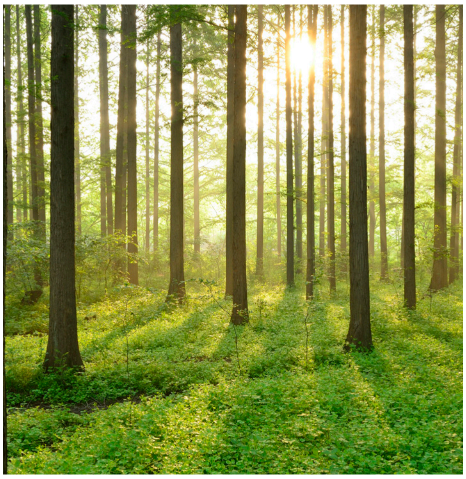
NON-DESTRUCTIVE TESTING OF CONCRETE STRUCTURES IN NUCLEAR APPLICATIONS

REPORT 2016:245



CONCRETE PROGRAMME
NUCLEAR

Energiforsk

Non-destructive testing of concrete structures in nuclear applications

Evaluation and follow up on the CONMOD project, Part I

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FORCE TECHNOLOGY

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Foreword

Non-destructive testing methods are vital to verify the integrity of the containment of a nuclear power plant. The design of the Nordic nuclear power plants with a thick concrete structure with the liner cast in concrete poses a great challenge for non-destructive testing (NDT) methods.

Several NDT methods were tested in nuclear applications in the EU-project CONMOD (2002-2005). I this project a review of the studied NDT methods has been performed to investigate how the methods have been developed since 2005.

The project is part of the Energiforsk Nuclear Concrete research programme, with the aim to initiate research and development that will contribute to a safe and cost effective long term operation of Swedish and Finnish nuclear power plants. The programme is financed by Vattenfall, Fortum, Karlstads Energi, Skellefteå Kraft, The Swedish Radiation Safety Authority (SSM), Teollisuuden Voima Oy (TVO) and Uniper.

Sammanfattning

Föreliggande rapport är en utvärdering av de delar av projektet CONMOD som behandlade oförstörande provningsmetoder (OFP) av betongkonstruktioner i Barsebäcksverket. CONMOD-projektet avslutades 2005. Rapporten är indelad i följande tre delar:

- En sammanfattning av de OFP-metoder som undersöktes i CONMOD,
- En sammanfattning som visar på framtida potential hos de undersökta OFP-metoderna,
- Utvecklingen som skett av de undersökta OFP-metoderna sedan projektet avslutades.

I sammanfattningen av de OFP-metoder som ingick i CONMOD beskrivs översiktligt hur testerna genomfördes, vilka OFP-metoder som användes samt resultaten från dessa. En översikt ges även över samtliga positioner i inneslutningen där OFP-metoderna applicerades. All mätdata från projektet finns tillgänglig, men av utrymmesskäl inkluderas dessa inte i föreliggande rapport.

Slutsatserna från CONMOD-projektet avseende OFP-metoder presenteras i sammanfattningen av framtida potentialer för de undersökta OFP-metoderna. En av slutsatserna från slutfasen av CONMOD-projektet var att de tre OFP-metoderna som gav mest tillförlitlig information om inneslutningen var ytvågsseismik (MASW multichanne lanalysis of surface waves), georadar (GPR, ground penetrating radar) samt högenerigröntgen (HECR, high energy computed radiography). Vidare påpekades det i resultaten från CONMOD att om försöken i Barsebäck skulle utföras igen skulle endast dessa tre metoder användas.

I den sista delen som behandlar utvecklingen av de undersökta OFP-metoderna har fokus varit på utveckling med applicering på tjocka betongkonstruktioner, t.ex. reaktorinneslutningar. Utvecklingen som skett inom georadar, högenergiröntgen, ytvågsseismik samt ultraljudsmetoder och då främst mätning med reflekterande akustiska vågor s.k. UPE (ultrasonic pulse echo) beskrivs i denna del av rapporten. Sammanställningen visar att georadar och UPE är de metoder som utvecklats mest vilket har medfört att tolkningen av mätresultaten har förbättrats sedan CONMOD-projektet genomfördes. För ytvågsseismik genomförs fortfarande mycket forskning och för närvarande finns inget färdigt system för undersökning av betongkonstruktioner på marknaden. Utvecklingen inom högenergiröntgen har gått framåt inom flera områden, dock kunde ingen information hittas om hur metoden utvecklats för användning på betongkonstruktioner.

Summary

The report is an evaluation follow-up on the CONMOD project that was finalised in 2005. The report only focuses on the non-destructive tests (NDT) performed during the project. The report is divided into 3 main chapters:

- A summary of the NDT methods used during the CONMOD project.
- A summary of the predicted potential of the used NDT methods.
- Developments in the used NDT methods.

In the summary of the NDT methods, used during the CONMOD project the various tests and results made with each NDT method are briefly described. Further the positions of all test locations used during the CONMOD project are provided, together with an overview of tests made with each NDT method in each position. Data results from each of these tests are still accessible, but not included in this report as it would be too comprehensive.

In the summary of the predicted potential of the NDT methods used during the CONMOD project, the conclusions made during the project are highlighted. One conclusion at the end of the project was that if the measurements should be repeated at Barsebäck unit 1, only ground penetrating radar (GPR), high energy computed radiography (HECR) and multichannel analysis of surface waves (MASW) would be chosen for the task. Or expressed in another way, GPR, HECR and MASW provided the most conclusive information about the structure.

In the chapter about the developments of the NDT methods used during the project, focus has been on development which is applicable to thick wall concrete structures such as nuclear power plant containment structures. The development has been described for GPR, HECR, seismic methods with focus on MASW and ultrasonic methods with focus on ultrasonic pulse echo (UPE). It is clear for this chapter that GPR and UPE have developed so that interpretation of the results has been clarified. MASW at concrete structures is still being researched and is not commercially available. HECR has developed, but there is lack of information about the use of these developments in thick walled concrete structures.

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1 Background

The CONMOD project was a joint European demonstrator project under the European 5th Framework Project. Participating in the project was FORCE Technology, Scanscot Technology, EDF and Barsebäck.

The aim of the project was to combine advanced finite element analysis and the latest non-destructive examination techniques in order to establish the actual condition and status of a NPP reinforced concrete containment structure, in its present condition and also in relation to its future behaviour/condition under various loading conditions including the effects of ageing. The subject of this work was been the nuclear power containment of Barsebäck 1 and the EDF MAEVA containment mock-up.

Parallel to the CONMOD project, a material testing programme was initiated mainly at the Barsebäck 1 containment, but to a minor extent also at unit 2. Even though the material programme was not a part of the CONMOD project and not funded from the European 5th Framework Project, it is usually referred to as an extension of the CONMOD project.

The main conclusion of the CONMOD project was that a new approach combining non-destructive examination with finite element analyses methods is both workable and necessary in order to be able to accurately determine and predict the condition of nuclear power containment structures.

With respect to ageing management CONMOD further demonstrated that other factors such as defects and unknown detailing introduced during construction may be at least, and often much, more critical than ”classic ageing” mechanisms.

During the CONMOD project several NDT techniques were used to examine various positions of the containment wall at reactor B1, at Barsebäck nuclear power plant. When the material testing program was initiated, some of the locations used for NDT were also used for material sampling.

In the reports from the CONMOD project the information about performed non-destructive testing are provided in brief. In some cases some of the results are given in the appendices, but in most cases the examinations are only referred to.

In order to be able to use the results from the CONMOD project in further projects for deeper analysis or comparison, more detailed information as to the performed non-destructive test and the precise coordinates of the performed examinations are required.

2 Purpose of present report

As mentioned above, the reports from the CONMOD project are not very detailed about the performed non-destructive test, and the exact location of the performed examinations. The purpose of the present report is to extract and highlight information from the CONMOD reports about the performed non-destructive testing. The following issues will be included in the present report:

1. A brief summary of the NDT methods applied in the CONMOD project. Tests made with each NDT method, the results and conclusions.
2. Summary of the predicted development potential for each NDT method from the CONMOD reports.
3. Investigation as to whether the NDT methods have been developed and if the methods can be used at Barsebäck
4. Summaries of all tests and test locations in the CONMOD project so that new tests may be performed in same locations for comparison. This information shall, if so required, be supplied to other research groups and consultants.

3 Summary of the NDT methods in CONMOD

During the CONMOD project series of measurements with non-destructive testing (NDT), various techniques on the containment of Barsebäck unit 1 were applied. Later, outside the scope of CONMOD, some tests were made on unit 2 as well. The objectives of these test were to:

- Test the capability and performance of selected NDT techniques in a thick structure-like containment.
- Obtain information about typical structure characteristics.

During the assessment of the reports and old data from the CONMOD project it has been possible to identify 16 positions at B1, where NDT and material sampling were performed. The positions are shown in the figure below, and also supplied in the table below.

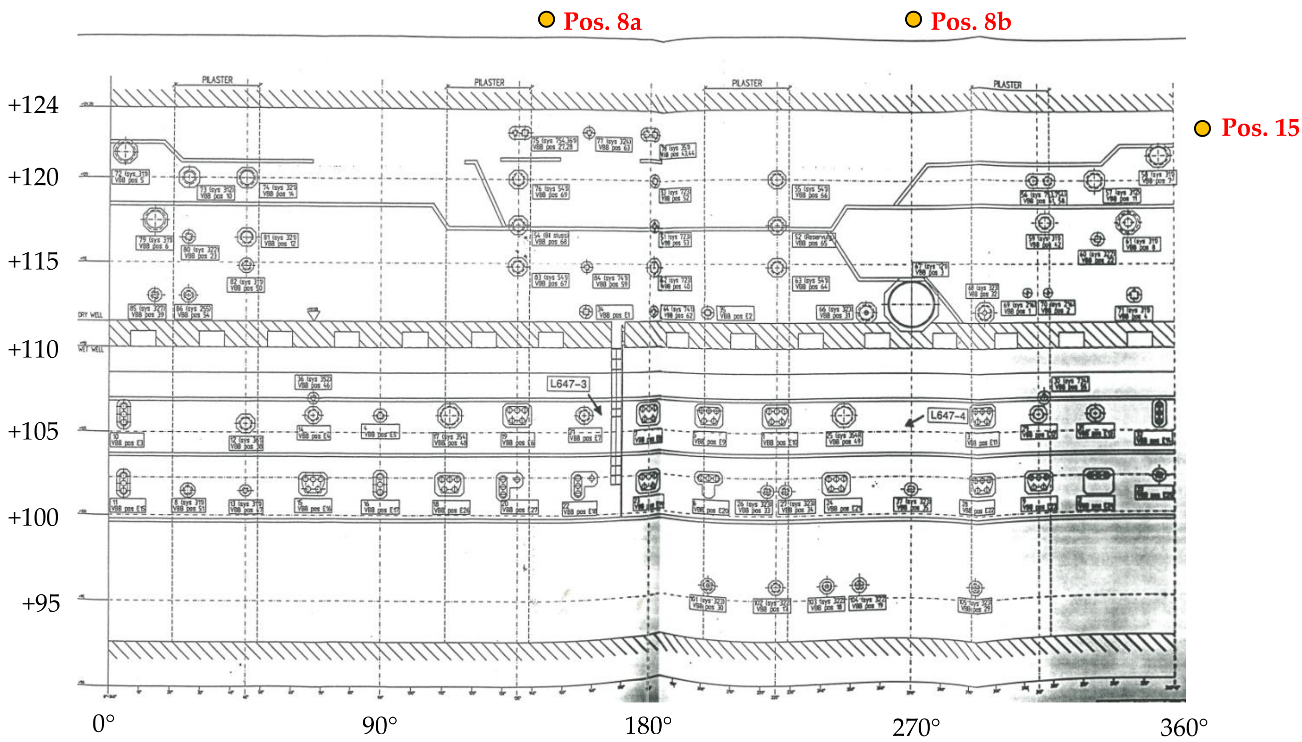


Figure 1: Illustration of positions used for non-destructive testing and material sampling at B1. The illustration is made on drawing from the inside, showing the penetrations in the containment.

Position	Height	Deg	Position	Height	Deg
1	122	0/180	8b	131	270
2	112	0	9	111-116	135
3	112	270	10	126.5	270
4	102	0	11	116.5	270
5	123.5	180/270	12	91	180
6	106	270	13	110	157
7	93.5	180	14	112.5	115
8a	131	140	15	123.5	335

Table 1: Detailed information about the location of chosen positions.

Please observe that positions 1 and 5 contain examinations made at two different locations even if the areas are only referred to as one position in the previous document.

A wide range of NDT and material testing have been made in each position. Not all examinations have been made in all positions. For example, in some positions only core testing has been performed. In the table below an overview is provided of the performed examinations in each position.

Position	GPR	HECR	IE	MASW	SASW	CORES	RH	UPE	UK1401	PUNDIT
1	x	x	x	x	x			x		
2	x	x	x	x	x	x				
3	x	x	x	x	x					x
4	x	x	x	x	x	x				
5	x	x	x	x	x	x	x			
6	x		x	x	x	x				x
7	x		x	x	x	x	x		x	
8a	x		x	x	x		x			
8b	x	x	x	x	x	x	x			
9	x	x	x	x	x					
10			x	x		x	x			
11						x	x			
12						x				
13						x				
14						x				
15						x				

Table 2: Detail information about the tests made in each area.

GPR	Ground Penetrating Radar
HECR	High Energy Computed Radiography
IE	Impact Echo
MASW	Multichannel Analysis of Surface Waves
SASW	Spectral Analysis of Surface Waves
CORES	Drilled Cores
UPE	Ultrasonic Pulse Echo
UK 1401	Ultrasonic measurements in the near surface area
PUNDIT	Ultrasonic measurements in the near surface area
RH	Relative Humidity measured in boreholes on-site

Besides these measurements and material samplings, many cover meter measurements were performed. Unfortunately the data files are all empty and no reference is made to the measurements in the reports or notes from the CONMOD project.

In Appendix 1, a detailed overview is provided for each position. The detailed overview provides information as to where the measurements are performed in the given location together with information as to the data file names. FORCE Technology still holds the original data files from the CONMOD project, so that these can be used for more thorough analyses or comparison in further projects.

For the cores and RH examinations sketches have been made, showing the coordinates for each examination. These sketches may be found in Appendix 2.

The core samples that were taken, were tested for different properties by various laboratories. In the table below, the test made at cores from a given position are shown. These results are only given in the "Material testing project", and no samples from the project have been saved.

