# NKS-R STATUS REPORT

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# 1 Overall status summary

This report provides a short overview of the current status of the NKS-R programme. Since the last NKS board meeting in January, final reports for four of the eight NKS-R activities started in 2015 have been published on the NKS website. Contracts have been agreed and signed for seven out of eight activities started in 2016. For all activities initiated earlier than 2015, final reports have been received.

## 1.1 Seminars and publications

| Project | Seminar date |
|---|---|
| L3PSA | Final seminar, L3PSA 2015, was held 28th of January 2016.<br>Final seminar for L3PSA 2016 is planned for Q4 2016 or Q1 2017. |
| SC_AIM | Internal seminar:16 June 2016,<br>International seminar 27-28 September 2016. |

| Project | Publications |
|---|---|
| ADdGROUND | *Opportunities for Source Modelling to Support the Seismic Hazard Estimation for Nuclear Power Plants", V. Jussila, L. Fülöp* has been submitted to the Nuclear Science and Technology Symposium - ST2016, in Helsinki, 2-3 November 2016 (not yet accepted). |
| FIREBAN | A Master thesis has been completed: Reliability of fire barriers, Erasmus Mundus Master in Fire Safety Engineering |
| SPARC | Takasuo, E. An experimental study of the coolability of debris beds with geometry variations. Annals of Nuclear Energy 92, 2016. pp. 251-261 |
| | Konovalenko A., Basso S., Kudinov P., Yakush S. E., "Experimental Investigation of Particulate Debris Spreading in a Pool", Nuclear Engineering and Design, Volume 297, pp208-219, 2016 |
| | Basso, S., Konovalenko, A., Kudinov, P. "Empirical Closures for Particulate Debris Bed Spreading Induced by Gas-Liquid Flow", Nuclear Engineering and Design, 297, 19-25, (2016) |

## 1.2 Young scientist travel support

No requests have been received.

## 1.3 Published reports

The following reports have been published within the NKS reports series since the last board meeting in January:

| | | | |
|---|---|---|---|
| NKS-354 | 2015-12-21 | Learning from Successes in Nuclear Power Plant Operation to Enhance Organisational Resilience | LESUN |
| NKS-357 | 2016-01-28 | Planning Safety Demonstration | PLANS |
| NKS-361 | 2016-03-15 | Modelling of Digital I&C | MODIG |
| NKS-363 | 2016-04-22 | Modelling as a tool to augment ground motion data in regions of diffuse seismicity | ADdGROUND |

The reports listed above are all final reports for work done in 2015 within the respective activities.

## 2 Summary for activities initiated in 2015

Eight activities were initiated in 2015. Three of the activities were continuing activities and five were new. Four final reports are still missing.
An overview of the status of 2015 NKS-R activities is presented below in table 1.

**Table 1. NKS-R 2015 activities**

| Activity | Description | First invoice | Report | Second invoice | Report number |
|---|---|---|---|---|---|
| ADdGROUND | Modelling as a tool to augment ground motion data in regions of diffuse seismicity | 4/6 | x | 2/6 | NKS-363 |
| ATR-2015 | Impact of Aerosols on the Transport of Ruthenium in the primary circuit of nuclear power plant | x | - | - | - |
| COPSAR | Containment Pressure Suppression Systems Analysis for Boiling Water Reactors | x | - | - | - |
| DECOSE | Debris coolability and steam explosion | x | - | - | - |
| L3PSA | Addressing off-site consequence criteria using level 3 PSA | x | | | - |
| LESUN | Learning from Successes in Nuclear Power Plant Operation to Enhance Organisational Resilience | 2/3 | x | 2/3 | NKS-354 |
| MODIG | Modelling of Digital I&C | x | x | 1/2 | NKS-361 |
| PLANS | Planning Safety Demonstration | 3/4 | x | 3/4 | NKS-357 |

**ATR-2015** In April, they stated that the final report would be submitted in June 2016, and have not responded to later requests for status updates (deadline in contract is the 31 of January 2016).
**COPSAR** states that the work with the final report is ongoing and will be submitted in June 2016 (deadline in contract is the 31 of January 2016).
**DECOSE** states that the final reports will be submitted in the end of June 2016 (deadline in contract is the 31 of January 2016).
**L3PSA** a final report has been circulated among the project partners and their comments have been included in the report. A completing conclusions chapter for a guidance document is being finalized, and it will be sent to stakeholders for comments before publication. The final report will be submitted within June 2016 (deadline in contract is the 31 of January 2016).

For further information regarding the not finalised 2015 NKS-R projects, please see **chapter 5.**

# 3 Summary for activities initiated in 2016

Eight activities were started in 2016. Three of these are continuing activities and five are new. Contracts have been signed for seven of the eight activities. The contract for BREDA is missing due to the delayed start of the project and some internal work at KTH. The BREDA contract is expected to arrive in June 2016. In this chapter short descriptions are given for the activities. For more detailed status reports see **chapter 6**.

## 3.1 ADdGROUND

*Modelling as a tool to augment ground motion data in regions of diffuse seismicity*

***Summary***

After the Fukushima accident, seismic safety of nuclear power plants and other nuclear installations has become an increasingly important topic also in regions with low seismic activity, including the Nordic nuclear sites. The technical aim of the AddGROUND project is to build new capabilities in earthquake source modelling for ground motion simulations. The scarcity of empirical observations of near-field ground motions from large magnitude earthquakes in Fennoscandia has been an impediment for deeper understanding of the possible earthquake loading scenarios on nuclear installations, even if empirical data has been exhaustively analysed. With recent advances in computational methods, the opportunity exists for numerical models to give realistic estimates of earthquake loads. In addition to the technical outcome, the AddGROUND project also aims to establish and maintain a network of experts focused on diffuse seismicity areas of the Nordic Countries, and further enhance the cooperation between VTT and Uppsala University in the area of earthquake source modelling. A longer term aim would be to extend the cooperation to the Baltic countries. The project outcomes will support STUK and SSM, providing background information for the safety assessments of nuclear plants, but are also relevant for nuclear repositories.
For 2016 we propose moving the focus of the activity from networking and data collection to model building, testing and outputs calibration using the real measurement from seismic events. 2016 will be dedicated to model building, calibration, and outputs calibrated using the real measurement from seismic events or from artificial earthquake produced by explosions. We return to collecting additional model inputs - fault measurement, bedrock properties for building a model for estimating ground motion need to be studied only if/when modeling requirements make it unavoidable.

***Activity leader***

Ludovic Fülöp, VTT Technical Research Centre of Finland.

***Funding***

500 kDKK

***Milestones***

| | |
|---|---|
| M.1. Input variable ranges for selected modelling cases. | 02.2016 |
| D.1. Conference/Magazine article on NPP seismic design in the Nordic context | 03.2016 |
| D.2. Conference paper on benchmark modelling | 09.2016 / Paper submitted for review 31.05.2016 |

***Status***
Progress according to plan.
The paper *"Opportunities for Source Modelling to Support the Seismic Hazard Estimation for Nuclear Power Plants", V. Jussila, L. Fülöp* has been submitted to the Nuclear Science and Technology Symposium - ST2016, in Helsinki, 2-3 November 2016. This is an important forum for popularizing the research activity to interested stakeholders in the nuclear field (http://www.ats-fns.fi/en/nst2016). If accepted, the paper would count towards Deliverable D.2. The consortium is considering several forums for Deliverable D.2.1, ranging from more scientific ones to more "commercial" ones. It is early to decide where the results will fit, and we are also considering the expected impact/readership carefully.

## 3.2 BREDA_RPV

*Studies of mechanical and microstructural properties of Irradiated Low Alloy Steel trepan samples from the RPV wall of Barsebäck 2*

Since submitting the proposal (October 2015) for the project BREDA_RPV and the NKS board decision to fund the proposal (January 2016), BREDA has been informed that it will not be possible to reach the reactor pressure vessel in Barsebäck 2 during 2016. This prevents them from obtaining the samples from the reactor pressure vessel, which was a large part of the work planned for 2016. An updated proposal was requested from the activity leader, which was sent to the NKS-R evaluators. The four of the six NKS-R evaluators responded. Three evaluators saw no need to change their evaluation, and thought the project was still very relevant. One evaluator thought the project had a lower merit now. The coordination group discussed the evaluations at the coordination meeting in Risö 25-26 april 2016. The coordination group found, based on the overall evaluation of the NKS-R evaluators, that the BREDA project still holds merit and should be funded. Contracts have been sent out but are not yet signed.

***Summary***
Irradiation induced ageing of the reactor pressure vessel steel is an issue that has been closely monitored though specified ageing management programs called surveillance program. These consists of a number of capsules or container chains that are fitted onto the reactor internals of the nuclear power plant to allow for accelerated irradiation of the pressure vessel material to predict the evolution of the mechanical properties of the material as a function of the neutron dose. A number of issues remains as open, or partially closed, knowledge gaps with respect to the irradiation induced ageing of low alloy steels and the effect on the reactor pressure vessel and their fitness for long term operation. Among these issues are representativeness of the production weld test blocks that make up the surveillance programs to the actual pressure vessel welds, the effect of weld material inhomogeneity on mechanical behaviour measured as either fracture toughness or impact toughness and the attenuation, i.e. the damping of the irradiation induced defect number with increasing depth from the media touched surface of the RPV. The weld material in the Swedish reactor program contains high levels of nickel and manganese. The material has been shown to exhibit large shifts in the DBTT caused by the formation of copper-nickel-manganese-silicon agglomerates. By the closure of the nuclear units at the Barsebäck site, an opportunity has opened up to harvest samples from the reactor pressure vessels.

The weld materials are the limiting materials from a Long term operation, LTO, perspective of the pressure vessels. One issue to verify is for example if the (often separately performed) heat treatment of the surveillance samples gives representative values as compared to the real RPV wall heat treatment. Secondly, the analysis of the material degradation gradient through the depth of the RPV thickness due to irradiation would be of importance, as the embrittlement properties at a ¼ of the wall thickness is used in the reporting to the radiation safety authority (SSM). A possibility to acquire for example three or four trepan samples from locations at different axial positions, would make it possible to study the metallurgic variability as well as the different ageing phenomena from thermal and radiation induced degradation: the core region has substantial neutron flux, while the RPV top lid has a substantial thermal component while the neutron flux is orders of magnitude lower.

During 2016, base line testing will be performed at KTH and VTT on un-irradiated material retrieved from the original testing of the reactor pressure vessel. In addition, a feasibility study on harvesting of material from the reactor pressure vessel at Barsebäck will be conducted to lay the foundation for testing on irradiated material. A minimum of two trepan samples (cut-out of RPV wall) will be withdrawn from Barsebäck 2 for further transport to VTT. The deliverable for 2016 include reconstitution of the un-irradiated test samples (charpy specimen) to fracture mechanical samples for continued testing. Due to other activities at the Barsebäck plant, there is no availability of the reactor hall for trepan cutting until late 2017. A feasibility study for the extraction will lay the foundation for a timely extraction of material, given that funding can be achived for this collaborative project. The proposal is planned over 5 years, and the main deliverables, including test results from the irradiated material are to expected by 2019-2020.

