Unclassified **NEA/CSNI/R(97)28**

Organisation de Coopération et de Développement Economiques
Organisation for Economic Co-operation and Development

OLIS : 11-Feb-1998
Dist. : 13-Feb-1998

English text only

NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

Cancels & replaces the same document:
distributed 13-Feb-1998

DEVELOPMENT PRIORITIES FOR NDE OF CONCRETE STRUCTURES IN NUCLEAR PLANTS

NEA WORKSHOP
Risley, United Kingdom, 12 November 1997

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Document incomplet sur OLIS
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NEA/CSNI/R(97)28
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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of scientists and engineers. It was set up in 1973 to develop and co-ordinate the activities of the Nuclear Energy Agency concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations. The Committee's purpose is to foster international co-operation in nuclear safety amongst the OECD Member countries.

CSNI constitutes a forum for the exchange of technical information and for collaboration between organisations which can contribute, from their respective backgrounds in research, development, engineering or regulation, to these activities and to the definition of its programme of work. It also reviews the state of knowledge on selected topics of nuclear safety technology and safety assessment, including operating experience. It initiates and conducts programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach international consensus in different projects and International Standard Problems, and assists in the feedback of the results to participating organisations. Full use is also made of traditional methods of co-operation, such as information exchanges, establishment of working groups and organisation of conferences and specialist meeting.

The greater part of CSNI's current programme of work is concerned with safety technology of water reactors. The principal areas covered are operating experience and the human factor, reactor coolant system behaviour, various aspects of reactor component integrity, the phenomenology of radioactive releases in reactor accidents and their confinement, containment performance, risk assessment and severe accidents. The Committee also studies the safety of the fuel cycle, conducts periodic surveys of reactor safety research programmes and operates an international mechanism for exchanging reports on nuclear power plant incidents.

In implementing its programme, CSNI establishes co-operative mechanisms with NEA's Committee on Nuclear Regulatory Activities (CNRA), responsible for the activities of the Agency concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with NEA's Committee on Radiation Protection and Public Health and NEA's Radioactive Waste Management Committee on matters of common interest.

FOREWORD

This workshop was hosted by the UK Health and Safety Executive Nuclear Safety Division. It was sponsored by Principal Working Group 3 (PWG-3), of the NEA CSNI. It was organised by AEA Technology and held at AEA Technology Risley.

PWG-3 deals with the integrity of structures and components, and has three sub-groups, dealing with the integrity of metal structures and components, ageing of concrete structures, and the seismic behaviour of structures.

A status report on the ageing of concrete NPP structures was prepared during 1995 by a task group to initiate activities in this field under PWG3. The topic of Non Destructive Examination was identified as one of the highest priority issues, and accordingly it was decided to organise this workshop. The other first priority topic was loss of tendon prestress, and a workshop to address this was also organised in 1997.

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DEVELOPMENT PRIORITIES FOR NDE OF CONCRETE STRUCTURES IN NUCLEAR PLANT

Introduction

In a number of civil engineering applications there is evidence of an increasing trend away from the traditional random sampling of concrete for material analysis (by taking cores) to the use of sophisticated non-destructive techniques to support assessments of the in-situ condition of concrete structures. In certain safety related structures within nuclear power plants, coring may not even be an option.

Characteristics of safety related concrete structures in nuclear power plants (in particular thickness of sections, congested reinforcement and restricted access) limits the application of NDE techniques. Quantification of these limitations, and developments of methods to overcome them, is driving research programmes in a number of OECD Member States.

OECD/NEA Principal Working Group 3 (PWG3) is supporting a number of activities in the area of ageing management of concrete structures in nuclear plant. The definition of requirements for development of NDE techniques for concrete structures where there are thick sections, or where access is difficult, is considered by PWG3 to be a high priority activity. Future activities are expected to include workshops on instrumentation and monitoring, and on analytical methods for assessing degraded structures.

The overall objective of the Workshop was therefore to help focus future activities relating to NDE of safety related concrete. It facilitated the exchange of current experience in order to understand existing and emerging NDE capabilities, and will assess the cost and benefit of developments in NDE techniques.

Scope

The workshop was directed towards application of NDE to support the engineering assessment of safety related concrete structures found in nuclear power plant and nuclear chemical plant. These structures are characterised by thick sections, heavy reinforcement and limited accessibility (often single sided access only).

The workshop focused on what was believed to be the more promising techniques (RADAR, acoustic, radiography) for assessing the condition of existing structures. Complementary assessment tools such as instrumentation/ systems for continuous monitoring of structural performance or destructive/semi-destructive tests were not considered in any detail.

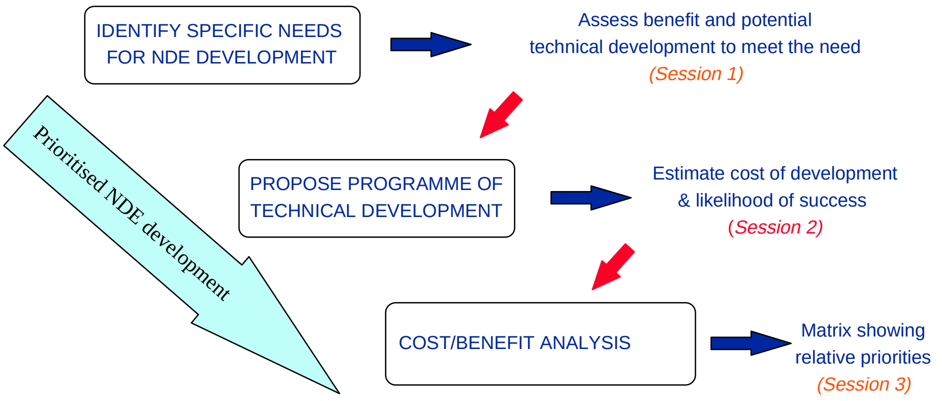
DRAFT REPORT

As part of the preparations for the workshop, a draft report was circulated to all participants. This formed the basis of much of the discussion. This draft report has been updated in the light of the workshop discussion, and will be considered further by the PWG3 concrete sub group and PWG3 before being submitted for CSNI approval and issued as a CSNI report.

APPROACH FOR ASSESSING DEVELOPMENT PRIORITIES

The approach taken for assessing development priorities is shown schematically below:

PROCESS FOR PRIORITISING
NDE DEVELOPMENT



In Session 1 detailed consideration was given to potential uses of NDE in safety related concrete structures, the extent to which these can be met using existing techniques and the potential for application of emerging techniques. This gives rise to a series of practical needs which must be addressed to advance the potential for routine application of NDE techniques. In order to assist prioritisation, the ‘benefit’ associated with each need has been qualitatively assessed.

Three groups of NDE techniques were identified as having the greatest potential to make significant progress towards meeting the identified needs: radar, acoustic methods and radiography. The existing capability of these techniques was reviewed and the cost of technical developments to address perceived short-comings was qualitatively assessed.

A summary matrix of NDE developments, plotting benefit against cost, provided the basis for ranking development priorities.

Session 1: NUCLEAR NDE REQUIREMENTS

The objective of this session was to specify what International Regulators/ Plant Operators want NDE techniques to deliver (ie to clarify applications and specify requirements).

Chairman: *Les Smith, Scottish Nuclear, UK*

Rapporteur: *Walter Heep, NOK, Switzerland*

Speakers: **International perspectives on current practice and needs for NDE development**

Richard Judge, AEA Technology, UK
Ken Philipose AECL, Canada
Walter Heep NOK, Switzerland
Jesus Rodriguez GEOCISA, Spain
Wally Norris US NRC, USA
Sergei Nefedov, Federal Nuclear & Radiation Safety Authority, Russia

Session 1: Identifying needs for NDE development

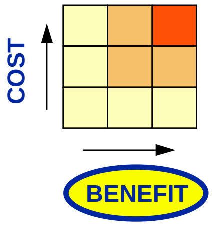
The following table summarises the key applications of NDE in safety related structures, and includes relevant comments made in Workshop discussions. The table identifies those applications where needs for NDE development were identified by the workshop.

