DEVELOPMENT PRIORITIES FOR NDE OF CONCRETE STRUCTURES IN NUCLEAR PLANTS

NEA WORKSHOP
Risley, United Kingdom, 12 November 1997

PRINCIPAL WORKING GROUP NO.3
ON INTEGRITY OF COMPONENTS AND STRUCTURES

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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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CONCRETE STRUCTURES IN NUCLEAR PLANTS

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The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of all OECD Member countries, except New Zealand and Poland. The Commission of the European Communities takes part in the work of the Agency.

The primary objective of the NEA is to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

This is achieved by:

— encouraging harmonization of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionizing radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;
— assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;
— developing exchanges of scientific and technical information particularly through participation in common services;
— setting up international research and development programmes and joint undertakings.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded a Co-operation Agreement, as well as with other international organizations in the nuclear field.

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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 meetings.

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.

This document is published under the responsibility of the Secretary-General of the OECD.
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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

- IDENTIFY SPECIFIC NEEDS FOR NDE DEVELOPMENT
- PROPOSE PROGRAMME OF TECHNICAL DEVELOPMENT
- COST/BENEFIT ANALYSIS
- Assess benefit and potential technical development to meet the need (Session 1)
- Estimate cost of development & likelihood of success (Session 2)
- Matrix showing relative priorities (Session 3)

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 (i.e., 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>
<thead>
<tr>
<th>Table</th>
<th>Application &amp; Purpose</th>
<th>Comment</th>
<th>Needs identified</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><em>Measurement of concrete thickness</em>, to obtain as built details.</td>
<td>Key input for selected NDE techniques (eg impact echo).</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td><em>Mapping / sizing of steel reinforcement and tendons</em> to establish as built details (including identification of reinforcement laps and couplers).</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td><em>Detection of corrosion in embedded steel</em> (both reinforcement and liners). Corrosion is recognised as a key issue for ageing concrete structures.*</td>
<td>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</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
<td><em>Detection of corrosion in prestressing tendons.</em></td>
<td>Comment as above</td>
<td>✓</td>
</tr>
<tr>
<td>6</td>
<td><em>Detection of voids &amp; inhomogeneity</em> (honeycombing), typically to locate construction flaws. Voids in grouted prestressing ducts are a particular issue, as these may lead to corrosion of tendon.*</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>7</td>
<td><em>Detection and sizing (depth, width, length) of cracks normal to the surface</em>.</td>
<td>Combinations of techniques may be appropriate: one to detect, one to characterise.</td>
<td>✓</td>
</tr>
<tr>
<td>Table</td>
<td>Application &amp; Purpose</td>
<td>Comment</td>
<td>Needs Identified</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------</td>
<td>---------</td>
<td>------------------</td>
</tr>
<tr>
<td>8</td>
<td>Detection of delamination/ cracks parallel to the surface</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>9</td>
<td>Detection of surface deposits/ visual symptoms of flaws which indicate material degradation and support quantification of findings.</td>
<td>Visual inspection generally adequate, but could be enhanced by tools which increase productivity and/or quantify findings.</td>
<td>✓</td>
</tr>
<tr>
<td>10</td>
<td>Measurement of concrete mechanical properties (eg strength, stiffness), and identification of spatial variations or ageing effects.</td>
<td>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.</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>Measurement of cover to reinforcement to establish as built details</td>
<td>Existing NDE techniques (eg covermeter) adequate for measurement of cover up to 150mm. No specific need identified</td>
<td>✗</td>
</tr>
<tr>
<td>11</td>
<td>Detection of changes in porosity/ permeability to assess condition of concrete (presence of flaws)</td>
<td>Variety of permeability tests available; RILEM currently assessing these with objective of developing agreed standard. Outside the scope of this report.</td>
<td>✗</td>
</tr>
<tr>
<td>12</td>
<td>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</td>
<td>Physical probing generally necessary, and so outside scope of report.</td>
<td>✗</td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Table</th>
<th>Need</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Quantification of capability for measuring concrete thickness for sections &gt; 1.0m thick</td>
<td>H</td>
</tr>
<tr>
<td>3</td>
<td>Quantify existing performance capability for mapping / sizing of steel reinforcement and tendons (including identification of reinforcement laps and couplers) with section depth</td>
<td>H</td>
</tr>
<tr>
<td>4</td>
<td>Quantify performance limits for detecting corrosion in reinforcement through measurement of loss of section, pitting or hydrogen embrittlement in heavily reinforced structures</td>
<td>H</td>
</tr>
<tr>
<td>4 (new)</td>
<td>Detection of corrosion in steel liners that are buried (covered by concrete) or inaccessible due to presence of moisture barriers.</td>
<td>H</td>
</tr>
<tr>
<td>5</td>
<td>Quantify performance limits for detection of corrosion by measuring loss of section/hydrogen embrittlement in prestressing tendons in heavily reinforced structures</td>
<td>H</td>
</tr>
<tr>
<td>6</td>
<td>Quantify void detection threshold (and inhomogeneities e.g. honeycombing) in thick sections (variables: size of void, depth)</td>
<td>H</td>
</tr>
<tr>
<td>6</td>
<td>Detection of voids &gt;20mm diameter in grouted tendon ducts in e.g. containments / waste store roofs</td>
<td>H</td>
</tr>
<tr>
<td>7</td>
<td>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 &gt;0.2mm</td>
<td>H</td>
</tr>
<tr>
<td>9</td>
<td>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</td>
<td>H</td>
</tr>
</tbody>
</table>
# MEDIUM BENEFIT NEEDS

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

<table>
<thead>
<tr>
<th>Table</th>
<th>Need</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Measurement of thickness of complex geometries to ±5% section thickness (eg accounting for edge effects; thickness changes)</td>
<td>L</td>
</tr>
<tr>
<td>1</td>
<td>Measurement beyond a fully bonded liner in containments and fuel ponds, with sensitivity of ±5% section thickness</td>
<td>L</td>
</tr>
<tr>
<td>3</td>
<td>Resolve tendon details within ducts in thin sections (&lt;1.5m) in eg containments and waste store roofs with sensitivity of ±10%</td>
<td>L</td>
</tr>
<tr>
<td>3</td>
<td>Resolve tendon details within ducts in thick sections (&gt;1.5m) in eg PCPVs with sensitivity of ±10%</td>
<td>L</td>
</tr>
<tr>
<td>3</td>
<td>Resolve reinforcement details in congested regions, including laps and couplers, with sensitivity to identify individual reinforcement at spacings ≤150mm and depths &gt;30mm AND measure reinforcement diameter with sensitivity of ±10%.</td>
<td>L</td>
</tr>
<tr>
<td>4</td>
<td>Enhanced speed of application for detection of corrosion through measurement of loss of section</td>
<td>L</td>
</tr>
<tr>
<td>5</td>
<td>Enhanced speed of application for detection of corrosion by measuring loss of section, pitting or hydrogen embrittlement in prestressing tendons</td>
<td>L</td>
</tr>
<tr>
<td>8</td>
<td>Detect debonding of prestressing tendons in containments &amp; other structures with grouted tendons</td>
<td>L</td>
</tr>
</tbody>
</table>
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: > 1.0 M

