NDE Research of Nuclear Power Plant Primary Circuit Components and Concrete Infrastructure in Finland

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Abstract. A profound understanding of the reliability of non-destructive examination methods is needed for safe operation of nuclear power plants. In Finland, a national Research Programme on Nuclear Power Plant Safety SAFIR2018 is sustaining research in several fields focusing on the safety of nuclear energy production. In SAFIR2018 research programme the project NDE of nuclear power plant primary circuit components and concrete infrastructure (WANDA) is focusing on the development and understanding of NDE methods.

In the WANDA project, the continuous development of the NDE methods for nuclear power plants in-service inspections is the main objective. The project has several focuses, of which the main are to analyse the differences in artificial defects and further verify the reliability of NDE simulations, to improve the eddy current inspection technique to map the existence of the magnetite piles in steam generators and to assess the existing and new NDT techniques and monitoring systems for concrete examination and improve the nuclear power plants in-service inspections techniques for concrete infrastructure.

1. Introduction

A profound understanding of the reliability of non-destructive examination (NDE) methods is needed for safe operation of nuclear power plants (NPP). A project concentrating on developing the methods and techniques for NPP in-service inspections (ISI) is introduced in this article. The project, named NDE on NPP primary circuit components and concrete infrastructure (WANDA), is funded by the Finnish National Research programme on Nuclear Power Plant Safety SAFIR2018 [1-2].

WANDA consists of two independent work packages. Work package 1 (WP1) addresses NDE on NPP materials of primary circuit components. WP1 concentrates on the non-destructive testing (NDT) of artificial defects of primary circuit components, simulation, probability of detection (POD) and the measurement of magnetite in steam generator with eddy current techniques. Work package 2 (WP2), focuses on the NDE of NPP concrete infrastructure, consists of the evaluation and calibration of the available NDT methods and monitoring systems for concrete structures, and provide guidelines for the implementation of performance based design and condition assessment of concrete structures. This includes the design and construction of a full-size reinforced concrete wall mock-up for NDE testing method development and education purposes.

Both WP’s are strongly linked by the common factor which is NDE based research, where in fact many methods and technology are similar but differing on application and
data interpretation. For this reason the sharing of competence is in vital importance to push the known boundaries of NDE knowledge and competences.

The main motivation of the WANDA project is to maintain the level of expertise of Finnish NDE research of the NPP component materials and to raise that of NDE research on concrete infrastructure.

2. Background

The NPP design life has typically been based on 40-year service life. That lifetime for working Finnish NPPs will soon to be full. The renewal of an operating licence requires that NPP demonstrates their facilities are ageing under controlled conditions and they have in place ageing management programs. This is where in-service inspection (ISI) programs play an important role in demonstrating sufficient structural integrity of materials and components and guarantee the structural safety to continue NPP operation in a reliable and safe manner. ISI has an important role in identifying adverse environmental loadings or ageing factor effects before they potentially deteriorate structures compromising the safety of NPP.

2.1 Primary circuit components

The ISI for primary circuit components is mostly performed in a short time period with limited accessibility. NDE techniques are the main tools to inspect the structural integrity of the primary circuit components in the NPP. The development of the NDE techniques towards more reliable and efficient ISI promotes the safety of NPP.

Artificial defects are typically used as a reference when the performance of an NDT procedure is demonstrated. Because of the lack of real defects, artificial defects are needed for certification and training of the inspectors. The Finnish NPP safety regulator guides (YVL E.5) [3] emphasise that the description of defect indications exceeding the recording level shall be given in the inspection report. Also some rules on the applicable defect types are imposed and it is thus important to verify the applicability of different available defects.