OVERVIEW OF NDE APPLICATIONS

Table	Application & Purpose	Comment	Needs identified
1	***Measurement of concrete thickness***, to obtain as built details.	Key input for selected NDE techniques (eg impact echo).	✓
3	***Mapping / sizing of steel reinforcement and tendons*** to establish as built details (including identification of reinforcement laps and couplers).		✓
4	***Detection of corrosion in embedded steel*** (both reinforcement and liners). Corrosion is recognised as a key issue for ageing concrete structures.	A range of electro-chemical techniques for assessing likelihood of corrosion exist. Within the scope of this report, the focus is on the ability to detect loss of steel section, pitting or hydrogen embrittlement	✓
5	***Detection of corrosion in prestressing tendons***.	Comment as above	✓
6	***Detection of voids & inhomogeneity*** (honeycombing), typically to locate construction flaws. Voids in grouted prestressing ducts are a particular issue, as these may lead to corrosion of tendon.		✓
7	***Detection and sizing (depth, width, length) of cracks normal to the surface***	Combinations of techniques may be appropriate: one to detect, one to characterise.	✓

Table	Application & Purpose	Comment	Needs identified
8	***Detection of delamination/ cracks parallel to the surface***		✓
9	***Detection of surface deposits/ visual symptoms of flaws*** which indicate material degradation and support quantification of findings.	Visual inspection generally adequate, but could be enhanced by tools which increase productivity and/or quantify findings.	✓
10	***Measurement of concrete mechanical properties*** (eg strength, stiffness), and identification of spatial variations or ageing effects.	Typically NDE used in conjunction with destructive tests (eg cores) to calibrate results. Looking for NDE techniques which provide relative measures to indicate material property variations with area or time.	✓
2	Measurement of cover to reinforcement to establish as built details	Existing NDE techniques (eg covermeter) adequate for measurement of cover up to 150mm. No specific need identified	✘
11	Detection of changes in porosity/ permeability to assess condition of concrete (presence of flaws)	Variety of permeability tests available; RILEM currently assessing these with objective of developing agreed standard. Outside the scope of this report.	✘
12	Measurement of concrete properties such as humidity and conductivity. Potential uses: to assess risk of corrosion and as input to NDE techniques such as radar	Physical probing generally necessary, and so outside scope of report.	✘

NEED FOR NDE DEVELOPMENT
(Session 1)



ASSESSMENT OF BENEFIT BASED ON:

- **NEED FOR IMPROVED EASE/ SPEED OF APPLICATION**
- **NEED FOR ENHANCEMENT IN CAPABILITY / SENSITIVITY**
- **BREADTH OF APPLICATION**

The following tables provide a summary of those needs for NDE development identified by the workshop, together with an assessment of the benefit which would be gained if these needs are met (high, medium, low).

The ‘Table Number’ column provides a cross-reference to Tables in the Draft Report, which was distributed to delegates in advance of the Workshop.

HIGH BENEFIT NEEDS

Table	Need	Benefit
1	Quantification of capability for measuring concrete thickness for sections > 1.0m thick	H
3	Quantify existing performance capability for mapping / sizing of steel reinforcement and tendons (including identification of reinforcement laps and couplers) with section depth	H
4	Quantify performance limits for detecting corrosion in reinforcement through measurement of loss of section, pitting or hydrogen embrittlement in heavily reinforced structures	H
4 (new)	Detection of corrosion in steel liners that are buried (covered by concrete) or inaccessible due to presence of moisture barriers.	H
5	Quantify performance limits for detection of corrosion by measuring loss of section/ hydrogen embrittlement in prestressing tendons in heavily reinforced structures	H
6	Quantify void detection threshold (and inhomogeneities eg honeycombing) in thick sections (variables: size of void, depth)	H
6	Detection of voids >20mm diameter in grouted tendon ducts in eg containments / waste store roofs	H
7	Improve variable performance statistics associated with depth measurement of surface cracks. For detection and sizing (depth, width, length) of cracks normal to surface aiming for sensitivity of ±10% for crack widths >0.2mm	H
9	Improve visual/optical scanning techniques for mapping cracks over large surface areas and for detecting surface deposits/ visual symptoms of flaws with sensitivity equivalent to visual inspection	H

MEDIUM BENEFIT NEEDS

Table	Need	Benefit
1	Enhanced ease and speed of application for measuring section thickness in all structures	M
1	Measure section thickness with single sided access, with sensitivity of ±5% section thickness	M
1	Measure section thickness in presence of congested steelwork, with sensitivity of ±5% section thickness	M
3	Enhanced resolution to measure reinforcement diameter with sensitivity of ±10% either in thick sections (>1m) or in presence of congested reinforcement (individual reinforcement at spacings <<150mm)	M
3	Resolve multiple layers of reinforcement, identifying individual reinforcement at spacings <<150mm and depths >30mm AND measure reinforcement diameter with sensitivity of ±10%.	M
4	Detect corrosion beyond first layer of rebar where there is only single sided access, through measurement of loss of section	M
5	Detect evidence of corrosion in grouted prestressing tendons by measuring loss of section, pitting or hydrogen embrittlement	M
6	Detect voids >20mm diameter behind liners in eg Fuel ponds, PCPVs, containment	M
6	Detect voids >20mm diameter around penetrations and encast items in eg bioshield, PCPVs, active process cells	M
6	Detect voids >20mm diameter in areas of congested reinforcement/ tendons	M
8	Improve variable performance statistics for detecting large laminar flaws at >10mm depth, and >100mm in any planar direction	M
8	Detect delamination between prestressing tendons in containments	M
11 (new)	Measurement of relative changes in concrete mechanical properties with time (ie detecting ageing processes), with sensitivity of ±1%	M
11 (new)	Measurement of spatial variations in concrete mechanical properties, with sensitivity of ±1%	M

LOW BENEFIT NEEDS

Table	Need	Benefit
1	Measurement of thickness of complex geometries to ±5% section thickness (eg accounting for edge effects; thickness changes)	L
1	Measurement beyond a fully bonded liner in containments and fuel ponds, with sensitivity of ±5% section thickness	L
3	Resolve tendon details within ducts in thin sections (<~1.5m) in eg containments and waste store roofs with sensitivity of ±10%	L
3	Resolve tendon details within ducts in thick sections (>~1.5m) in eg PCPVs with sensitivity of ±10%	L
3	Resolve reinforcement details in congested regions, including laps and couplers, with sensitivity to identify individual reinforcement at spacings <<150mm and depths >30mm AND measure reinforcement diameter with sensitivity of ±10%.	L
4	Enhanced speed of application for detection of corrosion through measurement of loss of section	L
5	Enhanced speed of application for detection of corrosion by measuring loss of section, pitting or hydrogen embrittlement in prestressing tendons	L
8	Detect debonding of prestressing tendons in containments & other structures with grouted tendons	L

Session 2: IDENTIFYING NDE CAPABILITY & TECHNICAL DEVELOPMENTS

The objective of this session was to help establish the true technical capability of NDE techniques which have been applied to both nuclear and non-nuclear structures.

Chairman: *John Bungey, University of Liverpool, UK*
Rapporteur: *Ron Smith, AEA Technology, UK*

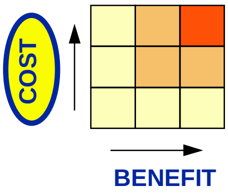
Speakers: **Tomographic imaging for investigation of concrete structures**
Michael Schuller, Atkinson-Noland Consulting Engineers, US

Four examples of modern NDE Techniques applied to the investigation of nuclear and non-nuclear concrete structures and a vision of future improvements
Peter Shaw, STK Inter Test AB, Sweden

Investigating concrete structures by 3D RADAR imaging and imaging using mechanical impact
Ulrika Wiberg, Vattenfall Utveckling AB, Sweden

Use of Ultrasonics and RADAR for NDE of Concrete
Brian Hawker, AEA Technology, UK

NDE DEVELOPMENT COSTS
(Session 2)



INDICATIVE LEVELS FOR DEVELOPMENT COSTS (US $)

Low	< 0.1 M
Moderate	0.1 - 1.0 M
High	>1.0M

The following tables provide a summary of the nature of development required to meet the ‘Needs’ identified in Session 1 of the workshop. An assessment is made of the likely cost of the development (high, moderate, low: as defined above).

Radar		
Need	**Development**	**Cost**
Improved quantification of capabilities for measuring thickness, mapping or sizing layers of reinforcement, detecting/mapping of voids: • in sections >1m thick • with depth/ reinforcement congestion • void detection thresholds (with volume/depth)	Laboratory sensitivity studies and well characterised structures. Complemented by experimental reference data and systematic documentation of application on specific types of problems. Note that this covers quantification of radar capabilities; qualification of methods/ personnel could add significant cost.	**L**
Improved sensitivity to resolve multiple layers of reinforcement, identifying individual reinforcement at spacings <<150mm and depths >30mm	Improved software for signal and image processing of multiple reflections; improved antennae design; variable frequency.	**M**
Improved sensitivity to measure reinforcement diameter in top layer with sensitivity ±10%	Improved software for signal and image processing of multiple reflections; improved antennae design; variable frequency.	**H**
Measurement of thickness with sensitivity of 5%, with single sided access	Little development needed	**L**
Assessment of the influence of concrete electric and dielectric properties (affected by moisture) on radar measurements	Combination of sensitivity studies and modelling/ analytical techniques. Low cost relies on results from CEC programme (2) becoming available.	**L**
Enhance performance of radar application (speed of use & sensitivity) by linking to other techniques	Link to ultrasonics (benefits from data being presented in similar formats, but response to different features)	**L**
Modifications to radar equipment to enhance ease of use in restricted spaces	Evolutionary development of existing equipment	**M**
Assessment of the effect of radar EMI, and checking against tolerable levels in nuclear plant.	? Standard tests? Cost would rise if significant developments were needed to design against unacceptable levels of EMI.	**L**