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).
<table>
<thead>
<tr>
<th>Radar Needs</th>
<th>Development</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved quantification of capabilities for measuring thickness, mapping</td>
<td>Laboratory sensitivity studies and well characterised structures.</td>
<td>L</td>
</tr>
<tr>
<td>or sizing layers of reinforcement, detecting/mapping of voids:</td>
<td>Complemented by experimental reference data and systematic documentation</td>
<td></td>
</tr>
<tr>
<td>• in sections &gt;1m thick</td>
<td>of application on specific types of problems.</td>
<td></td>
</tr>
<tr>
<td>• with depth/reinforcement congestion</td>
<td>Note that this covers quantification of radar capabilities; qualification</td>
<td></td>
</tr>
<tr>
<td>• void detection thresholds (with volume/depth)</td>
<td>of methods/personnel could add significant cost.</td>
<td></td>
</tr>
<tr>
<td>Improved sensitivity to resolve multiple layers of reinforcement,</td>
<td>Improved software for signal and image processing of multiple reflections;</td>
<td>M</td>
</tr>
<tr>
<td>identifying individual reinforcement at spacings &lt;&lt;150mm and depths &gt;30mm</td>
<td>improved antennae design; variable frequency.</td>
<td></td>
</tr>
<tr>
<td>Improved sensitivity to measure reinforcement diameter in top layer with</td>
<td>Improved software for signal and image processing of multiple reflections;</td>
<td>H</td>
</tr>
<tr>
<td>sensitivity ±10%</td>
<td>improved antennae design; variable frequency.</td>
<td></td>
</tr>
<tr>
<td>Measurement of thickness with sensitivity of 5%, with single sided access</td>
<td>Little development needed</td>
<td>L</td>
</tr>
<tr>
<td>Assessment of the influence of concrete electric and dielectric properties</td>
<td>Combination of sensitivity studies and modelling/analytical techniques.</td>
<td>L</td>
</tr>
<tr>
<td>(affected by moisture) on radar measurements</td>
<td>Low cost relies on results from CEC programme (2) becoming available.</td>
<td></td>
</tr>
<tr>
<td>Enhance performance of radar application (speed of use &amp; sensitivity) by</td>
<td>Link to ultrasonics (benefits from data being presented in similar formats,</td>
<td>L</td>
</tr>
<tr>
<td>linking to other techniques</td>
<td>but response to different features)</td>
<td></td>
</tr>
<tr>
<td>Modifications to radar equipment to enhance ease of use in restricted</td>
<td>Evolutionary development of existing equipment</td>
<td>M</td>
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<td>spaces</td>
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<tr>
<td>Assessment of the effect of radar EMI, and checking against tolerable</td>
<td>? Standard tests? Cost would rise if significant developments were needed</td>
<td>L</td>
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<tr>
<td>levels in nuclear plant.</td>
<td>to design against unacceptable levels of EMI.</td>
<td></td>
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Reference was made to the following document during discussion:
<table>
<thead>
<tr>
<th>Need</th>
<th>Development</th>
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| 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. |
| Improved performance for:                                          | Development of multiprobe pitch-catch and other coherent processing methods.  
- 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 | Improve signal-to-noise ratios.  
Development of a true pulse-echo technique would be high cost; the above represent a practicable way forward. |
| Detect debonding of prestressing tendons in grouted tendon ducts     | Develop scanning and interpretation methods. Two probe pitch-catch techniques |
| 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 |
| 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 |
| 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. |

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### Acoustic Stress Wave Methods (Surface Waves, Impact/Echo)

<table>
<thead>
<tr>
<th>Need</th>
<th>Development</th>
<th>Cost</th>
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| 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 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    |
<table>
<thead>
<tr>
<th>Radiography task</th>
<th>Development/Improvement</th>
<th>Cost</th>
</tr>
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</table>
| 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 quantification of radiography capabilities; qualification 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.

\[ \text{Th= Concrete thickness} \]
\[ F= \text{Peak Frequency (bottom echo)} \]
\[ C= \text{Wave Speed in Concrete} \]

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 ( \( F = C/(2.\text{Th}) \) ), 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 ( \( F = C/(4.\text{Th}) \) ) 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 40 mm. 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 MPa, 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 m$^3$ 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 honeycombing, 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 1 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 1 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.
Bridge slab

SASW-measurement conducted at upper surface
Receiver separation 1.5m

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (m)</th>
<th>Velocity (m/s)</th>
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<tr>
<td>1</td>
<td>0.15</td>
<td>2440</td>
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<tr>
<td>2</td>
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<td>2250</td>
</tr>
<tr>
<td>3</td>
<td>1.05</td>
<td>2580</td>
</tr>
</tbody>
</table>
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 2D 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.

<table>
<thead>
<tr>
<th>Development</th>
<th>Cost*</th>
<th>Benefit*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantification of capability</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Qualification of techniques</td>
<td>moderate/high</td>
<td>high</td>
</tr>
<tr>
<td>Combining techniques</td>
<td>low/moderate</td>
<td>medium</td>
</tr>
<tr>
<td>Ease of use (evolutionary)</td>
<td>moderate</td>
<td>medium</td>
</tr>
<tr>
<td>Equipment and software</td>
<td>high</td>
<td>low, medium and high.</td>
</tr>
</tbody>
</table>

* 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
Ulriska Wiberg, Vattenfall Utveckling AB, Sweden

- 3D radar imaging and imaging using mechanical impact has great potential for detailed investigation 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 T1EA

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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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

PRINCIPAL WORKING GROUP 3:
REACTOR COMPONENT INTEGRITY

REPORT OF THE TASK GROUP
REVIEWING NATIONAL AND INTERNATIONAL
ACTIVITIES IN THE AREA OF
AGEING NUCLEAR POWER PLANT
CONCRETE STRUCTURES.
NEA/CSNI/R(95)19 1996.
CSNI PROGRAMME OF WORKSHOPS

First Priority
- Loss of pretressing force in tendons
- In-service inspection of reinforced concrete structures having thick sections or where access is difficult

Second Priority
- Viability of performance based database
- Response of degraded structures (FEA and International Standard Problem)

Third Priority
- Instrumentation and monitoring
- Repair methods
- Criteria for condition assessment
DEVELOPMENT PRIORITIES FOR NDE OF CONCRETE STRUCTURES IN NUCLEAR PLANTS

SCOPE OF WORKSHOP.

Focus on applicability of NDE to:

- thick sections
- congested reinforcement
- limited access

Focus on promising techniques:

- RADAR
- Acoustic (ultrasonic and stress wave)
- Radiography

**NOT:** Instrumentation
Destructive/semi-destructive
Permeability tests
Corrosion monitoring.
OECD NEA WORKSHOP

DEVELOPMENT PRIORITIES FOR NDE OF CONCRETE STRUCTURES IN NUCLEAR PLANTS

OBJECTIVES

Session 3.
To prioritise development of NDE techniques for safety related concrete structures in nuclear installations

Session 1
To identify the perspectives of national regulators and plant operators on what is required of NDE.

Session 2
To provide opportunity for NDE practitioners to share experience and views on the status of development of key NDE techniques.
PROCESS FOR PRIORITISING NDE DEVELOPMENT

1. Identify specific needs for NDE development
2. Assess benefit and potential technical development to meet the need (CHAPTER 3)
3. Propose programme of technical development
4. Estimate cost of development & likelihood of success (CHAPTER 4)
5. Cost/benefit analysis
6. Matrix showing relative priorities (CHAPTER 5)
COST/BENEFIT ANALYSIS
(Chapter 5)

LOW

HIGH

COST

LOW

HIGH

BENEFIT

PRIORITY
NEED FOR NDE DEVELOPMENT

(Chapter 3)

ASSESSMENT OF BENEFIT

BASED ON:
• NEED FOR IMPROVED EASE/SPEED OF APPLICATION
• NEED FOR ENHANCEMENT IN CAPABILITY/SENSITIVITY
• BREADTH OF APPLICATION
NDE DEVELOPMENT COSTS...
(Chapter 4)

INDICATIVE LEVELS FOR DEVELOPMENT COSTS (US $)

- Low: < 0.1 M
- Moderate: 0.1 - 1.0 M
- High: >1.0M
PROPOSED OUTPUT FROM WORKSHOP

REPORT:

- Update main body of the text to take account of workshop discussion, in particular Tables & Conclusions
- Only corrections to Appendices, based on WRITTEN contributions which identify specific revisions proposed by participants
- Include workshop presentation material and summary of discussion as Appendix

RECOMMENDATIONS:

- Clear definition of actions (who, what, when)
Session 1: OBJECTIVE.