Pos.	RH %	Prop	TSA	% cl	f_c	E_{sta}	f_t	d	V_p - E_{dyn}
1									
2	x			x					
3									
4	x								
5	x	x	x	x	x	x			
6	x	x	x	x	x	x	x		x
7	x			x	x	x			x
8a									
8b	x			x	x	x	x		x
9									
10	x		x	x					
11	x				x	x	x		x
12	x			x	x	x		x	x
13				x	x	x		x	x
14	x			x	x	x		x	x
15				x	x	x		x	x

RH % Relative humidity determined and slices of the core.

Prop Capillary suctions, chemically bound water, cement content, TGA and CaO, sorption curves,
transport properties, chloride diffusion

TSA Thin section analysis.

% cl Chloride content in relation to concrete mass.

f_c Compressive strength.

E_{sta} E-modulus, determined by destructive testing.

f_t Splitting strength/tensile strength.

d Density.

V_p - E_{dyn} V_p and E_{dyn} determined by non-destructive testing.

The information about the core testing has been added to the present report as the material properties can be used for comparison with properties estimated by use of non-destructive testing.

In the following the non-destructive techniques used during the CONMOD project will be described together with a brief summary of the most important findings.

3.1 GROUND PENETRATING RADAR

During the CONMOD project several measurements were made with ground penetrating radar. The used equipment was from Malå GeoScience and the used antennas were 800 and 1000 MHz.

GPR is a high resolution near surface surveying tool. The transmitter antenna produces a short pulse of high frequency electromagnetic energy, which is transmitted into the concrete. The propagation of the wave is dependent on the properties and conductivity of the concrete. Best results are obtained on dry and homogeny well compacted concrete with small aggregates.

Information received is based on the difference in the ability of the material to transmit or reject the transmitted wave. The rejected/reflected part of the signal contains information about amplitude (damping of the wave energy) and travel time. By recording reflections along a survey line a depth section along the surveyed path is created. Normally 100-300 scans are made per metre survey line, when investigating concrete. The measurements are made continually and do not require good physical contact with the concrete surface. In this way a large area can be investigated relatively fast.

Of primary use is the strong reflections obtained from metals embedded in concrete, making the radar sensitive to reinforcement and metallic cable ducts and other metal objects such as steel profiles and plates.

In the CONMOD project, the GPR was primarily used for detecting reinforcement and cable ducts. During the project it was shown that it was possible to detect the reinforcement and in some areas also cable ducts. It was possible to measure the spacing and depth and to find reinforcement laps.

It is stated in the main report (CONMOD, 2005) that individual bars with a spacing of c-c 50 mm could be distinguished and that the maximum depth in which it was possible to detect, was 250-350 mm, depending on the conductivity of the concrete. It was possible to detect 3 layers of rebars/cable ducts.

Two trails were made with radar on mock-ups. In one case it was possible to detect a large artificial void (embedded polystyrene) 200x200x200 mm at a depth of 220 mm. This test is described in detail in "A practical guide to Non-Destructive Examination of Concrete" (Nordic Innovation, 2004).

In the other trail it was tested if an Ø70 mm hole in a 6 mm steel plate embedded in concrete, could be detected. The depth to the steel plate was 260 mm, which is similar to the designed depth of the steel liner in the containment at Barsebäck, from the inside. The conclusion is that the method offers good possibilities, but that the result will depend strongly on the amount of the interference from reinforcement.

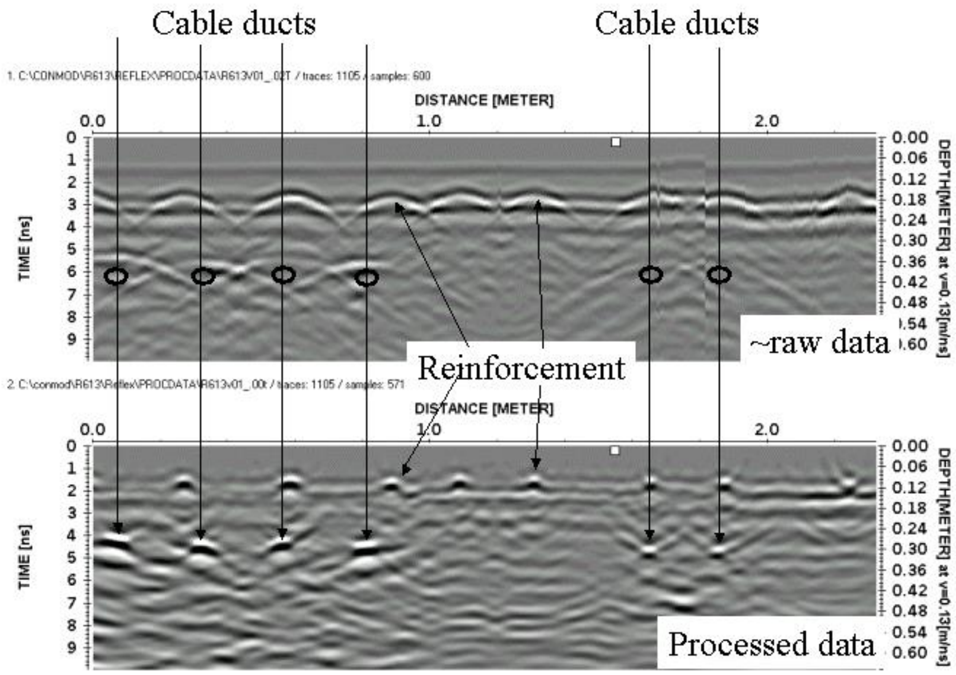


Figure 2: **Radar scan from the CONMOD report showing reflections from both reinforcement and cable ducts. At the top the raw data are show, and below processed data.**

All performed measurements with GPR has been made a single lines. No attempt has been made to combine several lines.

3.2 HIGH ENERGY COMPUTED RADIOGRAPHY

The equipment used during the CONMOD project was a 7.5 MeV Betatron X-ray accelerator from JME Ltd, digital image plates and a computed radiography system from Agfa Strukturix.

The Betatron is a compact circular electron accelerator producing pulsed radiation with a peak energy of 5 Rads/hour at 1 metre in air. The betatron is a heavy but portable x-ray equipment that can be used to investigate concrete up to 1500 mm thick.

Using an image plate as a detector placed on the other side, it produces a high-resolution digitized image of the object. The image plate is then inserted into a scanner. A laser beam scans the imaging plate with a pre-selected scanning resolution. The emitted light is captured by a photo-multiplier and converted into digital data by the system before it is sent to the work station for post-processing.

Imaging plates have a superior dynamic range compared to film and there is the possibility for image processing like contrast enhancement, latitude reduction, noise reduction, edge enhancement, zooming, spatial frequency control, measuring etc.

During the CONMOD project, the Betatron was used at several locations. The betatron was capable of detecting both reinforcement and cable ducts. Some tests were made at the pilasters containing the cable anchors. In these areas the wall thickness was 1300 and it was possible to see the reinforcement details and individual stands in the cables.

The Betatron was also used to test if there were any voids in the grout used to embed the pipe penetration in the hexagonal box outs left in containment for installation of pipe penetrations. Previous investigations at Barsebäck 2 had revealed that there could be such voids. In 2 out of 6 tested pipe penetrations voids were located over the pipe penetration. The history and results are described in detail in the "Main Project Summary Report" from the CONSAFESYS project (CONSAFESYS, 2015). The findings very verified by use of boreholes and an endoscope.

Several trials on mock-ups were made using HECR. One test was to see if it was possible to detect voids in cable ducts. It was found that it was possible to detect voids as small as 20 mm in width in a 1000 mm thick wall. Both air and water-filled voids were detectable.

Another test was to see whether small voids in the concrete could be detected. Ø 20 mm holes with a depth of 15, 30 and 40 mm were drilled on the side, where the image plate was installed. The test showed that the artificial voids were easily detected.

Two tests were made on mock-ups to see if it was possible to detect if there was a hole in an embedded steel liner. In one test the total thickness of the structure was 1000 mm and in the other 1500 mm. Six holes were drilled in a 8 mm embedded steel liner. Three holes were drilled through the line and 3 were drilled 4 mm into the liner. The diameters of the holes were Ø5, 20, 50 mm. In both cases the holes could be detected if the holes penetrated the steel liner. The holes with a depth of 4 mm could be detected at the 1000 mm thick structure (Ø5 is not very clear) whereas no conclusive result was gained from the 1500 mm thick structure.

For all tests made with the Betatron, it was concluded that the best results were obtained if the image plates were closest to the object that needed investigation. If for instance, the cable ducts are of interest, the Betatron should be positioned inside the containment, and the image plates on the outside, as the cable ducts are closer to the outside than the inside.

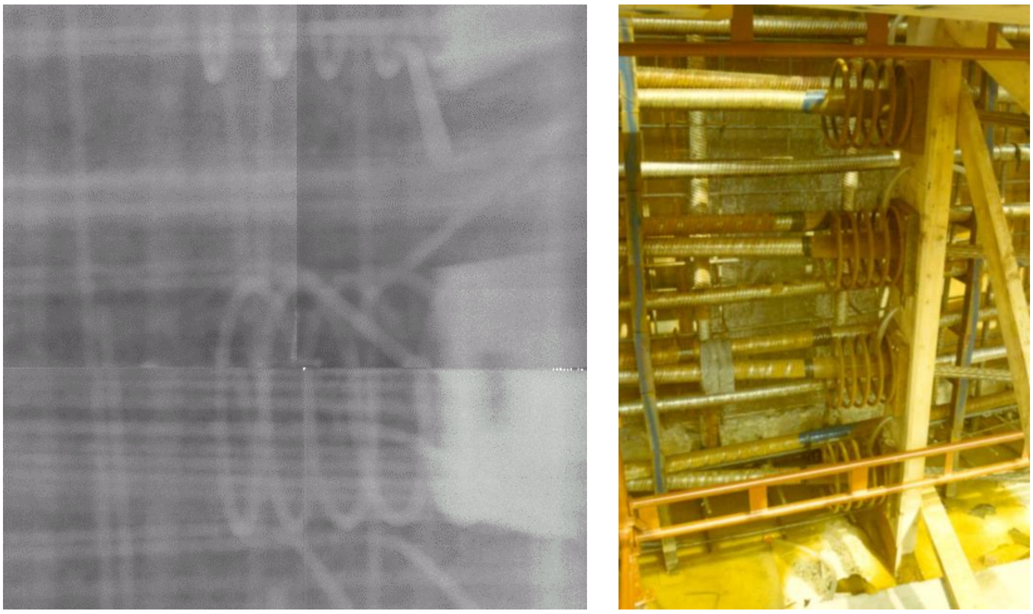


Figure 3: Example of X-ray picture from the CONMOD report. The X-ray picture is of the pilaster where the tensioned cables are anchored. The wall is 1300 mm thick, and still it is possible to distinguish single threads in the cables. To the right, a picture from the construction phase is shown, for comparison with the X-ray picture.

In the investigation of possible leakage causes from the condensation pool (at the Barsebäck 2 reactor containment) at the lower liner toroid (base level in wet well) the containment wall was initially investigated using HECR. This was done in order to examine the structure for voids, as voids could indicate favorable circumstances for corrosion. Several positions at the lower liner toroid were inspected using HECR. No immediate indications of damage or defects were found using HECR.

3.3 CORROSION MEASUREMENTS

The only attempt to directly detect corrosion was during the investigation of the liner toroid as described above. As one part of the investigation for the leak origin, several 100 mm diameter concrete cores were removed from the inside area at the lower liner toroid. During the process the drill were first stopped, and cores broke off, 50 mm from the liner to allow for electro-chemical measurements on the liner plate using both half cell potential (HCP) readings and galvanostatic pulse (GP) measurements.

The equipment used was a Galva Pulse with a modified measuring head that would fit into the bore hole. Connection to the liner was made by connection to a pipe penetration. Both the HCP and GP measurements methods are based on the change in the potential of the corroding metal measured towards a stable reference electrode (Galva Pulse uses a Ag/AgCl electrode). The HCP method measures the potential as it is. GP applies a current to the metal through the concrete and at the same time the changes in the potential of the reinforcement is measured. HCP can be used to evaluate if the is a risk of corrosion, while GP can also estimate the corrosion rate.

In the test at Barsebäck 2, the Galva Pulse measurements were conducted with the objective to investigate if any ongoing corrosion activity could be noticed. Results indicated moist conditions and that some corrosion activity were plausible, but the extent were not possible to quantify or verify. The core holes were continued to the liner and in some of them visible liner corrosion was detected. The circumstances and time off occurrence (during construction or later) were however not determined. At one of the positions it was further noticed that water collected at the bottom of the hole, close to the liner. In one location the presence of porous casting cold joints indicated strong correlation of ongoing corrosion activity using the Galva Pulse, and increased patterns of surface corrosion were confirmed visually at the exposed liner in drilled out concrete core holes.

The reason the measurements was made in the drilled holes and not at the surface of the concrete is that the method will investigate the metal closest to the measuring head, which would be the reinforcement, if it is connected to the pipe penetration. Further the resistance in the thick layer of concrete between the surface and steel liner would make the measurements impossible.

3.4 IMPACT ECHO

There is no information as to which type of equipment that was used for the Impact Echo (IE) testing but it was probably a system from Olson Instruments, based on a Freedom PC.

Impact Echo equipment consists of a hammer/metal ball and a dry transducer. The hammer generates a low frequency wave and the transducer records the wave that is reflected. In IE measurements is the compressive wave that is used. The result is a frequency spectrum of the received wave, and if the wave velocity is known, the frequency spectrum can be transformed into information about the depth to a reflection. It should be pointed out that the estimated value of the compressive wave is an average value for the concrete through which the wave passes.

In the CONMOD project the IE measurements, the frequency spectrum and the calculated depths to reflections were used for comparison with calculated/known depths to steel liner and backside of the containment. It was found that in several positions the depth to the liner and the thickness of the containment did not conform to the design values. It was concluded that the steel liner was not perfectly circular when it was embedded, which resulted in greater depths to the liner than others. In (CONSAFESYS, 2015) it is mentioned that in some areas, there was a difference of 20%.

For an example of the Impact Echo results, see example below under SASW.

3.5 SPECTRAL ANALYSIS OF SURFACE WAVES

There is no information as to which type of equipment that was used for the Spectral Analysis of Surface Waves (SASW) but it was probably a system from Olson Instruments, based on a Freedom PC.

