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"NDT MATRIX" - A TOOL FOR SELECTING NON-DESTRUCTIVE TESTING METHODS FOR NPP CONCRETE STRUCTURES

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ABSTRACT

As concrete structures in nuclear power plants (NPP) are exposed to various environmental conditions, concrete is affected by different deterioration processes during the life time of the power plant. To ensure the integrity and load bearing capacity of the concrete components, especially with regard to the extension of the life time of NPPs, the use of non-destructive testing (NDT) methods are essential for examining the quality of concrete and its reinforcement. However, current NDT techniques are faced with several challenges: (i) NDT inspection may primarily be performed only during the annual overhauls when testing is time-limited, (ii) the accuracy and reliability of NDT testing devices, (iii) uncertainty of the international uniformity of the methods used for NDT tests, and (iv) the creditability of results and analyses. An effective inspection of concrete components is only possible if the deterioration processes are identified and robust NDT testing techniques are available.

This paper describes the tool developed for selecting suitable NDT methods for NPP structures made of reinforced concrete based on the age and expected degradation mechanisms of the structures under concern. The paper also assesses critically the NDT techniques that fulfil the needs of the safety evaluation of NPPs in Finland and are currently available for testing of NPP concrete structures.

The tool comprises (i) the building materials used in structural components, (ii) ageing defects affecting NPP concrete structures, (iii) available NDT techniques and (iv) inspection schedule for concrete structures recommended for Finnish NPPs.

1 INTRODUCTION

Extending operation licences of NPP units generate new challenges for the condition assessment of concrete structures in NPPs as well as the actions required for guaranteeing problem-free operation of the plants. In Finland the operating licences of the NPP units have been originally granted or extended until the age of 50 or 60 years. Performance based evaluation of existing NPPs should be performed as a part of the renewal process of the operating licence. (Kainulainen, 2008). Periodic license renewals, which are typically made at intervals of 10 years, are the check points, where the inspection and assessment actions done during expiring license period are compiled for evaluating overall safety level.

The condition-based maintenance is a valid methodology to guarantee safety, reliability, and cos-effective use of the NPP. Condition monitoring can be continuous or periodic and it can be carried out by different on-line or off-line techniques. As NDT is one of the main alternatives for both detecting defects and monitoring material degradation, it has a fundamental role for the maintenance of NPPs and its effectiveness influences the maintenance performance (Davies, 2000)

Generally, inspection and assessment of existing NPP concrete structures is required for:

i) Identification of the degradation or abnormal performance,
ii) Supporting physical modifications,
iii) Periodical validation of structural integrity, and

iv) Comprehensive evaluation of the NPP concrete structures at periodic intervals is also desirable to observe operational effects and possible degradation due to environmental conditions.

As more advanced testing methods are developed, NDT procedures are being able to locate structural defects more accurately, and in a more efficient and timely manner. NDT techniques have become one of primary methods for operators to minimize plant downtime and promote enhanced performance of production assets (Harper, 2016).

This paper describes a NDT selection matrix and the procedural steps that can be performed to assist in selecting suitable NDT techniques via prioritized evaluation of the condition of NPP concrete structures (Al-Neshawy et. al 2016). The ultimate goal of the NDT selection matrix is to identify and describe the effective use of NDT technologies that can detect and characterize deterioration in NPP concrete structures.

This paper represents some of the research conducted within the R&D project “NDE on NPP primary circuit components and concrete infrastructure” (Jäppinen et. al. 2015), funded by the Finnish National Research programme on Nuclear Power Plant Safety SAFIR2018 (Hämäläinen and Suolanen, 2015).

2 PLANNING AND REQUIREMENT ANALYSIS OF THE NDT SELECTION MATRIX

The selection matrix, shown in Figure 1, includes representations of the building materials used, the defects or deterioration affecting NPP concrete structures, and the inspection schedule for concrete structures.