To identify the perspectives of national regulators and plant operators on what is required of NDE.
Nuclear Safety Related Concrete Structures

Examples
- Biological shields
- Containments
- PCPVs
- Spent fuel ponds
- Waste stores
- Waste silos
- Active process cells
- Auxiliary structures

Characteristics
- Section thickness >1.0m
- Reinforcement congestion
- Liners & external cladding
- Access constraints
ROLE OF NDE IN AGEING MANAGEMENT

Drivers
- Re-evaluation of design (due to operational changes, life extension, decommissioning planning etc)
- Periodic safety reviews
- Evaluation of identified flaws

Requirements
- Determination of as-built (or current) structural details
- Detection of flaws
- Characterisation and quantification of flaws
IDENTIFICATION OF NEEDS

• Build confidence through clear quantification of existing performance (reliability, sensitivity) for relevant applications

• Specific challenges identified in text:
  - sizing of reinforcement in areas of congested steelwork
  - detection of voids in grouted prestressing systems
Canadian Perspective on Current NDE Practice and Needs

K. (Ken) E. Philipose

AECL
Chalk River Laboratories,
Chalk River, Ontario, Canada

Risley Workshop, Nov 1997
NDE techniques commonly used

Field Techniques

- Impact Hammer (Schmidt Hammer)
- Surface Hardness (Windsor Probe)
- Mechanical Gauges
- Covermeter (generally only to avoid rebar when drilling)
- Half-cell Potential
- Ultrasonic pulse velocity
- Impact Echo
- Strain Gauging
- Video Cameras (borehole remote cameras)
- Tomography
Other NDE techniques examined

1. Thermal (Infra-red photography)
2. Acoustic Emission (to identify post-tension strand failure)
3. Holography
Common uses of NDE techniques

1- Measurement of concrete quality

   Ultrasonic pulse velocity measurements, impact hammers and surface hardness testing are used.
   These techniques do not give absolute values of the mechanical properties but an indication of the relative quality of concrete.

2- Detection of corrosion in steel

   Half-cell potential measurements are used.

3- Detection of voids (limited)

   Ultrasonic transmission is used to identify general presence of voids.
4- Detection of delaminations
   Sounding the surface with a hammer for shallow delaminations, and impact echo technique for deeper delaminations.

5- Detection and sizing of cracks normal to surface
   With ultrasonic or impact echo techniques, especially for narrow cracks, the signal bridges the crack before the end, giving an inaccurate crack depth.
Development priorities for NDE techniques

1- Structural aging
   Identifying and quantifying degradation of concrete elements due to aging.

2- Inaccessible areas.
   NDE techniques for the assessing condition of structures in inaccessible areas.

3- Detection of corrosion in steel reinforcing bars
   Improvements in half-cell potential measurement techniques.

4- Detection of corrosion in post-tension tendons
   This has been a need for a long time. Currently lift-off tests of greased tendons are used.
5- Detection of surface deposits
A means for quickly differentiating, in the field, between deposits due to soluble cement components and the manifestation of AAR.

6- Detection of changes in porosity/permeability
Various field techniques were reviewed, but there was concern that data obtained would not be relevant or accurate. Standardization of these measurement techniques is required.
Concluding remarks

In general, the NDE examination of the as-built condition of structures is not a need. The focus of future NDE should be on monitoring concrete aging. To our knowledge, the techniques promoted in this report, particularly radar and radiography, may not be suitable to monitor characteristics related to concrete aging.

Acknowledgment

The presentation was compiled from information provided by Ed. McCollm of Ontario Hydro and C. Sent of AECL.
<table>
<thead>
<tr>
<th>Application</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk areas</td>
<td>Visual/fibrescope</td>
</tr>
<tr>
<td>Concrete</td>
<td>Impact-Echo</td>
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<td>Thickness</td>
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<td>Reinforcement</td>
<td>Covermeter</td>
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<tr>
<td>Reinforcement Mapping</td>
<td>Covermeter with printouts</td>
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<tr>
<td>Crack measurement</td>
<td>Ultrasonic pulse velocity</td>
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Need for NDE Development Swiss Perspective

<table>
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<tr>
<th>Application</th>
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</tr>
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<tbody>
<tr>
<td>Detection of flaws throughout the structure with high sensitivity and characterisation (single sided access)</td>
<td>None identified</td>
</tr>
<tr>
<td>Application</td>
<td>Technique</td>
</tr>
<tr>
<td>---------------------------------------------------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>- Crack sizing normal/parallel to surface with sufficient level of accuracy to be accepted by the regulator</td>
<td>- Ultrasonic pulse velocity ?</td>
</tr>
<tr>
<td>Application</td>
<td>Technique</td>
</tr>
<tr>
<td>---------------------------------------------------------------------------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>- Condition monitoring (loss of section due to corrosion) of inaccessible parts embedded in massive concrete struct.</td>
<td>- None identified</td>
</tr>
</tbody>
</table>
SPANISH PERSPECTIVES
Dr. J. Rodríguez
GEOCISA (Dragados Group)

- SPANISH EXPERIENCES
- NEEDS FOR NDE TECHNIQUES
SPANISH EXPERIENCES

◆ FEW EXPERIENCES IN NDE TECHNIQUES FOR CONCRETE STRUCTURES IN NUCLEAR POWER PLANTS

◆ NO SPECIFIC STANDARDS FOR THIS FIELD OF APPLICATION

GEOCISA (DRAGADOS GROUP)
ULTRASONIC PULSE VELOCITY (DIRECT TRANSMISSION):

[TECNATOM]

- TO ASSESS CONCRETE CONDITIONS IN COLUMNS AFFECTED BY FOUNDATION SETTLEMENTS, IN THE CONTROL BUILDING U. II, (ASCO NUCLEAR POWER PLANT).

- EQUIPMENT: BP 5 KRAUTKRAMER (50 KHz)

- CAMPAIGNS EVERY 3 MONTHS SINCE 1984 AND EVERY 18 MONTHS SINCE 1997, WITH GOOD RESULTS.

GEOCISA (DRAGADOS GROUP)
RADAR MEASUREMENTS:

[UNIV. OF VALENCIA AND CATALUNYA]

- Work to cut the wall in the concrete containment to replace the steam generators (ASCO).
- To identify the position of the bars before the wall cutting.
- GEORADAR SIR 10 (Geophysical Survey Systems) AND 3100 ANTEenna.
- Accurate results (+/- 1cm)
CORROSION MEASUREMENTS:

[TORROJA AND GEOCISA]

– ASSESSMENT OF A CONCRETE CONTAINMENT IN A NUCLEAR POWER PLANT (25 YEARS OLD).

– CORROSION RATE MEASUREMENTS BY THE POLARIZATION RESISTANCE TECHNIQUE (Sensorized Confinement Method; GECOR6 [1])

– CORROSION RATE VALUES: 0.01 - 0.05μmA/cm²
– CORROSION POTENTIAL: +50 AND -350 mV


GEOCISA (DRAGADOS GROUP)
CORROSION MEASUREMENTS (CONT.):

[TORROJA AND GEOCISA]

- CONCRETE RESISTIVITY MEASUREMENTS (Disc Method; GECOR6 [2])

- VALUES: 1600 - 4300 Kohm cm

NEEDS FOR NDE TECHNIQUES

♦ RADAR:
  - Technique for cover size; mapping the reinforcement, ducts and other encastr items, without enough resolution to evaluate corrosion.
  - Limitations to detect items behind the first reinforcement layer.
  - Needs:
    - Directional antennas
    - New software developments to improve signal and image processing

GEOCISA (DRAGADOS GROUP)
ULTRASONIC PULSE VELOCITY:

- Technique for assessing concrete condition: quality, voids, delaminations, length of cracks at right angle to the surface, ...

- Needs:
  - Improving the coupling of concrete surface/transducers to improve the speed of application
• SPECTRAL ANALYSIS OF SURFACE WAVES:
  
  – TECHNIQUE TO MEASURE QUALITY AND THICKNESS IN LAYERED SYSTEMS.
  – APPLICATION IN CONCRETE FOUNDATIONS.
  – PROBLEMS WITH WAVE REFLECTION FROM REINFORCEMENT, ...
  – NEEDS:
    ✦ DEVELOPMENT OF A THEORETICAL SOLUTION FOR FINITE-SIZE LAYERED MEDIA

GEOCISA (DRAGADOS GROUP)
◆ IMPACT ECHO:

- Technique to measure concrete depth, delaminated concrete depth, detection of flaws, ...

- It could be applied to detect:
  ✦ Liner debonding (from the outside of the concrete container);
  ✦ Voids in ducts, ...

