RECENT EXPERIENCES IN RISK INFORMED REGULATION IN FINLAND

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In Finland, changes in PSA results during the 25 years period reflect the impact of risk informed regulation and continuous safety enhancement at nuclear power plants (NPPs). Operating NPPs in Finland have full scope detailed and up to date level 1 and 2 PSA models. In Finland PSA has been found to be useful tool that has been used to identify and prioritize possible safety improvements and to evaluate the adequacy of the design basis. PSA has also been used in support of licensing of new units and periodic safety reviews of operating units.

Risk-informed applications are integrated in the regulatory process of Finnish NPPs from the early design phase up to early phases of decommissioning. The required applications include risk-informed in-service inspection (RI-ISI), risk-informed technical specifications (RI-TechSpecs), risk-informed in-service testing (RI-IST) and safety classification of systems, structures, and components (RI-SC).

Finnish regulatory guides were updated in 2013. The current regulatory YVL Guide for PSA is guide A.7 titled "Probabilistic risk assessment and risk management of a nuclear power plant". It gives both quantitative and qualitative requirements about the PSA and PSA applications. Risk informed methods are required also in other guides dealing with e.g. safety design and in service inspections.

In the stress tests completed for Finnish NPPs after Fukushima accident no new threats or shortcomings that would require immediate action were found. Areas where nuclear safety can further be enhanced were identified and action plans how to address these areas in the Finnish NPPs, national legislation and regulation were created. Based on this action plan several plant improvements have been completed or are in progress for Finnish NPPs. Improvements will enhance the capability of Finnish NPPs to cope with the extreme events causing e.g. loss of ultimate heat sink.

I. INTRODUCTION

I.A. Background

The objectives of the paper are to introduce recent development in the risk informed regulation in Finland and have an overview on the main results of PSAs as well as on the recent safety improvements completed or under implementation phase in Finnish nuclear power plants. The paper will mainly focus on the operating nuclear power plants in Finland, which are Loviisa 1 and 2 and Olkiluoto 1and 2.

In Finland, STUK and licensees have introduced PSA as a widely used method in the nuclear safety regulation and safety management. Constantly updated PSA and risk-informed applications are formally integrated in the regulatory process and safety management of NPPs. PSA has been used to support regulatory decision making since the late 1980's and the Finnish regulatory guides require extensive use of PSA in the safety management and regulation of a nuclear power plant and other nuclear facilities throughout its life-cycle starting from the early design phase and running through the construction and operation phases up to the decommissioning phase.

I.B. Nuclear installations in Finland

There are four nuclear power plant units in Finland: the Teollisuuden Voima Oyj (TVO) power company has two 840 MWe BWR units supplied by Asea-Atom at the Olkiluoto site and Fortum (formerly Imatran Voima Oy) has two 500 MWe VVER 440/213 units at the Loviisa site. Seawater is used as the ultimate heat sink for both plants. All the units were commissioned between 1977 and 1982. On both sites there is a water pool intermediate storage for spent fuel and a final repository for low and intermediate activity nuclear waste.

At the Olkiluoto site a new unit, Olkiluoto 3 (OL3), has been under construction since 2005. OL3 is a 1600 MW EPR type pressurized water reactor supplied by Areva. In addition, the Finnish Government has granted a decision in principle for an additional unit for a new utility Fennovoima, on a green field site in Hanhikivi. Fennovoima applied for a construction licence in the summer of 2015.

The final repository for the nuclear fuel from the Olkiluoto and Loviisa NPPs is planned to be built in the Olkiluoto island by the company Posiva. The Finnish Government granted a licence to Posiva for the construction of a final disposal facility for spent nuclear fuel in the end of November 2015. The final disposal of the spent fuel into the Finnish bedrock is planned to start in the early 2020's.