***Activity leader***
Pål Efsing, Royal Institute of Technology (KTH)

***Funding***
400 kDKK

***Milestones***
Baseline testing on un-irradiated material.
Feasibility study on harvesting material from the reactor pressure vessel at Barsebäck.

***Status***
The first project phase which includes the pre-project planning and mechanical testing of unirradiated material can start at latest July 1st 2016 given that the project is funded, and that fracture mechanical specimens from base line testing are retrieved. Testing of surveillance capsules and material from the Barsebäck RPV will be dependent on the possibility that these are harvested in due time.

## 3.3 COPSAR

*Containment Pressure Suppression Systems Analysis for Boiling Water Reactors*

Since submitting the proposal (October 2015) to NKS and the evaluation of the board members and the subsequent decision to fund the COPSAR project (January 2016), the funding situation changed dramatically for COPSAR. SAFIR reduced its overall funding which affected COPSAR and NORTHNET decided to not fund COPSAR at all. This affected the COPSAR proposal, as submitted to NKS. An updated project proposal was requested from the activity leader by the NKS-R program manager. The received updated proposal was discussed at the coordination meeting in Risö, 25-26 of April 2016. The altered funding situation affected the quantity of experiment which can be performed at the Lappeenranta university of technology, which in turn affects the available data for VTT Technical Research Centre of Finland and the Royal Institute of Technology to simulate. The quality of the project was decided by the coordination group as still being very high. Contracts have been signed.

***Summary***

The details of the work are described in the proposal submitted by the Contractor in the NKS-R Call for Proposals 2016.

LUT participates in the COPSAR project by carrying out thermal hydraulic experiments on the behaviour of a safety relief valve (SRV) sparger and residual hear removal (RHR) system nozzle in the PPOOLEX facility. The effectiveness of mixing a thermally stratified water pool due to injection through a sparger and RHR nozzle is studied.

In 2016, a SRV sparger test with combined steam injection through the sparger head and load reduction ring (LRR) will be carried out to provide closures for the EMS model development for spargers by KTH. Integral effects with simultaneous activation of the head and LRR can be validated against the test results.

Experiments on mixing efficiency due to water injection through a RHR nozzle will be also done in 2016. Single phase water injection through the RHR nozzle is used to mix the pool. The effect of flow rate and water temperature on mixing efficiency will be studied. The experiment data will be used by KTH to further extend and validate the concepts of the EHS and EMS models.

*Milestones in October 2016:*

1. Mixing tests with a RHR nozzle in PPOOLEX have been done.
2. Specifications for the combined sparger head and LRR test have been determined.

In 2016, KTH will perform pre-test analysis and simulations for selection of operational regimes and test procedures, and post-test analysis and validation with EHS/EMS models implemented in GOTHIC against PPOOLEX tests with (i) RHR nozzles, (ii) combined sparger head and LRR injection. Further development of the EHS/EMS models for spargers and RHR nozzles will be pursued to simulate dynamics of the pool mixing and stratification. The models will be validated against respective separate effect tests.

In 2016, CFD simulations of PPOOLEX experiments on SRV spargers and RHR nozzles are performed by the Contractor. Detailed model of the sparger geometry is constructed in the CFD model. A sub-model for the condensation of clouds of small vapour bubbles is used in the ANSYS Fluent code. The thermal stratification of the pressure suppression pool during steam injection into the pool is studied with CFD calculations. Suitable time interval of stratification and mixing experiment of PPOOLEX is calculated. The CFD model provides detailed information of the energy and momentum sources in the vicinity of the sparger, which can be used in the development of the EMS/EHS model for the GOTHIC code at KTH. The CFD calculations provide information on the mass and heat sources from the pool surface to the gas space of the wet well that can be used in the modelling of wet well spray experiments. The results are compared to the results obtained in the PPOOLEX experiments and to the results of GOTHIC calculations performed at KTH.

***Activity leader***
Markku Puustinen, Lappeenranta University of Technology.

***Funding***
500 kDKK

***Milestones***
Lappeenranta University of Technology

*Deliverables of LUT in 2016:*

1. A SRV sparger test with combined steam injection through the sparger head and LRR
2. Mixing tests with a RHR nozzle
3. Delivery of relevant experiment data to the simulation partners

Royal Institute of Technology:

In 2016, KTH will perform pre-test analysis and simulations for selection of operational regimes and test procedures, and post-test analysis and validation with EHS/EMS models implemented in GOTHIC against PPOOLEX tests with (i) RHR nozzles, (ii) combined sparger head and LRR injection. Further development of the EHS/EMS models for spargers and RHR nozzles will be pursued to simulate dynamics of the pool mixing and stratification. The models will be validated against respective separate effect tests.

Deliverables of KTH in 2016:

1. Pre-test analysis for selection of operational regimes and test procedures.
2. Development of the EHS/EMS models.
3. Post-test analysis and validation with GOTHIC code.
4. Reporting.

VTT Technical Research Centre of Finland

Milestone in the end of October 2016:

1. CFD model of the PPOOLEX wet well is constructed. Calculation of stratification transient is in progress.

Deliverables of VTT in the end of December 2016:

1. CFD model for the wetwell
2. Report on the calculation of a time interval of stratification and mixing experiment in PPOOLEX.

***Status***
Work progressing according to updated plan.

## 3.4 FIREBAN

*Determination of fire barriers's reliability for fire risk assessment in NPP*

***Summary***
The scope of the project is to investigate and assess the reliability of fire barriers in NPP during realistic fire scenarios to support the plant-scale risk assessment.
The objective is to establish data and methods to determine the conditional probabilities for failure of fire barrier. The Methods used will be statistics, literature review, calculation and specific unique designed fire tests.

***Activity leader***
Patrick van Hees, Lund University

***Funding***
450 kDKK

***Milestones***
MS1: Risk-based acceptance criteria, June 2016
MS2: Current state of the art for determination of reliability of fire barriers
First year report

***Status***
Work is progressing according to plan. A first Master thesis has been produced at LTH and the first action will be finished during June.

## 3.5 HYBRID

*Development of hybrid neutron transport methods and data visualization tools*

***Summary***
The modelling of neutron transport typically relies on two rather opposite approaches: the probabilistic approach, and the deterministic approach. The probabilistic approach or Monte

Carlo approach relies on tracking the individual lives of neutrons, and requires a large computing power for nuclear reactors. The deterministic approach, on the other hand, is based upon fast running algorithms, that solve the problem at hand in only an approximate manner. The purpose of HYBRID is to combine both approaches in order to obtain fast running methods (thanks to the deterministic route) and accurate results (thanks to the probabilistic route). One promising hybrid method is the so-called response matrix method. This method was originally derived in the early seventies in a pure deterministic sense. In the proposed project, the computation of the collision probabilities required for applying the method will be carried out using a probabilistic solver. Due to the level of details of the simulations to be performed, the development of enhanced visualization tools will be necessary as an aid to development. This will require the construction of an adequate data management system and results visualization capabilities.
In the projects initial phase, the project will aim at investigating the feasibility of the proposed hybrid method, and at demonstrating the usefulness of the fine-scale results obtained, compared to traditional coarse-mesh approaches. The project will also result in the specification of a system architecture description for visualizing the results of the hybrid calculations. Examples of implementations will also be given.

***Activity leader***
Christophe Demazière, Chalmers University of Technology

***Funding***
500 kDKK

***Milestones***

| *Tasks* | *Milestones* | *Deliverables* |
|---|---|---|
| Determination using the Serpent Monte Carlo code of the required collision probabilities for the response matrix method<br><br>Development of a Matlab-based software for testing the response matrix method using Serpent-generated collision probabilities | Evaluation of which collision probabilities are necessary for the required accuracy of the system<br><br>Examples of simulation results obtained for small enough systems<br><br>Description of the computer resources required for a full scale version of the system | Progress report summarizing the work performed and the achieved milestones<br><br>to be ready by November 30, 2016 |
| Development of data storage, transfer strategies and visualization methods to facilitate development team. | Interviewed Chalmers and VTT team participants to determine data storage, transfer and visualization requirements.<br><br>Reviewed possible data | Progress report summarizing the work performed and the achieved milestones<br><br>to be ready by November 30, 2016 |

| | | |
|---|---|---|
| | solutions and evaluated against requirements. | |
| Study with the developed test software of the dependence of the deterministic solution onto the boundary conditions applied with respect to the spatial, angular, and energy dependence | Assessment of the dependence of the Monte Carlo solution onto the types of boundary conditions applied with respect to the spatial, angular, and energy dependence | Progress report summarizing the work performed and the achieved milestones<br><br>to be ready by December 31, 2016 |
| | | Final report<br><br>to be ready my January 31, 2017 |

***Status***

Chalmers :

- The project formally started on week 15 with an MSc student working 50% of his time on the project as part of his MSc thesis work. The student will work 100% on the project from the summer.
- Contacts have been taken with VTT in order to discuss how to estimate the probabilities necessary for the application of the response matrix method.

IFE:

- Interviews of MSc thesis students will take place on week 21. The selected MSc thesis student will start working this summer on the project.

VTT:

- Discussions with Chalmers are on-going in order to provide the probabilities required for the application of the response matrix method.

## 3.6 L3PSA

*Addressing off-site consequence criteria using Level 3 PSA*

***Summary***

Level 3 PSA provides a tool to assess the risks to society posed by a nuclear plant, and could be useful in making objective decisions related to the off-site risks of nuclear facilities. The intention of this study was to further Nordic understanding of the potential of Level 3 PSA to determine the influences and impacts of off-site consequences, the effectiveness of off-site emergency response, and the potential contributions of improved upstream Level 1 and Level 2 PSAs. Many activities will be completing in 2015 or and continuing during 2016

- During 2016 further IAEA work will be performed which the Level 3 PSA project's working group has worked within during the duration of the project.
- The ANS/ASME standard has cleared passed the necessary voting measures and after updates should be available for trial use within the year.
- The possibility to new recommendations from the Swedish Radiation Safety Authority may also come in the next year.

The proposed work for 2016 is a minor addition and will provide resources for the following:

- The continuation of the international cooperation that started during the first 3 years
- Articulate updates and provide interpretation to the many changes in the field
- 1-day workshop involving all stakeholder and working group members.

***Activity leader***
Andrew Wallin-Caldwell Lloyd's Register Consulting

***Funding***
140 kDKK

***Milestones***
1-day seminar Q4 2016 or Q1 2017.
2016 report provided in Q1 of 2017.

***Status***
There are several ongoing activities which the working group is monitoring while the 2015 activities are being finalized:

- No planned IAEA activities are made for 2016 due to agency budget constraints.
- Some exploratory work is being made at the OECD NEA WGRISK group regarding Level 3 PSA.
- The USNRC project on Level 3 PSA is being finalized, but NRC review usually takes some time, so it is not expected that significant documentation will be made available for some time.
- The ANS/ASME Level 3 PSA standard has been balloted an additional time. Minor changes have been made and it appears that the standard will be published in the "near future", something that did not seem likely even recently.

