EUROPEAN COMMISSION

nuclear science and technology

Signal Processing and Improved Qualification for Non-Destructive Testing of Ageing Reactors

(SPIQNAR)

Editors: N B Cameron, MBEL, and W Daniels, Serco Assurance (UK)

Contract No: FIKS-CT-2000-00065

Final report (summary)

Work performed as part of the European Atomic Energy Community's R&T specific programme Nuclear Energy, key action Nuclear Fission Safety, 1998-2002
Area: Operational Safety of Existing Installations

Directorate-General for Research
2004 Euratom

PARTNERS

Mitsui Babcock Energy Limited (MBEL)
Serco Assurance (Serco)
Tecnatom S.A. (Tec)
AIB-Vinçotte International (AVI)
British Energy Generation Ltd (BE)
Commissariat à l'énergie atomique (CEA)
Uppsala Universitet (UUpp)
Universität Kassel (UK)
Joint Research Centre, Institute for Energy (JRC-IE)
Nuclear Research Institute Řež Plc (NRI)
SQC Swedish NDT Qualification Centre (SQC)
EON Kernkraft GmbH (EON)

Note: Intercontrôle SA withdrew in October 2002.

CONTENTS

Introduction

Ultrasonic inspection plays an important role in assuring the safe and economic operation of nuclear plant. The SPIQNAR project was designed to address two key aspects of ultrasonic testing as it is applied to the emerging issue of stress corrosion cracking in austenitic weld materials. These aspects were identified in the overall project objectives which are as follows:

- to improve the performance of ultrasonic inspection for the detection and sizing of cracks in important austenitic stainless steel components (which are among the most difficult to inspect)
- to improve confidence in the way in which ultrasonic inspection procedures are qualified (demonstrate that performance matches requirements) by improving test piece trials

The first overall objective was to be achieved by developing and assessing signal processing methods designed to improve performance. The second objective was to be achieved by determining and comparing the ultrasonic responses of real and synthetic stress corrosion and fatigue cracks, to provide guidance on the extent to which synthetic or “virtual” defects can be used in test piece trials, instead of real defects.

The work involved measuring the ultrasonic response from real and synthetic defects, mainly in austenitic specimens and test pieces. From this work and subsequent destructive examinations, an evaluation of the effectiveness of using synthetic defects was determined as was the feasibility of using “virtual defects”. Data was provided to signal processing specialists to develop suitable techniques to try and improve the detection and sizing of defects in austenitic specimens. To complement this signal processing work the CIVA software platform was enhanced to implement the signal processing methods for ultrasonic data as acquired by industrial inspection companies. Trials were then performed to assess the capability of the signal processing algorithms.

The results of the project are to be comprehensively disseminated through the European Network on Inspection Qualification (ENIQ).

Originally Defined Work Scope

The following section is extracted from the contract preparation forms and describes the project scope as it was stated in the original project work specification.

The project covers work to improve confidence in test piece trials used as part of the ultrasonic inspection qualification process, and to develop optimised signal processing methods specifically designed to improve the performance of ultrasonic inspection methods to detect and size defects in austenitic stainless steel welds.

Work Package 1 involves identifying what specimens containing real service induced defects and test pieces containing synthetic defects are available and will be used for data generation. Other work includes defining in outline the ultrasonic measurements to be performed, and agreeing the functional specification for the signal processing methods. WP2 and WP5 can start on completion of WP1.

Work Package 2 covers the production of detailed procedures for the collection of ultrasonic data from the specimens and test pieces while **Work Package 3** covers the design and manufacture of test pieces containing synthetic defects.

Ultrasonic data is generated under **Work Package 4**. This work will be staged so that data from the real defect specimens sourced through WP1 are collected first, to be used as an additional input for the WP3 exercise, designing and manufacturing realistic and artificial defects, to maximise the similarity between real and synthetic defects. Data will also be generated from the test pieces containing synthetic defects as they become available from WP 3.

The data will be used to support two main “strands” of the project, namely for comparison between real and synthetic defects to support improvements in inspection qualification, and to allow signal processing methods to be developed. It is important that the signal processing methods are developed and evaluated on a broader range of defect types and locations than just the intergranular stress corrosion cracks which will be the main focus of the qualification tasks. Complementary data will therefore also need to be generated on other existing specimens or test pieces (as planned under WP1). Further inspections of these may also be required later in the project to meet specific requirements of the signal processing methods which emerge.

Under **Work Package 5** signal processing experts will use this ultrasonic data to develop signal processing methods which can help to distinguish defect signals from the background noise, and also improve defect sizing accuracy. As this work proceeds, methods may emerge which require further ultrasonic data to be acquired under WP 4.

There needs to be an interface between the signal processing methods developed, and the ultrasonic inspection systems which will employ them. **Work Package 6** therefore covers the production of a software tool to read ultrasonic data files from different inspection systems, display the resultant ultrasonic images in a common format and apply the signal processing methods to the images.

Part of the real defect specimen population will be destructively examined as part of **Work Package 8** over the same period as the specification and design of test pieces containing synthetic defects to further improve correspondence between real and synthetic defects. A significant proportion of the real defect specimens will be retained intact beyond the point at which the first ones are destructively examined. This will enable additional data to be collected in the event that the analysis shows this to be a necessity.

It is anticipated that more than 20 specimens and test pieces will be used in the project for comparison between real and synthetic defects in a rolling programme of ultrasonic data collection, preliminary data analysis, and destructive examination. In this way the specimen design, data gathering, library maintenance (**Work Package 7)**, destructive examination, and comparison (**Work Package 9**) activities which are strongly inter-related, will overlap in time. As the quantity of available data rises and conclusions start to emerge from the data analysis stage, the feasibility study of the use of virtual defects (**Work Package 10**) could begin.

Work Package 11 covers final ultrasonic inspection trials, with performance compared before and after applying the signal processing methods, in order to quantify the extent to which the original objectives for the signal processing methods have been met.

Work Package 12 addresses dissemination activities, with the main route being through ENIQ. Finally **Work Package 13** covers technical project management.

1 Work Package 1: Compilation of Specimen Data and Specifications

The objectives of this task were to:

- Identify plant samples which contained stress corrosion cracking (SCC) which could be used in the project.
- Define measurements to be taken upon the plant specimens.
- Produce a functional requirement for the signal processing tools to be produced by the project in terms of application, target improvements in capability and ease of use.

1.1 Identification of plant samples for use within the project

At project initiation it was known that JRC had a series of piping samples removed from operating BWR plant. These were thought to contain IGSCC defects. They had also been the subject of previous inspection trials and considerable NDT data were available.

