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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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DEVELOPMENT PRIORITIES FOR NON-DESTRUCTIVE EXAMINATION OF CONCRETE STRUCTURES IN NUCLEAR PLANT

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

– to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
– to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
– to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter; Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996) and the Republic of Korea (12th December 1996). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of 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 consist 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 ionising 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 organisations in the nuclear field.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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

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

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

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

Foreword

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 a workshop on this topic, which was hosted by the UK Health and Safety Executive Nuclear Safety Division, organised by AEA Technology and held at AEA Technology Risley in November 1997. A draft of this report was discussed at the workshop, and revised in the light of the workshop discussion. The proceedings of this workshop have been issued separately.

The other first priority topic identified in the status report was loss of tendon prestress, and a workshop to address this was organised in 1997. A start on the second priority topics has been made with a workshop on the Finite Element analysis of degraded concrete structures, in October 1998.

Contents

Executive Summary

The objective of this report is to provide a basis for assessing development priorities for NDE of safety related concrete structures in nuclear plants, taking account of both the benefit and the cost of potential developments in NDE techniques. An OECD/NEA Workshop which considered the requirements for NDE of safety related concrete structures was held in the UK on 12 November 97.

NDE techniques have the potential to satisfy at least some of the needs of the nuclear industry. 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.

There is 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 there is concern that NDE procedures lack the necessary qualification to permit their use on safety critical structures. There is no authoritative international guidance or standard for NDE of concrete structures.

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 at the recent OECD workshop a number of relevant national and European programmes were identified. The nuclear industry maintain its awareness of developments and should seek to influence the development of equipment.

The quantification of the capabilities of NDE techniques is seen as a priority area for development. The provision of authoritative documentation in the form of reports and Standards is desirable. However, the industry lacks an international standard for quantifying the NDE of nuclear safety related concrete structures. Qualification is important to the successful deployment of NDE techniques and will need to be considered when addressing this issue.

The high cost of developing software and equipment, with no guarantee of success, means that the nuclear industry is unlikely to consider this to be a priority area for funding. However, it is important for the industry to establish national networks with groups that are funding development. There is support for the principle of establishing a group of international experts to monitor national developments.

The recommendations of the report are:

- More formal liaison with other industries that use NDE techniques should be established and opportunities to work with suppliers to influence the development of new equipment should be sought
- Experts should be identified to monitor national programmes with the aim of improving the understanding of the availability and capability of NDE techniques within the nuclear industry
- CSNI should review this topic in approximately 3 years
- At the time of the review, consideration should be given to quantification of the capabilities of NDE techniques by means of a standard test specimen specification
- As a longer term issue qualification should be considered.

1. INTRODUCTION

1.1. OBJECTIVE

The objective of this report is to provide a basis for assessing development priorities for NDE of safety related concrete structures in nuclear plants, taking account of both the benefit and the cost of potential developments in NDE techniques.

1.2. BACKGROUND

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.

Following its review of ageing management issues for concrete structures in nuclear plant [Ref 6], OECD/NEA Principal Working Group 3 (PWG3) is supporting a number of activities. These have been prioritised; the definition of requirements for development of NDE techniques for concrete structures where there are thick sections, or where access is difficult, was considered by PWG3 to be a high priority activity.

1.3. OECD/NEA WORKSHOP

An OECD/NEA Workshop which considered the requirements for NDE of safety related concrete structures was held in the UK on 12 November 97. The purpose of the workshop was to facilitate the exchange of current experience in order to understand existing and emerging NDE capabilities, and to assess the cost and benefit of developments in NDE techniques.

As part of the preparations for the workshop, a draft version of this report was circulated to all participants. It has since been updated to take account of the workshop discussion.

Future OECD/NEA activities are expected to include workshops on instrumentation and monitoring, and on analytical methods for assessing degraded structures.

1.4. SCOPE

The scope of the report was tightly defined to ensure a clear alignment with the remit established by PWG3. The report focuses on the application of NDE to support the engineering assessment of the 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).

Corrosion of steel reinforcement is recognised as being one of the commonest causes of deterioration of reinforced concrete structures, which has resulted in significant research and development effort on methods to detect corrosion. Initiatives in this area have generally involved a combination of visual and electro-chemical techniques. However, these techniques may not be applicable to the thick-sectioned or inaccessible structures found in nuclear plant, and it is this particular aspect which is covered in this report.

The report focuses 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.

1.5. REPORT STRUCTURE

The approach taken for assessing development priorities is shown schematically in Figure 1.1.

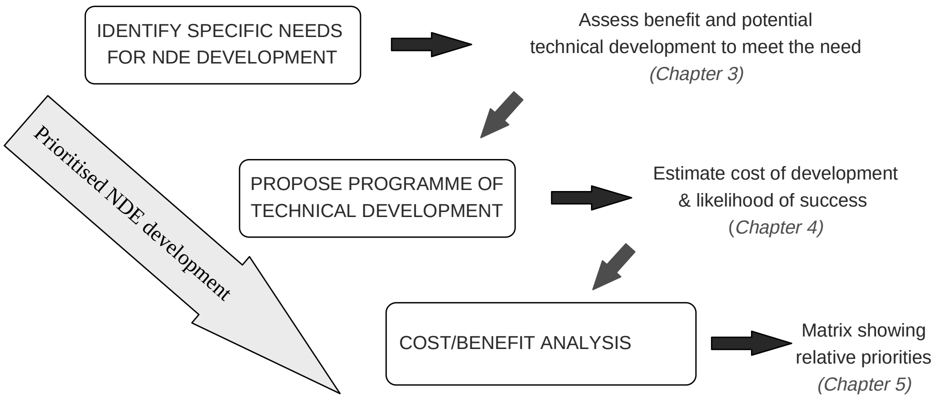
Section 2 provides an overview of typical safety related structures.

In Section 3, potential applications of NDE techniques in safety related concrete structures are identified. A comparison of potential applications and existing NDE capability is used to identify a series of development needs. To assist prioritisation, the benefit associated with each need has been qualitatively assessed.

Radar, acoustic methods and radiography are identified as having the greatest potential to make significant progress towards meeting the identified needs. In Section 4, the existing capability of these specific techniques are 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 given in Section 5. The report concludes with a series of recommendations for taking this forward.

Fig 1.1 PROCESS FOR PRIORITISING NDE DEVELOPMENT



2. NUCLEAR SAFETY RELATED CONCRETE STRUCTURES

This section provides a brief description of typical nuclear safety related concrete structures. Characteristics which are of particular relevance to the application of NDE are highlighted.

2.1. GENERAL

Structural reinforced and pre-stressed concrete has been used extensively in the construction of nuclear facilities since the birth of the civil nuclear industry in the late 1940's. As a material of construction, concrete is of relatively low cost, relatively high (compressive) strength, and the component materials of cement, aggregate and water are generally readily available. The process of manufacture means that bulk production at the construction site is generally practical and economic. Being of comparatively high density, concrete has the added benefit of providing attenuation of ionising radiation in addition to its properties as an engineering material.

Both reinforced and prestressed concrete structures are found in nuclear plants. In essence, the reinforcement and pre-stressing tendons in these structures perform a similar roles:

- Enhancement of the tensile and compressive strength of the concrete
- Control of deflections
- Resistance to thermal stresses
- Control of cracking

Reinforcement and stressing tendons are usually made from carbon steel. Although other materials and composites have been used as reinforcement in civil engineering applications, these are rarely found in nuclear plant. It is usual for pre-stressed concrete structures also to contain reinforcement.

2.2. SAFETY RELATED CONCRETE STRUCTURES

Given the safety significance of the containment as the final barrier to the release of radiation to the environment, it is typically this type of structure that has attracted greatest attention in terms of ageing management [eg IAEA, 1997]. This includes:

- reinforced and prestressed containment vessels in both BWRs and PWRs
- prestressed concrete pressure vessels in gas cooled reactors
- containment systems of CANDUs

A number of other structures impact, perhaps indirectly, on the overall safety of nuclear power plant. This influences their design and assessment requirements. Such structures are referred to as Safety Related Concrete structures. They would include building and structures housing critical plant components, where failure of the structure could lead to consequential damage or active waste contaminants. Examples might include fuel cooling ponds and supporting structures (eg crane platforms).

Nuclear chemical plant will also include Safety Related Concrete structures, for example active process cells and waste stores.

2.3. CHARACTERISTICS OF SAFETY RELATED STRUCTURES

The need to meet demanding design loading conditions dictated by function (e.g. thermal loading, dynamic loading, radiation) has led to a configuration and methods of construction that differ from conventional concrete structures. This gives rise to particular features which may limit the application of NDE:

Section Dimensions

Wall thicknesses in excess of 1.0m are common in safety related structures. In the extreme case of PCPVs, for example, prestressing tendons tend to be distributed across a section of 4–5 m thickness. Current NDE techniques tend to be limited to thin sections (<<1.0m), which restricts applications in safety related structures where there is a need to resolve objects and flaws at greater depths.

Steelwork Congestion

Safety related structures are often heavily reinforced, which can lead to significant steelwork congestion. For example, seismic design requirements can lead to increased reinforcement density and more complex detailing (staggered laps, couplers, multiple steel reinforcement layers etc.). Special steel reinforcement arrangements will be encountered local to penetrations and liners for windows and manipulators etc. There may also be multiple layers of reinforcement.

It is normal for a PCPV or containment structure to contain several hundred tendons, which may be grouted or ungrouted, within mild steel tendon ducts. Note that prestressed containment structures also include significant amounts of reinforcement, for example near crane corbels. Tendon anchorage zones, often an area of particular interest during inspections, tend to be areas of heavy tendon and steel reinforcement congestion.

Safety related structures can also contain a high proportion of penetrations and encast items, usually of carbon steel. For example, Bioshield and PCPV pilecap areas, contain numerous closely spaced penetrations surrounded by steel reinforcement (control and fuel rod channels). In addition, features such as service penetrations (pipework cables etc.) are generally lined with encast metallic ducts.

Such steelwork congestion presents a challenge for NDE techniques to distinguish the individual steel reinforcement elements within the concrete and ‘see’ the actual configuration. The presence of high densities of metallic objects in the structure may also lead to distortion of signals making it difficult to reliably detect and measure other flaws in the concrete matrix.

Liners and external cladding

In containments, PCPVs and fuel pond structures, the presence of liners prevent access to the surface of the concrete. Liners are typically simple carbon steel plate (up to 25mm thickness), but may themselves be inaccessible (for example where they are embedded in concrete, or where they are covered by thermal insulation, as in PCPVs). Established NDE techniques exist to assess condition (eg thickness, leak tightness) of liners. However, the steel forms an effective barrier to NDE measurement of features within the concrete immediately behind the liner (eg voids). This may be particularly relevant in pond structures where the external faces of the concrete may be inaccessible without excavation.

External cladding may also be present on some structures (e.g. waste stores, auxiliary buildings and containments) to provide added weather protection. Similar to liners this causes a physical barrier preventing direct access to the concrete surface. This can be further complicated by the presence of an interspace between the concrete surface and the cladding. It is possible however that localised removal of cladding materials to provide direct access to the concrete structure would be permissible in some circumstances.

Accessibility

Access constraints for application of NDE will depend upon the configuration of the structure and its environment. Physical restrictions due to structural configuration or inadequate access provisions can prevent direct access to a structure for manual deployment of an NDE technique. Harsh ambient environment founds within safety related structures, in particular high temperatures and radioactivity levels, may preclude man access making remote deployment essential for any NDE. Remote techniques may also be required for submerged structures, such as fuel ponds (which may be further complicated by the presence of liners). As a general criteria, NDE equipment needs to be as lightweight and as portable as possible.

Physical or environmental constraints can preclude access to more than one side of a structure. This situation is frequently encountered in the field, and can be complicated by the presence of a liner or cladding on one side of the structure. Examples of where this may occur include reactor bioshields and PCPV’s, active process cells, or fuel ponds.