- Needs:
  ✦ Improvement for an easy interpretation of the results
— REINFORCEMENT CORROSION
  — AVAILABLE TECHNIQUES FOR QUANTITATIVE EVALUATION OF THE CORROSION RATE (REINFORCING BARS; PRESTRESSING AND DUCTS)
    ✦ PORTABLE DEVICES (GECOR6, ...)
    ✦ EMBEDDED SENSORS.
  — CORROSION POTENTIAL
  — CONCRETE RESISTIVITY (FOUR POINT METHOD; DISC METHOD; ...)
  — NEEDS:
    ✦ CORROSION IN POSTEMIONED TENDONS
    ✦ REDUCTION OF TEST TIME FOR QUANTITATIVE EVALUATION.
    ✦ EVALUATION OF MAX. DEPTH AT THE PITS

GEOCISA (DRAGADOS GROUP)
SUMMARY

◆ CORROSION: ELECTROCHEMICAL TECHNIQUES
◆ VOIDS IN DUCTS: IMPACT ECHO; RADIOGRAPHY
◆ DELAMINATIONS: UPV; IMPACT ECHO; RADIOGRAPHY.
◆ CRACKS: UPV; IMPACT ECHO
◆ VOIDS: IMPACT ECHO; RADIOGRAPHY; RADAR (IN THE COVER)
◆ LINER DEBONDING: IMPACT ECHO; UPV (?)
◆ CONCRETE THICKNESS: IMPACT ECHO; UPV
◆ COVER SIZE: RADAR
◆ LOCATION OF REINFORCEMENT: COVERMETER, RADAR; RADIOGRAPHY

GEOCISA (DRAGADOS GROUP)
USNRC Perspectives on NDE of Nuclear Power Plant Concrete Structures

Wallace E. Norris, John S. Ma, and Pao-Tsin Kuo

Abstract

Safety-related nuclear power plant (NPP) structures are designed to withstand loadings from a number of low-probability external and interval events, such as earthquakes, tornadoes, and loss-of-coolant accidents. Thus, stresses incurred during normal operation are not high enough to cause any appreciable degradation. However, there are many age-related degradation mechanisms which may affect these structures. In the late 1980s and early 1990s, numerous occurrences of degradation of the concrete structures were discovered at various facilities, and yet, generally, inspection inspection (ISI) of these safety-related structures continued to be performed in a cursory manner. The U.S. Nuclear Regulatory Commission (NRC) has published several new requirements since 1991 to ensure that adequate ISI of these structures is performed. The primary nondestructive examination (NDE) method used to evaluate concrete structures has been a visual inspection (condition survey). However, structural deterioration can occur without perceptible manifestation and can sometimes be difficult to detect through routine visual examination. NDE methods such as impact-echo are valuable but have limitations. Other NDE methods such as those based on acoustics are still in various stages of development. The most promising of these other NDE methods need to be improved so that additional tools are available for the inspection of NPP concrete structures. Additional NDE methods would preclude, in some cases, the need to perform destructive examination. Destructive examination methods can reveal much regarding the condition of the structure, but are seldom utilized because of the attendant problems in restoration of the design basis. More effective ISI methods for the examination of safety-related concrete structures must be developed in order to assure that these structures are maintained in a safe and functional condition.

Structural Degradation Problem

As of November 1997, 109 commercial power reactors are licensed to operate in the United States (US). The median age of those operating reactors is 20 years. There have been many reported occurrences of degradation of safety-related structures and civil engineering features at operating NPPs in the US in the last 16 years. In 1992, the NRC Office of Nuclear Regulatory Research sponsored a survey questionnaire of the NPP owners to obtain information on the types and location of

distress in concrete structures, the types of repairs, and durability of repairs. Twenty-nine utilities totaling 41 reactor units responded. The most common locations for deterioration were the auxiliary building, secondary containment (shield building), walls, and slabs. Eight-six percent of the plants reported cracking of the NPP concrete structures, 65 percent reported spalling, and over 20 percent reported staining, honeycombing, efflorescence, and scaling. The reported prevalent causes of deterioration were drying shrinkage (48 percent), followed by freeze-thaw (31 percent), and abrasion (24 percent).

There are 71 concrete containments in the US; 31 reinforced concrete and 40 prestressed concrete. Degradation of the concrete or the post-tensioning system has been reported in more than 30 concrete containments. One plant reported extensive cracking and spalling of the containment dome due to freeze-thaw cycling which exposed rebar. Several plants, during their 15 and 20 year tendon ISI examinations, respectively, reported low tendon lift-off forces for isolated tendons. These lift-off forces were equivalent to those which would be expected near the end of the 40-year operating term. More than 30 occurrences of degradation have also been reported in steel containments.

There have been several instances of minor water leakage collected by the leakage monitoring systems from spent fuel pools, and of leakage through cracks in stainless steel liner welds. Intake structures of plants in coastal areas have undergone significant degradation. Tendon galleries of prestressed concrete containments and other underground structures have undergone degradation due to water intrusion.

Need for Inspection and Maintenance

The number of occurrences and the extent of degradation of NPP structures prompted the NRC to publish new rules regarding ISI and maintenance of NPP structures. To reduce the likelihood of failures and events caused by the lack of effective maintenance, the NRC published the maintenance rule on July 10, 1991, as 10 CFR 50.65, "Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants." As discussed in the rule summary, in order to maintain safety, it is necessary to monitor the effectiveness of maintenance, and to take timely and appropriate corrective action, when necessary, to ensure that the maintenance process

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continues to be effective for the lifetime of NPPs, particularly as plants age. Section 50.65 requires that plant owners monitor the performance or condition of structures, systems, and components (SSCs), against the owner-established goals, in a manner sufficient to give reasonable assurance that such SSCs are capable of fulfilling their intended functions. Section 50.65 further requires the licensee to take appropriate corrective action when the performance or condition of an SSC does not conform to established goals. In order to verify the implementation of 10 CFR 50.65, the NRC issued Inspection Procedure 62002, "Inspection of Structures, Passive Components, and Civil Engineering Features at Nuclear Power Plants."

On May 8, 1995, the NRC published a final rule amending 10 CFR Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants," which contained the requirements that an applicant must meet to renew their operating license. The final rule is intended to ensure that important systems, structures, and components will continue to perform their intended function in the period of extended operation. Only long-lived structures and components will be subject to an aging management review for license renewal, and the NRC license renewal review will focus on the adverse affects of aging. The NRC concluded that long-lived components should be subject to an aging management review because, in general, functional degradation of these components may not be apparent so that the regulatory process and existing licensee programs may not adequately manage detrimental effects of aging in the period of extended operation.

In June 1995, the NRC published NUREG-1522, "Assessment of Inservice Conditions of Safety-Related Nuclear Plant Structures." The NUREG compiled information related to the condition of NPP structures from sources such as NRC inspections, the licensees' Licensing Event Report System which are required by 10 CFR 50.73, and an industry survey. The main conclusion from this report was that safety-related NPP structures need to be periodically inspected and maintained.

10 CFR Part 50, Appendix J, "Primary Reactor Containment Leakage Testing for Water-Cooled Power Reactors," which was published in the early 1970s, requires a general inspection of the accessible interior and exterior surfaces of the containment structures and components to uncover any evidence of structural deterioration which may affect either the containment structural integrity or leak-tightness. The large number of reported occurrences (over 60) and the extent of the degradation led the NRC to conclude that this general inspection was not sufficient. Thus, on August 8, 1996, the NRC published an amendment to 10 CFR 50.55a of its regulations to require that licensees use portions of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) for containment ISI for the first time. Specifically, the rule requires that licensees adopt the 1992 Edition with the 1992 Addenda of Subsection IWE, "Requirements for Class MC and Metallic Liners of Class Components of Light-Water Cooled Power Plants," and Subsection IWL, "Requirements for Class CC Concrete Components of Light-Water Cooled Power Plants," of Section XI, of the
American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code). A five year implementation period was permitted for licensees to develop and implement the examinations of Subsections IWE and IW L.