Reference was made to the following document during discussion:

> Guidance on Radar Testing of Concrete Structures - Concrete Society Technical Report 48 - Dec 1997, 88p

Acoustic: Ultrasonic methods: pulse echo & pulse velocity		
Need	**Development**	**Cost**
Improved quantification of capabilities for measuring thickness, mapping or sizing layers of reinforcement, detecting/mapping of voids: • in sections >1m thick • with depth/ reinforcement congestion • void detection thresholds (with volume/depth)	Laboratory sensitivity studies and well characterised structures, complemented by experimental reference data and systematic documentation of application on specific types of problems. Note that this covers quantification of capabilities for ultrasonic techniques; qualification of methods/ personnel could add significant cost.	**L**
Improved performance for: • measurement of thickness to sensitivity of 5% section thickness with either single sided access or in presence of congested steelwork • characterisation/ sizing (depth, width, length) of open surface cracks normal to surface aiming for sensitivity of dimensions 10% for crack widths >0.2mm • detection of large laminar flaws at >10mm depth, and >100mm in any planar direction • detect voids >20mm diameter or broken tendons in grouted tendon ducts • detection of voids >20mm diameter around penetrations and in regions of congested reinforcement • Detection of voids >20mm behind liners in eg fuel ponds, PCPVs, containments	Development of multiprobe pitch-catch and other coherent processing methods. Improve signal-to-noise ratios. Development of a true pulse-echo technique would be high cost; the above represent a practicable way forward.	**M/H**
Detect debonding of prestressing tendons in grouted tendon ducts	Develop scanning and interpretation methods. Two probe pitch-catch techniques	**H**
For all ultrasonic pulse-echo applications quantify performance parameters for aggregates >16mm	Laboratory sensitivity studies to give modelling references for changes in concrete quality with time	**L**
Enhanced ease of use for all ultrasonic pulse-echo applications	Improved attachment of ultrasonic probes to surface of concrete/ couplants through development of coupling media	**M**
Capitalise on synergies between testing techniques by linking to radar (benefits from data being presented in similar formats, but response to different features).	Data merging techniques.	**L**

Acoustic: Stress wave methods (Surface Waves, Impact echo)		
Need	**Development**	**Cost**
Improved quantification of capabilities for measuring thickness, mapping or sizing layers of reinforcement, detecting/mapping of delamination/ cracks parallel to the surface • in sections >1m thick • with depth/ reinforcement congestion • layer detection thresholds (varying with layer thickness/ depth)	Laboratory sensitivity studies and well characterised structures. Complemented by experimental reference data and systematic documentation of application on specific types of problems. Note that this covers quantification of stress wave techniques; qualification of methods/ personnel could add significant cost.	**L**
Improved performance for: • measurement of thickness to sensitivity of 5% section thickness with either single sided access or in presence of congested steelwork • detection of large laminar flaws at >10mm depth, and >100mm in any planar direction	Adaptation of techniques for specific use and development of scanning procedures. Development of multi-array sensors.	M
Improved performance for: • characterisation/ sizing (depth, width, length) of open surface cracks normal to surface aiming for sensitivity of dimensions 10% for crack widths >0.2mm • detection of voids >20mm diameter around penetrations and in regions of congested reinforcement • Detection of voids >20mm behind liners in eg fuel ponds, PCPVs, containments	Adaptation of techniques for specific use and development of scanning procedures. Development of multi-array sensors.	H

Radiography		
Need	**Development**	**Cost**
Quantify limits of detection in heavily reinforced structures, and with section depths >1.0m for: • Mapping/sizing layers of reinforcement (including identification of reinforcement laps and couplers) • Detecting voids and inhomogeneities • Detecting corrosion in reinforcement or prestressing steel	Laboratory sensitivity studies and well characterised structures. Complemented by experimental reference data and systematic documentation of application on specific types of problems. Note that this covers <u>quantification</u> of radiography capabilities; <u>qualification</u> of methods/ personnel could add significant cost..	L
Improved resolution to: • detect voids >20mm diameter or broken tendons in grouted tendon ducts • detect voids >20mm diameter around penetrations and in regions of congested reinforcement • map/size layers of reinforcement by measuring bar/ tendon diameter with sensitivity of ±10% in thick sections or with congested reinforcement (individual reinforcement at spacing <<150mm) • Measure any evidence of corrosion in reinforcement or prestressing by detecting loss of section	Higher energy levels needed to improve resolution, requiring further equipment development.	H
Improved sensitivity to resolve multiple layers of reinforcement, identifying individual reinforcement spacings <<150mm and depths >30mm AND measure reinforcement diameter with sensitivity of ±10%	Use of tomographic techniques. (Lower cost for columns with 360° access). Also development of sensors, detectors and sources.	H
Detection of voids >20mm behind liners in eg fuel ponds, PCPVs, containments	Develop backscatter techniques to apply γ-radiography with single sided access	H
Enhance performance for all radiography applications (speed of use & sensitivity) by linking to other techniques	Use in parallel with radar (where radar detects/ locates flaws and radiography provides detail)	M
Enhanced speed of use for all radiography applications.	Real time scanning, possibly linked to tomography. Extensive equipment development needed	H

Session 2 - Identifying NDE Capability and Technical Developments

The four papers presented in this session focused upon the current capabilities and recent developments in the applications of Radar, Acoustic methods (including Ultrasonics and Impact Echo) and Radiography. Particular attention was given to the benefits of multi-channel scanning techniques to provide 3-dimensional or tomographic images of hidden features to aid interpretation where only single sided inspection is possible.

The current benefits of the increasingly popular impact-echo methods to detect delamination or other plate-like near-surface problems, and radar to detect metallic inclusions were identified together with the capabilities of spectral analysis of surface waves for monitoring changes in surface regions. The limitations imposed by metallic liners were also noted. Work on development of automated scanning techniques was described and the advantages of combinations of test methods were strongly emphasised by several speakers.

It was noted that radar is unlikely to approach radiography in terms of detailed inspection of reinforcing bars, including identification of loss of section, although the limitations of this latter technique are well recognised. Radar may however offer considerable potential in dealing with thick sections where reinforcement is not too heavy.

Future developments will include improvements in data handling and processing. This is necessary to speed-up acquisition and analysis of the large quantities of complex data associated with imaging techniques. Signal analysis and post processing for ultrasonic, radar and impact echo methods together with characterisation of likely responses for specific features of interest and defect simulation are also considered essential. Potential for developments of Synthetic Aperture Focusing Techniques was additionally noted.

There is a clear need to assimilate current field experience in these techniques to enhance confidence and to take account of the scale and contrasts of materials properties likely to be encountered in practice. In the case of radar, development of specialist antennas with more appropriate beam width and other characteristics for specific applications was considered useful, together with assessment of emission levels to permit usage adjacent to Nuclear Plants. Similarly, it was suggested that major technical improvements could be achieved by development of ultrasonic transducers and implementation of true pulse-echo techniques.

The tables relating to proposed developments included in the Draft report were debated leading to some modifications in terms of both priorities and cost levels. It was noted that there is an ongoing European Project on Radar in the Building and Construction Industries which is currently addressing some of the identified needs relating to that technique. Whilst not considered in detail it was also noted that laboratory work on magnetic imaging techniques is underway which may offer future field inspection potential.

There was a substantial agreement that there was a need to establish confidence in the capabilities of the currently available NDE methods, and that authoritative documentation in the form of Reports and Standards is desirable.

Tomographic Imaging for Investigation of Concrete Structures

Michael Schuller, P.E.
Atkinson-Noland & Associates, Inc.

A multi-year research project, funded by the U.S. Nuclear Regulatory Commission, developed a tomographic imaging technique for investigating large concrete structures. The imaging method applies an analytical technique to an array of pulse velocity information for the purpose of reconstructing a velocity distribution through the section in question. Internal features are identified and resolved based upon the reconstructed velocity distribution.

Tomography has proven to be useful both in the laboratory and in the field for defining the internal structure of concrete, including location and sizing of features of interest such as:

- cracks
- voids
- construction cold joints
- low density regions
- large steel inclusions
- post-tension ducts
- quantifying the success of repairs such as epoxy crack injection and grout injection
- separations of steel containment structure linings

The presentation will discuss accomplishments of the research project and associated work, including the theoretical background of the technique, equipment requirements, procedures for acquiring pulse velocity data, and applications of the technique. A powerful and portable system containing an ultrasonic purser, receiver, and digital storage device are used to record waveforms travelling through concrete. Data acquisition efficiency is improved by using an eight-channel array system with an electronic multi-plexer for scanning localised regions. Software enhancements developed during the research project include modifications to the data acquisition routine to speed field acquisition of pulse velocity information, implementation of a new reconstruction algorithm, and development of a post-processing filter to allow for more practical application to large civil structures. Using the RAYPT analytical technique and the spatial coherency filter improves accuracy of the final velocity reconstruction by considering the presence of isolated anomalies in a relatively uniform background, more closely approximating conditions typical to concrete structures and the effects associated with concrete deterioration processes.