British Energy supplied two samples of cracking in an austenitic component for use within the project. SQC also provided a piping sample (A23), extracted from plant, containing a large defect – thought to be IGSCC.

Throughout the project requests were made to European NPP owners for additional samples for use within the project. These requests were made directly by partners and through ENIQ. It was understood that a considerable number of EAC defects had been detected, sized and characterised. It became clear that any extracted material was of limited size or had priority use by the owning utilities or regulators, such as destructive examination to confirm failure mechanism or use in inspection qualification programmes.

A data set was obtained for a series of plant defects which had been used in another project. These data were collected by Cegelec and the project is very grateful for their assistance and support.

All the specimens identified above are detailed in:

Report Title	Document Ref.
List of Specimens (Deliverable 1)	D002

1.2 Inspection Specification

A team of inspection specialists drawn from Serco Assurance, JRC and Tecnatom considered the inspection and devised specifications for the fingerprint and standard ISI inspections of the piping specimens.

The inspection specifications were drawn up to ensure that data collected would be as required for the signal processing stage of the project.

The inspection requirements were captured in two reports:

Report Title	Document Ref.
UT Data Collection for the SPIQNAR project (Deliverable 2a)	D004
Finger Print UT data Collection for the SPIQNAR Project (Deliverable 2b)	D005

1.3 Signal Processing Functional Specification

A functional specification for the signal processing methods to be developed in SPIQNAR was written by British Energy as part of Work Package 1. The specification was drafted in November 2000 and approved for issue at the 6-month progress meeting in April 2001. The specification can be found in the report:

Report Title	Document Ref.
Functional Specification for Signal Processing Methods (Deliverable 1)	D001

The purpose of the specification was to set challenging performance targets for the signal processing methods, with the aims of:

- guiding the developers of the signal processing techniques on the needs of users in the utilities and other organisations

- providing a checklist against which the performance of the signal processing techniques could be measured.

The specification covered the following aspects:

- Applications (component geometry, thickness and material, welding parameters, ultrasonic procedures, defect types)
- Target improvements in capability (signal-to-noise ratio, false call rate, defect detection performance, sizing and location accuracy)
- Ease of use (user interface, computer requirements, image display, compatibility with existing software, level of expertise required).

The specification was used as a basis when setting criteria for the evaluation of the signal processing software in the final trials (Work Package 11).

2 Work Package 2: Inspection Procedures

2.1 Intention – statement of scope

The objective of this work package was to develop a series of detailed procedures for the ultrasonic inspection exercises (work package 4) to govern the way that NDT data is collected. This was to ensure that:

- All relevant information is acquired,
- The collection of this information is standardised between the different NDT techniques,
- Requirements of the signal processing tasks are addressed.

2.2 Progress against scope

Taking into consideration the output of Work Package 1, three detailed procedures have been written, which were:

- Time Of Flight Diffraction (AIB Vinçotte)
- Pulse echo with single and twin crystal probes (Tecnatom)
- Pulse echo with phased array probes (MBEL).

The three procedures have been structured in the same manner so that it is easier to follow and analyse their contents.

2.3 List of deliverables

Report Title	Document Ref.
UT Procedures for Inspection of SPIQNAR Test Specimens	D008

2.4 Remarks on future work

Inspection procedures are important documents that describe and define generalities and essential variables to allow correct and consistent application of inspection techniques. Their content and structure should be standardised to facilitate an ease of understanding and application.

3 Work Package 3: Test Piece Manufacture

The objectives of this work package were to design, source and manufacture test pieces representing components containing specific defects types. Ultrasonic inspection data to be acquired from these test pieces were to be used for the analysis of the responses from differing defect types; signal processing development and for the final assessment trials of the developed signal processing techniques.

3.1 Design of test pieces containing synthetic defects

Test piece materials, structure and defect sizes were based on the inspection data from the real defects available from the specimens of work package 1, the characteristics requested are summarised in Table 1.

Table 1 General characteristics of the test pieces

	Test piece
Material thickness (mm)	32
Width (mm)	600
Base material	AISI 304 L
Weld material	304 L or 308 L
Weld type	60 deg single V butt-weld
Weld crown (or cap)	Machined (dressed)
Weld root	As welded

The through-wall extent of the synthetic defects ranged from 3 mm (~ 10 % Wall Thickness (WT)) to 20 mm (~ 60 % WT). The defects were to be contained in the weld and within the heat-affected zone (HAZ) of the base material.

Due to restrictions of the purchasing procedure within JRC, samples were initially only ordered from Sonaspection. After discussion with partners, it was decided to make a second call for tender in which JRC reserved the right to purchase samples from different partners. This decision was made in order to have a pool of test pieces containing defects that should be representative of real IGSCC. A summary of the suppliers of these specimens and comments upon the manufacturing capabilities is given in Table 2.

3.2 Verification of test pieces containing synthetic defects

The supplied test pieces were radiographed by JRC-IE to confirm the size and location of the artificial defects and to ensure that the manufacturing process was acceptable. An example of a radiograph image of a manufactured test piece is illustrated in Figure 1.

Different approaches were used to produce the requested defects. These included: mechanical fatigue cracks made by implants, transgranular branched cracks manufactured by controlled thermal fatigue loading, full environmental assisted IGSCC by chemical and thermal loading and weld solidification implanted branched cracks.

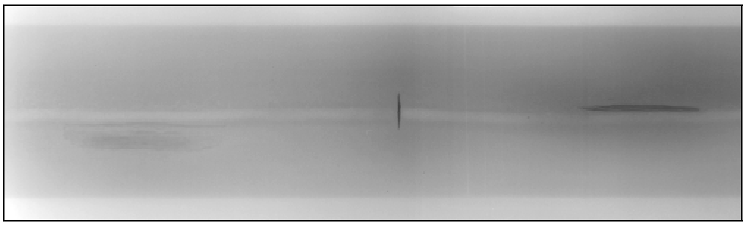

Figure 1 **Example of a plate supplied for the SPIQNAR project containing 3 defects revealed by radiography.**

Table 2 **Summary of manufacturers of realistic defect specimens**

Manufacturer	Delivery timescale
Sonaspection	10 Weeks
Uddcomb	11 Weeks
Institut de Soudure	25 Weeks
Trueflaw	20 Weeks
ENSA	Identified as a supplier but could not replicate defects of the type required.

3.3 Deliverables: Manufactured test pieces containing synthetic defects

A total of 12 test pieces have been manufactured and are available at JRC-IE (2 of these are defect free for reference purposes). These test pieces should be available to partners of future and current European projects and networks such as ENIQ.