According to the previously performed studies in SAFIR on artificial defects [4] the ultrasonic response varies with the type of the defect and with the technique used. To be able to evaluate the severity of the detected defects, it is highly important to know the exact type of the artificial defects in the reference samples and their correspondence to the actual defects. The use of artificial defect can lead to an error, if the limitations of the artificial defect used for the NDE procedure design or qualification compared to ISI -defects (e.g. stress corrosion crack) is not known. For example, signal-to-noise ratio between same size defects can vary a lot depending on the defect type, the shape and morphology of a crack affects the detectability of the defect when skew angle is introduced to the flaw, anisotropic austenitic material affects to the propagation of ultrasonic waves that raises the noise level and the high noise level reduces the defect detection and sizing capability, limited accessibility and complex geometries limit the inspection coverage. Also ultrasonic examination (UT) data analysis requires experience and knowledge of various kinds of indications.

The performance and reliability of NDE in nuclear industry is significant. Resources are used to confirm sufficient performance through extensive qualification procedures required nowadays around the world. The used qualification procedures have been very successful in confirming highly reliable NDE. However, in recent years, there has been increasing need to better quantify the expected performance and, in particular, to obtain quantitative data on POD for the used inspections. This information is needed, for example, to better facilitate risk-informed in-service inspection.
One of the NDE development targets are steam generators (SG). Especially detecting the corrosion product, magnetite, in the secondary circuit. Corrosion products in SGs have caused serious tubing degradation in the past. Deposit induced corrosion problems still remain a serious issue regarding nuclear safety. Deposits can be removed during outages by mechanical means such as sludge lancing or by chemical dissolution treatments. In order to determine the extent and nature of deposit formation more precise NDE techniques need to be developed. Eddy current (ET) method has been proved promising as a detection method, and needs more development to become a quantitative and reliable tool. The basis for such detection has been laid down in WANDA –project.

2.2 Concrete infrastructure

The safety significance of NPPs reinforced concrete structures (RCS), especially the containment, combined with the current trend towards life extension and the demand of the regulatory authorities for even higher levels of safety assurance, emphasises the importance of effectively controlling ageing degradation [5]. The inspection of NPPs concrete structures present challenges different from those of conventional civil engineering structures. As a result, there is a need for NDE of reinforced concrete structures to be able to undertake compliance testing, collection of specific data or parameters, condition assessments, and damage assessment.

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

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

The application of NDT methods to NPP RCS has several challenges: infrastructure wall thicknesses (typically >1.0 m), dense and complex reinforcement detailing, penetrations or cast-in-place items, limited accessibility (i.e. liners or other components), severe environments, inaccessible structures, limited experience with NDE methods for NPP and lack of specific equipment or knowledge for NDE of NPP RCS [6].

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

There is still a clear need for NDE methodologies to continue to evolve [7]. Research has shown the need for realistic specimens should be developed to allow direct comparisons between various techniques, with consideration given to ensuring a broad range of defects, and to ensure the probability of detection for a method can be properly determined.
3. Objectives

In the WANDA project, the continuous development of the NDE methods for ISI will continue addressing the expressed needs of the NPPs. One of the main focuses of the WANDA project is to maintain the expertise level of Finnish NDE research of the NPP component materials and to raise that of NDE of concrete infrastructure.

Additional objectives for WP1 are to analyse the differences in artificial defects and further verify the reliability of NDE simulations and to critically assess the NDT techniques and monitoring systems currently in use to fulfil the needs of NPP infrastructure evaluation in Finland. With regards to WP2, long term project goals are to develop guidelines for the use of NDE techniques in design and condition assessment, study the potential of coupling NDE and monitoring systems and define guideline-framework for the performance-based design and control of concrete durability of NPP RCS.

One important factor for the future is the transfer of know-how in the area of NDE to a younger generation of scientists. The WANDA project is an important channel of knowledge transfer to the younger generation in the field of NDE in Finland. Thus the project supports the education of new high-level experts for nuclear area and helps to link these young scientists to international co-operation.

4. Project plan and results

The project of NDE of NPP primary circuit components and concrete infrastructure is divided into two work packages, NDE of the primary circuit components and materials and concrete infrastructure NDE [8].