The nature of structures, such as foundations, may render them totally inaccessible. Although there is a challenge for NDE techniques to ‘see’ through overlying structures or soils to allow examination of such structures, a more practical approach in the short term is to assess structures indirectly (for example through quantification of environmental conditions).

3. IDENTIFICATION OF NEEDS

This Section begins by giving an overview of the generic requirements for NDE techniques as part of the assessment of safety related concrete structures in nuclear plant. It continues by assessing current capabilities against specific requirements and thereby identifying areas where improvements in measurement capability could bring real benefit. This benefit is assessed qualitatively, taking account of enhancements to ease/speed of application, the existence of alternative techniques and potential breadth of application.

The objective of the Section is to identify specific needs on which to focus developments in NDE, and the associated ‘benefit’. Techniques which offer the potential to meet these needs, and the associated costs of development, are considered separately (Section 4). Prioritisation of development activities (Section 5) takes account of both ‘benefit’ and ‘cost’.

3.1. THE ROLE OF NDE IN AGEING MANAGEMENT

3.1.1. Overview

NDE is expected to gain an increasingly important role in ageing management of nuclear plant. As existing structures age, effective inspection has become a greater issue. For example, instances of ageing degradation have occurred relatively early at some US plants which threatened continued operation. Had a reliable means of inspection been utilised and the degradation been detected at an earlier stage, then the consequences of the degradation would be expected to have been significantly lower. Also, US plants seeking to extend operating life to 60 years will have to demonstrate that passive structures are capable of continuing to fulfil their intended function. It is believed that new, innovative NDE techniques will have to be developed and/or optimised to demonstrate this capability.

NDE has potential applications in three key areas in the management of safety related concrete structures :

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

The latter include the use of NDE techniques as a means for monitoring concrete ageing.

A distinction has been drawn between detection, and characterisation and quantification of flaws, as the requirements for NDE in each application differ. Detection of flaws only requires that a given technique should identify that a flaw is present, and give an approximate indication of location and extent. Characterisation and quantification techniques should be able to measure the nature and extent of a flaw with sufficient sensitivity to allow an engineering assessment of the impact of the flaw on safety and serviceability of the structure to be undertaken.

In all cases, the objective is likely to be to obtain data for use in an engineering assessment. Examples of drivers for this assessment include:

- confirmation of continued satisfactory structural performance (perhaps as part of a periodic safety review)

- evaluation of the significance (or otherwise) of an identified flaw
- re-evaluation of design due to changes in operational conditions (eg increased design loads, extended plant life or decommissioning planning).

Although in this report we are focusing on NDE techniques, it should be noted that alternative destructive and semi-destructive techniques are available to carry out the above tasks. Also, in some structures (eg PCPVs, containments) extensive instrumentation is available. The attraction of NDE techniques is that they are non-intrusive and can be less costly or disruptive to implement. The potential for improved accuracy and quality of data about the condition and performance of a structure is also attractive, as this may help to avoid overconservatism and unwarranted expenditure on monitoring or remedial works.

The following sections discuss the key requirements for NDE associated with each of the three key roles identified above.

3.1.2. Determination of As-Built Structural Details

Determination of as-built details of safety related structures is an important application for NDE. The requirement for this application can arise from inadequate or missing construction records (drawings and documentation), or suspected discrepancies between as-built structural details and record documentation due to errors or out of tolerance construction.

NDE can support determination of as-built structural details through:-

- Measurement of concrete thickness and cover
- Measurement of concrete properties
- Detection and sizing of steel reinforcement, including laps, connections etc
- Detection of tendons

3.1.3. Detection of Flaws

Safety related concrete structures in operating nuclear plant throughout the world have generally performed well. A comparatively small number of instances of deterioration have been reported (listed for containments in IAEA, 1996). In the main, timely detection and remediation have served to limit the impact of defects on the safety related function of these structures to within tolerable levels.

The majority of identified problems in nuclear containments have initiated during construction (IAEA 1996); the relatively few occurrences is a testament to the effectiveness of quality control procedures. Construction flaws are of concern due to both direct effects on structural safety and serviceability and indirect effects in the promotion of progressive deterioration through ageing mechanisms (eg cracks acting as a pathway for aggressive agents). Thus, reported instances of degradation later in life which are associated with specific mechanisms (eg freeze-thaw, attack by aggressive aqueous solutions, reinforcement corrosion) can often be linked back to poor design or construction practice which resulted in a permeable concrete or inadequate cover.

Construction flaws can arise from shortcomings in methods, workmanship, and supervision, with typical symptoms being:

- missing or incorrectly positioned steel reinforcement or stressing tendons
- inadequate compaction resulting in voidage, particularly likely in areas of congested reinforcement, at construction joints, behind liners, or around encast items/penetrations
- excessive cracking due to uncontrolled early age volume changes (often in massive concrete pours).

Confirmation of quality construction is equally relevant to new and existing plant, although easier access conditions during the construction / commissioning phase may make the former easier in terms of NDE application.

Flaws in any engineering structure can arise later in the life of the structure due to the onset of a process of progressive deterioration or ageing. Numerous reviews of ageing mechanisms have been published (eg IAEA, 1997); a summary of mechanisms, likely locations and symptoms for concrete, reinforcement and prestressing tendons and liners is included in Appendix 2. The primary manifestations of ageing are:

- cracking
- spalling/delamination
- surface deposits (eg gel exudations, surface salts)
- increases in porosity/permeability
- reductions in stiffness/ strength
- loss of prestressing force

Detection of ageing in concrete structures therefore relies heavily upon techniques which can accurately and reliably measure and monitor these effects. NDE techniques should have sufficient sensitivity to distinguish between those irregularities and discontinuities inherent in the concrete material and others caused by a flaw or ageing mechanism.

Corrosion of steel reinforcement is recognised as being one of the commonest causes of deterioration of reinforced concrete structures. In properly detailed structures, a combination of visual and electro-chemical techniques may be used to detect corrosion of reinforcement before ultimate strength is significantly impaired. However, these techniques may not be applicable to the thick-sectioned or inaccessible structures found in nuclear plant. In these cases, detection may rely on the use of alternative techniques to measure section changes in the steel or (in the case of prestressing tendons) voids in the grouting where pockets of corrosion may be initiated.

Current inspection regimes for ungrouted pre-stressing tendons in containments rely on lift-off load determinations, and sampling and testing of tendon and corrosion inhibitor materials. However, this is not possible in the case of grouted tendons (found in pre-stressed roof and floor elements of ponds, waste stores, auxiliary buildings, as well as several containment designs).

3.1.4. Characterisation of flaws

Characterisation of flaws would be expected to be the final stage in a structural investigation, which typically would involve:

- preliminary investigation, including assessment of structure, environment, history etc. This pre-information may be supported by limited testing and physical probing to identify the actual problems that are relevant for the specific structure being considered
- engineering judgement to identify the nature of potential problems and define inspection requirements/ options
- inspection/scanning, with sufficient sensitivity to detect flaws (see previous section)

- characterisation of detected flaws.

By implication, characterisation of a flaw requires greater sensitivity than detection (which only requires identification and approximate location/ extent of a flaw). Characterisation techniques should be able to measure the nature and extent of a flaw with sufficient sensitivity to allow an engineering assessment of the impact of the flaw on safety and serviceability of the structure to be undertaken. It may also be desirable to use NDE tools to quantify and monitor the progress of the flaw with time. Sensitivity requirements will be dependent upon the specific acceptance criteria established as part of the engineering assessment process.

In the main, characterisation techniques may simply be more sensitive versions of tools developed to detect flaws. However, the distinction is significant in that whilst some NDE techniques may be well suited to flaw detection, the same techniques may not have sufficient sensitivity for use in characterisation. The converse may also be true, in that the more sensitive techniques may not provide an efficient and cost effective means of rapidly 'scanning' the surface of concrete structures to ascertain the general condition of the structure as part of a routine inspection.

Concrete cracking is a common symptom of a large number of ageing mechanisms. Inspection methods that support sizing and determination of cause are of primary interest when assessing significance of cracks. There is considered to be a specific requirement for 'characterisation' tools to size cracks (in particular depth).

3.1.5. Summary

Key applications of NDE in safety related structures are summarised in the following table. Comments on the existing approach are included to help indicate where NDE development may be of particular value. Where needs are identified, further detail is provided in Tables at the end of this section.

Table	Application & Purpose	Comment	Needs identified
3.1	***Measurement of concrete thickness***, to obtain as built details.	Key input for selected NDE techniques (eg impact echo).	✓
3.2	***Measurement of cover*** to reinforcement to establish as built details	Existing NDE techniques (eg covermeter) adequate for measurement of cover up to 150mm. No specific need identified	✗
3.3	***Mapping / sizing of steel reinforcement and tendons*** to establish as built details (including identification of reinforcement laps and couplers).		✓

Table	Application & Purpose	Comment	Needs identified
3.4	***Detection of corrosion in embedded steel*** (both reinforcement and liners). Corrosion is recognised as a key issue for ageing concrete structures.	A range of electro-chemical techniques for assessing likelihood of corrosion exist. Within the scope of this report, the focus is on the ability to detect loss of steel section, pitting or hydrogen embrittlement	✓
3.5	***Detection of corrosion in prestressing tendons***.	Comment as above	✓
3.6	***Detection of voids & inhomogeneity*** (honeycombing), typically to locate construction flaws. Voids in grouted prestressing ducts are a particular issue, as these may lead to corrosion of tendon.		✓
3.7	***Detection of surface deposits/ visual symptoms of flaws*** which indicate material degradation and support quantification of findings.	Visual inspection generally adequate, but could be enhanced by tools which increase productivity and/or quantify findings.	✓
3.8	***Detection and sizing (depth, width, length) of cracks normal to the surface***	Combinations of techniques may be appropriate: one to detect, one to characterise.	✓
3.9	***Detection of delamination/ cracks parallel to the surface***		✓
3.10	***Measurement of concrete mechanical properties*** (eg strength, stiffness), and identification of spatial variations or ageing effects.	Typically NDE used in conjunction with destructive tests (eg cores) to calibrate results. Looking for NDE techniques which provide relative measures to indicate material property variations with area or time.	✓
3.11	***Detection of changes in physical properties*** (eg porosity/ permeability) to assess condition of concrete	Variety of permeability tests available; RILEM currently assessing these with objective of developing agreed standard. Outside the scope of this report.	✗

Table	Application & Purpose	Comment	Needs identified
3.12	***Measurement of humidity and conductivity profiles***. Potential uses: to assess risk of corrosion and as input to NDE techniques such as radar	Physical probing generally necessary, and so outside scope of report.	✘

In addition, there are more general needs relating to specific NDE techniques (eg enhanced speed and/or ease of use) and application requirements (eg qualification of personnel, integration of methods). These are discussed in Section 4.

3.2. IDENTIFICATION OF NEEDS

3.2.1. Principal needs

Tables found at the end of this Section consider each of the above applications in the context of safety related concrete structures in nuclear plant. In each case the current position and limitations are identified. Limitations are often associated with the specific application constraints identified in Section 2.3 (ie thick sections, congested steelwork and restricted accessibility).

In order to assist prioritisation, a qualitative assessment has been made of the benefit associated with meeting the identified needs (ie high, medium, low). The basis for this assessment is discussed in Section 3.2.2, but note that cost is not considered at this point.

The main conclusions which may be drawn from the tables are:

- Although NDE techniques have been used successfully on a variety of reinforced and post-tensioned concrete structures, characteristics of structures in nuclear plant (section thickness, accessibility and congested reinforcement) may influence NDE results. There is a general lack of confidence in the techniques because there is little independent advice on their applicability, capability, accuracy and reliability in these circumstances. The immediate requirement is for quantification of the capabilities, based on an international standard (benchmark) application. Authoritative documentation in the form of reports and standards is desirable.