Regulatory Guide 1.127, "Inspection of Water-Control Structures Associated with Nuclear Power Plants," describes an appropriate ISI and surveillance program for dams, slopes, canals, and other water-control structures associated with emergency cooling water systems or flood protection of NPPs. NRC regulatory guides provide guidance and are not requirements. As discussed in NUREG-1522, there is very little information regarding inspection and reporting of occurrences of degradation relative to these structures available in the licensee event reports or in the Institute of Nuclear Power Operation (INPO) Nuclear Plant Reliability Data System (NPRDS). During NRC audits of these structures, some licensees have indicated, however, that extensive retrofitting was being considered due to the extent of degradation.

**Inspection Methods in the United States**

Visual examination is the primary method utilized in the US for examining concrete structures. Other nondestructive or destructive examination techniques are usually utilized only when perceptible degradation has occurred. ASME Section XI visual examination requirements are specified in IWA-2210. Section XI Subsection IWL, "Requirements for Class CC Concrete Components of Light-Water Cooled Power Plants," specifies VT-1C and VT-3C visual examinations for examining concrete containments ("C" specifying a concrete examination). VT-1C examinations are performed to detect discontinuities and imperfections such as cracks, wear, and erosion. A VT-3C is performed to determine the general structural condition. Table IWA-2210-1 specifies the maximum direct examination distance from the eye to the surface being examined. For a VT-1C examination, the minimum illumination required is 50 foot candles, the maximum direct examination distance is 2 feet, and the examiner must be able to distinguish a lower case character 0.044 inches in height. For a VT-3C examination, the minimum illumination required is 50 foot candles, the maximum direct examination distance is 4 feet, and the examiner must be able to distinguish a lower case character 0.105 inches in height. Remote examination may be substituted for direct examination if it is demonstrated that the remote examination is equivalent.

American Concrete Institute (ACI) 201.1R-92, "Guide for Making a Condition Survey of Concrete in Service," which provides a system for reporting on the condition of concrete, is one of the basic documents used by examiners. The guide states that a condition survey is an examination of concrete for the purpose of identifying and defining areas of distress. The guide cautions that the responsible committee has

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4 Available from the American Concrete Institute, Box 9094, Farmington Hills, Michigan 48333
attempted to include pertinent items that might affect concrete performance, and those responsible for making the survey should not limit their investigation to the items listed. Further, the guide cautions that those performing the survey should be experienced and competent in this field, and that following the guide does not eliminate the need for intelligent observations and the use of sound judgement.

ACI 349.3R-96, "Evaluation of Existing Nuclear Safety-Related Concrete Structures," is a report which provides recommendations for the development of an engineering review of an existing concrete NPP structure with the purpose of determining the physical condition and functionality of the structure. The report focuses on industry accepted evaluation practices and unique nuclear performance requirements, and the most effective practices for evaluation of safety-related concrete structures. By performing a thorough survey of the critical locations of structures and evaluating past structural performance, the current physical condition of the structure can be assessed and future structural performance may be predicted.

An extensive list of acceptance criteria is included in ACI 349.3R-96, Section 5.1.1, "Concrete Surfaces," to provide guidance to those performing visual inspections (condition survey) of concrete structures. With regard to conditions such as cracks and spalls, the following are generally acceptable without further evaluation: popouts less than 20 mm (¾-in.) in diameter or equivalent surface area; scaling less than 5 mm (⅞-in.) in depth; spalling less than 10 mm (⅝-in.) in depth and 100 mm (4⅞-in.) in any dimension; and passive cracks less than 0.4 mm (0.015-in.) in maximum width ("passive cracks" are defined as those having an absence of recent growth and absence of other degradation mechanisms at the crack). If the above conditions are exceeded and any popouts are less than 50 mm (2 in.) in diameter or equivalent surface area; scaling is less than 30 mm (1⅛ in.) in depth; spalling is less than 20 mm (¾-in.) in depth and 200 mm (8 in.) in any dimension; and passive cracks are less than 1 mm (0.04-in.) in maximum width, a review is required to judge their acceptability.

Where cracks and/or voids which may have potential consequences have been suspected in US NPP concrete structures, the impact-echo method has been utilized to map concrete cracks and voids. This method is an NDE technique that uses transient stress waves to detect flows in concrete.

Need for New NDE Method or Improvements To Existing Methods

Two candidate methods have been identified. The first application identified would require development of a new NDE method. A containment application is used for illustration purposes, but this method would have many other applications. Figure 1 shows a typical US large dry pressurized water reactor containment. The steel shell to concrete floor interface of such a containment is shown in Figure 2. This interface is sealed with a moisture barrier (silicone) during construction. Over time, as the moisture barrier dries out and shrinks, shell movement during normal operation and pressure
Figure 1. Typical PWR Large Dry Containment
Figure 2. Shell to Floor Interface
testing breaks the bond of the moisture barrier to the shell. This gap between the steel shell and the concrete floor permits condensation on the shell, and other fluids which may be present, such as borated water from leaking penetration lines, to run between the moisture barrier and the shell to collect below floor level. Industry experience to date has been that the fluids collects 2 to 4 inches below floor level initiating corrosion of the steel liner.\(^5\)

The second application requires improvements to existing methods for visual inspection of concrete structures. Concrete inspection is more of an art than a science in its present state. Although several ACI standards (as identified in previous paragraphs) provide guidance for the performance of condition surveys and acceptance standards for various types of conditions which may be detected, inspectors rely primarily on years of experience gathered through design, construction, and ISI in determining whether a condition is acceptable. This reliance on adequate experience presents three disadvantages to the manner in which inspection of concrete structures are presently performed. The first disadvantage is that, as evidenced by the dearth of Authorized Nuclear Inspectors with a “C” (concrete) endorsement, there are not enough qualified individuals with the necessary experience to perform adequate inspection of concrete structures. The second disadvantage is that visually inspecting every square foot of these structures is time consuming and costly. The third disadvantage is that acceptance of conditions based solely on judgement does not provide quantifiable results for the required licensee submittals to the regulatory authorities.

**Advances Required**

(1) A method is needed which can accurately determine the extent of corrosion and the remaining wall thickness of a steel containment shell. None of the NDE methods presently available are applicable to this application. At present, the only method available for accurately determining the condition of the steel shell is removing the concrete at the affected area. This method is not only destructive, but it is time consuming and costly. A nondestructive method is needed which provides the capability for penetrating the concrete to assess the condition of the steel shell. The method should be able to reliably and accurately determine the extent of corrosion and the remaining thickness of the shell. Further, the method (or a separate one) should be capable of penetrating both the concrete and the steel shell to assess the condition of the concrete behind the liner.

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(2) There is a need to better quantify the visual inspection of concrete structures. Engineering judgement cannot be entirely removed from the process nor should it be. However, the process should be improved so that quantifiable results are provided by condition assessments. Improvement could be made in several areas. For instance, to assist less experienced inspectors and also to provide reviewable results, a hand held instrument which is capable of measuring both the width and the depth of cracks and storing this information is needed. Another area for improvement, which is identified in the draft for workshop discussion, is the assessment of the condition of subsurface concrete. If acoustic, radar, or radiography NDE methods can be enhanced to accurately assess the condition of a structure, many of the concerns discussed in this paper would be addressed.
USNRC Perspectives on NDE of Nuclear Power Plant Concrete Structures

OECD-NEA Workshop on NDE of Concrete Structures in NPPs

November 12, 1997

Presented by: Wallace E. Norris
Outline of Presentation

☐ Need for Inspection (Structural Degradation Problem)

☐ Inspection Methods in the United States

☐ Need for New NDE Method

☐ Visual Inspection/Assessment Enhancements
Need for Inspection

- Research Survey of Concrete Structures - 41 Units
  - 86 Percent Reported Cracking
  - 65 Percent Reported Spalling

- Over 30 of the 71 Concrete Containments Have Experienced Degradation

- Intake Structures and Spent Fuel Pools
Inspection Methods Primarily Used in the United States

- Visual
  - ACI 201.1R-92
  - ACI 349.3R-96
  - ASME Section XI Subsection IWL

- Impact-Echo
Need for New NDE Method

- Steel Shell to Concrete Floor Interface
  - Problem Identified in Containments

- Method Would Be Utilized for Assessing Condition of Steel Liner and Concrete Behind the Liner
Typical Containment

Figure 1. Typical PWR Large Dry Containment
Shell to Floor Interface

.25" to .375" Liner
(6.35mm to 9.53mm)