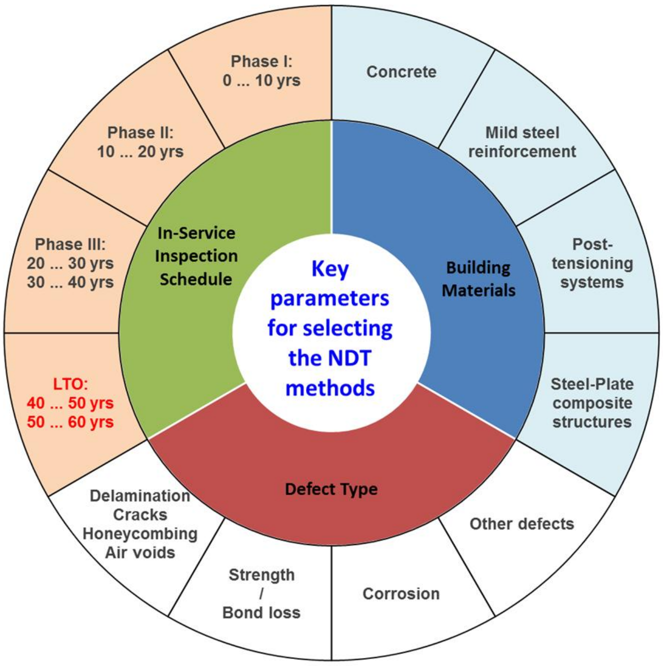

Figure 1. A schematic description of the NDT selection matrix, (*LTO = Long-Term Operation*).

2.1 Data of Building materials

Reinforced concrete structures in NPPs are composed of several components that perform multiple functions (e.g., load-carrying, radiation shielding, and leak tightness). Primarily, these components can include different types of concrete structures: plain concrete, concrete with conventional steel reinforcement, concrete prestressed by tensioned steel reinforcement, and concrete covered by steel liner plate.

Reinforced concrete has a significant role for the NPP reactor unit both as a material used for load-bearing systems and a material offering protection against radiation. Thus concrete structures are often maintaining and guaranteeing nuclear safety.

Post-tensioning is a method of reinforcing (or strengthening) concrete with high-strength steel wire, strands, or bars tendons in which The tendons are installed, tensioned, and anchored after hardening of the concrete. The post-tensioning system resists tensile stresses partly by applying compressive forces to the concrete to provide increased resistance against concrete cracking. The post-tensioned system is generally utilized with conventional steel reinforcement which can be called passive reinforcement, whereas tensioned tendons are considered active.

Typical post tensioned concrete structures at NPPs include containment structures which are post-tensioned both in the horizontal and vertical direction as shown in Figure 2. The vertical tendons can also be straight as in Fig 2 but the horizontal tendons are often more or less curved, in some cases with a total accumulated curving angle of even more than 360°. The major structural components of the post-tensioned containment building are a base slab, perimeter wall, ring beam, and upper dome. All the components listed are to ensure leak-tightness (Anderson, 2005).

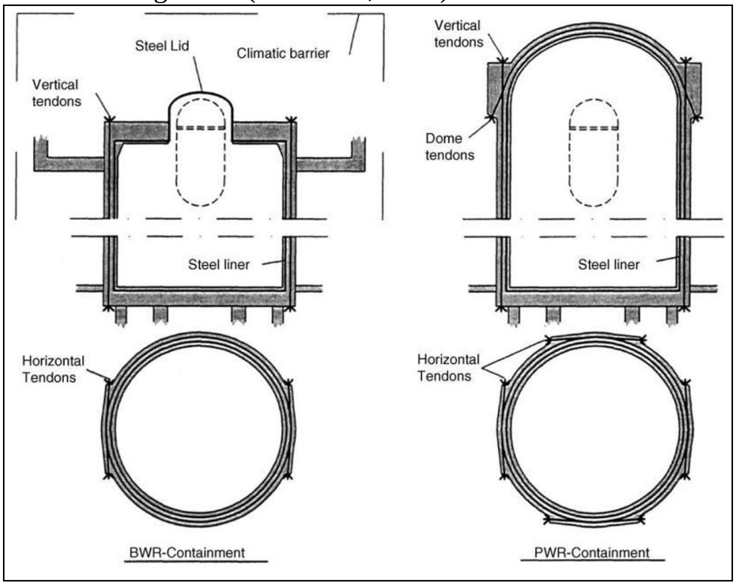

Figure 2. Example of post-tensioned containment structures (Anderson, 2005).

