 2018.

The Serpent photon physics model was compared to MCNP6 and PENELOPE in order to study the limitations of a photon-only transport mode. As a test case, a monoenergetic unidirectional photon beam was targeted on a small cylinder with a height and diameter of 5 cm, and the spectra of photons emitted through the surfaces of the cylinder were tallied. Lead and water were used as test materials. Good agreement was obtained below 1-2 MeV, but at higher energies electrons and positrons created in photoatomic interactions have to be taken into account. One major source of error in this type of calculation is that the angular distribution of bremsstrahlung photons is neglected in Serpent (and also in MCNP in photon-only transport mode). The possibility for improving the thick-target bremsstrahlung approximation could be studied in the future.

Serpent's newly developed variance reduction techniques have been tested by calculating photon dose rate and neutron flux on the surface of a castor storage cask. The cask was filled with burned UO<sub>2</sub> or MOX assemblies at different burnups and decay times. The figure of merit, FOM, of the calculations with and without variance reduction has been compared. In the case of photon dose rate, variance reduction improved FOM by several orders of magnitude compared to calculations without variance reduction for both fuel types. For neutron flux, FOM was approximately three times larger with variance reduction than without it. The castor storage cask absorbs photons considerably more effectively than neutrons and therefore the advantage of variance reduction is even more pronounced in the photon transport calculations. The photon dose rates and neutron flux calculated with variance reduction corresponded to the values calculated without variance reduction within relative standard deviation for most calculated cases. The differences in some cases between the results with and without variance reduction are most likely mainly caused by poor statistics of the calculations without variance reduction.

Another main objective was to analyse the heat transfer in a dry storage cask filled with spent nuclear fuel. The first goal of the analysis was to determine the largest cladding temperature within the storage cask, which was performed in 2015. The next step, performed in 2016, was to determine the temperature distribution at various time points up to 300 years after discharge. The information calculated so far was used in fuel integrity analyses in 2017. The decay heat source for the heat transfer was obtained through 3D fuel assembly burnup calculation with Serpent. The BEAVRS benchmark was found to provide a suitable model for the calculation. The CFD heat transfer analysis was performed with OpenFOAM for a CASTOR-V/21 dry storage cask, filled with 21 of the spent PWR assemblies. When the peak cladding temperature (PCT) of the stored fuel pins was calculated, the specific question was whether the PCT would remain below the 400°C limit suggested in the U.S.NRC guidelines. According to the calculations, the limit is fulfilled as far as the fuel is not stored into the dry cask earlier than 3.4 years after discharged from the reactor.

The main parameters of interest in the last stage of the analysis were the cladding creep hoop strain and stress during dry storage. VTT-ENIGMA was employed in the analysis and the parameters of interest were evaluated with the help of EDF and CIEMAT correlations.

The developed analysis methodology helps to ensure the safety of long-term dry storage, but validation of the calculation chain against experimental data is still needed.

Performing valid criticality safety analyses requires that the calculation system, consisting of a transport calculation code and the cross section library, is validated for the purpose. In practice, this means modelling a large series of critical experiments with the calculation system and comparing the computational results against the experimental data to obtain an estimate for the bias of the system. To automatize the validation of the calculation codes, a validation script is being developed. The script runs a series of calculations with Monte Carlo codes Serpent and MCNP, and automatically analyses the results. The number of criticality experiments included in the validation package has increased every year, and in 2017 the package for Serpent took a major step forward, when 12 sets of MCNP inputs obtained from the Dutch NRG in 2016 were converted for Serpent. Meanwhile for MCNP, 4 sets of critical experiments were modelled, all of them performed in VVER-type reactors. The validation package for Serpent contains more than 400 critical experiments and the one for MCNP slightly more than 100. Particularly the MCNP requires more cases, but it may also be necessary to add new cases to the Serpent package, since the modelled experiments have to be sufficiently similar to the target configuration. The validation script was not modified in 2017, however, several issues for development have been identified.

In order to contribute to the preparedness to use burnup credit in the criticality safety evaluations, Serpent was used in the calculation of the OECD/NEA burnup benchmark phase 6. The benchmark assignment was to computationally repeat the irradiation history of the VVER-440 fuel assembly, from which 8 specimens were taken and radiochemically analysed to determine the spent fuel compositions at various burnup levels. The task provided data to compare the burnup tools of Serpent to experimental measurements.

The primary objective in task performed in reactor dosimetry was to educate a new expert to handle the dosimetry calculation chain after the previous experts had retired or left VTT. VTT's reactor dosimetry tools were applied to a multi-cycle irradiation in the Loviisa-1 reactor. With the premise of educating a new expert, the objective of the work was focused on the use of the PREVIEW computer code (the current standard in VVER dosimetry at VTT), as well as on exploring the new variance reduction features in Serpent 2. Given that accurate activity predictions are a prerequisite for spectrum adjustment, the emphasis was shifted towards understanding how the quality and computational efficiency of Monte Carlo calculations could be improved, rather than on spectrum unfolding itself. The spectrum adjustment program LSLM2 was run, using spectra obtained by PREVIEW as input. The report, however, was focused on activity determinations with PREVIEW and Serpent 2.

Within the field of international collaboration, none of the meetings budgeted in the project plan was attended for various reasons, but the project was informed about the meetings of NEA NSC and WPNCS.

### **Deliverables in 2017**

- A journal article describing the calculation chain from neutronics and fuel depletion calculations to heat transfer (CFD) analysis and finally the fuel integrity analysis in a dry-storage cask was submitted to Annals of Nuclear Energy.
- A conference article was published in proceedings of the M&C 2017 conference describing the development of variance reduction methods in Serpent 2. The article was mostly written in the KATVE2016 project.
- A conference article published in proceedings of the M&C 2017 conference about the development of coupled neutron/photon transport mode into Serpent 2 to expand the

scope of applicability in radiation shielding analysis. The paper was mostly written in 2016 project.

- Report on dosimetry calculations to model surveillance chains irradiated at Loviisa NPP. The calculations were performed with PREVIEW and Serpent.
- Report on test calculations of the beta bremsstrahlung model implemented in Serpent. Comparison calculations were performed against MCNP and Geant4 Monte Carlo codes.
- Report on test calculations with Serpent's burnup and gamma transport calculations, including the variance reduction tools. First, the spent fuel composition were calculated for fuel assemblies that were located into a dry-storage cask. The figure-of-merit of the variance reduction was determined in several combinations of fuel type, burnup level and cooling time
- Status report on the development of the criticality safety validation package for Serpent and MCNP in 2017. The package itself can also be considered a deliverable.
- Report on OECD/NEA burnup credit benchmark calculation to determine a preliminary set of isotopic correction factors for Serpent with the used nuclear data libraries JEFF-3.1.2/3.1.1 and ENDF/B-VII.1.

#### 2.2.7 MONSOON - Development of a Monte Carlo based calculation sequence for reactor core safety analyses

The MONSOON project continues the development of the Serpent Monte Carlo code, started in 2004, and carried out within the previous SAFIR programmes, such as the KÄÄRME project in SAFIR 2014. Compared to KÄÄRME, the work is more focused on a specific field of applications, namely spatial homogenization, i.e. the production of group constants for deterministic fuel cycle simulator and transient codes. The primary objective and expected result is a first of a kind Monte Carlo based calculation tool, capable of performing group constant generation in a routinely manner. The code can be used to complement or even replace current state-of-the-art deterministic lattice physics codes, bringing the advantages of the continuous-energy Monte Carlo method to spatial homogenization.

The methodology implemented in Serpent was largely completed and put to practice during the first two years of the project. The results demonstrated that the Monte Carlo based calculation sequence can be used for producing the full set of homogenized group constants for LWR core calculations at an acceptable computational cost. During the course of the work it was discovered, however, that the accuracy of the full-core calculations was limited by methodological factors. The methods used in VTT's nodal diffusion codes originate from the 1970's, and no longer represent the state-of-the-art in reactor analysis. The accuracy of legacy codes is compromised in particular near sharp material discontinuities such as the core-reflector boundary, near control rod tips, and in modern fuel types with axial profiling.

To overcome this problem, the development of a new nodal diffusion solver called "Ants" was started in 2017. The code relies on Serpent-generated group constants and modern AFEN-FENM methodology, and is capable of handling both square and hexagonal lattice geometries in steady-state and transient conditions. The work is connected to the renewal of VTT's computational system for reactor core safety analyses, which was started in mid-2017 when a new research professorship was established in the field of reactor safety. In practice,

the Ants code forms the neutronics solver in a reduced-order calculation sequence of the “Kraken” computational framework.

Other specific research topics included developing methodologies for 3D homogenization to account for the effects of axial discontinuities in LWR core geometries, and including fuel temperature feedback in assembly burnup calculations, in an effort to study new approaches to state-point parametrization. The project shares topics and collaboration with the KATVE, SADE and PANCHO projects.

The international success of the Serpent code and the importance of developing a fully independent calculation system accompanied by source-code level understanding of the methodology was recognized in the SAFIR 2018 Framework Plan, where it was also recommended that the range of applications should be broadened.

### **Specific goals in 2017**

The project was divided into three main work packages focusing on development, validation and international collaboration.

In 2017 the main focus for code development was turned from Serpent into the Ants nodal diffusion solver. The main goal was to implement the capability to perform full-core steady-state calculations for rectangular-lattice cores in hot zero-power conditions (i.e. without state-point parametrization for cross sections). In order to reach this goal, the work was started with scoping studies to find the best methodology for the solution, followed by the development of a single-node solver, and finally the coupling of these solutions together for the full-core model. The results were validated by comparison to Serpent 3D calculations and other nodal diffusion codes. The work was carried out by two doctoral students and documented in technical reports and a conference paper submitted to the PHYSOR 2018 international conference.

Other topics for code development involve evaluating the effects of simplifications made regarding the assembly fuel temperatures in the generation of group constants for steady-state and transient calculations. The work was started in 2015-2016 with studies involving external coupling between Serpent and the ENIGMA fuel performance code. Major goals for 2017 include moving from Serpent-ENIGMA to Serpent-FINIX coupling and extending the studies to BWR fuels. The work was successfully completed and reported in a conference paper submitted to the international PHYSOR 2018 conference.

The validation task suffered from major budget cuts in 2016, and many of the original goals had to be dropped. In 2017 code validation relied mainly on collaboration with Serpent user organizations, in particular the Helmholtz-Zentrum Dresden-Rossendorf and Westinghouse, Sweden. Unfortunately the starting of these projects was delayed and no major results were yet obtained in 2017. A new project was also started in Fortum, involving the use of Serpent-generated group constants in the HEXBU fuel cycle simulator code. The study involved comparison to a CASMO-HEXBU calculation sequence and the results are reported in a conference paper submitted to the PHYSOR 2018 international conference.

International collaboration involves support and daily interaction with the Serpent users. Forms of interaction include maintaining the Serpent website, discussion forum and on-line wiki, organizing annual user group meetings and participation in the activities of the international reactor physics community. In 2017 this included participation in the ANS Reactor Physics Division meeting in November and the 7th International Serpent User Group Meeting hosted by University of Florida.

## Deliverables in 2017

All tasks planned for 2017 were completed. Specific deliverables are listed below.

- Conference paper on the estimation of the effects of the simplified fuel temperature profiles in BWR group constant generation history calculations was submitted to the PHYSOR 2018 international conference.
- Conference paper on a new stochastic sub-step based burnup scheme for Serpent 2 was submitted to the PHYSOR 2018 international conference.
- Multi-group AFEN-FENM methodology was chosen as the basis of the Ants nodal diffusion solver. The work was reported in a short memo.
- Capability to perform nodal diffusion calculations for rectangular geometries was implemented in the Ants solver. The work is reported in a conference paper submitted to the PHYSOR 2018 international conference.
- A D.Sc. Thesis for Aalto University on the development of multi-physics capabilities in Serpent was completed. The work included multi-physics coupling for burnup calculation, which was one of the topics in the MONSOON project.
- The international Serpent user community grew from 630 users in January 2017 to 760 users by the end of January 2018. The code has users in 194 universities and research organizations in 40 countries around the world. The Serpent website lists some 550 peer-reviewed scientific journal articles and conference papers and 145 theses published on Serpent-related topics worldwide.
- Two source code updates (2.1.28 and 2.1.29) were distributed to Serpent users in 2017.
- The 7th Annual Serpent User Group Meeting was hosted by University of Florida in Gainesville, FL, USA, on November 6-9, 2017.
- Serpent developers participated the M&C 2017 international conference in Jeju, Korea, April 16-20, 2017.
- International collaboration also included participation in the Executive Committee meeting of the Reactor Physics Division of American Nuclear Society in November 2017.
- Writing of a User Manual for Serpent 2 as an on-line Wiki was continued in 2017.
- Several papers from Serpent user organizations were co-authored in 2017.
- Several new capabilities were implemented in Serpent 2 in 2017.
- New neutron cross section libraries were produced for Serpent from the latest evaluated nuclear data files.

## 2.2.8 NURESA - Development and validation of CFD methods for nuclear reactor safety assessment

In the NURESA project, Computational Fluid Dynamics (CFD) methods are developed and validated for the identified most important topics in nuclear reactor safety assessment. In WP2, PPOOLEX spray and stratification experiments are modelled with CFD codes in co-operation with LUT and Swedish partners. In addition, the direct-contact condensation experiments performed with the Separate Effect test Facility of LUT are modelled with CFD calculations. In WP3, CFD models for departure from nucleate boiling (DNB) are developed for the OpenFOAM code in co-operation with international partners. The developed multiphase models and solvers can also be used for other applications of nuclear reactor safety. In WP4, two-way coupled CFD-Apros calculations of nuclear power plant components are performed. WP5 consists of the coordination of the project.

### Specific goals in 2017

In WP2, pre-calculations are performed with ANSYS Fluent for the small-scale Separate Effect Facility of LUT, where steam is injected through a few orifices into water pool (see Figure 2.2.8.1). The calculated condensation rate, pressure oscillation and penetration of the vapor jet into the pool are compared to experiments. In addition, a spray experiment performed with the PPOOLEX facility are calculated with ANSYS Fluent. The water pool is modelled with the Euler-Euler model of Fluent, where droplets are described with the Discrete Particle Model. The effect of the spray droplets on the stratified pool is calculated and the deterioration of the thermal stratification of the pool is studied. The work is done as co-operation of LUT, KTH and VTT.

In WP3, OpenFOAM CFD solver is developed and validated for nuclear reactor safety assessment. At VTT, boiling and condensations models are developed and integrated to the Eulerian multiphase solvers of the official OpenFOAM release. The work is done in co-operation with the OpenFOAM Foundation. At LUT, OpenFOAM simulations of POOLEX chugging tests are done and models for direct-contact condensation are developed and validated.

In WP4, coupled CFD-Apros simulations of NPP components are performed. Earlier, coupled models of steam generators have been developed, where the primary circuit has been modelled with Apros and the secondary side of the steam generator has been modelled with ANSYS Fluent CFD code. In 2017, modelling of the pressurizer of VVER-440 nuclear power plant has been started (see Figure 2.2.8.2). First, models for the heating elements and sprays of the pressurizer are developed. The boiling and condensation models are implemented in the pressurizer model. The model is first verified in simple pressure rise and pressure reduction transients. Later the model will be coupled with the Apros model of a generic VVER-440 nuclear power plant.

In WP5, project coordination is done. In addition, Northnet Roadmap 1 Meetings are participated. Co-operation with international OpenFOAM developers is participated.

## Deliverables in 2017

- Simulations have been performed for the direct-contact condensation pre-test done with the Separate Effect Facility at LUT. In the experiment, steam was injected into water pool through three orifices. The steam jet generated pulsating sources of momentum and heat into the water pool. The heat and momentum sources of the steam jets in the water pool were studied. The two-resistance heat transfer models and the evaporation/condensation models of ANSYS Fluent were used for the modelling of the experiment. The results are used in the analysis of the thermal stratification of pressure suppression pools, which is performed in co-operation of LUT, KTH and VTT.
- Preliminary wet well spray test SPR-T3 performed with the PPOOLEX facility has been calculated with the ANSYS Fluent CFD code. In the experiment, spray was injected from four nozzles into thermally stratified water pool. The deterioration of the thermal stratification of the pool was calculated. The thermal stratification reduces the pressure suppression capacity of the pool.
- At VTT, the subcooled nucleate boiling capability previously integrated to the OpenFOAM Foundation release was extended to polydispersed simulations. The thermal phase change models were generalized from previous two-phase implementation to support any number of phases. Inhomogeneous class method developed by HZDR was integrated into the `reactingEulerFoam` solver framework in co-operation between VTT, HZDR and CFD Direct Ltd. Polydisperse population balance models can now be coupled to any number of phases. The solver was restructured to support multiple simultaneous mass transfer mechanisms in order to support simultaneous use of thermal phase change and an inhomogeneous population balance models. The implemented models are publicly available in OpenFOAM Foundation development repository.
- The functionality resulting solver was verified by simulation of one-, two- and three-dimensional isothermal and subcooled nucleate boiling test cases and isothermal bubbly flow. Figure 2.2.8.2 shows a selection of test simulation variations from 3D simulations of DEBORA5 experiment. All test simulations were completed and the implemented functionality appears to work as intended (see Figure 2.2.8.3).
- At LUT, the Rayleigh-Taylor Interfacial (RTI) area model was included in the OpenFOAM two-phase solver for the interfacial area modeling. The PPOOLEX DCC-05-4 simulation with the RTI model in OpenFOAM had slow convergence and notably short time-stepping was needed. Results of a short simulation run showed that because of interfacial area growth the condensation rate was increased significantly in OpenFOAM simulation with the RTI model (Figure 2.2.8.4). The RTI model enhanced chugging and direct contact condensation (DCC) rate in OpenFOAM simulation and realistic chugging frequencies of 0.5-2.5 Hz were observed. However, the OpenFOAM cases predicted strong interface oscillations of 15-20 Hz (without RTI model) and 35-40 Hz (with RTI model) which did not correspond either to the test or to the NEPTUNE\_CFD simulations. Further, a rapid natural interface oscillation of 50 Hz was absent in the OpenFOAM cases. The DCC rate was still higher in OpenFOAM simulations than in NEPTUNE CFD ones despite the standard  $k-\epsilon$  turbulence model was used. The mixture  $k-\epsilon$  turbulence model seemed to yield occasionally higher turbulence values than the  $k-\epsilon$  turbulence model in NEPTUNE\_CFD. However, it is unclear whether that is the only explanation for different DCC rates. Two preliminary grids of 5 mm grid resolution at pipe outlet have been generated for 2D-axisymmetric simulations of PPOOLEX COL-3 (straight outlet) and PPOOLEX COL-13 (collar outlets) simulations, and simulations will be performed during 2018. Progress report on the DCC simulations of PPOOLEX experiments was written.

- At VTT, CFD model for PWR pressurizer has been developed and adapted to the model of VVER-440 pressurizer. The heater elements were described in a simplified manner as porous zones. Models for bulk evaporation and condensation were implemented by using user-defined functions for two-resistance heat transfer model. Steam tables for vapor and liquid water were implemented by using user-defined real gas model. Simple model for spray was implemented, where droplets are described as an Eulerian phase in the two-phase model. Verification simulation for the model was performed at VTT.
- At Fortum, CFD and Apros simulations of stand-alone pressurizer models were performed. This part of the work is an in-kind contribution of Fortum to the project. First, the geometry and computational grid for VVER-440 type pressurizer for CFD were created. Then simple pressure increase and decrease transient CFD simulations with models developed by VTT were made. Then transient with same boundary conditions was made with stand-alone Apros pressurizer model. Report on the simulation results was written.
- Project was coordinated by VTT. Northnet Roadmap 1 meeting was participated in May. Co-operation with international partners was coordinated in the development of the OpenFOAM multiphase CFD solver.

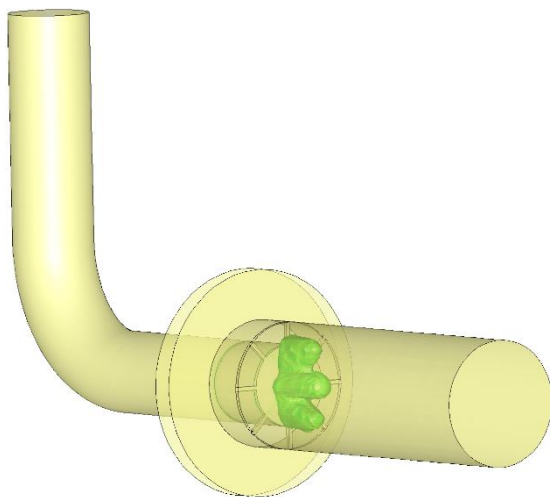


Figure 2.2.8.1. CFD simulation of direct-contact condensation of vapor bubbles in the Separate Effect Facility of LUT. Three vapor bubbles (green) are formed in a tube filled with water.



Figure 2.2.8.2. CFD model of VVER-440 pressurizer. The heating elements are located in the bottom part and the ring for spray injection in the top part of the pressurizer.

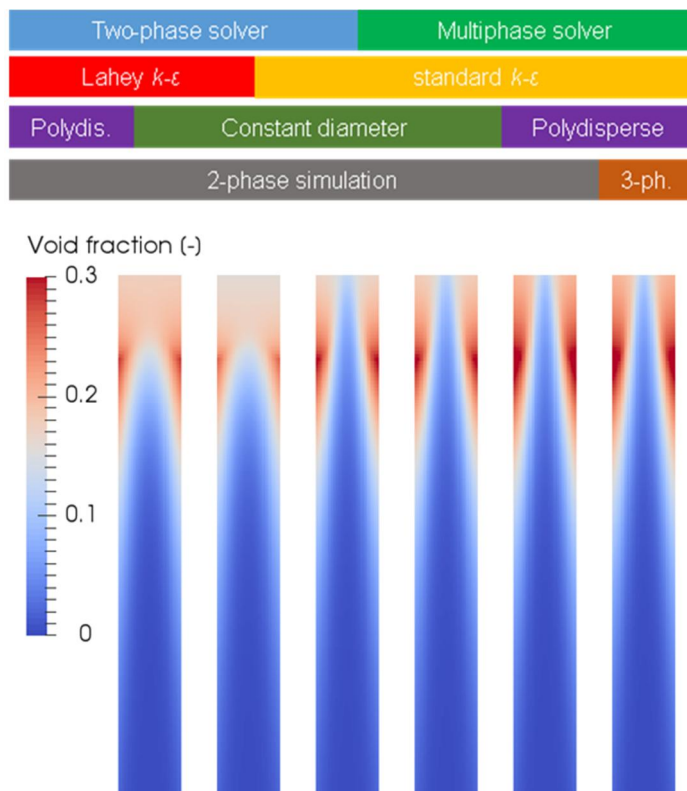


Figure 2.2.8.3. Comparison of void fraction distributions between six different simulation variants of DEBORA5 experiment. Different solvers, turbulence models and bubble diameter models are used as illustrated by the colorbars above the image.

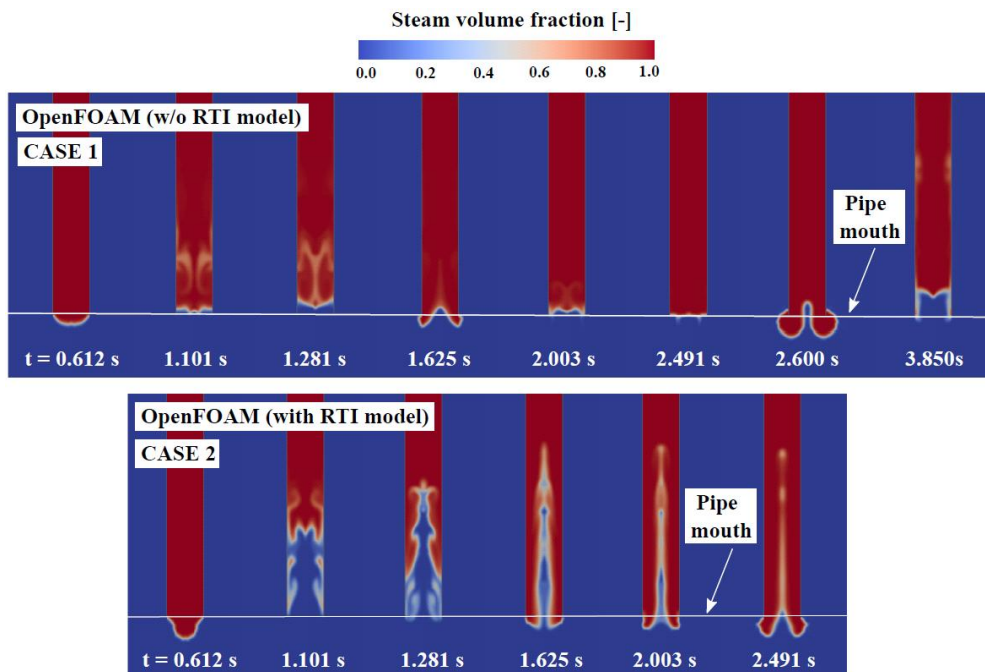


Figure 2.2.8.4. Instantaneous volume fraction fields of steam in the 2D-axisymmetric OpenFOAM simulation of the PPOOLEX DCC-05-4 experiment predicted by the Coste C model.

### 2.2.9 PANCHO - Physics and chemistry of nuclear fuel

Nuclear fuel both produces the energy in nuclear power plants and acts as the first two barriers to the spread of radioactive fission products. The UO<sub>2</sub> matrix of the fuel pellets contains approximately 99% of the born radionuclides, while the cladding tube contains the rest. Therefore the integrity of the fuel during normal operation and accidents is of utmost importance. Traditionally fuel performance has been analysed with integral fuel codes that contain semi-empirical correlations deduced from experiments. These correlations and models become more and more mechanistic as the understanding and the demands increase.

The project PANCHO – Physics and Chemistry of nuclear fuels investigates the integral fuel behaviour as well as combines the experimental and the modelling approaches in studying several topical features of nuclear fuel behaviour. These topics are the chemistry of the fuel pellet and the mechanical response of the cladding.

#### **Specific Goals in 2017**

Focus for 2017 was in development of FINIX fuel code and the validation system, the verification of the coupling of SCANAIR to thermal-hydraulic sub-channel code GENFLO and the review of cladding models suitable for the load follow operation. The international co-operation such as fuel behaviour part of VTT - Halden Reactor Project in-kind work, participation in working groups OECD/CSNI WGFS and ETSON SAG, as well as the following of CABRI progress is done under this project.

#### **Deliverables in 2017**

- Several improvements were made into the FINIX code to better model the steady state irradiation. Originally FINIX was just a transient module, with external initialization at burnup, but with these improvements the steady state irradiation prior to transient can be modelled. Integrated models include cladding creep strain and fission gas release model.

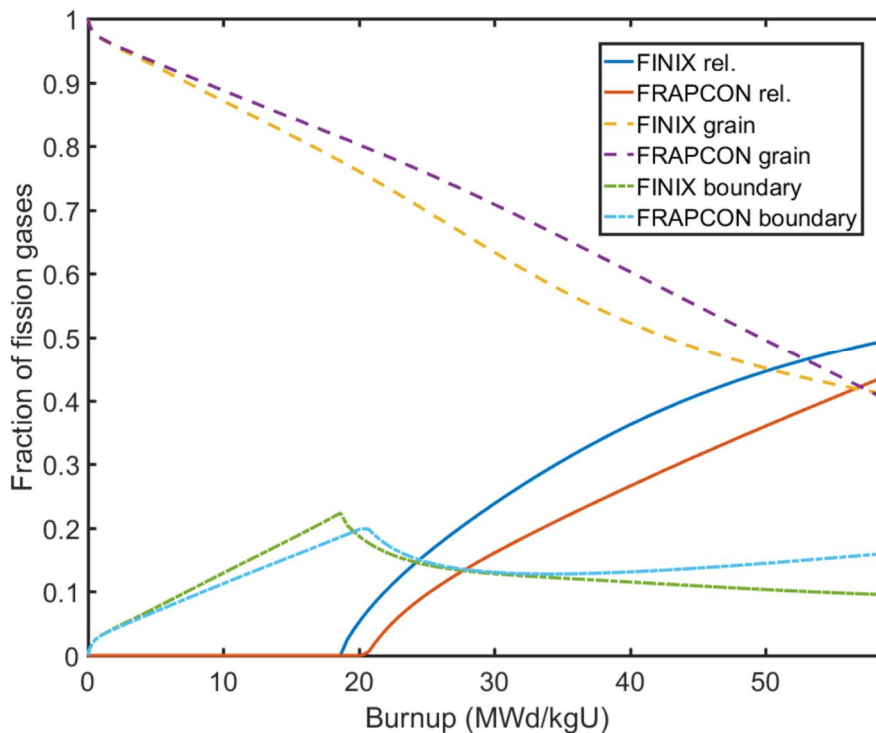


Figure 2.2.9.1: Fission gas distribution between grains, grain boundaries and free volume in FINIX and VTT-FRAPCON-4.0 with a constant linear heat generation rate of  $25 \text{ kWm}^{-1}$ .

- Validation system was tidied up for future use by non-developers, and is now ready for the subsequent validation of FINIX.
- IAEA Coordinated Research Project FUMAC had its final Research Coordination Meeting. VTT results were presented there.
- Several issues in the coupling of SCANAIR and GENFLO codes were solved, and a journal manuscript was sent to Nuclear Engineering and Design. The paper was published and, along with previous work, was integrated into Asko Arkoma's doctoral thesis. The thesis defence was on 8.3.2018.

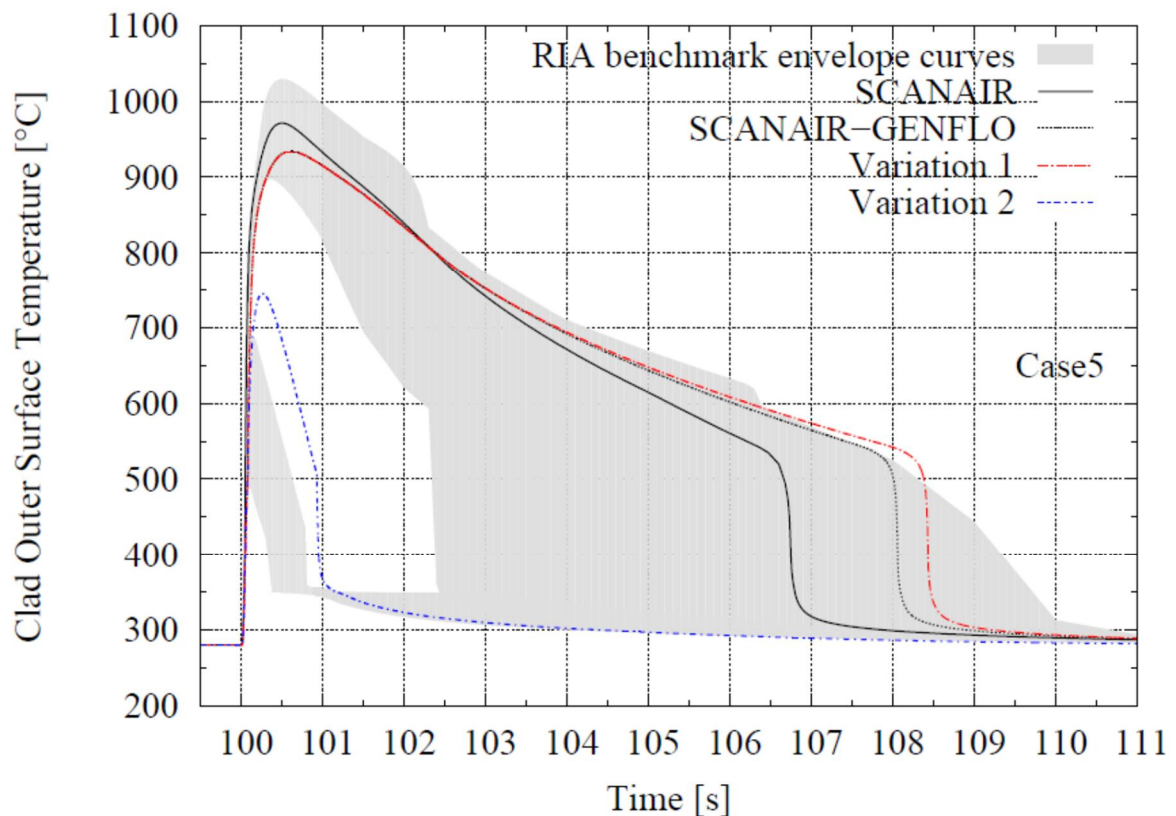
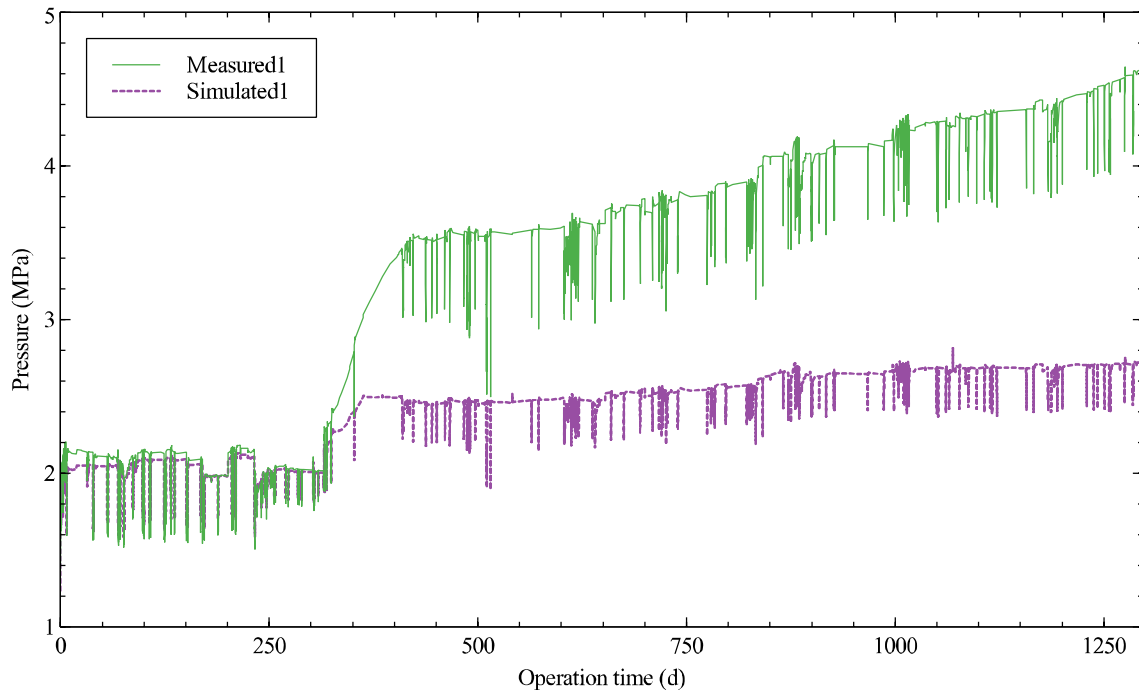


Figure 2.2.9.2: SCANAIR and variations of SCANAIR-GENFLO coupled code runs compared to RIA benchmark envelope curves. With GENFLO, the various thermohydraulic assumptions can be reproduced, demonstrating the differences observed in the benchmark calculations of the various parties.

- The behaviour of large grain fuel was investigated by modelling of Halden long term VVER fuel irradiation. Increasing the grain size would, according to the two stage release model based on modified Booth model, decrease the fission gas release as the intragranular diffusion path would increase. The observed fission gas release behaviour of the large grain cannot be explained through the traditional approach of using models based on modified Booth model. Instead it would appear that the large grain fuel exhibits larger fission gas release.



*Figure 2.2.9.3: Comparison between modelled and observed rod pressure stemming from fission gas release for a large grain fuel. The observed fission gas release behaviour of the large grain cannot be explained through the traditional approach of using models based on modified Booth model. Instead it would appear that the large grain fuel exhibits larger fission gas release.*

- PhD thesis of Emmi Myllykylä was finalized and defended on 16.6.2017.
- 3D Finite Element Method code BISON developed at Idaho National Laboratories USA was taken into use at VTT. This is the first FEM fuel code to be taken into use at VTT and will extend the analysis capabilities to non-axisymmetric scenarios.
- Nuclear fuel cladding mechanical models were reviewed and their performance on load follow analysis was assessed.
- HPG meetings were attended to and reported to the reference group.

In addition to this, a half day seminar was held on August 23<sup>rd</sup> discussing national and international projects and progress in the field of nuclear fuel research.

## 2.2.10 SADE - Safety analyses for dynamical events

Aim of the SADE project is to develop the modelling of transient events and accidents such that we can give more reliable answers to the safety requirements set in the YVL guides. To achieve this, the VTT's capabilities for independent transient safety analyses will be improved by routine coupled use of the CFD-type thermal-hydraulics solver PORFLO and the reactor dynamics codes HEXTRAN and TRAB3D. In addition, the neutronics modelling needs to be more detailed to get the full benefit on this improved accuracy of the thermal-hydraulics modelling. The goal is to have at VTT a fully self-developed, independent calculation system which can be used for the whole calculation sequence from basic nuclear data to coupled 3D transient analyses. Aim is the tool, which is more accurate and still fast and robust enough for practical safety analysis. The developed computational tool set of coupled neutronics, system codes and true-3D thermal hydraulics will be tested and demonstrated in cases relevant from safety analyses point of view. Objective is that by the end of the project we have calculated several transients and accidents of real interest. Developing and maintaining our own codes and in-depth understanding of them enables the best possible expertise on safety analyses.