Typical Area of Corrosion
Up to 4" (101.6 mm) Below Floor Level

Figure 2. Shell to Floor Interface.
Visual Inspection/Assessment Enhancements

- Visual Inspections Rely Too Heavily on Judgment Based on Experience
  - Lack of Quantifiable Results Makes Third Party Assessment Difficult
  - Instrumentation Needed

- NDE Methods Identified for Workshop Discussion Should Be Developed for Characterizing Subsurface Condition
  - Less Reliance on Judgment
S. S. Nefedov

The Federal Nuclear and Radiation Safety Authority of Russia
(Gosatomnadzor of Russia)

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OECD/NEA Workshop

Development Priorities for NDE of Concrete Structures
in Nuclear Plants

12 November 1997

Risley

United Kingdom
Using of NDE in evaluation of ferroconcrete constructions of NPP

OPERATING NUCLEAR POWER BLOCKS IN RUSSIA

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<th>Type</th>
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<td>RBMK - 1000</td>
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<td>With system of boxes</td>
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<tr>
<td>VVER - 440</td>
<td>6</td>
<td>With localisation tower</td>
</tr>
<tr>
<td>VVER - 1000</td>
<td>7</td>
<td>With containment</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>29</td>
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History of construction of now operating Nuclear Power blocks

Year of construction

Duration of work

<table>
<thead>
<tr>
<th>Period of operation</th>
<th>Number of blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 10 years</td>
<td>3</td>
</tr>
<tr>
<td>10 - 20 years</td>
<td>15</td>
</tr>
<tr>
<td>More than 20 years</td>
<td>11</td>
</tr>
</tbody>
</table>

The oldest block is in operation for 26 years (block 3 of Novovoronezh NPP)
AGEING OF FERROCONCRETE CONSTRUCTIONS

During service time constructions suffer:
- moral ageing
  due to changing of standards in direction of more severe requirements,
- physical ageing
  due to physical, mechanical, chemical processes.

Main mechanisms of physical ageing

**CONCRETE:**
- overheating (due to changing in equipment regimes)
- hot wetting (due to piping leakage)
- radiation
- freeze-thaw cycles
- sulphate attack

**Results:** structure loosening,
  reduction of strength characteristics,
  reduction of stiffness characteristics.

**REINFORCING, LINER:**
- corrosion,
- neutron embrittlement

**TENDONS:**
- corrosion
- relaxation

**ALL:**
- pressure cycles (due to accidents and testing)

Ageing monitoring:
  detecting and noting of all the ageing defects
by the staff of Building Service Division of Nuclear Power Plant at visual inspection

<table>
<thead>
<tr>
<th>Visual inspection</th>
<th>Volume</th>
<th>Ruling document</th>
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<tbody>
<tr>
<td>Revealing of extra displacements</td>
<td>Standard Instruction</td>
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</tr>
<tr>
<td>Cracking revealing and monitoring</td>
<td>TI 34-70-049-86</td>
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<tr>
<td>Determination of necessity of special examination</td>
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### ASSESSMENT OF SAFETY RELATED CONSTRUCTIONS

Regulators carry out assessment of safety related structures **at Renewal of License**
(once in 5 years for each nuclear power block)

<table>
<thead>
<tr>
<th>Steps of assessment</th>
<th>Carried out by</th>
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</thead>
<tbody>
<tr>
<td>Obtaining of necessary information about:</td>
<td></td>
</tr>
<tr>
<td>a) real sections area (net),</td>
<td>Operator</td>
</tr>
<tr>
<td>b) real mechanical characteristics of materials,</td>
<td>Contractor</td>
</tr>
<tr>
<td>c) physical state of materials,</td>
<td></td>
</tr>
<tr>
<td>d) actual loading regimes</td>
<td></td>
</tr>
<tr>
<td>Stress recalculation if necessary</td>
<td>Contractor (Designer)</td>
</tr>
<tr>
<td>Safety Report Renewal</td>
<td>Operator, Designer</td>
</tr>
<tr>
<td>Review of Safety Report and substantiating Analyses</td>
<td>Regulator</td>
</tr>
</tbody>
</table>

Using of NDE: steps a) – c)

Characteristic features of Nuclear Plant ferroconcrete constructions
(in connection with choice of NDE technique)

**ACCESS:**
- no direct access
- solely one-sided access
- short-time access

- tendons
- foundation slab
- bioshield, inner surface of containment (only in the frames of maintenance schedule after necessary preparation, deactivation etc)

**THICKNESS:**
- often more than 1 m
- sometimes more than 2 m

- containment
- bioshield, basement slab
- containment
- bioshield

**PRESENCE OF LINER:**
- one-sided liner
- two-sided liner

**STRUCTURE:**
- multilayered reinforcing (containment: up to 6 layers of rebars
  - 3 layers of tendons
  - 1 layer of liner)
- multiple encast details (bioshield)
- multiple penetrations

Means and technique of NDE would be much affected by: task of examination type of construction
LIST OF SAFETY RELATED STRUCTURES

Assessment by Regulator is applied only to safety related constructions.

List of Safety Related Constructions for each Nuclear Power Block:
- is worked out on the base of Safety Classification,
- is adjusted by interaction between Operator - Designer - Regulator.

Main classification item for building constructions is
category of responsibility for nuclear and radiation safety.

Ruling document PiN AE - 5.6 establish 3 categories. I-st category is the highest.

<table>
<thead>
<tr>
<th>Building/Construction</th>
<th>Construction technology</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor building:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- basement</td>
<td>monolithic ferroconcrete</td>
<td>I</td>
</tr>
<tr>
<td>- bioshield</td>
<td>cast-in-steel-cells.concrete</td>
<td>I</td>
</tr>
<tr>
<td>- containment</td>
<td>cast-in-sliding-formwork concrete</td>
<td>I</td>
</tr>
<tr>
<td>- surroundings</td>
<td>cast-in ferroconcrete-cells concrete</td>
<td>I</td>
</tr>
<tr>
<td>Fuel and waste storage:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- basement</td>
<td>monolithic ferroconcrete (linered)</td>
<td>I - II</td>
</tr>
<tr>
<td>- framework</td>
<td>precast ferroconcrete</td>
<td>III</td>
</tr>
<tr>
<td>- storage</td>
<td>cast-in-steel/ferroconcrete-cells concrete</td>
<td>I-II</td>
</tr>
<tr>
<td>Waste transportation bridges:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- supports</td>
<td>steel constructions</td>
<td>II</td>
</tr>
<tr>
<td>- piping corridor</td>
<td>cast-in ferroconcrete-cells concrete</td>
<td>II</td>
</tr>
<tr>
<td>Diesel-generator station</td>
<td>monolithic and precast concrete</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>of conventional type</td>
<td></td>
</tr>
<tr>
<td>Splash basins</td>
<td>concrete constructions</td>
<td>I-II</td>
</tr>
<tr>
<td></td>
<td>of hydrotechnical type</td>
<td></td>
</tr>
<tr>
<td>Cable or piping tunnels of safety systems</td>
<td>precast ferroconcrete tubes</td>
<td>I</td>
</tr>
</tbody>
</table>
Using of NDE in evaluation of ferroconcrete constructions of NPP

REACTOR BUILDING

<table>
<thead>
<tr>
<th>No.</th>
<th>Part</th>
<th>Thick., m</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>basement</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>bioshield</td>
<td>2.5</td>
</tr>
<tr>
<td>II</td>
<td>containment</td>
<td>1.2</td>
</tr>
<tr>
<td>III</td>
<td>surroundings</td>
<td>0.8</td>
</tr>
</tbody>
</table>

1 - reactor
2 - polar crane

CONTAINMENT

Containment type:
Prestressed shell with unbonded tendons
Lubricated tendons lay in ducts without injection

1 - helicoidal tendons of cylindrical part
2 - orthogonal tendons of dome
3 - anchors
4 - massive ferroconcrete ring
5 - increased thickness at fixation
6 - frame ribs of liner

Liner is used as inner framework at concrete placement
CAST-IN-CELL CONCRETE TECHNOLOGY

Steel cell

1 - liner sheets
2 - liner anchorage angles
3 - liner anchorage rods
4 - rebar diaphragm