Steel-concrete composite structures are a potential alternative to reinforced concrete for protective structures. Steel plates on the exterior surfaces to eliminate formwork and serve as equivalent reinforcement when shear connectors are used, shown in Figure 3. (Malushte et al., 2015)

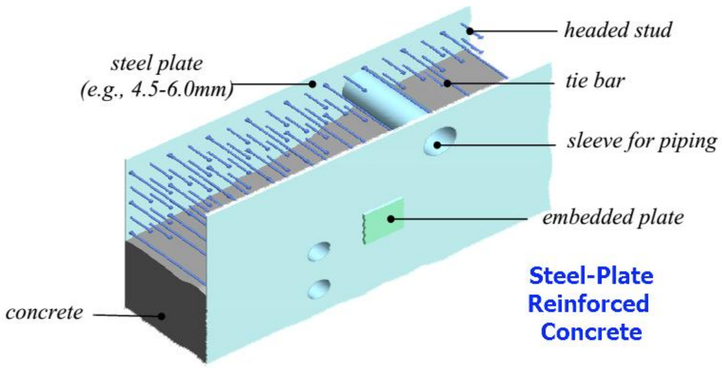

Figure 3. Illustration of steel-concrete composite wall (Schlaseman, 2004).

The structural information of the NPP concrete structures is divided into structural parts for the development of the NDT selection matrix. The purpose for identifying structural parts is to divide concrete structures into homogenous areas for analysis and to provide suitable NDT methods for each area.

The principle is that structural parts belonging to the same structure can be inspected and analysed without being divided into smaller parts. For instance, several columns, beams, slabs or walls can be treated as parts of the same module if they are materially and structurally similar and surrounded by same environmental conditions. On the other hand, a column or a wall that is exposed to different environmental conditions, e.g. water and air, cannot be treated as a single structural part and should be divided into two parts accordingly. An example of the classification of structural data and the used building materials is shown in Table 1.

Table 1. Examples of NPP concrete structures and their building materials.

Structure name	**Structural part**	**Building Materials**		
		Reinforced concrete	**Post-tensioned system**	**Steel-concrete composite structures**
Auxiliary cooling system channels	Structures under water level	●		
Concrete structures inside steel containment	Structures inside containment, crane wall	●		
	Internal cylinder of the reactor hole	●		
	Pool structures	●		
Containment	Foundation	●		
	Inner cylinder wall	●		
	Pre-stressed outer cylinder		●	
	Pre-stressed pool structures		●	
	Roof, under the steel liner			●
Cooling water intake plant	Basket filter area	●		
	Fine grating area	●		
	Sea water pump area	●		
Intake chamber	Structures under water level	●		
Outer shell	Cylinder (concrete) wall covered by corrugated steel sheet			●
	Structures under water level	●		
Pump sumps	Pump sumps structures	●		
Structures exposed to sea water	Channels, Inlet chambers of pumps	●		
	Foundation of the containment	●		
	Main level floor slab	●		
	Pump rooms, dry area	●		

2.2 Defects of NPP concrete structures

The exposure to the environment (e.g., temperature, moisture, cyclic loadings, etc.) can produce degradation of reinforced concrete structures. The rate of deterioration may by connected to structural design, selection of building materials, quality of construction, curing, and aggressiveness of environmental exposure, structural loads. Primary mechanisms that under unfavourable environmental conditions can produce premature deterioration of reinforced concrete structures include those that impact either on the concrete or steel reinforcing including tendons. Table 2 summarizes primary mechanisms for premature deterioration of reinforced and post-tensioned concrete structures.

Table 2. Degradation of the NPP concrete structures (IAEA, 2016).