4 Work Package 4: Acquisition of Ultrasonic Data

4.1 Work package objective

Initially 4 partners were to collect ultrasonic inspection data for the project: Mitsui Babcock, AIB Vincotte, Tecnatom and Intercontrole. Unfortunately during the course of the project Intercontrole had to withdraw. However other partners, SQC and NRI Rez, provided additional inspection capabilities as the project progressed.

4.2 Outline of proposed work package

The acquired ultrasonic data from specimens and test pieces containing real and synthetic defects was to be analysed. The corresponding reports would detail the location and size of the defects detected (without the application of any signal processing).

The test pieces sourced under work package 1 and 3 were to be inspected following the procedures defined in Work package 2. Four inspection methods were proposed:

- Contact pulse echo inspection (Tecnatom)
- Time of flight Diffraction (AIB Vincotte)
- Focused Immersion Scanning (Intercontrole)
- Focused phased array scanning (Mitsui Babcock).

4.3 Progress of work

A number of specimens containing service induced cracking were identified and made available to the project. These assemblies were extracts from active nuclear plant primary circuit and were contaminated with activation products (Co^{60} Isotope). This contamination presented problems for transportation and some inspections which delayed the initial set of ultrasonic inspections.

Tecnatom, MBEL and AVI performed inspections over the period June 2001 to December 2002. Given the surface conditions of the JRC assemblies and the complication of the pipe to elbow geometry, inspections were not straightforward. There were difficulties associated with penetration of a suitable signal into the weld region and also of coupling of large inspection probes.

The inspections of test piece containing artificial defects were performed during the winter of 2003/2004. There were no reported problems regarding these inspections and all techniques were applied successfully. MBEL managed to perform some immersion inspections of these flat plate specimens, utilising the funding released as a result of the withdrawal of

Intercontrole. MBEL SQC and NRI Rez also performed more specialised inspections of various components. A summary is presented in Table 3.

Table 3 Summary of inspected specimens

	Inspection method				
Specimen	**Defect type**	**Contact PE**	**TOFD**	**Immersion**	**Phased array**
#62	Real	✓ R	✓ R		✓ R
#63	Real	✓ R	✓ R		✓ R
#64	Real	✓ R	✓ R		✓ R
#70	Real	✓ R Tec NRI*	✓ R		✓ R
#71	Real	✓ R	✓ R		✓ R
A23	Real	✓ R SQC	✓ SQC		
Flat plate 001	Realistic	✓ R	✓ R	✓ R	✓ R
Flat plate 002	Realistic	✓ R	✓ R	✓ R	✓ R
Flat plate 003	Realistic	✓ R	✓ R	✓ R	✓ R
Flat plate 004	Realistic	✓ R	✓ R	✓ R	✓ R
BE Header sample #1	Real				✓ MBEL*
ENIQ 3	Synthetic	✓ R	✓ R		✓ R
ENIQ 8	Synthetic	✓ R	✓ R		✓ R
E4CS1	Synthetic	✓ R			✓
E6CS3	Synthetic	✓ R			✓
Inconel block	Synthetic	✓ MBEL*			

R = report available
Synthetic defects are simple reflectors (i.e. side drilled hole)
Realistic defects are manufactured or inserted cracks to mimic in-service cracking

* These techniques provided additional data for signal processing and the comparative study of real and synthetic defects.

5 Work Package 5: Development of Signal Processing

Work package 5 consisted of two parts. Work Package 5.1, which concerned the development of signal processing methods by Uppsala University and the development of a SAFT algorithm for austenitic steel by University of Kassel.

5.1 Intention – statement of scope (Uppsala)

The objective was to develop optimised and robust signal processing methods for austenitic welds using ultrasonic data acquired in Work package 4.

5.1.1 Original tasks in Work package 5.1

The sub-tasks in WP5.1 were originally described as follows:

1. Selection of the most promising techniques for the purpose of this project based on available knowledge and preliminary evaluation of the algorithms' performance, robustness and computer requirements.
2. Implementation of the techniques, their optimisation with regard to robustness and introducing means for their adaptation.
3. Detailed evaluation of the implemented techniques using data provided under Work package 4, including evaluation of performance and sensitivity to signal variation and essential parameters of the inspection procedure.
4. Final choice and optimisation of the best techniques according to the evaluation results.
5. Preparation for integration under Work package 6, and production of guidelines for their use.

Two main types of algorithms were studied, techniques for suppressing material noise (backscattering from grains) and deconvolution techniques for improving the image resolution.

In addition to the original scope of work Uppsala undertook an investigation of methods suitable for compression of ultrasonic RF data.

5.1.2 Progress against scope

The chosen noise suppression and deconvolution algorithms were implemented in separate Matlab toolboxes that could be run from graphical user interfaces. These were distributed among the project partners in September 2001 and June 2002 respectively. Both the toolboxes were distributed along with end user manuals. Furthermore, the added task of designing and evaluating compression methods for ultrasonic data also resulted in a Matlab toolbox complemented with a user manual. This was distributed in June 2002.

Guidelines specific to the implementation within CIVA were distributed in April 2004. These contained a description of the different algorithms' general use. and was complemented with guidelines for setting the parameters. These were distributed in February 2004. The method for handling saturated data was reported in [Olofsson01] and the algorithm for robust semi-sparse deconvolution was reported in [Olofsson02].

The compression toolbox assisted the evaluation of two versions of transform coding, one based on principal component analysis (PCA) and one based on the discrete wavelet transform (DWT). The general recommendation based on the evaluation was to use JPEG2000 for compressing ultrasonic RF images. The results were reported in [Zhang01].

5.1.3 Deliverables:

- ***Deliverable 9***: Matlab toolboxes and associated user manuals for noise suppression, deconvolution and data compression.

- Distribution of guidelines for the use of noise suppression and deconvolution algorithms as implemented within the CIVA software.

5.1.4 Comments

- The non-coherent detector should be implemented in CIVA and then verified using real data. This was the detection method recommended by Uppsala as the most suitable for general use.

5.2 Signal Processing Development, University of Kassel

5.2.1 Intention Statement of Scope

The Synthetic Aperture Focussing Technique (SAFT) is a well established tool to improve defect detection and sizing. In this sub-task the SAFT algorithm was to be extended to inhomogeneous anisotropic materials, thus allowing improved defect detection and sizing for the ultrasonic inspection of austenitic welds.

5.2.2 Progress against Scope

This new InASAFT algorithm was coded and compiled as a Microsoft Windows NT compatible executable (**Deliverable 10**). The executable was delivered to CEA in August 2002 to be built into CIVA. While originally planned to contain no other signal processing facilities, the application of the Hilbert transform to the RF data was later implemented. Its use improved the quality of images computed; the revised version of the deliverable was handed over to CEA in April 2004.