- Development of NDE techniques to meet the following needs would bring high benefit:
  - ⇒ Detection of corrosion in steel liners that are buried (covered by concrete) or inaccessible due to presence of moisture barriers.
  - ⇒ Detection of voids >20mm diameter in grouted tendon ducts in eg containments / waste store roofs

⇒ Improve variable performance statistics associated with depth measurement of surface cracks. For detection and sizing (depth, width, length) of cracks normal to surface aiming for sensitivity of ±10% for crack widths >0.2mm

⇒ 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

- The most promising NDE techniques for development were identified as being radar, radiography and acoustic methods (including ultrasonics and impact echo).

3.2.2. Review of needs and associated benefits

EXPLANATORY NOTES TO THE TABLES:

The tables consider possible applications for NDE in safety related structures, the extent to which requirements can be met using existing and emerging NDE techniques and hence the needs which may provide a focus for subsequent development of NDE. In order to assist prioritisation, an assessment of benefit has been made for each potential development.

Application:

The main applications which have been identified for NDE (see section 3.1.5) are covered in separate tables.

Current position:

The list of existing techniques is not intended to be exhaustive. It reflects those NDE methods which are most likely to be used to meet the defined requirement. Major limitations for the quoted methods are indicated.

Needs:

These draw out needs which may drive any subsequent NDE developments. These needs include both specific enhancements in technology and in the application of the technology (quantification of a capability where there is felt to be uncertainty over performance). An indication is given of the technique(s) which offer(s) the greatest potential to meet the need; a more detailed consideration of the techniques, and specifically the cost of the development, is covered separately in Section 4.

Benefit:

A qualitative assessment of ‘benefit’ is made for each proposed development, to help prioritise a wide range of possible developments. The measures are qualitative (low, medium, high), and based on the opinion of relevant technical experts. They take account of:

- Ease: Benefit over existing methods and techniques in terms of enhancements to ease or speed of application
- Need: Benefit over existing techniques in terms of enhancements to capability (eg sensitivity); this includes the development of capabilities to perform measurements that are currently not possible .
- Applicability: Relevance of need in terms of the number of safety related concrete structures that any development could be applied to.

3.1	Measurement of concrete thickness *Used to obtain as built details, and a key input for selected NDE techniques (eg impact echo).*	
Current Position Section thickness measurements limited to thin sections Limited by constraints such as access to single sided only, presence of liners and congested reinforcement.	**Existing Techniques** • Acoustic • Radar: (limited beyond first rebar; moisture dependent) • Radiography (dual sided access) • Gamma densitometers (dual sided access)	
Need	**Techniques offering greatest potential**	**Benefit** (Low, Medium,High)
Quantification of capability for measuring concrete thickness for sections > 1.0m thick	Radar; Acoustic; Radiography	**H**
Enhanced ease and speed of application for measuring section thickness in all structures	Radar; Radiography	**M**
Measure section thickness with single sided access, with sensitivity of ±5% section thickness	Radar; Acoustic	**M**
Measure section thickness in presence of congested steelwork, with sensitivity of ±5% section thickness	Acoustic	**M**
Measurement of thickness of complex geometries to ±5% section thickness (eg accounting for edge effects; thickness changes)	Acoustic	**L**
Measurement beyond a fully bonded liner in containments and fuel ponds, with sensitivity of ±5% section thickness	Acoustic	**L**

3.2	Measurement of concrete cover to reinforcement *Used to establish as built detail.*
Current Position Existing techniques adequate for measurement of cover up to 150mm. No specific needs identified.	**Existing Techniques** • Covermeter (up to ~150 mm cover)

3.3	Mapping / sizing of steel reinforcement and tendons *Used to establish as built detail*

Current Position	**Existing Techniques**
With double sided access, can measure reinforcement diameter / configuration through ~1m section. Radar can be used to detect reinforcement with 100mm separation at 50 mm depth	• Radar (limited beyond depth of first rebar) • Radiography (double sided access) • Covermeters

Need	**Techniques offering greatest potential**	**Benefit** (Low, Medium, High)
Quantify existing performance capability for mapping / sizing of steel reinforcement and tendons (including identification of reinforcement laps and couplers) with section depth	Radar; radiography	**H**
Enhanced resolution to measure reinforcement diameter with sensitivity of ±10% either in thick sections (>1m) or in presence of congested reinforcement (individual reinforcement at spacings <<150mm)	Radar; radiography; covermeter	**M**
Resolve multiple layers of reinforcement, identifying individual reinforcement at spacings <<150mm and depths >30mm AND measure reinforcement diameter with sensitivity of ±10%.	Radar; radiography	**M**
Resolve tendon details within ducts in thin sections (<~1.5m) in eg containments and waste store roofs with sensitivity of ±10%	Radar; radiography	**L**
Resolve tendon details within ducts in thick sections (>~1.5m) in eg PCPVs with sensitivity of ±10%	Radar; radiography	**L**
Resolve reinforcement details in congested regions, including laps and couplers, with sensitivity to identify individual reinforcement at spacings <<150mm and depths >30mm AND measure reinforcement diameter with sensitivity of ±10%.	Radar; radiography	**L**

3.4	Detection of corrosion in embedded steel (both reinforcement and liners) *Corrosion is recognised as a key issue for ageing concrete structures. Within the scope of this report, the focus is on the ability to detect of loss of section, pitting or hydrogen embrittlement*	
Current Position Radiography provides direct measure of reinforcement diameter, and indication of corrosion eg through 1.0m section.	**Existing Techniques** • Radiography (dual sided access)	
Need	**Techniques offering greatest potential**	**Benefit** (Low, Medium,High)
Quantify performance limits for detecting corrosion in reinforcement through measurement of loss of section, pitting or hydrogen embrittlement in heavily reinforced structures	Radiography	**H**
Detection of corrosion in steel liners that are buried (covered by concrete) or inaccessible due to presence of moisture barriers.	Radiography	**H**
Detect corrosion beyond first layer of rebar where there is only single sided access, through measurement of loss of section	Radiography	**M**
Enhanced speed of application for detection of corrosion through measurement of loss of section	Radiography	**L**

3.5	Detection of corrosion in prestressing tendons *Corrosion is recognised as a key issue for ageing concrete structures. Within the scope of this report, the focus is on the ability to detect of loss of section, pitting or hydrogen embrittlement*	
Current Position Radiography provides direct measure of tendon diameter, and indication of corrosion eg through 1.0m section.	**Existing Techniques** • Radiography (dual sided access)	
Need	**Techniques offering greatest potential**	**Benefit** (Low, Medium,High)
Quantify performance limits for detection of corrosion by measuring loss of section/ hydrogen embrittlement in prestressing tendons in heavily reinforced structures	Radiography	**H**
Detect evidence of corrosion in grouted prestressing tendons by measuring loss of section, pitting or hydrogen embrittlement	Radiography	**M**
Enhanced speed of application for detection of corrosion by measuring loss of section, pitting or hydrogen embrittlement in prestressing tendons	Radiography	**L**

3.6	Detection of voids and inhomogeneity Typically used to detect construction flaws (eg honeycombing).	
Current Position Radiography (alongside gamma scintillation) if dual sided access permitted.: reasonable detectability of internal damage in sections <1.0m. Acoustic methods have shown reasonable detectability of small voids and discontinuities to depths of ~0.5m in laboratory trials, but cannot distinguish lack of bond from voids. Can be helpful in identifying risk areas.	**Existing Techniques** • Radiography (dual sided access); backscatter (single sided access) • Gamma scintillation (dual sided access) • Acoustic (to identify risk areas) • Radar	
Need	**Techniques offering greatest potential**	**Benefit** (Low, Medium, High)
Quantify void detection threshold (and inhomogeneities eg honeycombing) in thick sections (variables: size of void, depth)	Radar Acoustic Radiography	**H**
Detection of voids >20mm diameter in grouted tendon ducts in eg containments / waste store roofs	Radiography; Acoustic	**H**
Detect voids >20mm diameter behind liners in eg Fuel ponds, PCPVs, containment	Acoustic Radiography (backscatter)	**M**
Detect voids >20mm diameter around penetrations and encast items in eg bioshield, PCPVs, active process cells	Radiography Acoustic	**M**
Detect voids >20mm diameter in areas of congested reinforcement/ tendons	Radiography Acoustic	**M**

3.7	Detection of surface deposits/ visual symptoms of flaws	
Current Position Visual inspections of accessible structures; supported by tools such as video, fibrescope for reaching inaccessible areas.	**Existing Techniques** • Visual (accessible structures)	
Need	**Techniques offering greatest potential**	**Benefit** (Low, Medium, High)
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	Standard descriptors for automated inspection	**H**

3.8	Detection and sizing (depth, width, length) of cracks normal to surface *Combinations of techniques may be appropriate, one to detect and one to size.*	
Current Position Cracks reaching surface most commonly detected through visual inspection (accessible surfaces). Acoustic techniques may be used to size open cracks, but variable performance shown in trials.	**Existing Techniques** • Visual to detect (accessible surfaces) • Thermography • Acoustic (to size open, surface cracks) • Leak tests (gas flow) for through cracks	
Need	**Techniques offering greatest potential**	**Benefit** Low, Medium,High
Improve variable performance statistics associated with depth measurement of surface cracks. For detection and sizing (depth, width, length) of cracks normal to surface aiming for sensitivity of ±10% for crack widths >0.2mm	Acoustic	**M**

3.9	Detection of delamination/ cracks parallel to surface	
Current Position Acoustic techniques are effective in detecting near surface delamination (to first layer of rebar).	**Existing Techniques** • Acoustic	
Need	**Techniques offering greatest potential**	**Benefit** (Low, Medium,High)
Improve variable performance statistics for detecting large laminar flaws at >10mm depth, and >100mm in any planar direction	Acoustic	**M**
Detect delamination between prestressing tendons in containments	Acoustic	**M**
Detect debonding of prestressing tendons in containments & other structures with grouted tendons	Acoustic	**L**

3.10	Measurement of concrete mechanical properties (eg strength, stiffness) *Typically used to identify spatial variation or ageing effects*
Current Position NDE may be used to map changes in properties over a section, and data calibrated against limited destructive testing (eg using cores). It is unlikely that NDE may be practically employed to determine the in situ properties of concrete.	**Existing Techniques** • Schmidt (rebound) hammer (surface properties)

Need	**Techniques offering greatest potential**	**Benefit** (Low, Medium, High)
Measurement of relative changes in concrete mechanical properties with time (ie detecting ageing processes), with sensitivity of ±1%	Acoustic	**M**
Measurement of spatial variations in concrete mechanical properties, with sensitivity of ±1%	Improved automatic scanning systems	**M**

3.11	Detection of changes in physical properties (eg porosity/permeability) *Semi-destructive tests generally needed, and so outside the scope of this report.*
Current Position Variety of permeability tests are available, but no agreed standard exists. RILEM are currently assessing tests with objective of developing an agreed standard. No needs identified.	**Existing Techniques** • Permeability tests (semi-destructive)

3.12	Measurement of humidity/ conductivity profiles. *To assess risk of corrosion and also as input to selected NDE techniques (eg radar)*
Current Position Physical probing generally needed (semi-destructive). No needs identified.	**Existing Techniques** • (semi-destructive)

4. DEVELOPMENT OF NDE TECHNIQUES

In this Section, key NDE techniques are examined to identify current capability and to propose specific technical developments which will enable progress to be made towards meeting the needs identified previously (Section 3). In order to assist prioritisation, a qualitative estimate has been made of the cost of the proposed technical developments.

4.1. SUMMARY OF DEVELOPMENT REQUIREMENTS

In Section 3, selected NDE techniques were identified as having the potential meeting the specific challenges posed by the characteristics of safety related structures in nuclear plants. These are:

- Radar
- Acoustic (ultrasonics & stress waves)
- Radiography.