Cell is prefabricated at the plant
brought to construction site
installed in design position
filled with concrete

Cell includes: reinforcing cage
penetration elements
encast details

FERROCONCRETE CELLS

1 - outer plates (precast), 2 - space for casting of concrete,
3 - reinforcing of joints

Outer plates

<table>
<thead>
<tr>
<th>types:</th>
<th>functions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>flat (thickness = 80 mm)</td>
<td>- serve as formwork</td>
</tr>
<tr>
<td>ribbed</td>
<td>- form protective layers</td>
</tr>
<tr>
<td></td>
<td>- include main reinforcement</td>
</tr>
</tbody>
</table>

Resulting section: in analysis - assumed as homogeneous
really - is not fully homogeneous
### CONTROL OF STATE OF CONCRETE CONSTRUCTIONS

<table>
<thead>
<tr>
<th>Control procedure</th>
<th>Executed by</th>
<th>How often</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual inspection</td>
<td>Staff of NPP</td>
<td>Usually twice a year</td>
</tr>
<tr>
<td>Standard examinations</td>
<td>Staff of NPP, Designer</td>
<td>Continuously in accord with regiment</td>
</tr>
<tr>
<td>Special examinations using destructive and non-destructive technique</td>
<td>Special Contractor</td>
<td>By decision of Operator (Regulator’s position: to each License Renewal)</td>
</tr>
</tbody>
</table>

#### Standard examination

<table>
<thead>
<tr>
<th>Volume</th>
<th>Technique</th>
<th>Ruling document</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constructions of hermetic measuring of stresses in concrete forces in rebars tightness testing <em>(after construction, then once a year)</em></td>
<td>enclosure (containment, boxes) using embedded apparatus <em>(at pressurisation)</em> using pneumatic equipment</td>
<td>PNAE G-10-021-90 p.3.1.3, 8.2.5 PNAE G-10-021-90 p.8.3</td>
</tr>
<tr>
<td>Containment control of tension of tendons <em>(first period - each year, then - each 4 years)</em></td>
<td>using special manipulator, which includes hydraulic measuring and tensioning system</td>
<td>Special instruction</td>
</tr>
<tr>
<td>Bioshield testing of radiation absorbing</td>
<td>radiography</td>
<td>PNAE G-10-021-90 p.8.7</td>
</tr>
<tr>
<td>Radioactive liquid storage tightness testing</td>
<td>leak testing</td>
<td>PNAE G-10-021-90 p.8.5</td>
</tr>
</tbody>
</table>

#### Special examinations

<table>
<thead>
<tr>
<th>Volume</th>
<th>Technique</th>
<th>Ruling document</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete density measuring</td>
<td>Radiography</td>
<td>GOST 17623-72</td>
</tr>
<tr>
<td>Concrete strength measuring</td>
<td>Acoustics</td>
<td>GOST 17624-72</td>
</tr>
<tr>
<td>Reinforcing mapping diameter measuring cover measuring</td>
<td>Radiography Magnetometry</td>
<td>GOST 17625-72</td>
</tr>
<tr>
<td>Cracking examination</td>
<td>Acoustics Radiography</td>
<td></td>
</tr>
<tr>
<td>Definition of concrete degradation layer</td>
<td>Acoustics</td>
<td></td>
</tr>
</tbody>
</table>
Session 2: OBJECTIVE.

To provide opportunity for NDE practitioners to share experience and views on the status of development of key NDE techniques.
**Tomographic Imaging**

Michael P. Schuller, P.E.

---

**Tomographic Imaging**

**Analytical Approach**

- Straight Ray
- Curved Ray

*Both techniques use SIRT - Simultaneous Iterative Reconstruction Technique*

---

**Tomographic Imaging**

**U.S. NRC Research**

- **Software**
  - Automate data gathering
  - Simplify analysis
  - Improve characterization

---

**Tomographic Imaging**

- **RAYPT Analysis**
  *Resolve discrete anomalies in a uniform background*

- **Spatial Coherency Filter**
  *Post-processing to remove minor anomalies*
### Tomographic Imaging

#### U.S. NRC Research
- **Software**
  - Automate data gathering
  - Simplify Analysis
  - Improve Characterization
- **Hardware**
  - Powerful data acquisition
  - Multi-sensor array

### Tomographic Imaging

#### Multi-Sensor Array

### Tomographic Imaging

#### Multi-Sensor Array

### Tomographic Imaging

#### Capabilities
- Identification
- Characterization
- Quantification

### Tomographic Imaging

#### Capabilities
- Cracks
- Voids
- Low density regions
- Large steel inclusions
- Construction cold joints
- Post-tension ducts
- Quantify repair success
- Steel containment lining separation

### Tomographic Imaging

#### Capabilities
- Laboratory Trials
  - Small-Scale Specimens
    - Low density inclusions
    - Low density area, with reinforcing bars
    - Voids
### Tomographic Imaging

**Low Density Inclusion**

- Low Density Concrete

---

**Capabilities**

- Laboratory Trials
  - Small-Scale Specimens
  - Large-Scale Specimens
    - Reinforced specimen
    - Crack identification
    - Low density zones

---

**Cracked Section - Reinforced**

---

**Capabilities**

- Laboratory Trials
  - Small-Scale Specimens
  - Large-Scale Specimens

- Field Trials
  - Highway Bridge Structures
    - Construction cold joint
    - Crack repair - epoxy injection

---

**Bridge Girder - Crack Repair**

---

**Bridge Girder - Crack Repair**
Tomographic Imaging
Bridge Girder - Cold Joint

Tomographic Imaging
Capabilities
- Laboratory Trials
  - Small-Scale Specimens
  - Large-Scale Specimens
- Field Trials
  - Highway Bridge Structures
  - Trojan Nuclear Power Plant
    - Steel liner separation
    - Post-tension ducts

Tomographic Imaging
Trojan Plant - Containment Structure Section

Tomographic Imaging
Trojan - Steel Liner Separation

Tomographic Imaging
Trojan - Post-Tension Ducts
Tomographic Imaging

Capabilities

- Laboratory Trials
  - Small-Scale Specimens
  - Large-Scale Specimens
- Field Trials
  - Highway Bridge
  - Trojan Nuclear Power Plant
  - University of Wisconsin
    - Blind trial
    - Highly attenuative historic masonry

Tomographic Imaging

Masonry Pier Analysis

Tomographic Imaging

Limitations

- Access to 2 or more sides required
- Localized information
- Resolution limitations
- Data gathering efficiency
- Analysis time

Tomographic Imaging

Future Research

- Incorporate attenuation into analysis
  - Wavelet Decomposition
    - Separate inhomogeneities from damage
    - Resolve multiple scattering, dispersion effects
    - Scalograms:
      - 3-dimensional plots, shows amplitude versus frequency, phase velocity

Tomographic Imaging

Wavelet Decomposition Scalograms

- Porosity Defect
- Good Concrete

University of Wisconsin
### Tomographic Imaging

<table>
<thead>
<tr>
<th>Wavelet Decomposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Determine which wavelet parameter must be optimized - time or frequency</td>
</tr>
<tr>
<td>- Need to build a database of representative defects</td>
</tr>
<tr>
<td>- Distribution of expected material variation</td>
</tr>
<tr>
<td>- Characterize typical defects</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Future Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Incorporate attenuation into analysis</td>
</tr>
<tr>
<td>- Increase data gathering efficiency</td>
</tr>
<tr>
<td>- Automated positioning system</td>
</tr>
<tr>
<td>- Adaptive data reduction</td>
</tr>
<tr>
<td>- Real-time imaging</td>
</tr>
</tbody>
</table>

### Tomographic Imaging

<table>
<thead>
<tr>
<th>Future Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Incorporate attenuation into analysis</td>
</tr>
<tr>
<td>- Increase data gathering efficiency</td>
</tr>
<tr>
<td>- Develop scanning capabilities</td>
</tr>
<tr>
<td>- Explore single-sided techniques</td>
</tr>
<tr>
<td>- Phased array scanning</td>
</tr>
<tr>
<td>- Time-reversed backscattering</td>
</tr>
</tbody>
</table>