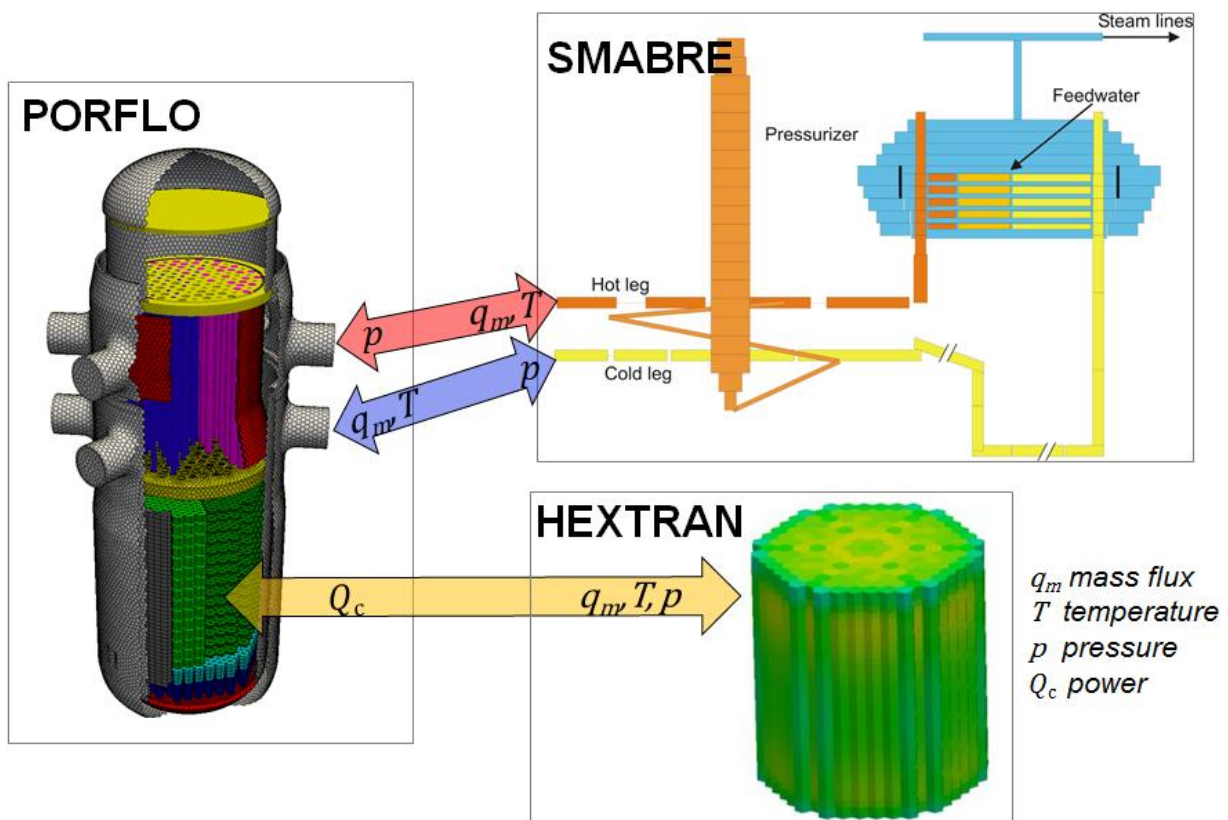


Figure 2.2.10.1: Coupling and data transfer between neutronics code HEXTRAN, system code SMABRE and CFD-style PORFLO code in a VVER-1000 simulations. All four loops are modelled with SMABRE, but only one loop is shown in this figure.

### Specific goals in 2017

The project has two main research areas. The objective of the first work package is to enhance the neutronics modelling of VTT's 3D reactor dynamics codes. Development of the solution methods and analysis of the methods versus accurate reference results is also an efficient way to study nodal codes in depth. In 2017 aim was further development of the neutronics model of the HEXTRAN code so that it can more reliably model transients of reactor cores with modern fuel assemblies. During the SAFIR2018 the aim is also that group

constants can be routinely created with the reactor physics code Serpent 2 for the reactor dynamics codes.

The second work package focuses on whole core transient analyses, focusing on cases where mixing in reactor pressure vessel or open core geometry play an essential role. Tools that enable more realistic modelling of the transients will be further developed and transients will be simulated with these improved tools. Modelling and development has two parallel branches: development of the tools such as internally coupled HEXTRAN-SMABRE that can be routinely used for safety analyses already during the SAFIR2018 program, and modelling of transients with CFD-style codes that have more detailed description. In 2017 work has focused on simulations, in which CFD-style code has been coupled with neutronics and system codes, Figure 2.2.10.1. Figure

The third work package involves work that supports the project's research aims and promotes the usefulness of the code system. The work package includes international co-operation and administration work demanded by SAFIR2018 program.

### **Deliverables in 2017**

- Journal article on Serpent 2 - HEXTRAN Code Sequence was done on the base of conference paper presented in 2016 at AER symposium and has been published in Kerntechnik AER issue in September 2017. In the paper Serpent 2 results were compared to measurements of the steady state of the V1000 zero-power facility. Serpent 2 was used to generate group constants for HEXTRAN and the results of a HEXTRAN calculation were compared to Serpent 2.
- Conference paper on application of Serpent 2 - HEXTRAN Code Sequence to V-1000 Core was presented in M&C 2017 International Conference on Mathematics & Computational Methods Applied to Nuclear Science and Engineering in Jeju, Korea.
- Axially heterogeneous fuel model has been partly implemented to the HEXTRAN code. Implemented model enables proper modelling of axially profiled fuel, e.g. partial length burnable absorber pins. Work has been reported in the research report.
- HEXTRAN code has been ported to the Windows environment to enable development in the Visual Studio environment.
- New CFD meshes has been created for VVER-440 and VVER-1000 reactor pressure vessels. The both new grids cover the whole RPV, whereas previously created meshes cover only downcomer and bottom part of the RPV, Figure 2.2.10.2.
- Main steam line break scenario of VVER-1000 (V1000CT benchmark) has been simulated with the fully two-way coupled HEXTRAN-SMABRE-PORFLO code using the new whole-RPV mesh. In these coupled simulations the reactor dynamics code HEXTRAN models neutronics and heat transfer in the fuel rods, PORFLO performs detailed 3D thermal hydraulics simulation in the whole RPV and the system code SMABRE models rest of the primary and secondary circuits as well as necessary plant automation, Figure 2.2.10.1. Example of the behaviour of the core power during accident is shown in Figure 2.2.10.4. Draft of the journal article has been written on this topic.
- The 7th AER benchmark problem, a VVER-440 loop reconnection, was simulated with the fully two-way coupled HEXTRAN-SMABRE-PORFLO code using the the new coarse whole-RPV mesh. Propagation of the cold coolant flow from reconnected loop to the reactor core is shown in Figure 2.2.10.3.
- Journal article on previous fully coupled simulations of the 7<sup>th</sup> AER benchmark problem using CFD mesh that covers part of the RPV from the cold leg main isolation

valves to the bottom of the core was written and has been published in Kerntechnik AER issue in September 2017.

- The project included participation in the meetings of AER working group D and AER scientific council.

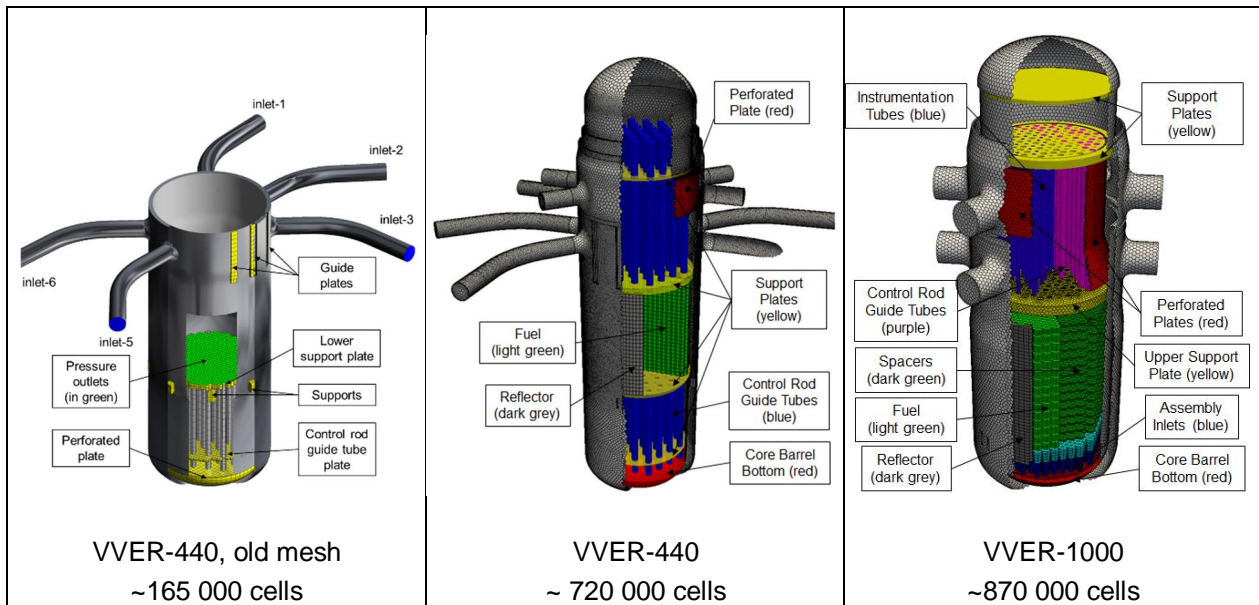


Figure 2.2.10.2: VVER-440 and VVER-1000 reactor pressure vessel meshes used in coupled simulations.

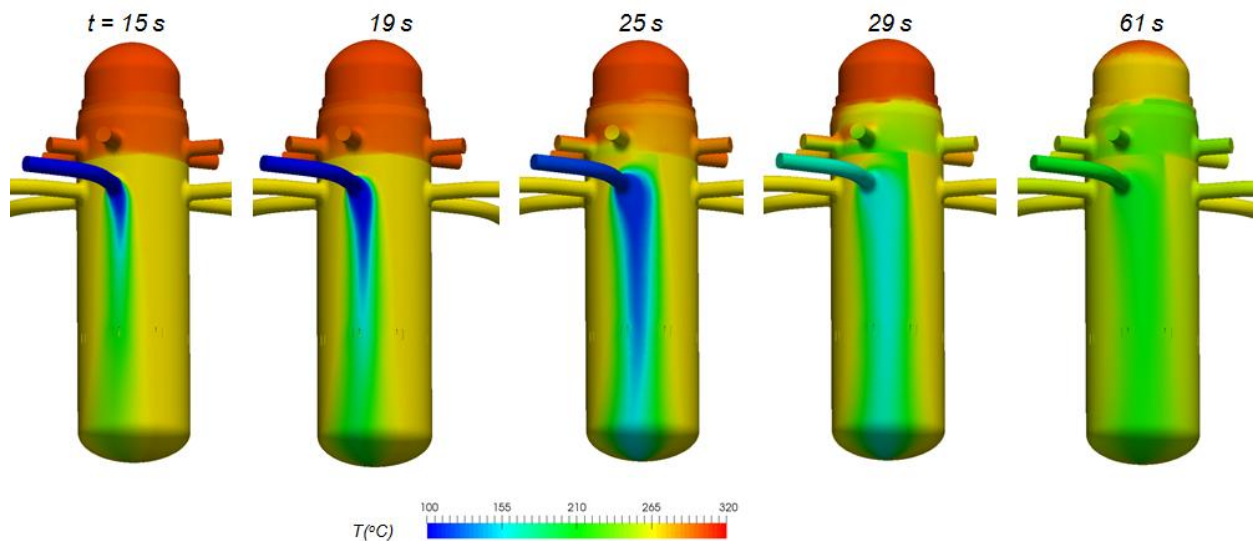


Figure 2.2.10.3: HEXTRAN-SMABRE-PORFLO simulation of the 7th AER benchmark problem, VVER-440 loop reconnection, with the new whole-RPV mesh: coolant temperature in the outer shell of RPV at selected time steps.

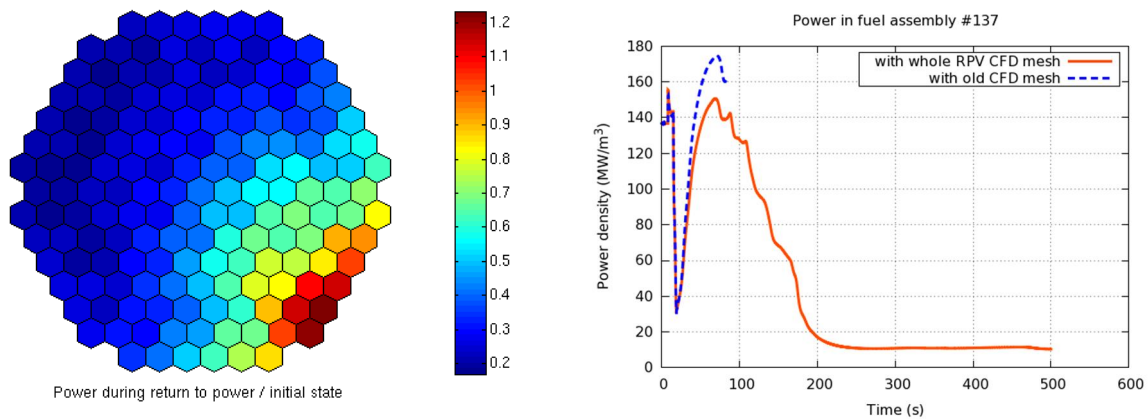


Figure 2.2.10.4: Power during VVER-1000 MSLB in HEXTRAN-SMABRE-PORFLO simulation. On the left assemblywise power distribution at time 68.8 s versus initial state. On the right power density in assembly 137, in which maximum power is reached during return-to-power, with the new whole RPV CFD mesh and with the old mesh.

#### 2.2.11 USVA - Uncertainty and sensitivity analyses for reactor safety

The general goal of the USVA project is to develop methods and practices in uncertainty and sensitivity analyses of multi-physics problems and calculation sequences in reactor safety. The goal supports the long-term aim of establishing a comprehensive methodology for uncertainty and sensitivity analysis for the entire reactor safety field. The project builds on the existing expertise in uncertainty and sensitivity analysis at VTT and Aalto University, and gathers the on-going research activities under one project. Also new experts in this area are trained. USVA promotes activities at the interfaces of the different disciplines in reactor safety.

Many of the tasks in USVA are related to the topics of OECD/NEA Benchmark for Uncertainty Analysis in Modelling (UAM) for the Design, Operation and Safety Analysis of LWRs.

##### Specific goals in 2017

The LB-LOCA scenario in an EPR type power plant has been analysed at VTT using statistical methods over several years. In 2016 the analysis moved from the use of surrogate neural networks to surrogate Support Vector Machines (SVMs) and the research in 2017 focused on using the SVMs in one of the simulated 59 global scenarios and evaluating their performance in that scenario.

The SVMs were applied both for predicting failed fuel rods in the scenario and for evaluating the sensitivity of the maximum cladding stress to various input variables. An iterative procedure was developed for training the SVM: An SVM was first trained using detailed simulations for 1000 individual fuel rods. In a second step, the fitted SVM was used to obtain more predictions of rods that are susceptible to failure. The third step of the procedure consists of detailed simulations of the additional fuel rods predicted to fail by the SVM. Finally, the results of the detailed simulations were included in the training data and the SVM was fitted anew.

This iterative procedure was seen to improve the SVM predictions regarding the failing rods notably. Further iterations are expected to provide even further improvement.

Regarding the input uncertainty determination for nuclear safety codes, demonstration codes were obtained from University of Illinois on the use of various statistical methods (MLE, MAP, MCMC) for data-assimilation. The work on applying the statistical methods on actual problems will start in 2018.

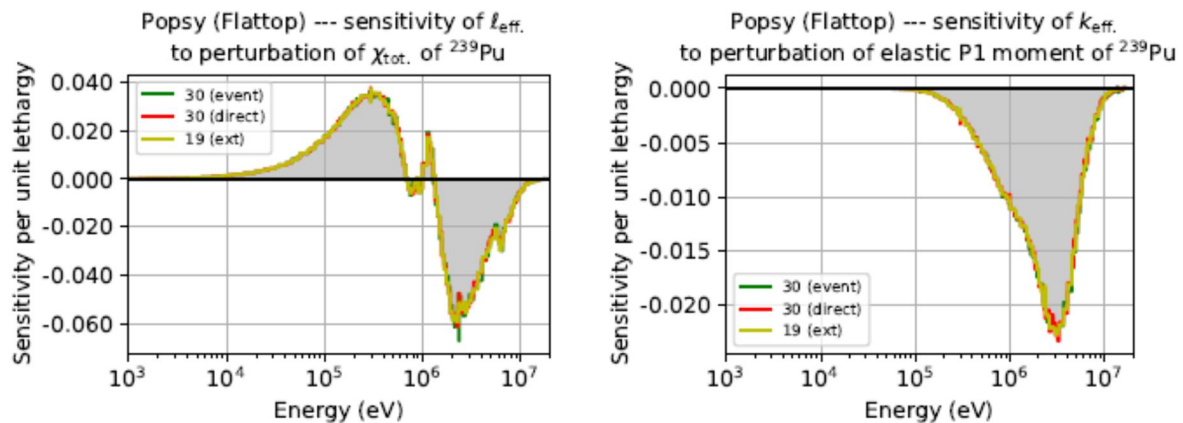


Figure 2.2.11.1. Two energy dependent sensitivity profiles calculated by Serpent for the Flattop critical assembly. **Left:** Sensitivity of the prompt neutron generation time to perturbation of inelastic scattering cross section of  $^{239}\text{Pu}$ . **Right:** Sensitivity of the multiplication factor to perturbation of the first Legendre moment of the elastic scattering distribution of  $^{239}\text{Pu}$ .

During 2017, a collision-history based capability for sensitivity/perturbation calculations was added for the Monte Carlo code Serpent 2. This capability allows Serpent to calculate the sensitivities of various output parameters such as k-effective or homogenized group constants to perturbations in data such as nuclide cross sections and secondary angle and/or energy distributions (see Figure 2.2.11.1). This facilitates the propagation of nuclear data uncertainties to the results of Serpent 2 using linearized first order perturbation theory.

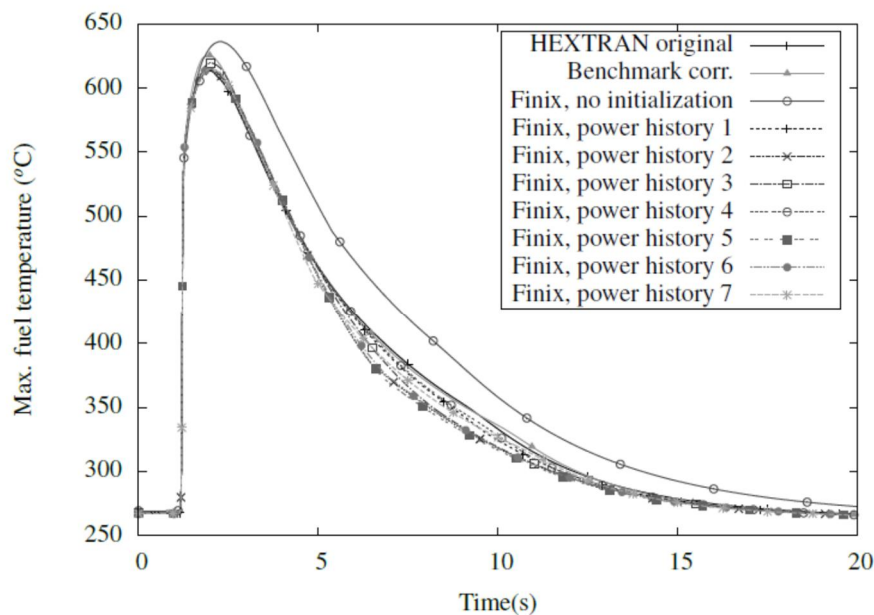


Figure 2.2.11.2. Maximum fuel temperature during CRE with different fuel rod models. Initial power 1%, EOC.

Studies were also conducted on the effects of burnup initialization and its related uncertainties in reactor dynamics codes in the context of simulation of a VVER-440 control rod ejection transient (see Figure 2.2.11.2) simulated using the HEXTRAN-FINIX coupled code system with an additional model developed for burnup initialization using the FRAPCON code.

### Deliverables in 2017

- A conference paper (*Predicting fuel rod failures and their contributing factors with surrogate support vector machines in statistical LOCA analyses*) on the application of Support Vector Machines to statistical simulations of LB-LOCAs was submitted to the ANS Best Estimate Plus Uncertainty (BEPU 2018) conference.
- A memorandum (*Status report of the USVA project task 1.2: Development of a generic methodology for determining input uncertainties in nuclear safety codes*) was prepared.
- A presentation (*Implementing history based GPT capabilities to the official Serpent 2 Monte Carlo code*) on the collision history based sensitivity/perturbation calculation capabilities in Serpent 2.1.29 was presented in LWR-UAM 11.
- A conference paper (*Collision-history based sensitivity/perturbation calculation capabilities in Serpent 2.1.30*) on the optimized GPT capabilities was submitted to the ANS Best Estimate Plus Uncertainty (BEPU 2018) conference.
- A draft journal paper (Working title: *Modeling burnup-induced fuel rod deformations and their effect on transient behaviour of a VVER-440 reactor core*) was prepared on the burnup initialization in reactor dynamics calculations.

## 2.3 Structural safety and materials

In 2017 the research area “Structural safety and materials” consisted of eight projects:

1. Experimental and numerical methods for external event assessment improving safety (ERNEST)
2. Fire risk evaluation and Defence-in-Depth (FIRED)
3. Analysis of fatigue and other cumulative ageing to extend lifetime (FOUND)
4. Long term operation aspects of structural integrity (LOST)
5. Mitigation of cracking through advanced water chemistry (MOCCA)
6. Thermal ageing and EAC research for plant life management (THELMA)
7. Non-destructive examination of NPP primary circuit components and concrete infrastructure (WANDA)
8. Condition monitoring, thermal and radiation degradation of polymers inside NPP containments (COMRADE)

### 2.3.1 ERNEST – Experimental and numerical methods for external event assessment improving safety

The general objective of ERNEST (2015 NEST + ESPIACS, 2016 - 2018 ERNEST) is to maintain and develop the capabilities to predict reliably and accurately the behaviour of large reinforced concrete structures under different types of loadings with the emphasis on aircraft crash against NPP containment building. In order to obtain this objective, the project combines impact testing and computational modelling and modelling tools updating and development. Testing yields valuable experimental data which can be used for validation of the used models and tools. Development and validation brings additional confidence on the models and tools.

#### **Specific goals in 2017**

WP1 of ERNEST focuses on carrying out impact tests that have been agreed collectively with operators in the field of domestic nuclear energy and safety (STUK, Fortum, TVO, Fennovoima) to be of particular interest of Finnish nuclear safety scheme. In 2017, one test was carried out within the project. The test was a punching type test in which a hard, relatively non-deformable projectile was shot against two consecutive 125 mm reinforced concrete slabs with a 50 mm gap between them. The goal was to study the resistance of this type of double-slab feature against punching failure and compare this resistance against the one of an equivalent single slab.

The result of the test verified that the punching resistance of this type of double-slab feature is clearly inferior to that of an equivalent single slab. The 47.5 kg projectile was shot against the structure with an initial velocity of 102.6 m/s. As a result, both of the slabs were perforated with the exit velocity of the projectile being 41 m/s. Based on experimental formulas, the just perforation velocity, i.e. the velocity with which the projectile is just able to perforate both slabs, is 81 m/s. As a comparison, based on previous tests, the corresponding just perforation velocity for an equivalent single slab is around 105-110 m/s. The test will serve in future as a validation case for the numerical model validation.

WP2 of ERNEST concentrates on computational simulation of the impact tests that have been carried out at VTT previously and also on improvement of the models, methods and tools used in the simulation process. In 2017, this work package was further divided into three tasks with the focus on concrete material model development and validation and simulation of different types of impact tests that have been carried out at VTT previously.

The concrete material model developed at VTT within task 2.1 was validated in 2017 against one punching type of test that has been carried out at VTT previously. In addition, a paper discussing the model was written to and presented in the 24<sup>th</sup> conference on Structural Mechanics in Reactor Technology (SMiRT24).

One of the simulated test cases, or set of cases, was a set of impact tests in which the combined bending and punching response of the tested slab was excited. This study was carried out within task 2.2. The tests were similar to each other except for the reinforcement. The goals of the simulations were to

- compare the results given by three different concrete material models against each other and the tests results and
- carry out sensitivity analyses on the effect of reinforcement on the simulation results.

The results highlight the difficulty of predicting both the shear as well as bending damage of the slab under impact with a single model. The first model, given in Abaqus FE code as default, predicts the extent of the bending failure quite well but seems to exaggerate the shear failure. The second model, which utilizes a user subroutine generated by VTT, seems to predict the extent of the shear failure well but grossly overestimates the stiffness of the target in bending. The third model, which utilizes a similar user subroutine generated by Spanish consultant company Principia, seems to underestimate the shear punching resistance of the slab and overestimates the stiffness of the target in bending.

The main challenges in near future are to update the VTT material model so that it can predict well also the bending type failure in addition to shear one. One of the obstacle in road to this is to obtain enough experimental data for material parameter characterization that has been lacking before.

One of the simulated test cases was a set of tests in which vibration behaviour of a wall-floor-wall structure under impact loading. This study was carried out within task 2.2. The main goal of the task was to write a paper to and present it in 24<sup>th</sup> conference on Structural Mechanics in Reactor Technology (SMiRT24). This goal was reached.

### **Deliverables in 2017**

- A research report describing the punching type impact test carried out at VTT in 2017 within the project.
- A research report describing the finite element impact simulations carried out within task 2.2.
- A conference paper submitted to SMiRT 24 about a physically motivated element deletion criterion for the concrete damage plasticity model
- A conference paper submitted to SMiRT 24 about numerical sensitivity studies on vibration propagation in impact loaded reinforced concrete structure.
- A conference paper submitted to SMiRT 24 about experimental and numerical studies on vibration propagation in impact loaded reinforced concrete structure

### 2.3.2 FIRED – Fire risk evaluation and Defence-in-Depth

The main objective of the FIRED –project is to develop the tools for fire risk evaluation and create a new methodology for assessing the defense-in-depth in the context of fire safety. In general, the results may be divided into three categories: the First one is the basic research that increases understanding and contributes to future work, second is the education of experts and developing the current methodology, and the third one is the direct applications to NPPs. The results of FIRED work packages are illustrated in Figure 2.3.2.1.

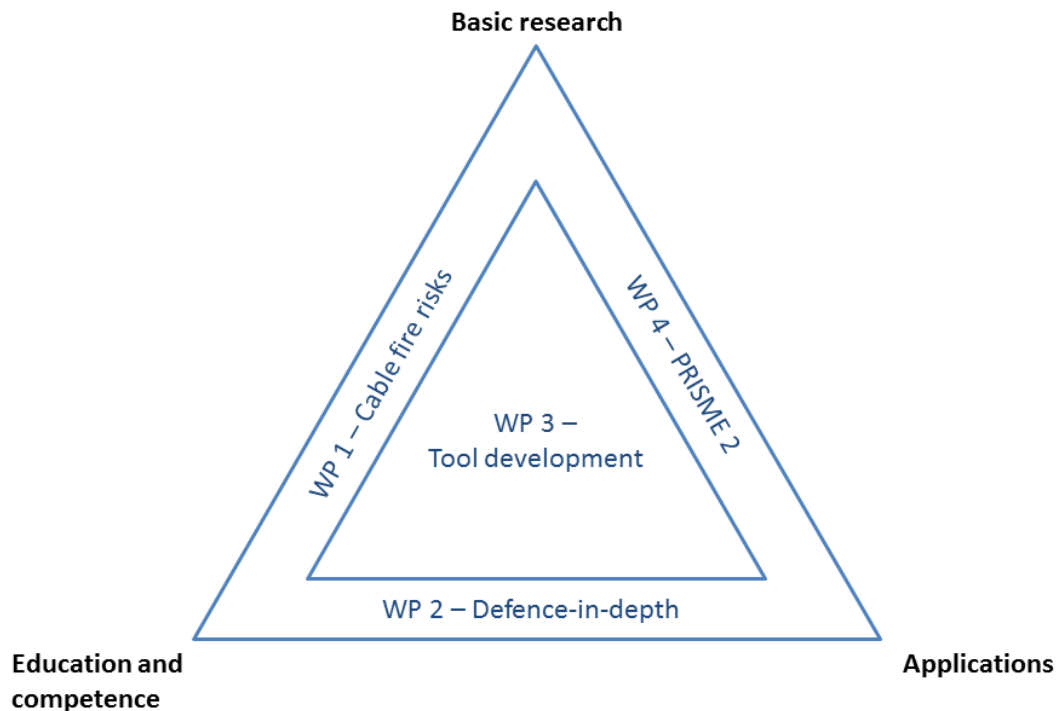


Figure 2.3.2.1. Result categories in WPs of FIRED.

#### Specific goals in 2017

The active tasks during 2017 were:

- WP 1: Cable fire risks during plant life cycle
  - Task 1: New flame retardant polymers,
- WP 2: Fire-Barrier performance assessment
  - Task 1: Barrier performance assessment with Fire-CFD.
  - Task 3: Fire PRA integration
- WP 3: Fire simulation development, maintenance and validation.
  - Task 1: FDS development, maintenance and validation.
- WP 4: Participation to PRISME3.
  - Task 1: PRISME utilisation,
  - Task 2: Participation fee.

In WP1, the work with the new flame retardant polymer continued using reactive molecular dynamics. Simulations based on reactive molecular dynamics using a PE-ATH model composite system were able to reproduce the well-established fire retardancy effects of ATH. The MD simulations reproduced energetics of gibbsite decomposition as well as the specific heat capacities of gibbsite, alumina, and water with good accuracy. When heated, crystalline gibbsite first went through a structural phase transition to form a structure that had no long-range order but showed boehmite-like short-range features. Thermal decomposition started after this phase transition was completed. Water molecules were the main decomposition product. Figure 2.3.2.2 shows the evolution of the material during thermal decomposition

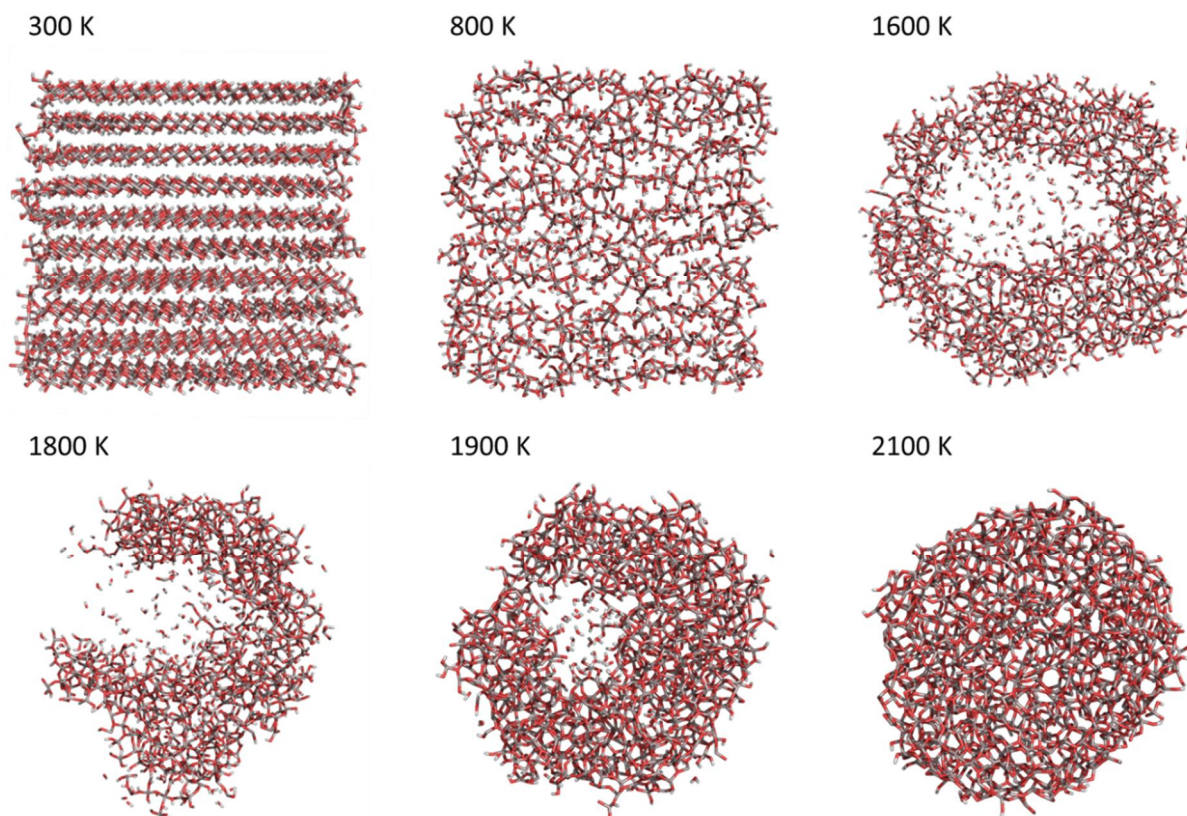


Figure 2.3.2.2. Evolution of the gibbsite structure during thermal decomposition

The barrier performance assessment the work concentrated on the uncertainty propagation between two models. Numerical simulations of a fire experiment conducted in a closed enclosure were carried out using Fire Dynamic Simulator (FDS). The systematic bias in the prediction of various output quantity observed from this study was compared with the one reported in the FDS validation guide. The temperature of the enclosure wall as a function of time was predicted in three different ways, and the modeling-error associated with each case was presented in terms of systematic bias and the random-error. In addition to the bias and random error in wall temperatures, the modeling-error in estimating the time at which the enclosure wall crosses a particular temperature threshold was examined. Figure 2.3.2.3 shows an example of the outcomes of this research. Figure 2.3.2.3 a) shows the probability of wall temperature in the compartment staying below 100 °C as a function of time. Figure 2.3.2.3 b) shows the uncertainty associated with the wall temperature prediction.

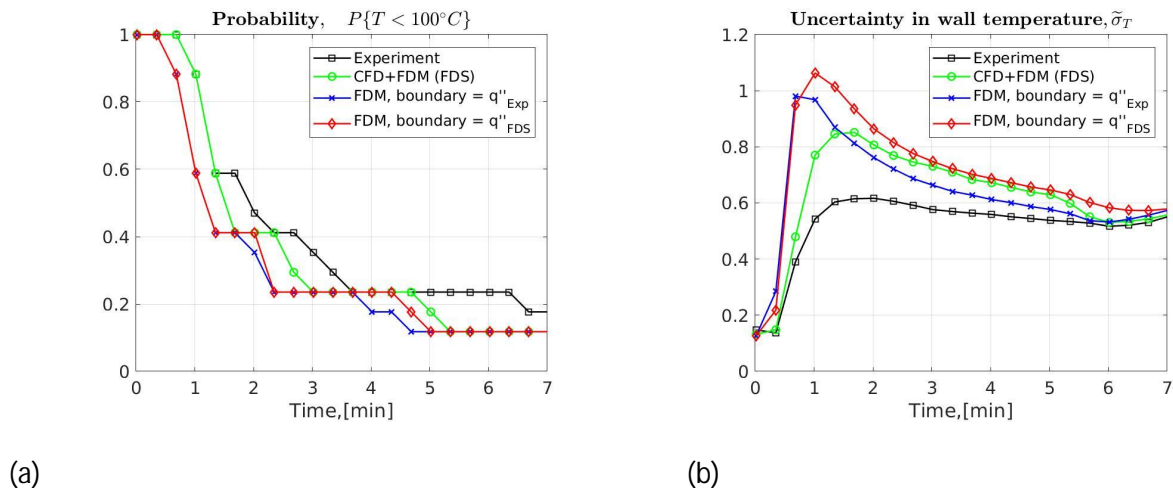


Figure 2.3.2.3. (a) the experimental and the predicted probability that the wall temperature remains under  $100^\circ\text{C}$  (b) experimental and measured output uncertainty in the wall temperatures.

VTT organized a workshop on the Fire PRA, and its relation to the Fire-DID and the main PRA. This one day workshop was organized in Espoo on 25.11.2017. Topics covered in the workshop were:

- Development of deterministic analyses, including their verification and validation, and their applicability on the Fire PRA.
- Present status of Fire PRA on Finnish plants and the near plans to upgrade them.
- Main PRA and its plans: Development work needed to address the main PRA and Fire PRA inter-face.

Participants of the workshop are mainly from the NPP companies, Finnish authorities, and research organizations. After the presentations from all participating organizations, a lively discussion on research needs for fire-PRA followed. Some issues that were suggested during the discussion were fire and smoke propagation through ventilation ducts and openings. Participants also considered the investigation of cabinet-to-cabinet fire spread as important.

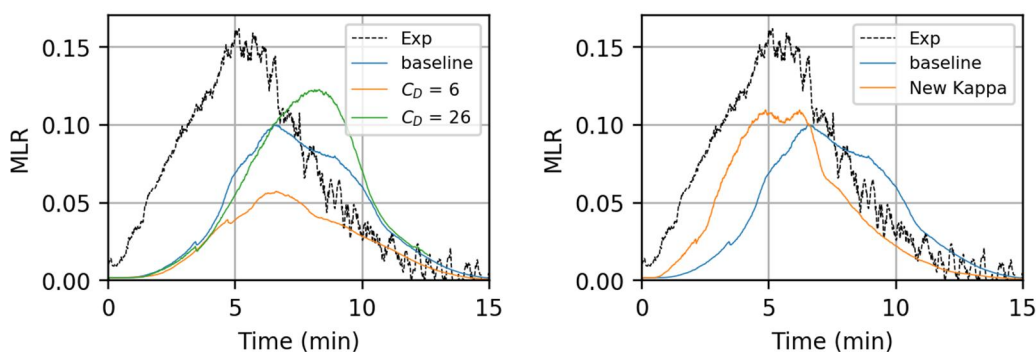


Figure 2.3.2.4. On the left: effect of varying drag coefficient on the burning rate. On the right: Effect of absorption coefficient modeling

In 2017, WP3 targeted modeling cable fire spread. The goal of the work was to model cable fire spread using the Lagrangian particle approach for pyrolysis modeling. The Cable Fire

Spreading Support (CFSS) test from the PRISME2 project was targeted since the cable used in the test was previously characterized by VTT. Problems in the handling of aerodynamic drag and radiation absorption by the Lagrangian particle model in Fire Dynamics Simulator (FDS) were identified. Modifications to the radiation absorption by solid particles were investigated. The proposed modification produced better initial fire spread in simulations but ultimately lead to unphysical results in predicted gas phase temperatures. A simple method for computing the drag of cable bundles, based on empirical correlations for heat exchangers, was proposed. The newly calculated drag coefficients improved the flame spread predictions. Figure 2.3.2.4 shows a comparison of experimental and predicted burning rates for CFSS test 1. The figure on the left illustrates the sensitivity of the results to cable tray drag and the figure on the right illustrates the effect of modifying absorption coefficient calculation.

