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Structural Health Monitoring of Piping in Nuclear Power Plants

– A Review of Efficiency of Existing Methods

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SSM perspective

Background

SSM needs to acquire knowledge about new applied Non-Destructive Engineering (NDE) techniques and their efficiency. One area that is discussed more frequently is Structural Health Monitoring (SHM). SSM needs to investigate the international experiences of SHM from the nuclear industry. SSM also wants to have more information about the capabilities and the limitations of NDE methods used for SHM of piping.

Objectives

The first part of the project is to investigate international experiences and potential benefits from the implementation of SHM at nuclear power plants. The second part of the investigation is to review the NDE methods and map their capabilities and limitations for remote monitoring of piping in nuclear power plants.

Results

The study in the first part has covered the following areas:

- Overview of different on-line monitoring methods
- NDE techniques suitable for on-line monitoring of nuclear reactors, experiences from USA and France

The second part of the study has covered the following:

- Presentation of long range ultrasonic techniques that can be used for monitoring piping in nuclear power plants
- A brief review of the theory for the NDE technique Guided Waves
- Results from test and investigation of capabilities and limitations for the use of Guided Waves on piping in nuclear power plants.

Need for further research

There is a need for further work within the research field SHM, to be able to develop and assess the reliability of the remote non-destructive inspection systems capability to detect, characterize and size defects when used for monitoring pipes in nuclear power plants.

Project information

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Contents

Abstract

In the first part of the report, we review various efforts that have been recently performed in the USA in the field of reactor health monitoring. They were carried out by different organizations and they addressed different issues related to the safety of nuclear reactors. Among other aspects, we present technical issues related to the design of a self-diagnostic monitoring system for the next generation of nuclear reactors. We also give a brief review of the international experience of such systems in today's reactors.

In the second part of the report we focus on long range ultrasonic techniques that can be used for monitoring piping in nuclear reactors. Common strategy used in the Swedish nuclear plants is leak before break (LBB), which relies on monitoring leaks from the pipelines as indications of possible pipe break. Significant parts of piping systems are partly or entirely inaccessible for the NDE inspectors, which complicates the use of proactive strategies. One solution to the problem could be implementing monitoring systems capable of monitoring pipelines over a long range. The method, which has shown much promise in such applications is the UT based on guided waves (GW) referred to as long range ultrasound testing (LRUT). In the report we give a brief review of the GW theory followed by the presentation the commercial GW instruments and transducers designed for the LRUT of piping. We also present examples of the baseline based systems using permanently installed transducers. In the final part we report capacity tests of the LRUT instruments performed in collaboration with two different manufactures.

Sammanfattning

I första delen av rapporten går vi genom olika insatser som har nyligen genomförts i USA inom kärnreaktorövervakning. De har utförts av olika organisationer och de tog upp olika frågor som rör säkerheten vid kärnkraft reaktorer. Bland annat presenterar vi tekniska frågor relaterade till utformningen av övervakningssystem för nästa generation av kärnreaktorer. Vi ger också en kort genomgång av internationella erfarenheter av sådana system i dagens reaktorer.

Den andra delen av rapporten är fokuserad på ultraljudstekniker med lång räckvidd som kan användas för övervakningen av rörledningar i kärnkrafts reaktorer. En strategi som används i svenska kärnkraftsverk är *leak before break* (LBB) bygger på övervakningen av läckor från rörledningar som indikationer på möjliga rörbrott. Betydande delar av rörsystem är helt eller delvis otillgängliga för ofp inspektörer, vilket försvårar användningen av proaktiva strategier. En lösning på problemet skulle kunna vara att skapa övervaknings system som skall kunna kontinuerligt övervaka långa sträckor av rörledningar. Metoden, som har visat mycket lovande resultat i sådana tillämpningar är UT som bygger på guidade vågor (*guided waves* – GW) känd som lång räckvidd ultraljudsprovning (LRUT). I rapporten, efter en kort genomgång av GWs teorin ger vi en presentation av kommersiella GWs instrument samt givare konstruerade speciellt för LRUT av rörledningar. Vi presenterar också exempel på system som bygger på permanent installerade givare.