Material System	Source of degradation	Primary defects												
		Corrosion	Cracking	Spalling	Scaling	Volume change/ Section loss	Disintegration/ material loss	Volume change	Bond loss	Strength loss	Ductility loss	Misalignment	Increased porosity	Leaching
Concrete	Physical processes													
	Salt crystallization		●				●							
	Freezing and thawing		●		●		●							
	Abrasion/erosion/cavitation					●								
	Thermal cycling		●	●						●				
	Irradiation		●					●						
	Fatigue/vibration		●											
	Settlement		●	●								●		
	Chemical processes													
	Efflorescence/leaching												●	
	Sulfate attack		●					●						
	Delayed ettringite formation		●					●						
	Acids/bases			●			●							●
	Alkali-aggregate reactions		●				●							
	Aggressive water						●							
	Biological attack					●							●	
Mild steel reinforcement	Corrosion	●	●	●		●								
	Elevated temperature									●				
	Irradiation										●			
	Fatigue								●					
Post-tensioning system	Corrosion	●								●	●			
	Elevated temperature									●				
	Irradiation										●			
	Fatigue		●											
	Stress relaxation/end effects									●				
Liner/structural steel	Corrosion	●				●								
	Elevated temperature									●				
	Irradiation										●			
	Fatigue		●											

2.3 Role of NDT methods for life-time management of concrete structures

Figure 4 represent the interconnections among concrete deterioration, structural functionality and service life of the NPP. Based on the figure the selection of NDT methods can be divided into the following categories:

1) **First phase NDT methods: (during construction and immediately afterwards)** The NDT methods are selected to monitor the actual conditions both regarding execution details such as homogeneity and quality, which over time may ensure that the structure fulfils its required function and design life. Examples of the first phase NDT methods are the detection of honeycombs, measuring the carbonation depth, the chloride content, concrete cover, and concrete quality measurements.
2) **Second phase NDT methods**: NDT methods for the structural conditions during the operation phase. Visual inspections only reveal what is visible at the surface, while NDT methods can

inspect the condition of concrete structures as such and give information about hidden detrimental features as cavities and air voids. The NDT methods during the initiation phase of deterioration are used to examine the concrete cover around reinforcement where the deterioration is connected to the surrounding environment.

3) **Third phase NDT methods**: NDT methods during the propagation phase (de-passivation to the spalling phase), which can assess the concrete structures cracking, delamination, corrosion and reinforcement placing.

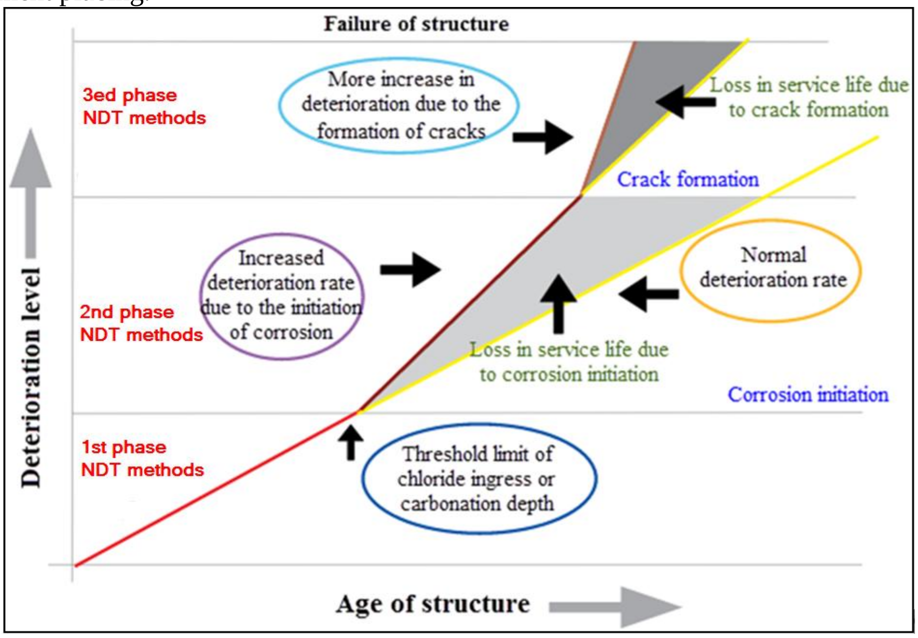

Figure 4. Phase of deterioration and structural aging (based on Verma et. al., 2013).