The project has interfaced extensively with the parallel NKS project NORCON, which has been very beneficial to the project. This has included meetings between working group members for each of the projects discussing in particular the NORCON study and Swedish Level 3 PSA Pilot Study.

## 3.7 SC_AIM

*Safety culture assurance and improvement methods in complex projects*

***Summary***
The concept of Safety Culture was first coined to explain the Chernobyl nuclear accident in the late 1980s. From the very beginning, the concept aimed at highlighting and illustrating that safety cannot ever be guaranteed by technical means alone, but rather safety

depends heavily on management, leadership, and so called human and organizational factors. Culture is repeatedly created and recreated as members behave and communicate in ways that seem natural, obvious, and unquestionable to them (Reiman & Rollenhagen, forthcoming). Despite a long research tradition, there is a large variance in conceptualisations of safety culture, ranging from descriptive studies on the social construction of safety to normative models of ideal safety culture/climate dimensions. Empirical studies of culture improvement in the safety field are scarce (Hale et al. 2010), especially in comparison to the amount of research on identifying the elements of safety culture or evaluation of safety culture. Major projects in the nuclear industry are typically carried out by networks of companies. Current safety culture and safety management models and practices are largely focused on single organisations and it is far from clear how to apply them in the dynamically changing project networks. Traditional cultural approaches emphasize that it takes time and certain amount of continuity to create a culture, both of which are in short supply in projects with short time frames, diversity in both personnel and companies involved, and often a high personnel turnover. Antonsen (2009) highlighted that safety culture studies seem to embody a harmonious view of the organization to be analyzed. Several issues remain unanswered, e.g., what should a safety culture improvement or assurance program be like in an “organization”, which is actually a dynamic network of actors from different companies? How to utilize the concept of safety culture in network and project settings?

A basic premise of the project is that so far there has been a lot of attention on how to diagnose and evaluate safety culture, but not so much on how to actually improve the safety culture. A second premise is that improvement of safety culture in projects sets some unique requirements due to e.g. multiple organizations interacting, diverse background of personnel, schedules and contract issues etc. The same methods may not work that have been applied in operating power plants. Further, the long supply chains and the licensee’s responsibility to oversee the safety culture of the entire network put more demands on safety culture assurance methods.

The project is planned as s two years' effort (2016-2017) and has two aims:
1. To identify and specify methods to improve and facilitate safety culture in complex projects
2. To identify and specify methods to assure safety culture in complex projects

The different ways of improving / facilitating safety culture can be for example the use of safety culture ambassadors, learning from experience, tool box talks, pre and post job briefs, cross-organizational working groups, and training.
Assurance methods can include auditing, self-assessment and independent assessment as well as questionnaires.

***Activity leader***
Elina Pietikäinen, VTT Technical Research Centre of Finland.

***Funding***
410 kDKK

***Milestones***

| Milestone / deliverable | Planned completion date | Status |
|---|---|---|
| Workshop on safety culture methods | June 2016 | Preliminary agenda has been drafted, invitations sent for relevant parties and practicalities handled. The workshop will be held in Stockholm on 16.6. |
| International workshop | October 2016 | Preparations are on-going, the workshop is planned to be held at the same time as HUSC seminar (27.-28.9.) in Finland |
| Conference paper or article | November 2016 | Not yet started, the content of the scientific publication will be internally discussed in project workshop and other meetings. |
| Intermediate report | December 2016 | Literature review has been nearly completed and will be integrated into the intermediate report. |

***Status***
Overall, the project is progressing according to plan. In February and March 2016, VTT carried out interviews in the Finnish case study at Fennovoima (10 interviews in total). The data has been summarized and is being analysed. In parallel to the empirical studies, a literature review has been carried out (VTT and Vattenfall jointly). Another primary source of empirical data comes from a seminar organized by Carl Rollenhagen (Vattenfall) with a topic of project management and safety culture, which is being prepared for. Furthermore, we have been in close contact with representatives from two Swedish nuclear organizations (SKB and Forsmark) that will function as information exchange partners. In addition, an information exchange partnership with Fortum is planned and currently under discussion. Currently we are preparing for the internal project workshop to be held in 16.6.

## 3.8 SPARC

*Scenarios and Phenomena Affecting Risk of Containment Failure and Release Characteristics*

***Summary***
A robust severe accident management strategy is paramount for minimizing the environmental impact in the case of a severe accident involving melting of a reactor core. Both physical phenomena (deterministic) and accident scenarios (stochastic) are sources of uncertainties in the assessment of effectiveness of the accident mitigation. Adequate approaches are necessary in order to address both deterministic (epistemic) and stochastic (aleatory) sources of uncertainty in a consistent manner.
KTH, VTT and LRC have been active in addressing phenomenological and scenario uncertainties in severe accidents in the framework of national programs such as APRI-MSWI, SAFIR, NPSAG, NKS-DECOSE and NKS-DPSA, European FP7 and Horizon2020 projects SARNET, SAFEST, CESAM, IVMR and in direct collaboration with nuclear power utilities and regulators.
WP1: Development and application of risk oriented accident analysis framework (ROAAM+) for prediction of conditional containment failure probability for a Nordic type BWR. (KTH)
WP2: Development of the methods for coupling of Integrated Deterministic Probabilistic Safety Analysis tools such as ROAAM+ developed by KTH with PSA in general and PSA-L2 in particular. (LRC).

WP3: Deterministic modelling of core degradation, melt relocation, vessel failure, debris spreading and coolability. (VTT).
WP4: Analysis of the factors that affect the energy (temperature), altitude and probability of the release in PSA-L2. The input is from KTH, LRC and VTT analysis in WP1, WP2 and WP3. (VTT).

***Activity leader***
Pavel Kudinov, Royal Institute of Technology.

***Funding***
600 kDKK

***Milestones***
KTH

**In 2016** ***KTH*** work will be focused in WP1 on Tasks 1, 2 and 3 with the following deliverables:

1. Development and validation of detailed (full) deterministic models for analysis of severe accident phenomena in Nordic BWRs.
2. Development and application of computationally efficient surrogate models for uncertainty and risk analysis.
3. Collaboration with VTT and LRC on cross code comparison, code validation, and development of approaches to informing PSA with the ROAAM+ framework results.
4. Reporting of the results.

VTT

**In 2016** in WP3 VTT will focus on Task 3 and 4 with the following deliverables:

1. Analyses of debris bed temperature in post-dryout conditions (for developing temperature-based coolability criterion).
2. Exploring accident scenarios that may lead to hydrogen explosions with MELCOR.
3. Comparison of obtained results with KTH and LRC data.
4. Reporting of the results (Milestone 1).

In WP4 VTT will focus on Task 1 and 2 with the following deliverables:

1. PSA-L2 analysis results addressing important factors for release characteristics.
2. Consideration of at least one relevant phenomenon, e.g. steam or hydrogen explosions.
3. Reporting of the results (Milestone 2).

Lloyd’s Register Consulting

In 2016 ***LRC in*** WP2 will be focused on Task 1 and 2 with the following deliverables:

1. PSA-L2 analysis results addressing important factors for the release characteristics.
2. Consideration of the relevant phenomena, namely steam and hydrogen explosions.
3. Reporting of the results.

***Status***

Overall the project is work is going according to plan.

# 4 Overview of all NKS-R activities 2010-2015

It is seen from the table below that all activities started in 2014 and earlier have been finalised. An activity is considered to be started at the January board meeting, and ended when the final report has been delivered.

| Activity | NKS number | Started | Ended |
|---|---|---|---|
| Decom-sem | NKS_R_2010_83 | 01/2010 | 12/2010 |
| DIGREL | NKS_R_2010_86 | 01/2010 | 12/2010 |
| IACIP | NKS_R_2008_61 | 01/2010 | 12/2010 |
| INCOSE | NKS_R_2009_75 | 01/2010 | 05/2011 |
| MOSACA10 | NKS_R_2008_69 | 01/2010 | 01/2011 |
| NROI | NKS_R_2008_70 | 01/2010 | 04/2011 |
| POOL VTT | NKS_R_2007_58 | 01/2010 | 05/2011 |
| POOL KTH | NKS_R_2007_58 | 01/2010 | 06/2011 |
| POOL LUT | NKS_R_2007_58 | 01/2010 | 03/2011 |
| AIAS | NKS_R_2011_98 | 01/2011 | 12/2012 |
| DIGREL | NKS_R_2010_86 | 01/2011 | 01/2012 |
| ENPOOL | NKS_R_2011_90 | 01/2011 | 03/2012 |
| ENPOOL | NKS_R_2011_90 | 01/2011 | 05/2012 |
| ENPOOL | NKS_R_2011_90 | 01/2011 | 05/2012 |
| MoReMO | NKS_R_2011_95 | 01/2011 | 02/2012 |
| NOMAGE4 | NKS_R_2008_63 | 01/2011 | 11/2011 |
| POOLFIRE | NKS_R_2011_96 | 01/2011 | 02/2012 |
| SADE | NKS_R_2011_97 | 01/2011 | 03/2012 |
| RASTEP | NKS_R_2010_87 | 06/2011 | 09/2012 |
| AIAS | NKS_R_2011_98 | 01/2012 | 06/2013 |
| DECOSE | NKS_R_2012_100 | 01/2012 | 07/2013 |
| DIGREL | NKS_R_2010_86 | 01/2012 | 02/2013 |
| ENPOOL VTT | NKS_R_2011_90 | 01/2012 | 04/2013 |

| | | | |
|---|---|---|---|
| ENPOOL LUT | NKS_R_2011_90 | 01/2012 | 03/2013 |
| ENPOOL KTH | NKS_R_2011_90 | 01/2012 | 05/2013 |
| MoReMO | NKS_R_2011_95 | 01/2012 | 03/2013 |
| Nordic-Gen4 | NKS_R_2012_103 | 01/2012 | 11/2012 |
| POOLFIRE | NKS_R_2011_96 | 01/2012 | 02/2013 |
| RASTEP | NKS_R_2010_87 | 01/2012 | 10/2013 |
| SADE | NKS_R_2011_97 | 01/2012 | 03/2013 |
| Decom-sem | NKS_R_2013_106 | 01/2013 | 02/2014 |
| DECOSE | NKS_R_2012_100 | 01/2013 | 10/2014 |
| DIGREL | NKS_R_2010_86 | 01/2013 | 03/2014 |
| DPSA | NKS_R_2013_107 | 01/2013 | 07/2014 |
| ENPOOL | NKS_R_2011_90 | 01/2013 | 10/2014 |
| Exam HRA | NKS_R_2013_110 | 01/2013 | 03/2014 |
| HUMAX | NKS_R_2013_108 | 01/2013 | 02/2014 |
| L3PSA | NKS_R_2013_109 | 01/2013 | 03/2014 |
| POOLFIRE | NKS_R_2011_96 | 01/2013 | 12/2014 |
| SADE | NKS_R_2011_97 | 01/2013 | 02/2014 |
| ATR | NKS_R_2014_111 | 01/2014 | 06/2015 |
| DECOSE | NKS_R_2012_100 | 01/2014 | 07/2015 |
| DIGREL | NKS_R_2010_86 | 01/2014 | 02/2015 |
| DPSA | NKS_R_2013_107 | 01/2014 | 08/2015 |
| ENPOOL | NKS_R_2011_90 | 01/2014 | 07/2015 |
| HUMAX | NKS_R_2013_108 | 01/2014 | 01/2015 |
| L3PSA | NKS_R_2013_109 | 01/2014 | 04/2015 |
| Nordic-Gen4 | NKS_R_2012_103 | 01/2014 | 02/2015 |
| ProCom | NKS_R_2014_112 | 01/2014 | 03/2015 |
| ADdGROUND | NKS_R_2015_113 | 01/2015 | 04/2016 |
| ATR-2015 | NKS_R_2014_111 | 01/2015 | Unfinished |
| COPSAR | NKS_R_2015_114 | 01/2015 | Unfinished |
| DECOSE | NKS_R_2012_100 | 01/2015 | Unfinished |
| L3PSA | NKS_R_2013_109 | 01/2015 | Unfinished |
| LESUN | NKS_R_2015_115 | 01/2015 | 12/2015 |
| MODIG | NKS_R_2015_116 | 01/2015 | 03/2016 |
| PLANS | NKS_R_2015_117 | 01/2015 | 01/2016 |

# 5 Status 2015 activities

## 5.1 ATR-2015

Status as of the 22nd of April, activity leader has not responded to request for updated status.