To validate the algorithm, imaging results of computed data for homogeneous and inhomogeneous specimens have been compared with results of conventional SAFT and a two-media SAFT, and have shown excellent coincidence for isotropic media. In a second step synthetic data for homogeneous anisotropic material was created using the geometry and properties of a homogeneous weld metal block produced by Serco, which contains various side drilled holes.

Imaging results show that the algorithm is very well suited for locating and sizing of defects in these specimens. Comparisons between imaging results of InASAFT and conventional SAFT have shown that anisotropic backpropagation is mandatory in particular for angular insonification in order to obtain focused images and avoid the miss location of defects.

Report Title	Document Ref.
Guidelines for using the imaging algorithm (InASAFT)	

5.2.3 Issues important for the overall project

As recognised in the functional specifications for the signal processing methods, SAFT requires more information than just the ultrasonic RF data. It is advisable to make sure the operators are trained in the use and understanding of InASAFT.

5.3 MBEL work on Snape Software

As defined under work package 5.1 MBEL were to investigate image processing methods appropriate to typical peak detected ultrasonic inspection data. This involved assessing software developed by Snape Signal Research.

Following the preparation and release of the functional specification, MBEL evaluated the Snape Signal Research software against the criteria defined. Essentially three image processing methods have been implemented within the software, these are:

- Linear Gaussian smoothing filtering
- Non-linear rank ordered filtering
- Connectivity filtering.

In overall summary except for the Gaussian filtering the signal processing methods require a significant amount of tuning for application to ultrasonic data. The most promising technique appeared to be the rank ordered bandpass filtering.

5.3.1 Deliverable

Report Title	Document Ref.
Assessment of Snape Signals Research Ultrasonic Processing Software	D008

6 Work Package 6: Interface of Signal Processing

6.1 Work package Objective

Different ultrasonic inspection systems are in use, which operate with different control and analysis software. The signal processing methods developed should ideally be flexible enough to be compatible with these different ultrasonic inspection systems. This flexibility will best be achieved if the signal processing software is a stand alone system which can read UT data specific to each inspection system. It was the task of CEA to produce this software tool (based on the existing CIVA package).

6.2 Progress against scope

The CIVA software operates within a Windows environment on a PC, and can read all the data formats supplied by the partners. Thus data files acquired with different acquisition systems can be displayed in a common format and processed using the signal processing toolbox of CIVA.

The first version of CIVA-SPIQNAR was released to some partners (MBEL, JRC, AVI, SERCO, IC and NRI) in June 2002. These partners have been able to install and operate the CIVA software. A training session was held at CEA premises on 30th April 2003 following the 30-month progress meeting.

The UUpp Consecutive Polarity Coincidence (CPC), Amplitude Minimization algorithms, robust and semi-sparse deconvolution tools have been made available within CIVA, as has the UK InASAFT algorithm.

In June 2004, the final release of CIVA-SPIQNAR was issued and included bug corrections (mainly changes in the UK Saft Graphical User Interface (GUI) and Robust deconvolution tools). The main improvement in the CIVA-SPIQNAR software was the capability to write processed data files in Multi2000 data format, which was open and thus facilitating ease of distribution through the SPIQNAR library.

6.3 Deliverables

Four releases of the CIVA-SPIQNAR software were achieved during the project

- Release one: June 2002 – First release of the CIVA-SPIQNAR software
- Release two: July 2003 - Capability to read RdTiff files, plus the integration of CPC and Amplitude minimisation algorithms
- Release three: January 2004 – Capability to read mono-channel MIPS files, multi channel Sumiad files, plus the integration of the Uupp deconvolution and UK InaSaft tools.
- Release four: June 2004 – Capability to generate Multi2000 data files, plus bug corrections relating to deconvolution and InASaft tools.

7 Work Package 7: Library of Defect Responses

The objective of this work package was to establish a library of electronic files of non-destructive testing (NDT) inspection data and destructive examination information from real service-induced and synthetic defects.

7.1 Progress against scope

The type of data stored was agreed among the project partners during progress meetings. It was concluded that data files should be stored both in their original format and in the open Multi2000 format made available by CEA.

Information on components and defects are also available in the NDT defect library database including where available destructive examination reports.

7.2 Set up the NDT defect library

It was agreed amongst all partners that the NDT defect library would be made available on-line through the Internet and that the data, if authorised, from the SPIQNAR project would be made available.

The defect library database has been developed and placed on-line at the following address: http://safelife.jrc.nl/eniq/projects/spiqnar/spiqnardb/

The database is accessible without a password to the whole NDT community.

8 Work Package 8: Destructive Examination

8.1 Destructive examination overview

Destructive examinations of A70 and A23 test assemblies were conducted according to the destructive examination procedures described in deliverable 13, DITE 300/178a "Procedures Used within Destructive Examinations" in order to verify non-destructive examination results. Except for additional dye penetrant examinations the sections of the test assemblies were subject to light optical microscopy, exploratory replication, metallography and relevant image analysis. The technical reports (Deliverable 14) summarise the results of the destructive examination of the A70 and A23 test assemblies in detail. Both test assemblies contained a circumferential weld joint of a straight pipe to an elbow, and an axial weld. The A23 test assembly piping is of 114 mm outer diameter with nominal wall thickness of about 10 mm. The A70 test assembly piping outer diameter is 711 mm with a wall thickness of about 33 mm.

8.1.1 Results of destructive examination of A70 test assembly

IGSCC cracking has been found, described and measured on 6 surfaces. The maximum through-wall extent was 4.3 mm. All were inner surface breaking defects, initiating from the weld fusion boundary/ heat affected zone and propagating vertically in to the weld metal.

8.1.2 Results of destructive examination of A23 test assembly

IGSCC cracking has been found, described and measured on 19 surfaces. Five types of defects were found in the A23 test block as follows:

1. main IGSCC on the inner surface,
2. shallow IGSCC in the weld root area on the boundary of weld metal and HAZ on the inner surface,

3. shallow IGSCC on the piping outer surface in the immediate vicinity of the weld,
4. pores in the weld joint,
5. technological flaws made during manufacturing of the straight piping.

It was also noted that the delta ferrite content in the material was lower than 1 %.

The main crack visible on the inner surface of the piping is an intergranular stress corrosion crack. The maximum depth (through wall extent — TWE) of the crack is 8.6 mm. Both ends of the crack gradually approach the weld metal. The propagation of the crack stops on the fusion boundary of the weld metal and the HAZ.

The shallow intergranular corrosion crack was found on the interface of the weld and base metal in the root area of the weld. Outer surface intergranular stress corrosion cracking up to 2 mm in throughwall extent was found near the weld metal.