SASW uses Rayleigh wave to determine the wave velocity with depth from the surface. The velocity of the waves is dependent on the density and shear modulus of the concrete. Any discontinuities in the concrete will tend to reduce the measured velocity.

The equipment consists of two dry transducers to receive the reflected wave, and a hammer to generate the wave. The measured velocity provides information as to the uniformity of the concrete in depth and globally, and may be used to estimated concrete properties such as dynamic E-modulus. The method is relative fast, and only requires measurements at one single point.

During the CONMOD project it was found that the concrete structure at the lower containment wall had a lower velocity than that at the upper containment wall. It was concluded that this was probably due to a crack in the outer surface of the lower containment wall, caused by the use of a slip form during the construction phase.

Another finding was that in some areas there was a dramatic drop in the measured velocity in the depth of the steel liner, indicating that there is an air gap between the concrete and the steel liner.

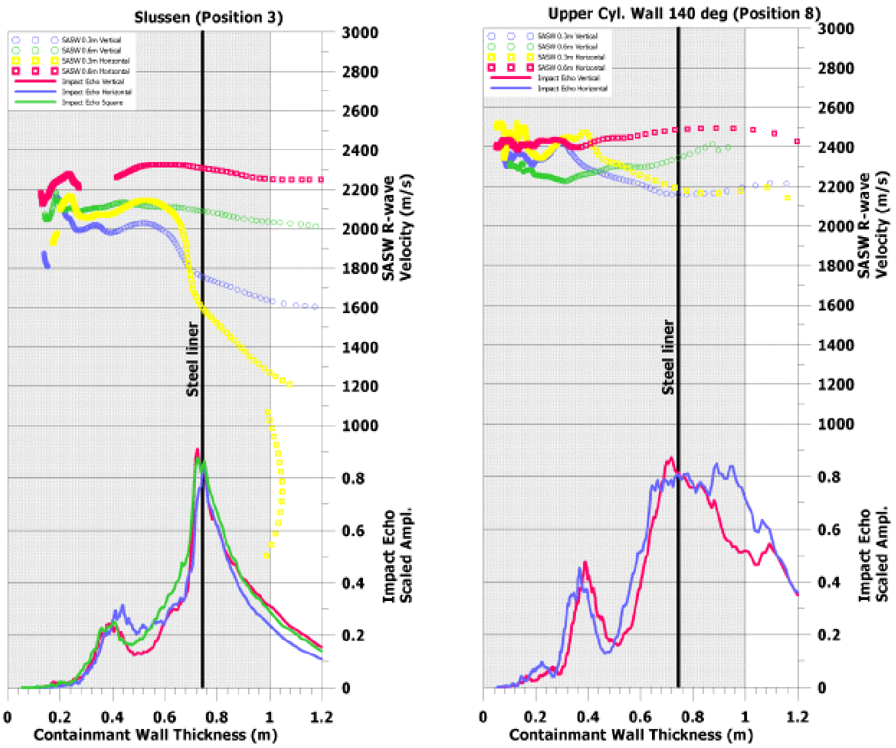


Figure 4: Example of IE and SASW measurements.

In figure 4 examples of IE and SASW measurements for two positions are shown. The graphs to the left are from the lower containment wall and the graphs to the right are from the upper containment wall.

The dominating frequencies found during the IE measurements have been calculated into a depth by use of an estimated velocity. When looking at the graphs from the lower containment wall the IE measurements in the lower part of the figure depict a strong reflection in the depth of the steel liner indicating that there is a poor bond between the steel liner and the concrete.

In the graph from the upper containment wall there is still a reflection from the steel liner, but it is not as dominant as for the lower part, and some of the wave energy still continues and provides a reflection from the backside of the containment wall.

When looking at the SASW data, it can be seen that the velocity is higher at the upper containment wall. Further it can be seen that there is a lower velocity in the outer part of the walls at the lower containment wall, caused by the crack in the outer surface. It can also be seen that measurements made with the transducers in a horizontal direction provide a higher velocity compared to measurements with the transducers in the vertical direction, for measurements made on the lower containment wall. This indicates that the cracks in the other surface are orientated in the horizontal plan.

3.6 MULTICHANNEL ANALYSIS OF SURFACE WAVES

The equipment used during the CONMOD project was an experimental setup developed by Lund University. The system consist of a datalogger collecting data about a wave reflection recorded with an accelerometer placed on the concrete surface and multiple impacts to the concrete with a hammer at increasing distances from the accelerometer. The collected data is compared with theoretical results in an iterative process, until there is a fit between the theoretical data and the measured data. In this way the wave velocity and depth to reflection can be determined. Like the SASW method the Multichannel Analysis of Surface Waves (MASW) provides information about the uniformity of the concrete in depth and globally.

In the CONMOD project MASW was used to test the properties of the concrete i.e. the compressive wave speed that can be used to estimate the dynamic E-modulus. Further it provided reflections from the embedded steel liner and the backside of the structure. In some locations reflections were not seen from the back side, indicating that there was no good bonding between the steel liner and the concrete.

The MASW method applied during the CONMOD project was changed during the project. In the end the method was developed to a stage, where the measured data was compared to theoretical data based on a FEM-modelling of the response. The FEM-model was based on a layered model where the outer part of the structure had a lower velocity than the inner. The method made an evaluation of the measured data both with respect to MASW and Impact Echo, which was seen to have the best potential as a suitable seismic method.

Input for the FEM model was obtained from thickness measurements with HECR and information about wave speed in the damaged outer layer was obtained from drilled cores.

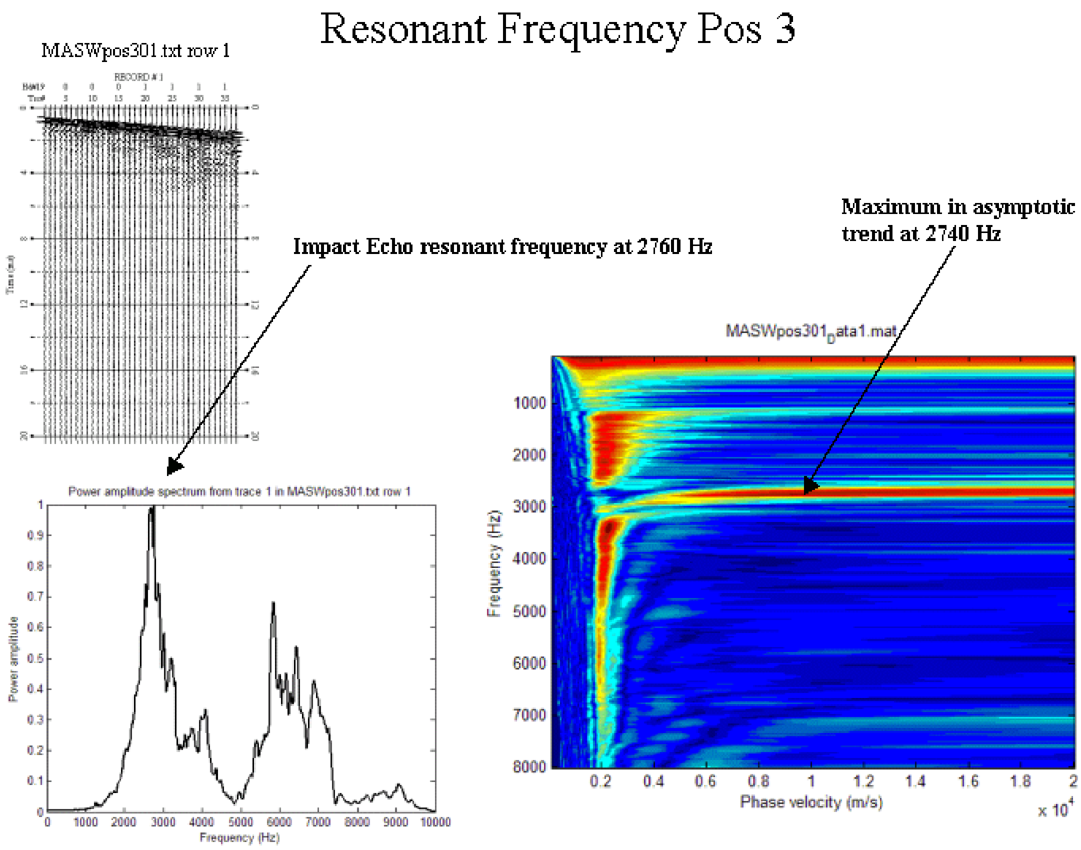


Figure 5: Example of MASW from the CONMOD report. The top left figure shows the stacked data recorded, with increasing distance from the accelerometer. The lower left figure shows the standing (compression) wave frequency peaks, which are similar to the IE measurements. A dominant frequency corresponding to a reflection from the steel liner is seen. The phase velocity spectrum is shown to the right and shows the guided wave velocity as a function of frequency (wavelength) as well as a distinct peak caused by compression wave reflections from the liner.

3.7 ULTRASONIC PULSE ECHO

The equipment used during the CONMOD project is a UPE 1220 from Spectrum. Ultrasonic Pulse Echo (UPE) is based on the propagation and reflection of shear waves and in this case with a selectable frequency between 33-120 kHz. The antenna has 4x6 dry-contact transducers in an array divided into two groups that can either send or receive waves.

Interfaces in the structure, such as backside and internal voids reflect the wave back to the antenna as amplitude in the received signal. Measurements are made as single point measurements. In the equipment there is the possibility of making several measurements in a line, and get the result presented as a 2D picture. There is no merging between the single points. If the spacing between each point is very dense, it is sometimes possible to detect interfaces as reinforcement and cable ducts.

Besides locating an object in the structure, the A1120 was also used to find the shear wave velocity of the material by a technique called common mid-point CMP). The shear wave velocity can be used to estimate material properties such as the dynamic E-modulus. The technique requires several measuring point in a line. This is the only report of equipment used the Ultrasonic Pulse Velocity measurement (UPV)

In the CONMOD project, tests were made using CMP, which resulted in the determination of the shear wave velocity of the concrete in the tested areas. During these test it was found that in some areas, it was possible to get a reflection from the interfaces between the concrete and the steel liner, indicating that there would be an air gap.

By making CMP measurement in the horizontal and vertical directions both, it was concluded that irregularities in the surface of the concrete were in a horizontal plane at more or less regular intervals.

It was also found that it was possible to get reflections from the cable ducts in some locations, but was concluded that it would be much easier to get information about the location of the cable duct by using GPR.

Below two examples of obtained data from the CONMOD project are provided. The upper is the result of a CMP measurement. The slopes of the upper curve are used to determine the near-surface velocity. In the displayed picture the velocity was found to be 2750 m/s. In this case the reflection from the liner plate is also clear and the velocity for the in-depth measurement can also be determined. In this way it was possible to compare the condition of the concrete in depth with that of surface conditions.

In the lower picture, UPE measurements have been made in a single line. In the displayed picture a clear reflection was seen from the steel liner. When making measurements this way, an estimated velocity is used in order to calculate the depth.

All performed measurements with UPE have been made as single lines. No attempt has been made to combine several lines.

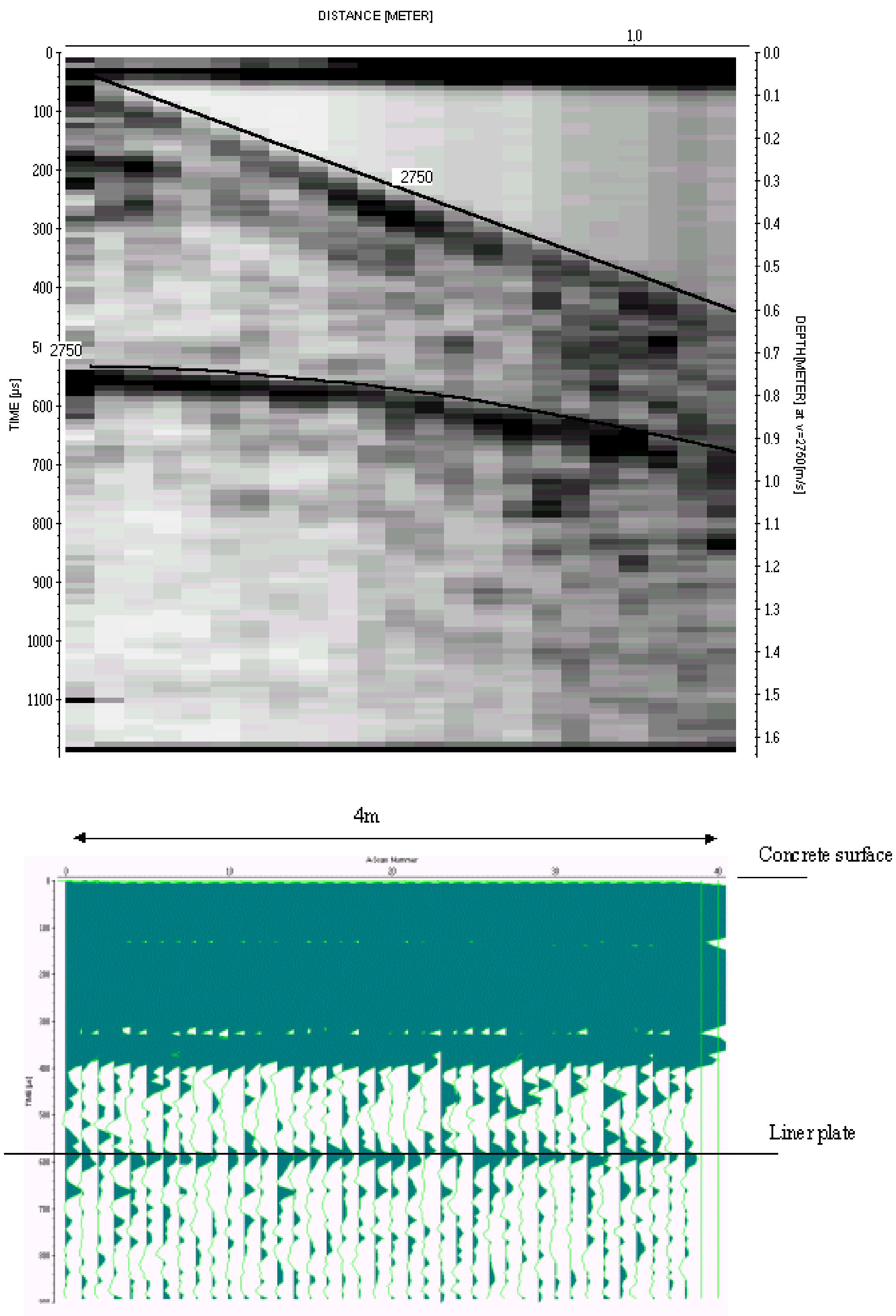


Figure 6: Example of UPE measurements made during the CONMOD. Both pictures are from the "Preliminary results of NDT investigations at Barsebäck 1" report.