**Description of the work done during the work period (16.11.2015 – 22.4.2016)**

The aim in NKS-R ATR activity during 2015 was to study the effect of representative air radiolysis products (N2O, NO2, HNO3) and aerosols (CsI; Ag was studied in 2014) on the transport of gaseous and particulate ruthenium through a model primary circuit. The experiments were performed at VTT Technical Research Centre of Finland Ltd by PhD students Teemu Kärkelä (VTT) and Ivan Kajan (Chalmers University of Technology). Ivan Kajan visited at VTT, when the experimental phase of the project was ongoing.

VTT's Ru transport facility was modified for the experiments in order to be able to feed gaseous additives after the vaporisation crucible filled with RuO2 powder. The experiments were performed at 1300K, 1500K and 1700K oxidation temperatures. After the release of ruthenium oxides from the crucible, the additional air radiolysis products and aerosols reacted with the vaporised Ru species. The reaction products were transported through the facility by the carrier gas flow of air and nitrogen. Aerosols were collected on a plane filter and gaseous products were trapped in NaOH solutions. Aerosols were also analysed with online devices, such as TEOM, ELPI and SMPS. The devices gave information on the number/mass concentration of particles, as well as, on the variation of the total mass concentration of particles in the experiments.

In total eleven experiments were performed. The most interesting result was the effect of oxidising NO2 on the transport of Ru. It seemed that NO2 was able to oxidise RuO3 within the facility to RuO4. And thus a significant concentration of gaseous RuO4 was observed at the outlet of the facility simulating containment atmosphere conditions. Similar outcome was also observed when CsI particles were fed into the flow of vaporised Ru oxides. The effect of other additives was not as prominent.

**Deviations from set objectives:**

There is no deviations to the project plan. Two extra tests were completed in addition to the experimental plan.

**Results produced during the performance period**

As result of 2015 experiments, two journal publications are prepared. The first one is dedicated on the study of N2O, NO2, HNO3 effects on rutheniu transport and the topic of the second one is the influence of CsI on Ru chemistry.

The results have been presented in the NKS seminar in Denmark during August 2015. An abstract has also been submitted to NENE2016 conference, but there is no information on the approval yet.

The results from ATR project has received internationally attention and the current OECD/NEA STEM-2 program has updated their experimental plan due to the outcomes of

ATR activity. In STEM-2 the plan is to perform similar experiments, e.g. they will study the effect of NO2 on the transport of Ru.

ATR activity under NKS-R programme has produced new information on the behaviour of Ru. The results have pointed out that the transport of radiotoxic gaseous Ru to the containment atmosphere can be significantly higher than what has been expected based on the thermodynamical equilibrium calculations. Especially the effect of air radiolysis products on Ru chemistry has been a crucial piece of information when considering a severe accident. This information has stirred up renewed discussion on the importance of Ru when considering source term. New experiments on the chemistry of Ru are being planned by other organisations as well.

**Scheduling situation**
The final results will be reported to NKS latest in June 2016.

## 5.2 COPSAR

**Work at LUT**

**Deliverable 1: Experiments with a SRV sparger and RHR nozzles**
Two SRV sparger tests, SPA-T1 and SPA-T7, were carried out in the PPOOLEX facility. Test specifications were decided together with KTH on the basis of earlier tests and pre-test simulations. In SPA-T1 part of the injection holes at the sparger head were blocked and in SPA-T7 all the holes at the sparger head were blocked but the injection holes of the load reduction ring (LRR) were open. Steam injection directed downwards from the LRR effectively mixed the pool even with quite a small flow rate. The report on the experiments was delivered on April 21st, 2016.

*Deviation from the plan: The sparger test SPA-T7 replaced the single phase water injection test originally planned for 2015. Additional data on the behavior of the sparger with injection through the LRR was considered more useful for the development of the EMS model than the single phase water injection data. The change in the plan was discussed and agreed in the SAFIR2018 Reference Group 4 meeting. RG4 supervises the work done in the SAFIR2018/INSTAB project.*

**Deliverable 2: Designing spray injection systems for the PPOOLEX facility**
Information on different spray systems in Nordic power plants was gathered. A preliminary design of the spray system to be installed to the PPOOLEX facility was drawn. *Note: Studies on the operation of a spray system in PPOOLEX were postponed in 2016 to later years due to unavailability of NORTHNET funding for 2016.*

**Deliverable 3: Single spray nozzle experiments in a separate test facility**
Droplet size measurements of a single spray nozzle with the help of the shadowgraphy application (light diffuser and software upgrade) of the PIV system in different flow conditions in an open test environment (no walls) were done. Some preliminary tests in a steam environment were done, too. The test environment was then developed to better suit for spray nozzles with a larger injection capacity and some additional tests were carried out. Five

different measurement positions underneath the spray jet were used. The majority of the droplets were in the size range of 0.2-0.8 mm in the centerline positions whereas the droplet distribution was broader in the two other positions, which were 300 mm away of the centerline axis. The report on the tests was delivered on April 21st, 2016.

**Deliverable 4: Delivery of relevant experiment data to the simulation partners.**
Measurement data and video clips of the SPA-T1 and SPA-T7 tests with a SRV sparger have been delivered to KTH and data of the shadowgraphy measurements of the first single spray nozzle injection tests have been delivered to VTT.

**Work at VTT**

**Deliverable 1: Improved condensation model for vapour on spray droplets**
The submodel developed earlier for the evaporation and condensation model for spray droplets has been transferred to new version of ANSYS Fluent. Since no experiments with spray and steam were performed during 2015 at LUT and no experiments will be performed in 2016. Therefore, much smaller amount of work than was originally planned was done on this topic. The resources were transferred to modelling of the single spray nozzle experiments (Deliverable 2).

**Deliverable 2: CFD calculation of the single spray nozzle experiment performed at LUT**
Modelling of single spray nozzle experiments has been performed. CFD models for two experimental configurations have been constructed. CFD calculations for two spray nozzles have been performed by using available information on the properties of the nozzles. Model for the size distribution of the spray droplets has been constructed based on the preliminary information from the LUT experiments and literature data. Report has been written on the simulations performed for two spray nozzles in two different test configurations.

**Deliverable 3: CFD model for the PPOOLEX facility with spray systems and pre-calculation of experiments**
Four spray nozzles have been included in the wetwell compartment of the CFD model of the PPOOLEX facility. The properties of the nozzles and droplets have been chosen based on the simulations of separate effect tests for the spray nozzles. Pre-calculation of PPOOLEX spray experiments has been performed, where the effect of the sprays on the thermal stratification of the wetwell water pool was studied. Report on the calculation has been written.

**Deliverable 4: Reports on the single spray nozzle calculations and PPOOLEX pre-test calculations**
Report on the single spray nozzle experiments and report on the pre-calculations of the PPOOLEX spray experiments have been written. They will be submitted to NKS on 6th of June, 2016.

**Work at Royal Institute of Technology (KTH)**

**Deliverable 1: Contribution to selection of the design of the spray injection systems for the drywell and wetwell of the PPOOLEX facility**

Information on spray nozzle models, nozzle diameters, droplet diameters, droplet distributions, mass flow rates, and jet expansion angles that has been obtained from literature. Discussion with LUT on the selection of the design has been carried out.

**Deliverable 2: Pre-test analysis for selection of operational regimes and test procedures**
Scaling and pre-test analysis for tests with pool mixing by RHR nozzles has been performed. A preliminary test matrix has been proposed to LUT.

**Deliverable 3: Post-test analysis and validation with GOTHIC code on spray**
No progress.

**Deliverable 4: Post-test analysis and validation of EHS/EMS on spargers and RHR nozzles**
Post-test analysis and preliminary validation of the EHS/EMS models for spargers has been carried out against the PPOOLEX SPA-T3, T4, T1 and T7 tests. Further development of the EMS model for spargers is ongoing as well as the validation of the EHS/EMS models against the remaining SPA tests.

Preparation of the report is ongoing and will be submitted by June 2016.

## 5.3 DECOSE

**Work at Royal Institute of Technology (KTH)**

1. Joint analytical activity on debris bed coolability which will include: code–to–code comparison, development of recommendations and best practice guidelines for simulations, defining reference cases for coolability analysis in plant accident conditions, post-test analysis and code validation against COOLOCE data and pre-test analysis to determine conditions for the future COOLOCE experiments (Tasks 7). Validation of the DECOSIM code against existing COOLOCE data with different configurations of debris bed has been carried out. The simulations showed that dryout conditions are very sensitive to particle diameter and porosity of the bed. Generally, reasonable agreement between simulations and experiments was achieved. DECOSIM analysis of debris bed coolability were carried for different ranges of debris bed configurations in pre and post-dryout conditions. The function describing the dependence of dryout heat flux on the width-to-height ratio was found for each shape. A surrogate model for 2D debris bed coolability is developed applicable to wide range of debris bed shapes, properties, and system conditions. The dependence of dry zone size and maximum temperature on problem parameters was obtained. It was shown that temperature can be stabilized by vapor cooling, provided that the size of dry zone is limited. It was shown that the relative size of dry zone is a linear function of relative heat flux excess above the dryout heat flux, and various geometric configurations can be described in a unified manner. On the basis of these findings, a surrogate model for post-dryout debris beds is suggested.
Reporting of the work and code–to–code comparison for the selected cases and development of recommendations and best practice guidelines for simulations is ongoing.

2. Investigation of particulate debris spreading, PDS-C tests and PDS-P (pool) tests on particulate debris spreading in a pool (Task 4).