4.1.1. Radar

In recent studies, radar technology proved to be the cheapest and easiest method for mapping reinforcements but neither characterisation of flaws by dimension and material nor crack detection could be demonstrated. Nevertheless radar has significant potential for development by way of software for signal and image processing to improve resolution around and immediately beyond the first reinforcement. This can be expected to achieve a capability to detect and locate further reinforcement (depending on rebar spacing), and to resolve gaps in the reinforcement. It thus offers considerable potential in dealing with thick sections, where reinforcement is not too heavy. Radar is unlikely to approach radiography in terms of detailed inspection of individual reinforcing bars, including loss of section.

The development of specialist antennas with more appropriate beam width and other characteristics for specific applications is considered to be useful. For application in nuclear plants, an assessment of emission levels may be needed to permit usage within the plant. There is an on-going European project on radar in the building and construction industries [Ref 8], and a recently completed concrete society report [Ref 5] which addresses some of the needs identified.

4.1.2. Acoustic

Acoustic testing methods or stress wave propagation methods encompass all forms of testing based on transmission and reflection of stress waves. Acoustic wave transmission can be used to obtain information about the physical condition of concrete structures. They are used either to characterise the properties of the concrete by wave speed measurements or to locate and identify discrete objects and flaws in the concrete by transmission and reflection of stress waves. The latter may be referred to as the ultrasonic pulse-echo technique.

Ultrasonic Pulse Velocity

Ultrasonic pulse velocity techniques (UPV) can be used effectively despite its dependence on so many variables. It is most useful when carrying out comparative surveys of concrete quality within a structure. In the case of changes in material properties that change with time (eg action of frost or AAR), these may be detected by measuring the frequency dependent attenuation of direct transmission ultrasonic pulses.

Ultrasonic Pulse Echo

Ultrasonics are seen to play a role in the detection of voids and characterisation of cracks. Recent studies having shown that transit times, in a time of flight mode, bore some correlation to the depth of surface-breaking cracks.

There is value in trialling multiprobe ultrasonic transmission and reception to interrogate to greater depth and below reinforcing. There is also a need to improve method of attachment or coupling of the transducers, in particular to enhance speed/ease of application. Implementation of true pulse-echo techniques is also viewed as offering the potential for significant improvements in performance.

Surface Waves (Spectral analysis of surface waves)

Spectral analysis of surface waves (SASW) has recently found use in testing concrete and in geophysical surveys. It involves the measurement of surface wave velocities by a pair of transducers at a fixed distance from an impact source. The wave velocity is affected by material properties and, by analysing the relationship between velocity and wave frequency, it is possible to obtain a profile of velocity with depth.

The method is particularly useful for testing layered systems, such as pavements, tunnel liners and thick concrete walls. It may also be used for determining the depth of foundations, but in this case is limited to wall-shaped structures such as bridge abutments, where the depth of foundation is relatively small compared with the lateral extent of the foundation needed for receiver spacings.

Impact echo

Impact echo is normally used in concrete structures of thickness up to 1 metre, although in principle it may be used for thicknesses of several metres. The compression wave which is sent out by impact on the surface of the concrete is reflected from the boundaries of the concrete element or from internal flaws. Information is therefore obtained from the a significant volume of concrete and, in this respect, it can be considered as a global measuring technique if enough local measurements are made. Impact echo has been effective for testing and detecting flaws in large surface areas of concrete, although analysis of results can be complicated by complex geometries.

Acoustic tomography

The availability of increasingly powerful computational tools has led to an increasing interest in the use of acoustic tomography. Recent field trials on bridge structures, a post-tensioned nuclear containment vessel and a masonry structure have underlined the potential uses of this technique.

There are several avenues for future development that are expected to enhance the resolution and precision of the technique. More sophisticated processing techniques may be applied to standard ultrasonic signal data sets to improve resolution and sensitivity to defects. In addition, there is the prospect for using new or multi-element sensors to provide 3-dimensional or tomographic images of hidden features to aid interpretation where only single sided inspection is possible.

4.1.3. Radiography

Radiographic techniques are not widely used in inspection of safety related concrete structures in nuclear plant because they are unsuited to penetration of the thick (>1m) sections commonly encountered, require dual sided access and can present significant operational difficulties. Nevertheless, gamma radiography (together with gamma scintillation techniques) has been effective for determining internal damage in thin, lightly reinforced structures. It is of particular value for detection and measurement of reinforcement/ prestressing tendons and voids but can only be used for structures less than a metre or so in thickness. Newly developed high-energy X-Ray accelerators are portable and compact. These allow practical inspection of concrete up to 1.2m thickness.

Real time radiography is a possible area for development which could be combined with tomographic techniques to obtain improved results.

4.1.4. Use of techniques in combination

There are two reasons for combining techniques. The first is to use a well developed technique to validate results from another that is less well developed, but which is assessed as having the potential to provide greater reliability or other benefits. This is mainly applicable during the demonstration phase for a technique. The second reason is to exploit synergies between techniques, where techniques give similar coverage of a structure but are not sensitive to precisely the same parameters or features, or where information gathered by one technique can be used as input data for interpreting/ calibrating the results from another technique.

Several of the above techniques have aspects that make them suitable for use in combination. One key area of commonality is that between ground penetrating radar and ultrasonics, where inspections present data in similar formats, and so can have the same processing techniques applied to them. However, radar and ultrasonic techniques are sensitive to different aspects of components within the concrete. Radar responds to changes in dielectric constant (conductivity) and density and consequently is ideal for the detection of rebars and encast metalwork. Ultrasonics, on the other hand, is most sensitive to changes in the characteristics of the concrete itself (aggregate size, voidage). This combination of techniques, therefore, gives a good overall complementarity.

Radar surveys of concrete structures can also be combined with radiography, the latter being used to highlight aspects of corrosion of encast steelwork; the caveats regarding the maximum thickness of concrete that can be radiographed must be borne in mind, but it is worth noting that plant applications have shown how powerfully these two techniques can combine: one (radar) to rapidly detect and locate, the other (radiography) to provide high-quality images that allow assessment of condition (dimension, orientation, corrosion). Both can be taken to the structure, and thus this partnership must be seen as powerful and practical.

4.2. DEVELOPMENT OF NDE TECHNIQUES.

4.2.1. Principal technical developments

Tables found at the end of this Section consider application of the above techniques in the specific context of safety related structures in a nuclear plant (ie the ability to cope with characteristics such as thick sections, poor accessibility and congested steelwork). In each case existing capability and limitations are identified. An assessment has been made of those techniques which show greatest promise for meeting the needs identified in Section 3, and an indication is given of the nature of the technical advance required. In order to assist prioritisation, the costs of NDE development have been qualitatively estimated.

Conclusions which may be drawn from the tables are:

- The need to quantify performance of a number of techniques could be achieved at relatively low cost through sensitivity studies. This may be on a combination of controlled laboratory specimens and well characterised structures in nuclear plant. It may be supported by the assimilation of field experience in NDE techniques, to enhance confidence and to take account of the scale and contrasts of material properties likely to be found in practice.

- Future developments will include improvements in data handling and processing. This is necessary to speed up acquisition and analysis of 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.

- Further benefits may be gained at low additional cost by capitalising on synergies between techniques, in particular between radar and ultrasonic.

4.2.2. Detailed Assessment Of Technical Development and Costs

EXPLANATORY NOTES TO THE TABLES:

The tables consider selected NDE techniques, their current capabilities in the context of application in safety related concrete structures and the technical developments needed to meet the needs identified in

Section 3. The NDE techniques covered in detail are those which are believed to offer greatest promise. In order to assist prioritisation, an initial (qualitative) estimate has been made of development costs. This estimate is based on opinion of relevant experts, rather than formal cost estimates.

Current position:

The list of existing applications is intended to reflect the most likely uses for the identified NDE technique. Major limitations of relevance to application in safety related concrete structures are indicated.

Need:

This column provides a cross-reference back to the needs identified in Section 3. Only those needs which are believe to offer a ‘medium’ or ‘high’ benefit have been addressed. The level of benefit (from Section 3) is identified.

Development:

The developments needed for the NDE technique include both specific technical enhancements (including speed, ease of use, sensitivity) to meet the needs identified in Section 3 and, more generally, quantification of a capability where there is felt to be uncertainty over existing performance. An indication is given of the nature of the advance required, and thus a possible way forward, and provides some basis for judgements of development costs involved. Where developments in more than one technique are needed, the level of dependence on advances in other techniques is reflected within the text.

Cost:

The prime consideration for assessing cost is technical feasibility (ie something with high feasibility would generally have low costs; conversely, something which is not feasible would have high cost).

The levels are deliberately qualitative, and described as ‘low, moderate, high’. To give an indication of orders of magnitude, they may be viewed as lying within the following ranges:

low:	<US$0.1M
moderate	US$0.1M — US$1.0M
high	>US$1.0M

NDE Technique	Radar		
Current Position Mapping of reinforcement eg 100mm separation at 50mm depth. Mapping of tendon ducts / encast items eg 25mm pipe at 670mm depth. Primary limitations are resolution capability, penetration and also quantification of sensitivity		**Existing applications** • Mapping reinforcement and other encast items • Detection of large volume voids and foreign bodies • Detection of moisture penetration • Wall thickness in lightly reinforced sections	
Need	**Benefit**	**Development**	**Cost**
Improved quantification of capabilities for measuring thickness, mapping or sizing layers of reinforcement, detecting/mapping of voids: • in sections >1m thick • void detection thresholds (with volume/depth)	H	Laboratory sensitivity studies and well characterised structures. Complemented by experimental reference data and systematic documentation of application on specific types of problems. Note that this covers quantification of radar capabilities; qualification of methods/ personnel could add significant cost.	**L**
Improved sensitivity to resolve multiple layers of reinforcement, identifying individual reinforcement at spacings <<150mm and depths >30mm	M	Improved software for signal and image processing of multiple reflections; improved antennae design; variable frequency.	**M**
Improved sensitivity to measure reinforcement diameter in top layer with sensitivity ±10%	M	Improved software for signal and image processing of multiple reflections; improved antennae design; variable frequency.	**H**
Measurement of section thickness with sensitivity of 5%, with single sided access	M	Little development needed	**L**
Assessment of the influence of concrete electric and dielectric properties (affected by moisture) on radar measurements	M	Combination of sensitivity studies and modelling/ analytical techniques. Low cost relies on results from CEC programme (2) becoming available.	**L**
Enhance performance of radar application (speed of use & sensitivity) by linking to other techniques	M	Link to ultrasonics (benefits from data being presented in similar formats, but response to different features)	**L**
Modifications to radar equipment to enhance ease of use in restricted spaces	M	Evolutionary development of existing equipment	**M**
Assessment of the effect of radar EMI, and checking against tolerable levels in nuclear plant.	H	? Standard tests? Cost would rise if significant developments were needed to design against unacceptable levels of EMI.	**L**

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

<table>
<tr><td colspan="2">NDE Technique</td><td colspan="2">Acoustic: Stress wave methods (Surface Waves & Impact echo)</td></tr>
<tr><td colspan="2">Current Position
Impact echo can detect near surface voids/delamination
Spectral analysis of surface waves can give information on quality of layered systems</td><td colspan="2">Existing applications
• Detect voids and delamination
• Thickness measurements</td></tr>
<tr><td>Need</td><td>Benefit</td><td>Development</td><td>Cost</td></tr>
<tr><td>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
• void detection thresholds (varying with layer thickness/ depth)</td><td>H</td><td>Laboratory sensitivity studies and well characterised structures.
Complemented by experimental reference data and systematic documentation of application on specific types of problems.
Note that this covers <u>quantification</u> of stress wave techniques; <u>qualification</u> of methods/ personnel could add significant cost.</td><td>L</td></tr>
<tr><td>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</td><td>M</td><td>Adaptation of techniques for specific use and development of scanning procedures.
Development of multi-array sensors.</td><td>M</td></tr>
<tr><td>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</td><td>M</td><td>Adaptation of techniques for specific use and development of scanning procedures.
Development of multi-array sensors.</td><td>H</td></tr>
</table>