The main cause of the origin/initiation and propagation of the cracks was material sensitisation after the welding process. All cracks were found in such sensitised areas.

8.2 Deliverables

Report Title	Document Ref.
Procedures Used Within Destructive Examinations	D012 (DITE 300/178a)
Report on the Destructive Examination of JRC Assembly 70	D013
Report in the Destructive Examination of Test assembly A23	D014

9 Work Package 9: Comparison of Real and Synthetic Defects

9.1 Report on Work Package

This work package was intended to examine the responses from plant defects and compare them to those from synthetic defects. However due to the late delivery of test pieces containing synthetic defect types it has only been possible to compare a small number.

From an inspection qualification point of view, the differences between real and synthetic defects is of great importance since the performance for real plant defects is generally inferred from performance measured on synthetic defects. Qualification does not require that defect responses are identical, but that differences in the main response parameters are known.

An individual defect is unique and thus it is not possible for any synthetic defect to be fully representative of plant defects. Nevertheless there are common characteristics that particular defects exhibit.

For the inspection data from plant defects generated during the SPIQNAR project, all were IGSCC near the weld initiating in sensitised material adjacent to the weld root.

Pulse Echo inspections detected defects through corner-trap and ideally would have sized defects based upon tip diffraction. For the pulse echo inspections that were used, tip diffraction was only observed from a small proportion of the defect length inspected. The PE inspections were generally performed from both sides of the weld and by far the best detection performance was for scans deployed on the same side of the weld as the crack. This meant that for pulse echo inspections with beams that passed through weld metal, detection performance was far from ideal. The welds examined appear to exhibit very high levels of anisotropy, noise and attenuation making inspection through them highly unreliable.

TOFD inspections were intended to detect defects exclusively by tip diffraction. In practice the TOFD inspections detected none of the plant defects they were deployed on. The TOFD inspections deployed were conventional twin probe scans with the probe pair straddling the weld. In this arrangement, beams must pass through the weld so the poor performance of TOFD in this case is not surprising.

While inspections have been performed on several plant samples, the best detection performance has been observed in two plant samples: A70 and A23 (see Table 3). These specimens have been destructively examined. They both exhibit defects of complex morphology. That in A70 is long (in excess of 700 mm) but has a small through wall extent (< 5 mm). A70 weld has a relatively shallow angled preparation. Consequently the crack shows a tendency to initiate in the HAZ and propagate nearly normally to the back wall and therefore enters the weld. This means that for the bulk of the crack length, the crack tips reside in the weld. This is probably part of the explanation for the failure of tip diffraction sizing methods for this crack. Another element of the failure is probably due to the relatively small through wall extent of the defects.

The crack in A23 is more remote from the weld and consequently the crack tip lies in parent plate. It is also significantly larger in through wall extent than the A70 defect.

In both samples, detection was by corner trap. The orientation of the cracks in both A70 and A23, with respect to the local back wall, changed considerably along the defect length.

The efficiency of the corner trap process is strongly linked to the angle between the defect face and the component surface from which beams reflect to complete the corner path. Therefore, it is expected that the echo amplitude from the corner will fluctuate along the defect length for the real plant sample. However, the defects in both A23 and A70 propagate nearly normally to the back wall, which means that for at least some of the defect length, near perfect incidence conditions are possible with beams which bisect the angle between the defect face and the component surface. The variation in corner trap amplitude and echo maximum location with respect to the transmitting probe has been extracted from the experimental data sample. Typical variation data are presented Figure 2.

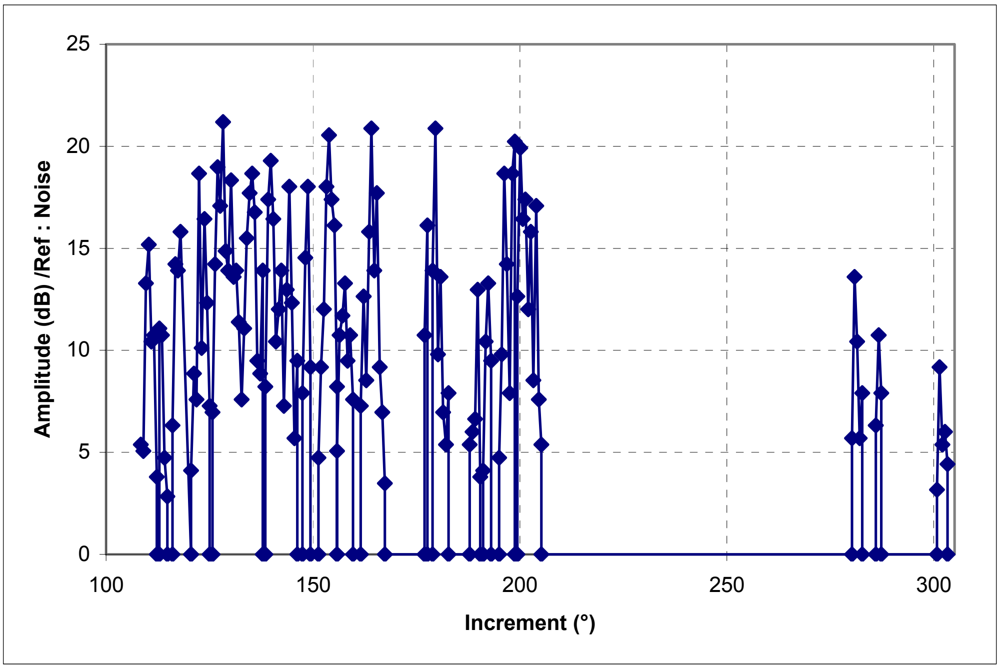

Figure 2 **Typical Corner Echo Amplitude Variation data from A70 specimen as a function of scanner position along the defect length**

A synthetic defect has been implanted in the A70 specimen close to a real one. Typical variation data are presented in Figure 3.