Extensive series of PDS-C (Particulate Debris Spreading – Closures) tests on self-levelling of the debris bed provided data for development of scaling approaches and empirical closures that have been implemented in a model for particle mass flow rate. The model has been implemented in the DECOSIM code. Analysis has been carried out for selected severe accident conditions of the Nordic-type BWR. A series of tests on the debris spreading driven by large turbulent flows in the pool (PSD-P) has been carried out. Further experimental work is required in order to cover wider ranges of pool configuration, particle properties and debris release conditions. The preliminary work on validation of the DECOSIM code against PDS-P experimental has been performed. Generally, good agreement between the simulated and measured data is observed for both steel and glass particles. Parity plots (experimental vs simulated results) show that DECOSIM predicts the mean spreading distance within 20% accuracy on average. Reporting of the work is ongoing.

3. Investigation of the effect of the particle size on the DHF in POMECO-HT and POMECO-FL (Task 1d).
Small particle beads used in COOLOCE facility to clarify the effect of the particle size and morphology on the DHF were delivered to KTH. A confirmatory test in POMECO-HT facility is planned. Reporting of the work is ongoing.

4. DEFOR-A series of tests with corium simulant material on debris bed formation (Task 2).
New DEFOR-A tests are under preparations. Reporting of the work is ongoing.

5. Application of MC3D and TEXAS-V to analysis of steam explosion in a BWR containment (Task 8).
TEXAS-V model complemented with an impulse propagation approach to estimate explosion loads at the pedestal wall and on the containment floor has been developed and used for generation of the database of steam explosion solutions for different combinations of the input parameters. In order to address significant variability of explosion impulse with respect to the triggering time a statistical characterization of the explosion energetics for a single melt release scenario was introduced. The non-influential input parameters of the Full Model were screened out based on detailed sensitivity study with the Morris method. A large database of FM solutions was then generated and used for the development of a Surrogate Model (SM). The Surrogate Model reproduces with sufficient accuracy statistical characteristics of the Full Model solutions, providing much higher numerical efficiency. This SM has been implemented in the latest version of ROAAM+ and used for failure domain analysis for Nordic BWRs. Reporting of the work is ongoing.

6. Reporting of the POMECO-FL, POMECO-HT and PDS experiments and code development results.
Reporting of the work is ongoing.

**Work at VTT Technical Research Centre of Finland Ltd DECOSE-NKS and SAFIR2018:**

1. Joint analytical activity on debris bed coolability (Task 7).
Simulations of the debris bed geometry variations were continued using MEWA, including sensitivity studies of the unheated layer in the case of the side-only flooded cylinder and a BWR case with a heapshaped bed. The sensitivity study showed somewhat similar behaviour

as DECOSIM, i.e. the dryout power depends on the presence or thickness of the unheated layer. The large-scale BWR simulation showed similar dryout characteristics as the small-scale simulation of the conical bed experiment, also in post-dryout conditions. These results have been described in a doctoral thesis published in October 2015. Guidelines and details helpful for the validation of simulation codes using the COOLOCE experiments were given in the thesis. The main results of the doctoral thesis were: 1) the coolability of the debris bed depends on both the flooding mode and the height of the bed; 2) multi-dimensional flooding increases the dryout heat flux and coolability in a heap-shaped debris bed by 47–58% compared to the dryout heat flux of a classical, top-flooded bed of the same height; 3) heap-like beds are higher than flat, top-flooded beds, which results in the formation of larger steam flux at the top of the bed, this counteracts the effect of the multi-dimensional flooding; 4) the maximum height of a heap-like bed can only be about 1.5 times the height of a top-flooded, cylindrical bed in order to preserve the direct benefit from the multi-dimensional flooding.

2. Steam explosion analysis using the MC3D code to analyze steam explosion in a BWR containment (Task 8).
The objective was to evaluate the effect of some key input variables to the pressure loads induced by steam explosions. Simple MELCOR calculations have been made in order to find realistic boundary condition limits for the sensitivity analysis in the reactor application. However, melt temperature in the lower plenum according to MELCOR results was considered too low (2250K–2300K). This is because part of the melt was assumed to be debris. Temperatures more close to oxide melting temperatures were used in the analyses. In the MC3D simulations, three different breaking locations were evaluated starting from central break continuing sideways. The selected parameters for the sensitivity analysis were drop size (1 mm, 2.5 mm, 3 mm, 4 mm, 6 mm, 8 mm), water level in drywell (6 m, 8m and 12 m), melt temperature (2900K, 2950K 3000K, 3050K and 3100K) and coolant temperature (subcooling of 0K and 50K) In each case for the comparison was selected the triggering time yielding the strongest explosion. What comes to the maximum pressures on wall, it was difficult to observe consistent behaviour when changing an input parameter. However, when analysing maximum impulses it was possible to make some conclusions. Maximum impulses were always located to the bottom corner of the drywell and explosions became weaker with decreasing water level as well as with decreasing melt temperature. The results are collected to a master’s thesis that is currently under review.

Status of all tasks from previous years
Task 1. Investigation of the effect of the bed geometry and particle size on coolability in 2D debris bed
Synthesis of the COOLOCE experiments performed 2011-2014 is being prepared to combine the results from all six debris shape variations: conical, truncated cone, cylindrical with top flooding, cylindrical with lateral flooding, cylindrical with an agglomerate simulant and cone on a cylindrical base. The geometries which allow multi-dimensional flooding generally have greater dryout power compared to geometries in which the water infiltration into the debris bed is limited by closed walls. On the other hand, it is emphasised that the coolability is strongly dependent on the height of the debris bed and, according to the experiments and the simulations; the effect of the bed height is often greater than the effect of the flooding mode.

Task 2. Investigation of the effect of debris agglomeration on coolability

The effect of agglomerate was studied in the COOLOCE-11 experiments performed in 2013. When comparing the results to previous experiments it was found out that the bed with both top and lateral flooding had the best coolability: the measured dryout heat flux (DHF) was 50-70% greater than the DHF of the test bed with top flooding only. Also, the test bed with the agglomerate simulant had better coolability than the top-flooded test bed, with 10-40% greater DHF. These results are also discussed in the synthesis performed in the frame of Task 1.
Task 3. Investigation of the effect of initial pool subcooling on coolability. The effect of initially subcooled water pool was analysed in the COOLOCE-9 experiments. The experiments suggest that the subcooling may increase dryout heat flux and increase coolability. A synthesis of the results is included in the 2014 report.

Task 4. Investigation of particulate debris spreading
No planned activities due to reductions in funding for SAFIR2018.

Task 5. Investigation of the effect of the heaters' geometry on the DHF
The effect of heater´s geometry will be assessed performing experiments in the POMECO-HT facility with the same ceramic beads as used in the COOLOCE experiments. The debris bed material has been received by KTH.

Task 6. Development of advanced instrumentation
No planned activities due to reductions in funding for SAFIR2018.

Task 7. Joint analytical activity on debris bed coolability
The experimental results, particularly the comparisons of dryout heat fluxes in all six geometries, were collected in a manuscript which has been submitted to Annals of Nuclear Energy.

Task 8. Analysis of steam explosion in a Nordic BWR containment
MC3D and TEXAS have been applied to analysis of steam explosion in Nordic BWR conditions. Results are summarised in the reports.

**Overall Project Summary**
Comparison between plans and results with explanation of any deviations:
There are no major deviations between plans and results except for:
- Additional experiments with COOLOCE facility at VTT (Task 2, Task 3, and Task 4) will not be performed due to the reduction of funding in SAFIR2018. Instead the focus will be on analytical activities and application of the validated codes to prototypic plant conditions.
- New experiment in DEFOR-A and POMECO are delayed and will be carried out during July – September 2016 due to current lack of manpower.
- Expected date for submitting the reports for 2015 is in the end of June 2016.

## 5.4 L3PSA

Over the course of the project many activities were undertaken and completed. The first activities in the project (starting in 2013), were mostly exploratory in nature and included an industrial survey, an investigation of appropriate risk metrics, and participation in the development of guidelines and standards. The later stages of the 3-year project focused on application through two concurrent pilot studies, and the development of a guidance document.

The 3rd year project seminar was held on January 28th 2016. The pilot project was split amongst a Finnish Project, and a Swedish Project. The Finnish project had been underway since 2013, while the Swedish project started in earnest during the second year of the project (2014). The Finnish project was completed during 2014, and the Swedish pilot was completed in January 2016.
A completed draft of the guidance document was provided to stakeholders on the 15th of December, one month prior to the 3rd year seminar. This draft did not, however, include a draft conclusion section. Report comments were received from Ringhals Nuclear Power Plant and the Swedish Radiation Safety Authority, by mid-March 2016. The working group has incorporate comments, and is currently completing the conclusions for the guidance document, where stakeholders will provide final comments to the conclusions before the first publication.

# 6 Status 2016 activities

## 6.1 ADdGROUND

*Modelling as a tool to augment ground motion data in regions of diffuse seismicity*
Activity leader: Ludovic Fülöp (VTT), May 31th, 2016

**Introduction/Scope**
After the Fukushima accident, seismic safety of nuclear power plants and other nuclear installations has become an increasingly important topic also in regions with low seismic activity, including the Nordic nuclear sites.
The technical aim of the AddGROUND project is to build new capabilities in earthquake source modelling for ground motion simulations. The scarcity of empirical observations of near-field ground motions from large magnitude earthquakes in Fennoscandia has been an impediment for deeper understanding of the possible earthquake loading scenarios on nuclear installations, even if empirical data has been exhaustively analysed. With recent advances in computational methods, the opportunity exists for numerical models to give realistic estimates of earthquake loads. In addition to the technical outcome, the AddGROUND project also aims to establish and maintain a network of experts focused on diffuse seismicity areas of the Nordic Countries, and further enhance the cooperation between VTT and Uppsala University in the area of earthquake source modelling.
A longer term aim would be to extend the cooperation to the Baltic countries. The project outcomes will support STUK and SSM, providing background information for the safety assessments of nuclear plants, but are also relevant for nuclear repositories.

**Foreseen milestones and deliverables**

| | Date |
|---|---|
| M.1. Input variable ranges for selected modelling cases. | 02.2016 |
| D.1. Conference/Magazine article on NPP seismic design in the Nordic context | 03.2016 |
| D.2. Conference paper on benchmark modelling | 09.2016 / Paper submitted for review 31.05.2016 |
| **Final report** | |

## Technical progress

The main progress item in AddGROUND is the realization of M1 and the submission of a conference paper, which is accepted, can count towards fulfilling D2. After the calibration work with measured data in 2015, the consortium agreed to move to hybrid modelling of earthquake scenarios deemed to be possible in the Fennoscandian context. The following variable ranges were decided (**Deliverable M.1**):

Hybrid means that slip on the seismic fault is modelled by dynamic modelling. Hence, the fault and its immediate vicinity are modelled in software respecting mechanical (i.e. stress strain) compatibility on the fault. The target is to develop this model to cover the frequency range up to 20Hz and so the fault has to be modelled with very good resolution, leading to very large models. Due to the very large models only the immediate vicinity of the fault can be discretised, and the vibration propagation cannot be modelled. 3DEC is the software of choice for the dynamic part of the model.