The participation to PRISME 3 was started. The project will provide high quality, large-scale experimental data on the topics that are relevant to fire safety of nuclear power plants. These results can be utilized directly in the safety assessments, or for simulating and validating the simulation tools.

On 19th of January 2018, Topi Sikanen defended his Ph.D. thesis, titled “Simulation of transport, evaporation, and combustion of liquids in large-scale fire incidents.” The thesis is based in large part on research done in FIRED and earlier SAFIR projects. The work on modeling fires following an aircraft impact was also used in IAEA Report Safety No. 89: Aspects of Nuclear Power Plants in Human Induced External Events: Assessment of Structures

### **Deliverables in 2017**

- Based on the research in Task 1.1 a journal manuscript was written. *Jukka Vaari, Antti Paajanen: Reactive molecular dynamics studies on the thermal decomposition of PE-ATH composites.*
- The uncertainty propagation from one model to another was studied numerically using Monte Carlo simulations. A method for calculating the acceptance criterion for the model uncertainty was also developed. *Deepak Paudel and Simo Hostikka: Model uncertainty propagation in fire-barrier performance analyses. Modeling uncertainty in the prediction of wall temperature in compartment fires.*
- Workshop on Fire PRA was organized in November
- A report, describing the modeling of cable fire spreading with FDS was written ( VTT-R-05491-17).
- PRISME results were utilized in the special assignment in physics of summer intern Janika Tang: *Development of radiation modeling for fire spread simulation in cable trays.*
- VTT has joined the PRISME3 project, and the project has started in 2017. VTT has participated in the planning of the first experimental campaign on cabinet fire spread.

### 2.3.3 FOUND - Analysis of fatigue and other cumulative ageing to extend lifetime

Project FOUND concerns cross-disciplinary assessment of ageing mechanisms for safe management and extension of operational plant lifetime. It develops deterministic, probabilistic and risk informed approaches in computational and experimental analyses with education of new experts. It consists of seven scientific work packages (WPs).

The focus areas are: WP1 Remaining lifetime and long term operation of components having defects; WP2 Susceptibility of BWR RPV internals to degradation mechanisms, including a dissertation; WP3 Fatigue usage of primary circuit, with emphasis on environmental effects; WP4 Fatigue and crack growth caused by thermal loads; WP5 Development of RI-ISI methodologies; WP6 Dynamic loading of NPP piping systems; and WP7 Residual stress relaxation in BWR NPPs.

#### **Specific goals, results and deliverables in 2017**

Each of the work packages of the project had separate and distinct goals as discussed below. The deliverables of each work package are presented directly after the chapter.

**WP1** was dedicated to investigation of criticality of defects found in NPP components. With the modern developing NDE methods, more indications are found year by year. The work in 2017 considered the evaluation of allowable flaw sizes in piping components according to the ASME section XI rules. The rules are applicable in determining the acceptability of flaws found by examinations but the methods can also be applied in determining the maximum allowable flaw size for a given component under known loads. In the WP, two ASME XI procedures (those in Appendix C and Appendix H) were compared against the FFS approach given in BS7910. The results are reported in D1.1.1.

The deliverables of this work package are:

- A study on the comparison of ASME XI and BS7910 allowable flaw sizes for piping components.

**WP2** package provides an investigation on the susceptibility of BWR RPV and its internals to various relevant degradation mechanisms. The work consists of a literature review, covering available relevant literature and databases, and of a set of computational analyses, including development of new computational applications. The computational part covers both deterministic and probabilistic approaches. The main purpose is to prepare a dissertation on the topic. In 2017, the scope was in computational assessment of the propagation of degradation in the susceptible BWR RPV internals, providing new computational developments for assessment of the propagation of degradation and providing conclusions on degradation potential of BWR RPV internals.

As many BWR plants are planning license renewal, it is important to consider more specifically long-term operation (LTO) related structural integrity analyses. These are time dependent degradation potential analyses that cover also the LTO period. Thus, the specific work topics for 2017 included degradation potential analyses to core shroud support legs, water level measurement nozzles, steam separator support legs, and spring beam brackets.

The deliverables of this work package are:

- Partial manuscript of the dissertation
- A report on a straightforward probabilistic crack growth computation procedure

**WP3** studying the fatigue usage of primary circuit aims to educate new experts and gain practical knowhow and learn of international progress and challenges related to the

transferability of laboratory fatigue data to primary circuit fatigue assessment and usage monitoring. Strain-controlled fatigue experiments using the FaBello facility in hot and pressurised reactor coolant water were performed (Figure 2.3.3.1). International networking was achieved through participation and presenting in scientific forums. The main objective of WP3 is to reveal the underlying mechanisms and develop a model to quantify the effects of hot water environment in fatigue of stainless steel. Limitations of the current  $F_{en}$  methodologies were identified with test results, which suggest that the plastic strain rate is a more relevant parameter than total strain rate to characterize the environmental effects on fatigue life.

The deliverables of this work package are:

- The results of and a report on strain-controlled fatigue tests in PWR water environment.
- A conference publication on direct strain-controlled fatigue testing in simulated PWR water
- A work plan formulating the next steps in developing the  $F_{en}$ -model

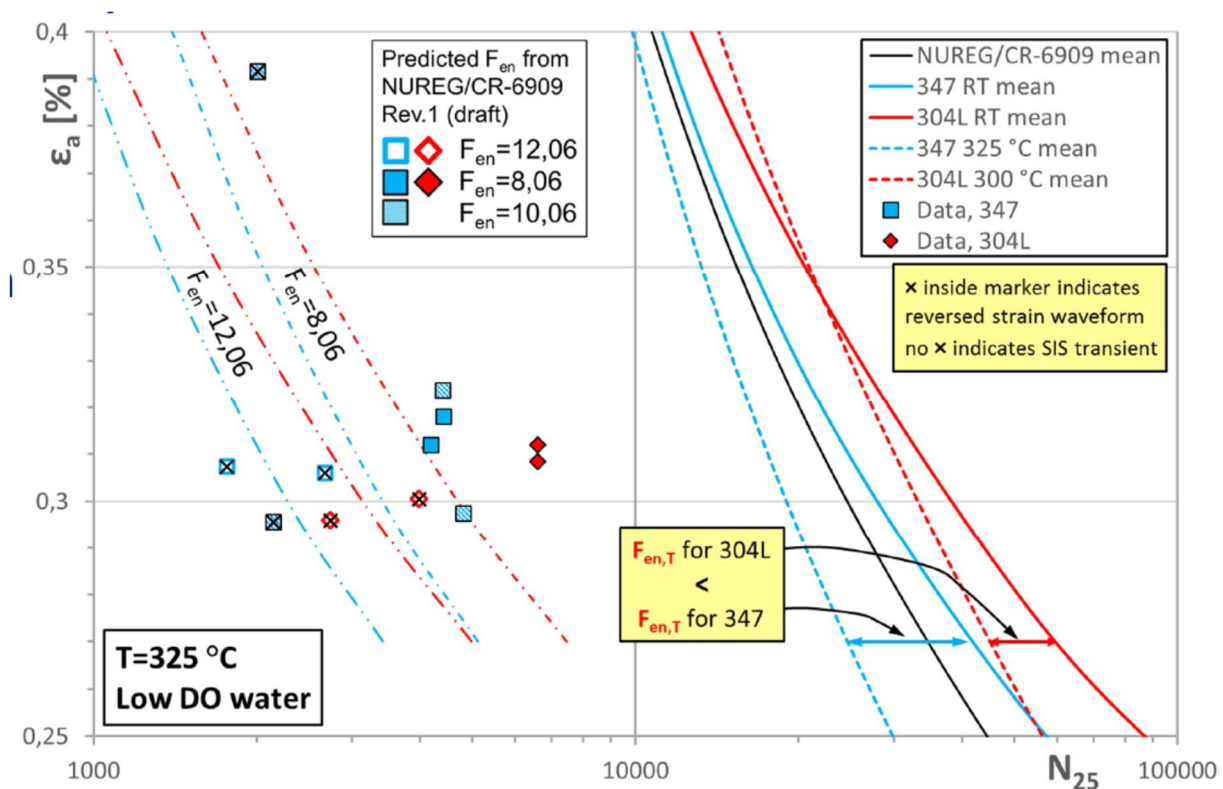


Figure 2.3.3.1. Fatigue test results in PWR water compared to the NUREG/CR-6909 mean curve and nominal expected  $F_{en}$ .

**WP4** concerns the thermal and structural evaluation of mixing loads and their effects on the degradation of piping components. Thermal mixing of hot and cold water with large temperature differences has led to fatigue and crack growth e.g. in piping T-junctions. Computational fluid dynamics and structural calculations of thermal mixing in a T-junction were performed with the commercial Star-CCM+ and Abaqus codes. In large-eddy simulations (LES), the fluctuating wall heat fluxes obtained with different wall treatments and meshes were compared. In the structural calculations, turbulent thermal loads from LES were applied in 3D modelling while turbulent, spectrum and sinusoidal loads were applied in 1D modelling. Crack growth results using the 1D and 3D models and the different thermal loads were compared. A journal article was prepared based on the research.

In addition, the crack growth and component lifetime in Trueflaw's crack manufacturing experiments that use tailored thermal load cycles were studied. The studied case corresponds to low-cycle conditions with considerable cyclic plasticity induced by the thermal load. The results indicated that including the crack in the analysis is needed to obtain realistic crack driving forces as the stresses calculated without the crack resulted in an overestimated growth rates. The use of a crack opening angle crack driving force parameter for low-cycle thermal fatigue was proposed in a conference paper.

The deliverables of this work package are:

- A journal article manuscript on the fatigue and crack growth rates resulting from different thermal mixing load definitions
- Conference paper on the use of CTOD as a crack driving force parameter for thermal fatigue

**WP5** provides further development of risk assessment procedures, as well as a supplementation and update of the quantitative VTT RI-ISI analysis procedure. The VTT RI-ISI procedure is a combination of deterministic and probabilistic flaw and degradation assessment tools for the evaluation of pipe failure possibilities and the risk informed planning of inspections. The procedure allows e.g. the quantitative evaluation of the influence of different inspection intervals and inspection capability on the leak probability. The procedure combines deterministic fracture mechanical models describing the crack growth with probabilistic models to evaluate the failure probability and effect of inspections. An example failure probability plot obtained with the VTT RI-ISI procedure is shown in Figure 2.3.3.2. In 2017, the VTT RI-ISI procedure was extended by including distributed crack growth model parameters and crack growth threshold data.

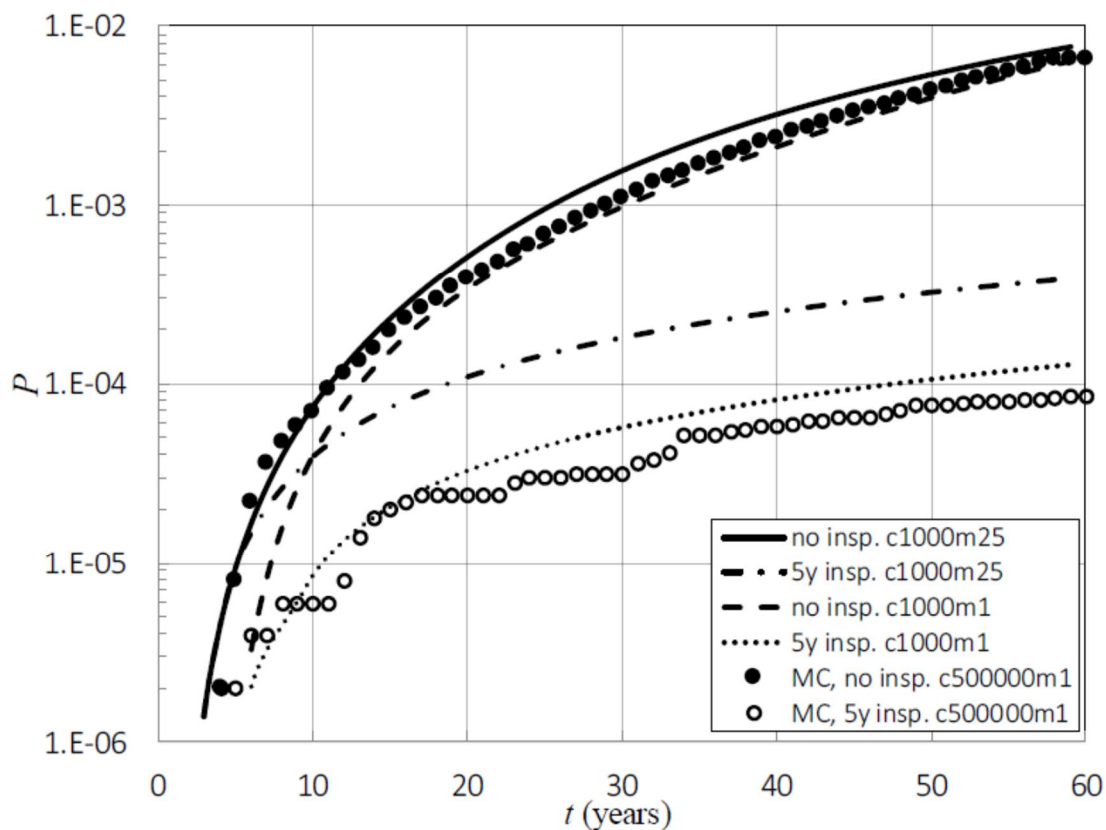


Figure 2.3.3.2. Cumulative yearly leak probabilities simulated with the VTT RI-ISI procedure (lines) and Monte-Carlo based procedure (dots). The red line and dots denote cases without in-service inspections and the black line and dots denote cases with inspections.

Another research topic addresses the connection between RI-ISI and PRA. Probabilistic risk assessment (PRA) is used to calculate the quantitative risk of nuclear accident and to analyse the importance of different systems and components. PRA's main purpose is to support risk-informed decision making. PRA also supports RI-ISI analyses by quantifying the consequences of pipe failures. There is much to be gained from better connection and mutual support between PRA and RI-ISI. One possibility to bring RI-ISI and PRA closer would be to develop a software support for the better integration. Even common analysis software is a possibility. In addition, it would be beneficial to develop an automatic piping failure consequence calculator into the PRA software. Consequently, the research introduced a new RI-ISI feature, which calculates CCDP and CLERP of piping component failures, in PRA software FinPSA.

The deliverables of this work package are:

- A research report detailing the improvement VTT RI-ISI calculation procedure to take into account distributed crack growth parameters and growth threshold.
- A research report on the computation of consequences of piping component failures in PRA software

**WP6** assesses piping systems subjected to dynamic loads. In 2017, the work considered water hammer loads in piping components. The work included a literature review on both the previously developed and most current assessment methods for determination of the loads and structural responses due to water hammer events such as a rapid valve closure. A development and testing of computation methods for the water hammer excited response of a representative piping structure was carried out after the literature review.

The primary stress limit equation in Section III of the ASME B&PV code requires a calculation of a piping resultant moment by combining the moments from simultaneous design loads. The combination procedure for the results from several dynamic time-history analyses may become computationally laborious, depending on the level of required accuracy. This aspect was studied in the project. To reduce unnecessary conservatism, the moment components applied in the summation equation can be selected physically from the same time instants, requiring a search of the maximizing instants from the time step combinations between the dynamic load cases. Combining the moments from time-history analyses was studied by using moments from dynamic piping analyses or by generating random moment signals. It was found that significant computational savings can be achieved by a simple screening procedure to remove the unnecessary time points from the load combination analysis.

The deliverables of this work package are:

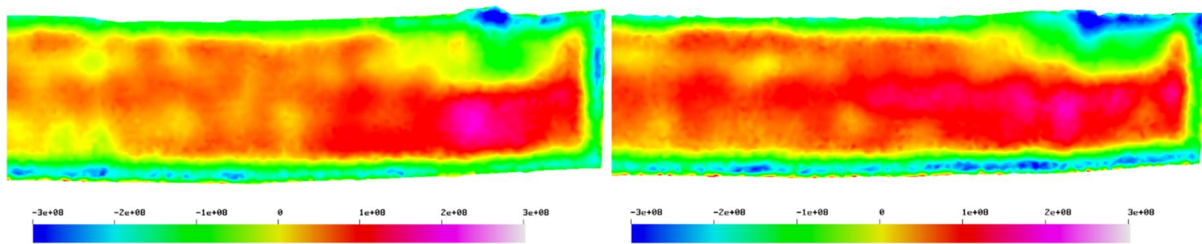
- A literature review and additional development of water hammer response analysis methods.
- Testing and validation of the developed moment resultant combination procedure.

**WP7** studies the relaxation of residual stresses. They play a major role in stress corrosion cracking (SCC), which is identified as significant degradation mechanism for various BWR components. Experience from ageing NPPs indicates slower stress corrosion crack growth in many components than would be expected under currently postulated stresses. Residual stress relaxation decreases the effective loads during the service life and therefore slows down SCC. The effect of residual stress relaxation on SCC is not, in general, considered in crack growth calculations although thermal and mechanical loads are known to relax residual stresses significantly. This is due to insufficient data available on the stress relaxation.

In the project, residual stress relaxation in BWR NPP was studied with co-operation of Aalto University and Teollisuuden Voima Oy. Previously used measurement methods are developed further, most notably the contour method. The spatial resolution of the contour method was significantly improved by adopting white light interferometry measurement to the

cut surface. This development also vastly increased the amount of measurement data to be analysed, and necessitated significant development of the measurement pipeline.

The residual stresses measured from the pipe sections removed from OL1 and OL2 were compared with the other experimental data. A removed T-junction was provided for the residual stress measurements. Prior to measurement, the component had been cut in two parts. This was done for other investigations, but also provided measurement access to inner surface of the T-junction. The components had also been decontaminated prior to measurement. The sections were measured using X-ray diffraction and the contour method (using white light interferometry and the newly developed measurement pipeline). Contour measurements were completed on four sample surfaces. Typical results are shown in in Figure 2.3.3.3.



*Figure 2.3.3.3. Circumferential residual stress contour measurements from two weld samples (stress in Pa).*

In 2017, the specimens were re-examined after removing the decontamination layer. The new results confirmed the findings that the performed decontamination affected the residual stress results.

Additionally, non-destructive residual stress measurements were performed for the TVO-provided feedwater nozzle mock-up containing repair welds. The results show that the repair welding affects the back surface residual stress state.

The deliverables of this work package are:

- The results and a report on the measurements of residual stresses from BWR welds removed from service
- A comparison of test samples and residual stresses from BWR welds removed from service.

## 2.3.4 LOST - Long term operation aspects of structural integrity

The general objective of the long term operation aspects of structural integrity (LOST) project is to develop methods and tools for structural safety analysis of primary circuit components, reactor pressure vessel (RPV) and dissimilar metal welds (DMW). In 2017 the project covered tasks related to fast fracture in the upper shelf area for RPV like materials, experimental and numerical work on dissimilar metal welds (DMWs) and international cooperation. In 2017, related to fast fracture, the stress strain behaviour between 25 and 300 °C was investigated to understand the material behaviour during temperature transients, like shut-down. Related to DMWs numerical and experimental methods were used to develop DMW specific equations for fracture mechanical analysis and a new numerical method for crack growth modelling was developed. In addition, residual stress fields in DMWs, after repair, were also investigated. Two scientific articles were written and one conference paper,

in addition to several reports. Also investigations on the Barsebäck 2 reactor pressure vessel weld were done, and Laura Sirkiä finished her master's thesis.

### Goals and results in 2017

One objective in 2017 was to investigate the stress strain behaviour of a RPV (reactor pressure vessel)-type of steel between 25 and 300 °C, and predict materials behaviour under temperature transients. The research topic is justified by the requirements in the Finnish regulatory requirements that state the following; In connection with the strength analysis of Safety Class 1 pressure equipment, an assessment shall be given on the potential for a fast fracture occurring in the upper shelf area where temperatures exceed the transition temperature zone. Physically, upper shelf is defined as the temperature range where brittle fracture cannot occur. Probability of fast fracture in upper shelf area during operation conditions is small, due to the high tearing resistance of the RPV material. It is more probable that fast fracture could occur in thick-walled components which undergo rapid cooling under high pressure.

The results from 2017 show that the fracture strain decreases from 25 to 200 °C, but increases from 200 to 300 °C. This is in line with the ductile fracture toughness (J-R curves) results from 2016. The yield strength and tensile strength behaviour is also in line with the previous results. Related to this work package, advanced structural integrity, the objective for the whole SAFIR2018 period is to develop new advanced structural integrity methods to describe the ductile crack growth during a temperature transient accounting for temperature history effects. The upcoming work consists of experimental investigations of ductile tearing resistance during transient temperatures.

Related to advanced structural integrity assessment methods, one objective in LOST is to use miniature size C(T) specimens in determination of ductile-to-brittle transition temperature. This new method reduces the material required for surveillance testing. In 2017 miniature sized specimens were validated for a RPV material, Barsebäck 2. The results were reported in Laura Sirkiä's Master's Thesis. The conclusion was that the  $T_0$  of the RPV material determined with miniature sized specimens yield similar results as standard sized specimens. Previous investigations have been mainly done on homogeneous materials. Yet, further investigations are required for the use of miniature sized specimens for welds. This is done by investigating the applicability of miniature sized specimens of irradiated welds. The work will be executed in the next SAFIR programme.

Another goal was to investigate the local stress-strain properties of near interface zones (NIZs) and the effect of the strength of these zones on tearing resistance in welds and DMWs. The interface region of dissimilar metal welds (DMW) consists of narrow microstructural zones with varying fracture mechanical and mechanical properties. The narrowest zones can be just few micro meters wide and between adjacent zones there can exist a major difference e.g. in strength properties. Even if the fracture occurs in a zone with nominally high tearing resistance, the strength mismatch of adjacent zones can lower the tearing resistance.

In 2017, the eta factors for the interface region of DMWs, were derived in LOST, with accurate information of mechanical properties of the narrow zones in the interface region. The eta factor affects the equations used for calculation of the fracture mechanical properties. After the eta factors have been derived with accurate models, one knows in which regions of the weld the standard homogeneous solutions can be applied and in which regions more precise eta factors are needed. The results show that at the interface, where the fracture toughness is the lowest, the current equations developed for homogeneous materials can be used reliably.

Another objective was to estimate how well the rotation correction and bending correction work for single edge bend specimens made of DMWs. These corrections correct the

calculated final crack growth estimated based on the experimental data. Typically, the calculated crack growth is shorter than the actual crack growth, thus, the obtained fracture toughness values are higher than expected. The results show that the corrections increase the calculated crack length and give a better fit to the actually measured crack lengths. This improves also the fracture toughness values.

A scientific article was written based on (DMW/fracture toughness)-results from European research projects MULTIMETAL and relies also on knowledge gained from BIMET, ADIMEW, STYLE, PERDI and National research projects SINI and FAR. The experimental article discussed tearing resistance curves measured with 10x10 and 10x20 SE(B) specimens and the effect of initiation location on tearing resistance. The initial crack was located in the interface region between a ferritic steel and weld metal Inconel 52 of a DMW. The main conclusion is that for DMW HAZ cracks that deviate to the fusion boundary tearing resistance is higher for the cracks initiating further away from the fusion boundary. This result affects how the lower boundary values of DMWs shall be determined. Because the initiation location in the heterogeneous interface of DMWs has a big impact on tearing resistance, a standard developed for heterogeneous materials shall contain guidelines on microstructural characterisation of the fracture initiation location.

A goal related numerical modelling of material behaviour was to develop a more efficient numerical method for damage mechanics analyses of elastic-plastic materials. The developed numerical approach can be used as a replacement to the GTN model for prediction of crack growth. Number of parameters used by the developed numerical method is only three, which is substantially less than nine parameters of the GTN model. This reduction in parameters eases the computational process and improves the accuracy of the model. The three parameters are calibrated based on experimental studies of voids or J-R curves.

A final objective related to DMWs was to compare numerically and experimentally obtained residual stresses. The existing experimental residual stress results of a large scale repair welding mock-up were utilized. 3D welding simulation were performed with a) Pass by pass modelling (movement of the welding torch is modelled), b) Using simplified block dumping technique and c) Using simplified rapid dumping technique. These simplified procedures are usually necessary in industrial cases. Computations were performed with the baseline model (pass by modelling), and with the model utilizing block dumping and with a combination of the previous techniques. Considering the simplified models, the model including both weld pass block dumping and weld torch movement modelling (last three weld passes of the girth weld) gives similar results compared to the baseline model that gives results that are in line with the measured residual stress. The solution times and result file sizes are greatly reduced, when the simplified models are used.

### **Deliverables in 2017**

- A journal article on the dependence between  $\eta$ -factor and crack location respective to a fusion boundary between hard and soft materials in a SE(B) specimen.
- A journal article on the effect of crack path on tearing resistance of a narrow-gap Alloy 52 dissimilar metal weld. The main conclusion is that for DMW HAZ cracks that deviate to the fusion boundary tearing resistance is higher for the cracks initiating further away from the fusion boundary. This result affects how the lower boundary values of DMWs shall be identified.
- A journal article describing a more reliable method for analyses of fracture toughness of SE(B) specimens made of dissimilar metal welds.

- A research report describing a simplified residual stresses simulation procedure that decreases the analyses time.
- A research report describing the possibility of applying a general irradiation trend curve for high Nickel steels.
- A research report describing a new special numerical local approach method to do the damage mechanics analyses under plastic deformation.
- A Conference abstract describing a more reliable method for analyses of fracture toughness of SE(B) made of dissimilar metal welds
- Master's Thesis on applicability of miniature Compact Tension specimens for fracture toughness determination in ductile-brittle transition range.
- Travel report from IGRDM20 giving a short summary of the presentations.

#### 2.3.5 MOCCA - Mitigation of cracking through advanced water chemistry

Corrosion problems in the PWR secondary circuit are mostly related to deposition of magnetite into steam generator (SG) and enrichment of impurities into crevices within the circuit. The enrichment is typically driven by boiling. Water entering the crevices within a SG (e.g. between tube and tubesheet or under a magnetite deposit on a straight tube) boils letting volatile species escape as steam and leaving non-volatile species (salts, lead, copper etc) in the small water volume of the crevice. After some time of operation, the crevice chemistry can become very aggressive (either acidic or basic) due to impurity enrichment.

This project focuses on advanced water chemistry tools by which the formation of magnetite particulates in the feed water line can be mitigated and their deposition into SG can be minimised. To that end, the mechanism of lead assisted stress corrosion cracking as a major threat to SG integrity is researched. In addition, substitutes for using hydrazine, a potentially cancerous chemical used in PWRs, are studied.

### Specific goals in 2017

The use of hydrazine, an oxygen scavenger routinely used in PWRs/WWERs both during outage and power operation to ensure low oxygen concentration and thereby low corrosion rates, is under consideration because it's negative effects on environment and health. In 2017, the target was to compare experimentally the effectiveness of several alternatives to hydrazine as oxygen scavengers. Especially alternatives which are active at low temperature, i.e. during plant shut-down were of interest here.

One of the primary causes of SG corrosion damage is magnetite particle formation in the secondary side feed water line and further deposition of magnetite particles into SGs – thus, finding ways to mitigate feed water line corrosion is a major goal in this study. In 2017, a series of experiments was conducted to determine the effect of a particular film forming amine, octadecylamine (ODA) on the rate of corrosion, i.e. the rate of formation of magnetite particulates. Another goal was to modify the equipment so that the maximum temperature could be increased from 250°C to 300°C.

Another clearly established cause of SG corrosion damage is the lead assisted stress corrosion cracking, PbSCC. In 2017 the target was to finalise the work on PbSCC of carbon steel in acidic crevice environment, representative of some steam generators.

International co-operation was continued in 2017 by e.g. attending the Eurocorr 2017 conference and by taking part in the European Co-operative Group on Corrosion Monitoring (ECG-COMON) work.

### Alternatives for hydrazine

The primary requirements for an oxygen scavenger are strong reducing action and good passivation ability. Strong reducing action keeps oxygen levels entering the steam generator low, thus minimising the risk of SG tube degradation by localised corrosion modes. Good passivation ability, on the other hand, reduces propensity to flow assisted corrosion (FAC) in the feed water line and thereby reduces rate of delivery of corrosion particles into SG where they could form deposits and enhance susceptibility to localised corrosion modes.

Based on a previous literature study, the present investigation focused on the effectiveness of several hydrazine alternatives as oxygen scavengers. The conditions used were representative of a steam generator under revision period, i.e. room temperature and alkaline pH. To evaluate the oxygen removal rate, measurements of dissolved oxygen concentration with time in borate buffer solutions with and without the addition of magnetite powder that contained different concentrations of carbohydrazide, diethyl-hydroxylamine, methyl-ethyl-ketoxime and iso-ascorbic acid were performed and analysed. All the reactions were found to be first order with respect to oxygen and either first or zeroth order vs. the scavenger concentration. A somewhat significant accelerating effect of magnetite powder added to the solution was observed.

Based on quantitative evaluation of the data, the following ranking of the studied compounds by oxygen scavenging ability at 21±1 °C and pH 9.2 can be proposed: iso-ascorbic acid >> carbohydrazide > diethyl-hydroxylamine > methyl-ethyl-ketoxime (Table 2.3.5.1). The presence of magnetite accelerated the removal rate of dissolved oxygen in some cases (see for an example with iso-ascorbic acid in Figure 2.3.5.1).

Table 2.3.5.1. The oxygen removal rate of four candidate alternatives to hydrazine.

Scavenger	oxygen removal rate in pure solution / $\mu\text{mol l}^{-1} \text{s}^{-1}$	Maximum oxygen removal rate with magnetite / $\text{mol l}^{-1} \text{s}^{-1}$
Carbohydrazide	0.043 (0.78)	0.043 (i)
DEHA	0.033 (0.60)	0.033 (0.60)
MEKO	0.0087 (i)	0.030 (i)
Iso-ascorbic acid	0.188 (i)	0.338 (i)

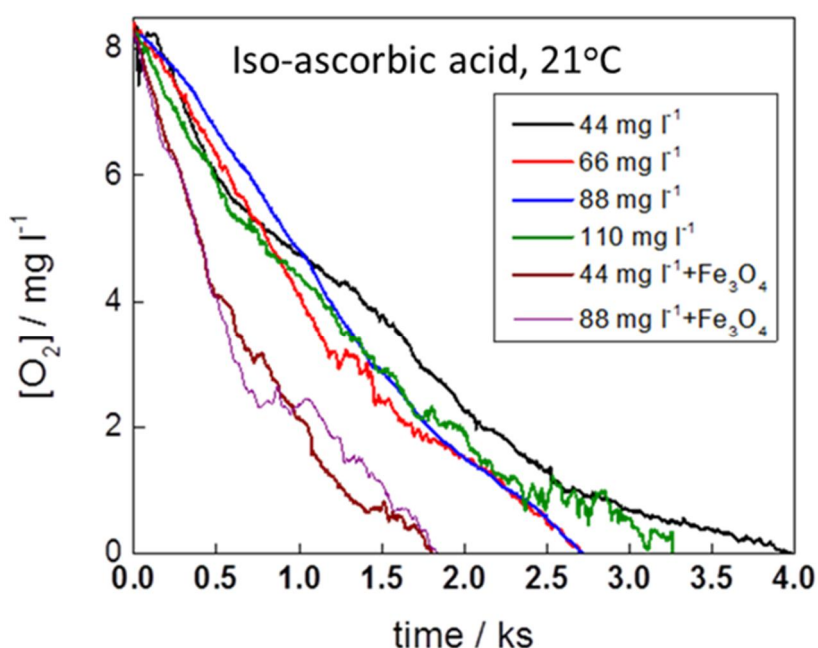


Figure 2.3.5.1. Effect of iso-ascorbic acid on the removal rate of dissolved oxygen. Ammonia water chemistry, pH = 9.2, T = 21°C.

### Mechanism of lead assisted stress corrosion cracking of carbon steel

The magnitude of corrosion damage around the SG tubes is typically enhanced by enrichment of impurities within crevices. This enrichment is driven by boiling, where water entering the crevices within a steam generator (e.g. between tube and tube-support or under a magnetite deposit on a straight tube) boils, allowing volatile species to escape as steam and leaving behind non-volatile species (salts, lead, copper etc.) in the small water volume of the crevice. Lead (Pb) has been detected in effectively all tube-support samples, crevice deposits and surface scales removed from steam generators. Typical concentrations seen are 100 to 500 ppm but in some plants, concentrations as high as 2,000 to 10,000 ppm have been detected. The cracking susceptibility is believed to have a strong dependence on the redox-potential of the crevice environment. Redox-potential, on the other hand, is affected by the amount of e.g. copper oxide in the crevice solution.

The PWR steam generator tube materials considered to be most resistive towards stress corrosion cracking (SCC), i.e. Alloy 600TT, Alloy 800 and Alloy 690 have each been shown to be susceptible to SCC enhanced by the presence of lead (PbSCC). In case of VVER-type PWRs, the steam generator tubing is most often stainless steel which has a relatively low

susceptibility to PbSCC. However, the VVER steam generator body material, carbon steel, has been shown to be susceptible to PbSCC.

The technique for studying SCC in this project is to perform slow strain rate tests (SSRT) in which a tensile specimen is loaded at a constant strain rate until fracture occurs. Susceptibility to SCC is deduced from the reduction in fracture strain as compared to that in an inert environment (e.g. air or the same environment but without the SCC promoting agent) and additionally from the morphology of the fracture surface.

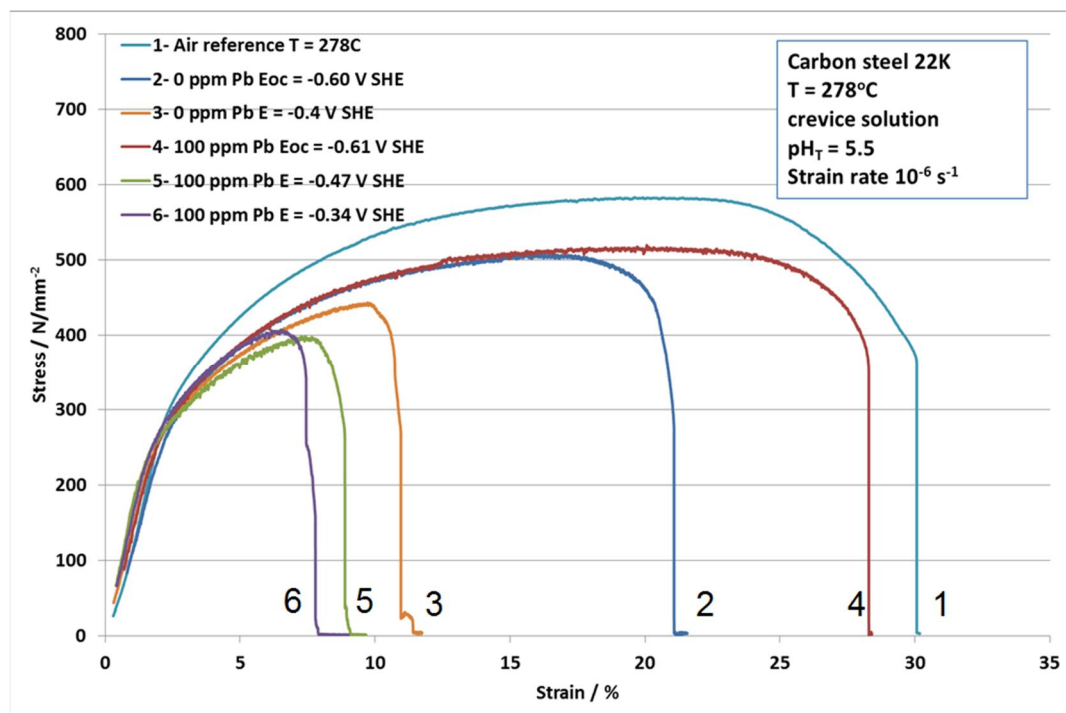


Figure 2.3.5.2. Comparison of stress-strain –curves of carbon steel 22K in crevice solution at  $T = 278^{\circ}\text{C}$  with and without Pb, at corrosion potential and at slightly elevated potentials.

Figure 2.3.5.2 shows a comparison of stress-strain curves of carbon steel 22K in crevice solution at  $T = 278^{\circ}\text{C}$  with and without Pb, at corrosion potential and at slightly elevated potentials. Surprisingly, addition of 100 ppm Pb at corrosion potential is seen to increase the fracture strain from 22% to 28%, i.e. make the material more ductile. However, increasing potential (simulating slightly oxidising environment produced by e.g. oxygen leakage into the SG) results in a dramatic reduction of the fracture strain to values at and below 10%.

The GDOES analysis of the surface films, Figure 2.3.5.3, shows that addition of 100 ppm Pb reduces the overall thickness of the film to roughly half of that without Pb. Concerning the distribution of alloying elements, Si is enriched at the metal/oxide interface, whereas some enrichment of Ni in the outer layer is observed. Sulfur is incorporated in the outer oxide and exhibits a maximum that is hypothesized to coincide with the inner layer/electrolyte interface. There is a significant amount of Pb at the surface and in the inner layer (ca. 0.45 at. %), and what is more interesting, the profile of lead in the outer layer seems to follow that of sulfur.