2.4 NDT testing techniques

NDT techniques for evaluating the structural integrity of concrete have been used in other civil engineering cases, such as testing of roads and bridges. However, in recent years, these methods have also become more common in nuclear industry. Wiggenhauser (2013) issued a report about non-destructive testing and examined techniques that could be used on concrete structures in nuclear power plants. The report broke down the various situations in which non-destructive testing could be used for:

- Locating tendon ducts and determining the condition of the grout materials.
- Detecting cracking, voids, delamination and honeycombing in concrete structures
- Detecting inclusions of different materials or voids adjacent to the concrete side of the containment liner
- Locating steel reinforcement in concrete and determining its cover depth
- Identifying corrosion on the surface of the containment liner against concrete

In Table 3 a summary of potential damage types and suitable non-destructive testing techniques for assessing them is given. In terms of reliability and usefulness the evaluation of methods is based on practical experience in specific situations and it is not intended that these evaluations are universally applicable to the given techniques

Table 3. Non-destructive Testing of Concrete structures (Show, 1997).

NDT method	Abbr.	Material	Application	Reliability	Usefulness
Acoustic Emission	AE	Concrete	Continuous monitoring of structure during service life	unknown	unknown
Concrete Cover Meter Testing	COV	Steel	Location of reinforcement / Size of reinforcement	Fair	Poor
Electrical Resistivity	ER	Steel / Concrete	Concrete resistivity (related to corrosion rate)	unknown	Good
Galvanostatic Pulse Method	GPM	Steel	Detection of actively corroding reinforcement (electrochemical)	Good	Good
Ground penetrating radar	GPR	Steel	Location and size of reinforcement / Location of pre-stressed cable ducts	Fair	Fair
Half-cell electrical potential method	HCP	Steel	Detection of actively corroding reinforcement (electrochemical)	Good or Fair	Good
Impact Echo	IE	Concrete	Cracking internally / Thickness of concrete member or layer	Good	Good
Impulse Response	IR	Concrete	Delamination and honeycombs / Voids in concrete and homogeneity	Fair	Poor
Infrared Thermography	IRT	Concrete	Delamination and honeycombs	unknown	unknown
Linear Polarization Resistance	LPR	Steel	Estimation of reinforcement corrosion rate (electrochemical)	Fair	Fair
MIRA - Ultrasonic Pulse Echo Imaging	MIRA	Concrete	Voids in concrete and homogeneity / Delamination and honeycombs / Detection of voids in pre-stressed cable ducts	unknown	unknown
Radiographic testing	RAD	Steel	Location and size of reinforcement / Grouting condition in the post-tensioning ducts	Fair	Fair
Schmidt Rebound Hammer	SRH	Concrete	Damaged concrete layers (reduced strength and elastic properties)	Fair	Fair
Spectral Analysis of Surface Waves	SASW	Concrete	Reduced strength and elastic properties / Thickness of concrete member or layer	Good	Good
Ultrasonic Pulse Echo	UPE	Steel	Detection of voids in pre-stressed cable ducts	Fair	Fair or Poor
		Concrete	Cracking in surface and internally	Good or Fair	Fair
Ultrasonic Pulse Velocity	UPV	Concrete	Cracking / reduced strength	Fair	Fair

3 SELECTION PROCEDURE OF THE NDT METHODS

Generally, NDT techniques are classified into four levels according to their damage detection, data analysis and test results:

Level 1 that only identifies if damage has occurred.
Level 2 that identify the occurrence of damage and its location.
Level 3 that identify the occurrence of damage, its location and also estimate its severity.
Level 4 that identify the occurrence of damage, estimate its severity, and evaluate its impact on structures.

A procedure for selecting suitable NDT methods to investigate reinforced concrete structures can be described as follows:

1. Select a structure, structural part and building material using Table 1.
2. Select expected defect and degradation mechanism using Table 2.
3. Select suitable NDT method(s) based on Table 3.