Laboratory specimens were fabricated to be representative of massive concrete construction, some containing dense mats of steel reinforcement such as may be present in nuclear containment structures. Various internal features were cast into the specimens to calibrate the technique and investigate resolution and sizing capabilities. The accuracy and resolution of the reconstructed image appears to be dependent upon a number of factors, including the accuracy and repeatability of acquired data, the size of the internal feature relative to the total cross-sectional dimension, the relative velocity of the anomaly, and the overall quality of surrounding concrete. Steel reinforcement will affect measured pulse velocities however can be taken into account by considering the concrete to have an anisotropic velocity distribution, with greater velocities parallel rather than perpendicular to the bars.

Results of field trials on bridge structures, a post-tensioned nuclear containment vessel, and a masonry structure will be shown to illustrate typical expected results. Tests on bridge structures in Colorado investigated the quality of crack repair by epoxy injection and the propagation of a separation crack at a cold joint. Sections of a nuclear containment vessel were tested at the Trojan plant near Portland, Oregon, USA, where the method accurately located: a) sections of the steel liner which had become detached from the concrete substrate; and b) two post-tension ducts, embedded deep within the concrete behind mats of

steel reinforcing bars. Tomography has also been used on masonry research projects to quantify the effects of grout injection techniques for filling internal cracks and voids. Results of field trials on masonry cross sections up to 3 meters thick show that tomography can be used even in highly attenuative materials with advanced stages of deterioration.

Tomographic imaging has proven to be quite useful in research and field trials, however, there are several avenues for future research that are expected to enhance the resolution and precision of the technique. Potential methods for eliminating some of the shortcomings of tomographic imaging will be discussed.

Four examples of modern NDE techniques applied to the investigation of nuclear and non-nuclear concrete structures and a vision of future improvements

Peter Shaw
STK Inter Test AB,
Sweden

The increase in demand for suitable test methods for concrete structures is coupled to an increasing awareness of damage mechanisms, structural and safety related deficiencies in existing structures, the need to locate reinforcement and the need to determine parameters which are related to the condition of the concrete and their effect on test method performance.

Structural deficiencies such as lack of concrete compaction and leak tightness are workmanship related and are common to a greater or lesser extent in most massive concrete structures. Damage mechanisms arising from unsuitable construction methods or materials in special environments is another problem area. These kinds of defect may go unnoticed throughout the entire life of a structure or, as is often the case, they may be discovered indirectly through secondary damage mechanisms such as corrosion and cracking.

There is therefore reason to make an assessment of all safety-related concrete structures, preferably at an early age, and in order to be able to do this it is necessary to have access to reliable and efficient test methods.

A suitable test method should be capable of rapidly scanning large volumes of concrete and quickly locating areas of deviating quality or flaws. It should be possible using complementary techniques to characterise discrete defects that have been identified, i.e. to determine their size, location and orientation with accuracy.

The inspecting engineer is faced with a number of problems when attempting to apply existing techniques to civil engineering structures. The technology is in many ways inadequate, having been developed for other applications. For example we have radar antennae which are clumsy and incapable of producing signals which can penetrate heavily reinforced concrete, and acoustic methods which place great demands on the user when attempting to interpret signal data.

In the initial stages of a project the engineering problem is often described by a structural engineer, himself having little or no knowledge of NDE techniques, their capability and the kind of information they will yield. The testing engineer may present data in the form of a qualitative survey of the structure, relying heavily on his experience and judgements based on a probabilistic evaluation of results. It is common therefore for the client to opt for destructive probing as an alternative to NDE, which cannot be convincingly demonstrated to those unfamiliar with the techniques.

If NDE is to be accepted in the civil engineering industry it will be necessary to improve test method capability, to be able to define capability in a way which can be understood, to formulate procedures and methodologies to improve test repeatability (qualification of methods) and to increase awareness of structural damage mechanisms and NDE. In addition to being able to define the capability of test methods the engineer must be able to predict the response of a structure to tests and to quickly evaluate the unexpected in planned investigations. This is particularly true of ultrasonic and seismic investigations.

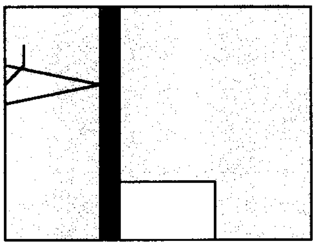
Existing techniques for non-destructive testing include acoustic and ultrasonic methods, high energy radiography, radar and inductive methods. Successful application of these methods to real structures requires sensible combinations of methods together with an understanding of the engineering problem, the behaviour of the concrete and of destructive methods of sampling and analysis.

There is a real danger in over-simplifying the problem and in assuming damage types which are based on accepted classical damage patterns and symptoms. For this reason NDE in civil engineering will always require a careful analysis by specialists despite improvements in test methodology, data collection and data processing.

Four examples of structural investigations using modern NDE techniques are presented below. A summary is given of the problem description and the performance of the techniques.

1. Nuclear containment

Leakage to a concrete containment was discovered by routine pressure tests and by further investigation using tracer gas, the leaks where located to pipe entries in the walls. The inner wall section was opened up and it was found that the steel liner between the wall sections was corroded .



Th= Concrete thickness

F= Peak Frequency (bottom echo)

C= Wave Speed in Concrete

A similar pattern was found at other locations selected at random. An investigation was started to determine the cause of the corrosion, construction methods and materials used and likely high risk areas. The corrosion of the steel plate was caused by separation of expansion material mixed with an injection grout used to fill up voids left in the slip-formed outer wall section. The soft filler material formed a moist layer and did not provide the alkaline protection to the steel plate. Methods were sought to locate uninjected voids and soft filler material. Initial tests were made using Impact Echo from the inner wall surface. The echo from a void at Th =250 mm would cause a peak signal at around 8 K Hz ($F = C/(2.Th)$), as the wave travels through the concrete and is reflected at the interface with an air-filled void. The presence of the steel liner would affect the signal response as the wave travels from concrete to steel, i.e. from a material with lower acoustic impedance to a material with higher acoustic impedance. The incident compression wave would in this case not change sign when reflected from the steel layer. Although the time between the compression wave arrivals is the same as in the case of an air-filled void in concrete, the period of the waveform is twice as long ($F = C/(4.Th)$) resulting in a peak frequency of 4 K Hz. The amplitude of this wave would be expected to be less than that of the reflection from a concrete: air interface as the contrast in acoustic impedance of the latter is greater. The case of a void behind the steel plate contra solid concrete would be expected to cause a change in amplitude of the reflected wave (F= (8 K Hz), the reflection from the steel: concrete interface being smaller compared with the case of steel: air.

In the event the reflections corresponding to around 8 K Hz were dominant in the case of solid concrete and void, and the usefulness of the method was hampered by the fact that there is often a lack of bond between the plate and surrounding concrete. Lack of bond between steel and concrete causes reflections at the steel: air interface in a similar manner to that of a void. It would therefore not be possible to distinguish a void from a lack of bond. Flexural responses of the outer concrete plate and shrinkage cracking in the near surface concrete were additional problems in analysis of the results.

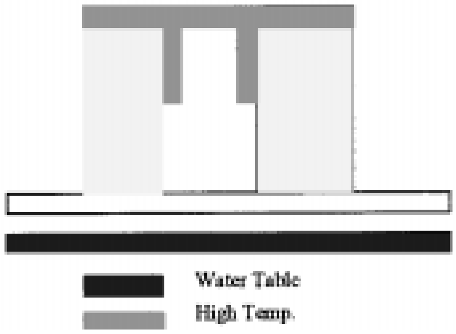
Further investigations were conducted using small diameter ultrasonic probes to measure the thickness and possible loss of section to the steel plate liner. All of the suspected pipe entries were opened up and repaired where necessary.

The geometry of the structure combined with the complicated nature of the problem and possible variables meant that in this case a more direct and reliable investigative technique was required. A similar structure was subsequently investigated using a 6 MeV Betatron and scintillating detectors

2. Industrial Foundation

The structural strength and integrity of a foundation structure in a smelter factory was investigated, as the working load was to be increased. A routine investigation of the compressive strength of cores from the structure developed into a series of special investigations following discovery of cracking caused by AAR.

The structure consists of two foundation blocks, of approximately 60 m3 each. These rest on a slab foundation of thickness 500 mm. The temperature at the concrete surface is estimated to be around 150 degrees Celsius. The bottom slab lies in a filler material which in turn is exposed to the ground water. When the heat-protective layer on the concrete surfaces was removed large horizontal and vertical cracks were visible at the surface. The cracks had a separation of around 400 mm and were similar to drying shrinkage cracks. Having removed cores from the side of the foundations it was found that the aggregates and cement paste were cracked. This aroused suspicion of AAR. The cracks were oriented in a plane parallel with the free surfaces of the foundations. No cracking was observed in the concrete near the surface.