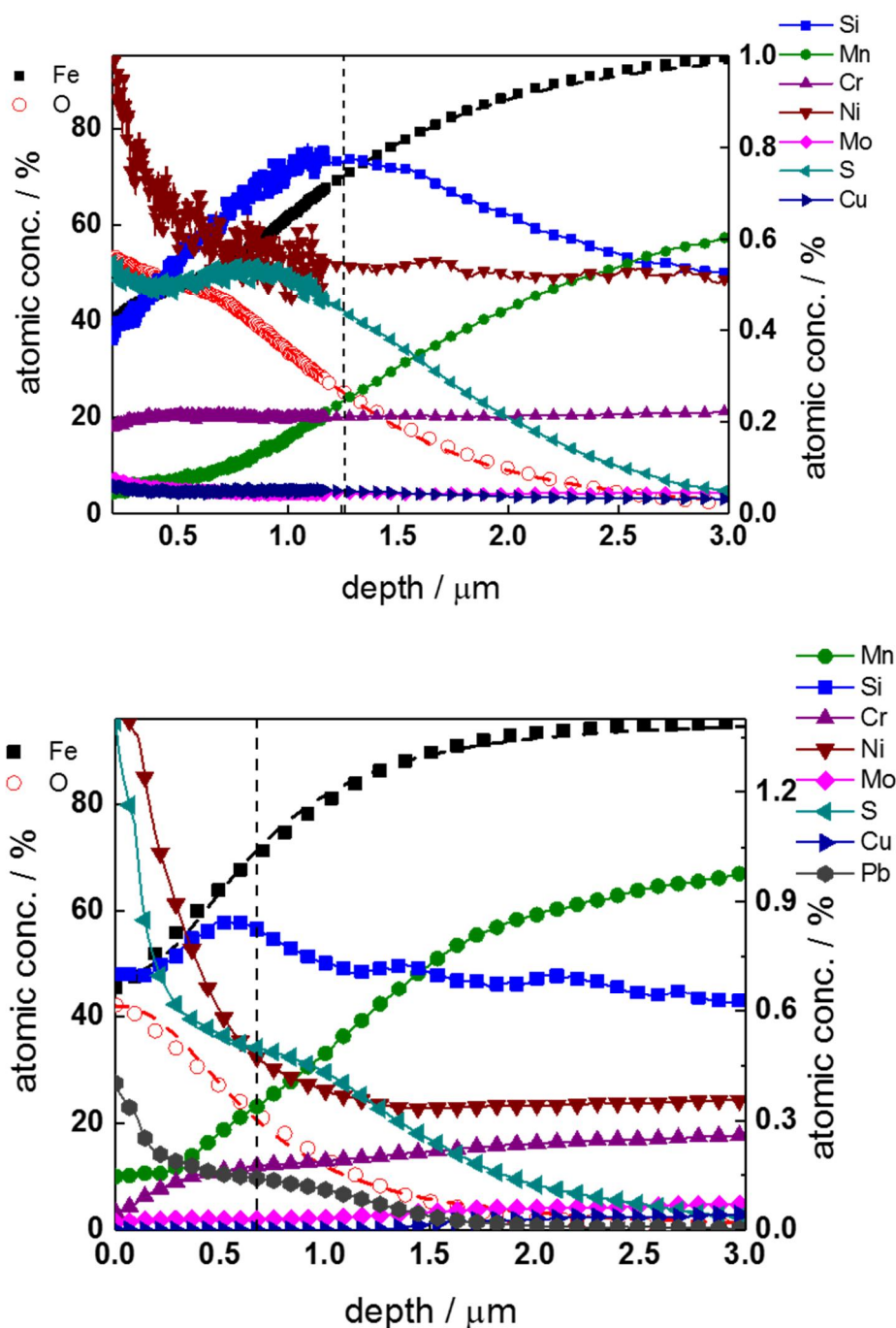


Figure 2.3.5.3. GDOES depth profiles of constituent elements (at.%) for the oxide on carbon steel formed for 140 h at 278°C in SG crevice solution without (a) and with Pb (b) at open-circuit potential. Dashed lines show sigmoidal fits of the Fe and O profiles to estimate the position of the metal/oxide interface.

In this investigation, the effect of potential on oxidation and general corrosion, as well as stress corrosion susceptibility of carbon steel exposed to simulated steam generator crevice solution with and without lead impurity was studied using in-situ impedance spectroscopy, ex-situ characterization of in-depth composition of oxide films and slow strain rate tests (SSRT). From the obtained data and their quantitative interpretation using the Mixed Conduction Model, it can be concluded that in the potential range -0.6 ...-0.5 V, the interaction of lead with the magnetite-type oxide during its formation results in reduction of both general corrosion / release rates and SCC susceptibility. On the other hand, at potentials higher than -0.5 V, there is a deleterious effect of lead on SCC susceptibility that

appears to be secondary to the effect of potential. Further investigations in alkaline crevice solutions are planned to gain a deeper insight in the effect of lead on general and localized corrosion of carbon steel in steam generators.

### 2.3.6 THELMA - Thermal ageing and EAC research for plant life management

The objective of the joint VTT – Aalto THELMA project is to support the safe operation of NPP's through increased understanding of the influence of light water reactor environments on the behaviour of nuclear materials. To meet these goals, several tasks are pursued dealing with thermal ageing of stainless steel cast material and weld metals and of wrought Alloy 690 material. The testing capabilities of crack initiation in simulated LWR environments are benchmarked in an international Round Robin exercise. The latest research results on corrosion fatigue assessment are brought to the SAFIR 2018 programme through participation in an EU-project and reporting the results within THELMA. A closer connection between mechanical and microstructural properties of pressure vessel steels are built through joint efforts in the SAFIR 2018 LOST and THELMA projects, where specimens, mechanically tested in the LOST project are microstructurally characterised in THELMA. International co-operation and publication at conferences is important as a tool for education, for bringing the latest knowledge to Finland, through submitting detailed travel reports SAFIR 2018, and to benchmark the scientific level of our own research. Most of the work in THELMA 2017 is performed by the YG, while the senior experts mentor the work. Mentoring and knowledge transfer is thus a day of the daily work, and the YG has great possibilities for learning by doing.

#### **Specific goals in 2017**

The THELMA 2017 project has several goals dealing with the long-term behaviour of nuclear materials.

The thermal ageing of cast stainless steel of type CF8M is investigated in co-operation with doctoral student M. Bjurman from KTH, Sweden. The materials, delivered to the project by the supervisor, professor Pål Efsing, Vattenfall and KTH, are from the cold and hot leg from a steam generator and have been thermally aged for 70 000 h at 291°C and 325°C, respectively. In 2017, further nano-indentation and electrochemical measurements, using a slower than standard scan rate, were performed. The nano-indentation hardness increase with ageing and the level is similar to that in thermally aged Type 316L weld metal. A slower scan rate increase the sensitivity of the measurements, and increase the reactivation peak. However, more measurements are needed to confirm, that the results really reflect thermal ageing and not general dissolution.

The characteristics and properties as well as the thermal ageing mechanisms of Alloy 690 materials (totally 36 conditions) are determined using thermally aged materials received from KAERI, Korea. The thesis *“Effect of thermal ageing on Alloy 690 and 52 in pressurized water reactor applications”* by R. Mougnot was successfully defended in 2017. Thermal ageing of Alloy 690 triggers an intergranular (IG) carbide precipitation which is known to promote an ordering reaction causing lattice contraction. Variations in hardness and lattice parameter were attributed to the formation of short-range ordering (SRO) in all four conditions investigated in most detail with a peak level at 420 °C, consistent with the literature, Figure 2.3.6.1. The strongest ageing temperature depends on the iron-content of the material, and is 420 °C for the material in question. Prior heat treatment induced ordering before thermal ageing. At higher temperatures, stress relaxation, recrystallization and  $\alpha$ -Cr precipitation were observed in the cold-worked samples, while a disordering reaction was inferred in all

samples based on a decrease in hardness. IG precipitation of  $M_{23}C_6$  carbides increased with increasing ageing temperature in all conditions, as well as diffusion-induced grain boundary migration.

Irradiated stainless steels are characterised for the Halden programme. In 2017, three materials of Type 316 cold worked and non-cold worked Type 304 with doses from 5 to 9 dpa were investigated. The main objective is to determine the deformation mode and possible formation of martensite close to the fracture surface of the specimens after in-pile crack growth testing at the Halden reactor. Both phenomena may influence irradiation-assisted stress corrosion cracking, which has been vastly observed in baffle bolts. The Type 316CW materials showed more slip bands and twins compared to the Type 304 material. Features similar to clear channels, which is regarded as the main deformation mode in irradiated stainless steels, were observed, but no indication of martensite, Figure 2.3.6.2. The amount of deformation features will be compared to those in specimens removed further away from the fracture surface in 2018, to evaluate what comes from deformation during crack growth and what from cold work from manufacturing of the materials.

The latest new test results and development of assessment methods for environmentally assisted fatigue are made available to the SAFIR 2018 programme through participation in the EU-INCEFA+ project. VTT focusses on the microstructural characterisation of the specimens, which has been performed, and later on fractography of tested specimens. The microstructural results show differences in the surface hardness profile and e.g. grain size in the materials, which are Type 304, 304L, 316L, 321 and 347. The testing focus is on assessing the effect of mean stress, hold time and surface finish on fatigue life. During 2017, the first test results in environment on a common Type 304L material became available. This first data imply a reduction in lifetime due to holds, which is a contradiction to the assumed effect of holds, Figure 2.3.6.3.

THELMA 2017 participated in a Round Robin on initiation testing, arranged by the International Co-operative Group on Environmental Assisted Cracking, ICG-EAC. One of the main goals of the group is to promote high-quality testing procedures and data production. VTT performed initiation testing in simulated PWR environment on two different Ni-based Alloy 600 materials, which were delivered by GE and PNNL, US. Testing was performed following the detailed testing protocol produced by the group. The PNNL heat was tested at ~90% and the GE/EPRI heat at 101% of 0.2% proof stress in simulated PWR water at 350 °C. Tests on the PNNL heat did not result in SCC within 2000 h exposure. In the GE/EPRI heat, SCC cracks initiated in 260 and 510 h. The results are in-line with other available test results from seven laboratories, Figure 2.3.6.4. Testing is still ongoing in several laboratories. VTT acquired also some lessons learned from the testing, which further increase our initiation testing quality. The meeting in 2020 will be hosted by Finland, and preparations for the meeting has started by selection of the venue.

The objective of the microstructural characterisation of pressure vessel steel is to improve the understanding of factors affecting brittle fracture initiation, and thereby increase the understanding of reasons for initiation and scatter in test data. The microstructural characterisation of fracture toughness test specimens from non-irradiated Barsebäck 2 pressure vessel materials showed the importance of investigating both specimen halves for true identification of the initiation site details, which is not customary. A further observation, which is important, is to compare the location of the initiation site with the shape of the pre-fatigue crack front. The highest stress, and thus the most likely initiation site, in a case, where initiation would be stress, and not microstructurally driven, is at the deepest point. In the performed investigations, specimens, which showed the largest distance of the initiation site from the deepest point of the pre-crack, also showed much lower fracture toughness values, compared to sister-specimens tested at the same temperature. This indicates that initiation in these specimens are more strongly influenced by microstructure than stress, while the stress seems to be the main driver on most specimens.

In addition to conference publications on results from THELMA 2017, a review article on intergranular stress corrosion cracking (IGSCC) was published at the Eurocorr 2017 conference. The review is an overview of IGSCC, a topic with which the THELMA project manager has worked with for decades. It was written mainly for the YG, summarising the issue and listing the main references.

### Deliverables in 2017

- Thesis on thermal ageing of Alloy 690 by Roman Mouginot, Aalto University approved and published. Short range ordering was observed, indicated both by the microstructure and contraction of the lattice.
- Scientific article and conference paper on thermal ageing of alloy 690 summarising the most important results from the thesis published.
- Research report on the VTT Round Robin results concerning initiation testing of Alloy 600 in simulated PWR conditions. The initiation test results of VTT are in line with others showing good testing practises at VTT.
- Conference publication and research report summarising the TEM-observation on 5-9 dpa dpa irradiated 304L and 316L stainless steels tested in-core in the Halden reactor. Clear channels, regarded as the most important deformation mode were observed as well as strain blooms from these on grain boundaries.
- Research report on the progress in 2017 in the EU-INCFEA+ project dealing with environmentally assisted fatigue assessment. The first test results indicate a detrimental influence of hold times on the fatigue life, which is contradiction to expectations.
- Research report on microstructural characterisation of fracture toughness specimens from non-irradiated Barsebäck 2 pressure vessel materials. The results indicate that brittle fracture initiation mostly is driven by stress and not microstructural in-homogeneity.
- Review article on intergranular stress corrosion cracking of austenitic stainless steel. The article is review, intended especially for the YG, and thus a part of knowledge transfer.
- Tutorial on fracture surface examination at the ICG-EAC meeting to the YG.
- Travel reports from conferences. Knowledge transfer from the international arena to the SAFIR 2018 is considered very important, as the material topics, including failures, benefit from early knowledge on incidents in plants.

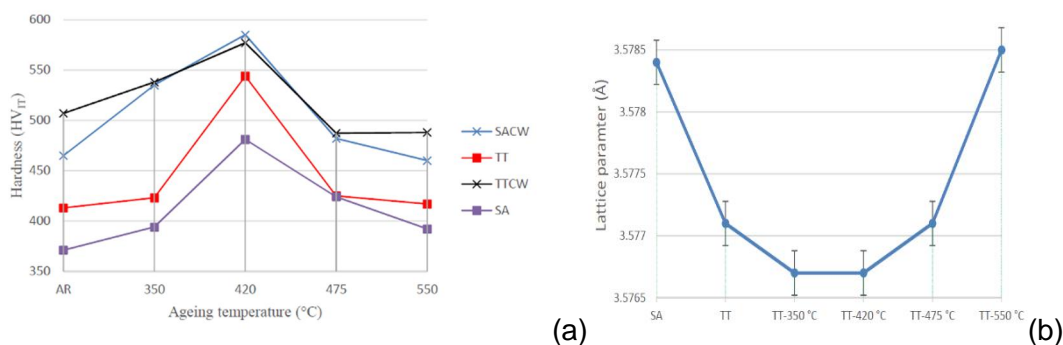


Figure 2.3.6.1: Nano-indentation hardness (a) and lattice parameters, determined using X-ray diffraction, of as-received SA and TT samples, and of the TT condition after ageing at 350, 420, 475 and 550 °C for 10 000 h.

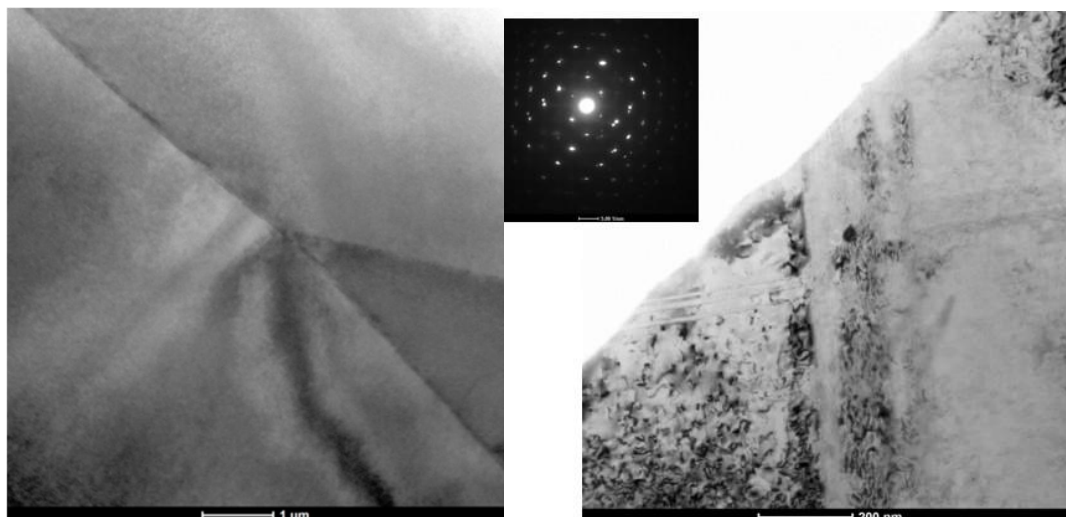


Figure 2.3.6.2: Deformation structures, i.e., strain field at a grain boundary (left) and probable clear channel (right) in a 9 dpa Type 316 CW material.

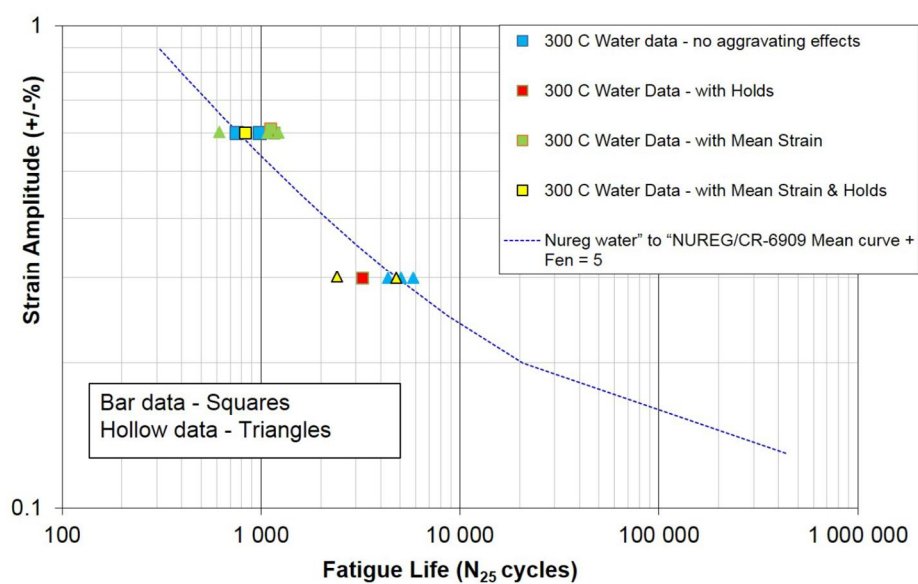


Figure 2.3.6.3: Strain amplitude vs. fatigue life ( $N_{25}$ ) in LWR environment.

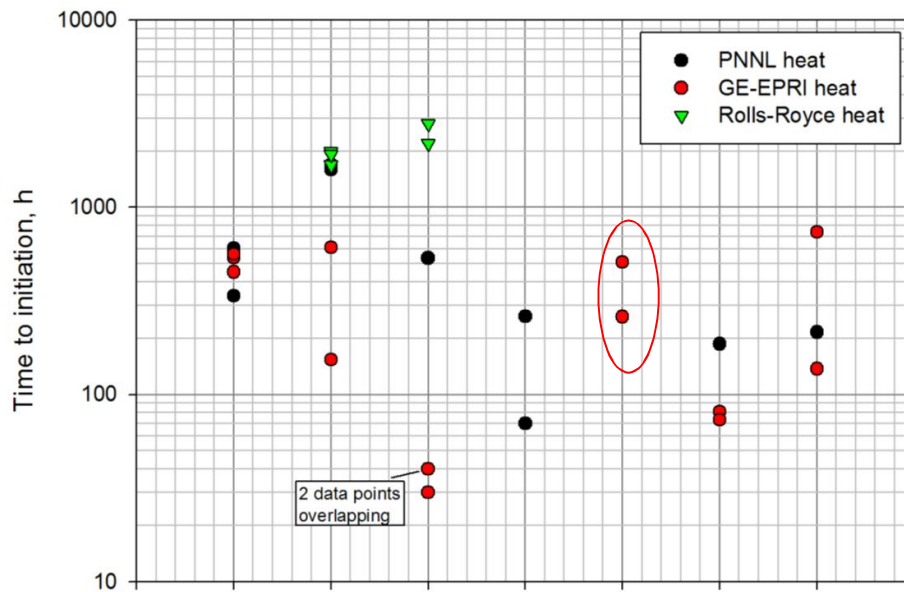
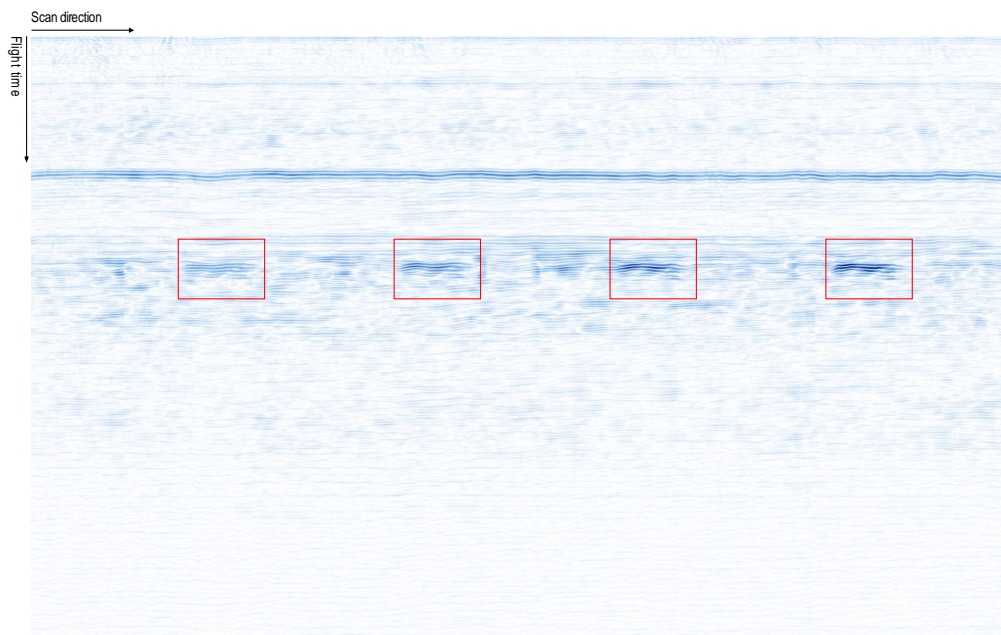


Figure 2.3.6.4: Available time to initiation data. The VTT data is circled, showing that the results are in line with those from other laboratories, including those with global top reputation in initiation testing.

### 2.3.7 WANDA - Non-destructive examination (NDE) of NPP primary circuit components and concrete infrastructure

A profound understanding of the reliability of non-destructive examination (NDE) methods is needed for safe operation of nuclear power plants (NPP). The project of NDE on NPP primary circuit components and concrete infrastructure (WANDA) applied to the SAFIR2018 programme is focusing on the development and understanding of NDE methods. WANDA consists of two work packages. Work package 1 (WP1) addresses NDE on NPP primary component materials and WP2 focuses on the NDE of NPP concrete infrastructure.

The ISI for primary circuit components is mostly performed in a short time period with limited accessibility. NDE techniques are the main tools to inspect the structural integrity of the primary circuit components in the NPP. The development of the NDE techniques towards more reliable and efficient ISI promotes the safety of NPPs. Artificial defects are typically used as a reference when the performance of an NDT procedure is demonstrated. Because of the lack of real defects, artificial defects are needed for certification and training of the inspectors. According to the previously performed studies in MAKOMON project in SAFIR2014 on artificial defects, the ultrasonic response varies with the type of the defect and with the technique used. To be able to evaluate the severity of the detected defects, it is highly important to know the exact type of the artificial defects in the reference samples and their correspondence to the actual defects. The use of artificial defect can lead to an error, if the limitations of the artificial defect used for the NDE procedure design or qualification compared to ISI -defects (e.g. stress corrosion crack) is not known. Also in recent years, there has been increasing need to better quantify the expected performance and, in particular, to obtain quantitative data on POD for the used inspections. This information is needed, for example, to better facilitate risk-informed in-service inspection.



*Figure 2.3.7.1. View along the weld with scaled cracks introduced to the data (red rectangles).*

The safety significance of NPPs reinforced concrete structures, especially the containment, combined with the current trend towards life extension and the regulatory authorities' demands for even higher levels of safety assurance, emphasises the importance of effectively controlling ageing degradation. The inspection of NPPs concrete structures present challenges different from those of conventional civil engineering structures. As a result, there is a need for NDE of RCS to be able to undertake compliance testing, collection of specific data or parameters, condition assessments, and damage assessment.

Determination of the condition of NPP concrete infrastructure is achieved through a structural condition assessment, initiating with a detailed visual assessment of the structure, followed by determination of need for additional surveys or use of destructive or non-destructive testing and evaluation of the NDT methods. The objective is to characterise the existing performance and the extent and causes of existing degradation.

NPP reinforced concrete structures (RCS) present a unique challenge for development of performance acceptance criteria because of their large size, limited accessibility in certain locations, the stochastic nature of past and future loads, as well as that of mechanical and durability performance characteristics due to ageing and possibly degradation, and the qualitative nature of many non-destructive evaluation methods. Improved guidelines and acceptance criteria to assist in the interpretation of condition assessment results, including development of probability-based degradation acceptance limits, are required.

The application of NDT methods to NPP RCS has several challenges: infrastructure wall thicknesses; dense and complex reinforcement detailing; penetrations or cast-in-place items; limited accessibility; severe environments; inaccessible structures; limited experience with NDE methods for NPP and lack of specific equipment or knowledge for NDE of NPP RCS.

It is understood that there is a clear need for means of ensuring concrete structures meet their design criteria, during and immediately following construction, where NDE methods can provide quality control and verification. However, with time, NPP RCS are subject to ageing resulting in their degradation and consequently deterioration in their performance. NDE methods can be used to characterize material properties, measure performance, and provide valuable input for the assessment of the RCS performance.

There is still a clear need for NDE methodologies to continue to evolve. Research has shown the need for realistic specimens should be developed to allow direct comparisons between various techniques, with consideration given to ensuring a broad range of defects, and to ensure the probability of detection for a method can be properly determined.

### Achievements in 2017

- Three conference papers written.
- Personnel have attended the conferences such as European-American Workshop on Reliability of NDE, in Potsdam, Germany and Structural Mechanics in Reactor Technology (SMiRT), in Busan, Korea. Also international collaboration with Nugenia Forum and IRSN's ODOBA Project.



*Figure 2.3.7.2. Construction of the foundation of the TVO -thick-walled concrete structure.*

### Specific goals in 2017

One of the main focuses of the WANDA project is to maintain the expertise level of Finnish NDE research of the NPP component materials and to raise that of NDE of concrete infrastructure. Also one of the important factors for the future is the transfer of know-how in the area of NDE to a younger generation of scientists. Objectives also are: to analyse the differences in artificial defects and further verify the reliability of NDE simulations by evaluating the structure of the austenitic weld and comprising a valid model, to participate the international cooperation within U.S. Nuclear Regulatory Commission (NRC) PARENT (Program to Assess the Reliability of Emerging Nondestructive Techniques) and its follow-on program PIONIC, to critically assess the NDT techniques and monitoring systems currently in use to fulfil the needs of NPP infrastructure evaluation in Finland, to develop guidelines for

the use of NDE techniques in design and condition assessment, for the implementation of monitoring systems, and for performance based design and ageing management of the concrete infrastructure.

#### **Deliverables in 2017**

- Scientific paper of Nuclear industry POD curves on ultrasonic testing.
- Travel report on reliability of NDE
- Report on the current state-of-the-art in using the probability of detection in the field of reinforced concrete structures condition assessment.

#### **These deliverables postponed to year 2018**

- Report on a) the definition of the condition zero for the mock-up wall and b) the detection of the imbedded defects in TVO-thick wall.
- Report on the current state-of-the-art in using probability of detection in the field of reinforced concrete structures condition assessment (Spring 2018)
- Report on design of mock-up: NDE and monitoring.

Deliverables of WP2 have been delayed due to delay in the construction of the mock-up wall. Also, personnel changes have affected the progress of the deliverable D2.2.1: Report on the current state-of-the-art in using probability of detection in the field of reinforced concrete structures condition assessment.

The budget for these have been used for the process of construction of the wall and characterization of the concrete (determination the condition zero for the foundation). All the necessary constituents of the wall have either being produced or already ordered/requested, and awaiting that they are brought together for the final phase of wall construction. Thus, meeting all the deliverables for 2018 is a realistic target.

#### **2.3.8 COMRADE – Condition monitoring, thermal and radiation degradation of polymers inside NPP containments**

Different polymer based materials are widely used in various applications in nuclear power plants and inside containments, e.g. cable jacketing/insulators, sealants, paint coatings, lubricants and greases. As any other material or component, polymers are susceptible to ageing. Elevated temperature, ionizing radiation and moisture are considered to be the most important ageing stressors and they tend to interact with the polymer structure in different ways. In addition to these ageing stressors, the properties of polymer blend, e.g. crystallinity degree, amount of fillers and antioxidants, has an effect to the ageing behaviour. Thus the degradation mechanism can be quite complex.

COMRADE was developed on input from a feasibility studies from Energiforsk AB and STUK and through discussions between VTT, RISE and the Nordic NPPs through Energiforsk. When developing COMRADE it was understood that there are gaps in knowledge for setting functional based acceptance criteria at the nuclear power plants. Furthermore a need in

gaining a better understanding on how a polymeric component reacts to different levels of low dose ionizing radiation and synergistic effects between thermo-oxidative and radiation degradation was identified.

### Specific goals in 2017

The work in COMRADE was divided in three different work packages (WPs) where each WP has their own specific goals. In WP1 the goal was to continue accelerated ageing test on EPDM o-rings and from the test data obtained, to suggest preliminary acceptance criterion for this specific o-ring design. Also the FEM model development, where the model could predict acceptance criterion as function of the o-ring cord size, was started as enough experimental data had been gathered. In WP2 the goal was to clarify whether polymer components aged at realistic conditions could be obtained for study from the operating Nordic NPPs. In WP3 various polymer ageing related issues was studied. First, related to the modelling work conducted with polymers, the goal was to launch the development work aiming to model and understand the reverse temperature effect on XLPE. Secondly, the experimental work concentrated on studying dose rate effects on EPDM and Lipalon cable jacketing material by applying semi-empirical power law model. Thirdly, the aim was to further develop the ToF SIMS technique to measure oxidation profiles induced by ageing on sample surfaces.

During 2017 two ageing test series were performed on EPDM test sheets and two dimensions of o-rings. Exposure of Viton o-rings are running but there are no sufficient results to draw any conclusions yet. One of the test series on EPDM o-rings was performed within a university master project and the second was performed by RISE personnel. The results show that high ageing temperatures causes high levels of compression set and hardness which correspond to leakage as seen in Table 2.3.8.1 below. Similar results are seen on both o-ring dimensions. Like in previous tests, the radiation does not have significant effect on any of the samples, since EPDM is known to be very resistant to radiation.

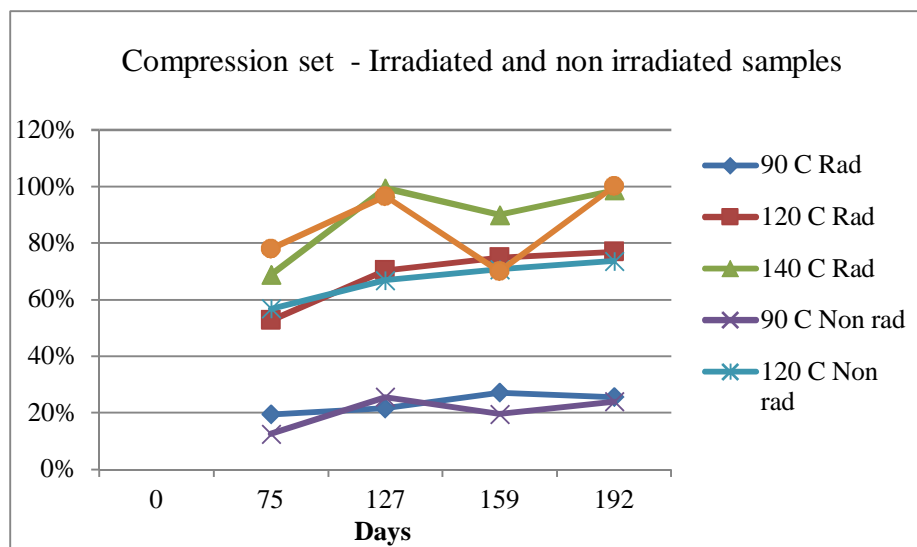
There is a correlation between material properties and leakage. However, the difference in hardening and compression of the rubber at the different ageing temperatures needs to be investigated and interpreted further and this will be done during 2018. Part of the property changes may be explained by further crosslinking and/or plasticizer loss.

*Table 2.3.8.1. Corresponding values of leakage and material properties. The data are taken from terminated experiments (192 days of exposure) on EPDM o-rings with core diameter of 7 mm. Hardness tests are measured on 2 mm thick test sheet.*

Exposure	Compression set (%)	Hardness (IRHD*)	Leakage
90°C	24	72	No
90°C, rad	25	73	No
120°C	73	79	No
120°C rad	77	79	No
140°C	100	87	Yes
140°C rad	99	90	Yes

\*IRHD international rubber hardness degrees.

Looking closer at the test sheets used for tensile tests, we observed small damages on the surface, looking like spots in the microscope. This effect was mainly present on those samples aged at 120 and 140°C and will be further investigated.



*Figure 2.3.8.1: Compression set measurements for 2017. Like in previous measurements the compression set increases significantly at elevated temperatures. There is a slight decrease in compression set after 59 days of exposure at 140°C followed by an increase. This needs to be investigated further since 140°C might be close to curing temperatures for rubber and cross linking may occur.*

For the FEM modelling on material properties Stress relaxation was also measured on EPDM and from these results a model was calculated. The model corresponded well to the measured data.

In WP2, the mapping of available polymer materials were continued and the focus was on the currently operating plants. A questionnaire was drawn up which was sent to power plant contact persons. The questionnaire compiled information on available polymer components, their service and storage history. Based on the results, few EPDM materials are available from the plants that can be potentially used in supporting the modelling work to be conducted in WP1.

WP3 content can be divided into three different subtasks where the first one focuses on using computational modelling techniques in polymer ageing. Based on the results obtained during 2016 literature survey modelling work is focused on explaining the “reverse temperature effect”. We used classical molecular dynamics (MD) to build united-atom structural models (one particle representing a CH<sub>2</sub> or a CH<sub>3</sub> unit) for the target material, polyethylene (PE). First, equilibrium structures for fully amorphous polyethylene were created. Then, methods were developed to convert the fully amorphous PE into partially crystalline and/or cross-linked forms. Methods were also tested for measuring the mechanical properties of PE. In addition, detailed all-atom reactive MD simulations were performed to study the mechanisms of radiation induced damage. The threshold recoil energy (energy required to introduce radiation damage) was estimated to be >20 eV in case of PE. Because MD timescales are significantly shorter than timescales for chemical reactions, the reactions of oxygen and radical species with the polymer will not be treated explicitly in the MD simulations, but will be taken into account in the structural details of the model system. This will require adding a chain scission mechanism to the united-atom PE model during 2018 for a proper description of the aging process.

The second subtask is related to developing technique measuring oxidation profiles on aged EPDM samples. During 2016 three different techniques were compared in oxidation profile measurements. ToF-SIMS seemed to be the most promising technique and the measurement procedure was further developed in 2017. The surface and bulk oxidation of EPDM were studied as function of absorbed dose and dose rate. ToF-SIMS seemed to be very sensitive technique in detecting oxidation products in the samples but identifying artefacts (caused by e.g. uneven surface and contamination during handling) from the normalized signals still causes uncertainty to the measurement results.

The third subtask focused on evaluating the dose rate effect by using semi-empirical power law model. The ageing of EPDM and Lipalon samples was studied as function of absorbed dose and dose rate. EPDM showed good radiation resistance which yielded in uncertain predictions of dose rate effect when the power law model was applied. In case of Lipalon the dose rate had an effect to the DED values but more experimental data from low dose rate irradiations would be required in order to confirm this observation. Overall, it should be stated that the used dose rates during the irradiations were relatively high and homogeneity of oxidation could not be confirmed which would ease the examination of the data quality.

WP4 focused on international cooperation. In 2017 COMRADE workshop was organized in Espoo, Finland by VTT. The two-day meeting was held at the VTT Centre of Nuclear Safety (CNS) during 27<sup>th</sup> and 28<sup>th</sup> of September. The first day concluded from lectures given by Dr. Sue Burnay with topics relevant to ageing of polymer components in nuclear power plants. The second day focused presenting the project results and discussing about them. In addition, visits to the CNS new laboratory premises and TK15 research hall were organized.

### **Deliverables in 2017**

- Development of condition monitoring technique for O-rings used in NPP applications (mid-term presentation at the COMRADE workshop)
- Development of FEM model and test run using data from T1.1 (RISE-research report)
- Organize a telephone conference with the industry team to present and discuss how the result from the first ageing test can be used (minutes of meeting)
- Identification of available polymers and their data nuclear power plants both running and shut down. (RISE-research report)
- Modelling efforts to understand the reverse temperature effect (mid-term presentation at the COMRADE Workshop)
- Dose rate effect study on EPDM and Lipalon cable jacketing materials (VTT-research report)
- COMRADE Workshop on polymer ageing issues at NPPs (Minutes of the meeting)

## 2.4 Research infrastructure

In 2017 the research area “Research infrastructure” consisted of three projects:

1. Development of thermal-hydraulic infrastructure at LUT (INFRAL)
2. JHR collaboration & Melodie follow-up (JHR)
3. Radiological laboratory commissioning (RADLAB).

### 2.4.1 INFRAL - Development of thermal-hydraulic infrastructure at LUT

#### **General objective of INFRAL**

The aim of the INFRAL project is to develop the thermal hydraulic measurement infrastructure of the LUT (Lappeenranta University of Technology) nuclear safety research laboratory. The up-to-date experimental research infrastructure is essential for the modern nuclear safety analyses. The implementation of novel measurement techniques in the thermal hydraulic experiments is needed for the validation of the Computational (Multi-)Fluid Dynamics (C(M)FD) methods. Important part of the INFRAL project is the further development of the techniques related to the advanced measurements and their applications. The goal is to build good in-house expertise in the use of recently acquired techniques to facilitate the needs of computational modellers in the future experiments in the best way if it is technically possible. The CFD grade measurements can give new insights into the physics behind the different flow phenomena that may ultimately lead in the improvements in the safety of nuclear power plants. Furthermore, the goal of the project is to secure the operability of (PWR) PACTEL and other test facilities, as well as to launch a study on the new major test facility to prepare for the post-PACTEL era.

#### **Specific goals in 2017**

In 2017, the INFRAL project was divided into four different work packages. The first work package (Advanced measurement techniques) includes activities that are related to the use of advanced measurement techniques at LUT. Part of the work is to develop analytical tools to extract the needed data from the measurements. The other part is to study the applicability of the techniques for different flow problems and to develop new measurement solutions. The second work package (Maintenance and equipment) aims on the maintenance of (PWR) PACTEL and other test facilities, and it comprises the yearly inspections, calibrations etc. The third work package (Modular Integral Test Facility (MOTEL)) aims on designing and constructing a new large-scale integral test facility in the LUT laboratory. The fourth work package (Project management, international co-operation and publications) includes the tasks related to the project management and participation to the reference group meetings and seminars. Also international co-operation actions, such as research visits, are a part of the work package.