![Figure 1. The Structure of the WANDA project.](image)

4.1 NDE on primary circuit components

Artificial defects are valuable tools when developing and enhancing the NDT methods to detect defects in NPP primary circuit components. Fatigue cracks can be produced artificially as thermal fatigue or mechanical fatigue cracks. Thermal fatigue crack production is very well controlled in matter of size and opening. Mechanical fatigue crack production is well known and widely used method.
One of the goals on the project is to test different sizes of artificial fatigue defects and to find the possible differences in reflector properties on indications. The artificial defects are examined with ultrasonic, radiography and eddy current methods. Tests are done e.g. of a tubular specimen with butt weld simulating PWR cooling line pipe. Ultrasonic techniques used are conventional UT and phased array ultrasonic (PAUT) techniques. Moreover, emerging ultrasonic techniques such as sampling phased array will be used to get a wider perspective to the differences of the similar defects of the different manufacturers. ET for the inside surface could answer the questions: What is the depth of a surface breaking crack that can be reliably measured with ET and how does the length of the defect effect on the crack depth measurements or what is the effect of different type of the crack on the depth sizing.

The sampling phased array (SPA) also known as full matrix capture (FMC) technique is not yet a qualified method for NPP use. SPA can improve the signal-to-noise ratio and reduce the possibility for mislocating the defect base and tip signals. Therefore this promising technique is studied further in WANDA –project.

NDE simulation in the project aims to produce a method for measurement of ISI reliability. Typically NDE reliability is measured by probability of detection -curves. However, to produce such a curve, tens or hundreds of measurement are needed. This amount of measurement cannot be achieved with actual measurements, so simulations are widely used. However, with simulations, there is a problem of verification. The simulation results will be compared to results produced in ultrasonic tests to verify the results. After this comparison, simulations could be then expanded to extend to tens or hundreds different scenarios with different location and size of flaws. This approach would allow the generation of POD-curves which have been verified with actual measurement data.

The risk-reduction attributed to NDE is highly dependent on the expected probability of detection achievable. The POD depends on the used method, personnel and other factors. However, quantitative and reliable evaluation of POD has remained challenging for the nuclear industry. Having quantitative, probabilistic information regarding the NDE methods would greatly help re-assessing NDE performance based on in-service experience and avoid the potential and costly recall of related NDE qualification.

The project also concentrates on possibilities to estimate the amount of magnetite in the NPP SGs in the secondary circuit. Magnetite in the SGs is detected with regular bobbin probe during ISI. One of the goals of the WANDA project will be the development of the ET to detect magnetite within secondary side of SG. The method to locate and size the piles of magnetite on the SG tubing is under development. The method requires very sensitive probes because the magnetite flakes composing piles are not engaged on the tube surface and the piles can be large.

4.2 NDE of NPP concrete infrastructure

The research in WP2 (NDE of NPP concrete infrastructure) is divided into four Tasks, as shown schematically in Figure 1, focusing on:

- Task 1. Non-destructive testing and evaluation methods and monitoring of concrete performance,
- Task 2. Design and construction of the mock-up of a full-size reinforced concrete wall,
- Task 3. Evaluation and calibration of NDT&E methods,

Task 1 has undertaken the preparation of three research reports summarizing the current use of NDE methods, sensors and monitoring systems for RCS, and a summary of NDE research on reinforced concrete with relevance to NPP.
The first research report, entitled NDE of thick-walled reinforced concrete structures – Selection matrix for non-destructive evaluation of NPP concrete structures [9], draws on previous studies to focus the advantages and disadvantages of different NDE methods for RCS. In the report, NDE methods currently in use are critically assess, and a selection matrix for NDE of NPP RCS is proposed. The selection matrix is proposed to address a need of NPP infrastructure evaluation in Finland. The ultimate goal of the NDE selection matrix is to identify and describe the effective use of NDE methods that can detect and characterize deterioration in NPP concrete structures especially considering the ageing phenomena affecting RCS.