Impact Echo measurements were made on the exposed surfaces. At some points there were indications of near-surface cracking. This was confirmed by coring.

Thin and plane section analysis was made on the cores and it was found that the concrete was suffering from AAR with 80 % activity in the aggregates. No AAR was found in the outer 65 mm of concrete.
The aggregates consisted mainly of granite and gneiss with aggregate sizes varying between 16 and 40mm. The water: cement ratio was estimated to be 0.6. Portions of leached crystalline ettringite were found in the pore system, suggesting water transport through the concrete.

A structural evaluation of the foundations was made on the basis of compressive and splitting tests on cores. The compressive strength was found to be on average 50 M Pa, which was more than adequate. The compressive tests were however made in a direction perpendicular to the cracks and it was felt that this may not be representative of the bearing capacity of the foundations considering that the load direction is parallel with the plane of the cracks The AAR was however considered to be in the intermediate state and since this does not normally have any significant effect on the strength of the concrete it was not considered necessary to repair or strengthen the foundations.

Some observations indicated that the AAR was no longer active. AAR-gel in the voids was found to be hard, and possibly even crystalline, which may have been caused by the extreme working temperature If the humidity in the concrete was less than 75-80 % RH then this would imply that AAR was no longer active.

Measurements of the relative humidity of the concrete were subsequently made at various points on the two foundations and up to 800 mm from the surfaces. It was found that the humidity of the concrete varied between 90 and 99%, even 500 mm from the top of the foundations. The water was assumed to come from the ground water through capillary action. Humidity measurements were made using conductivity probes (PW-sensors) left in sealed 16 mm diameter drilled holes for 5 days.

A pressing time schedule did not allow for further investigations of the concrete foundations or the slab underneath. Since the AAR could be assumed to continue the condition of the concrete can be expected to deteriorate with time. Some kind of reference measurement of structural integrity was required for comparison with future control measurements. For this purpose SASW-measurements were made at various points on the exposed surfaces of the two foundations. It was not possible to gain access to the bottom slab. The surface wave velocity profiles are similar with fairly even values to a depth of around 800 mm. In the upper section of one of the foundations the wave velocity is approximately 10 % lower to a depth of around 250 mm. An average wave speed of 2100 m/s was recorded.

This investigation was of special interest from a number of viewpoints:

1) AAR found in a structure made with aggregates which are not normally associated with AAR. The probable explanation is the combination of extreme temperature and high moisture content of the concrete which causes acceleration of the chemical process.

2) The classical map-cracking associated with AAR was absent. The macro-cracking at the surface may have been caused by tensile stresses as the foundation " grew " due to AAR. The lack of reinforcement in the outer 80 mm would have contributed to this effect.

3) The orientation of the cracks could affect the strength of the foundations and the representativity of the strength measurements on drilled cores.

4) The capillary action through the slab caused high humidity several metres above the ground water table.

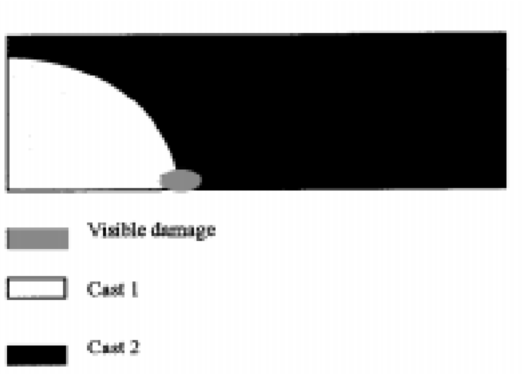
SASW may prove to be a convenient way of monitoring changes in the condition of the concrete with time. The method is restricted by access to good testing surfaces in the sense that the measuring depth is confined by the accessible surface area.
Impact Echo was useful in identifying near surface cracking. Impact Echo should always be compared with the results of drilled cores.
Ultrasonic measurements were made but were of little use due to the macro-cracking at the surface.

There appears to be no available method for non-destructively checking thin slabs to which access is restricted to parts of one surface.

3.) Bridge Structure

At the peak of the summer of 1997 in temperatures of up to 30 degrees Celsius a post-tensioned concrete bridge slab consisting of around 600 m3 concrete was cast. The temperature of the concrete as poured was recorded at 24 degrees.

The concrete was poured from both ends of the slab with some time interval between castings. Some difficulty was experienced in vibrating together the first and second castings, as the former had begun to harden.



The bridge slab contained 900 mm diameter hollow galvanised metal ducts as weight reducers, placed at c/c distance 1500 mm. The slab thickness was on average 1450 mm.

Having removed the bottom shutter from the slab some large voids were found underneath the post-tensioned cables and weight reducers. Four distinct lines with varying degrees of honeycombing could be seen stretching across the bridge. These lines coincided with the interface between castings. Concern grew about the possibility of hidden voids in the slab and of a weak bonded interface between the castings. A structural evaluation was made based on a truss analogy with regions of tension and compression in the concrete slab. The possibility of applying NDE to determine the condition of the slab was looked into. The purpose of NDE was to locate possible voids in the slab and to determine the location, orientation and condition of the casting joint interface at each end of the slab.

Three methods of test were suggested and these were:

1) Ultrasonic wave transmission through the slab and between weight reducers
2) SASW-measurements
3) Impact Echo

The through transmission ultrasonic measurements were made in several lines along the length and across the breadth of the slab. These were found to be very consistent and the results fell into three categories:

1) Steady and repeatable values corresponding to an apparent wave speed of 4200 m/s.
2) Less steady values corresponding to an apparent wave speed of around 2600 m/s.
3) No readings.

It was possible to obtain a rough correlation between UPV-results and density, compressive and splitting strength of cores. The areas of poorer compaction could be located and identified and were found to be restricted to an area near the supports corresponding with the casting joint. The remaining sections of the bridge fell into Category 1) and the results of UPV-measurements showed a low coefficient of variation (4 to 7 %). No transmission (Category 3) was caused by attenuation of the signal. The prolonged transmission times of around 550 μs were presumed to be caused by attenuation of the compression waves at local defects. The recorded signal was presumed to be the shear wave response (approximately 60 % of compression wave speed).

SASW measurements were made on the upper surface of the slab in the suspected areas. The chosen separation of the transducers was 500 and 1500 mm. The dispersion curves were convex with minimum velocity around 400 mm from the upper surface. By a forward modelling process a theoretical dispersion curve has been calculated indicating that the slab is made up of three layers of thickness 0.15, 0,3 and 1.05 m with corresponding surface wave velocities of 2440, 2250 and 2580 m/s respectively.

The coring results show that at the test points the slab is made up of three layers with strength and density varying by about 5 %, with lowest values around mid section. There were no serious honeycombings, but a weak interface running at an angle of about 45 degrees at mid-section could be distinguished.

The Impact Echo measurements were confined to the underside of the weight reducers and the object of these tests was to detect possible voids . Having had previous experience of Impact Echo in a similar structure the method was confined to this investigation, considering the fairly complex internal geometry of the bridge slab. The depth of the pipes from the lower surface was between 250 and 300 mm . The diameter of pipe: depth ratio is more than sufficient to obtain a clear and distinct echo from the apex of the pipe. Areas of poor compaction and voids resulted in higher frequency peaks in the frequency spectrum and lack of a clear bottom echo (in this case around 10 K Hz).

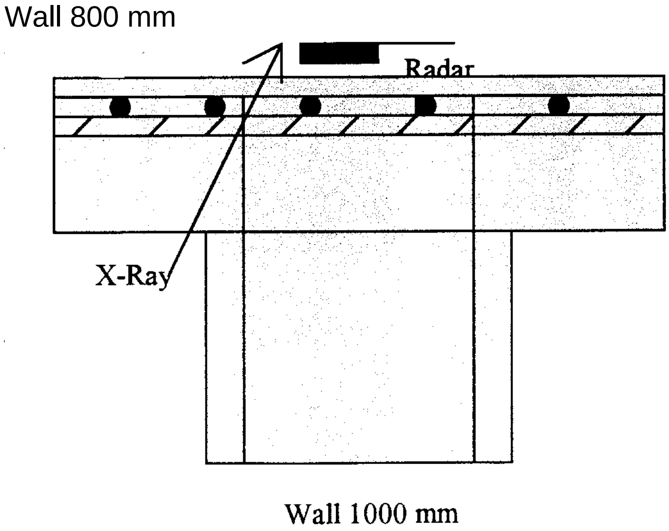
The SASW-method appears to be a sensitive technique in locating areas of deviating strength and density. It is not known how a weak interface running diagonally through the path of the surface waves has affected the wave speed. As usual the real structure problem is considerably more complex than the theoretical problem cases. There appears to be a general agreement between the SASW-results and the physical condition of the concrete. The SASW-technique was found to be a useful complement to UPV measurements giving the damage description another dimension. It would not have been possible to make SASW-measurements in between the weight reducers as the restricted volume between these would have affected wave transmission. An average surface wave speed of 2400 m/s corresponds approximately to a compression wave speed of 4140 m/s. The measured compression wave speed through the slab was 4190 m/s.