The work package 1 of INFRAL consists of research topics that are related to the study and application of the so-called advanced measurement techniques: Particle Image Velocimetry (PIV), Wire-Mesh Sensors (WMSs) and High-Speed Cameras (HSCs). The measurement systems were acquired to LUT already during the previous project (ELAINE) in 2011–2014. During the on-going SAFIR2018 research programme, the advanced measurement systems have been developed further and used in multiple applications. In 2017, various activities were carried out to strengthen the in-house expertise and the know-how related to the measurement systems. It is essential that the researchers are familiar with the equipment and can also acknowledge the possible limitations. Some of the application targets of the systems are also related to non-SAFIR projects.

PIV was utilized actively in 2017. On the first half of 2017, ambitious measuring scheme for a contract measurement was executed. Overall, almost quarter of million raw images were captured and analyzed. The measurements were conducted in planar-PIV mode and part of

the measurements with added second camera measuring with camera endoscope. The camera endoscope was first time utilized for the measurements in this scheme. The measurements were focused on water flow within a rectangular channel. Considerable amount of experience was achieved in this commercial project in physical arrangements for PIV as well as in data processing schemes.

PIV was also utilized as a part of the INSTAB project in SPR-4, SPR-5, SPR-6 and SPR-7 tests. In the tests, the PPOOLEX test facility was layered with cold water in the bottom and hot water on top. PPOOLEX was filled with 1800 mm of water in which 200 mm was hot water on top (SPR-T6 1500 mm of water and 200 mm of hot water on top). The hot water layer was approximately 50 °C and the cold water temperature was approximately 12 °C. Four spray nozzles situated on top of the wet well of PPOOLEX were used to spray cold water, 12 °C, on top of the hot water layer. The main motivation was to test out the optical environment and its suitability to PIV measurements and whether it was suitable to measure velocities. Unfortunately, the optical environment was not optimal for measuring with PIV. The cases were measurable only before the hot layer or mixing zone enters the measurement area creating aberrations. There were indications that the time before the hot layer or mixing layer enter the measurement area, the flow is highly turbulent. When the measurement area is clear of aberrations, the flow is more consistent with less turbulence intensity.

The PIV system was updated with external Programmable Timing Unit allowing the use of up to eight cameras in the future. The addition will also allow additional light source to be used with laser. This allows timing PIV cameras, laser, high-speed cameras and their light source in synchronous manner if needed. New hard drives for the system computer and new DaVis10 software that is compatible with the Windows10 operating system were acquired during 2017.

The advanced applications for the wire-mesh sensor technique have been actively studied at LUT. The axial sensor design (AXE) was designed and constructed in the previous ELAINE project in the SAFIR2014 programme to tackle the problems related to the measurement of the axial flow behavior. During the on-going SAFIR2018 programme, the functioning of the sensor has been studied. The results from the first axial WMS measurements were presented in the SWINTH-2016 workshop in June 2016. The SWINTH-2016 conference paper was selected to be published in Nuclear Engineering and Design (NED) special SWINTH issue. The paper was modified and submitted, and it was published online in May 2017.

During 2017, the axial WMS technique was studied further with measurements in swirling two-phase flow. Void fraction distribution measurements in the HIPE test facility with both radial and axial WMSs under swirling two-phase flow conditions were conducted in order to see how the sensors perform in those conditions. Swirling flow was created with two separate swirling devices with different blade angles (30 ° and 60 °). During the first half of 2017, some swirling flow measurements were conducted, until the WMS electronics unit itself was broken and it had to be sent for repair. The unit was received back to LUT in August. The rest of the tests were conducted in December 2017 with the exception that with higher water superficial flow the axial sensor was not able to measure the case with the swirling device with 60° blade angle. The flow was too strong for the actual sensor as the sender and receiver wires connected to each other making void fraction measurement biased. Thus, the initial design for a new kind of sensor has started. Changing the structure of the axial sensor in a way that the intrusive front end will be eliminated and adding the distance between the sensor wires either with insulation material or by using different thickness circuit boards are considered now. An example of the effect of the circuit board's intrusive front end can be seen in Figure 2.4.1.1.

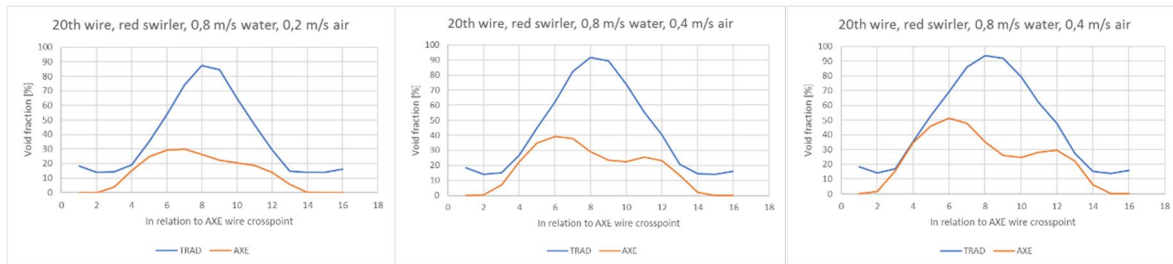


Figure 2.4.1.1. Void fraction comparison AXE vs. traditional radial sensor at the 20<sup>th</sup> wire of the axial sensor.

In 2017, it was also decided that a new WMS data analyzing software will be purchased from Helmholtz-Zentrum Dresden-Rossendorf (HZDR), and it will be used for the analysis instead of MATLAB codes. The idea for the procurement of the software came during a research visit to HZDR, Germany. The visit took place between 14<sup>th</sup> and 17<sup>th</sup> of August, and two researchers from LUT attended the visit. The new software has been in use and it offers relatively fast data analyzing capabilities compared to the old method by using MATLAB codes. A bachelor's thesis was written concerning the swirling two-phase flow measurements and related data analyzing with the new software. An example of a 3D representation of a WMS measurement result acquired with the software is presented in Figure 2.4.1.2.

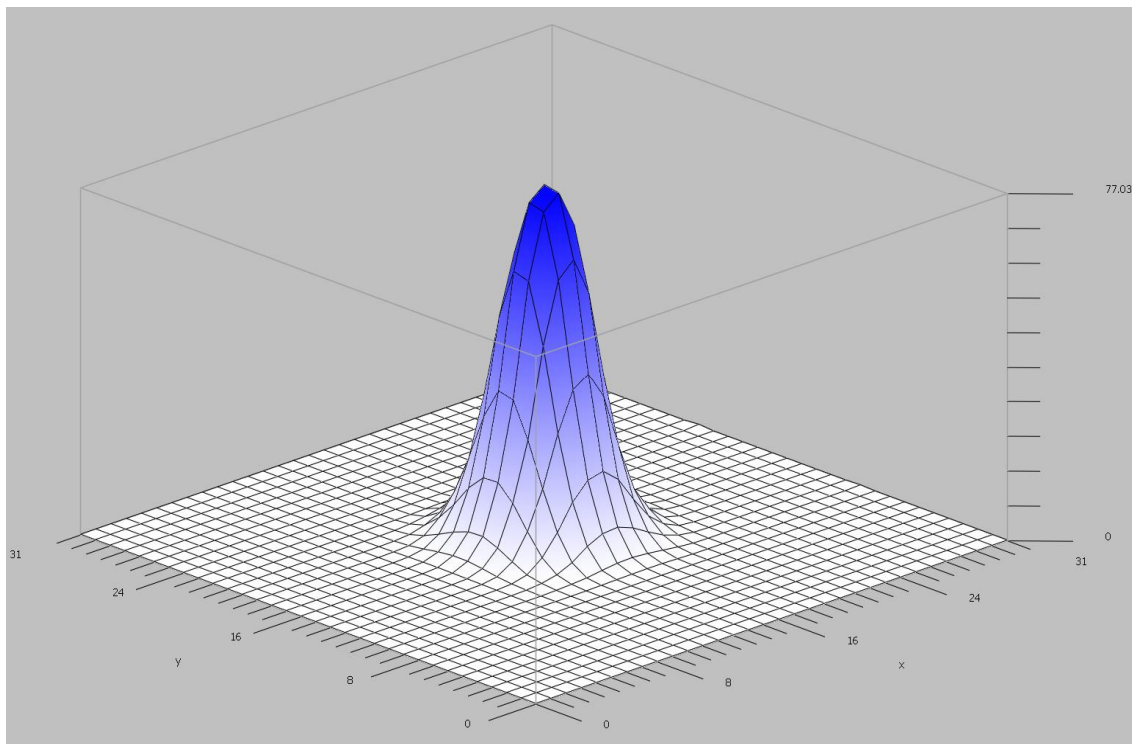


Figure 2.4.1.2. A sample of void fraction measurement result viewed in 3D mode in the new measurement software.

The HZDR visit served also other aims of the LUT laboratory. High temperature/pressure wire-mesh sensors used at HZDR were presented, and there were good discussions concerning them. LUT has followed closely the development of the high temperature/pressure WMSs, and there have been preliminary plans of applying them to the test facilities in the future. The newest sensors can operate at temperatures up to 286 °C and pressures up to 7 MPa, and in the future potentially up to 350 °C/22 MPa. This kind of sensors would significantly enhance the void fraction measuring possibilities in challenging circumstances. For example the planned operational temperature and pressure levels of the forthcoming large-scale LUT test facility, MOTEL, are 280 °C and 5–6 MPa, respectively.

During the research visit there were also valuable discussions related to possible applications of the “traditional” wire-mesh sensors. Initial talks and planning of using an axial sensor within blowdown experiments in PPOOLEX started in the last half of 2017. The sensor will be first tested in small-scale in a tank-like environment. The detailed planning will continue in 2018 with the help of HZDR. Results with this kind of testing scheme would produce valuable data for the validation of CFD calculations.

The high-speed cameras are used at LUT to support the data analysis of the PPOOLEX condensation experiments conducted within the INSTAB project. A pattern recognition algorithm has been developed for analysis of the HSC measurement data. In 2017, HSC data and the developed algorithm were used for inscription of one peer-reviewed article and a conference paper in 17<sup>th</sup> International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-17). In addition, some preliminary pattern recognition was made for an old transparent pipe (TRA) case.

In early December 2017, Technical Program Committee of NURETH-17 informed that the paper review committee has recommended the paper to be one of the potential papers to be published in a journal publication. Consequently, a new journal article about the frequency analysis is possible in the near future.

In 2017, the high-speed camera system has also been used in new steam momentum experiments within a separate effect pool where steam is injected through an inlet. The HSC data recorded during the experiments will be used in the near future.

In addition to PIV, WMSs and HSCs, development of other advanced measurement techniques is followed within the INFRAL project, too. One example of recently developed measurement techniques is the Distributed Temperature Sensor (DTS) based on Rayleigh-backscatter phenomenon. The sensor enables the measurement of temperature distribution in high detail in different geometries, such as a slab or a rod. There are preliminary plans for utilizing distributed temperature sensors in the LUT laboratory in the future. Possible applications of the DTS technique are presented in Figure 2.4.1.3.

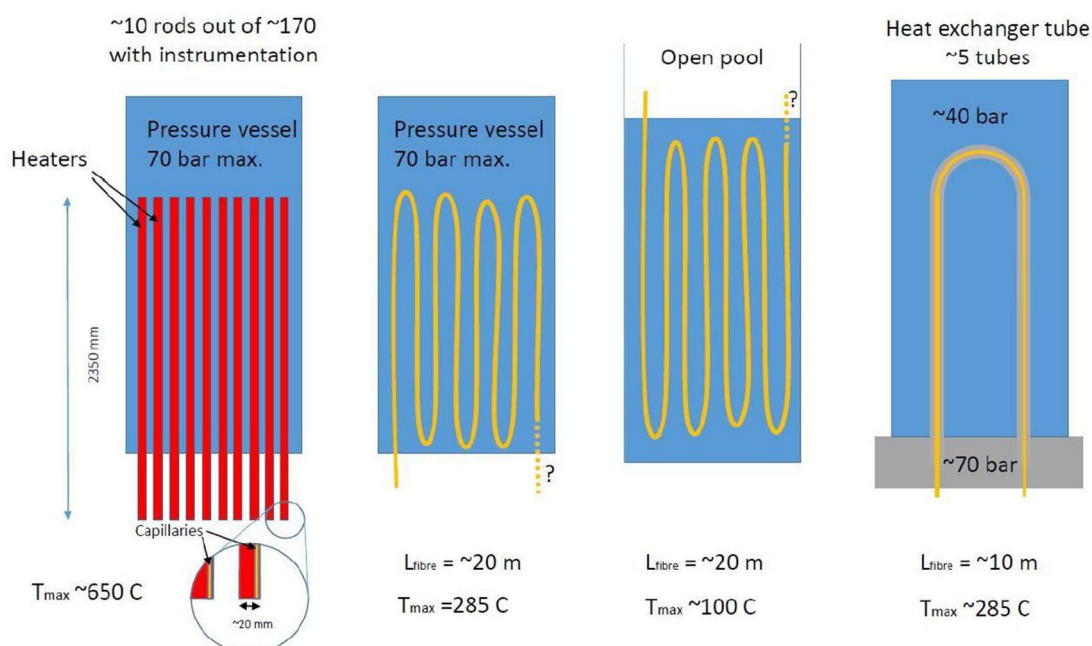


Figure 2.4.1.3. Different applications of the distributed temperature sensor.

In 2017, the manufacturer introduced the DTS technique at LUT. The electronic hardware for the DTS was purchased to LUT in 2017, and the functioning of the sensors will be tested in 2018.

In addition, the use and development of different tomography measurement techniques has been followed. During the visit to HZDR, different measurement systems of the HZDR were introduced. Among them were such imaging systems as a fast X-ray measurement system and a gamma tomography measurement system. The characteristics and requirements of those kind of systems were discussed. Tomography systems would provide novel and non-intrusive means to e.g. void fraction distribution measurement. It was once again learnt that both space-related and economic requirements of the tomography systems are significant.

Within the work package 2, the yearly calibrations of the (PWR) PACTEL measurements were carried out during the summer. The periodical pressure vessel inspections were successfully conducted. During 2016, a leakage in the PACTEL pressurizer relief valve was noticed, and the issue has been followed ever since. New stop valve has been installed to the pressurizer blow-out line. Some of the valves of PACTEL loops were repaired by fitting new seals. The upgrade of power transformers has been planned to enable higher heating power to be available for the thermal hydraulic experiments (1 MW to appr. 2.8 MW). The upgrade process has been postponed, and the options for the upgrade are being studied within the organizations involved. In 2017, new pipeline between PACTEL upper plenum and pressurizer was installed for easier pressure release after experiments. Measurement computers in the laboratory were replaced.

In the work package 3, the survey of the modularity-based requirements for the forthcoming modular integral test facility (MOTEL) was carried out. A research report was written on the issue. The report introduces the principles on how the modularity will be executed, as well as the physical scaling principles. The scaling of the facility will be based on the hierarchical two-tiered scaling methodology (H2TS). The design and the construction of the first components of the facility will be carried out during 2016–2018, and the experimental activities will begin in 2019. The actual design of MOTEL has started with the design of the heater and steam generator components. The design and the construction are funded by the Academy of Finland.

Within the work package 4, a presentation of the INFRAL project in the SAFIR2018 midterm seminar was given, and the above-mentioned research visit to HZDR, Germany, was made.

### **Deliverables in 2017**

- Status report on the advances in thermal-hydraulic measurements (WP1 report).

- Journal article: Pattern recognition algorithm for analysis of chugging direct contact condensation. Nuclear Engineering and Design. Note: the title was changed from the original due to topical issues.
- Maintenance of PWR PACTEL / PACTEL.
- Modularity based requirements of MOTEL -report. The report describes the principles on how modularity will be executed in the forthcoming modular test facility, as well as the physical scaling principles.
- Participation in the SAFIR2018 midterm seminar.
- Research visit to Helmholtz-Zentrum Dresden Rossendorf (HZDR). A travel report was written.

#### 2.4.2 JHR - JHR collaboration & Melodie follow-up

The Jules Horowitz Reactor (JHR), a new European material testing reactor (MTR), is currently under construction at CEA Cadarache research centre in France. Finland is participating in the construction with a 2 % in-kind contribution, which includes Underwater Gamma spectrometry and X-ray radiography (UGXR) and Hot-cell Gamma spectrometry and X-ray radiography (HGXR) systems, as well as a Mechanical Loading Device for Irradiation Experiments (MeLoDIE). With this in-kind contribution, Finland will have the opportunity to use and directly benefit the new JHR research infrastructure dedicated to nuclear safety related research. Furthermore, the in-kind contribution enables access to the results of the future experiments.

The JHR consortium has set up three working groups (WG) – (i) Fuel WG, (ii) Materials WG and (iii) Technology WG - to determine experimental needs and plan future experiments. To have our national interests brought forward and to be able to follow and participate in the planning of the experiments, VTT has named participants to each of the three WGs. The WGs hold meetings twice a year, and in spring an annual JHR Technical Seminar is held, where the outcomes of the WG meetings and the progress of in-kind work are presented. The first work package (WP) of this project focuses on this collaboration through WG participation. The latter WP concerned the in-kind contribution Melodie, which was finished in 2016.

#### **Specific Goals in 2017**

The goal in 2017 was the preparation of the continuation of the FIJHOP application, participation of the working group work, dissemination of the information of the progress of JHR to national stakeholders and arranging the technical meeting in Espoo in fall 2017.

#### **Deliverables in 2017**

- FIJHOP application was rejected by the European Commission, and the continuation of the work in preparing a joint project was initiated at the Nugenia Forum in Amsterdam. A travel report was prepared.
- JHR workshop in Cadarache on 20.-21.6.2017 was participated in.

- A day and a half seminar was arranged in Espoo, with participation from both the JHR consortium as well as the Finnish stakeholders.

#### 2.4.3 RADLAB – Radiological laboratory commissioning

The safe research and testing of radioactive and contaminated materials of the nuclear sector requires radiological facilities, and for highly radioactive materials, full hot cells for remotely handling the materials inside of heavy gamma shielding. The objective of the RADLAB project was to plan and execute the hot cell and hot laboratory portion of the radiological research infrastructure renewal, including the planning and making of critical equipment investments for the facility, and training of the technical personnel that will be staffing the facility, carried out in tandem with the completion and commissioning of the new VTT Centre for Nuclear Safety (CNS). The project was executed in 5 main work packages: the first one is focused on the hot cell design, fabrication, installation and commissioning process; the second one is tasked with hot laboratory equipment procurement particularly those financed through the RADINFRA project via the investment aid mechanism; the third one is dedicated to self-built research facilities; the fourth one aimed at the supporting facilities for handling and storage of radioactive materials and waste; and finally, in light of the integral nature of this work with the realization of the VTT CNS, a work package focused mainly on the organization and ramp-up of the new radiological facility.

##### Specific goals in 2017

The design and construction of the hot cell facility involves defining and guiding the technical aspects of the hot laboratory portion of the new laboratory in tandem with the realization of the Centre for Nuclear Safety (CNS) building itself. Central to the 2017 project year was installation of the hot cells as part of the design and fabrication subcontract with Isotope Technologies Dresden, GmbH, including incorporation of VTT's large devices, and the subsequent training of the hot cell operators.

Procurement of research equipment for installation in the hot laboratory facilities is an important area of effort in the infrastructure renewal. **The purchase cost of each piece of equipment supported by the investment aid mechanism is financed through the RADINFRA project.** In 2017 several equipment investments were scheduled to coincide with the completion of the hot cells and ramp-up of the laboratory facilities. The principle pieces of in-cell equipment for purchase in 2017 were a hot-cell-ready pre-fatigue device, a semi-automatic optical and contact precision dimensioning device, and metallographic specimen preparation devices. Additionally, devices purchased for installation in the laboratory with only local shielding included a large impact test hammer with semi-automatic specimen feeding, and a triaxial compression mechanical testing device for bentonite. Beside the latter device, a liquid scintillation crystal radioisotope analyzer was also purchased mainly for nuclear waste management research.

Some research and testing devices are not readily available on the market, but rather, require custom design, while many off-the-shelf devices also require further nuclearization before deployment in the hot cell environment. Development and construction of those research devices is carried out with the experts involved in utilizing the equipment for producing research results, and are then fabricated by in-house assembly of parts bought from component suppliers, or made by in-house or outside workshops. An important goal in 2017 was the procurement of components for the hot autoclaves and accompanying water circuit, and their installation in a dedicated room of the basement of the CNS. Another goal was the fabrication of the localized shielding for some large mechanical testing devices, designed in 2016. Finally, device nuclearization was carried out for the equipment installed

into the hot cells in tandem with the on-site assembly of the hot cells themselves. This included modifications to the electron beam welder and electric-discharge machining device.

The VTT CNS requires a number of supporting facilities for its research and testing operations. The supporting facilities task in 2017 continued with the procurement and installation of the facilities for three main areas: laboratory radioactive waste handling, radioactive research material logistics, and orderly temporary storage of radioactive specimens. These systems are mainly located in the basement of the CNS. Proper sorting, consolidation, packaging and temporary storing of radioactive waste is essential for the day-to-day operations of the new radiological laboratory. Therefore, effort has gone to designing and realizing a functional waste handling infrastructure. Likewise, The orderly storage of radioactive research materials is important for ensuring that the physical materials repository and the specimen handling are safe, that the radioactive inventory is known, and that particular specimens can be located, recovered, positively identified, and associated with specific relevant information.

The VTT CNS radiochemistry and electron microscopy laboratories were already licensed for operation in 2017, but upon installation of the hot cells, the license needed to be expanded to accommodate the A-class facilities as well. Therefore, in 2017 the remaining radiological commissioning had to be executed in parallel with ramping-up the activities, training of personnel, and production of the first research results in the other laboratory areas. A particular focus of the latter was the training and bench-marking of the utilization of the Inductively-Coupled Plasma Mass Spectrometer (ICP-MS) device in its new cleanroom location in the new facilities. Besides the primary goal of completing the radiological commissioning upon completion of the hot cells, a task has focused on expanding the use of the ICP-MS device.

#### **Deliverables in the RADLAB Hot Cells work package in 2017**

- Installation of the hot cells in the CNS was completed in mid-August. Technical commissioning took place in the latter half of August.
- Two weeks of training by ITD, during which 38 people were introduced at least to the basic functionality of the hot cells. Many of those people completed all of the training units offered.
- A comprehensive operation manual for the hot cells in both German and English-language versions was produced.



Figure 2.4.3.1: Installation of the hot cells in the VTT Centre for Nuclear Safety was completed in mid-August 2017.

### Deliverables in the RADLAB Equipment Procurement work package in 2017

This WP, focused on executing the procurement process for series-produced equipment for the hot laboratory, progressed mainly as expected. Besides management of the entire multi-year investment portfolio, some specific devices were featured for delivery in this project year.

**In-cell machining:** RPV surveillance capsules are typically comprised of a stainless-steel sheet-metal “can” containing pre-machined fracture toughness specimens. The first step upon receiving a surveillance capsule for testing, is to machine open the capsule and recover the specimens. Since the total radioactivity can be quite high, this must be done remotely.

- A report was written comparing various off-the-shelf remote machining options to the conceptual design of a custom in-cell CNC machining station made in 2016. The assessment concluded that machining equipment configuration is a compromise between hot cell space limitation and machine working area, and therefore a CNC machining device for in-cell use should be of a customized, purpose-built design that offers sufficient flexibility for use with different work piece geometries. Such a machine is to be procured in 2018.

**Remote pre-fatiguing device:** An essential and time-consuming phase of fracture mechanical testing of RPV surveillance specimens is formation of a pre-fatigue crack in the test specimen.

- The in-cell device procured from SCK-CEN was delivered and installed in the ready hot cell 1.5. The device is compact and features a cassette for semi-automatic feeding and pre-fatiguing of 10x10 Charpy size specimens one-by-one, without need for laborious manipulator-assisted remote specimen changing, as with more conventional prefatiguing by a servo-hydraulic universal testing device.

- Seven users were trained in the operation and functions of the device in a two-day training session held in October 2017.

Remote specimen dimension measurement: Many mechanical testing operations require accurate metrics quantification before and after testing, whether it be physical geometry and dimensions of the specimen before and after deformation, or crack length measurement following pre-fatiguing.

- OGP Smartscope CNC200 automatic optical and touch-probe dimensioning microscope was purchased, with factory adaptations enabling remote operation for deployment in a hot cell.
- Three people were trained in its use. Additional training will be held once the device is installed inside hot cell 1.6 in 2018.

Large impact tester: Whereas most devices are to be installed inside fully-shielded hot cells, some devices will be used mainly for non-irradiated reference testing, or for only occasional testing of radioactive specimens, and therefore justifiably installed with only local shielding.

- Zwick RKP450 full-sized instrumented Charpy impact hammer with tempering furnace and semi-automatic specimen feeding was delivered and installed in the CNS high-bay.
- Six mechanical testing people were trained in its use.

Nuclear waste management research activities were improved by procurement of two devices

- A 300 SL automatic TDCR LSC liquid scintillation counter (LSC) was purchased from Pagode Oy. It is used for radioactive isotope assessment of materials.
- Eight radiochemists participated in LSC device training offered by the supplier.
- A 250kN mechanical testing device with accompanying triaxial compression testing chamber was purchased from GDS Instruments as a direct purchase, ensuring compatibility with existing related devices. The testing station enables data generation for long term mechanical performance models of bentonite buffer materials, even at elevated temperatures.

### **Deliverables in the RADLAB Research Equipment work package in 2017**

The hot-autoclave facilities enable testing primary circuit materials in simulated LWR water chemistry and temperatures.

- A new Cormet autoclave and its associated components was purchased new
- New device was delivered to the CNS, and a refurbished water circuit has been moved from old research facilities to the CNS. The devices are now in place in their own room in the basement of the CNS. There is still room there for a second water circuit to then be purchased later if needed.

Locally-shielded equipment installations enable reference tests and tests of contaminated or low activity materials to be safely and easily executed outside the main hot cells, increasing testing capacity. In addition to mechanical testing of metallic specimens, the requirements for testing irradiated concrete were accommodated.

- A prototype shielding wall for the tensile test devices was fabricated.

- Another shielding wall was begun for use with the SEM.
- Concrete blocks planned for partial shielding of the new Zwick instrumented impact hammer were procured, painted, and delivered to VTT.
- Existing tensile test devices (Instron and MTS) were moved from the old hot facilities to the CNS and are now being set up.

The electron beam welder (EBW) is an essential device for reconstituting tested fracture toughness specimen pieces into new test specimens, which in turn enables more data generation from the same volume of irradiated test material. As a large device, the hot cell design process was executed to accommodate the device's integration.

- EBW device was decontaminated and moved from the old facilities to the new, and was then successfully installed in the new hot cell 1.2 in tandem with the hot cell assembly.
- EBW nuclearization package ordered from the EBW device supplier CVE was installed
- Some demonstration EB-welds were produced. Further nuclearization adaptations and functional improvements will be made by CVE in 2018.

The electric discharge machine (EDM) is a key device for the cutting of radioactive materials. For example, accurate test specimen fabrication for surveillance programs requires a good EDM machine. The small amount of waste and a flexible cutting process are the most important features of the device. However, the device uses a closed water circuit, and the water must be very clean. As a part of the nuclearization of the EDM, a custom set-up for removing the radioactive cutting debris from the EDM water circuit was designed so that the EDM device can circulate its water in parallel, semi-independently of the water cleaning circuit itself, making the whole system more robust in operating principle.

- The EDM water cleaning system was fabricated in a dedicated room in the basement.
- The EDM was moved from the old facilities to the CNS, and then correctly positioned in hot cell 1.1 during the hot cell installation.
- The water circuit was connected to the machine, and first tests of the water circuit functionality with the device were carried out.
- A self-cleaning permanent filter was procured to complement the centrifuge itself, offering diversity and redundancy in the system functionality.

### **Deliverables in the RADLAB Supporting Facilities work package in 2017**

- A report was written on the waste handling solutions selected for the new facility. Waste is firstly minimized through appropriate planning and execution of research activities. Inevitable waste is either in dry or liquid/wet form. Dry waste is to be sorted by activity level and ultimate destination, and temporarily stored in 200l barrels in the basement waste storage room. Wet waste is to first be processed such that only radioactive residues in a stabilized solid form are then delivered to their ultimate destination.
- The remotely-controlled bridge crane procured for the waste barrel interim storage was installed by Erkkilä Oy in late 2017, with some refinements subsequently made to their specially-designed barrel grapple.
- The concrete shielding blocks for the waste storage modular shielding wall were purchased, painted, and then delivered to VTT.

- A subcontract was carried out with Platom Oy for the design of a wet waste handling system, which had first been recommended in the overall waste handling concept Platom made for VTT on an earlier subcontract.
- After VTT attempted to procure key components on their own, the system designed by Platom was ultimately ordered directly from them as a single turn-key delivery. The delivery of the fabricated system and its components is expected in April 2018. The system facilitates the safe processing of radioactive liquids by a choice of three main paths: evaporation and re-condensation (mainly for water), passing through ion-exchange resin (for many acidic ion solutions), and solidification by cement or bitumen (sludges and wet residues).
- The Pergament materials logistics database software was completed on a subcontract with Ambiente Oy. It not only enables recording of specimen locations, but can retain the history of their movements through the testing processes in the facility. Specimens are recorded in the database together with basic necessary technical data and customer association, and the test result documentation can be linked to it.
- For the orderly physical storage of radioactive materials, a final concept was concluded in early 2017, comprised of a series of alphanumerically organized compartments, located within a gamma-shielding basin. Long, narrow, vertical pillars with a series of compartments holding small, removable specimen “baskets” with 3 different sizes of lockers, including some with a 5 x 5 grid of slots for e.g. Charpy specimens.
- An EU-wide tender awarded the fabrication and installation of the physical specimen store to ITD. After several detailed design iterations were evaluated, the final design was fixed in the beginning of 2018 (Figure 2.4.3.2). Delivery of the completed system is slated for the end of 2018.

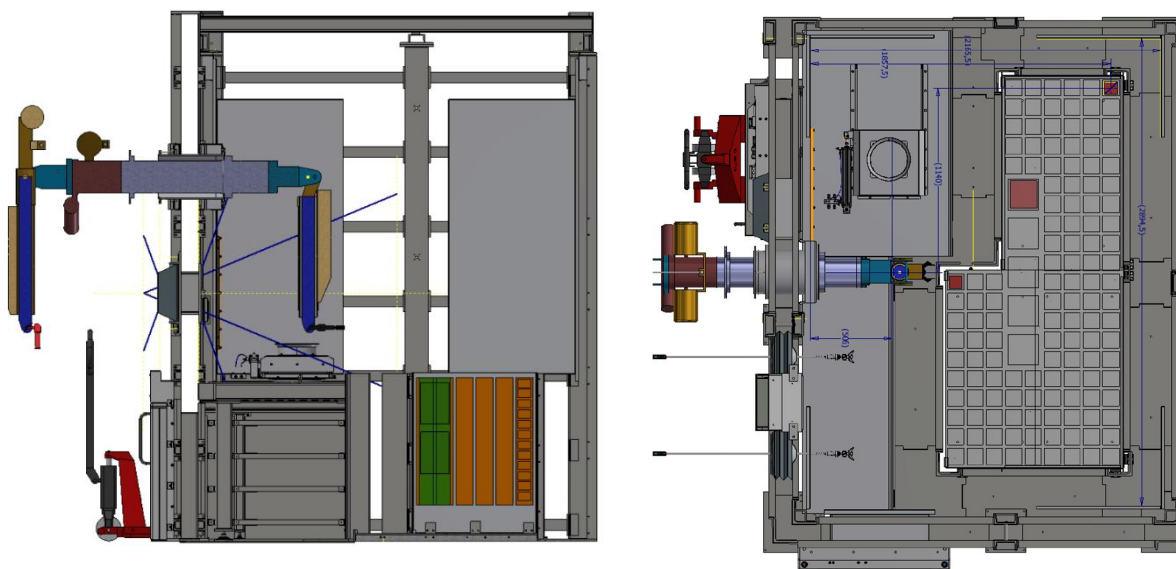


Figure 2.4.3.2: Detailed design of physical storage for radioactive specimens from side view (left) and top view (right).

**Deliverables in the RADLAB VTT CNS work package in 2017**

- A report was produced describing preparations for participation in ICP-MS Round Robin testing run by Suomen Ympäristökeskus. The next series of tests with common specimens relevant to our sector will be in spring 2018.
- A travel report was produced describing the participation in the NKS ICP conference in RISÖ/Roskilde, Denmark, where partners were sought for an international nuclear-sector ICP-MS Round Robin.
- Two operators of the HR-ICP-MS device were trained through an intensive 5 day course in Bremen, Germany.
- The IAEA carried out baseline swipe tests of the hot cells as part of their radiological commissioning process.
- STUK carried out an on-site inspection of the new hot cells. The level of radiological safety evident in the completed hot cells was satisfactory, so the final application papers were invited to be submitted for their approval. Submission of the license expansion papers is scheduled for February 2018.

### 3. Financial and statistical information

The planned and realised volumes of the SAFIR2018 programme in 2017 were 6,72 M€ and 6,82 M€, and 42 and 47 person years, respectively. The funding partners were VYR with 4,028 M€, VTT with 1,463 M€, Lappeenranta University of Technology with 0,195 M€, Aalto University with 0,153 M€, Halden Reactor Project with 0,134 M€, NKS with 0,125 M€, TVO with 0,101 M€, SSM with 0,065 M€, and other partners with 0,556 M€. The planned and actual funding by the major funding partners are illustrated in Figure 3.1. The planned and actual costs by cost category are shown in Figure 3.2. The personnel costs make up the major share.

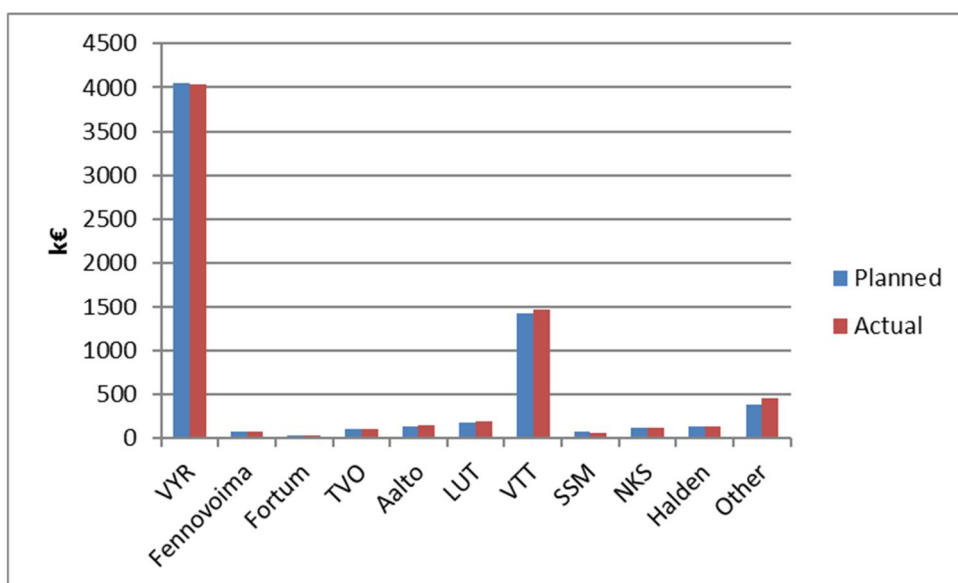


Figure 3.1. Planned and actual funding of the SAFIR2018 programme in 2017.

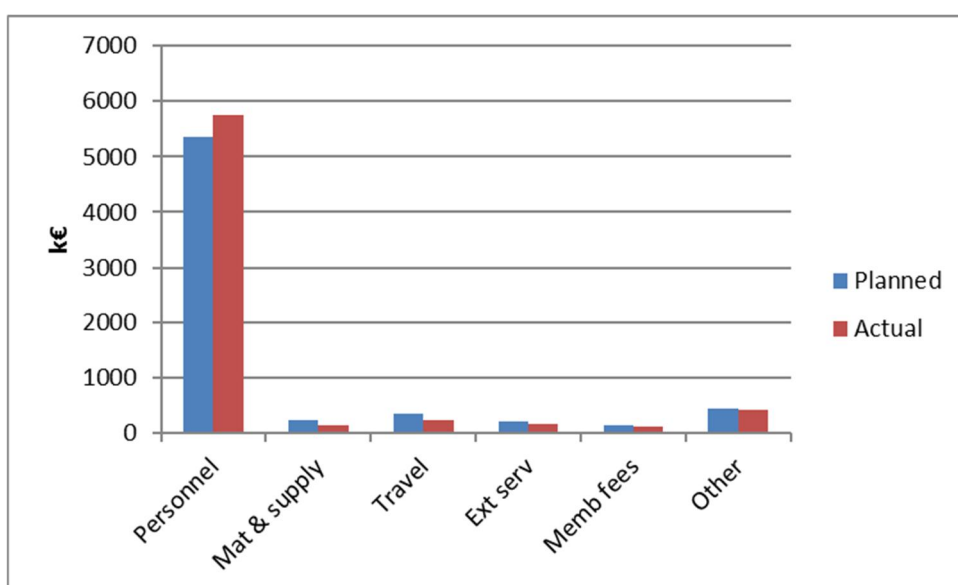


Figure 3.2. Planned and actual costs of the SAFIR2018 programme in 2017.

Figures 3.3-3.6 show the cost and volume distributions by research area. In the figures the following abbreviations are used for the steering group research areas: SG1 Plant safety and systems engineering, SG2 Reactor safety, SG3 Structural safety and materials, and RG6 Research infrastructure.

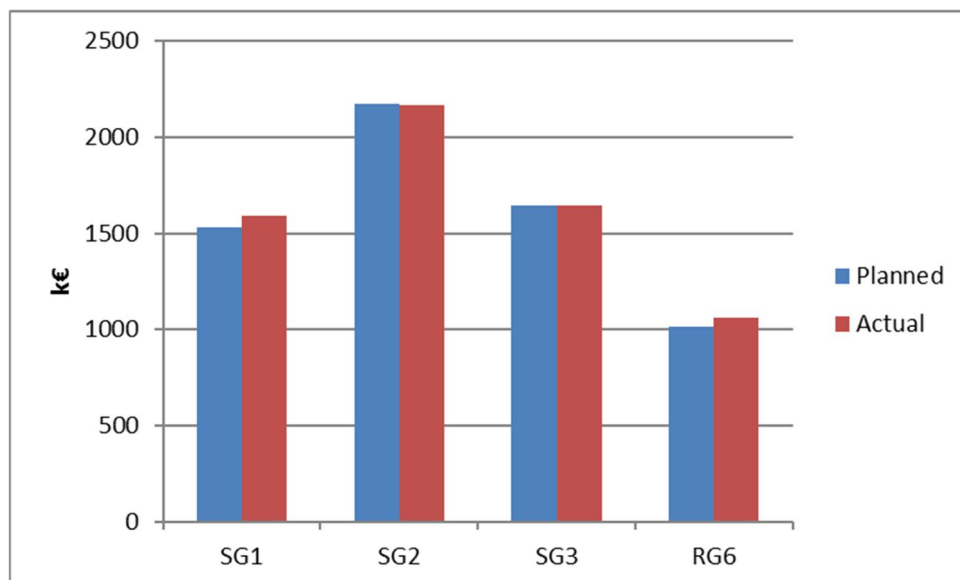


Figure 3.3. Planned and actual costs by research area in 2017.