We extract the displacement/fault-slip data from the dynamic model and use it as an input in a kinematic model. This model is used to predict the vibration propagation away from the fault. The Compsyn software and capabilities developed in AddGROUND-2015 are used for this section. Since the modelling here is not FEM or FDM based, there is no problem with the discretization of large area around the epicentre leading to huge numerical models. We can extend observations to 10, 20, 40 even 80km distance range.

Hence this hybrid modelling technique overcomes to computational limitations related to this complex problem. Both the fault movement and the vibration propagation can be modelled realistically.

The method is being benchmarked on a calculation case. Later, a couple of magnitude 5.2+ earthquake fault scenarios will be chosen. This corresponds to a fault size in the range of 4x4km, 5x5km. Strike-slips and reverse faults will be studied, without the faults rupturing the ground surface. The fault types will be selected compatible with the stress state in the crust in Fennoscandian.

Some variation of the scenarios using the faults will be parametrically studied (e.g. varying depth of the fault, dip orientation, rake-direction, discontinuities on the fault, etc.). But, since there is still a step of "manual" data transfer between 3DEC and Compsyn we cannot carry out a very large parametric study.

## Progress towards deliverables

The paper *"Opportunities for Source Modelling to Support the Seismic Hazard Estimation for Nuclear Power Plants", V. Jussila, L. Fülöp* has been submitted to the Nuclear Science and Technology Symposium - ST2016, in Helsinki, 2-3 November 2016. This is an important forum for popularizing the research activity to interested stakeholders in the nuclear field (http://www.ats-fns.fi/en/nst2016). If accepted, the paper would count towards Deliverable D.2. The consortium is considering several forums for Deliverable D.2.1, ranging from more scientific ones to more "commercial" ones. It is early to decide where the results will fit, and we are also considering the expected impact/readership carefully.

## 6.2 BREDA_RPV

*Studies of mechanical and microstructural properties of Irradiated Low Alloy Steel trepan samples from the RPV wall of Barsebäck 2*

Due to the time schedule and the changes of the activities during 2016, the project is not scheduled to start up until 1st of July 2016. Thus no firm activities apart from project planning and discussion regarding the test material and test matrix for the fracture mechanical testing of un-irradiated material has been undertaken. Material to test in the baseline experiments, utilizing specimens from the original baseline impact tests during the manufacturing of the reactor pressure vessel of Barsebäck 2, has been identified and collected. The signing of the contract is currently held up by the internal process at KTH, but is expected to be conducted with-in the first half of June. A start-up meeting regarding the fracture mechanical testing will be held at VTTs offices in Esbo, Finland at the 13th of June involving the partners from VTT/Aalto University and KTH.

## 6.3 COPSAR

*Containment Pressure Suppression Systems Analysis for Boiling Water Reactors*

**Work at LUT**

Deliverable 1: A SRV sparger test with combined steam injection through the sparger head and LRR

The test, where the effect of combined injection of steam through the sparger head and load reduction ring is studied, will be carried out in autumn after the RHR nozzle tests have been finished. Expected submit date of the report is December 31st, 2016.

Deliverable 2: Mixing tests with a RHR nozzle

Three RHR nozzle tests have been carried out in the PPOOLEX facility. Test specifications were decided together with KTH on the basis of earlier tests and pre-test simulations. Both vertical (pointing downwards) and horizontal orientation of the RHR nozzle have been used. Mixing succeeded when the nozzle was in the vertical position. The effect of nozzle flow rate and temperature was visible. Mixing was incomplete with the horizontal orientation of the nozzle if the used flow rate was small but successful with a clearly larger flow rate. One more test could be carried out in August. Expected submit date of the report is November 30th, 2016.

Deliverable 3: Delivery of relevant experiment data to the simulation partners

Measurement data of the three RHR nozzle tests (NZL-T0V, NZL-T1V and NZL-T1H) have been delivered to KTH.

Note: Deviation from the original NKS-COPSAR plan: Studies on the operation of a spray system in PPOOLEX have been postponed due to unavailability of NORTHNET funding for 2016. The smaller than applied SAFIR2018 funding has also reduced the number of the SRV sparger and RHR nozzle tests that can be performed. The changes to the original plan have been discussed and agreed in the SAFIR2018 Reference Group 4 and in the NKS coordination group meetings. RG4 supervises the work done in the SAFIR2018/INSTAB project.

**Work at VTT**
Deliverable 1: CFD model for the wetwell

CFD model for the sparger has been constructed for the studies of condensation of bubble clouds in the pressure suppression pool. Test calculations have been performed for the condensation of the bubble clouds injected from the sparger to the water pool. Vapor temperature was 110 °C, and the pool temperature was 50 °C. In the CFD calculations, penetration of vapor into the water pool was smaller than expected. The behavior of the condensation model is examined and improved.

Deliverable 2: Report on the calculation of a time interval of stratification and mixing experiment in PPOOLEX

The starting of the stratification and mixing have been delayed by three months. The calculations will be started in the beginning of August, when the condensation model for the bubble clouds has been validated.

**Work at Royal Institute of Technology (KTH)**
Deliverable 1: Pre-test analysis for selection of operational regimes and test procedures
Scaling and pre-test analysis of the sparger and RHR nozzle tests have been performed and used in the design and test matrix of the PPOOLEX and PANDA experiments.

Deliverable 2: Development of the EHS/EMS models
A preliminary validation of the current EHS/EMS models for spargers has been done against the PANDA HP5 tests. Validation against the PPOOLEX tests is on-going. EHS/EMS models for coarse mesh containment simulations have also been developed based on the Richardson scaling of the PPOOLEX and PANDA data.

For blowdown pipes, a containment model integrating the EHS/EMS models has been implemented in GOTHIC. The model allows (i) imposing the effective heat and momentum based on the condensation regime and (ii) time-average the numerical oscillations at the blowdown pipe outlet.

Deliverable 3: Post-test analysis and validation with GOTHIC code on spray
The work is postponed due to the changes in LUT work-plan.

Deliverable 4: Reporting
NKS-2016 report will be provided in June 2017.

## 6.4 FIREBAN

*Determination of fire barriers's reliability for fire risk assessment in NPP*

**Status**
A first Master thesis has been produced at LTH and the first action will be finished during June.

**Any major deviations between the original plan and the progress of your activity,**

No deviations at the moment. We are aware that we started a bit later due to confirmation of the project being earlier this year.

**Performed or upcoming seminars (if any), publications etc,**
One master thesis, Jonathan Valee, Reliability of fire barriers, Erasmus Mundus Master in Fire Safety Engineering
http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=8876398&fileOId=8876406

**Any other issues or highlights you would like the NKS board to be informed about regarding your project?**
No specific items.

## 6.5 HYBRID

*Development of hybrid neutron transport methods and data visualization tools*

**Status of the activity**
*On the Chalmers side*:

- The project formally started on week 15 with an MSc student working 50% of his time on the project as part of his MSc thesis work. The student will work 100% on the project from the summer.
- Since then, the student got acquainted with the computing environment and started to use the tools to be used within the project (Matlab and Serpent).
- Contacts have been taken with VTT in order to discuss how to estimate the probabilities necessary for the application of the response matrix method.

*On the IFE side:*

- Interviews of MSc thesis students will take place on week 21. The selected MSc thesis student will start working this summer on the project.

*On the VTT side:*

- Discussions with Chalmers are on-going in order to provide the probabilities required for the application of the response matrix method.

**Major deviations between the original plan and the progress of the activity**
None

**Performed or upcoming seminars, publications, etc**.
None

**Other issue to be brought to the attention of the NKS board**
Although the researcher originally planned to be involved at VTT has left, the project can still be carried out as planned.

nks
Nordic nuclear safety research

## 6.6 L3PSA

# Memo

**NPSAG / NKS-R L3PSA - Addressing off-site consequence criteria using Level 3 PSA: Spring 2016 status report**

| | | | |
|---|---|---|---|
| To: | NPSAG / NKS-R | Cc: | |
| From: | Level 3 PSA working group | Date: | 03 June 2015 |
| Project no: | 211975 | | |

## 1 Summary

Purpose of Project

Level 3 PSA provides a tool to assess the risks to society posed by a nuclear plant, and could be useful in making objective decisions related to the off-site risks of nuclear facilities. The intention of this study was to further Nordic understanding of the potential of Level 3 PSA to determine the influences and impacts of off-site consequences, the effectiveness of off-site emergency response, and the potential contributions of improved upstream Level 1 and Level 2 PSAs.

Progress of the activity 2015 activities

Over the course of the project many activities were undertaken and completed. The first activities in the project (starting in 2013), were mostly exploratory in nature and included an industrial survey, an investigation of appropriate risk metrics, and participation in the development of guidelines and standards. The later stages of the 3-year project focused on application through two concurrent pilot studies, and the development of a guidance document. The 3$^{rd}$ year project seminar was held on January 28$^{th}$ 2016.

The pilot project was split amongst a Finnish Project, and a Swedish Project. The Finnish project had been underway since 2013, while the Swedish project started in earnest during the second year of the project (2014). The Finnish project was completed during 2014, and the Swedish pilot was completed in January 2016.

A completed draft of the guidance document was provided to stakeholders on the 15$^{th}$ of December, one month prior to the 3$^{rd}$ year seminar. This draft did not, however, include a draft conclusion section.

Report comments were received from Ringhals Nuclear Power Plant and the Swedish Radiation Safety Authority, by mid-March 2016. The working group has incorporate comments, and is currently completing the conclusions for the guidance document, where stakeholders will provide final comments to the conclusions before the first publication.

Progress of 2016 activities

There are several ongoing activities which the working group is monitoring while the 2015 activities are being finalized:

- No planned IAEA activities are made for 2016 due to agency budget constraints.
- Some exploratory work is being made at the OECD NEA WGRISK group regarding Level 3 PSA.

Table 1. List of project deliverables.

| Deliverable | Date |
|---|---|
| Detailed project plan | May 2013 (complete) |
| Reference group meeting | May. 2013 (complete) |
| Project seminar 1 | Jan. 2014 (complete) |
| First year report | Jan. 2014 (complete) |
| *Major Sub-report*<br>Survey of Level 3 PSA Industrial Purpose/Application<br>Status of Task 1 - Risk Metrics (complete)<br>Status of Task 2 - Regulation & Standards (complete)<br>Status of Pilot Application (SAFIR/PRADA – VTT) | |
| Project seminar 2 | Jan. 2015 (complete) |
| Second year report | Jan. 2015 (complete) |
| *Major Sub-sections*<br>Level 3 PSA Regulation, Guides and Standards Report<br>Status of Pilot Application (33%) | |
| Final report (Following year 3) (ongoing) | Jan. 2016 (seminar complete, report ongoing) |
| *Major Sub-report*<br>Level 3 PSA Guidance document (ongoing)<br>Input from previous tasks including pilot application (complete) | |

## 6.7 SC_AIM

Project: Safety culture assurance and improvement methods in complex projects (SC_AIM)

Description: The SC AIM project aims to increase understanding on how to improve nuclear safety culture in complex project settings (e.g. in the presence of multiple organizations interacting, diverse background of personnel, etc.). The practical goals of the projects are to identify and specify methods to improve and facilitate safety culture in complex projects and to identify and specify methods to assure safety culture in complex projects.