<table>
<tr><td colspan="2">NDE Technique</td><td colspan="2">Radiography</td></tr>
<tr><td colspan="2">Current Position
γ and X-radiography may be used to locate internal flaws such as voids, and reinforcing/prestressing steel location and general condition. Superior to other NDE methods in terms of quality, amount and reliability of information.
The equipment is expensive and needs special licensing.
It is not suitable for partially accessible, thick (>1.0M) and heavily reinforced members. This depth reduces if increased sensitivity is required.</td><td colspan="2">Existing applications
• Mapping and sizing reinforcement, and detection of corrosion
• Mapping and sizing of prestressing tendons, and detection of corrosion/fracture
• Detection of encast steelwork
• Detection and sizing of voids</td></tr>
<tr><td>Need</td><td>Benefit</td><td>Development</td><td>Cost</td></tr>
<tr><td>Quantify limits of detection in heavily reinforced structures, and with section depths >1.0m for:
• Mapping/sizing layers of reinforcement (including identification of laps and couplers)
• Detecting voids and inhomogeneities
• Detecting corrosion in reinforcement or prestressing steel
• Measuring concrete thickness</td><td>H</td><td>Laboratory sensitivity studies and well characterised structures.
Complemented by experimental reference data and systematic documentation of application on specific types of problems.
Note that this covers <u>quantification</u> of radiography capabilities; <u>qualification</u> of methods/ personnel could add significant cost..</td><td>L</td></tr>
<tr><td>Improved resolution to detect voids >20mm diameter or broken tendons in grouted tendon ducts</td><td>H</td><td>Higher energy levels needed to improve resolution, requiring further equipment development.</td><td>H</td></tr>
<tr><td>Improved resolution to:
• detect voids >20mm diameter around penetrations and in regions of congested reinforcement
• map/size layers of reinforcement by measuring bar diameter with ±10% sensitivity in thick sections or with congested reinforcement (individual reinforcement at spacing <<150mm)
• Measure any evidence of corrosion in reinforcement or prestressing tendons by detecting loss of section</td><td>M</td><td>Higher energy levels needed to improve resolution, requiring further equipment development.</td><td>H</td></tr>
<tr><td>Improved sensitivity to resolve multiple layers of reinforcement, identifying individual reinforcement spacings <<150mm and depths >30mm AND measure reinforcement diameter with sensitivity of ±10%</td><td>M</td><td>Use of tomographic techniques.
(Lower cost for columns with 360° access). Also development of sensors, detectors and sources.</td><td>H</td></tr>
<tr><td>Detection of voids >20mm behind liners in eg fuel ponds, PCPVs, containments</td><td>M</td><td>Develop backscatter techniques to apply γ-radiography with single sided access</td><td>H</td></tr>
<tr><td>Enhance performance for all radiography applications (speed of use & sensitivity) by linking to other techniques</td><td>M</td><td>Use in parallel with radar (where radar detects/ locates flaws and radiography provides detail)</td><td>M</td></tr>
<tr><td>Enhanced speed of use for all radiography applications.</td><td>M</td><td>Real time scanning, possibly linked to tomography. Extensive equipment development needed</td><td>H</td></tr>
</table>

5. PRIORITIES FOR NDE DEVELOPMENT

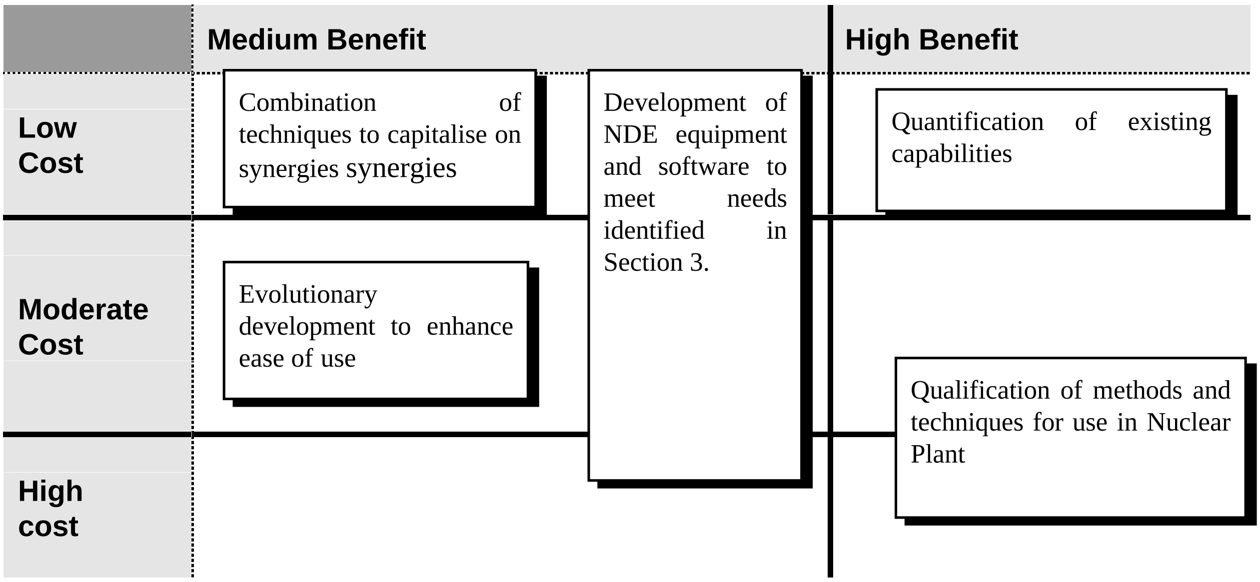
5.1. CONCLUSIONS

NDE techniques have the potential to satisfy at least some of the needs of the nuclear industry identified in Section 3. 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.

There is 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 there is concern that NDE procedures lack the necessary qualification to permit their use on safety critical structures. There is no authoritative international guidance or standard for NDE of concrete structures.

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 at the recent OECD workshop a number of relevant national and European programmes were identified. The nuclear industry maintain its awareness of developments and should seek to influence the development of equipment.

Specific examples of development needs, their cost and the perceived benefits are given in Section 4 . The following figure summarises the principal development areas:



* See Section 4 for definition of costs/ benefit

The quantification of the capabilities of NDE techniques is seen as a priority area for development. The provision of authoritative documentation in the form of reports and Standards is desirable. However, the industry lacks an international standard for quantifying the NDE of nuclear safety related concrete structures. Qualification is important to the successful deployment of NDE techniques and will need to be considered when addressing this issue.

The high cost of developing software and equipment, with no guarantee of success, means that the nuclear industry is unlikely to consider this to be a priority area for funding. However, it is important for the industry to establish national networks with groups that are funding development. There is support for the principle of establishing a group of international experts to monitor national developments.

5.2. RECOMMENDATIONS

- More formal liaison with other industries that use NDE techniques should be established and opportunities to work with suppliers to influence the development of new equipment should be sought
- Experts should be identified to monitor national programmes with the aim of improving the understanding of the availability and capability of NDE techniques within the nuclear industry
- CSNI should review this topic in approximately 3 years
- At the time of the review, consideration should be given to quantification of the capabilities of NDE techniques by means of a standard test specimen specification
- As a longer term issue qualification should be considered.

6. REFERENCES

1)INTERNATIONAL ATOMIC ENERGY AGENCY, *Working Material: Pilot Study On Management Of Ageing Of Concrete Containment Buildings: Results Of Phase 2*, IAEA/NENS, Limited Distribution, IAEA, Vienna, Austria (1997).

2)McFARLANE JP, SMITH LM, DAVIES DR, McCLUSKEY DT, *In-service Monitoring of AGR and PWR Nuclear Safety Related Structures,* INucE International Conference on Nuclear Containment, Cambridge, England (Sept 1996)

3)REFAI TM, LIM MK: 1991 *In-service inspection and structural integrity assessment methods for nuclear power plant concrete structures*, Oak Ridge National Laboratory Report, ORNL/NRC/LTR-90/29, Sept 1991

4)BUNGEY J H (ed), 1997 *Proceeding NDT-CE97* Brit Ind NDT April 1997 (2 Vols)

5)CONCRETE SOCIETY 1997, *Guidance on Radar Testing of Concrete Structures,* Technical Report 48, Dec 1997, 88p

6)OECD NEA/CSNI/R(95)19, OCDE/GD(96)31, Report of the task group reviewing national and international activities in the area of ageing of NPP concrete structures

7)OECD NEA/CSNI/R(97)28, Proceedings of workshop at Risley, UK on Development priorities for NDE of concrete structures in nuclear plants.

8)BRITE EURAM BE95-2109 Subsurface Radar as a Tool for Non-Destructive Testing and Assessment in the Construction and Building Industries

7. ACKNOWLEDGEMENTS

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Appendices

CONTENTS

Appendix 1
Discussion at PWG3 subgroup meeting

Mr. McNulty said that the workshop on Development priorities for NDE of concrete structures in NPPs had been held at Risley in November 97. There had been a variety of presentations about NDE of nuclear and conventional structures. The proceedings of the workshop, including the rapporteurs' reports, had been issued as a CSNI report. There had been a draft report prepared for the workshop. This had been amended in the light of the discussion there, and afterwards distributed to the group.

The main conclusions had been that NDE techniques had a potential role to play, and there had been some degree of success in their application. There was a general lack of confidence in their reliability, and quantification of the capability was a priority. The nuclear industry was not prepared to fund the development. However the civil industry was supporting it, and this should be followed. (The secretary agreed to contact Hochtief for information on the CEC project on radar (ACTION 4).) One of the main recommendations of the draft report was that a specification for an international test specimen should be developed. Quality control was a concern. This was costly for steel components, and was not a priority for concrete at the moment.

There was a conclusion in the proceedings of the workshop that was not included in the report, that detection of corrosion was a requirement, but NDE, radar and ultrasonics would not detect this. However electrochemical techniques had been excluded from the scope of the workshop, and Dr. McNulty recommended that detection of steel reinforcement corrosion should be added as a future topic for the group. The Spaniards did much work on this.

Prof. Sundquist said that although the techniques had been successfully used in Sweden, there was little experience, and the liners caused problems. Dr. Costello said that the technique showed promise, but the burden should be put on the vendors. Dr. McNulty said that if the nuclear industry was to realise the potential benefits from NDE of concrete structures then it must seek opportunities to influence the development of new techniques. Ultrasonic techniques had been evaluated in the UK, but the results had been very poor.

Mr. Touret said that designers were interested in information on mechanical properties, and asked if it was possible to measure the properties by NDE. Dr. McNulty said that maybe permeability and porosity could be measured, but that radar and ultrasonic / impact techniques were unlikely to give an accurate measurement of the mechanical properties of concrete such as stiffness. Dr. Kluge said that the utilities were interested in a specification for vendors for testing crack depth with acoustic methods.

Prof. Eibl said that the only specifically nuclear aspect was radiation, and maybe the thickness of the sections, and it was not necessary to define something specifically nuclear. Porosity was of interest to everyone. Concrete NDE was still at the stage of basic research, and the techniques were not sufficiently developed for such a proposal. Ultrasonic could only see 8-10cm. The only success at present was the detection of broken steel by electrical current. It was interesting to follow the developments.

A revised set of draft recommendations was agreed.