II. REGULATORY REQUIREMENTS IN FINLAND

In Finland, the foundation for risk-informed licensing, regulation, and safety management is laid in the nuclear safety legislation[1]. The general principles of the use of nuclear energy, the implementation of nuclear waste management and the licensing and control of the use of nuclear energy are laid out in the Nuclear Energy Act. Nuclear Energy Act is the highest level of regulation. Mandatory safety requirements for NPPs are presented in the Nuclear Energy Decree and the new STUK Regulations. Nuclear Energy Decree presents the major technical prerequisites required to ensure an adequate safety level of the use of nuclear energy. It is the highest level of regulation that specifically requires the use of probabilistic risk assessment. It requires that the licensee has to submit probabilistic risk assessment in conjunction with the construction and operating license applications. Previously the next level of regulations was the Government Decrees. These have been superseded by STUK Regulations in the beginning of the year 2016. In addition to STUK Regulations, STUK issues detailed regulations called YVL Guides (nuclear regulatory guides)[2]. YVL guides are formally less obligatory than the acts, decrees and STUK regulations. YVL guides were updated and the new guides were published in 2013. Lessons learned in the OL3 construction project and Fukushima Dai-ichi accident were taken into account in the update process. Other objectives were to improve the consistency in the structure and terminology, to improve clarity and user friendliness. Updated YVL guides also cover the latest international safety standards, e.g. by IAEA and WENRA. All of the regulations in the updated YVL guides are in force for the new NPP projects. For NPPs that are in operation (LO1/LO2, OL1/OL2) a separate decision about the application of the new YVL guides was made in 2015 and this process is currently ongoing for Olkiluoto 3. In this process the utilities made their own assessment how the new regulations are fulfilled. For the requirements that were not fulfilled utilities either applied for exception about the requirement or proposed improvements and changes to fulfill the requirement. STUK then reviewed the assessments and made decision about the exceptions and required improvements. Previously granted exceptions were also re-evaluated, they were not valid automatically. For example, licensees re-applied and were granted exceptions in numerical requirements for core damage frequency and the frequency for large radioactive release. Exceptions were also applied for different design requirements, e.g. related to seismic design. Seismic safety of the operational plants has been evaluated previously and will also be evaluated in the future in the PSA framework.

The first Finnish regulatory guide on the use of PSA was issued in 1987. The first edition of the guide set forth several requirements to the licensees on how to use PSA in the safety management of the NPPs. Guide was updated in 1996 and 2003 to expand the use of PSA applications. The current regulatory YVL Guide for PSA is guide A.7 titled “Probabilistic risk assessment and risk management of a nuclear power plant” issued in 2013. The use of risk informed methods will also be required in regulatory guides related to design of systems, safety classification, aging management, operation, determination of design basis earthquake and design basis for other site-dependent external events. Therefore risk informed approaches are also included in YVL guides B.1 “Safety design of a nuclear power plant”, B.7 “Provisions for internal and external hazards at a nuclear facility” and E.5 “In-service inspection of nuclear facility pressure equipment with non-destructive testing methods”.

YVL A.7 specifies the following probabilistic design objectives:

- Mean value of the core damage frequency, as estimated from a comprehensive level 1 PSA, is less than 10^{-5} / year.
- Mean value of a large radioactive release frequency (more than 100 TBq Cs-137), as estimated from a comprehensive level 2 PSA, is less than $5 \cdot 10^{-7}$ / year.
- The accident sequences, in which the containment function fails or is lost in the early phase of a severe accident, have only a small contribution to the reactor core damage frequency.

The design has to be improved if these objectives are not met but for operating NPP units they act as target values to be reached by continuous safety improvements. First two objectives are not new, they were also in the previous iteration of the YVL guides. The requirement about the contribution of accident sequences in which the containment function fails or is lost is a new one. The objective of the requirement is ensure that protective measures, like evacuation or iodine tablet administration, are not needed when there is not sufficient time to implement them. Protective measures are usually analyzed in the level 3 PSA, but in Finland level 3 PSA is not required. In YVL A.7 the scope of the PSA was also extended to cover all storages and pools containing spent nuclear fuel. As a consequence of Fukushima accident the analysis was also required to cover accidents of long duration, e.g. a long-term loss of AC power and the loss of the ultimate heat sink. For level 2 PSA overpressure in the containment was added to be covered as a possible cause for containment failure. The experiences gained in the Olkiluoto 3 lead to defining the update and delivery schedule of models and documents of the PSA and PSA applications more exactly especially in the construction phase of the new unit.