Overall evaluation: The project is progressing according to plan.

Project group: Kaupo Viitanen (VTT, coordinator), Carl Rollenhagen (Vattenfall), Nadezhda Gotcheva (VTT), Mika Kari (VTT)

Milestones and deliverables for 2016

| Milestone / deliverable | Planned completion date | Status |
|---|---|---|
| Workshop on safety culture methods | June 2016 | Preliminary agenda has been drafted, invitations sent for relevant parties and practicalities handled. The workshop will be held in Stockholm on 16.6. |
| International workshop | October 2016 | Preparations are on-going, the workshop is planned to be held at the same time as HUSC seminar (27.-28.9.) in Finland |
| Conference paper or article | November 2016 | Not yet started, the content of the scientific publication will be internally discussed in project workshop and other meetings. |
| Intermediate report | December 2016 | Literature review has been nearly completed and will be integrated into the intermediate report. |

Overall status

Overall, the project is progressing according to plan. In February and March 2016, VTT carried out interviews in the Finnish case study at Fennovoima (10 interviews in total). The data has been summarized and is being analyzed. In parallel to the empirical studies, a literature review has been carried out (VTT and Vattenfall jointly). Another primary source of empirical data comes from a seminar organized by Carl Rollenhagen (Vattenfall) with a topic of project management and safety culture, which is being prepared for. Furthermore, we have been in close contact with representatives from two Swedish nuclear organizations (SKB and Forsmark) that will function as information exchange partners. In addition, an information exchange partnership with Fortum is planned and currently under discussion. Currently we are preparing for the internal project workshop to be held in 16.6.

| Task description | Estimated completion % | Progress by end of May 2016 |
| --- | --- | --- |
| 1) Identification of the currently used and potentially useful methods to improve, facilitate and assure safety culture in complex projects from literature | 80 % | • Essential literature has been identified and reviewed<br>• Text is being drafted |
| 2) Identification of the currently used methods to improve, facilitate and assure safety culture in the selected case studies | 50 % | • Fennovoima case study interviews are completed, all interviews have been summarized and data analysis is ongoing<br>• Seminar on project management and safety culture (to be held in 20.6.) organized by C. Rollenhagen<br>• Forsmark is an information exchange partner and provides additional data for the study through interviews<br>• SKB is an information exchange partner – a tele-interview has been completed<br>• Collaboration with Fortum is under discussion |
| 3) Identification of the safety culture challenges and method development needs in the case organizations | 50 % | • This work is done within case studies and in collaboration with representatives from the case study organizations in regular meetings and in internal workshop |
| 4) Evaluation of the pros and cons of the identified methods by expert judgment and workshop with the case organizations as well as international partners | 20 % | • This work is done in the internal project workshop with contact persons from VTT, Vattenfall, SKB, and Fennovoima |
| 5) Specification of the identified best practices (tentatively at least the following will be specified: definition of practice, do's and don'ts of the practice, field of application, necessary background knowledge of the user, and contextual issues to consider) | 20 % | • To be carried out partially in the project internal workshop and as a result of the project's activities this year. |
| 6) Arranging an international workshop for presenting, clarifying and discussing the identified best practices (October 2016) | 5 % | • Agenda will be drafted based on the insights from our internal workshop, empirical case studies and literature review. |
| 7) Intermediate report and dissemination of the existing best practices, including a networked safety culture questionnaire (December 2016) | 10 % | • Preliminary report structure has been constructed<br>• Literature review will be integrated to intermediate report as one of the chapters |
| 8) Scientific publishing (2016-2017) | 0 % | • A conference paper or journal article manuscript is planned to be written in autumn 2016 |
| 9) Administration | 50 % | • Ongoing |

## 6.8 SPARC

*Scenarios and Phenomena Affecting Risk of Containment Failure and Release Characteristics*
*May 31, 2016*

**Work at Royal Institute of Technology (KTH)**
WP1: Development and application of risk oriented accident analysis framework (ROAAM+) for prediction of conditional containment failure probability for a Nordic type BWR.
In 2016 *KTH* work will be focused in WP1 on

Task 1: Development and validation of detailed (full) deterministic models for analysis of severe accident phenomena in Nordic BWRs including.
Task 2: Development of computationally efficient (surrogate) models for approximation of the full model response parameters.
Task 3: Coupling of the surrogate models into ROAAM+ framework.
with the following goals:

1. Development and validation of detailed (full) deterministic models for analysis of severe accident phenomena in Nordic BWRs.

2. Development and application of computationally efficient surrogate models for uncertainty and risk analysis.

3. Collaboration with VTT and LRC on cross code comparison, code validation, and development of approaches to informing PSA with the ROAAM+ framework results.

4. Reporting of the results.

***1.1 Core degradation and relocation to the lower head (using MELCOR code). Obtained results will be compared with VTT analysis for Station Blackout (SBO) with delayed power recovery and other scenarios of risk importance.***

MELCOR model of Nordic BWR has been used to evaluate the effect of severe accident scenario (timing of activation of safety systems) on the resultant properties of relocated debris in LP. The analysis of the effect of severe accident scenario and possible recovery actions showed that:
i) the whole scenario domain can be represented by four groups, namely: small relocation domain; transition domain; large relocation domain with significant debris oxidation; large relocation domain with small debris oxidation;
ii) the major part of the core relocates to LP within ~30-60min after onset of core support plate failure;
iii) ECCS is effective in preventing massive core relocation only within relatively small time window after activation of ADS; delay in activation of ADS can significantly delay massive core relocation to LP, however it results in greater extent of core materials oxidation;
iv) debris composition (i.e. metallic/oxidic debris fraction) in different layers are highly influenced by severe accident scenario and can be classified in a limited number of groups.

Sensitivity analysis has been performed to evaluate the effect of modelling options in MELCOR on the resultant properties of relocated debris in LP. The most influential parameters for determining debris mass in LP and time of core support plate failure are: oxidized fuel rod collapse temperature and particulate debris porosity. Hydrogen generation and metallic debris fraction in the first axial level are mostly affected by: velocity of falling debris and particulate debris porosity. Complex non-linear interactions between physical models in MELCOR make results sensitive to selection of numerical parameters and achieving numerical convergence. Currently it is planned to develop further MELCOR model of Nordic BWR; in particular, it is planned to:

i) Refine lower plenum nodalization for spatial distribution of the debris properties in LP.

ii) Perform sensitivity analysis with updated model, to identify the most influential parameters.

iii) Generate a new data base of MELCOR solutions, taking into account the effect of modelling options.

The new data base will be used to develop computationally efficient Core Relocation Surrogate Model, to predict the properties of relocated debris in LP for the analysis of in-vessel debris coolability, debris remelting, melt pool formation and vessel failure in ROAAM+ framework.

***1.2 In-vessel debris coolability (using DECOSIM code).***

Coolability of a porous heat-releasing debris bed in a water pool was studied in the case where some zone within the bed is impermeable (a “cake”). Such a zone can develop in the process of debris bed formation from fragmented melt jet if agglomeration role is significant due to insufficient water pool depth. Numerical simulations were performed by DECOSIM code in axisymmetric framework. A mound-shaped debris bed having an impermeable “cake” in its top part was considered; the debris bed was placed on the bottom surface of a deep water pool, simulations were started from the initially quenched state. It is shown that while a dry and hot zone almost certainly develops in the debris bed with a “cake”, there exist conditions under which the dry zone temperature rises only to some level where it is stabilized by steam cooling. The influence of particle diameter, decay heat power and “cake” size on the maximum temperature and possibility of material remelting were considered.

***1.3 Debris remelting, melt pool formation and vessel failure (using PECM model).***

The PECM model has been developed and validated for prediction of debris bed heatup, remelting, melt pool formation and thermal load on the vessel wall. The PECM calculations are computationally expensive. The computational cost has been significantly reduced in the order of hours when 3D slice model for the debris bed heat transfer and 2D slice for the structural analysis are used. We are implementing corrections in the slice models (to address the effect of the differences in surface to volume ratios and the effect of penetrations) in order to obtain the same results as in the 3D quadrant models in terms of debris bed melt characteristics and timing of the vessel wall failure, while keeping the same computational efficiency of the original slice models. The resulting approach is useful for further sensitivity and uncertainty analysis.

To generate the output for the melt release and vessel ablation model (discussed below), we are in the process of generating a database of solutions using PECM. From this, we can characterize the data according to: Failure mode; Failure timing; Melt mass available for release; Melt superheat; and Initial break size as functions of initial debris properties.

***1.4 Experiments on multi-component debris remelting will be carried out to understand basic physical phenomena.***

The process of preparation for the construction and commissioning of the experimental setup is ongoing.

The necessity of commissioning tests is dictated by possible complexity of the exploratory facility which is envisaged as an intermediate step towards development of experimental platform for investigation of the debris bed remelting phenomena under different conditions. Three series of commissioning tests are planned. In the first series of commissioning tests the temperature profile in the debris bed as a function of

debris bed heat up rate and absolute temperature will be investigated. Tests with different size particles of (i) tungsten carbide, (ii) metal, and (iii) mixtures of tungsten carbide and metal particles will be performed.
Recommendations concerning experimental procedure (heat up rate and power distribution between the heaters) allowing establishment of uniform temperature profile within the test section for different debris materials will be developed and adjusted in the commissioning tests based on the obtained experience.
The second series of commissioning tests will evaluate the effect of specific interfacial area (determined by the particle size) of non-wettable solid debris on retention of liquid metal in the bed under uniform heating conditions. The materials of the debris chosen for the second series of commissioning tests is tungsten carbide (for high-melting temperature debris simulant) and tin (for low melting temperature simulant). The test with this combination of materials do not require application of inert atmosphere. The test series will be performed with two different sizes of tungsten carbide particles: 3 and 8 mm.
The third series of commissioning tests will be performed using copper as high melting temperature debris simulant and tin as low melting temperature material simulant. Debris bed behavior in this group of tests is expected to be sensitive to the oxygen potential in the atmosphere. Therefore, the objectives of these tests will be devoted to the investigation of different approaches and design solutions for providing inert atmosphere.

***1.5 Melt release and vessel ablation model and experiments for validation of the model.***
Melt release and vessel ablation model is currently based on the simplified modelling approach that allows prediction of the ablation rate of a breach given conditions of melt release: melt properties, transient release velocity and vessel wall conditions. Melt plugging is not modelled.
The preliminary analysis using the model has demonstrated that melt release velocity (availability of melt for release) is the key parameter defining the ablation rate, final jet diameter and respective risks of containment failure due to steam explosion or debris bed coolability.
Currently a simplified modelling approached are introduced into the model to provide insight into the importance of different phenomena of melt relocation that may delay, limit or enhance melt release from the vessel. The respective parametric study is ongoing.
Experimental program and experimental setup for the investigation of wall ablation under impinging jet and breach ablation under flowing through it melt is currently under development.