Appendix 2
Relevant degradation mechanisms

CONTENTS

TABLE DEGRADATION FACTORS THAT CAN IMPACT THE PERFORMANCE OF SAFETY-RELATED CONCRETE STRUCTURES.

a. Concrete

Ageing Stressors/ Service Conditions	Ageing Mechanism	Ageing Effect	Potential Degradation Sites	Remarks (e.g., Significance)
Percolation of fluid through concrete due to moisture gradient	Leaching and efflorescence	Increased porosity and permeability; lowers strength	Near cracks; Areas of high moisture percolation	Makes concrete more vulnerable to hostile environments; may indicate other changes to cement paste; unlikely to be an issue for high quality, low permeability concretes
Exposure to alkali and magnesium sulphates present in soils, seawater or groundwater	Sulphate attack	Expansion and irregular cracking	Subgrade structures and foundations	Sulphate-resistant cements or partial replacement of cements used to minimise potential occurrence
Exposure to aggressive acids and bases	Conversion of hardened cement to soluble material that can be leached	Increased porosity and permeability	Local areas subject to chemical spills; adjacent to pipework carrying aggressive fluids	Acid rain not an issue for containments
Combination of reactive aggregate, high moisture levels, and alkalis	Alkali-aggregate reactions leading to swelling	Cracking; gel exudation; aggregate pop-out	Areas where moisture levels are high and improper materials utilised	Eliminate potentially reactive materials; use low alkali-content cements or partial cement replacement
Cyclic loads/vibration	Fatigue	Cracking; strength loss	Equipment/piping supports	Localised damage; fatigue failure of concrete structures unusual

TABLE (cont.) DEGRADATION FACTORS THAT CAN IMPACT THE PERFORMANCE OF SAFETY-RELATED CONCRETE STRUCTURES.
a. Concrete (cont.)

Ageing Stressors/ Service Conditions	Ageing Mechanism	Ageing Effect	Potential Degradation Sites	Remarks (e.g., Significance)
Exposure to flowing gas or liquid carrying particulate and abrasive components	Abrasion; Erosion; Cavitation	Section loss	Cooling water intake and discharge structures	Unlikely to be an issue for containment
Exposure to thermal cycles at relatively low temperatures	Freeze/thaw	Cracking; spalling	External surfaces where geometry supports moisture accumulation	Air-entrainment utilised to minimise potential occurrence
Thermal exposure/ thermal cycling	Moisture content changes and material incompatibility due different thermal expansion values	Cracking; spalling; strength loss; reduced modulus of elasticity	Near hot process and steam piping	Generally an issue for hot spot locations; can increase concrete creep that can increase prestressing force losses
Irradiation	Aggregate expansion; hydrolysis	Cracking; loss of mechanical properties	Structures proximate to reactor vessel	Containment irradiation levels likely to be below threshold levels to cause degradation
Consolidation or movement of soil on which containment is founded	Differential settlement	Equipment alignment, cracking	Connected structures on independent foundations	Allowance is made in design; soil sites generally include settlement monitoring instrumentation
Exposure to water containing dissolved salts (e.g., seawater)	Salt crystallisation	Cracking	External surfaces subject to salt spray; intake structures	Minimised through use of low permeability concretes, sealers, and barriers

TABLE (cont.) DEGRADATION FACTORS THAT CAN IMPACT THE PERFORMANCE OF SAFETY-RELATED CONCRETE STRUCTURES.
b. Mild Steel Reinforcing

Ageing Stressors/ Service Conditions	Ageing Mechanism	Ageing Effect	Potential Degradation Sites	Remarks (e.g., Significance)
Depassivation of steel due to carbonation or presence of chloride ions	Composition or concentration cells leading to corrosion	Concrete cracking and spalling; loss of reinforcement cross-section	Outer layer of steel reinforcement in all structures	Prominent potential form of degradation; leads to reduction of load-carrying capacity
Elevated temperature	Microcrystalline changes	Reduction of yield strength and modulus of elasticity	Near hot process and steam piping	Of significance only where temperatures exceed ~200°C
Irradiation	Microstructural transformation	Increased yield strength; reduced ductility	Structures proximate to reactor vessel	Containment irradiation levels likely to be below threshold levels to cause degradation
Cyclic loading	Fatigue	Loss of bond to concrete; failure of steel under extreme conditions	Equipment/piping supports	Localised damage; fatigue failure of concrete structures unusual

TABLE (cont.) DEGRADATION FACTORS THAT CAN IMPACT THE PERFORMANCE OF SAFETY-RELATED CONCRETE STRUCTURES

c. Prestressing

Ageing Stressors/ Service Conditions	Ageing Mechanism	Ageing Effect	Potential Degradation Sites	Remarks (e.g., Significance)
Localised pitting, general corrosion, stress corrosion, or hydrogen embrittlement	Corrosion due to specific environmental exposures (e.g., electrochemical, hydrogen, or microbiological)	Loss of cross-section and reduced ductility	Tendon and anchorage hardware of prestressed concrete containments	Potential degradation mechanism due to lower tolerance to corrosion than mild; steel reinforcement
Elevated temperature	Microcrystalline changes	Reduction of strength; increased relaxation and creep	Near hot process and steam piping	Thermal exposure not likely to reach levels that can produce ageing effects in prestressing
Irradiation	Microstructural transformation	Increased strength; reduced ductility	Structures proximate to reactor vessel	Containment irradiation levels likely to be below threshold levels to cause degradation
Cyclic loading due to diurnal or operating effects	Fatigue	Failure of prestressing under extreme conditions	Tendon and anchorage hardware of prestressed concrete containments	Not likely as cyclic loadings are generally small in number and magnitude
Long-term loading	Stress relaxation; creep and shrinkage of concrete	Loss of prestressing force	Prestressed concrete containments	Larger than anticipated loss of prestressing forces

TABLE (cont.) DEGRADATION FACTORS THAT CAN IMPACT THE PERFORMANCE OF SAFETY-RELATED CONCRETE STRUCTURES.
d. Liners

Ageing Stressors/ Service Conditions	Ageing Mechanism	Ageing Effect	Potential Degradation Sites	Remarks (e.g., Significance)
Electrochemical reaction with environment (metallic)	Composition or concentration cells leading to general or pitting corrosion	Loss of cross-section; reduced leaktightness	Areas of moisture storage/accumulation, exposure to chemical spills, or borated water	Corrosion has been noted in several containments near the interface where the liner becomes embedded in the concrete
Elevated temperature (metallic)	Microcrystalline changes	Reduction of strength; increased ductility	Near hot process and steam piping	Thermal exposure not likely to reach levels that can produce ageing effects in metallic liners
Irradiation (metallic and non-metallic)	Microstructural transformation (metallic); increased cross-linking (non-metallic)	Increased strength; reduced ductility	Structures proximate to reactor vessel	Containment irradiation levels likely to be below threshold levels to cause degradation
Cyclic loading due to diurnal or operating effects (metallic and non-metallic)	Fatigue	Cracking; reduced leaktightness	Inside surfaces of concrete containment building	Not likely as cyclic loadings are generally small in number and magnitude
Localised effects (non-metallic liners)	Impact loadings; stress concentrations; physical and chemical changes of concrete	Cracking; reduced leaktightness	Inside surfaces of concrete containment building	Potential problem in high traffic areas

Appendix 3
Review of concrete NDE techniques

CONTENTS

Review of NDE Techniques

APP 3.1 INTRODUCTION

A wide range of techniques applicable to inspection of concrete structures are reviewed in this section. Given previous reviews of NDE techniques (eg ref 14), this Appendix focuses more on the relevance and practicality of the techniques than on the detail of how they work.

Note that techniques specifically applicable to commissioning of safety related structures or to continuous monitoring are not covered.

APP 3.2 NDE TECHNIQUES

APP 3.2.1 Mechanical

Schmidt Hammer

The Schmidt or rebound hammer is used to determine the hardness of the surface layer of concrete. Its use is limited to the zone within 30mm of the surface. It is typically used for mapping variations in concrete properties, with calibration against limited destructive tests (eg cores) where accuracies of ±15% on concrete strength have been achieved. It is limited by its sensitivity to surface condition and its need of application-specific calibration.

Falling Weight Deflectometer

This device was the most successfully utilised approach within the US Strategic Highways Programme (SHRP). It involves a large weight impacting the surface. An array of displacement sensors are used to measure the movement of the concrete. When these results are amalgamated with plate modelling techniques, the data can be used to assess thickness and provide a qualitative measure of overall condition. The programme invested in two truck-mounted systems for concrete pavement assessment. Significant engineering effort would be needed to transform this technique from the mode of operation above, where it is reliant on use of the vertical plane and objects that are in the horizontal plane. Applications to nuclear safety related structures are limited.

Mechanical Gauges (eg Demec)

Mechanical gauges, such as the Demec gauge, are intended to measure small movements of the structure, such as crack opening and volumetric changes. The Demec gauge is fitted between two fixed reference points which are bonded to the surface, typically astride a region known to be defective, such as a crack. This is a cheap and simple alternative to the electrical strain gauge but normally has only a clock dial display and is not well suited to online monitoring.

APP 3.2.2 Electrical

Covermeter

Covermeters are routinely used in inspection of nuclear structures. They measure variations in one of several possible electrical parameters of a detector as it is scanned over the test area (1). Changes in the parameter being measured due to the presence of steel and other objects in the sub-surface enable an estimate the size of the object or its depth below the surface to be determined. By using ratio measurements made with a covermeter, it may be possible to improve the accuracy of its results and obtain a measurement of rebar diameters (2). A marinised covermeter has been produced that is capable of working underwater. (3)

APP 3.2.3 Electrochemical techniques

Half-cell Potential Measurement.

This electrochemical technique is widely used to monitor the condition of encast steel items, particularly for the presence of corrosion. There are difficulties associated with making reliable quantitative measurements with this system, and it is often necessary to use a statistical analysis of measurements on an individual structure to establish areas where steelwork is undergoing active corrosion and inert areas (4,5). Some factors influencing results have been reviewed elsewhere (6). Nevertheless, this technique can be used to estimate corrosion rates and the effects of chloride in reinforced concrete structures (7). Novel electrode configurations have been tried, and several of these have been found to have advantages over standard arrangements (8).

There is a case for combining results from electro-potential surveys with resistivity surveys (see below) to obtain a greater reliability (9) and such surveys could also be combined with radar surveys to assess the capabilities of radar in this field. For example, the electro-potential survey can identify areas of active corrosion with a reasonable degree of reliability and it may be possible to correlate these with specific signatures in radar signals. However, the practical application of this technology needs to be quantified if it is to become routinely applied.

Resistivity

Measurements of resistivity can provide an indication of the presence, and possibly the amount, of moisture in a concrete structure, so clearly can have a bearing on evaluating the extent and rate of corrosion of rebars and other included steelwork (9,10,11). However, resistivity measurements are sensitive to the disposition of steelwork within the structure, so assessment of conditions in a structure and the likelihood of corrosion occurring needs to be made with careful reference to its construction (12).

APP 3.2.4 Electromagnetic and Nuclear

Radar

Ground penetrating radar (GPR) has been adapted for inspection of civil engineering structures. It has the capability to penetrate some considerable depth into concrete and responds to a number of features found in reinforced concrete structures (RCS's). AEA Technology has successfully used GPR on a variety of reinforced concrete structures, and a number of reports detailing its use have been produced (13,14,15,16). The use of radar in NDE inspection of nuclear structures is now relatively common (17,18,19) and many significant developments in system hardware - particularly in data analysis and enhancement software - have been reported (20,21,22).

A major use for radar inspection is detection of reinforcements and other encast items and there are possibilities for significant development of signal processing to improve resolution (23,24). Aspects that are also likely to have potential for development include assessing the degree of corrosion and integrity of reinforcing bars (24, 25) and detection of excess chloride in concrete (26).

Theoretical and modelling studies have also been carried out to increase the understanding of the inspection processes (22,27).