It is recommended when carrying out UPV-measurements to always have access to the signal display in order that the wave arrival can be established, together with the relative wave amplitudes and if possible the frequency dependent attenuation of the signal. Without this information the interpretation of results can be speculative and unreliable.

As previously experienced the Impact Echo method works well for simple geometries and relatively simple problem cases.

4.) Nuclear Structure

High frequency radar and High Energy Radiography were used to locate reinforcement in concrete elements up to I m thick. The radar used in this project was of type RAMAC/GPR from Mala Geoscience in Sweden. The radar data was processed using the REFLEX software to give a 3-D picture of the reinforcement which was subsequently compared with
X-rays. The radiographic tests were as far as we know the first in which a 7.5 MeV Betatron had been applied to reinforced concrete. The previous work in this area has involved the Betatron PXB 6, which has an output of 6 MeV and approximately half the dose compared to the PXB 7.5 (up to 8 Rads).



The objective of this investigation was to X-Ra, determine the reinforcement detail at the intersection between the walls, as shown in the Figure. The size, location and number of reinforcing bars could be determined by combining radar and HER measurements.

Radar

The surface of the structure was scanned along horizontal and vertical lines with a separation of 50 mm at the area of interest. The data is stored and then processed. In this case the near surface reinforcement consists of a grid of 12 mm diameter diameter bars with c/c-separation of 200 mm. The first bars are located 25 mm from the surface. The main wall reinforcement consists of 32 mm diameter bars running vertically at a depth of approximately 120 mm from the surface and horizontal bars behind these.

In this kind of situation the near surface reinforcement tends to have a screening effect on the deeper lying bars. A normal 2D profile of the wall may be difficult to interpret. However, by processing the collected data profiles it is possible to obtain a 3D image of the reinforcement and by a process of migration to reduce the "tail " effect from the individual reflectors, thus giving a better perspective and clearer identification of detail.

It was possible to identify the individual bars and determine their depth and separation quite accurately. The near surface bars of diameter 12 mm and the first layer of 32 mm diameter bars can be seen quite clearly. By first determining the depth of the near-surface bars with an ordinary covermeter, it is possible to accurately determine the depth of deeper lying bars by comparison between reflectors in the radar image. It was estimated that the depth of the bars at around 120 mm could be estimated to an accuracy of around 4%

High Energy Radiography

Radiographic images of reinforcing provide the greatest possible amount of detail compared with any other technique. The size, orientation and depth of the bars can be determined accurately, as can additional details such as reinforcement grade, visible by the rib spacing on the bars. The Betatron has a very small focal spot (1,0 x 0,2 mm) which provides an image with low geometric unsharpness.

The exposure times in these experiments varied from 10 min, 15 min, 25 min and 60 min for concrete thicknesses of 600, 800, 900 and 1000 mm respectively.

Non destructive Methods of testing Concrete

High Energy radiography

The Betatron 7,5 MeV equipment has been applied to concrete structures up to 1 m thick. The high energy output of this equipment and high dose rate mean that it is a practical tool for in-situ investigations of concrete structures, with a limiting thickness probably of around 1200 mm. For such a powerful! radiation source it has a relatively moderate dose output, which means that it can be used without causing severe background radiation and associated safety problems at an acceptable range.

The 6 MeV equipment will reveal voids in pre-stressing ducts cast in concrete corresponding to about 15 % reduction in mass density and better. The quality of the radiographic image, i.e. the geometric sharpness and contrast in film density, deteriorate for concrete thicknesses above approximately 650 mm. It is probably unlikely that higher energy sources will improve film quality for thicker concrete. Development in this area could be possible using computer technology, signal acquisition, e.g. digital enhancement of x-ray images.

High energy radiography is a superior technique in locating and sizing reinforcement and can be effectively used for concrete at least I m thick. The film technique is time consuming and developments in this area will hopefully lead to real-time systems using scintillating cameras. A real time system would mean considerable time savings not least in obtaining good angles of shot in congested reinforcement.

Radar

High frequency radar is an quick and effective method of locating reinforcing and pre-stressing cables in concrete. Our work has shown that it is restricted by near-surface reinforcement and has a maximum measuring depth of around 250-300 mm. The limited investigation depth of radar is partly due to the screening effect of reinforcing bars and partly due to the electrical properties of the concrete.

Radar in its present form has been developed for geophysical surveys and is therefore not optimal for concrete testing. Improvements in data collection could be made by improvement of methodology, development of systems which could combine the high resolution of high frequency with the greater penetration depth of low frequency antennae.

Our work using the REFLEX software has demonstrated the advantages of using data processing and 3D imaging. The time-slicing technique was found to be useful for visualising the reinforcing bars and the migration technique can help to distinguish deeper lying bars below the near-surface reinforcement. Collection of data over a grid with a sufficient number of profiles is time consuming This combined with the fact that it can be difficult to maintain exact profile position by manual scanning suggests that the data collection might be improved by automation using a rig.

Spectral Analysis of Surface Waves (SASW)

SASW is a non-destructive seismic method which is based on the dispersion of Rayleigh waves, i.e. the variation of surface wave velocity with depth in a layered medium. The variation of phase velocity with wavelength is related to the structural stiffness of the medium through which the waves are travelling. The method has so far been largely restricted to soil investigations, but is finding some application in concrete testing. It is suited for application to thicker concrete structures where there is good access to a testing surface.

Four concrete structures with nominal thicknesses varying from 800 mm to 1500 mm have been investigated using this method. The data allows a dispersion curve to be calculated showing surface wave speed variation with wavelength (approximately equal to the depth from the testing surface). In two cases the SASW results could be compared with physical tests of the material and a reasonable agreement between these was found. The SASW method was combined with UPV-measurements in a thick concrete slab and indicated areas of deviating quality in parts of the section.

The SASW-method is seen as a promising method for non-destructively investigating thick structures which are only accessible from one side and for monitoring changes to the condition of the concrete which may occur with time. More work is needed to improve understanding of surface wave behaviour in concrete structures and in data interpretation.

Impact Echo

Impact Echo can in many respects be regarded as a global measuring technique as a large volume of concrete will respond to the wave input. In this respect it is, in the opinion of the author, best suited to simple concrete geometries and relatively simple damage cases, such as delaminations or large cracks. Local defects such as voids can be detected if the ratio of size of defect: measuring depth is sufficiently large, i.e. around 1.

Two commercially available Impact Echo systems have been used for several years. One of these systems provides real-time displays of frequency spectra and can be used effectively on site, consisting of a fairly rugged field computer and specially adapted impact and receiver source. The frequency content of the input signals is varied by using spherical steel balls of varying diameter, thus allowing sensitivity to be varied depending on the depth of investigation.

The other system is combined with the SASW-system and employs the same basic hardware. The frequency spectra is not displayed in real-time. The data collection allows several measurements at the same testing point and an averaging of signals, with the option of removing signals of poor quality.

Both systems have been found to be useful in locating relatively large defects in concrete. A golden rule when applying Impact Echo to concrete structures, especially when the damage pattern may be more complicated, is to confirm the echo response with actual conditions at the outset of an investigation. This can be done by coring.

Suggested improvements to the Impact Echo Systems are in data collection (automation) and in field equipment, e.g. allowing one operator to perform data collection and signal viewing in real time and in reasonable comfort.

A common factor in many NDE investigations is that they are seldom planned as part of a maintenance and inspection programme, as is normally the case with traditional NDE. Some of the cases described here are the result of problems highlighted indirectly by other investigations or by visual observation. The strongest motivation for inspection is safety, the economical aspects being less apparent unless there is a danger of disrupting production. A certain amount of visible damage such as cracking is expected in concrete structures and normally does not cause concern. Serious defects are often concealed, and why go looking for them particularly if the testing technology can be uncertain, as it can today. Although it has been our experience that costs are no hinder in investigating identified problems in nuclear structures, there remains the problem of how and when to apply general integrity inspections to large structures. The testing technology must be effective and reliable, the possible high risk areas must be predicted and found, and the assessment must be correct. It will probably remain the task of the experienced engineer to detect unexpected damage types in planned investigations. The complexity of damage mechanisms, the non-uniformity of concrete structures and the variables affecting test results are altogether too complicated and do not lend themselves to blind data collection and analysis according to a fixed set of rules.