The licensees of the operating units were required to do the primary PSA development in-house, but consultants can be used for special topics or methodological issues. The PSA models must be available to STUK for cross-checking and review. The PSA models are full-scope for levels 1 and 2 and they are kept up-to-date (living PSA), i.e. the licensee has to prepare and regularly update PSA model corresponding to the operating experience, substantial changes in the plant design or in the procedures or when a new substantial risk factor is found. Currently, there are full-scope level 1 PSA models available for power operation as well as for low power and shutdown states for operating NPPs at Loviisa and Olkiluoto. Events to be analyzed include internal failures, disturbances and faults, loss of off-site power, fires, floods, severe weather conditions, seismic events and other external and human caused initiators. Level 2 PSA models are practically full scope, models include e.g. the analyses for leak or bypass of the containment in consequence of containment overpressure, isolation failure, steam generator failure, interfacing systems LOCA, or seal failures of containment penetrations or access locks, reaction forces and missiles in various accident phases, effects of hydrogen burn and explosions, melt-through mechanisms of the reactor pressure vessel, recriticality of the reactor core, phenomena leading to rapid or slow pressure increase inside of the containment. For Olkiluoto 3 level 1 and level 2 PSA has been submitted to STUK for review as a part of the operating license application.

The required risk-informed applications include risk-informed in-service inspection (RI-ISI), risk-informed technical specifications (RI-TechSpecs), risk-informed in-service testing (RI-IST) and safety classification and risk relevance of systems, structures, and components, the development of the disturbance and emergency operating procedures and selection of safety relevant topics for personnel training. PSA is used to optimize the test intervals and procedures of components and systems which contain major risk reduction potential. The relevance of allowed outage times of safety systems has to be evaluated with PSA as well[3].

III. PSA DEVELOPMENT AND RESULTS

The possibilities of probabilistic methods in nuclear safety management were recognized by the Finnish authorities and licensees already in the early 1970s while the Loviisa and Olkiluoto NPPs were under construction. STUK formally required the Finnish licensees to perform level 1 and level 2 PSA studies in 1984. The first level 1 PSA studies were submitted to STUK in 1989.

The PSA of the Finnish NPPs is based on detailed calculation models, which are continuously developed and kept up to date. A total of 200 man-years have been used at Finnish NPPs to develop the models. The basic PSA data includes globally collected reliability information of components and operator activities, as well as operating experience from Finnish NPPs.

When using the PSA model to evaluate the changes in the risk level of the NPP over long periods of time, one must keep in mind that the result is affected by both the development of the NPP and the development of the calculation model.

III.A. Loviisa nuclear power plant

Figure 1 presents the annual core damage frequency and most important initiators for the Loviisa NPP. Loviisa NPP's accident risk has continued to decrease over the last ten years as the new risk factors, discovered as the scope of the PSA was extended, have been efficiently eliminated. At the end of 2015, the core damage frequency calculated with the PSA model was about 1.7×10^{-5}/year for Loviisa 1 and 2.0×10^{-5}/year for Loviisa 2. Based on the uncertainty analysis the uncertainty factor of the CDF is estimated to be about 4 (95% fractile / 50% fractile).