I sista rapportdelen presenterar vi resultat av kapacitetstester av LRUT instrument genomförda i samarbetet med två olika systemtillverkare.

1

Introduction

An urgent need to optimize maintenance aiming at improving both reliability and competitiveness of nuclear power plant operation has been observed recently. Facing extended operation period of the present reactors and the new reactor designs, a strategy must be developed to allow extended periods of continuous and safe operation that would enable less frequent maintenance actions. There is an increasing tendency to move from the preventive (scheduled) maintenance concept to the proactive one, dependent on plant and component conditions.

Due to this demand, various on-line condition and structural health monitoring, nondestructive inspection techniques and diagnostics are to be developed and implemented. Component selection for condition based maintenance, parameter selection for monitoring condition, evaluation of condition monitoring results are issues influencing the effectiveness of condition based maintenance.

Interestingly, there exist at least two apparently different terms used for the techniques used for monitoring systems and structures:

- on-line condition monitoring (OLM) used in relation to nuclear power plants, and
- structural health monitoring (SHM) used in relation to aerospace, marine and civil structures.

On-line condition monitoring of plant's equipment, systems and processes includes the detection and diagnosis of abnormalities via long term surveillance of process signals while the plant is in operation. According to the definition from IAEA's report [1] the term *on-line condition monitoring* of nuclear power plants refers to the following:

- The equipment or system being monitored is in service, active and available (on-line).
- The plant is operating, including startup, normal steady-state operation and shutdown transient.
- Testing is done in situ in a non-intrusive, passive way.

A *structural health monitoring* system is defined as the process of implementing a damage detection strategy that involves:

- the observation of a system over time using periodically sampled dynamic response measurements from a network of sensors (preferably wireless),
- the extraction of damage-sensitive features from these measurements and the statistical analysis of these features to determine the current state of structural health, and if possible,
- to perform the prognosis of the system's life length.

The most important benefits of implementing a SHM system are avoidance of premature breakdown, reduced maintenance cost, supervision at remote sides and remote diagnosis, and improvement of the system's capacity factor.

At the present stage the SHM development is to a large extend focused on creating a kind of 'nerve network' for monitoring structure elements and process parameters while the OLM deals with the selection of parameters and components for monitoring using existing sensor technology and evaluation of the monitoring results.

Due to some inexplicable reasons there is very little overlap between SHM and OLM in terms of publications and conferences. Nuclear power plants have very rarely served as objects for the applications of SHM methodology presented in Journal of Structural Health Monitoring and at annual SHM Workshops.

The term *health monitoring* is seldom used in relation to nuclear power plants although it seems to be relevant; for example, the authors of report included in Annex V to [2] claim that the effective management of plant systems requires continuous monitoring of the "plant's system health". This should produce answers to the questions related to the actual plant performance comparing to that when the plant was designed and commissioned. It should also indicate the actions that are required for managing the future performance at the station. Another example can be found in reports by Nakagawa et al [3, 4] from the Ames Laboratory and Center for NDE, USA where the term *on-line health monitoring* (OLHM) is used.

In the remaining part of this report we will respect the unwritten rules and we will use the term OLM in relation to nuclear power plants.

The most important benefits of implementing OLM systems at nuclear power plants are:

- It prevents catastrophic failures and their secondary defects,
- It is done while the reactor is in operation since it does not require shutdown for inspection and/or monitoring activities,
- It is done remotely, thus greatly reducing exposure levels,
- It reduces maintenance cost – inspection interval can be increased with on-line inspection and replacement of intact parts is avoided by condition-based maintenance,

- It improves the system's capacity factor due to early warning of impending failures; repair action can be taken during refueling and hence will not affect the capacity factor.

Work within OLM is by necessity highly interdisciplinary. Novel technologies, such as smart materials, micro-electromechanical systems (MEMS), smart sensor networks, and modern multivariate signal/data analysis constitute the foundation of OLM, enabling the development of miniaturized intelligent distributed systems with higher resolution, faster response and greater reliability.