Radiography

Radiographic techniques are not widely used in inspection of concrete structures because they are unsuited to penetration of the thick (>1m) sections commonly encountered and can present significant operational difficulties. The techniques inspect areas of the order of 400 x 300mm and require access to both sides of the structure. They are rather slow to apply, with a typical radiograph of a 1/2m thick component requiring an exposure time of 15 minutes. Radiography can nevertheless be effective for determining larger internal damage in thin, lightly reinforced structures. AEA Technology has considerable experience in applying these techniques. (28,29)

X-Radiography

X-radiography is useful for detection of encast items and voids but can only be used for structures less than a metre or so in thickness. Real time radiography is a possible area for development which, in appropriate circumstances, could be combined with tomographic techniques (30,31) to obtain improved results.

γ-radiography and scintillation counting

γ-radiography can be used to inspect structures up to 1/2 metre thick and is especially suited for detecting changes in concrete density or of voids within the section. γ-radiography can again require lengthy exposure times but an improved speed of response may be obtained for localised measurements by using γ-scintillation counting techniques.

Neutron radiography

Neutron radiography has been used to inspect modest thicknesses of concrete, and has been shown to provide information on concrete densities, the presence of voids, grouting packing materials (32). It is less suited to the detection of encast steelwork than its counterparts above and is generally much less practical.

Thermography

Thermography is a surface measurement technique with some capabilities to indicate sub-surface conditions and the presence of defects through features of the thermal image at the surface (33). It generally has a low spatial resolution because of the low thermal conductivity of concrete materials, but has been used to show the presence of voids, porosity, spalling or de-lamination and cracks.

It may be used in a “static” mode, where steady state, in-service, temperature variations at the surface can be related to features below the surface; a “dynamic” application is also possible - transient thermography (34). More so than the “static” application, this latter version of the technique is essentially limited to surface or near surface inspections.

Both techniques have been shown capable of locating rebars in concrete structures, although the time involved is significant and their practicality is somewhat questionable. The SHRP programme, and other similar studies, have shown that thermography can be used as a means of determining the location of de-laminations on roads and pavements. This is a dynamic approach, reliant on the diurnal heating from the sun and consequently limited to outdoor usage over specific time slots (sun-rise and sun-set). There are a number of reports indicating a similar approach for building inspection, key features being identified being ingress of moisture and breakdown of thermal insulation. However, it is fair to say that the ability to detect specific faults depends heavily on an analysis that is presently subjective; that is, there may be several viable causes for producing the same thermal distortion. Reliable assessment can thus be difficult to achieve.

APP 3.2.5 Acoustic Methods

Ultrasonics

Defects in a concrete structure (cracks, voids etc.) may be expected to produce signals with characteristics differing from those from an undamaged component. There are different approaches that can be considered under the heading of ultrasonic methods.

One approach is to analyse the ultrasonic signal for its frequency content, and use this to assess the condition of the structure. This approach works best with distinct and well characterised items, but it has the possibility of detecting near surface defects through changes in surface wave spectra (35, 36).

Another approach with a broader applicability is to analyse signals in the time-domain for its amplitude content. For example, impact testing can relate the condition of concrete at or near the surface to the characteristics of the received signals and an indication of conditions in the bulk material may be derived from ultrasonic pulse velocities.

A common approach, and probably the most useful, uses ultrasonic scanning techniques to generate images of components within the unit using pulse-echo type technology.

Each approach has its drawbacks, often associated with the complexity of the structure’s geometry, its composition and inclusion of encast items. It is not clear whether procedures can be developed for general application to entire structures because of difficulties in predicting how amplitude or frequency components will vary within different structures. However, the ultrasonic scanning approach appears to have the capability of providing a useful tool, though signal generation and processing techniques could usefully be improved.

Ultrasonic pulse velocity measurements can provide a means of assessing variations from the norm. The difficulty in this technique lies in what to attribute any changes to. Moisture content, surface condition, stress and reinforcement all affect the velocity of the signal, and consequently, it is most suited to routine testing of products made in batch. A system employing ultrasonic acoustic velocity measurements has been developed that can operate in a marine environment, providing an indication of general concrete condition (3). There are companies producing equipment that is claimed to provide advanced pulse-echo testing of concrete (detection of fine-cracking) and “high-sensitivity” transducers. It is suggested that these claims be pursed within specific parts of the programme where they match the requirements of the remit.

The availability of increasingly powerful personal computers has led to a developing interest in the use of ultrasonic tomography (37,38,39,40). More sophisticated processing techniques may also be applied to standard ultrasonic signal data sets to improve resolution and sensitivity to defects (41). In addition to this, there is a prospect for using new or multi-element sensors, which can further improve the quality of the inspection (42,43).

Because of similarities in the penetration, resolution and signal processing, there seems to be considerable scope for using ultrasonics and radar inspection techniques in combination.

Laser ultrasonics

This technique has been addressed within AEA Technology as part of the US SHRP programme. Lasers are used as a remote source for generating ultrasound in the concrete or asphalt. Interferometers are used to measure the subsequent surface displacement caused by the return of ultrasonic pulses from planar defects in the roadway. The application was shown to be most suited to thickness measurement. The feasibility of this approach was demonstrated but the inherent costs are considered too high to be pursued.

Acoustic emission

This is mainly applicable to dynamic situations where processes occurring generate acoustic emission. It is most likely to be suitable for monitoring a specific area or unit, but may have problems with ambient noise. It has greatest applicability to investigations of relative movement between concrete and encast items (rebars, etc.) and to the detection and monitoring of crack growth.

The main use of acoustic emission is the detection of areas of growing degradation in concrete structures. It may be possible to differentiate between different types of defect through analysis of the acoustic emissions generated as the defects develop (44,45,46). An example might be within the containment during the integrated leak rate tests.

A further application is the detection of non-growing cracks through the weak acoustic emissions generated by relative movements of the crack walls. (47).

Some structures may be suited to carrying out ultrasonic and AE investigations at the same time because of the similarities in the energy detected (48).

Modal analysis

Modal analysis (impact testing or resonance testing) is essentially a means for carrying out a global (or at least regional) assessment of the integrity and condition of components. It uses acoustic/ultrasonic resonances generated in the component, often through excitation by a controlled impact. Defects anywhere within the component may influence the pattern of resonances it will support. Consequently, an analysis of the resonance spectra in a component can be used to assess its integrity.

Resonance spectra for an undamaged component may be evaluated empirically, or by modelling. This means that the technique of modal analysis is best suited to applications where many similar structures are to be evaluated, or where the structure is simple and can be modelled confidently. It is unlikely to be suitable as a general tool, as it will rarely be possible to adequately quantify the resonance characteristics of the system being inspected.

APP 3.2.6 Minor inspection and monitoring techniques.

There are many NDE techniques that are used in inspection or monitoring of civil structures to a minor extent. They are frequently used because they have highly specific characteristics making them suitable for particular jobs, but are normally unsuited for general use. The following indicates some of these techniques.

Holography

This technique may be used to detect and record dimensional changes in a structure, and may be used in static or dynamic configurations. Holographic systems can be arranged to cover either small or large areas of a structure and generally can record dimensional deformation down to micron scales. The major drawback in that it is extremely sensitive to vibration, so is unlikely to be suited to in-service testing.

Holography is essentially a surface measurement technique, though it may be possible to infer conditions at depth from patterns of movement expressed at the surface. It may be used to inspect for surface breaking features and for indications of near surface defects by identifying local changes in surface topography (49) and to register degradation and dis-aggregation of concrete (50).

Strain gauging

Strain gauging is a well developed and sensitive means of monitoring local deformation of structures.

Barkhausen noise

This is a technique used to determine stress levels in steel-work incorporated in civil structures, rather than a technique to look at the structure as a whole. It measures the stress level within ~100 mm of the surface of the steel, directly beneath the probe. Access to the metal-work and specialised preparation of the metal surface is required, so that it is of restricted use in the present context.

Automated visual inspection

Visual inspection should not be overlooked as a good first-hand indication of problems. Work within the US SHRP programme has shown that a pattern recognition system can be produced to provide rapid visual inspection of highways for cracking defects. The results of the test are usually based on acceptance levels of the amount of cracking, as opposed to detection of cracked to un-cracked areas. It may also be of particular value in inaccessible areas.

X-Ray Tomography

This is included for completeness as it is thought to be of little relevance to the requirement but useful for the purposes of qualification within the project. X-ray tomography is an excellent way of providing two-dimensional cross-sections from real-time X-radiography. It works by rotating the object within the X-ray beam. The series of standard radiographs can then used to mathematically reconstruct cross-sections. It has the benefit of providing a cross-sectional image that is a direct measure, positionally, of density. It therefore highlights aggregates, voids, cracks and other density-related structural changes. The potential information from such an image is considerable, but unfortunately, this technique is not easy to apply directly to the structures in-situ unless they are of limited thickness and cylindrical in nature. It does, however, offer a useful means of qualification, particularly on laboratory specimens.

APP 3.3 REFERENCES

1 Carino, N J, ‘Characterisation of electromagnetic covermeters’, Non-Destructive Testing in Civil Engineering, Liverpool (United Kingdom), 14-16 Apr. 1993. Vol. 2, pp. 753-765. Edited by J.H. Bungey. The British Institute of NDE (1993)

2 Alldred, J.C., ‘An improved method for measuring reinforcing bars of unknown diameter in concrete using a cover meter’, Non-Destructive Testing in Civil Engineering, Liverpool (United Kingdom), 14-16 Apr. 1993. Vol. 2, pp. 767-788. Edited by J.H. Bungey. The British Institute of NDE, (1993)

3 Smith, A.; Goff, D.; and Rhoads, C. , ‘Underwater inspection equipment’, US Naval Civil Engineering Lab. Report AD-236 578/1/GAR (1991)

4 Elsener, B.; Wojtas, H.; Bohni, H., ‘Inspection and monitoring of reinforced concrete structures - electrochemical methods to detect corrosion’, Non-Destructive Testing in Civil Engineering, Liverpool (United Kingdom), 14-16 Apr. 1993. Vol. 2, pp. 579-595. Edited by J.H. Bungey. The British Institute of NDE (1993)

5 Clemena, G.G., ‘Benefits of measuring half-cell potentials and rebar corrosion rates in condition surveys of concrete bridge decks’, Virginia Transportation Research Council, Charlottesville (United States), PB93-188159/GAR, 58 pp. (Jun. 1992)

6 Flis, J.; Sehgal, A.; Li, D.; Kho, T.; Sabol, S., ‘Condition evaluation of the concrete bridges relative to reinforcement corrosion rate of reinforcing steel’, Pennsylvania Transportation Inst., (United States), PB93-142974/GAR, 117pp. (Sep. 1992)

7 Dhir, R.K.; Jones, M.R.; McCarthy, M.J. ‘Half-cell potential to estimate chloride-induced corrosion rates in structural concrete’, Non-Destructive Testing in Civil Engineering, Liverpool (United Kingdom),14-16 Apr. 1993. Vol. 2, pp. 605-620. Edited by J.H. Bungey. The British Institute of NDE (1993)

8 Francois, R.; Arliguie, G., ‘Measurement of electrode potential of concrete reinforcing bars using abi-electrode system’, Non-Destructive Testing in Civil Engineering, Liverpool (United Kingdom),14-16 Apr. 1993. Vol. 2, pp. 597-604. Edited by J.H. Bungey. The British Institute of NDE (1993)

9 Millard, S.G., ‘Corrosion rate measurement of in-situ reinforced concrete structures’, Proceedings of the Institution of Civil Engineers, Structures and Buildings, Vol. 99, No. 1, pp. 84-88 (1993)

10 Millard, S.G.; Harrison, J.A.; Edwards, A.J., ‘Measurement of the electrical resistivity of reinforced concrete structures for the assessment of corrosion risk’, British Journal of Non-Destructive Testing, Vol. 31, No. 11, pp. 617- 662 (Nov. 1989)