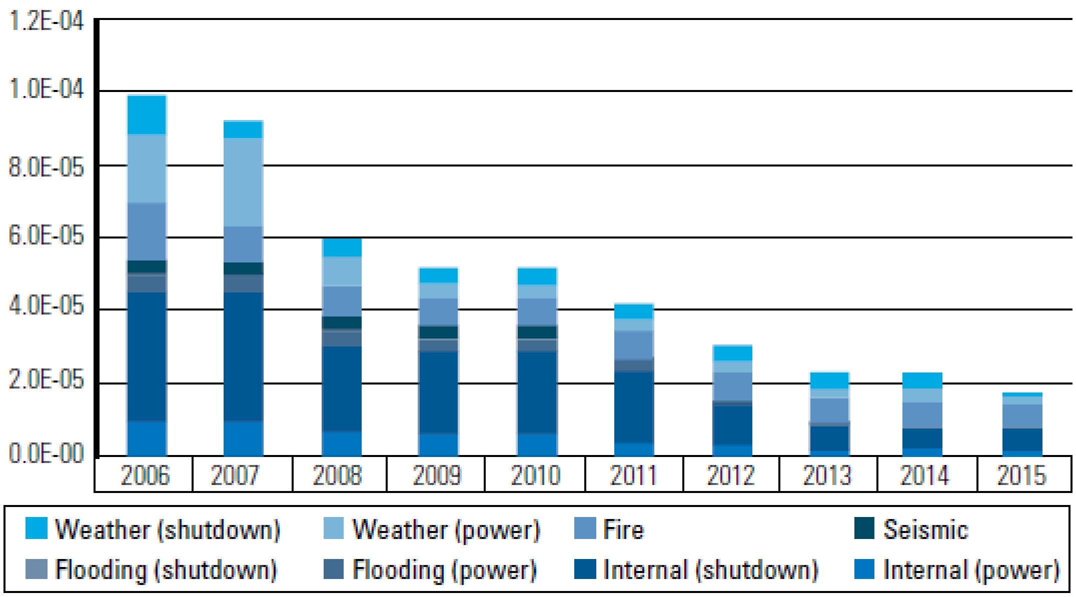

Fig. 1. Fluctuation of the calculated annual core damage frequency for Loviisa plant units during 2006 – 2015.[4]

The indicator decreased in 2007 due to the new service water line completed during the period. The new line allows for the alternative intake of seawater from the outlet channel to cool the NPP when it is at a shutdown. The change decreases the risks in situations where algae, frazil ice or an oil spill endangers the availability of seawater via the conventional route. The decrease of the indicator in 2008 and in the following years result from more detailed assessments performed for the renewal of the operating license process, as well as changes at the NPP planned to be carried out earlier or in connection with the license renewal. Changes include decreasing the probability of a criticality accident using, for example, boron analyzers, and decreasing the probability of an external leak. The decrease in risk in 2015 is mainly because of the new air-cooled cooling units that were commissioned in 2015 (see chapter V). They allow for the removal of residual heat in the long term also if the service water systems are unusable.

III.B. Olkiluoto nuclear power plant

Figure 2 presents the annual core damage frequency and most important initiators for the Olkiluoto NPP. At the end of 2015, the calculated core damage frequency was 0.9 x 10^{-5}/year for Olkiluoto 1 and 1.5 x 10^{-5}/ year for Olkiluoto 2. Based on the uncertainty analysis the uncertainty factor of the CDF is about 4 (95% fractile / 50% fractile).

At Olkiluoto NPP, the most important factors affecting the overall accident risk include internal events during power operation (component failures and pipe ruptures leading to an operational transient). The large difference between the plant units is mainly caused by the fact that Olkiluoto 1 underwent modifications in 2014 that ensured longer operability of the auxiliary feedwater system, which is used to cool the reactor, in case seawater cooling is lost because of a blockage at the seawater intake or component failures (see chapter V). These modifications have not been implemented at Olkiluoto 2 yet.

The decrease in the risk of Olkiluoto NPP in 2008 was mainly caused by the more detailed modelling of earthquake events and plant modifications carried out at the NPP to improve seismic qualification. The increase in 2009 was caused by the fact that a heat exchanger could not be used for residual heat removal, contrary to earlier assessments. In 2010 the modelling of DC systems was changed (inclusion of battery diversity) causing the decrease in risk. The increase in 2011 resulted from reassessment of fire frequencies. Slight increase in core damage frequency in 2015 is caused by the minor changes in the PSA model specifications and updated reliability information.