### Phased Array Scanning

<table>
<thead>
<tr>
<th>Future Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Detects flaws in solids</td>
</tr>
<tr>
<td>- Linear or 2-dimensional transducer array</td>
</tr>
<tr>
<td>- Adaptive time-delay focusing</td>
</tr>
<tr>
<td>- Accommodates scattering and dispersion effects with heterogeneous materials (concrete)</td>
</tr>
<tr>
<td>- Improves accuracy for locating and characterizing defects</td>
</tr>
</tbody>
</table>

### Phased Array Scanning

<table>
<thead>
<tr>
<th>Future Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Increase data gathering efficiency</td>
</tr>
<tr>
<td>- Low to moderate funding, less than 1 year</td>
</tr>
<tr>
<td>- Wavelet decomposition techniques</td>
</tr>
<tr>
<td>- Moderate funding, 1 to 2 years</td>
</tr>
<tr>
<td>- Phased Array Scanning</td>
</tr>
<tr>
<td>- Moderate to high funding, 2 to 3 years</td>
</tr>
</tbody>
</table>
Investigating concrete structures by 3D radar imaging and imaging using mechanical impact

Imaging

- **When?**
  - Detailed information from limited areas
  - Extent and distribution of damage
  - Location of objects and distinct defects

- **How?**
  - Scanning the structure
  - Direct interpretation through pictures
3D radar imaging

METHOD

- Based on pulsed radar measurements (GPR)
- Several measurement lines on the structure
  - For large areas - multiple antennas
  - For limited areas - one single antenna

TRANSPORTATION

- The equipment can be
  - carried and lifted by two people
  - transported on the rooftop of a car
3D radar imaging

SETTING UP MEASUREMENTS

- The equipment can be lifted into place by an overhead crane or a block
- Measurements can be made on horizontal and vertical surfaces

» Equipment set up in the intake of a hydro power station

Verification of capability

EXPERIMENTS

- Detection of material variations
- Imaging cast in objects

» Image using mechanical impact of blocks of air-entrained concrete
Performance in-situ

EXPERIMENTS

- Defect detection
- Imaging reinforcement

» Radar image of a defect behind the reinforcement in the wall of a hydro power station

Performance in-situ

EXPERIMENTS

- Lack of uniformity

» Radar image of variations in material quality in the intake structure of a hydro power plant
Capability for detection

<table>
<thead>
<tr>
<th>Defect/Method</th>
<th>Radar</th>
<th>Mechanical Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>PVC-tubes</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>Reinforcement</td>
<td>Good</td>
<td>None</td>
</tr>
<tr>
<td>Delamination</td>
<td>-</td>
<td>Good</td>
</tr>
</tbody>
</table>

Conclusions

- Potential for detailed investigation
- Objects of known shape can be
  - detected
  - approximately located
- Uniformity of concrete can be investigated
- Distinct anomalies behind reinforcement can be imaged
Possible applications

- Checking structures for non-uniform or porous concrete
- Checking leakage through cracks and leaching out
- Checking the results of injection
- Making remote controlled measurements
Use of Ultrasonics and RADAR for NDE of Concrete

Brian Hawker
National NDT Centre
NDT of Concrete

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

- Aggregate
- Matrix
- Reinforcement
  - all well bonded together
Inspections are to look for:

"As-built" faults:
- reinforcement pattern
- poor compaction/voids
- cracking

Service induced defects:
- corrosion of reinforcements
- cracks & delamination
- deterioration of the matrix
What can be done now?

A. With access front and rear :-
   - Ultrasound velocity (matrix)
   - Radiography (rebars, voids)

B. Access from one face :-
   - Covermeter (Cover & rebar location)
   - RADAR (Rebar pattern, cover & voids?)
   - Ultrasonics (Spalling, other cracks?)
   - Porosity (at the surface)
Inspection requirements

To establish confidence in the integrity of the structure:

- look for known types of faults
- also recognise unexpected faults
- reliable sentencing
What makes this difficult?

- Inhomogeneous on multiple scales
  (i.e., cement, grit, aggregate and re-bars)
- Large dimensions
- Contrasting materials:
  Steel - high velocity, conducting
  Matrix - lower velocity, poor conductor
Comparison with Cast Metals

Some cast austenitic stainless steel has coarse randomly oriented grains which are anisotropic. Wave propagation for both can be predicted by theoretical modelling.
Comparison of concrete and cast stainless steel

Equiaxed cast stainless steel

Concrete

(NB. The scales are different)

Ray paths can be predicted using Fermat’s Principle. Ultrasound will find the quickest route between two points.
Loss of wave coherence

1. The correlation length across the wavefront does not vary with range but is proportional to the grain size.

2. The standard deviation on travel time varies with range, $d$, the grain size, $g$, and the variation in velocity as:

\[
\frac{\sigma_T}{T} \propto \sqrt{\frac{d}{g}} \frac{\sigma_{V}}{V}
\]
Loss of wave coherence

The roughness of the wavefront after propagation through a slab can be imaged experimentally:
The consequences:

1. Higher frequencies become incoherent and highly scattered (noise)
2. Reduced coherent bandwidth gives poorer resolution
3. Reduced bandwidth and wavefront roughness jeopardises SAFT and spatial averaging performance
The lessons for ultrasonics:

1. Use low frequencies but broadband (resolution depends on the bandwidth, not just the frequency)

2. Use coherent summation from many viewpoints widely spaced (the s/n ratio improves with root N, but only if the noise is uncorrelated)

3. Avoid effects of reinforcements
What can be expected :-

1. To find and locate large voids, cracks, etc., at depths 300mm+, beneath rebars if the rebar spacing permits access and these are mapped out first and avoided.

2. Characterisation of the defect will be limited to resolution of 50mm or worse.
Ground-penetrating RADAR

Electromagnetic method so :-

- resolution depends on bandwidth
- insensitive to loss of material (i.e. cracks)
- slightly sensitive to inhomogeneity
- highly sensitive to metal
RADAR - the capability

- locate uppermost rebars
- measure cover
- measure rebar spacings
- verify lapping
- detect large voids/objects - but only if there is no surface reinforcement
• improved resolution
• clearer images
• penetration to beyond surface rebars
Assessment Trials
Test piece design

TP1C, Mesh 1, Front view
Test piece design

TP1C, Meshes 2 and 3, block rear view

Block
Mesh 2 16mm uprights
Mesh 2 25mm uprights
Mesh 2 25mm horizontals
Mesh 2 16mm horizontals
Mesh 3 25mm uprights
Mesh 3 16mm uprights
Mesh 3 16mm horizontals
16mm round bar
Mesh spacers
Resolution of Covermeter

Covermeter axis vertical

Cover (mm)

X position (mm)

Z position (mm)

- 80-70
- 50-60
- 40-50
- 30-40
- 20-30

AEA Technology

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Region scanned by Covermeter

NB. The vertical rebars are behind the horizontals and the covermeter axis is held vertical.
Targets for capability assessment:

- Various rebar spacings
- Varying cover
- Double layer rebars
- Resolution test gaps (30, 50, 70mm)
- Various laps
- Mechanical, grease and tape disbonds
- Voids (Plastic foam)
- Poor compaction (Aggregate in bags)
- Rebars of differing diameters
Conclusions - ultrasonics

- Only modest improvements to capability are possible by spatial averaging/summation
- Greatest potential is in attention to transducer design and instrumentation to optimise pulse characteristics and versatility
- Alternatively signals could be optimised retrospectively
Conclusions - RADAR

- Good for locating and recording reinforcements
- Difficult to get clear results
- Capability still incomplete
- Still lots of unexplored options
Session 3: OBJECTIVE.

To prioritise development of NDE techniques for safety related concrete structures in nuclear installations
NEXT STEPS...

What is the objective?
How will this be achieved?
Who will fund?

Actions required?
(Who, what, when)
IDEAS FOR INTERNATIONAL COLLABORATION...

OBJECTIVE

- Capitalise on collective international experience to enhance confidence in the application of NDE techniques and maintain awareness of best practice

MECHANISM

- International NDE benchmarking exercise to provide independent validation & qualification of techniques

- Establishment of NDE ‘expert group’ to enhance international networking, with tri-annual workshops to disseminate technical developments