Annex – POOLFIRE - Predictive analysis of pool fires in enclosures using CFD models for the risk assessment of nuclear power plants

Background

Safe shutdown of a reactor after internal or external events is a key factor in the overall safety design of a nuclear power plant. Pool fires caused by oil from the Reactor Cooling Pumps (RCP) is such a significant event that can affect the reactor safety and the capability of safe shutdown. When the event is a fire, the fire can not only be the cause for the shutdown but can also jeopardize the safe shutdown by destroying critical components needed for the shutdown process. In order to prevent this, redundant systems are used to decrease the probability of failed shutdown. When analysing the fire consequences, the functional performance of components such as cables, electronic circuits, etc. is of highest importance. With respect to fire, events can be classified in 3 major groups depending on the position of the subsystems. The three cases are given illustrative in figure 1. In the first class (left), the redundant systems A and B are located in the same enclosure within a fire compartment and a fire can have a great impact on one or both subsystem and the risk of loosing the redundancy is consequently high. Probability for failure might e.g. be 1 on 100 years. In the second class of events, the systems A and B are in the same fire compartment but not in the same enclosure and the risk of failure will depend on the fire spread between enclosures. Probability will be 1 on 1000 years. Finally the subcomponents A and B can be in 2 different fire compartments, and the risk for loosing both subsystems will be due to failure of fire compartmentation, something very seldom to happen. The utilization of the physical separation is an important part of the defence-in-depth principle of NPP safety. The consequences of loosing the physical separation may not be well-known because these events are often ignored in fire-PSA as a result of the screening process [1,2]. The loss of separation may take place either by mechanical damage to the structure or by the penetration of heat and smoke through the leakages or the ventilation network.

Figure 1 Example of event classification for fire incidents with probability for failure

One way to determine the overall risk in a PSA analysis is by using probabilistic methods using statistics. Another possibility is to investigate the likelihood for critical conditions by using calculation methods, which predicts fire growth, fire and smoke spread and critical temperature of the components. This is a so-called deterministic approach, which can be a complement to the probabilistic methods in PSA analysis. Today more and more CFD (Computational Fluid Dynamics) methods are used instead of empirical and zone models. The use of the method puts however high requirements on the correctness of the prediction methods and therefore validation experiments are necessary. Another key issue here is the correct prediction of the fire growth within an enclosure. CFD fire models have been carefully
validated for the prediction of fire conditions resulting from a prescribed fire. For many of the NPP fire loads, empirical data is available for the specification of the fire growth as a CFD boundary condition. For some fire loads, such as electrical cables and large liquid pool fires, generalized empirical data may not be available and the capability is needed to predict the fire growth. The fire growth depends on the properties and geometry of the enclosure, ventilation conditions and the type and load of the fire fuel [3,4].

In an on-going OECD PRISME project [1], a large amount of experimental data is gathered with respect to enclosure fires where mechanical ventilation is involved. Most of the tests have been carried out using oil pool fires with varying number of rooms and different ventilation conditions. Pool fires are namely one of the major fire incidents in NPP[2,5]. The project will be extended by another 5 years and will include also experiments with other set-ups (e.g. two enclosure above each other with a horizontal opening), another liquid fuel, cables as fire load, and extinguishment systems (sprinklers). This international project constitutes of an important and unique database set of experiments. The international project focuses mainly on the fire tests while the use of the fire test results and the validation of CFD models is a national or regional responsibility and subject to local funding.

Up to now Sweden and Finland have participated on national basis but it has been seen clearly that synergy is possible between the research groups involved in the project (Lund university and VTT). Activities have been related to the validation of the most widely used CFD tool called FDS [6] and to the sensitivity analyses for this tool. In the future the important aspect of coupling fire growth with the enclosure conditions as mentioned above is an important aspect in the applicability of CFD fire models in the fire risk assessment of nuclear power plants. Incorporating Haugesund University College in Norway will complement the CFD and validation competence of both VTT and Lund University.

Scope

The scope of the project is to provide improved tools for the deterministic evaluation of the risk for loss of functional performance in redundant systems critical for shut down of the reactor within PSA analyses. The improved tool will contain an advanced pool fire model, which takes into account all aspects of the enclosure (geometry, properties, ventilation) and fuel (amount, type, surface area, thermal boundaries).