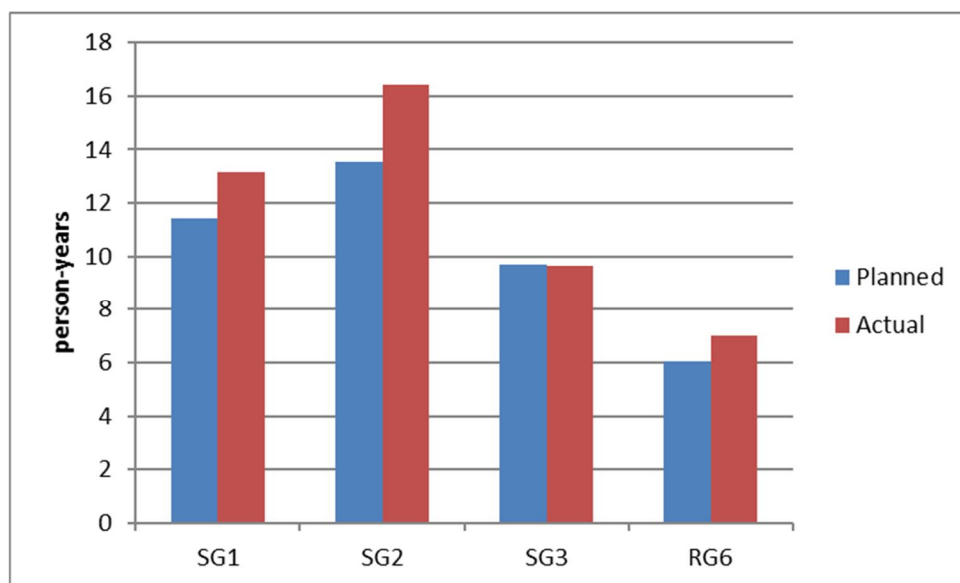


Figure 3.4. Planned and actual volumes by research area in 2017.

The actual costs coincided well with the planned costs in all research areas (Figure 3.3). On the other hand, the actual volumes in person-years were higher than the planned volumes except in SG3 area (Figure 3.4). The fact is also reflected in the higher actual than planned personnel costs (Figure 3.2).

In the research areas SG3 and RG6 the shares of person-years were lower than their shares of total funding because of higher other than personnel costs (Figures 3.5-3.6). In SG1 and SG2 the shares of the person-years were bigger than their shares of the total funding, respectively.

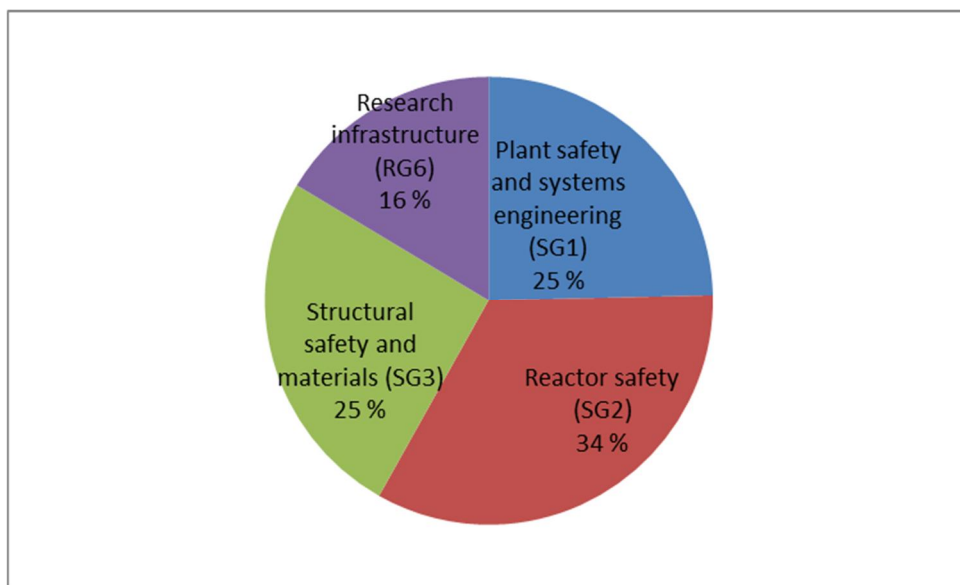


Figure 3.5. Distribution of total funding in SAFIR2018 research areas in 2017.

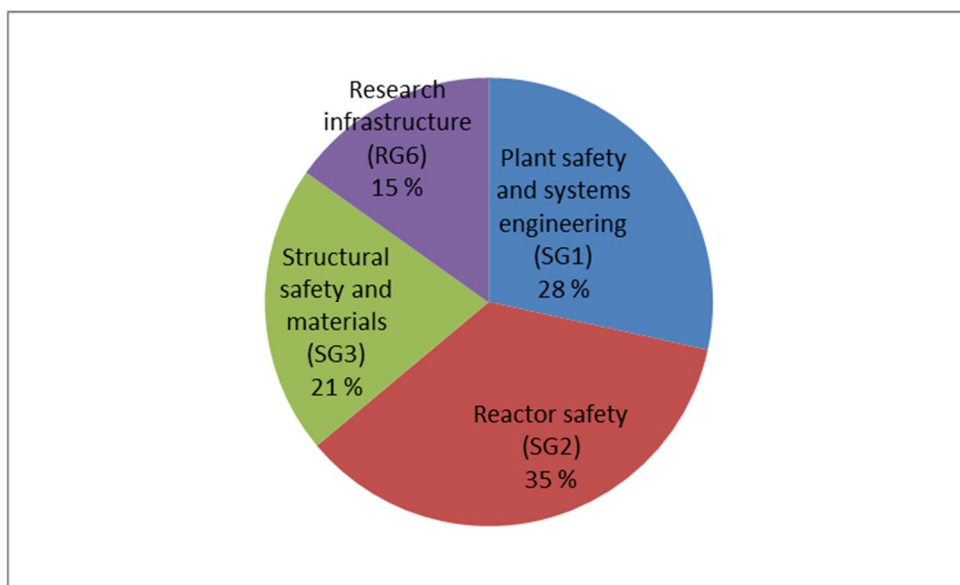


Figure 3.6. Distribution of person-years in SAFIR2018 research areas in 2017.

The numbers of different kind of publications made in SAFIR2018 research projects during 2017 are listed in Table 3.1. The programme produced 247 publications in 2017 consisting of 36 scientific journal articles, 55 conference articles, 96 research reports of the participating organisations, and 60 other publications (theses, reports of other organisations, etc.).

The average number of publications in the research projects was 5,2 per person-year, and the average number of scientific journal articles was 0,8 per person-year. There were differences in the number and type of publications between the projects but almost all projects wrote also scientific and conference articles in addition to research reports.

*Table 3.1. Publications in the SAFIR2018 projects in 2017.*

Project acronym	Volume (person years)	Research reports	Scientific journal articles	Conference articles	Others	<b>Total</b> (number of publications)
CORE	2,1	2	2	4	6	<b>14</b>
EXWE	2,6	2	6	1	10	<b>19</b>
MAPS	1,3	2	0	5	0	<b>7</b>
PRAMEA	2,6	11	3	2	5	<b>21</b>
SAUNA	2,7	5	0	12	0	<b>17</b>
GENXFİN	0,6	2	0	0	0	<b>2</b>
ESSI	1,2	2	0	2	0	<b>4</b>
CASA	1,2	5	0	3	1	<b>9</b>
CATFIS	0,9	3	2	0	3	<b>8</b>
COVA	1,6	4	1	0	1	<b>6</b>
INSTAB	1,4	4	1	0	1	<b>6</b>
INTEGRA	2,7	1	1	0	0	<b>2</b>
KATVE	1,6	5	1	2	0	<b>8</b>
MONSOON	1,1	3	2	3	1	<b>9</b>
NURESA	2,4	7	1	0	2	<b>10</b>
PANCHO	2,0	5	1	0	8	<b>14</b>
SADE	0,6	1	3	1	0	<b>5</b>
USVA	0,9	0	0	2	3	<b>5</b>
ERNEST	0,5	2	0	3	0	<b>5</b>
FIRED	1,4	1	3	1	2	<b>7</b>
FOUND	2,1	9	1	2	3	<b>15</b>
LOST	1,6	3	3	1	2	<b>9</b>
MOCCA	0,7	2	2	0	1	<b>5</b>
THELMA	1,3	4	1	3	6	<b>14</b>
WANDA	1,2	0	0	3	2	<b>5</b>
COMRADE	0,8	3	0	2	1	<b>6</b>
INFRAL	2,5	2	2	2	0	<b>6</b>
JHR	0,2	0	0	0	2	<b>2</b>
RADLAB	4,3	4	0	1	0	<b>5</b>
ADMIRE	1,0	2	0	0	0	<b>2</b>
<b>Total</b>	<b>47,3</b>	<b>96</b>	<b>36</b>	<b>55</b>	<b>60</b>	<b>247</b>

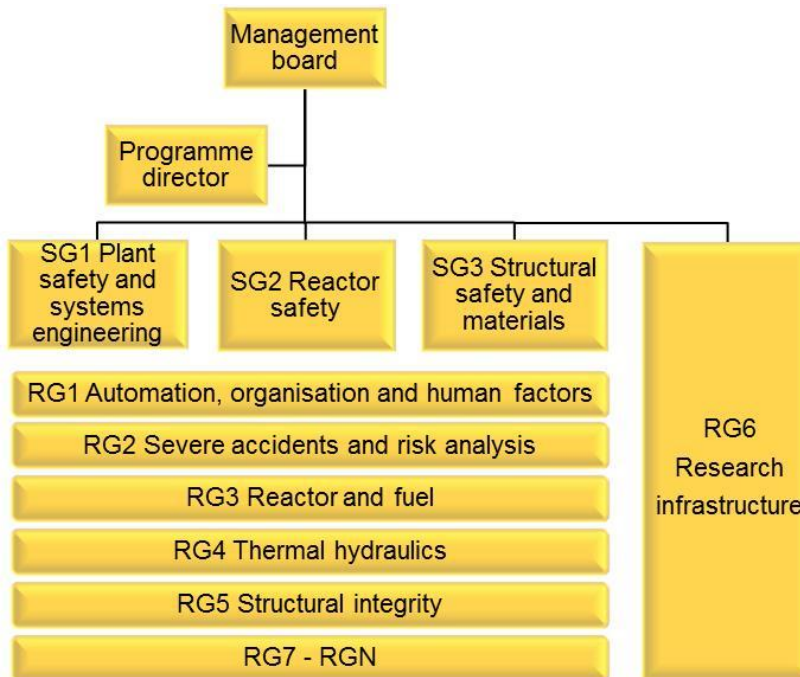
Altogether 14 higher academic degrees were obtained in the research projects in 2017: eight Doctoral degrees and six Master's degrees (Table 3.2). The academic degrees are listed in Appendix 3.

*Table 3.2. Academic degrees obtained in the projects in 2017.*

Project acronym	Doctor	Master
EXWE	2	
PRAMEA	1	
ESSI		1
INSTAB		1
MONSOON	1	
PANCHO	2	
FIRED	1	
LOST		1
THELMA	1	
WANDA		1
COMRADE		1
INFRAL		1
<b>Total</b>	<b>8</b>	<b>6</b>

## 4. Programme management

The organisation of SAFIR2018 is shown in Figure 4.1 and its function described in detail in the Operational management handbook ([4], available on SAFIR2018 website).



*Figure 4.1. Structure of SAFIR2018 organisation. In 2017 each project belonged to one research area Steering Group (SG) and one Reference Group (RG). RG6 “Research infrastructure” has a special role of a steering and reference group [4].*

During the administrative period (January 2017 – March 2018) the SAFIR2018 steering group held 4 meetings. Each of the steering groups SG-SG3 had 4 meetings and RG6 as a steering group 3 meetings. The reference groups RG1-RG6 had 4 meetings. The persons involved in the management board (MB) as well as the persons appointed by the MB to the steering and reference groups are listed in Appendix 5. Appendix 5 also shows the staff of the research projects and their main duties.

The SAFIR2018 management board can annually initiate small preliminary type studies with the order procedure. Decisions on the small sprojects are made after the funding recommendation for the research projects. The small projects support the implementation of the framework plan in topics where actual research projects have not been started. They can also introduce new topics. In 2017 two projects were ordered and carried out: (1) Overall Safety and Organisations: Institutional Strength-in-Depth and National Actors (VTT, LUT), and (2) Seismic monitoring and corresponding safe shutdown criteria of NPPs in low/moderate seismicity areas (SEMA) (VTT). The projects were formally realised as subcontracting in the administration project (ADMIRE). The final reports of the small projects can be found on SAFIR2018 extranet.

A competence survey about the number experts in different fields of nuclear energy sector in Finland was carried out in the administration project. The survey was sent to all recognised national actors and companies. The summary of the results was presented to the SAFIR2018 management board and SAFIR2022 planning group. A preliminary summary

was also presented in the nuclear safety seminar ("Ydinturvallisuusseminaari") in November 2017.

The programme director participated in the work of the Euratom Programme Committee (Fission configuration) as an expert member (two meetings in 2017) and one meeting of the national support group was also organised by SAFIR2018. The programme director also participated in the work of OECD NEA CSNI that had meetings in June and December in 2017.

The information on the research performed in SAFIR2018 is communicated formally via the progress reports of the projects for the reference group meetings, the annual reports of the programme and SAFIR2018 website (public and protected extranet). Additional information was given in seminars organised by the research projects. The detailed scientific results were published as articles in scientific journals, conference papers, and research reports.

The interim seminar of SAFIR2018 was held on 23.-24.3.2017 at Innopoli. The seminar was for the first time also held as a webinar. The seminar material consisting of the programme and abstracts, slides and posters, and recorded video presentations can be found on SAFIR2018 public website ([link](#)). The SAFIR2018 Interim report [5] describing the work carried out in the programme during its two first years can also be found on the website.

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## **Appendix 1**

### **Publications in the projects in 2017**

## Crafting operational resilience in nuclear domain (CORE)

### Scientific journal articles

Pakarinen, S., Korpela, J., Torniainen, J., Laarni, J., Karvonen, H., Cardiac measures of nuclear power plant operator stress during simulated incident and accident scenarios. In press to Psychophysiology.

Teperi, A.-M., Puro, V., Ratilainen, H., Applying a new human factor tool in the nuclear energy industry. Safety Science 95, 125–139.

<http://dx.doi.org/10.1016/j.ssci.2017.02.013>

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Liinasuo, M., Koskinen, H., Porthin, M., Communication in an Emergency Exercise. 40th Enlarged Halden Programme Group Meeting (EHPG 2017), September 24-29, 2017, Lillehammer, Norway.

Viitanen, K., Koskinen, H., Skjerve, A.B., Axelsson, C., Liinasuo, M., Bisio, R., Modelling Organizational Learning From Successes in the Nuclear Industry – Staff Meetings as Forums of Knowledge Sharing and Acquisition. 7th REA (Resilience Engineering Association) Symposium, June 26-29, 2017, Liege, Belgium.

Wahlström, M., Kuula, T., Seppänen, L., Rantanummi, P., Kettunen, P., Resilient power plant operations through a self-evaluation method. 7th REA (Resilience Engineering Association) Symposium, June 26-29, 2017, Liege, Belgium.

Wahlström, M., Kuula, T., Laarni, J., Supporting resilience in nuclear power plant operation - Conceptual frames for human factors development and validation. 10th International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies (NPIC&HMIT), June 11-15, 2017, San Francisco, California, USA

### Research reports

Liinasuo, M., Koskinen, M., Principles and practices of emergency exercises. Research Report, VTT-R-00552-18.

Teperi, A.-M., Puro, V., Tiikkaja, M., Ratilainen, H., Developing and implementing human factors (HF) tool to improve safety management at nuclear industry. Research Report. Työterveyslaitos.

### Others

Laarni, J., Descriptive modeling of team troubleshooting in nuclear domain. To be submitted to Multi Conference on Computer Science and Information Systems (MCCSIS 2018).

Laarni, J., Cognitive heuristics and biases in process control and maintenance work. To be submitted to Multi Conference on Computer Science and Information Systems (MCCSIS 2018).

Laarni, J., Monen tehtävän yhtäaikaiseen suorittamiseen liittyvä kysely – SAFIR2018-CORE-hanke.

Laarni, J., Multitasking - concept analysis. Slide set. VTT.

Pakarinen, S., Slide set to be presented at TVO Käytön koulutuspäivät.

Skjerve, A. B., Viitanen, K., Axelsson, C., Bisio, R., Koskinen, H., Liinasuo, M., Learning from Successes in Nuclear Operations – A Guideline. Presented at the ESREL2017, Portorož, Slovenia.

## Extreme weather and nuclear power plants (EXWE)

### Scientific journal articles

Kämäräinen, M., Hyvärinen, O., Jylhä, K., Vajda, A., Neiglick, S., Nuottokari, J., and Gregow, H., 2017: A method to estimate freezing rain climatology from ERA-Interim reanalysis over Europe, *Nat. Hazards Earth Syst. Sci.*, 17, 243-259, <https://www.nat-hazards-earth-syst-sci.net/17/243/2017/>, doi:10.5194/nhess-17-243-2017.

Leijala, U., Björkqvist, J.-V., Johansson, M.M., Pellikka, H., Laakso, L., and Kahma, K. K., 2018: Combining probability distributions of sea level variations and wave run-up to evaluate coastal flooding risks, *Nat. Hazards Earth Syst. Sci. Discuss.*, in review, <https://doi.org/10.5194/nhess-2017-438>.

Olsson, T., Perttula, T., Jylhä, K., and Luomaranta, A. 2017: Intense sea-effect snowfall case on the western coast of Finland, *Adv. Sci. Res.*, 14, 231-239, <https://doi.org/10.5194/asr-14-231-2017>.

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<https://journals.ametsoc.org/doi/abs/10.1175/JAMC-D-16-0361.1>, DOI: 10.1175/JAMC-D-16-0361.1 (ei open access)

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Jylhä, K., Johansson, M., Kämäräinen, M., Pellikka, H., Leijala, U., Fortelius, C., Gregow, H., Venäläinen, A., 2017: Researching extreme weather and sea level events to support nuclear plant safety in Finland. In: Kroke, J., A.G. Olabi, D. Goričanec, S. Božičnik (eds): 10th International Conference on Sustainable Energy and Environmental Protection: Environmental Management and Impact Assessment. <http://press.um.si/index.php/ump/catalog/book/244>

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Vira, J., 2017: Data assimilation and numerical modelling of atmospheric composition. Finnish Meteorological Institute Contributions 130, <http://hdl.handle.net/10138/175913>, <https://helda.helsinki.fi/bitstream/handle/10138/175913/Julius%20Vira%20Vaitoskirja.pdf?sequence=1> (Academic dissertation in physics)

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Björkqvist, J.-V., Vähä-Piikkiö, O., Alari, V., Kuznetsova, A., and Tuomi, L., 2018. WAM, SWAN and WaveWatch III™ in the Finnish archipelago – The effect of spectral performance on bulk wave parameters. EXWE/SAFIR2018 deliverable D2.2.1 in 2017, Finnish Meteorological Institute. (ei open access)

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## **Management Principles and Safety Culture in Complex Projects (MAPS)**

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A. Mancuso, M. Compare, A. Salo, E. Zio. “Portfolio optimization of structural safety measures for dynamic systems”, submitted to Reliability Engineering and System Safety for peer review.

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Alessandro Mancuso, Michele Compare, Ahti Salo, Enrico Zio, “Risk informed decision making under incomplete information: Portfolio decision analysis and credal networks”, Safety and Reliability: Theory and Applications - Proceedings of the 27th European Safety and Reliability Conference, ESREL 2017, pp. 743-750 (2017).

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### **Research reports**

Ola Bäckström, Anna Häggström, Xuhong He. SITRON – Pilot study Ringhals 3&4, Report 212634-R-002. Sundbyberg: Lloyd’s Register Consulting, 2018. (limited distribution)

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Kuutti, J. FOUND2016: Review of results. VTT Research Report VTT-R-05223-17.

Seppänen T. 2017. LCF of AISI 347 and 304L in Simulated PWR Water. Presentation given in SAFIR RG5 meeting on 6.10.2017.

Seppänen, T. 2018. Research plan for studying the mechanisms and developing a new FEN model (PhD Thesis of Tommi Seppänen), Deliverable 3.2.2. Updated January 11, 2018.

## **Long term operation aspects on structural integrity (LOST)**

### **Scientific journal articles**

Sebastian Lindqvist, Dependence between  $\eta$ -factor and crack location respective to a fusion boundary between hard and soft materials in a SE(B) specimen, International Journal on Fracture, Espoo, 2018.

Sebastian Lindqvist, Applicability of bending and rotation correction for SE(B) specimens of an Alloy 52 narrow-gap dissimilar metal weld, Engineering fracture mechanics, Espoo, 2018.

Sebastian Lindqvist, The effect of crack path on tearing resistance of a narrow-gap Alloy 52 dissimilar metal weld, Engineering fracture mechanics, Espoo, 2017.

### **Conference articles and abstracts**

Sebastian Lindqvist, Optimizing the calculated crack size for single edge bend specimens of a dissimilar metal weld, 19th International Conference on Fracture, ICF19, 20-24 June 2017, Rhodes, Greece.

### **Research reports**

Heikki Keinänen, Residual stresses in a case of local repair, Research Report, VTT-R-07120-17, Espoo, 2017.

Kim Wallin, Sebastian Lindqvist, Irradiation trend curves for high Nickel steels, Research Report, VTT-R-00664-18, Espoo, 2016.

Qais Saifi, Damage mechanics analyses under plastic deformation with special numerical method by local approach, Research Report, VTT-R-00486-18, Espoo, 2017.

### **Others**

Laura Sirkiä, Applicability of miniature Compact Tension specimens for fracture toughness determination in ductile-brittle transition range, Master's Thesis, Espoo, 2017.

Jari Lydman, Sebastian Lindqvist, Travel report from IGRDM20, Travel report, Espoo, 2017.

## **Mitigation of cracking through advanced water chemistry (MOCCA)**

### **Scientific journal articles**

Essi Jäppinen, Tiina Ikäläinen, Sari Järvinmäki, Timo Saario, Konsta Sipilä, Martin Bojinov, Effect of Octadecylamine on Carbon Steel Corrosion in Secondary Circuits of Pressurized Water Reactors, J. of Materi Eng and Perform (2017), 26:6037-6046, DOI 10.1007/s11665-017-3035-6.

Bojinov, M., Jäppinen, E., Marja-aho, M., Saario, T., Sipilä, K. and Toivonen, A., "Effect of lead and applied potential on general and localized corrosion of carbon steel in steam generator crevice solution. Presented for publication in Journal of the Electrochemical Society.

### **Research reports**

Iva Betova, Martin Bojinov, Timo Saario, "Kinetics of oxygen removal by hydrazine alternatives in conditions of steam generator preservation during outage", Research report VTT-R-05209-17

Tiina Ikäläinen, Timo Saario and Konsta Sipilä, "Further investigations into surface charge of magnetite", Research report VTT-R-00442-18

### **Others**

Konsta Sipilä, Presentation: "Lead-assisted stress corrosion cracking of steam generator body carbon steel", 13<sup>th</sup> Annual Meeting of ECG-COMON, June 12 and 13, 2017, Budapest, Hungary

## **Thermal ageing and EAC research for plant life management (THELMA)**

### **Scientific journal articles**

Mouginot, R. et al. Thermal ageing of Alloy 690 between 350 and 550 °C. Journal of Nuclear Materials. Elsevier. Vol. 485 (2017), 56-66.  
<http://dx.doi.org/10.1016/j.jnucmat.2016.12.031>

### **Conference articles and abstracts**

Ehrnstén, U., Carpen, L., Tompuri, K. Microbially induced corrosion in fire fighting systems – experience and remedies. The Minerals, Metals & Materials Society 2018. J.H. Jackson et al. (eds.), Proceedings of the 18<sup>th</sup> International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, The Minerals, Metals & Materials Series. [https://doi.org/10.1007/978-3-319-67244-1\\_21](https://doi.org/10.1007/978-3-319-67244-1_21)

Ehrnstén, U. Intergranular stress corrosion cracking of austenitic stainless steels – is it still an issue? Joint EUROCORR 2017, 20th ICC & Process Safety Congress 2017, "Corrosion Control for Safer Living", 3 - 7 September 2017, Prague, Czech Republic. Proceedings. DECHEMA e.V.; Czech Association of Corrosion Engineers (AKI); Czech Association of Corrosion Engineers (AKI) (2017), 22 p.

Mouginot, R. et al. Development of short-range order and intergranular carbide precipitation in Alloy 690 TT upon thermal ageing. The Minerals, Metals & Materials Society 2018. J.H. Jackson et al. (eds.), Proceedings of the 18<sup>th</sup> International Conference on Environmental Degradation of Materials in Nuclear

Power Systems – Water Reactors, The Minerals, Metals & Materials Series. [https://doi.org/10.1007/978-3-319-67244-1\\_21](https://doi.org/10.1007/978-3-319-67244-1_21)

### Research reports

Huotilainen, C. Progress report on INCEFA+ (Horizon2020) for SAFIR2018 - THELMA. VTT-R-06331-17, 24.11.2017. 20 p.

Ivanchenko, M. Microstructural characterization of in-reactor tested stainless steels: 4 dpa CW 316 Ti SS, 5.9 dpa 304L SS and 9 dpa CW 316 SS. VTT-R-00158-18, 7.2.2018.

Lydman, J., Nevasmaa, P., Ehrnstén, U. Microstructural characterization of non-irradiated Barsebäck RPV material. VTT-R-05554-17, 7.12.2017. 116 p.

Toivonen, A., Autio J-M., Ivanchenko, M. ICGEAC Inconel 600 Round Robin – Final report of VTT results. VTT-R-06561-1, 8.12.2017, 26p.

### Others

Mouginot R. Effect of thermal ageing on Alloy 690 and 52 in pressurized water reactor applications. Aalto University publications series doctoral dissertations 81/2017.  
<https://aaltodoc.aalto.fi/handle/123456789/25405>

Hänninen, H. et al. Development of short-range ordering and intergranular carbide precipitation in Alloy 690 TT upon thermal ageing, and their effect on hydrogen embrittlement. Presentation at the 2017 ICG-EAC meeting, 7-12.5.2017, Chester, UK.

Ehrnstén, U. Fracture surface characterization. Invited tutorial at the 2017 ICG-EAC pre-meeting tutorial session, 7-12.5.2017, Chester UK.

Ehrnstén, U. Travel report from 18<sup>th</sup> International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors conference.

Ehrnstén, U. travel report from the Eurocorr 2017 conference, Prague 3-7 September, 2017.

Ivanchenko, M. Presentation of results on 4 - 9 dpa irradiated stainless steels. Halden IASCC meeting, Oslo, Norway, 8-9.11.2017.

## NDE of NPP primary circuit components and concrete infrastructure (WANDA)

### Conference articles and abstracts

Virkkunen, I., Haapalainen, J., Papula, S., Sarikka, T., Kotamies, J., Hänninen, H., Effect of Feedback and Variation on Inspection, Reliability. 7th European-American Workshop on Reliability of NDE, Potsdam, Germany, 4.–8. September, 2017.

Al-Neshawy, F., Ferreira, M., Bohner, E., Puttonen, J., NDT Matrix - A Tool for Selecting Non-Destructive Testing methods for NPP Concrete Structures. SMIRT 24, Busan, Korea, 20. - 25. August ,2017. D8-S1.

Ferreira, M., Bohner, E., Al-Neshawy, F., NPP containment wall mock-up for long term NDE and monitoring. Nordic Concrete Research seminar (NCR) 2017. 21. - 23. August, 2017. Aalborg, Denmark. 71-74.

### Others

Jäppinen, T., Travel report from 6<sup>th</sup> Nugenia Forum, Amsterdam, Netherlands, 28. - 30. March, 2017

Koskinen, T., Travel report from 7<sup>th</sup> European-American Workshop on Reliability of NDE, Potsdam, Germany, 4.-8. September, 2017.

## **Condition Monitoring, Thermal and Radiation Degradation of Polymers Inside NPP Containments (COMRADE)**

### **Conference articles and abstracts**

Molander, M., Jansson, A., Sandström, J. Development of condition monitoring methods for polymeric components including low dose rate radiation exposure. FONTEVRAUD 9 17–20 September 2018, Avignon, France.

Jansson, A., Carlred, L., Sjövall, P., Sipilä, K., Joki, H. Surface sensitive analysis for investigation of oxidation profiles in rubber sealing material. FONTEVRAUD 9 17–20 September 2018, Avignon, France.

### **Research reports**

Development of FEM model and test run using data from T1.1 (RISE-research report)

Identification of available polymers and their data from Nordic NPPs. (RISE-research report)

Dose rate effect study on EPDM and Lipalon cable jacketing materials (VTT-research report)

### **Others**

COMRADE Workshop on polymer ageing issues at NPPs (Minutes of the meeting)

## **Development of thermal-hydraulic infrastructure at LUT (INFRAL)**

### **Scientific journal articles**

Telkkä, J., Ylönen, A., Hyvärinen J., Varju, T., 2017. Estimation of velocity fields from the axial wire-mesh sensor data. Nuclear Engineering and Design. <https://doi.org/10.1016/j.nucengdes.2017.05.010>

Patel, G., Tanskanen, V., Hujala, E., Hyvärinen, J., 2017. Direct contact condensation modeling in pressure suppression pool system. Nuclear Engineering and Design. <https://doi.org/10.1016/j.nucengdes.2016.08.026>

### **Conference articles and abstracts**

Hyvärinen J., Telkkä J., Kauppinen, O.-P., Purhonen, H., 2017. MOTEL – Modular design and physical scaling principles of the next generation thermal hydraulics test facility at LUT. 17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-17), Xi'an, China, September 3–8, 2017.

Hujala, E., Tanskanen V., Hyvärinen, J., 2017. Frequency analysis of chugging condensation in pressure suppression pool system with pattern recognition. 17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-17), Xi'an, China, September 3–8, 2017.

### **Research reports**

Joonas Telkkä, Juhani Hyvärinen, Otso-Pekka Kauppinen, INFRAL 1/2017: Modularity based requirements of MOTEL, Research report, Lappeenranta University of Technology, Nuclear Engineering, 2017.

Lauri Pyy, Joonas Telkkä, Elina Hujala, INFRAL 2/2017: Status report on the advances in thermal hydraulic measurements, Research report, Lappeenranta University of Technology, Nuclear Engineering, 2017.

## **JHR collaboration & Melodie follow-up (JHR):**

### **Others**

#### *Travel reports*

- MWG meeting 30.3.2017
- Technical seminar 20.-21.6.2017

## **Radiological laboratory commissioning (RADLAB)**

### **Conference articles and abstracts**

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

### **Research reports**

Siivinen, J. VTT:n Ydinturvallisuustalon jatteiden kasittely, VTT Report VTT-R-06888-17, 2018, 23 p.

Myllykylä, M., Heikola, T. and Lavonen, T. Vertailumittaukseen valmistavat alkuaineanalyysit - RADLAB, VTT Report VTT-R-00697-18, 2018, 35 p.

Tähtinen, S., VTT Ydinturvallisuustalon kuumakammioiden toimintaperiaate, VTT Report VTT-R-00485-18, 2018, 18 p.

Tähtinen, S., Background study on machining options in the VTT hot cells, VTT Report VTT-R-03878-17, 2017, 26 p.

## **Appendix 2**

### **Participation in international projects and networks in 2017**

## **Crafting operational resilience in nuclear domain (CORE)**

OECD/NEA WGHOF (Working Group on Human and Organisational Factors)

OECD/NEA WGHOF Task group on Achieving Reasonable Confidence in Validation Test Results of Integrated System Performance for Nuclear Power Plant Main Control Rooms

NUGENIA (Nugenia Generation II & III Association)

Learning From Successes in Nuclear Power Plant Operation to Enhance Organisational Resilience (LESUN) – VTT, Ringhals AB and IFE joint project

## **Extreme weather and nuclear power plants (EXWE):**

EU-C3S project DECM (Data Evaluation for Climate Models), co-designing recommendations for evaluation of multi-model climate model products CMIP and CORDEX (2016-2018)

EU-C3S project Clim4Energy, a service providing climate change indicators tailored for the energy sector (2016-2018)

ERA4CS project SERV\_FORFIRE, Integrated services and approaches for assessing effects of climate change and extreme events for fire and post fire risk prevention (2017-2020)

ERA4CS project URCLIM, impacts of heat stress, flooding risk, and snow clearing and slipperiness in winter in alternative future urban environments (2017-2020)

ERA4CS project WINDSURFER, wind and wave scenarios, uncertainty and climate risk assessment for forestry, energy and reinsurance (2017-2020)

ESSEM COST Action ES1404 “A European network for a harmonised monitoring of snow for the benefit of climate change scenarios, hydrology and numerical weather prediction” (2014-201z)

COST-CA15211 Atmospheric Electricity Network: coupling with the Earth System, climate and biological systems. Finnish MC delegate from FMI.

The Nordic Council project ERMOND (Ecosystem resilience for mitigation of natural disasters) (2015-2017)

NORDRESS is a Centre of Excellence under the Social Security Programme of NordForsk to carry out multidisciplinary studies to enhance societal security and resilience to natural disasters (2015-2019)

EUMETSAT Optical Lightning Imager (LI) Mission Advisory Group (MAG). FMI is an Invited Expert Institute.

Finnish Management Committee member, COST CA15211 “Atmospheric Electricity”, since 2016. [http://www.cost.eu/COST\\_Actions/ca/CA15211](http://www.cost.eu/COST_Actions/ca/CA15211)

Nepal World Bank Project 2014-2018, Nepal. Funded by World Bank. Lightning location data usability in severe weather monitoring and early warning services.

FISU II ICI: Promoting Adaptation to Climate Change by Reducing Weather and Climate-Related Losses through Improved Services in Sudan and South Sudan, 2016-2018.

SSWSS: Severe Storm Warning Service for Sri Lanka, 2016-2018. Supporting the early warning services for thunderstorms in Sri Lanka. Funded by the Ministry of Foreign Affairs of Finland and the Finnish Agency for Technology and Innovation (Tekes).

Nordic Framework Climate Services (NFCS), Heavy Rainfall Activity, Finnish delegate, since 2016.

The international HIRLAM programme develops short range numerical weather prediction since the 1980's. <http://hirlam.org/index.php/hirlam-programme-53>

FMI is active in the following ECRA (European Climate Research Alliance) Collaborative Programmes: i) Arctic Climate Stability and Change; ii) High Impact Events and Climate Change; iii) Sea Level Change and Coastal Impacts

Collaboration with the European Centre for Medium-Range Weather Forecasts (ECMWF) for various subjects, including running case study simulations, and storm prediction development with (ERF) extended range forecasts.

Collaboration with Nansen Environmental and Remote Sensing Center (NERSC) for studies about extreme wave and sea level events.

### **Management Principles and Safety Culture in Complex Projects (MAPS)**

Co-operation with KTH Royal Institute of Technology in Stockholm and the Swedish nuclear industry (Forsmark, OKG)

Co-operation with NKS - funded project Safety Culture Assurance and Improvement Methods in Complex Projects (SC\_AIM)

Co-operation with International Atomic Energy Agency (IAEA), Operational Safety Section, Division of Nuclear Installation Safety, Department of Nuclear Safety and Security in terms of safety culture continuous improvement.

### **Probabilistic risk assessment method development and applications (PRAMEA):**

NKS project L3PSA (Addressing off-site consequence criteria using Level 3 PSA) (Ilkka Karanta, Jan-Erik Holmberg)

NKS project SPARC (Scenarios and Phenomena Affecting Risk of Containment Failure and Release Characteristics) (Ilkka Karanta, Tero Tyrväinen)

Nordic co-operation project SITRON (SITE Risk Of Nuclear installations) (Jan-Erik Holmberg, Erik Cederhorn, Carl Sunde, Kim Björkman, Tero Tyrväinen)

PSAM Topical Conference on Human Reliability, Quantitative Human Factors and Risk Management, 7-9 June 2017, Munich

- Conference paper and presentation: Markus Porthin, Terhi Kling, and Marja Liinasuo. New Challenges for Performance Shaping Factors in Advanced Control Rooms

FinPSA End User Group

OECD/NEA WGRISK (Working Group on Risk Assessment)

- Proposed new activity “Comparative application of Digital I&C Modelling Approaches for PSA (DIGMAP)”, co-lead by Korea and Finland. The new 3-year task was approved and started in June 2017. (Markus Porthin)
- Participation in the activities on Status of Practice for Level 3 Probabilistic Safety Assessment and Status of Site Level PSA (Including Multi-unit PSA developments) (Ilkka Karanta, Markus Porthin)

ETSON (European Technical Safety Organizations Network), working group on Probabilistic Safety Assessment

- Participation in group activities by workshop, meeting and email (Markus Porthin)

IAEA expert group for the development of the Safety Report on Human Reliability Assessment for Nuclear Installations

- Member of the expert group (Jan-Erik Holmberg)
- Participation in group activities by technical meeting and email (Markus Porthin)

ISCH COST Action IS1304, Ahti Salo management committee member

Program Committee Memberships of International Conferences and Workshops:

- 3rd Nordic chapter of the Society for Risk Analysis Europe Risk Conference to be organised 1–2 November 2017, Espoo (Ahti Salo, Jan-Erik Holmberg).
- Member of the Programme Committee of the 21<sup>st</sup> International Federation of Operational Research Societies, 17-21 July 2017, Québec, Canada (Ahti Salo)

### **Integrated safety assessment and justification of nuclear power plant automation (SAUNA)**

OECD/NEA Working Group on Risk Assessment (WGRISK), proposed new activity “Comparative application of Digital I&C Modelling Approaches for PSA (DIGMAP)”, co-lead by Korea and Finland. The new 3-year task was approved and started in June 2017. (Markus Porthin)

OECD/NEA WGHOE (Working Group on Human and Organisational Factors)

OECD/NEA WGHOF Task group on Achieving Reasonable Confidence in Validation Test Results of Integrated System Performance for Nuclear Power Plant Main Control Rooms

NUGENIA (Nugenia Generation II & III Association)

ISO/IEC JTC1 SC7 Software and systems engineering - WG7 Life cycle management; WG10 Process assessment.