2

OLM in Nuclear Industry

2.1 Introduction

Operating experience from nuclear power plants indicates that degradation of power plant performance in terms of unscheduled shutdowns, extensive maintenance, and operational efficiency occurs most commonly because of vibration, erosion/corrosion, thermal stress and the resulting degradation on the system.

Generally, while there exists likelihood that components degrade during operation, any potential component failures must be mitigated to prevent any system failure. In the Risk-Informed approach, which is used in nuclear power industry, degradation modes of critical components are considered and their potential degradation mechanisms are anticipated [4]. Then, a specific defense mechanism against each of those mechanisms is build into the system design.

However, there are significant uncertainties in damage growth predictions since the degradation initiation and progression are stochastic processes that are difficult to model and predict. Those uncertainties yield conservative estimates concerning the required period of maintenance cycles, and as a result of that, it is difficult to extend them beyond the current 1- to 1.5 year period.

Current nuclear reactors achieve high levels of availability and reliability by employing outage-based maintenance (i.e., performing methodical, periodic, off-line inspections, preventive maintenance, and component repair/replacement during planned refueling periods). The extended refueling interval, which is a critical feature of the planned Generation IV nuclear reactor designs, creates new maintenance challenges. New approaches are required to keep maintenance from interrupting operation, while ensuring the current level of safety. This requirement compels the reactor owner to consider some of current outage-based routine maintenance converted to the on-line structural health monitoring as much as possible.

Below, we present a short review of various projects performed recently in the USA and France in the field of reactor health monitoring. The projects were carried out by different organizations and addressed different issues related to the safety of nuclear reactors. Although those projects were concerned with actions on different levels, their common denominator was the increase of reactor safety by continuous and accurate monitoring of its state variables and intelligent processing the information gathered from those measurements.

The report is organized in a top-down manner, we start from the top – lessons learned from an extensive program concerned with intelligent processing information acquired in the process of monitoring various variables and sensors in nuclear power plants. Then, we review technical issues related to the design of a self-diagnostic monitoring system for the next generation of nuclear reactors. Finally, we present selected measurement NDE techniques feasible for the OLM of nuclear reactors.

2.2 Intelligent processing of OLM information

According to the definition formulated by Hines & Davis in [5] the OLM systems use historical plant data to develop empirical models that capture the relationships between correlated plant variables. These models are then used to verify that the relationships have not changed. A change can occur due to sensor drift, equipment faults, or operational error.

Note, however, that the authors apply this general definition to the process of designing *computational intelligence* (CI) capable of addressing complex nuclear engineering issues. One of the most challenging issues for the CI is to effectively handle real-world uncertainties that cannot be eliminated, and include for instance, sensor imprecision, instrumentation and process noise or unpredictable environmental factors. These uncertainties result in a lack of the full and precise knowledge of the system including its state and interaction with the environment.

According to EDF's policy, summarized in Annex IV to [2], OLM is a vital part of condition based maintenance of the EDF's reactors, see Fig. 2.1. The purpose of monitoring is an early detection of degradation followed by diagnosis and prognosis that would enable condition-based operations to bring the equipment into fully operational condition.

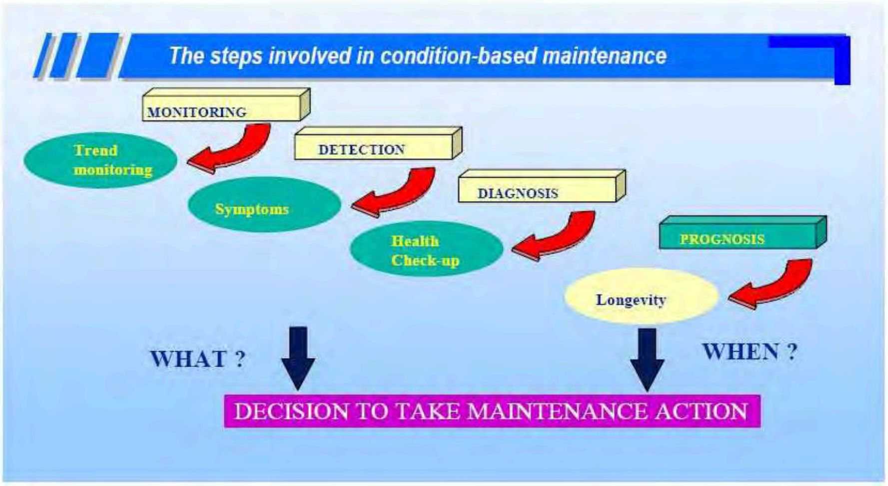


Figure 2.1: Steps involved in condition based maintenance.