11 Saravanan, K.; Srinivasan, S.; Suresh Bapu, R.H.; Nayak, N.U.; Balasubramaniyan, T.M.; Rengaswamy, N.S.; Balakrishnan, K., ‘Electrochemical non-destructive testing of reinforcement corrosion in existing concrete structures’, Bulletin of Electrochemistry, Vol. 6, No. 4, pp. 385-386 (Apr. 1990)

12 Gowers, K.R.; Millard, S.G.; Bungey, J.H., ‘The influence of environmental conditions upon the measurement of concrete resistivity for the assessment of corrosion durability’, Non-Destructive Testing in Civil Engineering, Liverpool (United Kingdom), 14-16 Apr. 1993. Vol. 2, pp. 633-659. Edited by J.H. Bungey. The British Institute of NDE (1993)

13 Smith, R.L.; Crook, M.J., ‘The non-destructive detection and mapping of ASR cracking in concrete.’ AERE G5007 (C-in-C) (1989)

14 Joinson, A.B.; Charlesworth, J.P. ‘The role of NDE in assessing the integrity of concrete in unclear plant.’, AEA-RS-4313 (1993)

15 Hawker, B.M.; Collett, N.J. ‘NDE of Concrete: Final Report’, AEA-RS-4456 (C-in-C) (1993)

16 Naish, C. ‘Detection and monitoring of corrosion of steel in concrete.’ Private communication

17 Bungey, J.H.; Millard, S.G. ‘Radar inspection of structures’, Proc. Institution of Civil Engineers (Structures & Buildings), Vol. 99, No. 2, pp. 173-186 (May 1993)

18 Forde, M.C.; McCavitt, N.; Batchelor, A.J. ‘Evaluating structures using impulse radar and sonic techniques’, Decommissioning and Demolition 1992, Manchester (United Kingdom), 25-26 Mar. 1992. pp. 118-122. Edited by I.L. Whyte, Thomas Telford Ltd. (1992)

19 Millard, S G; Bungey, J H; Shaw, M ‘The assessment of concrete quality using pulsed radar reflection and transmission techniques’, Non-destructive Testing in Civil Engineering, Liverpool (United Kingdom), 14-16 Apr 1993. Vol.1, pp 161-185. Edited by J H Bungey. The British Institute of NDE (1993)

20 Warhus, J.P.; Mast, J.E.; Johansson, E.M.; Nelson, S.D. ‘Advanced ground penetrating radar’, Advanced Microwave and Millimetre-Wave Detectors. Proceedings, San Diego, California (United States), 25-26 Jul. 1994. pp. 177-185. Edited by S.S. Udpa and H.C. Ham. SPIE Vol. 2275 (1994) ISBN 0-8194-1599-5

21 Okamoto, P.A.; Ciolko, A.T. ‘High resolution impulse radar imaging- civil engineering applications’ Nondestructive Testing and Evaluation for Manufacturing and Construction. Edited by H.L.M. dos Reis. pp. 225-236. Hemisphere Publishing Corporation, (1990). ISBN 0-89116-926-1

22 Nelson, S.D. ‘EM modelling for GPIR using 3D FDTD modelling codes’, Advanced Microwave and Millimetre-Wave Detectors. Proceedings, San Diego, California, 25-26 Jul. 1994. pp. 186-195. Edited by S.S. Udpa and .C. Ham. SPIE Vol. 2275 (1994) ISBN 0-8194-1599-5

23 Flohrer, C; Bernhardt, B ,‘Detection of prestressed steel tendons behind reinforcement bars, detection of voids in concrete structures - a suitable application for radar systems’, Non-destructive Testing in Civil Engineering, Liverpool (United Kingdom), 14-16 Apr 1993. Vol. 1, pp 227-234. Edited by J H Bungey. The British Institute of NDE (1993)

24 Zoughi, R.; Cone, G.L.; Nowak, P.S. ‘Microwave non-destructive detection of rebars in concrete slabs’, Materials Evaluation, Vol. 49, No. 11, pp. 1385-1388 (Nov. 1991)

25 Broomfield, J.P. ‘The assessment of corrosion of reinforcing steel on highway bridges’, Non-Destructive Testing in Civil Engineering, Liverpool (United Kingdom), 14-16 Apr. 1993. Vol. 2, pp. 551-566. Edited by J.H. Bungey. The British Institute of NDE (1993)

26 Lim, K.; Gress, D.L. ‘Detecting areas of high chloride concentration in bridge decks’, Symposium on Nondestructive Monitoring of Materials Properties, Boston, Massachusetts (United States), 28-30 Nov. 1988. pp. 335-340. Edited by J. Holbrook and J. Bussiere, MRS (1989)

27 Temple, J.A.G. ‘Modelling radar inspections of concrete’, AEA Industrial Technology, Harwell, AEA-Intec-0900, 15pp. (Mar. 1992)

28 Kear, P.; Jones, P.; Kenway-Jackson, D, ‘Radiographic examination of the post-tension tendons on a bridge and viaduct.’, AEA Industrial Technology, Harwell, AEA-Intec-1846, 1994

29 Carter, P; Moggeridge, J.; Hillier, M. ‘Radiographic examination of the post-tension tendons in one leg of the Wytham Bridge.’, AEA Technical Services Division, Harwell, AEA-TSD-0693, 1995

30 Martz, H.E.; Schneberk, D.J.; Azevedo, S.G.; Logan, C.M. ‘Applications of computerised tomography’, Energy and Technology Review, pp. 35-50 (Nov. 1990)

31 Heiskanen, K.A.; Rhim, H.C.; Monteiro, P.J.M. ‘Computer simulations of limited angle tomography of reinforced concrete’, Cement and Concrete Research, Vol. 21, No. 4, pp. 625-634 (Jul. 1991)

32 Stade, J. ‘The use of neutron radiography for some problems in civil engineering’, Neutron Radiography (3), Osaka (Japan), 14-18 May 1989. pp. 653-661. Edited by S. Fujine, K. Kanda, G. Matsumoto and J.P. Barton. Kluwes Academic Publishers (1990)

33 Weil, G.J. ‘Infrared thermograhic techniques’, CRC Handbook on Nondestructive Testing of Concrete. Edited by V.M. Malhotra and N.J. Carino. pp. 305-316. CRC Press (1991)

34 Milne, J.M., ‘Thermodynamic inspection of concrete using a controlled heat source’, Infrared Technology and Applications, London (United Kingdom), 26-28 Jun. 1990. Vol. 1320, pp. 227-241. Edited by A.H. Lettington. SPIE (1990)

35 Bowen, B.R.,’Damage detection in concrete elements with surface wave measurements’, Dissertation Abstracts International, Vol. 53, No. 4, p. 1966-B (Oct. 1992) (DA 9225529)

36 Sack, D.A.; Olson, L.D. ‘Advanced NDE methods for concrete structures’, Int. Conf. Nondestructive Testing of Concrete in the Infrastructure, Dearborn, Michigan (United States), 9-11 Jun. 1993. pp. 353-369. Society for Experimental Mechanics, Inc., (1993) ISBN 10912053429

37 Kharrat, Y.; Rhazi, J.; Ballivy, G.; Cote, P. ‘Auscultation of concrete hydraulic structures using sonic tomography’, Canadian Journal of Civil Engineering, Vol. 22, No. 6, pp. 1072-1083 (Dec. 1995)

38 Heiskanen, K.A.; Rhim, H.C.; Monteiro, P.J.M. ‘Computer simulations of limited angle tomography of reinforced concrete’, Cement and Concrete Research, Vol. 21, No. 4, pp. 625-634 (Jul. 1991)

39 Thomas, M.D.A. ‘Ultrasound tomography applied to AAR-affected concrete structures ‘, Proc. 2nd Int. Conf. Alkali-Aggregate Reactions in Hydroelectric Plants and Dams, Chattanooga, TN (United States), 22-27 Oct. 1995, pp. 359-372. Acres International Corporation (1995)

40 Jalinoos, F.; Olson, L.D.; Aouad, M.F.; Balch, A.H. ‘Acoustic tomography for qualitative non-destructive evaluation (QNDE) of structural concrete using a new ultrasonic scanner source’, Review of Progress in Quantitative Nondestructive Evaluation, Vol. 14B. Proc. 21st Symp. Quantitative Nondestructive Evaluation, Snowmass Village, Colorado (United States), 31 Jul. - 5 Aug. 1994, pp. 2177-2184. Ed. D.O.Thompson and D.E. Chimenti. Plenum Press ISBN 0306450623. (1995)

41 Haskins, R.; Alexander, A.M. ‘Computer interpretation of ultrasonic pulse-echo signs for concrete dams’, Nondestructive Evaluation of Ageing Structures and Dams, Oakland, California , 7-8 Jun. 1995. pp. 182-194. Edited by S. Nazarian and L.D. Olsen. SPIE. Vol. 2457 (1995) ISBN 0-8194-1810-2.

42 Andrews, D.R. ‘Future prospects for ultrasonic inspection of concrete’, Proc. Institution of Civil Engineers, Structures and Buildings, Vol. 99, No. 1, pp. 71-73 (1993)

43 Kovalev, A.V.; Kozlov, V.N.; Samodrutov, A.A.; Shevaldikin, V.G.; Yakovlev, N.N. ‘Ultrasonic testing of the structurally inhomogeneous materials by one- sided access’, Non-Destructive Testing 92. Proceedings of the 13th World Conference on Non-Destructive Testing, Sao Paulo (Brazil), 18-23 Oct. 1992. Vol. 2, pp. 911-913. Ed.
C. Hallai and P. Kulcsar. Elsevier (1992)

44 Ohtsu, M. ‘A review of acoustic emission in civil engineering with emphasis on concrete’, Journal of Acoustic Emission, Vol. 8, No. 4, pp 93-98 (Oct-Dec. 1989)

45 Okamoto, T.; Ayata, T.; Fujiwara, H.; Yuyama, S. ‘Discrimination of cracking pattern developed in reinforced concrete structures by acoustic emission’, 4th World Meeting on Acoustic Emission. (AEWG-35) 1st International Conference on Acoustic Emission in Manufacturing. Boston, Massachusetts (United States), 16-19 Sep. 1991. pp. 208-214. Edited by S.J. Vahaviolos. ASNT (1991)

46 Reddy, D.V.; Sailappan, R.N. ‘Acoustic emission as a NDE tool - certain laboratory and field investigations’, Proc. Conf. Nondestructive Evaluation of Materials and Structures Using Vibration and Acoustic Techniques, San Francisco, California , 10-15 Dec. 1989, pp. 45-54, The American Society of Mechanical Engineers, (1989) ISBN 0791804321

47 Sklarczyk, C.; Gries, H.; Waschkies, E., ’Detection of cracks in concrete by acoustic emission’, Testing During Concrete Construction, Mainz (Germany), 5-7 Mar. 1990. pp. 297-308. Edited by H.W. Reinhardt. Chapman and Hall (1991)

48 Rogers, L.M.; Phillips, L.P. ‘Acoustic emission and ultrasonic testing of concrete structures’, Structural Integrity Assessment. Edited by P. Stanley. pp. 300-313. Elsevier , Applied Science (1992)

49 Paoletti, D.; Schirripa Spagnolo, G. ‘Sandwich holospecklegram: a practical tool for studying damage in concrete’, Measurement Science and Technology, Vol. 1, No. 10, pp. 1067-1071 (Oct. 1990)

50 Boone, P.M. ‘Early detection of deterioration of concrete by holographic interferometry’, Holographics International '92, London (United Kingdom), 23-29 Jul. 1992. pp. 502-516. Edited by Y.N. Denisyuk and F. Wyrowski. SPIE. Vol. 1732 (1993) ISBN 0-8194-0905-7