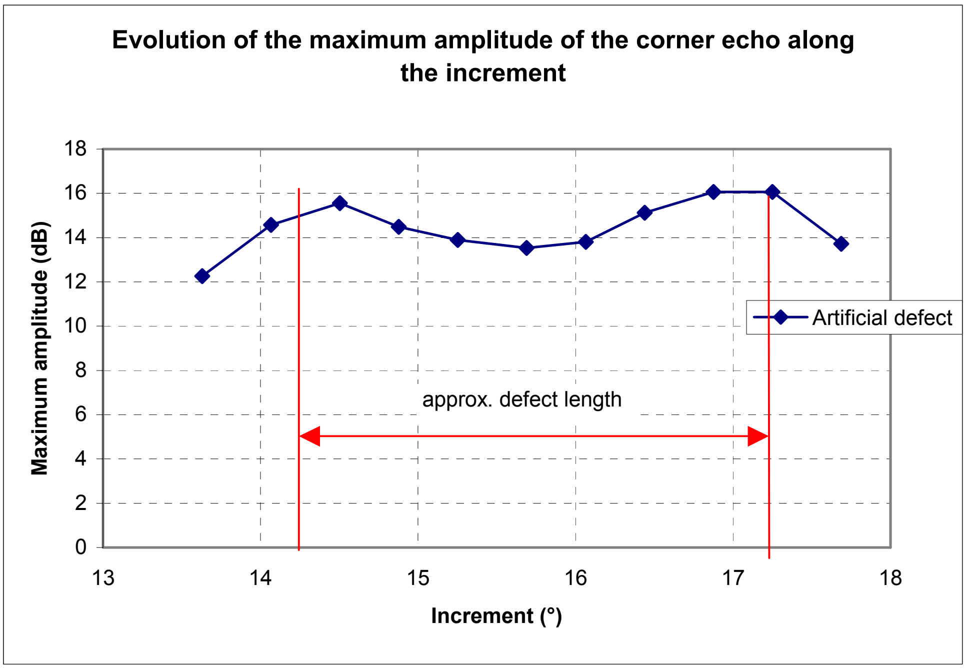

Figure 3 Echo Amplitude Variation as a function of scanner position along the defect length for synthetic defect located in the A70

The work package has extracted comparison data between real and simple synthetic defect species. These data are presented in detail in the final report from this work package.

Mathematical Modelling has also been used to investigate the feasibility of a transfer function, to modify the flaw response from some simple reflector to make it resemble the response from a complex plant flaw. Due to the limited data available the process has yet to be proved successful.

9.2 Deliverables

Report Title	Document Ref.
CEA Report on comparison of Real and Synthetic Defects	D015

10 Work Package 10: Feasibility Study of Virtual Defects

10.1 Outline of Proposed Work

The objectives of this study as defined in the original work scope for the project are as follows:

- To use the ultrasonic data and analyses generated in the preceding work packages to establish the feasibility of using simulation methods in qualification.

- To identify cases in which virtual test pieces could be used for inspection qualification and to outline methods for their use

10.2 Progress against Scope

It was known that a number of systems had been developed since the 1980s aimed at reducing the reliance of inspection qualification (or training) upon test pieces. Following a review the systems could be categorised into the following types:

- Computer (PC) based training aids which replay data to a simulated flaw detector. The main target for these devices is manual inspection.
- Full manual inspection simulation using either pre-recorded experimental data or the output from theoretical models.
- Full automated inspection simulation once again using pre-recorded experimental data or output from theoretical models.

The first option is readily achieved using contemporary computers (indeed a system was demonstrated in 1986) and presents few technical challenges. However the general method does suffer from some significant technical limitations – particularly related to concerns about the validation of some of the methods for prediction of echo shape and amplitude.

The second and third options present significant technical challenges and some level of approximation/limitation. Systems capable of working for both automated and manual inspection were demonstrated in the 1990s. These are discussed in the report which forms the deliverable from this project.

The work progressed well. However, due to the delays in the arrival of CIVA-SPIQNAR and the Multi2000 format, it was not possible to work extensively with the data generated for the project. The intention is still to process a sample of data from the library and store in the Multi2000 format.

10.3 Deliverables

Detail of the work is contained in the project deliverable:

Report Title	Document Ref.
On The Use of Virtual Defects for Inspection Qualification	D009

11 Work Package 11: Final Trials

11.1 Work package objective

Final trials were planned to provide some evaluation of the industrial applicability of the signal processing methods and software platform developed during the project against the initially defined objectives and criteria.

The results were to be analysed in “before” and “after” states. In the “before” state, analysis was to be performed without the application of the signal processing methods. For the assessment of the “after” state, the signal processing methods developed in Work package 5 would be applied to the data using the software platform produced in Work package 6.

The trials would be mainly performed in an “open” situation, with details of the defects within the test pieces being known, however some of the trials would be performed “blind”.

11.2 Progress of work

The final trials were discussed at the 36-month meeting, where MBEL were asked to draw up a detailed plan. This was achieved and disseminated amongst the partners during November 2003. A telephone conference was held during December, with a planning meeting at, CEA Saclay, in January to finalise the details. The discussions defined what data was available for the trials, approaches for the application of the signal processing methods, evaluations techniques and a timescale to complete the trial by the end of May 2004. The trials were split amongst MBEL, CEA, JRC, NRI, SQC, UK and UU.

When the trials were planned it was decided to utilise the data that had been acquired during the project. It was recognised that the inspection data from JRC assembly 70 containing service induced defects was the most valuable. Use was also made of the inspection data from the flat plate specimens procured for the project from Sonaspection (PO 34154 plates _001, _002, _003 and _004) which contained realistic synthetic defects. Details of the specimens and data sets used during the final trials are given in Table 4.

Details of specimen PO34154_002 were withheld from the data analysts for the blind aspects of the assessments.

11.3 Trials conclusions

From initial results there appeared to be some improvement in the signal to noise ratio of defects already detected and the background noise in general was reduced. Where a defect was not detected by ultrasonics in the unprocessed data, no signal was realised despite the application of the signal processing. An assessment of the capability of the software against the signal processing functional specification, deliverable 1, showed up some good performance of certain algorithms, but drawbacks and limitation of others.

The biggest drawback was the processing time of the deconvolution algorithms. Some solutions were proposed such as reducing the size of the data set to be processed.

Due to problems of implementation within CIVA-SPIQNAR there was no assessment of the InaSAFT algorithms during the final trials. However the InaSAFT software was implemented successfully within the final release of CIVA-SPIQNAR and UK produced some guidelines for its application that are included in the report on the final trials, D010.

Overall the trials were limited from the point of view of the data available and the effect of software bugs which prevented successful implementation of the processing methods or assessment of the processed data.

11.4 Deliverable from Work Package 11

Report Title	Document Ref.
Signal Processing Final Trials	D010
Signal Processing Target Performance Achievements	D011

Table 4 Summary of data files assessed and signal processing methods applied during final trials

Organisation	Data Source	Signal Processing Applied
MBEL	JRC ass 70, PA data PO34154_001 PA data PO34154_003 PA data PO34154_002 PA data (blind trial)	Split Spectrum – Amplitude minimisation Split Spectrum – Consecutive polarity coincidence Deconvolution with robust and semi sparse data handling
JRC	JRC ass 70, PE data PO34154_003 TOFD data PO34154_004 TOFD data	Split Spectrum – Amplitude minimisation Split Spectrum – Consecutive polarity coincidence Deconvolution with robust, semi sparse and saturation data handling
CEA	PO34154_001 PA data PO34154_002 PA data (blind trial)	Split Spectrum – Amplitude minimisation Split Spectrum – Consecutive polarity coincidence Deconvolution with robust and semi sparse data handling
NRI	A23 PE data	Split Spectrum – Amplitude minimisation Split Spectrum – Consecutive polarity coincidence Deconvolution (Weiner, Wavelet and parametric)
SQC	A23 PE data	Split Spectrum – Amplitude minimisation Split Spectrum – Consecutive polarity coincidence

12 Work Package 12: Dissemination

The stated objectives of the dissemination task were as follows:

"Dissemination and planning of exploitation of the project results in order to improve inspection capability for austenitic welds through signal processing, and assure more cost effective qualification with real, realistic and artificial reflectors."