OECD Halden Reactor Project, Man-Technology-Organization, Halden Programme Group, Janne Valkonen represents Finland

Collaboration with ITMO University (Russia) under the project “Development of methods, tools and technologies for design, verification and testing of reliable cyber-physical systems”

### **Safety of new reactor technologies (GENXFIN)**

8th International Symposium on Supercritical Water-cooled Reactors (ISSCWR-8)

IAEA (International Atomic Energy Agency) Consultants’ Meeting to Finalize the TECDOC on the Status of SCWR (Supercritical Water Cooled Reactor) R&D

GIF (Generation IV International Forum) SCWR Materials & Chemistry (M&C) Project Management Board (PMB)

IAEA Technical Meeting on Next Generation Reactors and Emergency Preparedness and Response

### **Electric Systems and Safety in Finnish NPP (ESSI)**

Cooperation with Energiforsk GINO project, Sweden. Video meeting with ESSI and GINO project Steering group was organised 15.11.2017. Information exchange regarding the topic Open Phase Condition, Lightning overvoltages and Adaptive operation of NPP. Matti Lehtonen, Anna Kulmala and Riku Pasonen represented ESSI project.

### **Comprehensive Analysis of Severe Accidents (CASA):**

OECD/NEA BSAF-2 (Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station, phase 2)

OECD/NEA THAI-3 (Thermal-hydraulics, Hydrogen, Aerosols, Iodine)

U.S.NRC CSARP (Co-operative Severe Accident Research Program)

NKS SPARC (Scenarios and Phenomena Affecting Risk of Containment Failure and Release Characteristics)

### **Chemistry and transport of fission products (CATFIS):**

OECD/NEA STEM-2 (Source Term Evaluation and Mitigation)

OECD/NEA BIP-3 (Behaviour of Iodine)

NUGENIA TA2.4 Source term area

NUGENIA TA2.4 Integration of Pool scrubbing Research to Enhance Source-term Calculations (IPRESCA) project

### **Comprehensive and systematic validation of independent safety analysis tools (COVA):**

OECD/WGAMA (Working Group on Analysis and Management of Accidents)

OECD/HYMERES Phase 2 (Hydrogen Mitigation Experiments for Reactor Safety)

OECD/PKL-4 (Primary Coolant Loop Test Facility)

FONESYS (The Forum & Network of System Thermal-Hydraulic Codes in Nuclear Reactor Thermal-Hydraulics)

USNRC/CAMP (Code Applications and Maintenance Program)

### **Couplings and instabilities in reactor systems (INSTAB)**

NKS project COPSAR (Containment Pressure Suppression Systems Analysis for Boiling Water Reactors)

**Integral and separate effects tests on thermal-hydraulic problems in reactors (INTEGRA):**

OECD/NEA PKL Phase 4 project

**Nuclear criticality and safety analyses preparedness at VTT (KATVE):**

OECD/NEA NSC (Nuclear Science Committee)

OECD/NEA WPNCS (Working Party on Nuclear Criticality Safety)

AER WG E (Atomic Energy Research, working group E: radwaste, spent fuel and decommissioning)

EWGRD (European Working Group on Reactor Dosimetry)

**Development of a Monte Carlo based calculation sequence for reactor core safety analyses (MONSOON)**

Collaboration with International Serpent user community (770 users in 193 universities and research organizations in 40 countries worldwide).

Participation in the activities of American Nuclear Society (ANS) Reactor Physics Division (RPD).

Membership in the Editorial Board of Annals of Nuclear Energy.

Membership in the Technical Program Committee of the M&C 2017 international conference.

Membership in the Technical Program Committee of the PHYSOR 2018 international conference.

Membership in the OECD Nuclear Energy Agency, Working Party on Nuclear Criticality Safety (WPNCS), Expert Group on Advanced Monte Carlo Techniques (EGAMCT).

Membership in the OECD Nuclear Energy Agency, Working Party on Scientific Issues of Reactor Systems (WPRS).

### **Development and validation of CFD methods for nuclear reactor safety assessment (NURESA):**

OECD/NEA HYMERES Panda HP1\_6\_2 CFD blind benchmark on the erosion of stratified helium layer.

Nordic Thermal Hydraulic Network (Northnet), Roadmap 1 (OpenFOAM CFD-solver for nuclear reactor safety assessment).

NKS project COPSAR (Containment Pressure Suppression Systems Analysis for Boiling Water Reactors) in co-operation with KTH and LUT.

OpenFOAM multiphase CFD solver development in co-operation with Helmholtz-Zentrum Dresden-Rossendorf and the OpenFOAM Foundation.

### **Physics and chemistry of nuclear fuel (PANCHO):**

OECD Halden Reactor Project

OECD/NEA Working Group on Fuel Safety

Halden Programme Group Fuel&Materials

Jules Horowitz Reactor Fuel Working Group

OECD/NEA – IRSN Cabri Water Loop Project, Technical Advisory Group (TAG)

OECD/WGFS RIA benchmark Phase II

IAEA Coordinated Research Programme (CRP) Fuel modelling in accident conditions (FUMAC).

### **Safety analyses for dynamical events (SADE):**

AER working group D on VVER safety analysis

AER scientific council

### **Uncertainty and sensitivity analyses for reactor safety (USVA):**

OECD/NEA UAM-LWR (Expert Group on Uncertainty Analysis in Modelling / Coupled Multi-physics and Multi-scale LWR analysis).

IAEA Technical Meeting on Nuclear Data Processing, Ville Valtavirta represented Finland.

### **Experimental and numerical methods for external event assessment improving safety (ERNEST)**

Participation in ERNCIP European Reference Network for Critical Infrastructure Protection, Thematic group Resistance of Structures to Explosion Effects

### **Fire Risk Evaluation and Defence-in-Depth (FIRED)**

OECD/NEA PRISME3

### **Analysis of Fatigue and Other Cumulative ageing to extend lifetime (FOUND)**

NUGENIA Association Technical Area 8 (TA8), ENIQ (European Network for Inspection and Qualification) Task Group Risk (TGR) activities.

Co-operation with the Swedish-Finnish Beräkningsgrupp (BG)

European Technical Safety Organization Network (ETSON)

Nugenia: Project ATLAS+ (Advanced structural integrity assessment tools for safe long term operation)

ASME PVP: Informal networking with the main contributors in the field of environmental fatigue.

### **Long term operation aspects of structural integrity (LOST):**

ASTM E08 fatigue and fracture committee meeting

IGRDM20: International Group on Radiation Damage Mechanisms

14<sup>th</sup> International Conference on Fracture

ATLAS+ (Advanced Structural Integrity Assessment Tools for Safe Long Term Operation)

### **Mitigation of cracking through advanced water chemistry (MOCCA):**

European Co-operation Group on Corrosion Monitoring (ECG-COMON)

International Co-operative Group on Environmentally Assisted Cracking (ICG-EAC)

The International Association for the Properties of Water and Steam (IAPWS)

### **Thermal ageing and EAC research for plant life management (THELMA):**

International Co-operative group on environmentally assisted cracking, ICG-EAC (U. Ehrnstén).

Round Robin on initiation in Alloy 600 arranged by the ICG-EAC group (A. Toivonen)

EU H2020 project INCEFA+ - Increasing Safety in NPPs by Covering gaps in Environmental Fatigue Assessment (C. Hurley).

Co-operation with doctoral student Martin Bjurman, KTH and professor P. Efsing on thermally aged cast stainless steel (U. Ehrnstén).

Co-operation with professor Young Suk Kim, KAERI, Korea on thermally aged Alloy 690 (R. Mouginot).

Co-operation with professor M. Short, MIT, USA on thermally aged weld metals (H. Hänninen).

Nugenia TA4 - Integrity assessment & ageing of systems, structures & components (U. Ehrnstén)

OECD Halden project (M. Ivanchenko)

### **NDE of NPP primary circuit components and concrete infrastructure (WANDA):**

International cooperation within U.S. Nuclear Regulatory Commission (NRC)  
PARENT (Program to Assess the Reliability of Emerging Nondestructive Techniques)

Collaboration with ICIC - International Committee on Irradiated Concrete

Collaboration with IRSN's ODOBA Project - devoted to studying concrete related pathology in nuclear structures

Participation in worldwide NDT&E Round Robin on Standardized crack formation in concrete specimens for Civil Engineering applications

Participation in Nugenia (Nuclear GENeration II & III Association)

### **Condition Monitoring, Thermal and Radiation Degradation of Polymers Inside NPP Containments (COMRADE):**

2<sup>nd</sup> annual COMRADE workshop, 27 – 28<sup>th</sup> September 2017, Espoo, Finland.

Participation in Horizon 2020 project "TeaM CABLES - European Tools and Methodologies for an efficient ageing management of nuclear power plant cables".

### **JHR collaboration & Melodie follow-up (JHR):**

Jules Horowitz Reactor Working Groups

### **Radiological laboratory commissioning (RADLAB)**

HOTLAB Steering Committee member of Working Group on "Hot Laboratories and Remote Handling"

## **Appendix 3**

### **Academic degrees obtained in the projects in 2017**

## **Extreme weather and nuclear power plants (EXWE)**

*Doctor of Philosophy:*

Julius Vira: Data assimilation and numerical modelling of atmospheric composition, University of Helsinki, Department of Physics, date of the defence 23.2.2017

Ilari Lehtonen: Projected climate change impact on fire risk and heavy snow loads in the Finnish forests, University of Helsinki, Department of Physics, date of the defence 22.8.2017

## **Probabilistic risk assessment method development and applications (PRAMEA)**

*Doctor of Technology:*

Tero Tyrväinen: Theoretical and methodological extensions to dynamic reliability analysis, Aalto University, Department of Mathematics and Systems Analysis, date of the defence 13.10.2017

## **Electric Systems and Safety in Finnish NPP (ESSI)**

*Master of Science in Technology:*

Deepak Subedi: Lightning Induced Over-voltages in Power Transformer and Voltage Spikes in Connected Load. Aalto University, 28 September 2017.

## **Couplings and instabilities in reactor systems (INSTAB)**

*Master of Science in Technology:*

Vasilyev Vladislav: Steam sparger modelling for boiling water reactor suppression pool, Lappeenranta University of Technology, School of Energy Systems, Energy Technology, October 2017, <http://www.urn.fi/URN:NBN:fi-fe201709298827>, 75 p.

## **Development of a Monte Carlo based calculation sequence for reactor core safety analyses (MONSOON)**

*Doctor of Technology:*

Ville Valtavirta: “Development and applications of multi-physics capabilities in a continuous energy Monte Carlo neutron transport code.” D.Sc. Thesis, Aalto University, 2017.

## **Physics and chemistry of nuclear fuel (PANCHO)**

*Doctor of Technology:*

Emmi Myllykylä, Investigation of ThO<sub>2</sub> as a structural analogue for spent nuclear fuel dissolution under repository conditions, VTT Science 156, dissertation 15.6.2017.

Janne Heikinheimo, Applications of positron annihilation spectroscopy in nuclear materials research, Aalto University publication series DOCTORAL DISSERTATIONS, 224/2017, dissertation 26.1.2018.

## **Fire risk evaluation and Defence-in-Depth (FIRED)**

*Doctor of Technology:*

Topi Sikanen: “Simulation of transport, evaporation, and combustion of liquids in large-scale fire incidents”. Aalto University, Date of defense 19.1.2018

## **Long term operation aspects of structural integrity (LOST)**

*Master of Science in Technology:*

Sirkiä Laura: Laura Sirkiä, Applicability of miniature Compact Tension specimens for fracture toughness determination in ductile-brittle transition range, Master’s Thesis, Espoo, Aalto University, Department of Engineering Materials, date of the graduation 30.11.2017

## **Thermal ageing and EAC research for plant life management (THELMA)**

*Doctor of Science (Technology):*

Roman Mouginot, Effect of thermal ageing on Alloy 690 and 52 in pressurized water reactor applications, date of the defence 15.5.2017.

## **NDE of NPP primary circuit components and concrete infrastructure (WANDA)**

*Master of Science in Technology:*

Iiro Honkanen: Master of Science in Technology, Aalto University, June 2017. Reiän tekeminen ydinvoimalaitoksen turvallisuusluokiteltuun teräsbetoniseinämään.  
<https://aaltodoc.aalto.fi/handle/123456789/26735>

## **Condition Monitoring, Thermal and Radiation Degradation of Polymers Inside NPP Containments (COMRADE)**

*Master of Science in Technology:*

Erik Bernmalm Törnström: Degradation of polymeric materials in nuclear applications – Study of the end of life criteria, Chalmers University of Technology, Chemistry and chemical engineering - Applied chemistry. September 2017.

## **Development of thermal-hydraulic infrastructure at LUT (INFRAL)**

*Bachelor of Science in Technology:*

Siiri Jämsen: Void fraction measurement with wire-mesh sensor in swirling two-phase flow, Lappeenranta University of Technology, School of Energy Systems. Graduation expected 3/18.

## **Appendix 4**

### **International travels in the projects in 2017**

## **Crafting operational resilience in nuclear domain (CORE)**

Koskinen, H., 10th International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies (NPIC&HMIT), June 11-15, 2017, San Francisco, California, USA.

Koskinen, H., HUSC Steering Group meeting, November 7-8, 2017, Solna, Sweden.

Laarni, J., 10th International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies (NPIC&HMIT), June 11-15, 2017, San Francisco, California, USA.

Liinasuo, M., 40th Enlarged Halden Programme Group Meeting - EHPG 2017, September 24-29, 2017, Lillehammer, Norway.

Liinasuo, M., HUSC Steering Group meeting, November 7-8, 2017, Solna, Sweden.

Teperi, A.-M., Prevention of Accidents at Work (WOS 2017), October 3-6, 2017, Prague, Czech Republic.

Viitanen, K., 7th REA (Resilience Engineering Association) Symposium, June 26-29, 2017, Liege, Belgium.

Viitanen, K., HUSC Steering Group meeting, November 7-8, 2017, Solna, Sweden.

Wahlström, M., 7th REA (Resilience Engineering Association) Symposium, June 26-29, 2017, Liege, Belgium.

## **Extreme weather and nuclear power plants (EXWE)**

Gregow, H., European Climate Research Alliance (ECRA) General Assembly, March 8, 2017, Brussels, Belgium

Johansson, M., 4th International Conference on Energy & Meteorology (ICEM), June 27-29, 2017, Bari, Italy

Jylhä, K., 10th International Conference on Sustainable Energy & Environmental Protection (SEEP2017), June 27.-30, 2017, Bled, Slovenia

Korpinen, A., Fortelius, C., HIRLAM-ALADIN High Resolution Workshop, December, 4-6, 2017, Copenhagen, Denmark

Laurila, T., Research visit to ECMWF, March 12 – April 12, 2017, Reading, UK.

Laurila, T., 9th European Conference on Severe Storms (ECSS), September, 18-22, 2017, Pula, Croatia

Leijala, U., Research visit to Nansen Environmental and Remote Sensing Center (NERSC), January 9 – February 28, 2017, Bergen, Norway

Leijala, U., European Geosciences Union (EGU) General Assembly 2017, April 23-28, Vienna, Austria

Leijala, U., American Geophysical Union (AGU) Fall Meeting, December 11-15, 2017, New Orleans, Louisiana, USA,.

Mäkelä, A., COST Atmospheric Electricity Network September 25-27, 2017, Porto, Portugal.

Mäkelä, A., 9th European Conference on Severe Storms (ECSS), September, 18-22, 2017, Pula, Croatia

Pellikka, H., Joint Congress of the 6th International Conference on Meteorology and Climatology of the Mediterranean & Challenges in Meteorology 5, February, 20-22, 2017, Zagreb, Croatia

Rauhala, J., 2nd European Hail Workshop, April 19-21, 2017, Bern, Switzerland

Rauhala, J., 9th European Conference on Severe Storms (ECSS), September, 18-22, 2017, Pula, Croatia

## **Management Principles and Safety Culture in Complex Projects (MAPS)**

Gotcheva, N. Invited participation at IAEA meeting on CS to Review IAEA Safety Culture Continuous Improvement Plan (SCCIP) Support, Vienna, Austria, 2-5 May 2017.

Gotcheva, N. and Viitanen, K. Workshop with the NKS research partners, Stockholm, Sweden, 5-6 June 2017.

Aaltonen, K. and Kujala, J. International Research Network on Organizing by Projects (IRNOP), Boston, USA, 11-14 June 2017.

Viitanen, K. Resilience Engineering Symposium, Liege, Belgium, 26-29 June 2017.

Gotcheva, N. and Viitanen, K. WOSNET2017, 9<sup>th</sup> International Conference on the Prevention of Accidents at Work, Prague, Czech Republic, 3-6 October 2017.

## **Probabilistic risk assessment method development and applications (PRAMEA)**

Jan-Erik Holmberg. IAEA Consultancy Meeting on the development of the Safety Report on Human Reliability Assessment for Nuclear Installations, Vienna, 3-6 April, 2017.

Jan-Erik Holmberg. SITRON project stakeholders meeting, Stockholm, 21 April, 2017.

Jan-Erik Holmberg. Nordic PSA Group Autumn seminar, Gothenburg, 4 October, 2017.

Ilkka Karanta. NPSAG/NKS level 3 PSA seminar, Sundbyberg, Sweden, 14 February, 2017.

Alessandro Mancuso. Workshop on “Applications and future developments of Bayesian Networks in risk and impact assessments and environmental decision making”, Lund University, 28-29 March 2017.

Alessandro Mancuso. Exchange research period under the supervision of professor Enrico Zio. Politecnico di Milano, Milan (Italy), 1 April-1 June 2017.

Alessandro Mancuso. ESREL 2017, European Safety and Reliability. University of Ljubljana, Slovenia, 18-22 June 2017.

Alessandro Mancuso. ICSRS 2017, International Conference on System Reliability and Safety, Politecnico di Milano, 21-22 December 2017.

Markus Porthin. OECD/NEA Working Group on Risk Assessment (WGRISK) 18<sup>th</sup> Annual Meeting, Paris, France, 8 - 10 March 2017.

Markus Porthin. ETSON expert group meeting. Garching, Germany, 6 June 2017.

Markus Porthin. PSAM topical conference on Human Reliability, Quantitative Human Factors and Risk, Munich, Germany, 7 - 9 June, 2017.

Markus Porthin. ETSON expert group workshop: PSA from a TSO perspective - Experts from TSOs provide lessons learned through PSA application and review, Paris, France, 8 November, 2017.

Jan-Erik Holmberg and Markus Porthin. IAEA Technical Meeting on the Development of the Safety Report on Human Reliability Assessment for Nuclear Installations, Vienna, Austria, 13 - 17 November 2017.

## **Integrated safety assessment and justification of nuclear power plant automation (SAUNA)**

Papakonstantinou, N., Reliability and Maintainability Symposium (RAMS 2017), January 23–26, 2017, Orlando, FL, USA.

Porthin, M., 17<sup>th</sup> Annual Meeting of the CSNI Working Group on Risk Assessment (WGRISK), March 16–18, 2017, Paris, France.

Valkonen, J., 26<sup>th</sup> biennial regular meeting of the IAEA Technical Working Group on Nuclear Power Plant Instrumentation and Control (TWG-NPPIC), May 24–26, 2017, Vienna, Austria.

Pakonen, A., 27th European Safety and Reliability Conference (ESREL 2017), June 18–22, 2017, Portoroz, Slovenia.

Koskinen, H., Linnosmaa, J., Pakonen, A., 10th International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies (NPIC & HMIT 2017), June 11–15, 2017, San Francisco, CA, USA.

Papakonstantinou, N., ASME 2017 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2017, August 6–9, 2017, Cleveland, Ohio, USA.

Varkoi, T., 24<sup>th</sup> European Conference on Software and Services Process Improvement (EuroSPI 2017), September 6–8, 2017, Ostrava, Czech Republic.

Buzhinsky, I., 22nd IEEE Conference on Emerging Technologies & Factory Automation (ETFA 2017), September 12–15, 2017, Limassol, Cyprus.

Varkoi, T., International Conference on Computer Safety, Reliability, and Security (SAFECOMP 2017) / SASSUR: Next Generation of System Assurance Approaches for Safety-Critical Systems Workshop, September 12, 2017, Trento, Italy.

Valkonen, J., 40<sup>th</sup> Enlarged Halden Programme Group Meeting (EHPG), September 24–29, 2017, Lillehammer, Norway.

Buzhinsky, I., Vyatkin, V., 43rd Annual Conference of the IEEE Industrial Electronics Society (IECON 2017), October 29 – November 01, 2017, Beijing, China.

Vyatkin, V., Seminar at ITMO University on comparison of explicit-state and symbolic model checking, July 27–28, 2017, St. Petersburg, Russia.

## **Safety of new reactor technologies (GENXFIN)**

Ilvonen, M, IAEA Technical Meeting on Next Generation Reactors and Emergency Preparedness and Response, 13-17 February 2017, IAEA HQ, Vienna, Austria

Penttilä, S., The 8th International Symposium on Supercritical Water-cooled Reactors (ISSCWR-8) and GIF (Generation IV International Forum) SCWR (Supercritical Water Cooled Reactor) Materials & Chemistry Project Management Board (PMB) meeting in Chengdu, China, on March 13-16, 2017

Penttilä, S., IAEA (International Atomic Energy Agency) Consultants' Meeting to Finalize the TECDOC on the Status of SCWR R&D, 19 - 21 April 2017, IAEA HQ, Vienna, Austria

Penttilä, S., Generation IV International Forum (GIF) SCWR Materials & Chemistry (M&C) Project Management Board (PMB) Meeting, 12 September 2017, KIT, Karlsruhe, Germany

## **Comprehensive Analysis of Severe Accidents (CASA)**

Taivassalo, Veikko. 1<sup>st</sup> MITHYGENE benchmark meeting. 21 March 2017. Orleans, France.\*

Nieminen, Anna & Sevón, Tuomo. ERMSAR2017 seminar. 6-18 May 2017. Warsaw, Poland.

Taivassalo, Veikko. 2<sup>nd</sup> MITHYGENE benchmark meeting. 16 June 2017. Paris, France.\*

Nieminen, Anna. THAI-3 PRG3 and MB3 meetings. 19-20 June 2017. Frankfurt, Germany.

Sevón, Tuomo. 5<sup>th</sup> OECD BSAF-2 meeting. 10-14 July 2017. Tokyo, Japan.

Sevón, Tuomo. CSARP/MCAP meeting. 11-15 September 2017. Bethesda, USA.

Nieminen, Anna. OECD BIP-3 PRG3 and OECD STEM-2 PRG3 meetings. 24-26 October, 2017. Paris, France.

Taivassalo, Veikko. 3<sup>rd</sup> MITHYGENE benchmark meeting. 22 November 2017. Paris, France.\*

Nieminen, Anna. THAI-3 PRG4 and MB4 meetings. 15-17 January 2018. Paris, France.

Sevón, Tuomo. 6<sup>th</sup> OECD BSAF-2 meeting. 22-26 January 2018. Paris, France.

*\* Travel expenses compensated later by ETSO.*

## **Chemistry and transport of fission products (CATFIS)**

Kärkelä, T., Gouëllou, M., OECD/NEA STEM-2 meeting (Programme Review Group and Management Board), Paris, France, February 2017.

Gouëllou, M., Kärkelä, T., OECD/NEA BIP-3 meeting (Programme Review Group and Management Board), Paris, France, February 2017.

Kärkelä, T., OECD/NEA THAI-3 meeting (Programme Review Group), Frankfurt, Germany, June 2017.

Hokkinen, J., Kärkelä, T., Integration of Pool scrubbing Research to Enhance Source-term Calculations (IPRESCA) “kick-off meeting”, Frankfurt, Germany, June 2017.

Kärkelä, T., 26th International Conference Nuclear Energy for New Europe, Bled, Slovenia, September 2017.

## **Comprehensive and systematic validation of independent safety analysis tools (COVA)**

Karppinen, I. OECD/NEA PKL-4 meeting. 14.-16.5.2017. Paris, France.

Hillberg, S. OECD/NEA PKL-4 meeting, 6-9.11.2017, Erlangen, Germany.

Karppinen, I. OECD/NEA WGAMA meeting. 19.-22.9.2017. Paris, France.

Karppinen, I. OECD/NEA HYMERES Phase 2 meeting. 4.-6.10.2017. Villigen, Switzerland.

Hillberg S. USNRC/CAMP meeting, 27.11.-1.12.2017 , Washington DC, USA.

## **Integral and separate effects tests on thermal-hydraulic problems in reactors (INTEGRA)**

Heikki Purhonen, Vesa Riikonen, The Programme Review Group and Management Board meetings of the OECD/NEA PKL Phase 4 Project, Paris, France, 15<sup>th</sup> – 16<sup>th</sup> May 2017.

Heikki Purhonen, Vesa Riikonen, The Programme Review Group and Management Board meetings of the OECD/NEA PKL Phase 4 Project, Erlangen, Germany, 7<sup>th</sup> – 8<sup>th</sup> November 2017.

## **Nuclear criticality and safety analyses preparedness at VTT (KATVE)**

Leppänen, J., M&C 2017: International Conference on Mathematics & Computational Methods Applied to Nuclear Science & Engineering, April 16 - 20, Jeju, Korea

Kaltiaisenaho, T., Tuominen, R., 7<sup>th</sup> International Serpent User Group Meeting, November 6 - 9, Gainesville, Florida, USA

## **Development of a Monte Carlo based calculation sequence for reactor core safety analyses (MONSOON)**

April 16-20, 2017 Jeju, Korea – International conference M&C 2017 (Leppänen, Valtavirta, Sahlberg).

October 28 - November 2, 2017, Washington, DC, USA – ANS Winter Meeting and Reactor Physics Division Executive Committee Meeting (Leppänen)

November 6-10, 2017, Gainesville, FL, USA – 7th International Serpent User Group meeting (Serpent developer team)

## **Development and validation of CFD methods for nuclear reactor safety assessment (NURESA)**

Rämä, T., Nordic Thermal Hydraulic Network (Northnet), Roadmap 1 Reference Group Meeting, 30 May, 2017, KTH, AlbaNova, Stockholm, Sweden (in-kind contribution of Fortum).

Pättikangas, T., Nordic Thermal Hydraulic Network (Northnet), Roadmap 1 Reference Group Meeting, 30 May, 2017, KTH, AlbaNova, Stockholm, Sweden.

## **Physics and chemistry of nuclear fuel (PANCHO)**

Kättö, J., HRP VVER Workshop, 21.-22.2.2017, Slovakia.

Kättö, J., OECD/NEA Workshop on Nuclear Fuel Modelling, 7.3.2017-9.3.2017, Paris, France.

Tulkki, V., HPG meeting, 8.-10.5.2017, Berlin, Germany.

Loukusa, H., NuFuel workshop, 3.-9.9.2017, Lecco, Italy

Heikinheimo, J., 40th Enhanced Halden Programme Group Meeting, 25.-29.9.2017, Lillehammer, Norway.

Heikinheimo, J., IAEA CRP FUMAC 3<sup>rd</sup> Research Coordination Meeting, 13.-16.11.2017, Vienna, Austria.

### **Safety analyses for dynamical events (SADE)**

Sahlberg, V., AER working group D on VVER reactor dynamics and safety, May 10-11, 2017, Erlangen, Germany

Sahlberg, V., M&C 2017 conference, April 16-20, 2017, Jeju, Republic of Korea

Räty H., AER scientific council, November 27-28, 2017, Budapest, Hungary

### **Uncertainty and sensitivity analyses for reactor safety (USVA)**

Valtavirta, V., LWR Uncertainty Analysis in Modelling (UAM)-11 benchmark workshop, Areva, Erlangen, Germany, 10-12 May 2017.

Valtavirta, V., IAEA Technical meeting on nuclear data processing, IAEA, Vienna, Austria, 4-7, Dec. 2017.

### **Experimental and numerical methods for external event assessment improving safety (ERNEST)**

Saarenheimo, A., 24th conference on Structural Mechanics in Reactor Technology (SMiRT24), Busan, Korea, August 20-25, 2017

Fedoroff, A., 24th conference on Structural Mechanics in Reactor Technology (SMiRT24), Busan, Korea, August 20-25, 2017

### **Fire risk evaluation and Defence-in-Depth (FIRED)**

Sikanen, Topi: Participation to OECD/NEA PRISME meeting 27-28.4.2017 in Aix-en-Provence, France.

Sikanen, Topi. International Symposium on Fire Safety Science 2017, 10.-16.6.2017, University of Lund, Sweden

Sikanen, Topi: Nordic fire safety days, 17.-18.8.2017, Aalborg University in Copenhagen.

Sikanen, Topi: Participation to OECD/NEA PRISME meeting 20.-22.11-2016 in Aix-en-Provence, France.

## **Analysis of fatigue and other cumulative ageing to extend lifetime (FOUND)**

Cronvall, O., IAEA WG on statistical modelling of ageing effects, 26.2.-2.3.2017, Vienna, Austria.

Cronvall, O. ENIQ TGR meeting, 14-16.3.2017, Zurich, Switzerland.

Kuutti, J. SMiRT24 Conference, August 20-25, Busan, Korea.

Seppänen, T., ASME PVP Conference July 16–20, 2017, Waikoloa, Hawaii, USA.

## **Long term operation aspects of structural integrity (LOST)**

Wallin, K. ASTM E08 fatigue and fracture committee meeting, 2-6<sup>th</sup> May, Toronto, Canada.

Wallin, K. ASTM E08 fatigue and fracture committee meeting, 14-18<sup>th</sup> November, Atlanta, 2017, Georgia, USA.

Lindqvist, S., ICF17, 14th International conference on fracture, 20-24<sup>th</sup> June, Rodos Palace Hotel, Rhodes, Greece.

Lindqvist, S., IGRDM20, International Group on Radiation Damage Mechanisms, 15<sup>th</sup>-20<sup>th</sup> October, Santiago de Compostela, Spain

## **Mitigation of cracking through advanced water chemistry (MOCCA)**

Saario, T., International Conference on Film Forming Amines and Products (FFP), April 4 – 6, 2017, Lucerne, Switzerland.

Saario, T., International Cooperation Group on Environmentally Assisted Cracking of Water Reactor Materials (ICG-EAC) meeting, May 7-12, 2017, Chester, UK

Sipilä, K., European Co-operative Group on Corrosion Monitoring (ECG-COMON) meeting, June 12-13, 2017, Budapest, Hungary

Sipilä, K., Eurocorr 2017, September 4-7, 2017, Prague, Czech Republic

## **Thermal ageing and EAC research for plant life management (THELMA)**

Ehrnsten, Ulla. International Co-operative Group on Environmentally Assisted Cracking, ICGEAC2016, Steering committee meetings and yearly meeting, Chester, UK, 7-12.05.2017.

Ehrnstén, Ulla. Eurocorr 2017. 20<sup>th</sup> international corrosion congress & process safety congress 2017. Prague, Czech Republic, 3-7.9.2017.

Ivanchenko, Mykola. Halden IASCC meeting, Oslo, Norway, 8-9.11.2017

## **NDE of NPP primary circuit components and concrete infrastructure (WANDA)**

Jäppinen, T., 6<sup>th</sup> Nugenia Forum, Amsterdam, Netherlands, 28. - 30. March, 2017

Koskinen, T., 7<sup>th</sup> European-American Workshop on Reliability of NDE, Potsdam, Germany, 4.-8. September, 2017.

Ferreira, M. - Participation in NDT&E in Civil Engineering Advanced Training Workshop, 5-11.07.2018, Berlin, Germany

Bohner, E., Collaboration with IRSN's ODOBA Project - devoted to studying concrete related pathology in nuclear structures (Partner project discussions, Review of ODOBA platform work) 7-8.11.2017, Aix-en-Provence, France.

Al-Neshawy, F. - Participation in SMIRT 24, 20-25.08.2017, Busan, Korea.

Ferreira, M. (PARTLY SUPPORTED by WANDA) - Collaboration with ICIC - International Committee on Irradiated Concrete (EU project proposal discussions, Technical review of SOTA, Discussion of partner projects, Rez Group Visit) 7-10.11.2017, Prague, Czech rep.

## **Condition monitoring, thermal and radiation degradation of polymers inside NPP containments (COMRADE)**

Molander, M., Jansson, A., Bondeson, A., Bernmalm E. COMRADE workshop, 27-28<sup>th</sup> September, VTT CNS, Espoo, Finland.

## **Development of thermal-hydraulic infrastructure at LUT (INFRAL)**

Pyy Lauri & Telkkä Joonas. Research visit to Helmholtz-Zentrum Dresden-Rossendorf (HZDR), August 14-17, 2017, Dresden, Germany

## **JHR collaboration & Melodie follow-up (JHR)**

S. Huotilainen, 7<sup>th</sup> JHR MWG meeting, 30.3.2017 Amsterdam, Netherlands.

V. Tulkki, P. Kinnunen, 7<sup>th</sup> Technical seminar, 20.-21.6.2017 Cadarache, France.

## **Radiological laboratory commissioning (RADLAB)**

Lyytikäinen, T., Palosuo, I., Tähtinen, S. Factory Acceptance test of mechanical testing hot-cell unit, 6-8<sup>th</sup> February, 2017, Dresden, Germany

Tähtinen, S., Kukkonen, A., Karlsen, W. Factory acceptance test of final hot-cell unit, 20-21<sup>st</sup> March, 2017, Dresden, Germany.

Myllykylä, M. ICP-MS device operator training, 26.2-3.3.2017, Bremen, Germany

Karlsen, W., Annual meeting on Hot Laboratories and Remote Handling, HOTLAB 17-22.9.2017, Mito, Japan

Myllykylä, M. NKS-B Nordic ICP-MS device operators seminar 24-26.9.2017, Roskilde, Denmark

Lavonen, T. ICP-MS device operator training, 24-30.9.2017, Bremen, Germany

Palosuo, I., Zwick impact pendulum FAT and training, 6-10.11.2017, Ulm, Germany

Karlsen, W., Working Group on Hot Laboratories and Remote Handling, HOTLAB Steering Group, 4.12.2017, Brussels, Belgium

## **SAFIR2018 administration (ADMIRE)**

Hämäläinen J., Programme Committee for the Research and Training Programme of the European Atomic Energy Community (2014-2018) complementing the Horizon 2020 Framework Programme for Research and Innovation, Meeting of 'Fission' configuration, 9.3.2017, Centre de Conférence Albert Borschette, Brussels, Belgium.

Hämäläinen J., Programme Committee for the Research and Training Programme of the European Atomic Energy Community (2014-2018) complementing the Horizon 2020 Framework Programme for Research and Innovation, Joint meeting of the 'Fission' and 'Fusion' configurations, 6.6.2017, Centre de Conférence Albert Borschette, Brussels, Belgium.

Hämäläinen J., The Sixty First (61st) Meeting of The Committee on the Safety of Nuclear Installations (CSNI), 1.-2.6.2017, OECD Conference Centre, Paris, France.

Hämäläinen J. , The Sixty Second (62nd) Meeting of The Committee on the Safety of Nuclear Installations (CSNI), 6.-7.12.2017, OECD Conference Centre, Paris, France.