4 Predicted potential of NDT methods used

In the conclusions made at the end of the CONMOD project it was stated that if the measurements/investigations at Barsebäck 1 should be repeated, the investigation techniques would be confined to ground penetrating radar, high energy computed radiography and multichannel analysis of surface waves.

The radar would be preferred for rebar and cable ducts positions and depths. X-ray for the size and condition of embedded steel, details in the structure, voids and foreign objects in the concrete and exact thickness measurements. MASW would be used for total thickness and thickness of layers in the concrete, material properties and quality, bond between steel liner and concrete and delamination in general.

It is further stated that it has emerged that MASW provides better and more robust data than the SASW and IE.

It is mentioned in the report that UPE has some limitations in obtaining good results in some areas, which is thought due to a cracked outer surface in the lower containment wall.

Apart from these formulations, there are no conclusions or predicted development potential for any specific NDT methods.

It is concluded that a means for predicting the condition and behaviour of containment structures under loading and at the influence of ageing has not been fully achieved and validated. It is however believed that the NDT techniques available at the time of the CONMOD project in combination with FEA modelling of seismic responses can determine and characterise condition changes, such as cracking etc.

In order to detect the condition changes, an initial condition is however needed. The reason is that the response from NDT measurements in various locations at one plant and at different plants are too diverse so that changes would not be possible to detect if an initial response is not recorded. The reasons for the difference in the response may be boundary condition, difference in reinforcement, cable duct, initial properties, initial cracks, foreign object etc.

Changes in the conditions apply to embedded steel as well as the concrete and to how the two materials interact.

The potential of the existing NDT methods should be investigated further and procedures should be developed in order to detect specific types of ageing effects, natural changes and deterioration both.

There is a potential in examining wave velocity profiles and reflection patterns when recognising and characterising crack growth. Seismic wave motion in structures has however not been fully understood yet. More should be done to understand the wave dispersion dependent on the relationship between wavelength and wall thickness, as various wave modes depend on the interactions in concrete. The effect of a low-velocity surface layer should also be examined more thoroughly. These phenomena should be more clearly defined in order to make the seismic method (MASW) a more reliable method of monitoring concrete conditions. This should be achieved through digital mock-ups combined with a collection of empirical data on physical mock-ups and actual structures.

If seismic methods should be used for periodic checks of concrete containment conditions, it requires that the method has a very high degree of test repeatability, which needs to be proved. Further new methods of sensor technology should also be tried, for example the use of non-contact receivers.

5 Development in the used NDT methods

This chapter will focus on the development in the NDT methods used during the CONMOD project. Focus will be on:

Ground Penetrating Radar (GPR)

High Energy Computed Radiography (HECR)

Seismic methods, mainly Multichannel Analysis of Surface Waves (MASW)

Ultrasonic methods based on an array of sensors and shear waves.

A general comment for the NDT methods is that the ground principle of the method has not changed. Developments have been made in the hardware (computers in the hardware have become better and faster) and in the software (better interfaces and new possibilities as computers are faster).

5.1 GROUND PENETRATING RADAR

Radars are still based on the same principle. What have changed significantly are the areas of computers, antennas and software. The computer and software together have enabled the possibility of relatively easily creating 3D pictures of what is under the surface.

The main achievement by getting a faster computer is that it can collect and analyse the received signal faster. This results in quicker data collection than earlier. Resent tests performed by BAM at Barsebäck unit 1 in 2014 (BAM, Demonstration of State of the Art NDT-methods for Nuclear Concrete Reactor Containments, 2014), showed that high quality data from a large survey field (roughly 10m2) with several measuring lines with a spacing of 50 mm could be recorded in 1.5 hours. (CONSAFESYS, 2015).

During the CONMOD project, antennas with frequencies of 800 and 1000 MHz were used for testing the concrete structures. Since then new antennas have emerged with higher frequencies up to 2.6 GHz.

Normally, a lower frequency would result in larger penetration, and less accuracy. But for highly reinforced concrete structures the best results are usually gained by choosing a high frequency antenna. Tests performed by FORCE Technology at Oskarshamn 3 in 2010 (FORCE, 2012) and at Barsebäck 1 in 2011 (FORCE, B1: Measurements 2011 Summary Report, 2013) with different antennas showed that the best results were obtained by using high frequency antennas. The dense reinforcement prevents the low frequency antennas from penetrating deeper than what is possible with the high frequencies, and therefore the high frequency antennas are preferred as they provide better accuracy and resolution. The reason why lower frequency antennas are not effective for detecting deep reflections is because of the too dense reinforcement near the surface. The outer reinforcement leads to a shadowing effect of the underlying reflectors due to an unfavourable ratio between reinforcement spacing and wavelength of the low frequency wave. The spacing of the rebars should be more than double the wavelength of the used antenna.

The main development in GPR measurement is however constituted by how the measurements are performed. Most measurements for simple tasks are still performed as single line measurements as was the case for the CONMOD project. This provides information about objects in the concrete in that survey line, presented as hyperbolas as shown in the 2D plot below.

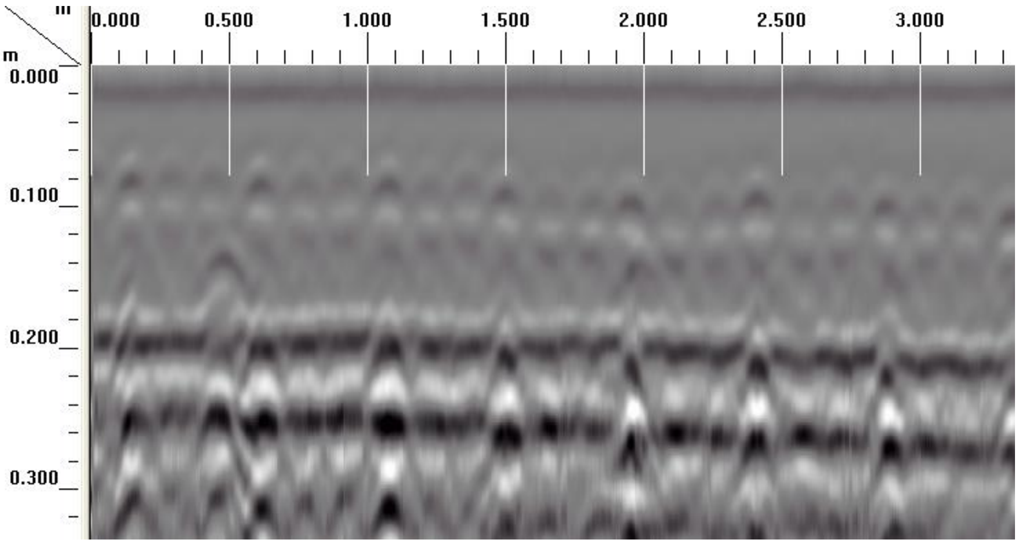


Figure 7: Radar scan from Barsebäck measurements in 2011. The reinforcements are seen as hyperbolas at a depth of 60 mm and another reflection is seen from the cable ducts at a depth of 180-200 mm.

But for more detailed investigations, where more information is needed, new software provides the possibility of combining several scan lines into a 3D picture. Usually these scan lines are made in a preplanned grid with measurements in two directions perpendicular to each other, and a spacing between the lines of 50 mm. The reason why the measurements are made in two directions perpendicular to each other is in order to capture the reinforcement in both polarization directions.

Below two examples of 3D scans performed by BAM at Barsebäck in 2014 is given. The illustrations are taken from (CONSAFESYS, 2015). The first example shows a section of the above mentioned 10m2 survey field. The scan shows the distribution of the reinforcement at a depth of 80 mm. The picture clearly shows the position, spacing, direction and overlaps.

Figure 8: Examples of combined radar scan lines (3D measurements). Measurements at a section of the containment at Barsebäck 1.

Below the result from measurements performed at the edge of a pilaster is provided. For comparison the picture from the construction is shown again.

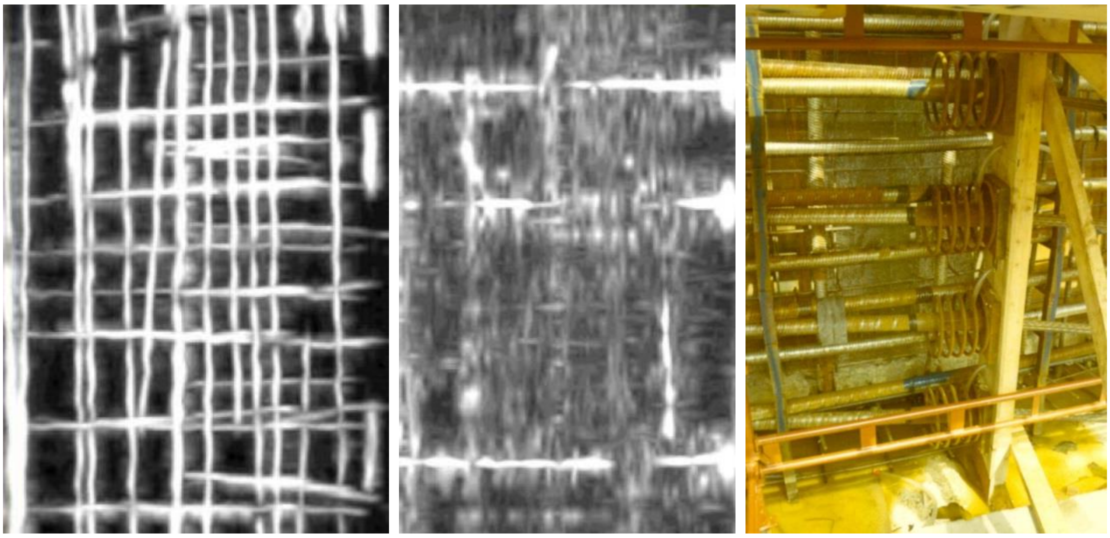


Figure 9: Examples of combined radar scan lines (3D measurements). Measurement at a pilaster at Basebäck 1.

To the left the results from the 3D scan focus on 80 mm depth. In the middle the focus is set to 150 mm. The embedded steel plate that is anchor plate of the tendon duct head, can easily be seen in the illustration. To the left the reinforcement is detectable and the cable duct can be seen in the focus in the middle picture. The spring reinforcement and the single strains in the wire cannot be seen. The latter because the cable duct is made of steel and reflects all of the radar wave energy.

During the CONMOD project, GPR was also used during a trial to see if it was possible to detect a hole in the steel liner with measurements performed from the inside of the containment. Since the CONMOD project, new ways of analysing the reflected waves have been adopted. When looking after a hole in the steel liner a method where analysis of the phase shift is used, could be adopted.

When evaluating the phase shift, the difference between the phase of the transmitted and received wave pulse is of interest. Depending on the interface at which the pulse is reflected, phase information of the wave pulse varies. When an electromagnetic wave (GPR wave) reaches a metallic interface, such as the steel liner, the wave is completely reflected resulting in a phase shift of 180°. If there is a hole, (no steel) there will be no phase shift.

Analyses of phase shifts have been widely researched for ultrasonic pulse echo measurements when trying to verify whether a grouted cable duct is fully grouted or contains air void, and with success. Software for the analysis is however not currently commercially available to the author's knowledge. Further, no research has been found focusing on similar issues as a hole in an embedded steel liner.

Another interesting potential of radar is its capability to detect cracks. Several researches have been made to test if GPR could detect cracks perpendicular and parallel to the surface. The conclusion is that GPR is insufficient for detecting perpendicular cracks in general, and cracks parallel to the surface if the crack opening is limited (BAM, 2013). This because of the low dielectric contrast between the concrete and air in connection with the comparatively large wavelength. Radar measurements are however sensitive to the moisture content in the concrete, and therefore cracks can sometimes be indirectly detected if the cracks have a high moisture content. Put differently, the increase in moisture can be detected but not the crack itself. During the CONMOD project several tests were made at Barsebäck unit 2, in order to determine the possibility of leakage causes from the condensation pool. As mentioned earlier HECR was used to examine the structure for voids, as voids could indicate favorable circumstances for corrosion. If corrosion is to occur, moist is also needed in the void. Hence it might be that the use of GPRs potential to detect changes in the moisture content could be adopted to look for areas where there is a risk of corrosion. The success would however depend strongly on the distance, reinforcement density and quality of the concrete.

5.2 HIGH ENERGY COMPUTED RADIOGRAPHY

The principle of X-ray has not changed since the CONMOD project, at least not for X-ray methods that are possible to implement at an NPP containment structure. X-ray is still the NDT method that provides most and precise information about the concrete structure and its embedded steel parts. As it was the case during the CONMOD project, X-ray in thick concrete structures requires long exposure times, and powerful equipment, which is also heavy equipment. The total weight of the X-ray system used during the CONMOD project was 300 kg, for which the accelerator (sending out the X-ray beam) weights 110 kg. This provides some logistical challenges.

If X-ray should be more useful in thick concrete structures, the exposure time should be shorter, and the logistic should not be more difficult than during the CONMOD project. It would not help much if the exposure time was reduced from 1 hour to half an hour if the preparation time is simultaneously increased from 1 to 2 hours.

When looking at the development in X-ray, there are 3 areas of interest:

- X-ray source
- X-ray receiver
- Data analysis

If a shorter exposure time should be achieved the X-ray source would have to be more powerful. During the CONMOD project a 7.5 MeV Betatron was used, which provided a dose rate of >5R/min at a distance of 1 metre.

There are more powerful Betatrons available today. JME, who supplied the Betratron used during the CONMOD project, has made a single custom made 9 MeV Betatron with a dose rate >20R/min. There is no information as to the weight of this type (JME, 2015).

RadiaBeam Systems have several Betatrons with energy above 7.5 MeV with dose rates up to 16 cGy/min, which is equal to 16 R/min, with a weight of 300 kg for the accelerator alone (Radiabeam, 2015).

Another possibility would be to use a linear accelerator instead of a circular accelerator such as the betatron. Linear accelerators are widely used in the medical industry. The advantage of using linear accelerators is that the dose rate is much higher. The disadvantage is that they are heavy and usually cost much more than betatrons.