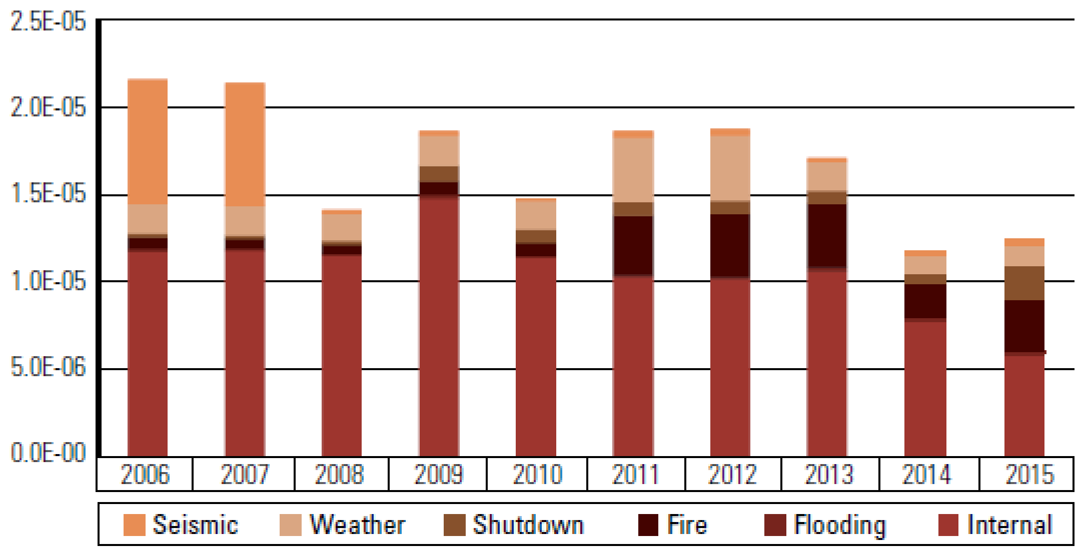

Fig. 2. Fluctuation of the calculated annual core damage frequency for Olkiluoto plant units during 2006 – 2015.[4]

III.C. Olkiluoto spent fuel storage

As a new survey in Finland, PSA was used in the design phase of the enlargement of existing intermediate spent fuel storage building in Olkiluoto. According to the completed study, the frequency of uncovery of spent fuel in the water pools is very low compared to the Olkiluoto NPP core damage frequency. The main risk contributors were found to be related to earthquakes that can render fuel pool cooling systems inoperable. Based on the PSA results, implementation of safety improvements was started, e.g. to enhance pipeline supports and important components mounting in the fire water pump station. Additional diesel driven fire water pump containers were provided to the site and they can be used to supply fire water to the spent fuel pools, as well.

III.D. Posiva spent fuel encapsulation plant

Finnish government granted the Posiva company a construction license for the final repository of the nuclear fuel in November 2015. PSA of the spent fuel handling process was part of the construction license application. Further on, the PSA is used to support the detailed design of the facility and to reduce the probability of identified release sequences of the spent fuel handling process, although the estimated release frequency is very low. The main contributors for the release sequences were found to be related to ventilation and power supply systems. Additionally, PSA methods were used to identify possible sequences, when the facility personnel could be exposed to fatal radiation doses mainly due to human reasons. Later on, the procedures can be developed to avoid the critical human mistakes.

IV. PSA APPLICATIONS

In Finland risk-informed applications are integrated in the regulatory process of NPPs from the early design phase up to early phases of decommissioning. The required applications include risk-informed in-service inspection (RI-ISI), risk-informed technical specifications (RI-TechSpecs), risk-informed in-service testing (RI-IST) and safety classification of systems, structures, and components (RI-SC)[5].