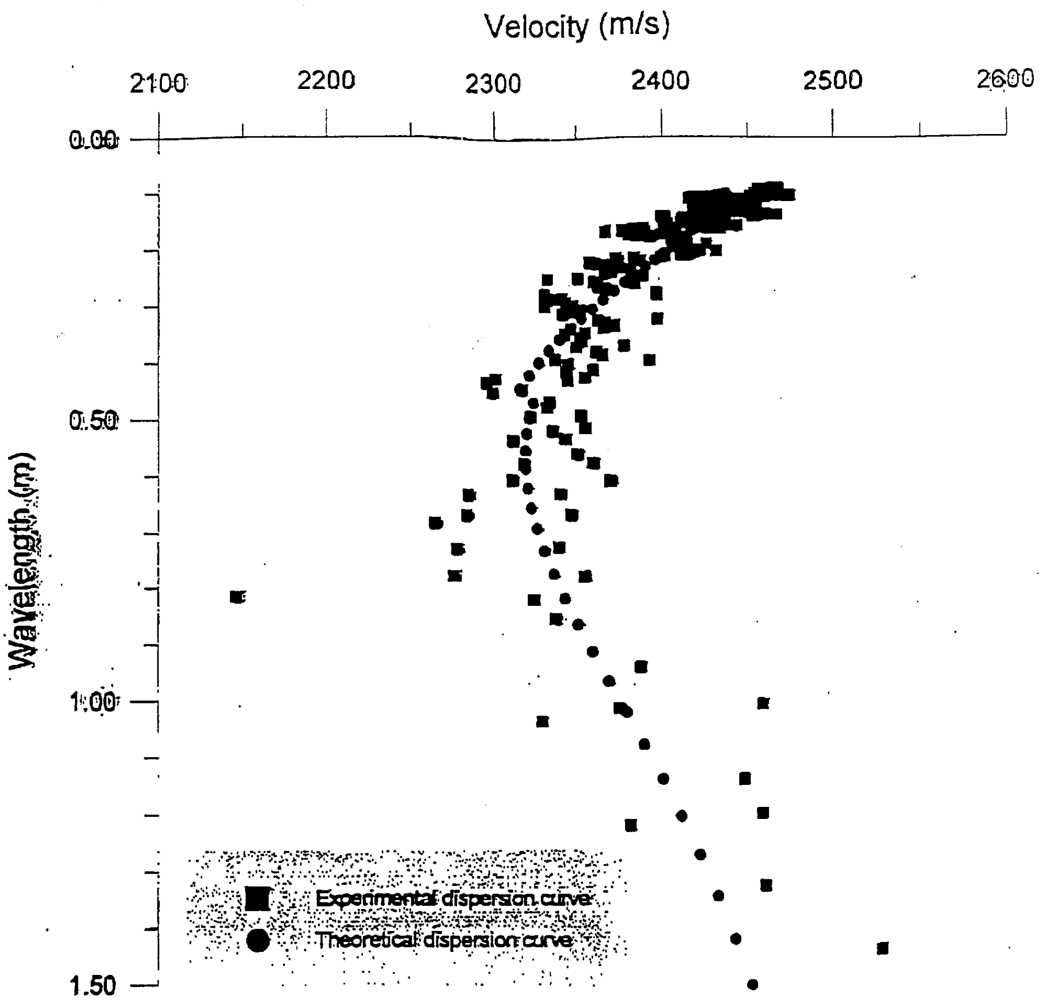
General inspections of civil engineering structures are normally confined to the analysis of durability and expected lifetimes of structures. In Scandinavia the budget available for an investigation of an average road bridge is of the order of US$6000 to 12000, which allows little scope for more advanced NDE of structural integrity.

A modern concept in NDE and one which will eventually find use in NDE of concrete is that of "Qualification" of test methods, i.e. for a given test method be able to demonstrate that the task can be executed as promised. This process is divided into three parts:

1) Detection
2) Characterisation
3) Size determination

The testing " system ", i.e. personnel and equipment is treated in a similar manner parallel with the actual qualification of tests. The tests are qualified on "open" and "blind" test blocks prior to execution of a project. The size of concrete structures would make this process impractical, but the problem could possibly be solved by having a central test facility, e.g. a de-commissioned reactor containment, for experimental purposes and for setting up realistic reference objects.

Brigde slab
SASW-measurement conducted at upper surface
Receiver separation 1.5m



Layer	Thickness (m)	Velocity (m/s)
1	0.15	2440
2	0.30	2250
3	1.05	2580

Investigating concrete structures by 3D RADAR imaging and imaging using mechanical impact

Ulrika Wiberg, Vattenfall Utveckling AB

Background

In safety related concrete structures within hydro power plants, non-destructive testing as an aid for assessment of dams and spillway structures has been much discussed and to some extent used.

Methods based on single measurements have been used to provide information about the concrete in the measurement point. Such a local measurement technique is the Impact-Echo method. More complex structural geometry or situations of damage however require that the information from more than one measurement be evaluated jointly. An example of a method which does that is Ground Penetrating Radar (GPR), which produces a profile of the material along a measurement line on the structure. Further developments of measurement methods, enabling the size and shape of defects to be visualised can be achieved through scanning of structures.

Scanning provides a global measurement technique and it also allows for results from more than one method to be compared. A measurement of this type can also be made automatically after installation of the equipment. Measured data provides means for imaging structures and defects.

Scanning techniques with automated positioning, data gathering and presentation

The imaging procedures are based on a measurement technique which allows 2D scanning of the surface of a structure. 3D presentation is possible for measurement methods such as GPR and UPE which produce time domain records corresponding to depth. When the response to a mechanical impact is measured, imaging primarily offers a 2 D presentation.

Equipment developed at Lund Technical University by Dr. Peter Ulriksen with the financial support from owners of bridges and hydro power stations, has been used for laboratory as well as field experiments. A mechanical scanner moves an antenna or acoustic probe from one measurement point to the next thus allowing measurements to be made in a grid over the surface of the structure. The measurement equipment is positioned in the in line direction of a scanner beam with one servo motor, and in the transverse or cross line direction the entire beam is moved on wheels controlled by a second servo motor.

A cube of measurement data is thus produced with two physical dimensions and the third being the time domain. The data set resulting can be used to present images of the structures at different levels from the surface or to show profiles through structures along any chosen line. The format for gathering and storing data makes it easy to extract the information from any part of the scanned area, and it also makes it possible to compare the results from different methods.

Verification of capability

The measurement methods have been tested in a number of laboratory set-ups to verify the capabilities for imaging of defects. It has been shown that cast in objects such as tubes, reinforcement and air-entrained concrete can be imaged using radar scanning. Scanning using mechanical impact has successfully imaged a simulated delamination as well as cast in blocks of air-entrained concrete. All measurements have been limited to blocks of 0.4 m thickness. No specialised processing has been used.

Calibration of wave speed has not been done and therefore determination of structural thickness has not been made. In order to more accurately determine the shape and size of objects further data processing will be necessary. In the cases of mechanical impact no propagating waves have been measured with the present system.

3D radar imaging and imaging using mechanical impact has great potential for detailed investigation of suspect areas of structures.

Performance in-situ

Radar imaging has been tested for performance in-situ. Measurements on walls of a power station and measurements on the intake structure of a hydro power station have been made. Scanning has proven to work well on real structures in horizontal as well as vertical applications. In one structure an anomaly was discovered in otherwise uniform concrete behind the reinforcement in a concrete wall. In the other structure old and non uniform concrete was distinguished from uniform concrete which had been replaced at a late date.

Conclusions

Imaging of various types of anomalies at limited depths can be achieved even behind a layer of reinforcement.

Linking radar data to data from acoustic methods is made possible in the scanning system. It has been shown that different types of objects appear differently depending on the measurement method and thus a better understanding of types of defects can be achieved by combinations of results.

The equipment has not been tested at greater depths but it is likely that information will be picked up. The size and shape of objects will however be more distorted thus making further processing of data necessary in order to improve the sensitivity of sizing defects.

Synopsis
NDT of Concrete using Ultrasonics and RADAR
Brian Hawker, AEA Technology

At least until recently, NDT methods for inspecting concrete were very limited in capability and in the reliability of sentencing. Radiography could be used to locate reinforcement and voids if the wall thickness was modest and if there was access to both sides. The cover-meter provided, and still provides, useful rebar location and cover measurement. Other techniques have been claimed to indicate rebar corrosion and deterioration of the matrix

But the structural engineer requires reliable inspection: methods which will assure him that there are no hidden cracks or voids of significance, that the steel reinforcements are present and that they are still fulfilling their intended purpose.

This paper examines two leading candidates for providing reliable inspection: Ultrasonics and RADAR. It examines the existing technologies, their potentials for development and also their inherent limitations. In highlighting the near inevitability of these limitations it questions the value of some development targets and tries to focus on development objectives which are realistic and which help the engineers. It also looks at other areas of work for ideas which can be borrowed, notably the methods directed previously at the problems of inspecting coarse-grained cast austenitic steel.

Ultrasonics and RADAR have several features in common. Both lend themselves to B-Scan style image presentation of the unrectified imagery; to coherent waveform summation algorithms, such as phased arrays, synthetic aperture focusing and spatial averaging, to non-linear numerical transforms and to feature subtraction methods. Both are similarly affected by random velocity variations and scatter through the coarse aggregate. But they are affected very differently by void regions and by the presence of the metal reinforcement. For this reason only the ultrasonic methods offer good prospects for crack detection or sizing, while RADAR offers the best prospects for characterising large voids and for detailed surveys of the reinforcement.