The second research report, entitled NDE of thick-walled reinforced concrete structures – Technologies and systems for performance monitoring [10], assesses monitoring technologies and sensing techniques for RCS. The work focuses on identifying the potentials of different available techniques, equipment and/or procedures. The review includes a determination of existing monitoring methods and techniques as well as the identification of limitations and restraints of the technology readiness with respect to their application in thick-walled RCS, as commonly used for e.g. NPP containments. The technologies are shortly described by taking into account the history and background of sensor development, working principle, signal type, existing experiences with the technology as well as advantages and disadvantages of the use and operation of the sensor. In addition, data acquisition systems of automated multi-sensor monitoring systems are presented and evaluated.

The third research report, entitled NDE of thick-walled reinforced concrete structures – International research review [11], an overview of the research on NDE methods being used for NPP and similar type structures is provided. If focuses on the difficulties that have been encountered, and what has been achieved in the respective research projects. An overview of NPP concrete structures in Finland is given, including a brief section on testing and inspection requirements according to the YVL guidelines. This is followed by a compilation of information from other related research projects, and the lessons learnt relevant to the construction of a mock-up. The output from this report will contribute to an improved basis for the preparation of the mock-up design.

These three reports will provide the basis for defining the design criteria for the mock-up of a testing element (geometry, concrete characteristics, reinforcement, testing, monitoring, type and layout of sensors, location and size of defects, NDE methods, etc.).

Task 2 concentrates on the conceptual and detailed design of the mock-up specimen, and its construction. Considerations on the design criteria include the specimen geometry, reinforcement types and displacement, concrete material characteristics, inclusion of defects, location, accessibility, exposure conditions, etc. Considerations address the type of sensors and monitoring system to be included in the design, and also take into account the types of NDE methods to be used. Task 2 culminates with the construction of the specimen and the initiation of the NDE testing and monitoring period.

Task 3 is concerned with the evaluation and calibration of NDE methods. It addresses several aspects related to the NDE methods for the condition assessment of RCS. A testing program will defined which will cover calibration of test methods, correlation between test methods, effect of time dependency and testing conditions on test methods, accuracy of test methods, among other aspects yet to be defined. The focus will be on the available and new test methods, especially considering the difficulties associated with NPP RCS.

Task 4 is concerned with the evaluation and calibration of sensors and monitoring methods for performance assessment of RCS. A testing program will be defined that covers calibration and validation of sensors, correlation between different NDE methods and sensors, effect of time dependency and testing conditions on sensors results, resolution and
accuracy of sensors, among other aspects yet to be defined. The focus will be on the available and new sensors and monitoring systems.

An important aspect of the mock-up is to allow for continuous long term testing. The intention is for the specimen to be available for a long period of time (i.e. more than 20 years) which allows for different or new equipment to be assess in a well-documented situation, and to assess in real-time the effects of ageing of RCS. Furthermore, the mock-up will be available for users of NDE equipment to test and calibrate performance accordingly. The education of a new generation of engineers with NDE experience is another goal. The mock-up will allow for the training of young engineers in the use different NDE equipment and in the development of expertise with RCS similar to that of NPPs.

5. Conclusion

The Finnish national Research Programme on Nuclear Power Plant Safety SAFIR2018 is guiding research towards nuclear power plant safety. In the SAFIR2018 research programme, the project NDE of nuclear power plant primary circuit components and concrete infrastructure, WANDA, is focusing on the development and understanding of NDE methods, with special focus on reactor internals (Work Package 1) and more recently concrete infrastructure (Work Package 2).

The main motivation of the WANDA project is to maintain the level of expertise of Finnish NDE research of the NPP component materials and to raise that of NDE research on concrete infrastructure.

Both Work Packages are strongly linked by the common factor which is NDE based research, where in fact many methods and technology are similar but differing in application and analysis. For this reason the sharing of competence is in vital importance to push the known boundaries of NDE.

Specific results of this project are presented in the WCNDT2016 in three different articles [12-14]. And will be actively presented in the future.

6. References

[4] Koskinen, A. & Leskelä, E., Comparison of Artificial flaws in Austenitic Steel Welds with NDE Methods, 11th Int. Conf. on NDE in structural integrity for NPP components, 19th – 21st May, Jeju, Korea