The objective of risk-informed in-service inspection (RI-ISI) programs is to allocate inspection resources to the targets that are most critical from the point of view of risk. STUK conducted a pilot study on risk-informed in-service inspection in 1998-1999 in co-operation with the licensees[6]. The pilot study included two safety systems both from Loviisa and Olkiluoto NPPs. The study produced insight on the applied method and gave guidance for further development. Based on these results and overall experience, the general suitability of the method for further applications was evaluated. In 2003 new requirements that made RI-ISI applications mandatory on the ISI programs for piping of operating and new NPPs were issued. RI-ISI approach ensures that the current inspection objects are well-justified, identifies new objects and omits certain less safety-critical objects from the old deterministic inspection program.

In Loviisa NPP approved RI-ISI program was started in 2008 for Loviisa unit 1 and 2011 for Loviisa unit 2. The risk assessment was applied to whole unit including all safety classes and nonnuclear safety class classified piping. The basis for risk classification and all selected systems were evaluated by independent expert panel. As a result of the program the number of inspections was increased, but the focus shifted from high safety classes to lower safety classes. This is caused by the high risk significance of some of the lower safety class piping belonging to the important support systems of the safety systems. Although the number of inspections was increased, radiation doses to personnel were decreased. [7]

In Olkiluoto operating NPPs approved RI-ISI program for piping was started in 2013 for unit 1 and 2012 for unit 2. The results were similar to Loviisa. Number of inspections was increased but the radiation doses are expected to decrease substantially. For Olkiluoto 3 PSA shall be used when developing the inspection programs for piping,. Olkiluoto 3 will be the first NPP in the world to fully apply risk-informed methods to develop pre-service inspection (RI-PSI) and in-service inspection (RI-ISI) programs for piping.

In Finland PSA is used in several ways when evaluating Technical Specifications. When licensee applies for an exception from Techical Specification requirement, licensee submits a risk analysis together with the exception application to indicate that the risk from the exemption is insignificant. Risk analysis will be reviewed in STUK. PSA is used to evaluate the changes in the Technical Specifications in conjunction to significant plant changes or if new previously unidentified risk factors are found. In addition PSA is used to evaluate situations where plant shutdown may cause a higher risk than continuing power operation and repairing the failures taking into account the times spent in different plant configurations. PSA is also used to optimize and evaluate the test intervals and procedures of components and systems which contain major risk reduction potential.

Safety classification of systems, structures and components (SSC) has to be evaluated with the PSA and the probabilistic review of the safety classification has to be submitted to STUK together with the safety classification document. In addition to SSCs the licensee has to use PSA in the design phase to show that the plant design and the design requirements are acceptable.

Licensees use PSA in the development of the disturbance and emergency operating procedures to ensure that they cover all relevant situations. PSA results are taken into account when licensees plan the training of their personnel, for example in the training of the control room crew, the most important accident sequences have to be trained periodically.

PSA is used in the area of operational events and risk follow-up as a standard tool to evaluate the safety significance of failures and incidents. STUK started systematic annual risk follow-up for the operating Finnish NPPs in 1995.

STUK is currently developing risk informed tools in grading regulatory activities based on their safety significance[5]. Activities included are such as the planning of the inspection programs and regular document and application review and approval process.

V. STRESS TESTS AND IMPROVEMENTS AFTER FUKUSHIMA ACCIDENT

After the Fukushima accident STUK participated in two parallel safety assessment processes. A few days after the accident the Finnish Ministry of Employment and the Economy requested STUK to prepare a report on how the Finnish NPPs have prepared for exceptional external events and loss of electric power. The report was to cover the nuclear power plants currently in use, the plant currently under construction and the nuclear power plant units that have been granted decisions-in-principle. The European Commission initiated comprehensive assessments, so called stress tests[8], for all NPPs in the European Union. The member states submitted their reports[9] by the end of 2011 and an international peer review was arranged in early 2012.