As an example RadiaBeam systems have a miniaturized X-ray system with an energy of 9 MeV and a dose rate of 200 cGy/min. The weight of the linear accelerator head including shielding is however 550 kg. This makes it extremely difficult to move around and not very flexible.

It has not been possible to find any literature about the used of 9 MeV betatrons or powerful linear accelerator systems on concrete structures.

During the CONMOD project, the receiver of the X-ray beam constituted digital image plates. The development in digital image plates has resulted in a higher resolution. This provides a higher quality image, which can be useful for the further analysis. But when it comes to concrete structures, where small objects are normally not of interest, this higher quality is not really needed. The disadvantage in the higher resolution is that it requires more energy to be absorbed, which results in a longer exposure time in order to get more energy through.

In 2014, FORCE Technology made some X-ray exposures at Barsebäck unit 1, in some of the same positions as used during the CONMOD project. Our experience was that it required longer exposure times in order to get a quality similar to the one used during the CONMOD project. When it comes to the reading of the image plate data and transferring it to an image that can be analysed at a computer, the main development has been the change from an 8 bit system to 16 bit systems. This is an advantage for the later filtering and analysis of the images as this will go faster.

An alternative to using image plates is the use of flat panels. A flat panel contains a layer of scintillator material, usually gadolinium oxysulphide or cesium iodide, which converts the x-rays into light. Directly behind the scintillator layer is an amorphous silicon-on glass detector array similar to a digital camera's image sensor chip. The signals from the photodiodes are amplified and encoded by additional electronics positioned at the edges or behind the sensor array in order to produce an accurate and sensitive digital representation of the x-ray image (Wikipedia, 2015). Flat panels are more sensitive that image plates, meaning that of the X-ray beam penetration through the structure, more is absorbed at a flat panel than on an image plate. Hence, the exposure time is shorter.

In the illustration below it is seen how little of the energy that is absorbed by the image plate. The Betatron used at the CONMOD project is 7500 keV.

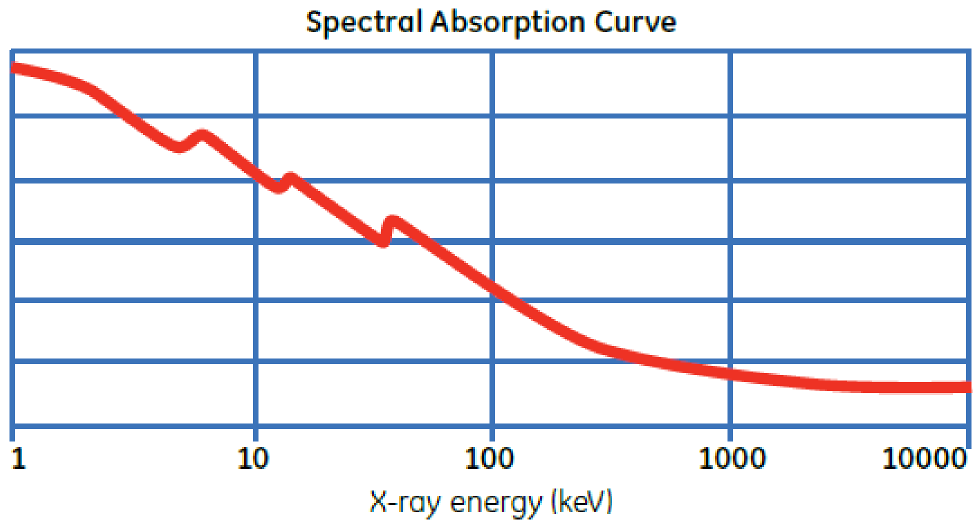


Figure 10: Spectral Absorption curve for IPC 2 image plates from GE. (GE, 2015)

However, at the moment, flat panels are not developed directly for examination of thick concrete structures.

An optimal flat panel for thick concrete structures should be capable of receiving the heavy energy, produced by 7.5-9 MeV Betatrons. Flat panels capable of receiving 20 MeV have been developed. The scintillator material should be capable of absorbing much of the penetrating X-ray beam. Some of the flat panels that absorb much energy are thicker, which is not advantageous as this can give cause for more noise in the image. The flat panel should preferably be thin to reduce the noise. An optimum between thickness and absorption should be used. The last limit is the time window in which the flat panel can be exposed. The suppliers have made a limitation in time. For example the DXR 250 provided by GE has a maximum opening window of 150 seconds, which would not be enough to get a clear image at a NPP containment structure.

No literature has been found about the use of flat panel systems on thick concrete structures such as NPP containments.

A disadvantageous to flat panel is that the panel area is not large. The abovementioned panel from GE has an active area of 410x410 mm. The possibility of using several flat panels next to each other is not an easy option as the panel has a wide frame, resulting in dead spots between the panels. For comparison measurements made in 2014 at Barsebäck 1 were made with 4 pieces of IPC 2 image plates from GE with a size of 350x430 mm given a combined image plate area of 700x860 mm without any dead spots.

When it comes to data analysis of the data images, for most of the methods then has been a development in the image reconstruction algorithms and more filter options have been available.

It has however not been possible to find any literature were the effect of these improvements one images from thick concrete structures have been documented.

5.3 SEISMIC METHODS

At the end of the CONMOD project it was concluded that MASW measurements gave better and more reliable results that SASW and IE measurements, hence MASW would be the only seismic method used if the investigations made during CONMOD should be repeated.

At the time of the CONMOD project the equipment used was an equipment under research and development by Lund University. To the knowledge of the author this situation has not changed since. The MASW method has not become wide and commercially used yet as is the case for IE and SASW. Currently several international academic institutions pursue research on the MASW method.

In the CONSAFESYS project, one of the original issues was to develop numerical models as they are necessary to make accurate predictions of the results from the MASW examination methods.

It was soon recognised that a large amount of development resources were needed to develop the MASW application for thick concrete structures, and hence a Ph.D. project were initiated at Lund University in 2011.

In the Ph. D. project experimental testing and numerical wave propagation simulations are used as complementing techniques. Developed methods have been tested on mock-ups up to 450 mm in thickness (reported in literature (Baggens & Ryden, Systematic errors in impact-echo thickness estimation due to near field effects, 2015), (Baggens & Ryden, 2015-2)) and some tests have also been performed at Barsebäck 1 in 2014 (CONSAFESYS, 2015), but without any conclusive literature published yet.

Some of the interesting conclusions made during the project concerns systematic errors for plate thickness estimations using both IE and MASW methods (Baggens & Ryden, 2015) and a new approach to estimate Poisson´s ratio, based on polarization of acoustic zero-group velocity Lamb mode (Baggens & Ryden, 2015-2).

In the case of the systematic errors for plate thickness estimations, it is found that the ordinary approach underestimates the thickness up to around 5-15 % depending on Poisson´s ratio, measurement setup and source pulse. In the case of the new method of estimating Poisson´s ratio it has been found that the new method results in an accuracy in determining the nominal thickness of 1% where the traditional approach has an accuracy of 6 %.

As mentioned earlier, the CONMOD project emphasizes that if the MASW method should be used to detect changes due to ageing/deterioration of the structure, the method must have a very high degree of test repeatability.

Since the CONMOD project several measurements have been performed at NPP in the Nordic countries. At several occasions measurements have been repeated with several years between them and sometimes with different operators. Below is a list of such repeating measurements.

Location	1st test	2nd test
Barsebäck 1	2002 [1)]	2011 [2)]
Oskarshamn 3	2007	2010 [2)]
Olkiluoto 1 & 2	2006	2011

Table 3: Information about repeated MASW measurements.

[1)] CONMOD project

[2)] CONSAFESYS project

In all of these test, it has been found that the method has a very high degree of repeatability, which also have been reported in (FORCE, 2012). Tests have been performed with different setups for performing the test, but it seems that the most reliable and widely used is still a single line, with the receiver in a fixed position and stocks to the surface with increasing distances in one direction.

Other tests have been performed with contact free receivers such as microphones and laser. The best method for the vertical thick containment structures however seems to be by use of an accelerometer fixed to the surface in different ways.

It should be emphasised that MASW is still in a research and development phase and that no commercial equipment or software for concrete structures exists.

There is no doubt that MASW provides more reliable information than SASW and IE. MASW is however more time-consuming and will be an average result from the concrete within the field of the measurement. If however the task is to look for delamination in a large area, IE will be able to perform this task faster.

Since the CONMOD project the IE method has not changed. A lot of research is still being made on IE, but not any that affects its capability to detect delamination compared the level at which it was developed at the time of the CONMOD project, as long as the exact depth to the delamination is not an issue.

An example of the use of IE for delamination survey at a containment was at the NPP Crystal River where severe delamination was found in 2009 and 2011 (BAM, 2013). Among other methods IE was used to determine the extent of the delamination and the depth of the delamination (COMMISSION, 2009).

The software from many of the IE suppliers has changed so that single measurements now automatically can be transformed into survey plots showing the depth of the dominant reflection. This way delaminated areas can be illustrated more clearly.

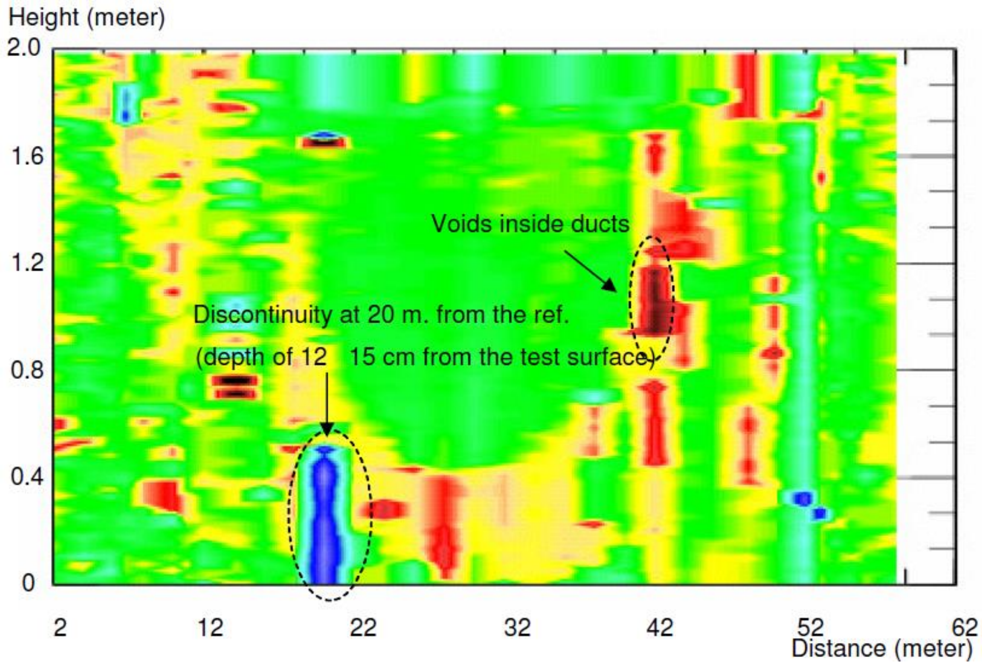


Figure 11: Example of survey plot from IE measurements. In the present case a bridge web wall has been examined, containing some cable ducts. (Olson, 2010)

Some suppliers have also made Impact Echo scanners, for which the equipment is moved in lines along the surface and impact echo measurements are automatically performed at a fixed interval. This makes the Impact Echo method capable of covering a large area, relatively fast.

5.4 ULTRASONIC METHODS

At the end of the CONMOD project ultrasonic methods were not included in the methods that would be used if the project was to be repeated. Developments in ultrasonic methods have however developed since the CONMOD project, which is the reason why the method is included in the present chapter.

The ultrasonic Pulse Echo method used during the CONMOD project is still a widely used method. Changes in the principle of the measurements have not changed since. The hardware, software and evaluation options have however changed.

Single measuring points do often not provide clear information about smaller reflectors as reinforcement and small voids, as the ultrasonic wave beam is not sharply focused on the information. Therefore measurements are usually made in a line with regular spacing, which provides enough information to carry out a reconstruction calculation. This way it is possible to detect for example reinforcement covered by a thick concrete cover. This method is similar to those made during the CONMOD project as shown at the bottom of figure 5.

With faster computers and software it is now also possible to stack several measuring lines into a 3D model of the examined area. This approach has been researched and widely used, for instance in attempts to inspect the quality of grouted cable ducts, with a high degree of success.

Compared to the measurements performed during the CONMOD project the presentation of the results has developed which gives rise to better interpretation of the measured data.

As the wave field is widely spread, a single measurement may contain reflections from many reflectors or several probe positions can contain reflections from the same reflector, as shown in the illustration below.

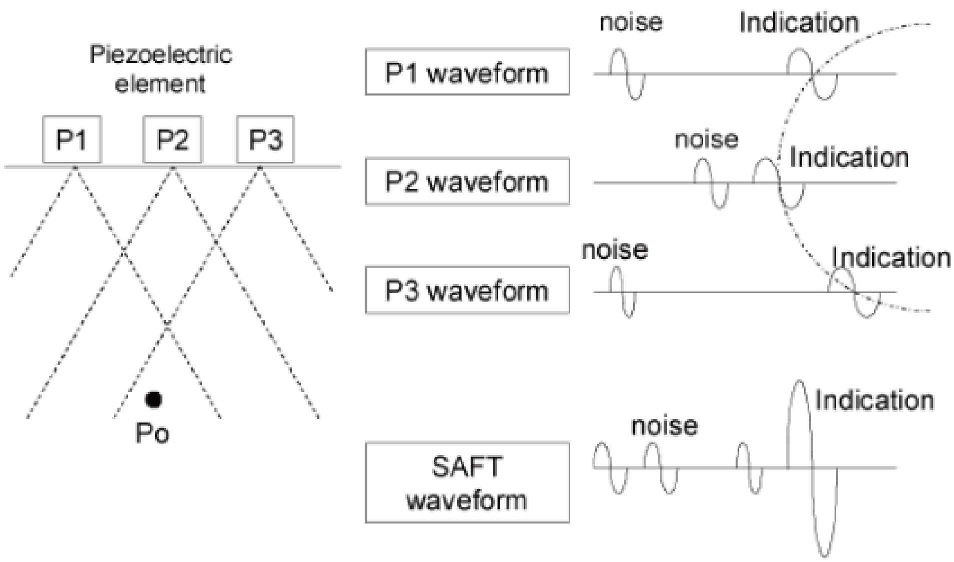


Figure 12: Illustration of SAFT principle. Illustration is taken from (Toshiba, 2010).