Historically, periodic manual calibrations have been used to assure that sensors are operating correctly. This technique, however, is insufficient since sensor conditions are only checked periodically and faulty sensors can continue to operate for periods up to the calibration frequency.

New technologies have been developed for the nuclear power plants in USA to ascertain the condition of plant equipment, in particular, to monitor the condition of sensors and their associated instrument chains. Early EPRI research included the development of the *Instrument Calibration and Monitoring Program* (ICMP) for monitoring physically redundant sensors, [5]. Subsequent work expanded to monitoring both redundant and non-redundant sensors. The systems currently in use in the USA are based on the *Multivariate State Estimation Technique* developed at *Argonne National Laboratory*, [5, 6].

The major lesson learned in applying empirical modeling strategies for the nuclear plants in USA are, [5] :

- relevant sensor data should be used to get accurate result and optimal prediction,
- robust models and regularization techniques should be used to produce repeatable results,
- an analytical method to estimate the uncertainty of the predictions should be available,
- the methods should be easily trained and easily retrained for new or expanded operating conditions.

The costs of an on-line implementation include software licensing, equipment, model development, training, and maintenance. The benefits of an on-line monitoring system include direct benefits from the reduction in manual calibrations, and indirect benefits including performance enhancements and equipment monitoring.

Although the role of OLM in the nuclear power industry is difficult overestimate, it entirely relies on the relevant information provided by various sensors installed in a nuclear plant. Below, we will present some engineering solutions to monitoring of various parts of nuclear reactors.

2.3 Intelligent self-diagnostic monitoring system for next generation nuclear power plants

Pacific Northwest National Laboratory (PNNL), Battele, USA, in collaboration with two universities in South Korea, has conducted a large research project concerned with proof-of-principle demonstration for online intelligent *self-diagnostic monitoring system* (SDMS) for next generation nuclear power plants. SDMS includes a distributed system of sensors integrated with active components and passive structures of types expected to be encountered in the next generation nuclear power reactor systems, [7].

The objective of this project was to design and demonstrate the operation of intelligent or smart self-diagnostic and prognostic capabilities for potential application to both current and next generation of nuclear power plant systems.

The project had very wide technical scope including:

- designing and demonstrating an SDMS architecture that uses smart components, neural networks, and artificial intelligence,
- implementing the SDMS methodology on a PC platform,
- developing advanced radio frequency (RF) module/multi-sensor units for condition monitoring,
- developing the detailed design and fabricating an SDMS computer demonstration system,
- validating the SDMS system capabilities through baseline verification testing and degradation trials on a pilot-scale service water system,
- providing an assessment of the potential economic impact of SDMS data analysis and related software tools for improved safety and efficiency of reactor operations, reduction of potential for unscheduled outages, reduction in maintenance activities, and extending reactor system design lifetimes.

The ultimate goal of the project was to provide a significant increase in reactor safety system reliability by developing methodologies that would integrate or devise new ways to measure and correlate: stressor intensity, degradation rate, performance levels, and remaining useful service life for selected categories of reactor components. Three components were included in this study: a centrifugal pump, a heat exchanger, and a reverse osmosis filter.

The main incentive acting as a driving force for the project was an evolution towards the condition-based operations and maintenance of nuclear plants that, according to the report [7], is characterized by

- understanding the stressor levels intended during the machinery design process,
- measuring suitable parameters to quantify the existing stressor levels, and
- correcting operating environments to make these levels compatible with economic production versus equipment lifetimes.

This evolution can be illustrated graphically by the four zones (steps) illustrated in Fig. 2.2, the degradation, the preventive, the predictive and the proactive zones.