When the operating NPPs were built, there were no requirements for seismic design in the Finnish regulations, as seismic activity in Finland is very low. Extreme weather was considered in design mainly according to the general building code. Although the stress tests were based on deterministic principles, in Finland the capabilities of the operating units to resist earthquakes and other exceptional external events have been analyzed in the PSA framework. Therefore PSAs were important sources of information in the stress tests. For Olkiluoto 3 seismic events and other external events were included already in the design basis.

Based on the studies carried out after Fukushima accident no new threats or shortcomings that would require immediate action were found. One of the reasons for this is that significant reductions in the risks due to seismic effects and harsh weather conditions have been achieved with a number of realized plant modifications, e.g. protection against algae or frazil ice causing blockage of the seawater intake, blockage of diesel generator combustion air intakes by snow, improvement of ventilation cooling systems for instrumentation rooms, and strengthening the anchorages of electric and electronics equipment. Although immediate actions were not needed, areas where nuclear safety can further be enhanced were identified and action plans how to address these areas in the Finnish NPPs, national legislation and regulation were created. The realization of this national action plan is followed and reported[10]. Below a selected list of improvements completed or planned on the NPPs is presented:

- In Olkiluoto 1 the recycling line of the auxiliary feedwater pumps has been replaced by a line to the water tank so that possible excessive heating of the water is avoided. The previous configuration was vulnerable for loss of seawater cooling. Same modification will be carried out in Olkiluoto 2.
- In Olkiluoto NPP the emergency diesel generators will be renewed during the coming years. New diesels have diverse cooling options, they can be cooled with seawater or air.
- In Olkiluoto 1 and 2 an independent way of pumping water to the reactor pressure vessel in case of loss of AC power is under design by the licensee. The arrangement will consist of two systems, high and low pressure systems. The low pressure system will supply water to the core from the fire water system with additional diesel driven pumps through the reactor spray system. The high pressure system (Auxiliary Coolant Injection System, ACIS) is planned to consist of steam driven turbine pump, which will supply water from the demineralized water tank to the core.
- In Loviisa NPP a modification to create alternative ultimate heat sink has been built. The modification consists of two air-cooled cooling units per plant unit. One of the cooling units removes decay heat from the reactor and the other one ensures the decay heat removal from the spent fuel pools inside and outside of the containment. The modifications will create a possibility to residual heat removal in case of sea water systems are not available.
- In Loviisa NPP flood protection has been improved with two modifications. The design water level was increased from +2.1 m first to +2.45 m and later to +2.95 m during certain annual outage states with open man holes in the condenser cooling seawater system (height of the protective dam structures in the cooling water outlet channels will be increased). Flood protection level of the diesel driven auxiliary emergency feedwater pump station has been increased from +3 m to +4.11 m. According to the latest estimations, in Loviisa the frequency for daily sea level maximum to exceed the +4,11 m level is less than 5×10^{-7}/ year and that frequency is less than $1/1000^{th}$ of the frequency to exceed the sea level of +3 m.

VI. CONCLUSIONS

Operating NPPs in Finland have full scope detailed and up to date PSA models. According to the Finnish experience, detailed and up to date PSA is a useful tool in the safety management and regulatory control on nuclear power plants. In Finland PSA has been used to identify and prioritize possible safety improvements and to evaluate the adequacy of the design basis. PSA has also been used in support of licensing of new units and periodic safety reviews of operating units.

In Finland risk-informed applications are integrated in the regulatory process of NPPs from the early design phase up to early phases of decommissioning. The required applications include risk-informed in-service inspection (RI-ISI), risk-informed technical specifications (RI-TechSpecs), risk-informed in-service testing (RI-IST) and safety classification of systems, structures and components (RI-SC).

STUK is currently developing and implementing risk informed tools in grading regulatory activities based on their safety significance. Activities included are such as the planning of the inspection programs and regular document and application review and approval process.

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Based on the stress tests completed after Fukushima accident, several plant improvements have been completed or are in progress for Finnish NPPs. Improvements will enhance the capability of Finnish NPPs to cope with the loss of ultimate heat sink or the loss of external electric grid.

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