The spatial propagation characteristic of the waves is the reason for the emergence of hyperbolas in data sets, as indicated by the arc line in the right side of the illustration displayed above. In order to get a clear picture these features should be removed, which is possible by evaluating the raw data with a reconstruction algorithm called Synthetic Aperture Focusing Technique (SAFT). The SAFT reconstruction algorithm has been ready for application in the field and is by now implemented in many commercial equipment's.

An implementation of the phase evaluation and reconstruction calculation of the reflected signal has made the evaluation of the test results even more reliable. The phase analysis is however still in the research and development phase. More knowledge on how elastic waves behave in interfaces with embedded elements is still needed, for an example how the wave penetrate or circulates a cable duct depending on the condition of the grouting. All research has focused on one layer of cable ducts, and more attention needs to be on detecting of the condition in a second or third layer. This would represent the conditions on a NPP containment.

As mentioned above research has been made with focus on grouted cable ducts. Below an example of the results is shown.

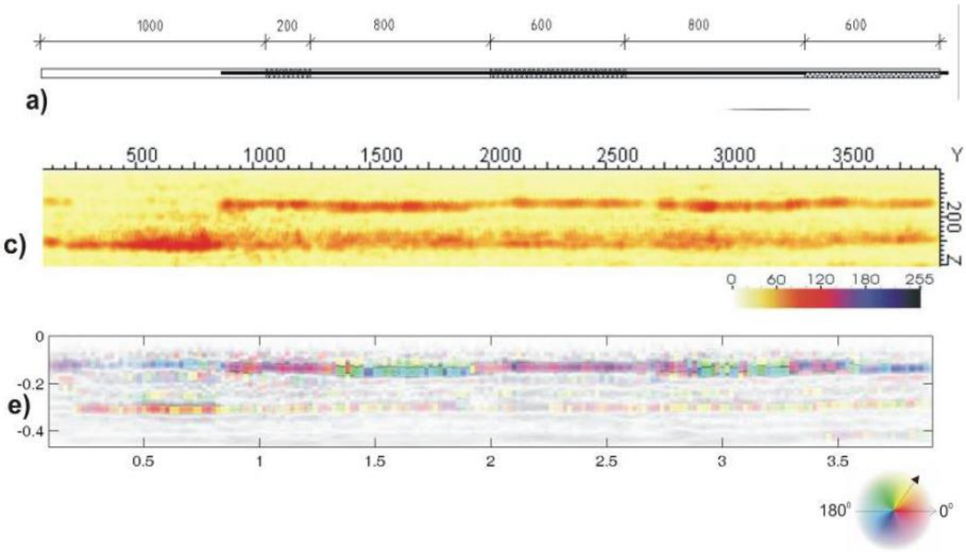


Figure 13: Illustration of structure with embedded cable duct inspected with ultrasonic waves. Illustration is taken from (Krause , et al., 2008).

In a) a sketch of the cable duct with the intended faults is shown. In c) the results are shown with a SAFT reconstruction algorithm applied. In e) the same results are shown, but this time a phase evaluation of the reflected wave pulses has been shown.

The phase change for ultrasonic waves would result in a 180° phase shift if the wave pulses reach an interface with air, and a phase change of 0° if the interface is steel.

The method looks promising and literature predicts that reflections can be received from depths up to 1.7 meters, only limited by poor surface conditions or by dense reinforcement layers.

In 2014, BAM performed measurements at Barsebäck unit 1 with Ultrasonic Pulse Echo equipment similar to the one used during the CONMOD project, but with a modern version, and with the analysis options mentioned above.

The measurements were made as several parallel lines, creating a 3D picture. The conclusion from the measurements was that the surface conditions with the cracks in the outer part, and the dense reinforcement affected the results negatively. No clear reflections were obtained from depths deeper than the outer reinforcement at a depth of 80 mm. Hence it was not possible to detect the cable ducts in the measurements.

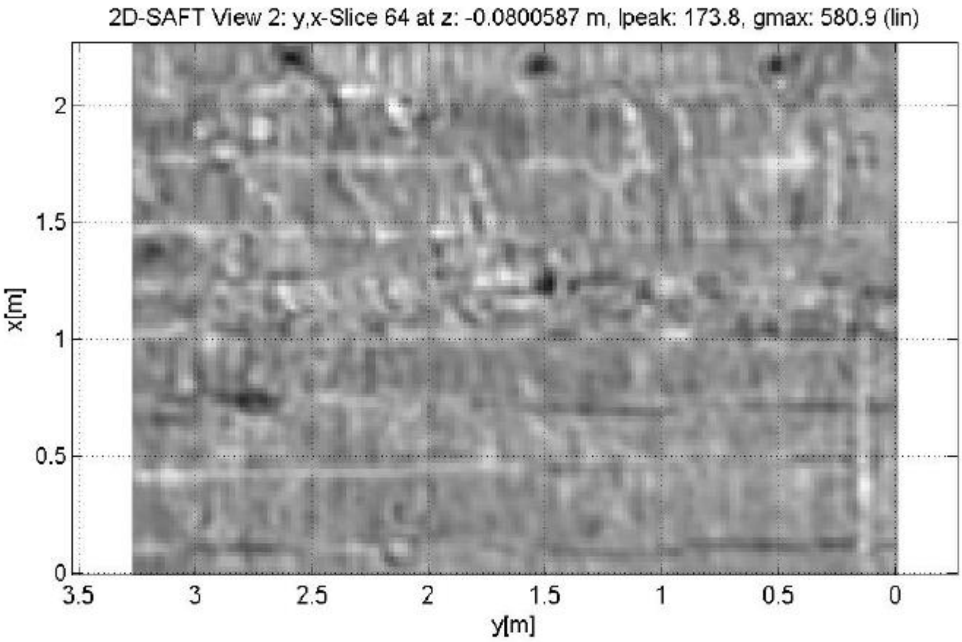


Figure 14: Results from measurements at Barsebäck with UPE and SAFT reconstruction algorithm. Illustration is from (CONSAFESYS, 2015).

In the figure above reflections from a depth of 80 mm are provided. The horizontal reinforcement can be seen as brighter than then horizontal lines. The darker areas are reflections that cannot be assigned for.

In another test, a core was drilled from the inside of the containment, until the steel liner. The objective was to see if it was possible to detect this artificial "void" from the outside of the containment by use of UPE and use of a phase evaluation algorithm. The conclusion of this test was also that no conclusive results could be obtained, probably also caused by the surface near cracks and dense reinforcement.

Another development in ultrasonic measurements it the development of a new type of equipment using an ultrasonic array, A1040 MIRA – Acoustic Control Systems (ACSYS). The difference between the UPE and MIRA is that at the MIRA there are 12 groups of transducers that are both capable of sending and receiving pulses. Within one measuring point the equipment automatically lets each group send and receive pulses in turn. In this way a total of 132 single scans are recorded sequentially and processed to reconstruct a SAFT image.

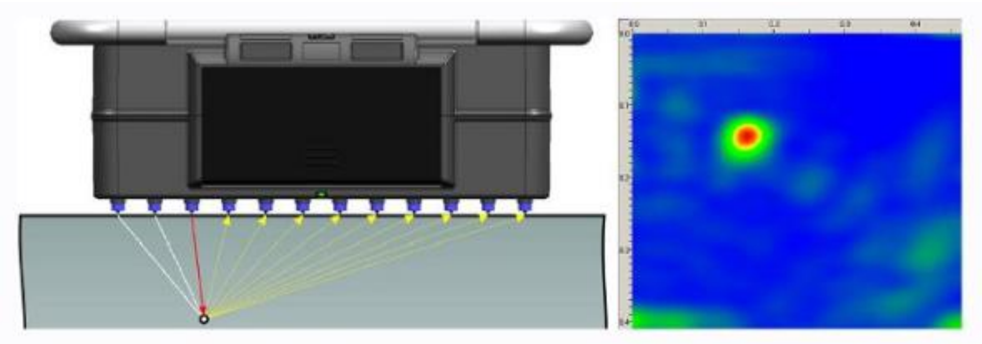


Figure 15: Schematic illustration of some of the travel paths of the sound pulse of on transmitter and all receiving positions. To the right the result a SAFT image is given. Illustration is from: http://www.pcte.com.au/mira-ultrasonic-pulse-echo-imaging

Best results are still obtained if several measurements are combined in a single line or if several lines are stacked together to create a 3D picture.

In 2011 FORCE Technology (FORCE, B1: Measurements 2011 Summary Report, 2013) made some preliminary measurements with a MIRA equipment at Barsebäck unit 1. The conclusion from the trail tests was that reflections could be obtained from reinforcement, cable duct, steel liner and backside. It was however not possible to get all reflections with the same setting or in all positions. The spacing of the measurements was coarse (up to 250 mm) and in grids. The equipment did however look promising.

In 2014 BAM made a more detailed investigation with a similar equipment at Barsebäck unit 1 (CONSAFESYS, 2015). BAM used a spacing of 25 mm, but did not perform measurements in grid, only as single lines. The reconstructed data mostly show reflections from reinforcement, and in a single case maybe also from a cable duct. No conclusive reflections were received from the liner or back side. It was concluded that the MIRA equipment was not capable of detecting the liner, and that the measurements in general were in agreement with the measurements carried out with the UPE method.

- O -

6 References

Baggens, O., & Ryden, N. (2015). Systematic errors in impact-echo thickness estimation due to near field effects. *NDT&E International 69*, 16-27.

Baggens, O., & Ryden, N. (2015-2). Poissons´s ration form polarization of acoustic zero-group velopcity Lamb mode. *The Journal of the Acoustical Society of America 138*.

BAM. (2013). *Non-destructive Testing of NPP Concrete structures.* Berlin: BAM Federal Institute for Materials Research and Testing.

BAM. (2014). *Demonstration of State of the Art NDT-methods for Nuclear Concrete Reactor Containments.* Berlin: BAM Federal Institute for Materials Research and Testing.

COMMISSION, U. S. (2009, Decemeber 4). Retrieved from http://pbadupws.nrc.gov/docs/ML0933/ML093360229.pdf

CONMOD. (2005). *CONMOD - Main report.* Brøndby: FORCE Technology.

CONSAFESYS. (2015). *Main Project Summary Report.* Lund: ScanScot Technology.

FORCE, T. (2012). *O3: Measurements 2010 Summary Report.* Lund: Scanscot Technology.

FORCE, T. (2013). *B1: Measurements 2011 Summary Report.* Lund: Scanscot Technology.

GE. (2015, 11 26). Retrieved from https://www.gemeasurement.com/sites/gemc.dev/files/phosphor_imaging_plates_brochure_english_0.pdf

JME. (2015, 11 26). Retrieved from http://www.jme.co.uk/JME-Products-Betatron-9mev.aspx

Krause , M., Gräfe, B., Mielentz , F., Milmann, B., Friese, M., Wiggenhauser, H., & Mayer, K. (2008). Ultrasonic Imaging of Post-tensioned Concrete Elements: New Techniques for Reliable Localization of Grouting Defects.

Nordic Innovation. (2004). *A Practical Guide to Non-Destructive Examination of concrete.* Brøndby: FORCE Technology.

Olson, L. (2010). INNOVATIONS IN BRIDGE SUPERSTRUCTURE CONDITION. *ASNT Structural Materials Technology Conference 2010, LaGuardia, New York*.

Radiabeam. (2015, 11 26). Retrieved from http://radiabeam.com/upload/catalog/pdf/1423164779141212_betatron_datasheet.pdf

Toshiba. (2010). Application of 3D Ultrasonic Inspection System for pipe wall thinning. *E-Journal of Advanced Maintenance - New Technology, Vol.1, No.4, NT17*. Retrieved from http://www.jsm.or.jp/ejam/Vol.1.No.4/NT/17/article.html

Wikipedia. (2015, 11 26). Retrieved from https://en.wikipedia.org/wiki/Flat_panel_detector

Appendix 1 – Overview of NDT test and positions in each test location.

In the following information is provided about the NDT made in each position. In the first column the various NDT methods are stated. The other information highlighted with bold letters constitute the file names of the measurements. The raw data file and in some cases also analysed results are still available from the CONMOD project.

GPR	Ground Penetrating Radar
HECR	High Energy Computed Radiography
IE	Impact Echo
MASW	Multichannel Analysis of Surface Waves
SASW	Spectral Analysis of Surface Waves
CORES	Drilled Cores
UPE	Ultrasonic Pulse Echo
UK 1401	Ultrasonic measurements in the near surface area
PUNDIT	Ultrasonic measurements in the near surface area or through cores.
RH	Relative Humidity measured in boreholes at site

Position 1						
Main coordinates	**Level +122, 0 deg.**					
Investigations and Coordinates						
GPR	***P1 V01***	Start 121,5 Upwards End 122,65	***P1 V06***	Start 122,46 Upwards End 124,13		
	There is 6 files but location is only known for above given.					
HECR	***Pos1 c1***	0°+900mm, 122.20				
	There is a total of 2 files. Source is outside reactor.					
IE	***IE pos 101***	X or Level (m) : pkt 4 = 121,5 m Y or Angle (clock wise): ca. 0 deg	***IE pos 102***	X or Level (m) : 123,45 m Y or Angle (clock wise): 0 deg - 0,1 mod 0 deg and towards 90 deg	***IE pos 103***	X or Level (m) : 124,25 og 5,5 m down Y or Angle (clock wise): 0 deg + 1,9 m towards 90 deg
MASW	***MASW pos 101***	X or Level (m) : Ch1 i 122,80 og down Y or Angle (clock wise): ca. o deg	***MASW pos 102***	X or Level (m) : 123,45 Y or Angle (clock wise): 0 deg - 1,9 m towards 0 deg		
SASW	***P1 H3 F&R***	No position is given	***P1 H6 F&R***	No position is given		
CORES	-	No cores have been drilled in this position				
UPE	Several files. Starting position is only given for a few. Called position 1 even if it is made at 180 deg.					