Results dissemination has been achieved through:

- existing networks/working groups (ENIQ)
- publications, conferences, training
- Inevitably, some advances have also been made by partners in commercial contracts, but these are not documented.

12.1 ENIQ Briefing

Partners who attend the ENIQ meetings have kept ENIQ apprised of the project progress. A formal presentation will also be made to ENIQ following project completion. A likely venue for this briefing is the 4th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurised Components, to be held in London from 6 to 8 December 2004.

12.2 Conference Papers

To date the following papers have been produced describing the SPIQNAR project:

Report Title	Author	Conference and date
Signal Processing and Improved Qualification for Non-Destructive Testing of Ageing Reactors (SPIQNAR)	B J Dikstra	FISA 2001, Luxembourg, 12-15 November 2001
Signal Processing in Qualified Inspections of Stainless Steel Welds: The SPIQNAR Project	B J Dikstra, N B Cameron	8th EC-NDT conference, Barcelona, 17th-21st June 2002
Signal Processing in Qualified Inspections of Stainless Steel Welds: The SPIQNAR Project	B J Dikstra N B Cameron	British Institute of NDT, annual conference at Southport, 17th–19th September 2002
Signal Processing and Improved Qualification for Non-Destructive Testing of Ageing Reactors (SPIQNAR)	N Cameron X E Gros	FISA 2003, Luxembourg, 10-13 November 2003

In addition to these, three papers are to be presented at the 4th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurised Components, to be held in London from 6 to 8 December 2004.

These are:

Report Title	Author	Date
Inspection Qualification Aspects of the SPIQNAR Project	WL Daniels et al	December 2004
Signal Processing for Ultrasonic Inspection of Austenitic Welds: Developments from SPIQNAR	N Cameron et al.	December 2004
On-line library of ultrasonic responses from inspections of austenitic stainless steel materials	X Gros et al	December 2004

12.3 PhD thesis

Dr Hanneman of the UK has published her PhD thesis via an internet publisher. Work related to SPIQNAR is detailed within Dr Hanneman's PhD, which can be found at

http://www.dissertation.de/englisch/buch.php3?buch=1260

Mr Zimmer of the UK has performed a significant amount of work for his PhD thesis based upon the SPIQNAR project.

12.4 Deliverables

Two summary reports have been produced to facilitate dissemination which describe the:

- The extent and capability of the signal processing methods developed
- Guidelines for Inspection Qualification

Report Title	Document Ref.
Signal Processing Target Performance Achievements	D011
ENIQ Guidance from SPIQNAR Project	D016

12.5 Publications

A number of publications have been produced mainly by the universities related to the work of SPIQNAR, these are:

- R. Hannemann: Modelling and Imaging of Elastodynamic Wave Fields in Inhomogeneous Anisotropic Media, dissertation.de, 2001
- R. Marklein, K. Mayer, R. Hannemann, T. Krylow, K.Balasubramanian, K.J. Langenberg, V. Schmitz: Linear and nonlinear inversion algorithms applied in nondestructive evaluation, Inverse Problems, 2002
- K.J. Langenberg, R. Marklein, K.Mayer, R. Krylow, P. Ampha, M. Krause and D. Streicher: Wave field inversion in nondestructive testing. In: Proceedings on the Workshop Electromagnetics in a complex world, University of Sannio, Benevento, Italy, Springer Verlag, Vienna 2003.
- K.J. Langenberg, R. Marklein: Transient elastic waves applied to nondestructive testing of transversely isotropic lossless materials: a coordinate free approach, to be published in Wave Motion (Special Issue), 2004
- K.J. Langenberg, R. Hannemann, K. Mayer, A. Zimmer, R. Marklein: Implementierung eines SAFT-Algorithmus für inhomogen-anisotrope Materialien zur quantitativen Ultraschallprüfung austenitischer Schweißnähte, DGZfP-Jahrestagung, Mainz, 2003
- K.J. Langenberg, R. Marklein, K.Mayer: Linear and non-linear inverse scattering in ultrasonic and electromagnetic non-destructive evaluation, International Symposium on Inverse Problems , Design and Optimisation, Rio de Janeiro, Brasil, 2004
- K.J. Langenberg: Anwendung der Beugungstomographie in der zerstörungsfreien Materialprüfung, Workshop on Tomography and Inversion, Neustadt, Germany, 2003.

13 Work Package 13: Project Management

The project commenced on 1st October 2000 and was originally scheduled to run for three years. A nine month extension was granted and the project was completed by 30th June 2004.

13.1 Deliverables

Table 5 summarises the list of deliverables achieved during the SPIQNAR project.

13.2 Change of work package activity

The project has generally progressed in the direction of the original project scope; there have been however a number of deviations relating to the availability of test specimens, partners' timetable for inspection requirements and problems relating to the integration of particular aspects of the project. The biggest overall change was the withdrawal of Intercontrole from the project and the necessary requirement for another partner to perform their work.

1. **Work package 1: Compilation of Specimen Data and Specifications**
   A number of specimens defined in the original work description, became unavailable. Alternative specimens were sourced.
2. **Work package 2: Inspection Procedures**
   As a result of the withdrawal of Intercontrole no inspection procedures relating to focused immersion scanning techniques have been produced.
3. **Work package 3: Test Piece Manufacture**
   A plan to implant defects within spare section of the JRC assemblies was stopped when it became clear that contamination by ionising radioactive isotopes posed a significant problem. Ultimately a number of flat plate specimens were procured from a variety of defect manufacturers.
4. **Work package 4: Acquisition of Ultrasonic Data**
   The withdrawal of Intercontrole from the project resulted in MBEL performing alternative immersion inspections during January 04.
5. **Work package 5: Development of Signal Processing Methods**
   No significant changes to this work package, however an additional investigation into data compression methods suitable for ultrasonic data was performed.
6. **Work package 6: Interface Signal Processing Methods with Ultrasonic Systems**
   There has been no significant change to this work package.
7. **Work package 7: Library of Defect Reponses**
   There have been no significant changes to the work scope of this work package.
8. **Work package 8: Destructive Examination**
   Considerable effort has been applied to the destructive examination of JRC assembly 70 and A23.
9. **Work package 9: Comparison of Real and Synthetic Defect Response**
   There have been no significant changes to this work scope, however a reduced amount of trials and modelling was performed due the late delivery of appropriate test specimens.
10. **Work package 10: Study of Virtual Defects**
    There have been no significant changes to this work package.
11. **Work package 11: Final Trials**
    There have been no significant changes to this work package.