## **Appendix 5**

**The management board, the steering groups, the reference groups and the scientific staff of the projects in 2017**

## SAFIR2018 Management Board – MB

(Status in August 2017)

Organisation	Member	Vice member
<b>STUK</b>	Marja-Leena Järvinen (Chair)	Tomi Routamo
<b>STUK</b>	Tomi Routamo	Nina Lahtinen
<b>Aalto</b>	Filip Tuomisto	Eila Järvenpää
<b>Fennovoima</b>	Hanna Virlander	Jussi Leppänen
<b>Fortum</b>	Kristiina Söderholm	Matti Kattainen
<b>LUT</b>	Juhani Hyvärinen	Heikki Purhonen
<b>MEAE</b>	Jorma Aurela	Linda Kumpula, Jaakko Louvanto
<b>SSM</b>	Nils Sandberg (on leave)	N/A
<b>Tekes</b>	N/A	Reijo Munther
<b>TVO</b>	Arto Kotipelto	Antti Tarkiainen
<b>VTT</b>	Eija Karita Puska	Petri Kinnunen
<b>SAFIR2018 (Secretary)</b>	Jari Hämäläinen	Vesa Suolanen

## SAFIR2018 Steering Groups:

(Status in August 2017)

### SG1 – Plant safety and systems engineering

Organisation	Member	Vice member
STUK	Tomi Routamo (Chair)	Eero Virtanen
Fennovoima	Pekka Viitanen	Juho Helander
Fortum	Eero Vesaoja	Maria Vuokko
TVO	Jari Pesonen (Vice chair)	Mikko Lemmetty
SAFIR2018 (Secretary)	Jari Hämäläinen	Vesa Suolanen

### SG2 – Reactor safety

Organisation	Member	Vice member
STUK	Nina Lahtinen (Chair)	Antti Daavittila
Fennovoima	Pekka Nurmilaukas	Jukka Rintala
Fortum	Satu Sipola	Timo Toppila
TVO	Juha Poikolainen (Vice chair)	Matti Paajanen
SAFIR2018 (Secretary)	Jari Hämäläinen	Vesa Suolanen

### SG3 – Structural safety and materials

Organisation	Member	Vice member
STUK	Martti Vilpas (Chair)	Pekka Välikangas
Fennovoima	Erkki Pulkkinen	Pasi Lindroth
Fortum	Ritva Korhonen	Ossi Hietanen
TVO	Timo Kukkola (Vice chair)	Paul Smeekes
SAFIR2018 (Secretary)	Jari Hämäläinen	Vesa Suolanen

## SAFIR2018 – Reference Groups and Projects:

(Status in August 2017)

Reference Group	Projects	Comments
<b>RG1 Automation, organisation and human factors</b>	CORE (SG1), ESSI (SG1), MAPS (SG1), SAUNA (SG1)	SG1 area
<b>RG2 Severe accidents and risk analysis</b>	EXWE (SG1), PRAMEA (SG1), GENXFIN (SG1), CASA (SG2), CATFIS (SG2), ERNEST (SG3), FIRED (SG3)	SG1, SG2 and SG3 areas
<b>RG3 Reactor and fuel</b>	KATVE (SG2), MONSOON (SG2), PANCHO (SG2), SADE (SG2), USVA (SG2)	SG2 area
<b>RG4 Thermal hydraulics</b>	COVA (SG2), INSTAB (SG2), INTEGRA (SG2), NURESA (SG2)	SG2 area
<b>RG5 Structural integrity</b>	COMRADE (SG3), FOUND (SG3), LOST (SG3), MOCCA (SG3), THELMA (SG3), WANDA (SG3)	SG3 area
<b>RG6 Research infrastructure</b>	INFRAL, JHR, RADLAB	RG6 area

## RG1 – Automation, organisation and human factors

Organisation	Member	Vice member
Aalto	N/A	N/A
Fennovoima	Janne Peltonen (Vice chair), Anna Aspelund	Topi Tahvonen
Fortum	Juha Lamminen, Jussi Lahtinen, Leena Salo	Ville Nurmilaukas
LUT	Anne Jordan, Eetu Kotro	N/A
STUK	Mika Johansson, Pia Oedewald, Paula Savioja	Mika Kaijanen, Hanna Kuivalainen, Ann-Mari Sunabacka-Starck, Heimo Takala
TVO	Mauri Viitasalo (Chair), Petri Koistinen	Lauri Tuominen
VTT	Juha Kortelainen, Heli Talja	N/A

## RG2 – Severe accidents and risk analysis

Organisation	Member	Vice member
Aalto	Ahti Salo	N/A
Fennovoima	Juho Helander (Vice chair), Antti Paajanen, Janne Vahero	Leena Torpo
FMI	Heikki Tuomenvirta	Lauri Laakso
Fortum	Tapani Kukkola, Reko Rantamäki, Sami Siren	Tommi Purho
LUT	Jani Laine	N/A
STUK	Ellen Hakala, Ilkka Niemelä, Pekka Välikangas	Lauri Pöllänen
TVO	Lasse Tunturivuori (Chair), Timo Kukkola, Maria Lindholm	N/A
VTT	Ilona Lindholm, Tony Rosqvist, Kim Wallin	N/A

## RG3 – Reactor and fuel

Organisation	Member	Vice member
Aalto	Jarmo Ala-Heikkilä	N/A
Fennovoima	Jussi Kumpula, Kaisa Pellinen, Jukka Rintala	Libor Klecka
Fortum	Simo Saarinen, Laura Kekkonen	Jaakko Kuopanportti
LUT	Ville Rintala, Heikki Suikkanen	N/A
STUK	Antti Daavittila (Chair), Lena Hansson-Lyyra	N/A
TVO	Arttu Knuutila (Vice chair), Anssu Ranta-aho	Kari Ranta-Puska
VTT	Sami Penttilä, Eric Dorval	N/A

## RG4 – Thermal hydraulics

Organisation	Member	Vice member
Aalto	N/A	N/A
Fennovoima	Calle Korhonen, Jukka Lumela	Leena Torpo
Fortum	Timo Toppila (Vice chair), Aino Ahonen, Tapani Raunio	Tommi Rämä
LUT	Juhani Vihavainen, Lauri Pyy, Otso-Pekka Kauppinen	N/A
STUK	Eero Virtanen (Chair), Miikka Lehtinen	N/A
TVO	Janne Wahlman, Matti Paajanen	Timo Virtanen
VTT	Mikko Ilvonen, Anitta Hämäläinen, Jaakko Leppänen	N/A

## RG5 – Structural integrity

Organisation	Member	Vice member
Aalto	Simo-Pekka Hannula, Iikka Virkkunen	N/A
Fennovoima	Mika Helin, Juha Rinta-Seppälä, Pasi Lindroth	Cem Ecevitoglu, Harri Lipiäinen
Fortum	Ossi Hietanen (Vice chair), Sanna Ala-Kleme, Sampsa Launiainen	Ritva Korhonen
LUT	Vesa Tanskanen	N/A
STUK	Mika Bäckström, Mirka Schildt	Jukka Härkölä
TVO	Erkki Muttilainen (Chair), Paul Smeekes, Vesa Hiltunen	Kimmo Tompuri
VTT	Kim Wallin, Aki Toivonen, Pertti Auerkari	N/A

## RG6 – Research infrastructure

Organisation	Member	Vice member
STUK	Juha Luukka	Martti Vilpas
Fennovoima	Petri Sane	Jussi Leppänen
Fortum	Jyrki Kohopää (Chair)	Kristiina Söderholm
MEE	Jorma Aurela	Linda Kumpula
TVO	Mikko Lemmetty (Vice chair)	Erkki Muttilainen
Aalto	Mikko Alava	Filip Tuomisto
LUT	Heikki Purhonen	Juhani Hyvärinen
VTT	Petri Kinnunen	Satu Helynen
KYT2018	Jarkko Kyllönen (STUK)	Kari Rasilainen (VTT)

## Project personnel

### Crafting operational resilience in nuclear domain (CORE)

Research organisations: VTT, TTL

Project manager: Jari Laarni, VTT

Person	Org.	Tasks
Jari Laarni, PhD	VTT	Project manager, Human factors engineering, Work design, Cognitive modelling, Cognitive psychology
Hannu Karvonen, MA	VTT	Human factors, Functional situation modelling
Hanna Koskinen, MA	VTT	Human factors, Learning from successes, Emergency management
Timo Kuula, MA	VTT	Work-based learning, Work design
Marja Liinasuo, PhD	VTT	Human factors, Learning from successes, Emergency management
Markus Porthin, MScTech	VTT	Emergency management
Mikael Wahlström, PhD	VTT	Human factors, Work-based learning, Work design
Kaupo Viitanen, MA	VTT	Safety culture, Learning from successes, Operating experience review
Satu Pakarinen, PhD	TTL	Deputy project manager, Psychophysiological methods, Stress management, Biofeedback
Heli Heikkilä	TTL	Psychophysiological methods and analysis, Stress management
Jussi Korpela	TTL	Psychophysiological methods and analysis, Stress management
Kristian Lukander, MScTech	TTL	Psychophysiological methods and analysis, Stress management
Kati Petterson, MScTech	TTL	Psychophysiological methods and analysis, Stress management
Vuokko Puro, MScTech	TTL	Human factors, Safety Management, Operational experience review
Henriikka Ratilainen, MScTech	TTL	Human factors, Safety Management, Operational experience review
Marika Schaupp, MA	TTL	Work-based learning, Work design
Laura Seppänen, PhD	TTL	Work-based learning, Work design
Anna-Maria Teperi, PhD	TTL	Human factors, Safety Management, Operational experience review
Maria Tiikkaja, PhD	TTL	Human Factors, Safety Management Systems

### Extreme weather and nuclear power plants (EXWE)

Research organisation: Finnish Meteorological Institute (FMI)

Project manager: Kirsti Jylhä, FMI

Person	Org.	Tasks
Kirsti Jylhä, Dr	FMI	Project management; WP1 coordination; freezing rain; sea-effect snowfall
Antti Mäkelä, Dr	FMI	Deputy project manager; warm-season extreme convective weather
Jan-Victor Björkqvist	FMI	Joint effect of high sea level and waves
Carl Fortelius, Dr	FMI	Fine scale numerical weather prediction
Hilppa Gregow, Dr	FMI	Freezing rain: contributing to writing
Sebastian Heinonen	FMI	SILAM interface development
Otto Hyvärinen, Dr	FMI	Freezing rain: optimization methods
Milla Johansson, Dr	FMI	Joint effect of high sea level and waves
Ari Karppinen, Dr	FMI	Dispersion modelling; WP3 coordination
Natalia Korhonen, MSc	FMI	Reanalysis data for sea level simulations
Anniina Korpinen	FMI	Fine scale numerical weather prediction
Matti Kämäräinen, MSc	FMI	Freezing rain
Terhi Laurila, MSc	FMI	Extreme convective weather; storm Mauri
Ilari Lehtonen, MSc	FMI	Synoptic analysis of meteotsunami cases
Ulpu Leijala, MSc	FMI	Joint effect of high sea level and waves
Anna Luomaranta, MSc	FMI	Sea-effect snowfall, HARMONIE runs
Taru Olsson, MSc	FMI	Sea-effect snowfall, HARMONIE runs
Havu Pellikka, MSc	FMI	Short-period sea level oscillations, WP2 coordination
Tuuli Perttula, MSc	FMI	Sea-effect snowfall, data assimilation
Jenni Rauhala, MSc	FMI	Warm-season extreme convective weather
Mikhail Sofiev, Dr	FMI	Dispersion modelling: development
Jani Särkkä, Dr	FMI	Joint effect of high sea level and waves
Peter Ukkonen, MSc	FMI	Warm-season extreme convective weather
Andrea Vajda, Dr	FMI	Freezing rain: contributing to writing

### Management Principles and Safety Culture in Complex Projects (MAPS)

Research organisations: VTT, University of Oulu, Aalto University

Project manager: Nadezhda Gotcheva, VTT

Person	Org.	Tasks and expertise
Nadezhda Gotcheva, PhD	VTT	Project management, safety culture, safety management and leadership, WP5 leader, WP1, WP3
Kaupo Viitanen	VTT	Safety culture, Task leader T3.3 (NKS SC_AIM project)
Sampsa Ruutu, PhD	VTT	WP4 (system dynamics modelling)

student		
Joona Tuovinen, PhD student	VTT	WP4 leader (system dynamics modelling)
Jaakko Kujala, Professor	University of Oulu	Governance of inter-organizational project networks, WP1 leader; system dynamics modelling support (WP4), WP5
Kirsi Aaltonen, Assistant Professor	University of Oulu	Governance of inter-organizational project networks (WP1, WP5)
Karlos Artto, Professor	Aalto University	Project business, megaproject management, scientific advisor (WP1, WP5)

### **Probabilistic risk assessment method development and applications (PRAMEA)**

Research organisation: VTT, Risk Pilot, Aalto

Project manager: Ilkka Karanta, VTT

<b>Person</b>	<b>Org.</b>	<b>Tasks</b>
Ilkka Karanta, LicTech	VTT	Project management, Level 2 PRA, Level 3 PRA method development and case studies
Kim Björkman, MScTech	VTT	Site level PRA, Method support for level 2
Terhi Kling, MScTech	VTT	Requirements for HRA for advanced control rooms
Marja Liinasuo, DrPsych	VTT	Requirements for HRA for advanced control rooms
Teemu Mätäsniemi, MScTech	VTT	Method support for levels 1 and 2 tight integration
Joonas Linnosmaa, MScTech	VTT	Method support for levels 1 and 2 tight integration
Markus Porthin, MScTech	VTT	Requirements for HRA for advanced control rooms
Tero Tyrväinen, DrTech	VTT	Site level PRA, Dynamic flowgraph methodology, IDPSA, Method support for level 2 PSA, Method support for levels 1 and 2 tight integration
Jan-Erik Holmberg, DrTech	Risk Pilot	IAEA safety guide on HRA, Site level PRA
Erik Cederhorn, MScTech	Risk Pilot	Site level PRA
Carl Sunde, DrTech	Risk Pilot	Site level PRA
Ahti Salo, DrTech, professor	Aalto	Project management, Reliability analysis of defence-in-depth in organizations
Alessandro Mancuso, MScTech	Aalto	Reliability analysis of defence-in-depth in organizations

## **Integrated safety assessment and justification of nuclear power plant automation (SAUNA)**

Research organisation: VTT, Aalto University, Risk Pilot, FiSMA

Project manager: Antti Pakonen, VTT

<b>Person</b>	<b>Org.</b>	<b>Tasks</b>
Antti Pakonen, MScTech	VTT	Project management, Explicit state model checking, Requirement editing and refinement for formal verification
Jarmo Alanen, MScTech	VTT	Overall plant automation safety demonstration, MBSE methods for architecture level DiD analysis
Kim Björkman, MScTech	VTT	Modelling of digital I&C (MODIG)
Hanna Koskinen, MA	VTT	Structured safety demonstration of control room systems, Overall plant automation safety demonstration
Jari Laarni, PhD	VTT	Structured safety demonstration of control room systems
Joonas Linnosmaa, MScTech	VTT	MBSE methods for architecture level DiD analysis, Overall plant automation safety demonstration
Teemu Tommila, MScTech	VTT	MBSE methods for architecture level DiD analysis, Overall plant automation safety demonstration
Nikolaos Papakonstantinou, DrTech	VTT	MBSE methods for architecture level DiD analysis
Markus Porthin, MScTech	VTT	Modelling of digital I&C (MODIG)
Tero Tyrväinen, DrTech	VTT	Modelling of digital I&C (MODIG)
Janne Valkonen, MScTech	VTT	Overall plant automation safety demonstration
Igor Buzhinskii, MSc	Aalto	Project management, Explicit state model checking, Requirement editing and refinement for formal verification
Valeriy Vyatkin, PhD	Aalto	Explicit state model checking, Requirement editing and refinement for formal verification
Jan-Erik Holmberg, DrTech	Risk Pilot	Project management, Modelling of digital I&C (MODIG)
Timo Varkoi, LicTech	FiSMA	Project management, Process assessment methods and tools
Risto Nevalainen, LicTech	FiSMA	Process assessment methods and tools

### Safety of new reactor technologies (GENXFIN)

Research organisation: VTT

Project manager: Jarno Kolehmainen, VTT

Person	Org.	Tasks
Jarno Kolehmainen, M.Sc.	VTT	Project management, Safety features of SMRs
Mikko Ilvonen,	VTT	Safety features of SMRs, International co-operation
Riku Tuominen, M.Sc	VTT	Safety features of SMRs
Ville Sahlberg, M.Sc	VTT	Safety features of SMRs
Sami Penttilä, M.Sc.	VTT	International co-operation

### Electric Systems and Safety in Finnish NPP (ESSI)

Research organisation: VTT and Aalto University

Project manager: Seppo Hänninen, VTT

Person	Org.	Tasks
Seppo Hänninen, DrTech	VTT	Project management, adaptive operation of NPP, requirements for maneuvering capabilities of NPP, interviews of Finnish plant operators and STUK.
Anna Kulmala, DrTech	VTT	Analyses of unbalance conditions, interviews of Finnish plant operators and STUK.
Riku Pasonen, , MScTech	VTT	Adaptive operation of NPP, requirements for maneuvering capabilities of NPP, interviews of Finnish plant operators and STUK.
Antti Alahäivälä, DrTech	VTT	Analysis of Open Phase Condition Influence on an Induction Motors, laboratory tests.
Matti Lehtonen, Prof, DrTech	Aalto University	Project management, modelling of NPP electrical systems for lightning strokes, interviews of Finnish plant operators and STUK.
Deepak Subedi, MScTech	Aalto University	Modelling of NPP electrical systems for lightning strokes
Mohammed Rizk, PhD	Aalto University	Modelling of NPP electrical systems for lightning strokes

### Comprehensive Analysis of Severe Accidents (CASA)

Research organisation: VTT

Project manager: Anna Nieminen, VTT

Person	Org.	Tasks
Tuomo Sevón, , M.Sc. (Tech.)	VTT	OECD BSAF-2 project participation and U.S.NRC CSARP contact, Fukushima accident analyses with MELCOR.
Veikko Taivassalo, Ph.Lic. (Phys.)	VTT	Comparing VTT's MEWA and Fluent results on debris bed post-dryout temperature behaviour to KTH's DECOSIM results, participating in the MITHYGENE ETSON benchmark on hydrogen combustion.
Magnus Strandberg, M.Sc. (Tech.)	VTT	Analysing the effect of RPV breaking location on load induced by a steam explosion, simulating pool scrubbing experiments with MELCOR.
Anna Nieminen, M.Sc. (Tech.)	VTT	Project management, OECD THAI-3 project participation, analysing the effect of post-accident pH control on iodine behaviour, simulating pool scrubbing experiments with ASTEC.
Jukka Rossi, M.Sc. (Tech.)	VTT	ARANO analyses on health effects.
Mikko Ilvonen, Lic.Sc. (Tech.)	VTT	Augmenting VALMA with the calculation of acute and late health effects of radiation doses.

### Chemistry and transport of fission products (CATFIS)

Research organisation: VTT

Project manager: Teemu Kärkelä, VTT

Person	Org.	Tasks
Teemu Kärkelä, MScTech	VTT	Project management, Ruthenium, Iodine, HNO <sub>3</sub> and Pool Scrubbing experiments, Interpretation of results, Follow-up of OECD/NEA projects
Mélany Gouëlle, PhD	VTT	Iodine experiments in primary circuit conditions, HNO <sub>3</sub> formation experiments, Follow-up of OECD/NEA projects
Jouni Hokkinen, MScTech	VTT	Iodine experiments in primary circuit conditions, Pool Scrubbing experiments, Construction of experimental facilities

Karri Penttilä, MScTech	VTT	ChemPool calculations on pool pH
Tommi Kekki, MScTech	VTT	HNO <sub>3</sub> formation experiments
Petri Kotiluoto, PhD	VTT	HNO <sub>3</sub> formation experiments
Emmi Myllykylä, MSc	VTT	Chemical analysis - iodine experiments
Jaana Rantanen, Technician	VTT	Chemical analysis - iodine experiments
Tuula Kajolinna, Engineer	VTT	Analysis of gaseous compounds - iodine experiments

### **Comprehensive and systematic validation of independent safety analysis tools (COVA)**

Research organisation: VTT

Project manager: Seppo Hillberg, VTT

<b>Person</b>	<b>Org.</b>	<b>Tasks</b>
Seppo Hillberg, M.Sc. (Tech)	VTT	Project manager, thermal-hydraulic analysis, nuclear power plant modelling, international cooperation/communication through research programmes (USNRC/CAMP)
Ismo Karppinen, M.Sc. (Tech)	VTT	thermal-hydraulic analysis, nuclear power plant modelling, international cooperation/communication through research programmes (OECD/NEA WGAMA, HYMERES Phase 2, PKL-4)
Jarno Kolehmainen, M.Sc. (Tech)	VTT	thermal-hydraulic analysis, nuclear power plant modelling, containment modelling, international cooperation/communication through research programmes (OECD/NEA HYMERES Phase 2)
Ari Silde, M.Sc. (Tech)	VTT	thermal-hydraulic analysis, nuclear power plant modelling, containment modelling
Joona Kurki, Lic. (Tech)	VTT	international cooperation/communication through research programmes (FONESYS)
Marton Szogradi	VTT	thermal-hydraulic analysis, nuclear power plant modelling
Saila Nojonen	VTT	Master's thesis worker

### **Couplings and instabilities in reactor systems (INSTAB)**

Research organisation: LUT

Project manager: Markku Puustinen, LUT

<b>Person</b>	<b>Org.</b>	<b>Tasks</b>
Markku Puustinen, MScTech	LUT	Project manager, Experiment planning and analysis

Jani Laine, MScTech	LUT	Deputy project manager, Experiment analysis, Data conversion
Heikki Purhonen, DrTech	LUT	International tasks, Experiment planning
Vesa Riikonen, MScTech	LUT	Data acquisition, Experiments
Antti Räsänen, MScTech	LUT	Instrumentation, Data acquisition, Data conversion, Visualization, Control systems, Experiments
Vesa Tanskanen, DrTech	LUT	Computer simulations, Experiments
Giteshkumar Patel, MScTech	LUT	Computer simulations, Literature survey
Harri Partanen, Engineer	LUT	Designing of test facilities, Experiments
Kimmo Tielinen, Trainee	LUT	Designing of test facilities, Experiments
Hannu Pylkkö, Technician	LUT	Construction, operation and maintenance of test facilities, Experiments
Ilkka Saure, Technician	LUT	Construction, operation and maintenance of test facilities, Experiments
Lauri Pyy, MScTech	LUT	Assessment of measurement techniques, Experiments
Joonas Telkkä, MScTech	LUT	Assessment of measurement techniques, Experiments
Elina Hujala, MScTech	LUT	Pattern recognition, Experiment analysis
Tatu Hovi, MScTech	LUT	Computer simulations
Eetu Kotro, MScTech	LUT	Construction, operation and maintenance of test facilities, Instrumentation, Data acquisition, Data conversion, Visualization, Control systems

### **Integral and separate effects tests on thermal-hydraulic problems in reactors (INTEGRA)**

Research organisation: LUT

Project manager: Vesa Riikonen, LUT

<b>Person</b>	<b>Org.</b>	<b>Tasks</b>
Vesa Riikonen, MScTech	LUT	Project manager, experiment planning, analysis and reporting, data acquisition
Markku Puustinen, MScTech	LUT	Deputy project manager
Heikki Purhonen, DrTech	LUT	International tasks
Juhani Hyvärinen, DrTech	LUT	International tasks
Virpi Kouhia, MScTech	LUT	APROS code modeling and calculations
Otso-Pekka Kauppinen, MScTech	LUT	TRACE code modeling and calculations
Joonas Telkkä, MScTech	LUT	Designing of test facilities
Antti Räsänen, MScTech	LUT	Instrumentation, data acquisition, process control, experimental work

Harri Partanen, Engineer	LUT	Designing of test facilities
Ilkka Saure, Technician	LUT	Construction, operation and maintenance of test facilities, experimental work
Eetu Kotro, MScTech	LUT	Construction, operation and maintenance of test facilities, experimental work
Kimmo Tielinen, student	LUT	Construction, operation and maintenance of test facilities, experimental work

### **Nuclear criticality and safety analyses preparedness at VTT (KATVE)**

Research organisation: VTT

Project manager: Pauli Juutilainen, VTT

<b>Person</b>	<b>Org.</b>	<b>Tasks</b>
Pauli Juutilainen, M.Sc.	VTT	Project management, Validation package, Burnup credit
Riku Tuominen, M.Sc.	VTT	Validation package
Silja Häkkinen, D.Sc.(Tech)	VTT	Shielding analysis of dry storage
Toni Kaltiaisenaho, M.Sc.	VTT	Gamma transport in Serpent, Radiation transport in severe accidents
Jaakko Leppänen, D.Sc.(Tech.)	VTT	Gamma transport in Serpent
Eric Dorval, D.Sc.	VTT	Neutron dosimetry
Asko Arkoma, M.Sc	VTT	Fuel integrity in dry storage cask
Petri Kotiluoto, PhD	VTT	International co-operation

### **Development of a Monte Carlo based calculation sequence for reactor core safety analyses (MONSOON)**

Research organisation: VTT

Project manager: Jaakko Leppänen, VTT

<b>Person</b>	<b>Org.</b>	<b>Tasks</b>
Jaakko Leppänen, D.Sc.	VTT	Project manager, head developer of the Serpent code, development of methods for spatial homogenization and automated calculation sequence.
Ville Valtavirta, D.Sc.	VTT	Deputy project manager, Serpent developer, development of methods for assembly burnup calculations with fuel temperature feedback.
Ville Sahlberg, M.Sc.	VTT	Ants developer, Serpent user, group constant generation for TRAB3D transient analysis code.
Antti Rintala, M.Sc.	VTT	Ants developer, Serpent user, group constant

		generation for the HEXBU-3D core simulator.
Toni Kaltiaisenaho, M.Sc.	VTT	Serpent developer and user
Riku Tuominen, M.Sc.	VTT	Serpent developer and user

### Development and validation of CFD methods for nuclear reactor safety assessment (NURESA)

Research organisations: VTT, Aalto, LUT Energy, Fortum (in-kind contribution)

Project manager: Dr Timo Pättikangas, VTT

Person	Org.	Task
Timo Pättikangas, D.Sc.	VTT	Project manager, CFD modelling of PPOOLEX experiments
Risto Huhtanen, Lic. Tech.	VTT	CFD modelling of PPOLEX facility
Ville Hovi, M.Sc	VTT	CFD model development of VVER-440 pressurizer
Juho Peltola, M.Sc	VTT	OpenFOAM solver for nuclear reactor safety assessment
Vesa Tanskanen, D.Sc.	LUT	CFD model development and validation for direct-contact condensation
Giteshkumar Patel, D.Sc.	LUT	CFD model development and validation for direct-contact condensation
Tommi Rämä, M.Sc.	Fortum	CFD simulation of VVER-440 pressurizer (in-kind contribution)
Timo Toppila, M.Sc.	Fortum	CFD simulation of VVER-440 pressurizer (in-kind contribution)

### Physics and chemistry of nuclear fuel (PANCHO)

Research organisation: VTT

Project manager: Ville Tulkki, VTT

Person	Org.	Tasks
Asko Arkoma, MSc (Tech)	VTT	Analysis of reactivity initiated accidents and loss of coolant accidents, implementation and development of SCANAIR code.
Timo Ikonen, D.Sc. (Tech)	VTT	FINIX development
Joonas Kättö, MSc (Tech)	VTT	Improvement of validation database system, FINIX development. FUMAC participation.
Henri Loukusa, MSc (Tech)	VTT	FINIX mechanical models development
Emmi Myllykylä, MSc	VTT	Dissertation
Rami Pohja, MSc (Tech)	VTT	Cladding mechanical models,
Ville Tulkki, D.Sc (Tech)	VTT	Development of cladding creep models,

		project manager.
Janne Heikinheimo MSc(Tech)	VTT	Analysis of Halden VVER experiment, FUMAC participation.

### **Safety analyses for dynamical events (SADE)**

Research organisation: VTT

Project manager: Ville Sahlberg, VTT until August 2017

Elina Syrjälähti, VTT since September 2017

<b>Person</b>		<b>Task</b>
Hovi Ville, MSc (Tech)	VTT	3D thermal hydraulics
Räty Hanna, MSc (Tech)	VTT	International co-operation;
Sahlberg Ville, MSc(Tech)	VTT	Neutronics; project manager until August 2017
Syrjälähti Elina, MSc (Tech)	VTT	Project manager since September 2017
Taivassalo Veikko, PhLic(Phys)	VTT	3D thermal hydraulics

### **Uncertainty and sensitivity analyses for reactor safety (USVA)**

Research organisation: VTT

Project manager: Ville Valtavirta, VTT

<b>Person</b>	<b>Org.</b>	<b>Tasks</b>
Ville Valtavirta, DScTech	VTT	Project management, collision history-based GPT capability for Serpent
Asko Arkoma, MScTech	VTT	Deputy project manager, analysis of rod failures in LB-LOCA
Torsti Alku, MScTech	VTT	Methodology for determining input uncertainties
Elina Syrjälähti, MScTech	VTT	Coupled calculations with fuel performance and reactor dynamics codes

### **Experimental and Numerical methods for External event assessment improving Safety (ERNEST)**

Research organisation: VTT

Project manager: Ari Vepsä, VTT

<b>Person</b>	<b>Org.</b>	<b>Tasks</b>
Ari Vepsä, MScTech	VTT	Project management, impact testing

Alexis Fedoroff, DrTech	VTT	Concrete material model development, numerical modelling
Arja Saarenheimo, LichTech	VTT	Numerical modelling
Kim Calonius, MScTech	VTT	Numerical modelling

### **Fire Risk Evaluation and Defence-in-Depth (FIRED)**

Research organisation: VTT, AALTO

Project manager: Anna Matala, VTT (1-5/2017), Topi Sikanen, VTT (6-12/2017)

<b>Person</b>	<b>Org.</b>	<b>Tasks</b>
Topi Sikanen, MScTech	VTT	Project management, FDS development and validation.
Anna Matala, DrTech	VTT	Project management, Investigation of cable ageing.
Antti Paaanen, MSc	VTT	Atomistic simulations of novel flame retardants
Jukka Vaari, DrTech	VTT	Atomistic simulations of novel flame retardants
Simo Hostikka, DrTech	Aalto	Project management, Barrier performance assessment with Fire-CFD,
Deepak Paudel, Doct student	Aalto	Barrier performance assessment with Fire-CFD, Uncertainty propagation between models.
Teemu Isojärvi, Doct student	Aalto	Liquid pool radiation modelling using k-distribution method

### **Analysis of fatigue and other cumulative ageing to extend lifetime (FOUND)**

Research organisation: VTT, Aalto

Project manager: Juha Kuutti, VTT

<b>Person</b>	<b>Org.</b>	<b>Tasks</b>
Juha Kuutti, M.Sc. Tech.	VTT	Project management; WP1 – Remaining lifetime and long term operation of components having defects; WP4 – Fatigue and crack growth caused by thermal loads
Otso Cronvall, Lic. Tech.	VTT	WP2 – Susceptibility of BWR RPV internals to degradation mechanisms; WP5 – Development of RI-ISI methodologies
Antti Timperi, M.Sc. Tech.	VTT	WP4 – Fatigue and crack growth caused by thermal loads; WP6 – Dynamic loading of NPP piping systems
Jouni Alhainen, M.Sc. Tech.	VTT	WP3 – Fatigue usage of primary circuit

Esko Arilahti, Res. Eng.	VTT	WP3 – Fatigue usage of primary circuit
Tommi Seppänen, M.Sc. Tech	VTT	WP3 – Fatigue usage of primary circuit
Jussi Solin, M.Sc. Tech	VTT	WP3 – Fatigue usage of primary circuit
Tero Tyrväinen, Dr. Tech.	VTT	WP5 – Development of RI-ISI methodologies
Qais Saifi, M.Sc. Tech	VTT	WP5 – Development of RI-ISI methodologies
Ahti Oinonen, Dr. Tech.	VTT	WP5 – Development of RI-ISI methodologies; WP6 – Dynamic loading of NPP piping systems
Iikka Virkkunen, Prof.	Aalto	WP7 – Residual stress relaxation in BWR NPPs

### Long term operation aspects of structural integrity (LOST)

Research organisation: VTT

Project manager: Sebastian Lindqvist, VTT

Person	Org.	Tasks
Sebastian Lindqvist Project manager, Research scientist	VTT	Project management, Doctoral thesis on dissimilar metal welds (experimental), International co-operation,
Kim Wallin Deputy project manager, Research professor	VTT	International co-operation/project management
Päivi Karjalainen-Roikonen Senior Scientist	VTT	Doctoral thesis on fast fracture in upper shelf region
Qais Saifi Research scientist	VTT	Doctoral thesis on dissimilar metal welds (numerical)
Heikki Keinänen Senior scientist	VTT	Numerical analysis on residual stresses in dissimilar metal welds
Juha Kuutti	VTT	Numerical simulations based on experimental results on dissimilar metal welds
Jorma Hietikko Senior Research Technician	VTT	Materials testing
Tommi Seppänen, Research Scientist	VTT	Materials testing

### Mitigation of cracking through advanced water chemistry (MOCCA)

Research organisation: VTT, University of Chemical Technology and Metallurgy (BG), Fortum Loviisa NPP

Project manager: Timo Saario, VTT

Person	Org.	Tasks
Timo Saario, D.Sc. (Tech)	VTT	Project management, data analysis, reports, scientific publication writing
Konsta Sipilä, MSc (Tech)	VTT	Experiments on effects of ODA, scientific publication writing (deputy project manager)
Essi Jäppinen, MSc (Tech)	VTT	Experiments on magnetite surface charge, scientific publication writing
Tiina Ikäläinen, BSc (Tech)	VTT	Water chemistry control, grab sample analysis
Seppo Peltonen, BSc (Tech)	VTT	Experimental design
Martin Bojinov, Prof., D.Sc. (Tech)	UCTM	Corrosion modelling, scientific publication writing
Sari Järvimäki, MSc (Tech)	Fortum	Plant data on N <sub>2</sub> H <sub>4</sub> and ODA, scientific publication writing

### Thermal ageing and EAC research for plant life management (THELMA)

Research organisation: VTT and Aalto

Project manager: Ulla Ehrnstén, VTT

Person	Org.	Tasks
Ulla Ehrnstén, MSc	VTT	Project management, mentoring, thermal ageing, international co-operation
Mykola Ivanchenko Dr (Tech)	VTT	Characterisation of irradiated stainless steels, transmission electron microscopy
Jari Lydman, MSc	VTT	Scanning electron microscopy, microstructural characterisation of RPV steels
Caitlin Huotilainen, Dr (Tech.)	VTT	fatigue initiation, electrochemical measurements
Aki Toivonen Dr (Tech)	VTT	Autoclave testing, initiation Round Robin
Roman Mougnot Dr (Tech)	Aalto	Thermal ageing of Alloy 690, doctoral student until May 2017
Teemu Sarikka, Dr (Tech.)	Aalto	Thermal ageing of Alloy 690
Risto Ilola Dr (Tech)	Aalto	Project manager at Aalto
Hannu Hänninen professor	Aalto	Supervisor, mentoring, international co-operation

### NDE of NPP primary circuit components and concrete infrastructure (WANDA)

Research organisation: VTT, Aalto University

Project manager: Tuomas Koskinen, VTT

Person	Org.	Tasks
Tuomas Koskinen, M.Sc.	VTT	Project management, Ultrasonic applications, POD
Tarja Jäppinen, Lic.Sc.	VTT	Previous project manager
Miguel Ferreira, PhD	VTT	Deputy project manager, Concrete infrastructure
Iikka Virkkunen, D.Sc.	Aalto	POD
Fahim Al-Neshawy, D.Sc.	Aalto	Concrete infrastructure
Teemu Ojala, M.Sc.	Aalto	Concrete infrastructure

### **Condition Monitoring, Thermal and Radiation Degradation of Polymers Inside NPP Containments (COMRADE)**

Research organization: VTT and RISE

Project manager: Konsta Sipilä, VTT

Person	Org.	Tasks
Konsta Sipilä, M.Sc.	VTT	Project management, polymer ageing mechanisms and effects inside NPP containments
Antti Paajanen, M.Sc.	VTT	Modelling tools for the synergistic effects of radiation and heat
Sami Penttilä, M.Sc.	VTT	Polymer ageing mechanisms and effects inside NPP containments
Harri Joki, M.Sc.	VTT	Polymer ageing during service failure, effects of radiation and heat on oxidation depth
Tiina Lavonen, M.Sc.	VTT	Development of condition monitoring methods for polymeric components including low dose rate radiation exposure
Marcus Granlund, M.Sc.	RISE	Project management, development of condition monitoring methods for polymeric components including low dose rate radiation exposure
Anna Bondeson, M.Sc.	RISE	Barsebäck pre-study
Anna Jansson, D.Sc.(Tech.)	RISE	Effects of radiation and heat on oxidation depth. Project management and development of conditioning monitoring methods from November 2017.
Louise Wogelred, D.Sc.(Tech.)	RISE	Effects of radiation and heat on oxidation depth.
Johan Sandström, M.Sc.	RISE	Modelling

### **Development of thermal-hydraulic infrastructure at LUT (INFRAL)**

Research organization: LUT

Project manager: Joonas Telkkä, LUT until 8/17, Lauri Pyy, LUT from 9/17

Person	Org.	Tasks
Joonas Telkkä, Project researcher	LUT	Project manager until 8/17, WP1, WP2, WP3, WP4
Lauri Pyy, Project researcher	LUT	Project manager from 9/17, WP1, WP2 WP3, WP4
Vesa Riikonen, Research scientist	LUT	WP2, WP3
Markku Puustinen, Research scientist	LUT	WP3
Antti Räsänen, Research scientist	LUT	WP1, WP2, WP3
Heikki Purhonen, Research director	LUT	WP1, WP2, WP3
Virpi Kouhia, Project researcher	LUT	WP3
Jani Laine, Research scientist	LUT	WP3
Harri Partanen, Design engineer	LUT	WP2, WP3
Eetu Kotro, Project researcher	LUT	WP1, WP2
Ilkka Saure, Technician	LUT	WP1, WP2
Elina Hujala, Doctoral student	LUT	WP1
Vesa Tanskanen, Post-doctoral researcher	LUT	WP1, WP3
Heikki Suikkanen, Assistant professor	LUT	WP3
Juhani Vihavainen, Research scientist	LUT	WP3
Otso-Pekka Kauppinen, Doctoral student	LUT	WP3
Ville Rintala, Doctoral student	LUT	WP3
Juhani Hyvärinen, Professor	LUT	WP3, WP4
Kimmo Tielinen, Research trainee	LUT	WP1, WP2

### JHR collaboration & Melodie follow-up (JHR):

Research organisation: VTT

Project manager: Ville Tulkki, VTT

Person	Org.	Tasks
Santtu Huotilainen MSc(Tech)	VTT	Project Management (until 5/2017), Materials WG participant (until 5/2017)
Caitlin Huotilainen, PhD	VTT	Materials WG participant (from 5/2017)
Petri Kinnunen, D.Sc (Tech)	VTT	Technology WG representative
Ville Tulkki, D.Sc (Tech)	VTT	Project Management (from 5/2017), Fuels

		WG participant
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### **Radiological laboratory commissioning (RADLAB)**

Research organisation: VTT

Project manager: Wade Karlsen, VTT

<b>Person*</b>	<b>Org.</b>	<b>Tasks</b>
Wade Karlsen, Ph. D.	VTT	Project Manager
Seppo Tähtinen, MSc	VTT	Lead, hot-cell technical realization
Arto Kukkonen, Tech	VTT	Hot-cell and equipment realization
Mika Jokipii, TechEng	VTT	Design engineering, EBW nuclearization
Ilkka Palosuo, MSc	VTT	Mechanical testing devices and shielding
Kimmo Rämö, Tech	VTT	Mechanicals
Marko Paasila, Tech	VTT	Database system development oversight
Pekka Moilanen, DrTech	VTT	Design engineering, EDM nuclearization
Tuomo Lyytikainen, TechEng	VTT	Mechanical testing, remote handling
Jarmo Siivinen, TechEng	VTT	Waste handling systems realization
Aki Toivonen, PhD	VTT	Hot autoclave infra realization
Veli-Matti Pulkkanen, MScTech	VTT	Radiochemistry laboratory realization
Tiina Lavonen, MSc	VTT	Radiochemistry laboratory realization
Kirsti Helosuo, TechEng	VTT	Radiochemistry laboratory realization
Joonas Järvinen, MScTech	VTT	Radiochemistry laboratory realization
Emmi Myllykylä, MSc	VTT	Radiochemistry laboratory realization

\*Personnel making less than 1 person week of contribution are not listed