Position 2								
Main coordinates	**Level +112, 0 deg.**							
Investigations and Coordinates								
GPR	***P2 V02***	Start 114,47 Downward End 111,67	***P2 H01***	Start Centre of pipe entry	Towards 0 deg.	Length 3,9 m		
	There is 3 files but location is only known for above given.							
HECR	***Pos2, c1***	360°-2337, 113.525	***Pos2, c2***	360°-2689, 113.625	***Pos2, c3***	360°-2789, 113.325	**Pos2, c4**	360°-2991, 113.525
	There is a total of 10 files. 2 for C1, C2 and C3, and 4 for C4. Source is inside reactor.							
IE	***IE pos 201***	X or Level (m) : 112,5 Y or Angle (clock wise): cl pipe -4,0 m towards 0 deg	***IE pos 202***	X or Level (m) : 114,5 and down per 0,5 m til 111,5 Y or Angle (clock wise): cl pipe -0,50 m towards 0 deg			***IE pos 203***	X or Level (m) : Pkt. 1 i +113,0 Y or Angle (clock wise): cl pipe +0,50 m towards 270 deg
MASW	***MASW pos 201***	X or Level (m) : ch1. 112,41 Y or Angle (clock wise): cl pipe +0,30 m towards 270 deg	***MASW pos 202***	X or Level (m) : ch1. 113,68 Y or Angle (clock wise): cl pipe +1,0 m towards 270 deg				
SASW	***P2 H3***	No position is given	***P2 H6***	No position is given	***P2 V3***	No position is given	***P2 V6***	No position is given
CORES	Tested for:	RH % % cl/concrete weight						

Position 3								
Main coordinates	**Level +112, 270 deg.**							
Investigations and Coordinates								
GPR	***P3 V01***	Start 113,8 Downward End 111,82	***P3 H01***	Start 0,255 from entrance wall	Towards 0 deg.	Length 1,9 m		
	There is 4 files but location is only known for above given.							
HECR	***Pos3, c1***	270°+2400, 112.325	***Pos3, c2***	270°+2098, 112.325				
	There is a total of 8 files. 4 for C1 and 4 for C2. Source is inside reactor.							
IE	***IE pos 301***	X or Level (m) : 112.6m Y or Angle (clock wise): 270 + ?	***IE pos 302***	X or Level (m) : 112.6m+1,2 og down Y or Angle (clock wise): 270 + ?			***IE pos 303***	X or Level (m) : 112.6m+0,4 Y or Angle (clock wise): 270 + ?
MASW	***MASW pos 301***	X or Level (m) : 112.6m Y or Angle (clock wise): 270 + ?	***MASW pos 302***	X or Level (m) : ch1=111.5+2.3m ch2=11.5+0.2m Y or Angle (clock wise): edge of entrance + 1m towards 360 deg			***MASW pos 303***	X or Level (m) : ch1=111.5+2.3m ch2=11.5+0.2m Y or Angle (clock wise):Edge of entrance + 1m towards 360 deg
SASW	***P3 H3***	No position is given	***P3 H6***	No position is given	***P3 V3***	No position is given	***P3 V6***	No position is given
	Some coordinates are however given in the document "Concrete Quality. Thickness and liner bond" level 122 m by sluss. It is however not sure if the given coordinates represents these datafiles as the names are not consistent.							
CORES	-	No cores have been drilled in this position						
Pundit	***In-direct UPV***	Data shown in "Concrete Quality. Thickness and liner bond" level 122 m by sluss, but coordinates are not given.						

Position 4										
Main coordinates	**Level +102, 0 deg.**									
Investigations and Coordinates										
GPR	***P4 V01***	Start 103,38 Downward End 101,04	***P4 H01***	Start 1 m left of centre E24	Towards 0 deg.	Length 1,72 m				
HECR	***Pos4, c1***	360°-4635, 102.65	***Pos4, c2***	360°-4335, 102.65	***Pos4, c3***	360°-4035, 102.65	***Pos4, c4***	360°-3735, 102.65	***Pos4, c5***	360°-3435, 102.65
	Source is inside reactor									
	Pos4, c1+440mm	360°-4645, 102.56	***Pos4, c6***	360°-3955, 101.95	***Pos4, c7***	360°-3626, 101.95	***Pos4, c8***	360°-3297, 101.95		
	Source is outside reactor. There is a total of 18 files.									
IE	***IE pos 401***	X or Level (m) : 101.875 Y or Angle (clock wise): 1m towards 0 from cc E24	***IE pos 402***	X or Level (m) : 101.875+1,5 Y or Angle (clock wise): 2m towards 0 from cc E24			***IE pos 403***	X or Level (m) : 101.875+0,4 Y or Angle (clock wise): 2m towards 0 from cc E24		
MASW	***MASW pos 401***	X or Level (m) : 101.875 Y or Angle (clock wise): 3,5 m fra cc pipe penetration	***MASW pos 402***	X or Level (m) : 101.875+1,5 Y or Angle (clock wise): 2,0 m from cc pipe penetration						
SASW	***P4 V3***	No position is given	***P4 V6***	No position is given						
CORES	Tested for:	RH %								

Position 5

Main coordinates **Level +123.5, 270 deg.**

Investigations and Coordinates

GPR	***R613 V01***	Start 124,06 Downward End 121,74	***R613 H01***	Start 0.165 left of 270 deg fix. Towards 0 deg. Length 3,7				
	There is 3 files but location is only known for above given.							
HECR	***Pos5, c1***	270º-296, 124.05	***Pos5, c2***	270º-296, 123.00	***Pos5, c3***	270º-296, 123.85	***Pos5, kf***	270º-628, 124.05
	A total of 10 files. Source is outside reactor.							
IE	***IE pos 501***	X or Level (m) : 124.25-0.4m Y or Angle (clock wise): 180-1.89m towards 90 deg	***IE pos 502***	X or Level (m) : 124.25-0.7m Y or Angle (clock wise): 180-0.89m towards 90 deg (start) 0.2 m towards 90	***IE pos 503***	X or Level (m) : 124.25-2.3m Y or Angle (clock wise): 180-0.89m towards 90 deg (start) 0.2 m towards 90		
	IE pos R613 01	X or Level (m) : 122.5+1.2m down Y or Angle (clock wise): 270 + 2.5m towards 360	***IE pos R613 02***	X or Level (m) : 122.5+1.1 towards 270 deg Y or Angle (clock wise): 270 + 2.5m towards 360	***IE pos R613 03***	X or Level (m) : 121.85 towards 270 deg Y or Angle (clock wise): 270 + 2.5m towards 360		
MASW	***MASW pos 501***	X or Level (m) : 124.25-0.3m down Y or Angle (clock wise): 180-1.89m towards 90 deg	***MASW pos 502***	X or Level (m) : Ring beam - 0.7m Y or Angle (clock wise): 180 -0.89 (Ch1) towards 90 deg	***MASW pos 503***	X or Level (m) : Ringbalk - 2.3m Y or Angle (clock wise): 180 -0.89 (Ch1) towards 90 deg		
SASW	***P5 H3 upper***	No position is given	***P5 H3 Lower***	No position is given	***P5 V3 upper***	No position is given	***P5 V3 Lower***	No position is given
	P5 R613 crack	No position is given	***P5 R613 adjacent 2 cracks***	No position is given	***P5 R613 good concrete***	No position is given		
CORES	***P5 C1, C2, C3, C4 and C5***	Some position accoring to drawings.						
	Tested for	RH %						
		Capilar suctions, chemical bound water, cement content, TGA and CaO, sorption curves, transport properties, chlorid difusion						
		Thin section analysis						
		% cl/concrete weight						
		E_{dyn} and compressive strength						
RH	According to drawing							
Remark	IE measurement have been made both at 180 deg and 270 deg.							
	MASW has only been made at 180 deg.							
	SASW measurement have been made both at 180 deg and 270 deg.							

Position 6

Main coordinates **Level +106, 270 deg.**

Investigations and Coordinates

GPR	***P6 V02***	Start 107,29 Downward 105,49 111,67	***P6 H01***	Start 270 deg + 0.86 Towards 180 deg Length 2,64 m				
	There is 4 files but location is only known for above given.							
HECR	-	No HECR has been performed in this position						
IE	***IE pos 601***	X or Level (m) : 107m Y or Angle (clock wise): 270	***IE pos 602***	X or Level (m) : 106,4m Y or Angle (clock wise): 270+0,4 m				
MASW	***MASW pos 601***	X or Level (m) : 106 Y or Angle (clock wise): 270+1.5	***MASW pos 602***	X or Level (m) : 107,4 Y or Angle (clock wise): 270				
SASW	***P6 H3***	No position is given	***P6 H6***	No position is given	***P6 V3***	No position is given	***P6 V6***	No position is given
CORES	***P6 C1, C2, C3, C4 and C5.***	Some positions according to drawing						
	Tested for	RH %						
		Capilar suctions, chemical bound water, cement content, TGA and CaO, sorption curves, transport properties, chlorid difusion						
		Thin section analysis						
		% cl/concrete weight						
		Compressive strength						
		E-modulus						
		Splitting strength/tensile strength						
		V_p and E_{dyn}						
Pundit	***In-direct UPV***	Data shown in "Concrete Quality. Thickness and liner bond" level 122 m by sluss, but coordinates are not given.						

Position 7

Main coordinates **Level +93.5, 180 deg.**

Investigations and Coordinates

GPR	***P7 V03***	Start 96,92 Downward End 95,376						
	There is 4 files but location is only known for above given.							
HECR	-	No HECR has been performed in this position						
IE	***IE pos 701***	X or Level (m) : 93.969 Y or Angle (clock wise): 180 agains 90	***IE pos 702***	X or Level (m) : 94.369 Y or Angle (clock wise): 180 +1.4 m agains 90				
MASW	***MASW pos 701***	X or Level (m) : 93.969 Y or Angle (clock wise):180 - 0.8m	***MASW pos 702***	X or Level (m) : 94.969 Y or Angle (clock wise): 180-1.8m				
SASW	***P7 H3 For***	No position is given	***P7 H6 For***	No position is given	***P7 V3 For***	No position is given	***P7 V6 For***	No position is given
CORES	***P7 C1, C2, C3***	Some positions according to drawing						
	Tested for	RH %						
		% cl/concrete weight						
		Compressive strength						
		E-modulus						
		V_p and E_{dyn}						
RH	According to drawing.							
UK1401	Position is not given							

Position 8a

Main coordinates **Level +131, 140 deg.**

Investigations and Coordinates

GPR	***P8 V03***	Start 2340 above edge Downward End 175 above klak	***P8 H03***	Start 110 mm right of left edge Towards 90 deg. Length 1,946				
HECR	-	No HECR has been performed in this position						
IE	***IE pos 802***	X or Level (m) : 2.5m upper edge Y or Angle (clock wise):ca135 - midt edge (1250mm)						
MASW	***MASW pos 802***	X or Level (m) : 2.5m upper edge Y or Angle (clock wise): ca. 135 - mid edge (1250mm)	***MASW pos 803***	X or Level (m) :1.1mupper edge Y or Angle (clock wise): ca 140? -50mm from edge (1200 from vertical line 9				
SASW	***P88 H3 FOR***	No position is given	***P88 H6 FOR***	No position is given	***P88 V3 For***	No position is given	***P88 V6 F(***	No position is given
CORES	-	No cores have been drilled in this position						
RH	According to drawing							

Position 8b

Main coordinates		**Level +131, 270 deg.**										
Investigations and Coordinates												
GPR	***P8 V01***	Start	214 below	Downward	End	1192 below roof	***P8 H01***	Start	270 deg + 0.66	Towards 180 deg	Length	1.7695 m
HECR	***Pos8, c1***	315°+465, 100.08										
	Source is inside reactor.											
IE	***IE pos 801***	X or Level (m) : 130,72 lower edge roof -0,25 m										
		Y or Angle (clock wise): 270 deg - 1,0 m og towards 180 deg										
MASW	***MASW pos 801***	X or Level (m) : 130,72 lower edge roof-0,40 m										
		Y or Angle (clock wise): cl pipe +0,30 m towards 270 deg										
SASW	***P8 H3 FOR***	No position is given				***P8 H6 FAOR***	No position is given		***P8 H6 FBOR***	No position is given	***P8 V3 FOR***	No position is given
CORES	***P8 C1, C2, C3***	Some positions according to drawing										
	Tested for	RH %										
		% cl/concrete weight										
		Compressive strength										
		E-modulus										
		Splitting strength/tensile strength										
		V_p and E_{dyn}										
RH	According to drawing.											

Position 9

Main coordinates		**Level +111-116, 135 deg.**				
Investigations and Coordinates						
GPR	***PEL V01***	Position not known				
HECR	***Pos9, c1***	270°+308, 117.288				
	Source inside reactor.					
IE	***IE pos 901***	X or Level (m) :0.2m below U-beam	***IE pos 902***	X or Level (m) : 1,0m below U-beam		
		Y or Angle (clock wise): 0.8m towards 180 deg from 2. pilaster R352		Y or Angle (clock wise): 1,4m towards 180 deg from 2. pilaster R352		
MASW	***MASW Vert 01***	X or Level (m) : 0.4 m belwo U beam				
		Y or Angle (clock wise): 0.8 m towards 180 deg from 2. pilaster R352				
SASW	***P9 H3 FOR***	No position is given	***P9 V3 FOR***	No position is given	***P9 V6 FOR***	No position is given
CORES	-	No cores have been drilled in this position				

Position 10

Main coordinates		**Level +126.5, 230-270 deg.**		
Investigations and Coordinates				
GPR	*Non have been found*			
HECR	-	No HECR has been performed in this position		
IE	***IE pos 1001***	X or Level (m) : 127,1 - 0,25 m	***IE pos 1002***	X or Level (m) : 127,1 - 0,25 m
		Y or Angle (clock wise): 270 deg - 5,385 m towards 0 deg and test mod 270		Y or Angle (clock wise): 270 deg - 4 m towards 0 deg and test towards270
MASW	***MASW pos 1001***	X or Level (m) : 127,1 - 0,8 m down towards floor		
		Y or Angle (clock wise): Center in 270 deg - 2,88, ch1 closest towards 0 deg		
SASW	*Non have been found*			
CORES	***P10 C1, C2, C3***	Some positions according to drawing		
	Tested for	RH %		
		% cl/concrete weight		
		Thin section analysis		
RH	According to drawing.			

Position 11

Main coordinates		**Level +116.5, 270 deg.**
Investigations and Coordinates		
CORES	***P11 C1***	Some positions according to drawing
	Tested for	RH %
		Compressive strength
		E-modulus
		Splitting strength/tensile strength
		V_p and E_{dyn}
RH	According to drawing.	