Structure	Structural part	Building Materials	Expected defects 0 - 10 years	Expected defects 10 - 20 years	Expected defects 20 - 30 years	Expected defects 30 - 50 years	Suitable NDT methods 0 - 10 years	Suitable NDT methods 10 - 20 years	Suitable NDT methods 20 - 30 years	Suitable NDT methods 30 - 50 years
Containment	Foundation	Concrete Material Systems	Air Voids	External cracks	Delamination	Reduced strength	UPV, UPE, SASW, IE, GPR	UPV, UPE, SASW	UPV, UPE, SASW, IE	SRH, UPV, SASW, GPR
			Layer Thickness	Internal cracks			COV	UPV, UPE, SASW, IE		
	Inner cylinder wall		Honeycombs	Carbonation depth			UPV, UPE, SASW, IE, GPR	CARB	CARB	
				Reduced strength				SRH, UPV, SASW, GPR		
	Foundation	Mild Steel Reinforcing Systems	Bar location	Estimation of reinforcement corrosion rate	Corrosion		COV	HCP, ER, LPR, GPM, RAD	HCP, GPM, GPR	
	Inner cylinder wall		Bar size	Concrete resistivity			COV	ER		
			Concrete Cover depth				COV			
	Pre-stressed outer cylinder	Post-Tensioning Systems	Location of pre-stressed cable ducts	Estimation of reinforcement corrosion rate	Corrosion		MIRA, RAD	HCP, ER, LPR, GPM, RAD	HCP, GPM, GPR	
	Pre-stressed pool structures			Concrete resistivity				ER		
	Roof, under the steel liner	Steel-concrete composite	Honeycombs	Reduced strength	Corrosion		MIRA, RAD	SRH, UPV, SASW, GPR	HCP, GPM, GPR	

Figure 5. Example of the NDT methods' selection for a NPP containment structure (abbreviations of the NDT methods' names are shown in Table 3).

The literature survey and the NDT selection approach described provide basis for the research and actions within the WANDA project. A testing program including a full-scale thick concrete wall (Figure 6) covering the building materials discussed in this paper is set up. Common defects occurring during the construction process will be created to the wall, and the wall will also be subjected to a time-depended cumulative degradation of the concrete. The representative defects are honeycombing, air filled voids, water filled voids, cracks and delamination of concrete, and corrosion of the reinforcement steel. The testing procedure of the wall is planned for calibrating NDT methods, investigating correlation between the results received by different methods, studying the effect of time dependency and testing conditions on the results and their relative accuracy. The purpose of this full-scale concrete wall is to provide conditions for continuous long-term testing (longer than 10/20 year) which makes it possible to assess the reliability of different tools and methods in a well-documented situation (Jäppinen et. al., 2015).

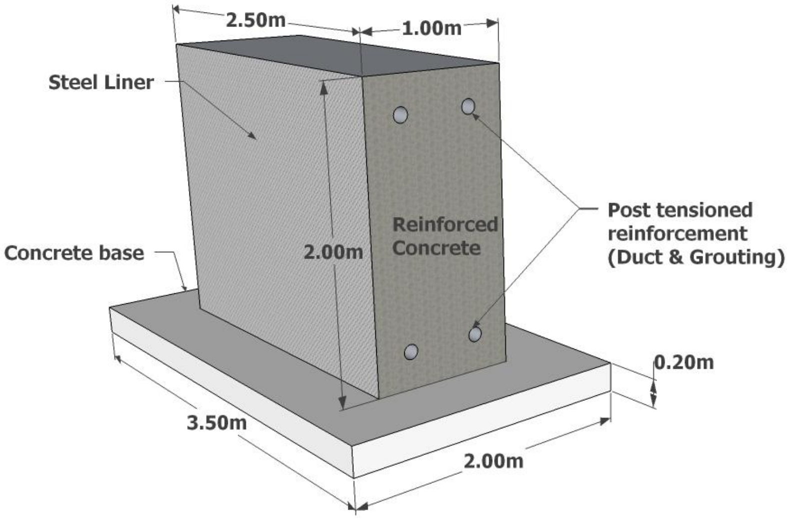

Figure 6. Schematic overview of the thick reinforced concrete wall.

4 CONCLUSION

This paper describes a systematic approach for selecting an appropriate NDT method, which makes it possible to choose the method effectively by a prioritized and condition-based evaluation of NPP concrete structures. The objective of the NDT selection matrix developed is to identify suitable case-specific NDT technologies for detecting and characterizing deterioration in NPP reinforced concrete structures and guarantee that these techniques will be utilized. The NDT selection criteria considers the building materials used, possible defects affecting NPP reinforced concrete structures, and inspection schedule defined for reinforced concrete structures in NPPs.

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