***1.6 Ex-vessel debris bed formation, agglomeration, spreading and coolability (using DECOSIM and Agglomeration models). The focus is on the mechanisms of the debris spreading that can help to reach a coolable state. Particulate Debris Spreading (PDS) experiments on debris spreading in the pool and after settlement will be carried out using different particles. Collaboration with VTT will be established for validation of the models.***
The shape, and therefore, coolability of the debris bed is affected by debris particle spreading (i) after settlement on the debris bed; (ii) in the water pool above the bed. The fist phenomenon has been intensively investigated experimentally (in PDS-C or Particulate Debris Spreading – Closures test series) and analytically using scaling approach and empirical closures. The model has been used to carry out sensitivity analysis and quantify the uncertainty in the efficacy of the particulate debris spreading in prototypic accident conditions. The modeling of the debris bed coolability with DECOSIM code taking into account debris bed self-leveling has been performed for selected severe accident conditions of the Nordic-type BWR. For extensive sensitivity analysis computationally efficient surrogate model (SM) using artificial neural network (ANN) has been developed and validated against results for the full model (DECOSIM). The preliminary uncertainty quantification and sensitivity analysis of the debris coolability SM coupled to particle spreading (bed self-leveling) model is ongoing.

The work on the debris spreading driven by large turbulent flows in the pool (PSD-P) is ongoing. Further experimental work is required in order to develop a database on particle spreading in the pool with wider ranges of pool configuration, particle properties and debris release conditions. The work on validation of the DECOSIM code against PDS-P experimental has been started. Particle mass distributions over the pool bottom were determined obtained for each pool geometry, injection rate, and particle properties. These mass distributions were compared with the experimental results, in terms of local distribution functions, and integral quantities characterizing particle spreading: the mean spreading distance defined by the horizontal coordinate of the center of mass of collected particles, and the tangent of the spreading angle. Generally, good agreement between the simulated and measured data is observed for both steel and glass particles. Further work on improvement of the code is ongoing.

***1.7 Steam explosion analyses (using TEXAS code) will be carried out with quantification of different sources of uncertainty.***
The Full Model (FM) for analysis of steam explosion in Nordic BWR was implemented in TEXAS-V. The effect of the triggering time on energetics of steam explosion was investigated. In order to address significant variability of explosion impulse with respect to the triggering time a statistical characterization of the possible explosion energetics for a single melt release scenario was introduced. A large database of FM solutions is generated and is used for the development of a computationally efficient Surrogate Model (SM) that reproduces statistical characteristics of the Full Model solution. The SM was trained to predict 50, 65, 78, 95, 99 and 100% percentiles of the cumulative distribution faction for the explosion impulse. This SM has been implemented in the latest version of ROAAM+ and used for (i) failure domain analysis for Nordic BWRs and (ii) example calculation of the risk of containment failure in melt release scenario similar to SERENA-2 BWR benchmark exercise.
The results of the failure domain analysis suggest for Nordic BWR the impulse will be higher than ~6kPa s in most of the possible met release scenarios if jet diameters is larger than Ø26 cm (independently on the other parameters) or if jet diameters >Ø10 cm in case if melt release velocity is high (>7 m/s) and water pool depth is large (>9m). If jet diameters are limited to 30 cm the probability of exceeding 50 kPa s impulse is less than $10^{-3}$ for the most of the possible combinations of eth distributions of the uncertain parameters.

Work on Tasks 4-6 is postponed due to reduction of the project budget:
Task 4: Connection of the framework to PSA-L1 and different plant damage states will be carried out in collaboration with LRC and VTT.
Task 5: Development and implementation of the methods for quantification of uncertainty, identification of failure domains and prediction of the conditional failure probabilities using ROAAM+ framework will be carried out.
Task 6: Development of data clustering techniques for coupling of ROAAM+ frameworks with PSA-L2, source term prediction tools and PSA-L3 will be done in collaboration with LRC and VTT.

## Work at LRC Loyd's Register Consulting – Energy AB

LRC is responsible for WP2: Development of the methods for coupling of Integrated Deterministic Probabilistic Safety Analysis tools such as ROAAM+ developed by KTH with PSA in general and PSA-L2 in particular.

*In 2016 LRC* work will be focused in WP2 on Task 1 and 2 (see detailed status of each task below) with the following goals:

1. Development of demonstration case for integration of the IDPSA generated data into PSA.

2. Defining requirements on dynamic cut sets and success and failure paths for dynamic events.

3. Reporting of the results.

**Task 1: Development of IDPSA generated data processing techniques for informing PSA about importance of (i) timing of events and (ii) epistemic uncertainty.**
Status. No activities has been performed during this phase.

**Task 2: Different approaches will be considered in collaboration with KTH and VTT to addressing of dynamic events and physical phenomena in (i) cut sets; (ii) success and failure paths; (iii) connections to PSA-L3.**
Status. No activities has been performed during this phase.

**Task 3: Cross code comparison for modelling of key phenomena of different accident progression scenarios (in collaboration with WP1 and WP3).**
Status. No activities has been performed during this phase.

### Work at VTT Technical Research Centre of Finland Ltd

VTT is responsible for WP3 and WP4 of the SPARC project:

**WP3: Deterministic modelling of core degradation, melt relocation, vessel failure, debris spreading and coolability. (VTT)**
***In 2016 VTT*** work in WP3 will be focused on Task 3 and 4 (see detailed status of each task below) with the following goals:
1. Analyses of debris bed temperature in post-dryout conditions (for developing temperature-based coolability criterion).

2. Exploring accident scenarios that may lead to hydrogen explosions with MELCOR.

3. Comparison of obtained results with KTH and LRC data.

4. Reporting of the results.

Work on Tasks 1-2 is postponed due to reduction of the project budget:

**Task 1: Development and verification of modelling approaches to core degradation, melt relocation and vessel failure. Comparison of MELCOR and ASTEC results for SBO with delayed power recovery and other scenarios of risk importance in collaboration with KTH.**

**Task 2: Implementation and validation of debris bed spreading models (e.g. Lagrangian particle tracking model in CFD) against PDS-P data in collaboration with KTH.**

**Task 3: Analytical investigation of the effect of debris bed multidimensionality on coolability (using the CFD approach developed at VTT and the MEWA code). This consist of refining the temperature-based coolability criteria for heap-like debris beds, which is a main unresolved question in the coolability of realistic debris beds. Collaboration with KTH on comparison of results obtained with DECOSIM code analysis.**

The task includes advanced investigations of the debris bed coolability of multi-dimensionally flooded beds, review of the simulation models and comparisons of the results to the results by KTH. The focus of the simulations is on the long-term post-dryout behaviour, and the possibility of establishing a temperature-based dryout criterion, which is more realistic but less conservative than the void fraction based coolability criterion (dryout heat flux). The effects of available heat transfer models on the post-dryout behavior of reactor application debris bed have been studied by MEWA simulations. The variation between the results obtained with the models which can be considered as the best is small.

**Task 4: MELCOR analyses of hydrogen explosions in order to address the interactions between deterministic phenomena, stochastic events and operator actions (in collaboration with WP1 and WP4).**
The existing MELCOR input deck for Nordic BWR plant will be converted for the latest MELCOR version, i.e. from MELCOR 1.8.6 to MELCOR 2.1. Accident scenarios that may lead to bypassing the filtered containment venting and to hydrogen explosions in the Nordic BWR reactor hall will be examined. Planning of the accident scenarios to be analyzed has been started.

**Task 5: Consideration of the implications of the analysis results for source term characteristics in collaboration with KTH, LRC and WP4.**
The effect of obtained results especially on source term will be summarized in the reports following discussions with other project partners.
Ilkka Karanta, Tero Tyrvainen

**WP4: Analysis of the factors that affect the energy (temperature), altitude and probability of the release in PSA-L2.**

***In 2016 VTT** in* WP4 will be focused on Task 1 and 2 (see detailed status of each task below) with the following goals:
1. PSA-L2 analysis results addressing important factors for the release characteristics.
2. Consideration of the relevant phenomena, namely steam and hydrogen explosions.
3. Reporting of the results.

**Task 1: PSA-L2 analysis with the focus on the factors affecting source term characteristics, i.e. release energy (temperature), altitude, and probability. The factors to be considered are: (i) plant damage states (from PSA level 1), (ii) plant design and (iii) accident progression phenomena.**
Release height and temperature have been considered tentatively for different accident scenarios based on general knowledge, literature and discussions with deterministic safety analysis experts. Roughly speaking, there are three different cases with regard to the release height:
- The release height is the height of the place where the containment fails.
- The release height is the height of the stack if filtered venting is performed.
- An explosion throws the releases in the air above/surrounding the containment.

Literature search gives very little about the release heights directly. Some papers where release heights for Fukushima accident were given were found. Concerning release altitude when the containment fails, construction of a list of possible containment failure modes for generic BWR's and PWR's is being considered; the list is based on international guidance (IAEA, Asampsa), and will contain the failure modes, prerequisites of failure in a particular mode, and some major possible causes of a failure in a particular mode.
Also release energy has not received much attention in the scientific literature. Release temperatures are in most cases close to 100°C because steam is expected to be a dominant constituent of the release. Some scenarios where the release energy might differ significantly from that temperature have been tentatively identified, but more work is needed on this. It is possible to calculate accurate temperatures

using deterministic severe accident analysis software such as MELCOR. An explosion can be a special case with regard to release temperature too. Fire in reactor building can also potentially increase the temperature of a radioactive release.
The plan is to develop old BWR containment event tree model (see VTT-R-05974-13) further by including release heights and energies, improving hydrogen explosion modelling and implementing uncertainty analysis for probabilities. A tentative uncertainty analysis implementation has already been done, and release height and temperature variables have been added to the model.

**Task 2: Consideration of the factors affecting the probability and magnitude of relevant phenomena such as (i) hydrogen explosions (in collaboration with WP3), (ii) steam explosions (in collaboration with WP1); (iii) non-coolable debris bed formation and core-concrete interaction (in collaboration with WP1 and WP3).**
This year, the plan is to improve hydrogen explosion modelling in the BWR containment event tree model. The subject has been discussed with deterministic safety analysis experts (WP3). The results of forthcoming MELCOR analyses will be utilised in this task.

## Overall Project Summary

**Comparison between plans and results with explanation of any deviations:**
Active work on the project at LRC is planned for the second half of the year.
There are no major deviations between plans and results so far.

**Expected submit date of the final report**
- Expected date for submitting the reports for 2016 is mid of June 2017.

**Any issues you would like the board to know**
- No.

### Publications:

1. Takasuo, E. An experimental study of the coolability of debris beds with geometry variations. Annals of Nuclear Energy 92, 2016. pp. 251-261.
2. Konovalenko A., Basso S., Kudinov P., Yakush S. E., “Experimental Investigation of Particulate Debris Spreading in a Pool”, Nuclear Engineering and Design, Volume 297, pp208-219, 2016.
3. Basso, S., Konovalenko, A., Kudinov, P. “Empirical Closures for Particulate Debris Bed Spreading Induced by Gas-Liquid Flow”, Nuclear Engineering and Design, 297, 19-25, (2016).