There is still considerable work to be done to establish the capability of the available methods. At present there is much more documentary evidence of what the techniques cannot do than of what they can do. AEA Technology’s CETWG Project for the IMC has a test block specifically designed to quantify the present capability and to provide valuable controlled target features on which to develop enhanced and validated inspection capability. These will then be proven in field trials on UK nuclear plant and the results made available to the members.

Session 3: PRIORITISING DEVELOPMENTS

The objective of this session was to draw together information from earlier in the day, and to use this as the basis for prioritising development of NDE

Chairman: *Tony McNulty, HSE/NSD, UK*
Rapporteur: *Wally Norris, US NRC, US*

Speakers: **Key conclusions from earlier sessions**
Les Smith, Scottish Nuclear, UK
John Bungey, University of Liverpool, UK

Proposed priorities and next steps
Richard Judge, AEA Technology, UK

Session 3: Workshop Conclusions and Recommendations

Delegates to the workshop acknowledged that NDE techniques have the potential to satisfy at least some of the needs of the nuclear industry discussed in Section 3 of the report. NDE techniques have been used successfully on a variety of reinforced and post-tensioned concrete structures, notably highway and reservoir structures. However, there is limited experience of their use to evaluate typical nuclear safety related structures having thick sections, steel liners or access to one side only.

Delegates expressed a general lack of confidence in the techniques because there is very little independent advice on their applicability, capability, accuracy and reliability. The information obtained by techniques such as RADAR, ultrasonics, stress wave and radiography appears qualitative rather than quantitative and a number of delegates expressed concern that NDE procedures lack the necessary qualification to permit their use on safety critical structures. It was noted that there is no international guidance or standard for NDE of concrete structures.

Some delegates expressed concern that the scope of the workshop had excluded consideration of electrochemical techniques that have the capability of detecting and measuring the corrosion of reinforcement and steel embedments - a need identified by several countries.

NDE of concrete structures is often based upon equipment developed for other materials and technologies, eg. examination of steel, evaluation of ground conditions. Other industries are developing equipment specifically for civil engineering applications and the workshop identified a number of relevant national and European programmes. Delegates agreed that the nuclear industry should keep abreast of developments and seek opportunities to influence the development of equipment.

Delegates considered the qualitative assessment of the cost of developing NDE techniques (Section 4) to meet the needs and/or address the concerns of the nuclear industry (Section 3) They identified the principal areas of development, their cost and the perceived benefits to be as follows.

Development	**Cost***	**Benefit***
Quantification of capability	low	high
Qualification of techniques	moderate/high	high
Combining techniques	low/moderate	medium
Ease of use (evolutionary)	moderate	medium
Equipment and software	high	low, medium and high.

* See Sessions 1 and 2 for definition of costs/ benefit

Delegates went on to consider development priorities with a view to preparing a set of draft recommendations for the consideration of CSNI. The workshop agreed that quantification of the techniques is a priority area for development and supported the principle of an international standard test specimen. Qualification is important to the successful deployment of NDE techniques and may need to be considered when designing the test specimen. It was agreed that the high cost of developing software and equipment, with no guarantee of success, meant that the nuclear industry was unlikely to consider this to be a priority area for funding. However, delegates agreed that it was important for the industry to establish national networks with, for example, the highway and reservoir industries that were funding development. There was also support for the principal of establishing a group of international experts to monitor national developments.

The workshop agreed that PWG3 Task Group on Concrete should be asked to
revisit the issue of detecting and monitoring corrosion of steel.

Draft Recommendations:

I. The task group on concrete should recommend the following development priorities for consideration by PWG3 and CSNI.

  A. The quantification of the capabilities of NDE techniques is seen as a priority area for development. However, the industry lacks an international standard for quantifying the NDE of nuclear safety related concrete structures. The CSNI should ask the task group on ageing of concrete to prepare a specification for the design of an International Standard Test Specimen that will help to establish a common standard for evaluating the capability of NDE techniques to meet the requirements identified by this workshop.

  B. The design of the International Standard Test Specimen should consider the longer term need for qualification.

  C. The nuclear industry is unlikely to fund the high cost of developing bespoke NDE equipment and software to meets its requirements for concrete structures. However, it is recommended that nuclear regulators and operators establish more formal national networks with other industries that use the techniques on their structures and seek opportunities to influence the development of new equipment.

  D. The workshop has identified a number of national and European development programmes that are due to report progress in the coming months and years. The national networks proposed above should help promote improved understanding of the availability and capability of NDE techniques within the industry. It is recommended that a group of international experts are asked to monitor national programmes and report progress to the OECD/NEA at intervals to be agreed by the task group.

II. The task group should consider including adding a workshop on the detection and monitoring of corrosion of reinforcement and steel embedments to the existing programme of activities.

Programme of workshop

INTRODUCTION

9:00 Welcome and Opening Remarks
Tony McNulty, HSE/NSD
Alex Miller, OECD/NEA

Session 1
NUCLEAR NDE REQUIREMENTS

Chairman: Les Smith, Scottish Nuclear, UK
Rapporteur: Walter Heep, NOK, Switzerland

The objective is to specify what International Regulators/ Plant Operators want NDE techniques to deliver (ie clarify applications and specify requirements).

9:15 **Identification of needs on which to focus NDE developments**

Richard Judge, AEA Technology, UK

- Characteristics of nuclear safety related structures
- The role of NDE in ageing management and current practice
- Identification of needs, and associated benefits

9:35 **International perspectives on current practice and needs for NDE development**

Ken Philipose	*AECL, Canada*
Walter Heep	*NOK, Switzerland*
Jesus Rodriguez	*Geocisa, Spain*
Wally Norris	*NRC USA*

10:00 **Discussion**
(Based around Chapter 3 of the Draft Report circulated in advance of the meeting)

- Have the Tables in Section 3.2.2 captured the major needs for NDE?
- What are the nature of advances most needed (speed, sensitivity etc)?
- Is the assigned benefit appropriate?

10:45 COFFEE

Session 2
IDENTIFYING NDE CAPABILITY & TECHNICAL DEVELOPMENTS

Chairman: John Bungey, University of Liverpool, UK
Rapporteur: Ron Smith, AEA Technology, UK

The objective is to help establish the true technical capability of NDE techniques which have been applied to both nuclear and non-nuclear structures.

11:15 **Tomographic imaging for investigation of concrete structures**
Michael Schuller, Atkinson-Noland Consulting Engineers, US

- Tomographic imaging is a powerful technique for providing information on the internal composition of concrete members
- Recent developments in equipment and data processing software has improved the general accuracy and resolution of the technique
- Limitations related to data gathering, frequency and energy attenuation, and the need for full access to the concrete member can potentially be solved with further developments

11:35 **Four examples of modern NDE Techniques applied to the investigation of nuclear and non-nuclear concrete structures and a vision of future improvements**
Peter Shaw, STK Inter Test AB, Sweden

- NDE, even for concrete structures but not at any cost
- NDE should be capable of recognising the unexpected in planned investigations
- Improve NDE method capability and the use of test data beyond qualitative assessments

12:00 **Investigating concrete structures by 3D RADAR imaging and imaging using mechanical impact**
Ulrika Wiberg, Vattenfall Utveckling AB, Sweden

- 3D radar imaging and imaging using mechanical impact has great potential for detailed investigation of suspect areas of suspect areas of structures
- Measurements based on automated positioning and data gathering can be used to image concrete structures, cast in objects and defects
- Scanning techniques and multi-sensor systems can be used to link information from various measurement methods

12:20 **Use of Ultrasonics and RADAR for NDE of Concrete**
Brian Hawker, AEA Technology, UK

- What can already be achieved ?
- What can we learn from other technologies ?
- What do we expect to achieve, how, and is it enough ?

12:45 LUNCH

14:00 **Discussion**
(Based around Section 4 of Draft Report circulated in advance of the meeting)

- Do the Tables in Section 4.2.2 include the most likely technical options for satisfying the identified needs?
- Are current capabilities and limitations recognised?
- Is the assigned cost appropriate, and does it reflect perceived timescales and technical difficulty of the proposed development?

15:00 TEA

Session 3
PRIORITISING DEVELOPMENTS

Chairman: Tony McNulty, HSE/NSD, UK
Rapporteur: Wally Norris, US NRC, US

The objective is to draw together information from earlier in the day, and to use this as the basis for prioritising development of NDE

15:30 **Key conclusions from earlier sessions**
Les Smith, Scottish Nuclear, UK ***(to be confirmed)***
John Bungey, University of Liverpool, UK

15:45 **Proposed priorities and next steps**
Richard Judge, AEA Technology, UK

- Prioritising future developments
- Options for international collaboration

16:00 **Discussion & Conclusions**
(Based around Section 5 of Draft Report circulated in advance of the meeting)

- Is there agreement with the relative ‘Benefit’ and ‘Cost’ of NDE developments, as shown in Matrix in Section 5?
- What is the preferred way of building on the findings of the Workshop?

16:45 **Closing Remarks**
Alex Miller, OECD/NEA

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