Position 12 - Base slab side		
Main coordinates		Level +91, 180 deg.
Investigations and Coordinates		
CORES	*P12 C1*	Might be main coordinates.
	Tested for	RH %
		% cl/concrete weight
		Compressive strength
		E-modulus
		Density
		V_p and E_{dyn}

Position 13		
Main coordinates		Level +110, 157 deg.
Investigations and Coordinates		
CORES	*P13 C3 (C2 & C4)*	Might be main coordinates.
	Tested for	% cl/concrete weight
		Compressive strength
		E-modulus
		Density
		V_p and E_{dyn}

Position 14 - Inner liner wall		
Main coordinates		Level +115, 112.5 deg.
Investigations and Coordinates		
CORES	*P14 C1 (C2 & C4)*	Might be main coordinates.
	Tested for	RH %
		% cl/concrete weight
		Compressive strength
		E-modulus
		Density
		V_p and E_{dyn}

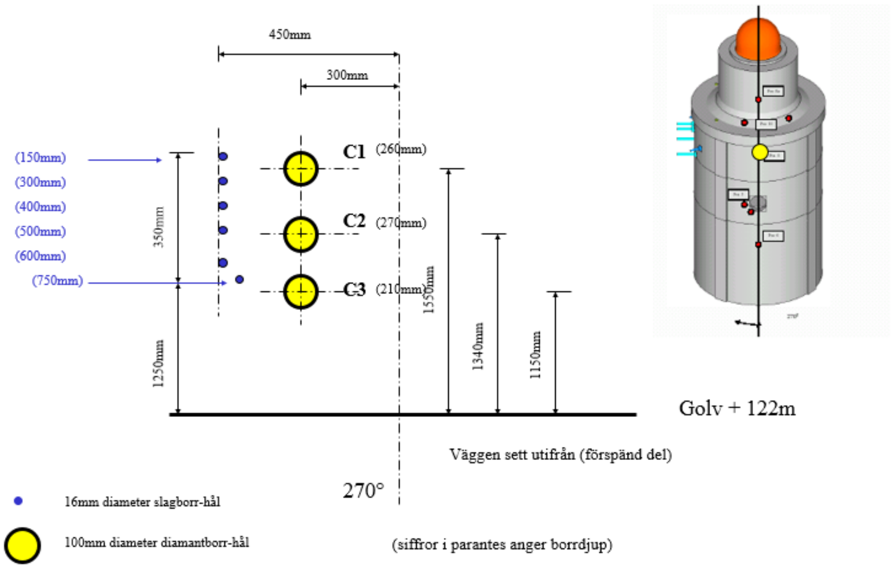
Position 15 - Biological shield (Outside)		
Main coordinates		Position 5.2-1, 335 deg.
Investigations and Coordinates		
CORES	*P15 C1*	Might be main coordinates.
	Tested for	% cl/concrete weight
		Compressive strength
		E-modulus
		Density
		V_p and E_{dyn}

Appendix 2 – Overview of material test positions in each test location.

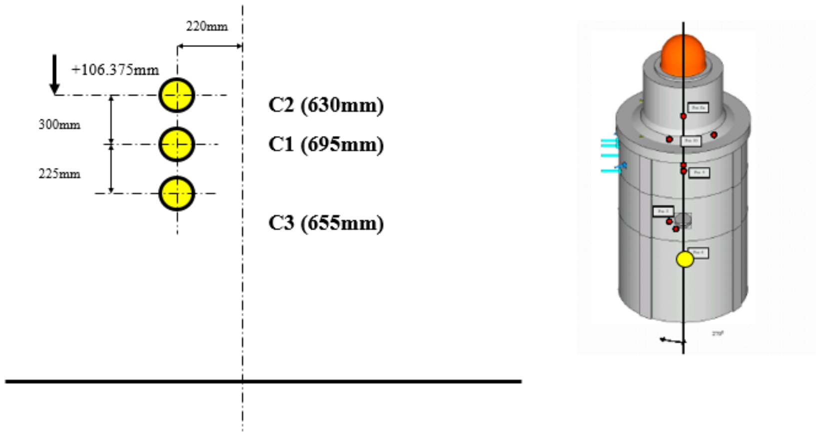
In the following sketches are given for the position of cores drilled and holes made for relative humidity measurements for each test location where material properties have been tested with destructive testing.

For position 2, 4, 12, 13, 14 and 15 there is no information about where the cores have been drilled. Hence no sketch have been made for these areas.

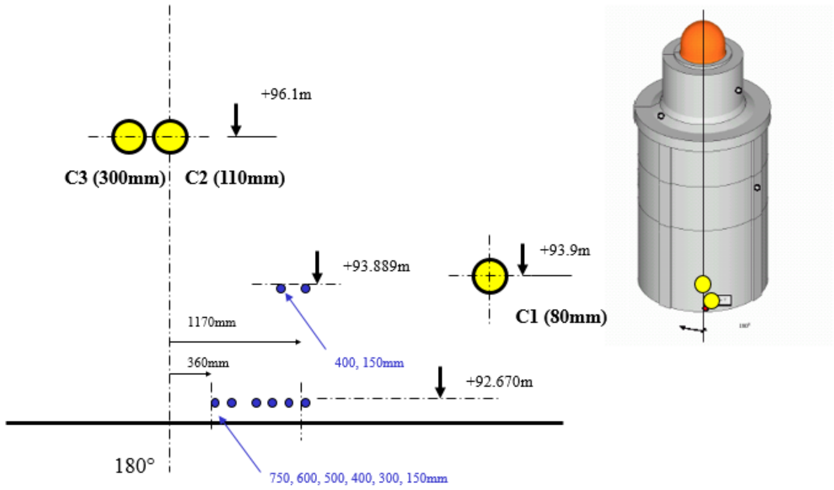
Position 5 – Materialprovning. Kärnprov och fuktprov borrpositioner i R6.13



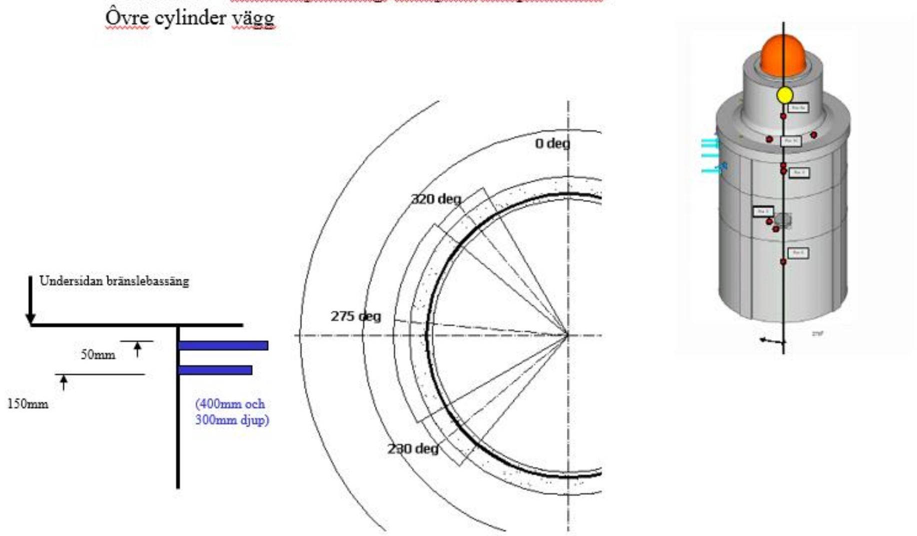
Position 6 – Materialprovning. Kärnprov borrpositioner. Nedre cylindervägg



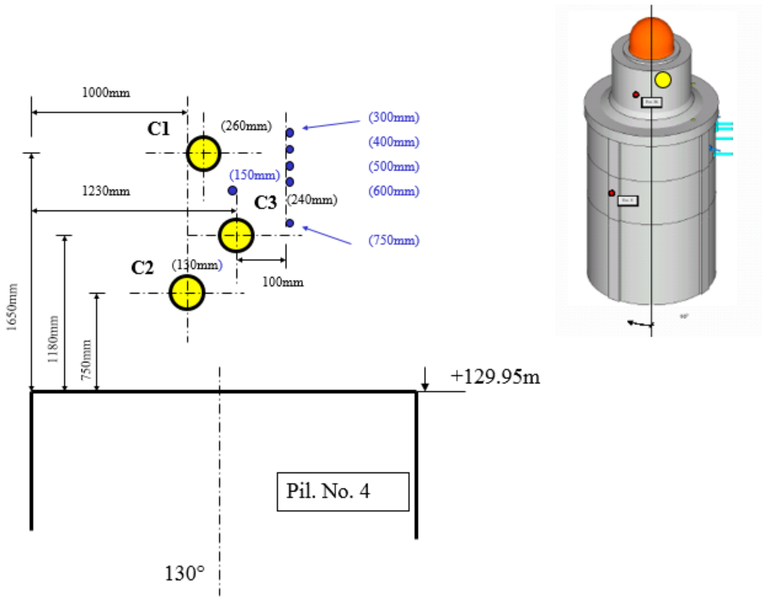
Position 7 – Materialprovning. Kärnprov och fuktprov borrpositioner. Nedre cylindervägg



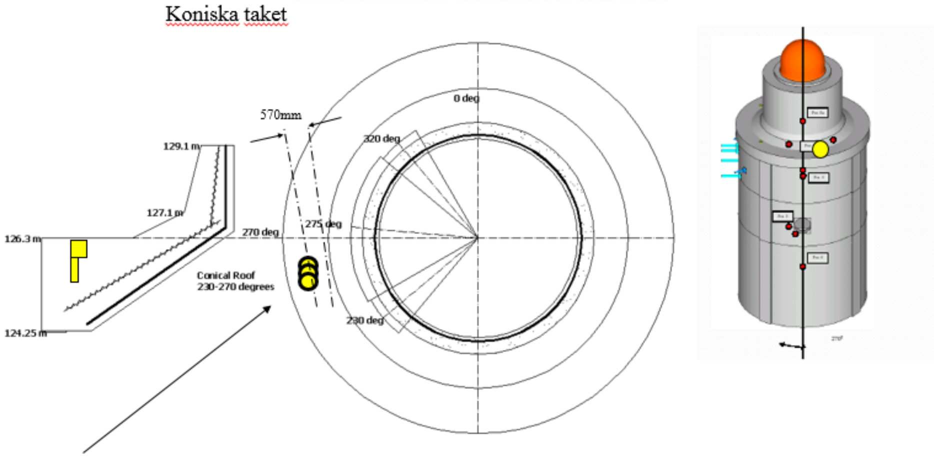
Position 8a – Materialprovning. Fuktprov borrpositioner. Övre cylinder vägg



Position 8b – Materialprovning. Kärnprov och fuktprov borrpositioner. Övre cylinder vägg



Position 10 – Materialprovning. Kärnprov borrpositioner. Koniska taket

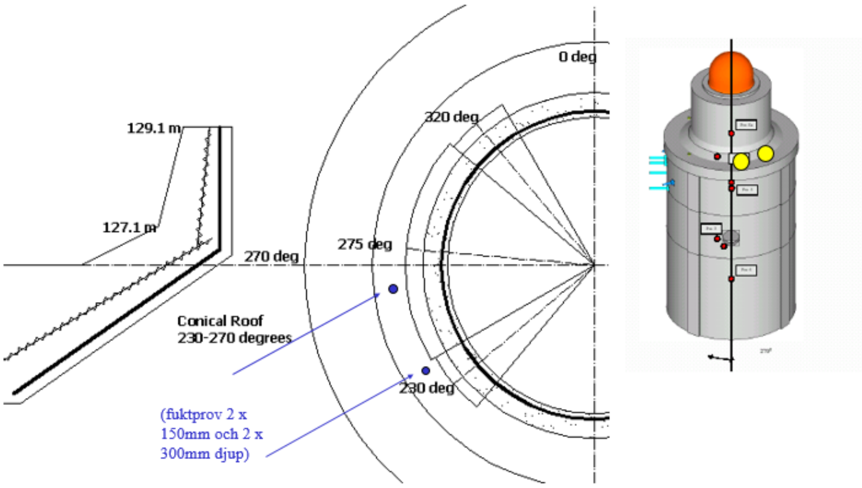


C1 diameter 100mm, djup 80mm/ C1' diameter 48mm, djup 310mm (390mm från golv)

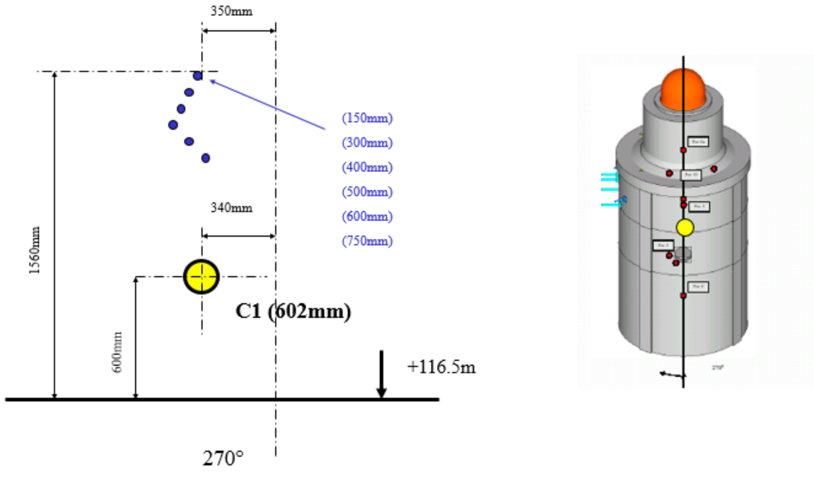
C2 diameter 100mm, djup 80mm/ C2' diameter 48mm, djup 300mm (380mm från golv)

C3 diameter 100mm, djup 80mm/ C3' diameter 48mm, djup 135 mm

Position 10 – Materialprovning. Fuktprov borrpositioner. Koniska taket



Position 11 – Materialprovning. Kärnprov och fuktprov borrpositioner. Nedre cylindervägg



NON-DESTRUCTIVE TESTING OF CONCRETE STRUCTURES IN NUCLEAR APPLICATIONS

Non-destructive testing methods are vital to verify the integrity of the containment of a nuclear power plant. The design of the Nordic nuclear power plants with a thick concrete structure with the liner cast in concrete poses a great challenge for non-destructive testing (NDT) methods.

A conclusion of the project is that the most promising NDT methods for nuclear applications are ground penetrating radar (GPR), high energy computed radiography (HECR) and multichannel analysis of surface waves (MASW).