Content of the project

The project major core of activity is the development and validation of a pyrolysis model for pool fires in enclosures and will contain the following work packages:

1. **Work package 1: Current state of the art.**
   Evaluation of the actual state of the art of pool fire models within CFD codes especially FDS, and the review of validation data available within open literature and the OECD PRISME -project. The result of this work package will be an overview of the need for further development and the requirements for additional data both as input data for the models and for validation purposes.
   Responsible organisations: VTT and Lund University

2. **Work package 2: Development of advanced model and method for input data**
   This work will contain the development of an advanced model for pool fires, which takes into account important aspects form the enclosure and pool fire. The enclosure geometry (volume, openings, height, etc.) will define e.g. the hot smoke layer temperature, which on its turn defines the thermal radiation levels towards the burning liquid. Ventilation inside the enclosure is also an important factor since the ventilation affects the burning rate (ventilation controlled or not) and the burning rate affects on its turn the ventilation (overpressures, back flow, etc.). Finally the type of fuel and how it is located in the enclosure is of importance. Fuel leakages
mainly run on a surface and hence the thermal boundaries are important, as they will affect the heat losses of the burning liquid and needed to be incorporated in the model. Advanced pyrolysis models for liquid pools need special input data, such as the absorptivity of infrared radiation. It will be investigated how these can be obtained from literature or small-scale test data which can be conducted at Lund University which have advanced measuring techniques [7].

**Responsible organisations:** VTT and Lund University

3. **Work package 3: Validation of the model**

Validation of the model will utilize the existing knowledge of pool fire burning rate in open atmosphere [4,8] and within enclosures [3,8]. Test from the international OECD project PRISME will be used for validation of the capability to account for strongly under-ventilated but high temperature environments. As part of the validation also a parameter investigation will be performed.

**Responsible organisations:** Lund University, VTT and Haugesund University College.

4. **Work package 4: Implementation of the model in a real case scenario for risk identification.**

In this work package the obtained knowledge will be applied on a real case study in a nuclear power plant within a deterministic evaluation of the risk for loss of functional performance of critical components, and the failure of the defence-in-depth principle.

**Responsible organisations:** Lund University and Vattenfall Ringhals.

5. **Work package 5: Dissemination of results**

Results from the project will be reported in scientific journals and at conference. A small workshop for interested parties will be organised at the end of project. Due to the fact that data from the OECD project PRISME is used the partners will follow the rules of OECD for publication of the results. The most efficient way is to report by means of scientific papers, which are approved by the OECD project group.

**Responsible organisations:** All partners

6. **Work package 6: Management**

Management of the project includes aspects such as communication with partners, meeting organisation, economical follow up and progress follow up. The management part will also include the set-up of a confidentially agreement between the partners with respect to the OECD project PRISME. Vattenfall Ringhals, VTT and Lund University are now part of the PRISME project but Haugesund University College is not and due to the rules of OECD a contract between the partners and Haugesund will be necessary. At this moment no hinder is seen in establishing this contract.

**Responsible organisation:** Lund University

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**Area of NKS-R (reactor safety) and NKS-B (preparedness)**

The major focus of the project is related to reactor safety and includes following several aspects of this call for proposals:

1. Organisation, man and safety culture.

The project will give new models and methods for safety reviews and will implement new techniques and new working methods

2. Probabilistic methods

As the models can be used as part of a PSA analysis it will be also related to this theme. Also aspect of uncertainty through sensitivity analysis will be obtained. However since the project relates to fires there is also an important aspect of preparedness in this project with links this project also the NKS-B area.
Project group.
The project group consists of Lund University (coordinator) and includes both Prof. Patrick van Hees and PhD student Jonathan Wahlqvist. Lund University is an active partner in several projects with respect to validation of CFD models and has within the validation project supported by the Strategic Research Foundation Fund (part of the CECOST competence centre) access to advanced laser techniques for detailed sub-validation of the models. More information on the coordinator of this project can be found on www.brand.lth.se.

Dr. Simo Hostikka and PhD student Topi Sikanen represent VTT. Dr. Hostikka is the principal developer of the thermal radiation and pyrolysis submodels within the FDS code [6] and is hence a key resource for implementing the new liquid pyrolysis model into FDS code. At VTT, the project is managed as a part of the fire safety research project 'Risk Assessment of Large Fire Loads (LARGO)', within the national research program SAFIR2014. More information can be found on www.vtt.fi/research/technology/fire_safety_technology.jsp?lang=en.

An important part of the project is to predict extinction of fire. Ass. Prof. Bjarne Husted has been working a lot in this area looking to modelling of sprinkler systems[9]. He is also active in providing submodels to CFD codes. Furthermore Ass. Prof. Alf Reidar Nilsen has done experimental work on pool fires in different enclosures and modelled pool fires in tunnels [8]. Information on the group can be found at http://www.hsh.no/fou/fouprogram/atom/ts.htm. Tommy Magnusson is active in safety assessment at Vattenfall Ringhals and is hence involved in the connection of this research project to the actual industrial application.

Additional budget information.
The majority of the tests at full scale will be part of the PRISME project step 1, to be ended this year, which had a budget of 7 M€. The step 2, a prolongation of another 5 years has a proposed budget of 7 M€ and has scheduled another set of pool fires which will also be used. However the OECD project does only cover the testing costs. Any validation of CFD codes or use of the test data should be sponsored at national or regional (Nordic level) for the step 2.

References