12. **Work package 12: Dissemination and Exploitation of Results**
    There have been no significant changes to this work package.

13. **Work package 13: Project Management**
    There have been no significant changes to this work package. Mitsui Babcock coordinated the project, with significant support from Serco Assurance. A good working relationship was established between the two organisations during this project.

13.3 Consortium Management

This project involved the coordination between 13 partners at the outset of the project, dropping to 12 partners following the withdrawal of Intercontrôle. A Consortium Agreement was generated and signed by all.

13.4 Meetings

A total of 24 meetings have been held throughout the project, which includes 8 progress meetings and 3 co-ordinator meetings, plus a number of technical meetings. In addition, a number of successful telephone conference calls were held during the last 12 months of the project to discuss various issues. Such conference calls were a cost effective approach to meetings, but they must be limited in the number of participants, and the agenda needs to be restricted to one or two well-defined items. The familiarity between all partners made such conference calls easier and thus would not have been an appropriate route for communication at the outset of the project.

Table 5 **Summary of deliverables from the SPIQNAR project**

Deliverable Identifier	Deliverable Title	Dissemination	Proposed Delivery Month	Actual Delivery Month	Comments
1.	List and availability of specimens	PU	2	24	
2.	Report containing UT analysis measurements required	RE∗	3	24	Deliverable 2 and 3 were combined and two separate documents were produced, "Guidelines for Fingerprint Inspections" and "Guidelines for Data Acquisition"
3.	Guidelines for data collection	RE∗	3	24	
4.	Functional specification for signal processing methods and software platform	RE∗	2	6	
5.	Detailed inspection procedures	RE	6	36	Significant delay was due to change in various inspection specimens along with internal reviews
6.	Manufactured test pieces	PU	14	36-45	A number of tenders were required, along with a resubmital
7.	Digitised ultrasonic data	PU	12	6-45	Digitised data became available form the end of the 1st year and subsequently throughout the remainder of the project
8.	Preliminary analysis of UT data	RE/PU	12	12-45	A number of inspection reports were produced throughout the project, it was agreed that summary reports could be made available via the Defect Library, if organisation concerned gave permission
9.	Signal processing methods and code	PU/RE	25	12-30	
10.	SAFT method and code	RE	25	24-45	Further refinements for integration within UT Signal Processing toolbox was required
11.	UT Signal processing toolbox (CIVA)	CO	30	24-45	First draft issue was produced during Summer 2002, final issued tool box will be achieved at the end of the project, incorporating fixes to technical bugs identified during the final trials
12.	Library of UT defect responses	PU	36	36-45	Data added to library as project progressed
13.	Handbook of destructive examination	PU	18	45	

Deliverable Identifier	**Deliverable Title**	**Dissemination**	**Proposed Delivery Month**	**Actual Delivery Month**	**Comments**
14.	Reports containing digitised crack profiles	PU	20	45?	
15.	Comparison report between real and synthetic defects	RE*	33	45?	
16.	Synthetic-real defect transfer function report	RE*	33	45?	
17.	Feasibility report on virtual defects	RE*	31	45	First draft at 41 months
18.	Inspection report before and after signal processing	CO	34	45	
19.	Report on extent to which target performance achieved	PU/RE	34	45	
20.	Final report	PU/RE*	36	45	
21.	Proposals for ENIQ Recommended Practice.	PU	36	45	
22.	Technology Implementation Plan	PU/CO	6 (preliminary 18 (intermediate) 36 (final)	45	
Additional deliverables achieved					
23.	Ultrasonic Data compression toolbox and manual	PU		18	Generated as a result of an enquiry into the practical implications of gathering full RF data for ultrasonic inspections
24.	SPIQNAR Website	PU		30	Requested as a route to disseminate information regarding the project and meetings

* Denotes that the deliverable is available to ENIQ Steering Committee members and also members of the ENIQ Task Group on Qualification.

14 Recommendations for Further Work

- The project has sectioned only part of the JRC specimen set and so there remains some scope for performing further inspection and sectioning of these IGSCC defects.
- The project manufactured a considerable number of specimens which still exist and could be used in further investigative work, this could include:
  - Comparisons between the ultrasonic responses of real and synthetic defects
  - Further evaluation of the signal processing algorithms.

15 Conclusions

- Real IGSCC from plant have been inspected using standard inspection techniques using pulse echo probes, phased arrays and TOFD.
- A total of ten synthetic defect samples have been manufactured. Some of these samples have been inspected.
- An on-line library of inspection data has been produced.
- Data in the library is available, unrestrictedly in both native and open data formats. Details of the open format are available from the on-line library.
- The drafting of inspection procedures containing the same structure and similar implementation bases has allowed their understanding by the different partners and subsequent use when necessary.
- Inspection reports have been produced and are available on the on-line library.
- Destructive Examination of plant samples has been performed which has been used in comparison of real and synthetic defect responses.
- Computer modelling has been performed to improve understanding of response signals from plant and synthetic samples
- The feasibility of virtual defects has been investigated for qualification purposes and methods proposed for the use of virtual defects in inspection qualification programmes.
- Signal Processing Algorithms have been developed and applied to real data.
- Guidelines for the application of these algorithms for practical inspection applications have been developed.

- The application of the developed algorithms to plant data has shown some improvement for real plant inspections.
- When developing complex software, tests should be taken into account at the beginning of the project and should be clearly specified by both the development specialists and the software team implementing any new algorithms.
- Guidance notes for ENIQ have been generated from the project.

16 References

- [Olofsson01]: T. Olofsson, "Deconvolution and model based restoration of clipped ultrasonic signals", accepted for *IEEE Transactions on Instrumentation and Measurement*, 2005.
- [Olofsson02]: T. Olofsson, "Semi-sparse deconvolution robust to uncertainties in the impulse responses", *Ultrasonics, 42, (2004)*, pp. 969-975.
- [Zhang01]: G.M. Zhang, T. Olofsson, and T. Stepinski, **"**Ultrasonic NDE image compression by transform and subband coding", NDT&E International, vol. 37, no. 4, June 2004, pp. 325-333.