PNNL created a pilot plant which was used for design and testing of the experimental SDMS system. The pilot plant included pumps, heat exchanger and reverse osmosis filter bank.

Figure 2.2: Evolution of condition based maintenance, [7].

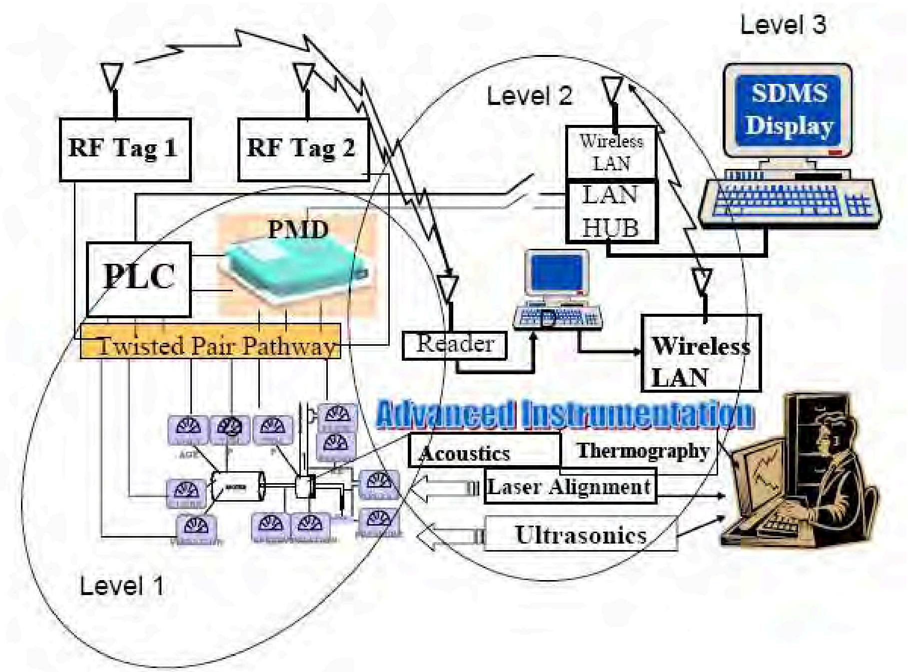


Figure 2.3: Information transmission and processing in the SDMS system, [7].

Information acquired by the sensors was transmitted, processed and displayed in the computer-based system shown in Fig. 2.3.

Project conclusions

According to the authors, the results of SDMS demonstration, presented in the report [7], show that this technology is now ready to prove its relevance to the U.S. nuclear initiative. SDMS diagnostics and prognostics can demonstrate significant value by reducing or eliminating some of the most prevalent degradation and failure modes that drive core damage frequency calculations for Generation II, III, and IV reactors.

The authors expect that a set of deterministic or statistical models will be formulated as a result of this research that can be utilized to calculate failure risk probabilities from degradation rate and equipment physical condition status. Further, this failure information can then be useful in performing an self-learning on-line probabilistic risk assessment that utilizes stressor feedback to update the risk evaluation based on the equipment condition.

Preliminary calculations have shown that the application of SDMS technology to current generation (II) reactors has the potential to reduce core damage frequency by as much as a factor of 2.

The above conclusions formulated by the authors seem to be slightly too optimistic taking into account that the tests were performed in laboratory conditions only using mock-ups subjected to artificially produced stressors.

2.4 NDE techniques suitable for the OLM of nuclear reactors

2.4.1 Experience from USA

In the reports coauthored by *Ames Laboratory and Center for NDE, Iowa, USA* and *Science & Technology Department, Westinghouse Electric, PA*, USA [3, 4, 8] the authors advocate on-line health monitoring (OLHM) approach as a key component of the safety-by-design approach that makes possible maximizing the benefit of advanced reactor designs. In their opinion *'in order to operate the reactor continuously without interruption while meeting regulatory requirements, it is necessary to shift routine maintenance actions, as much as possible, from the outage-based inspections to active on-line monitoring'.*

The authors coined the term OLHM to indicate the difference with respect to OLM, which is, in their opinion, mainly associated with monitoring of aerospace systems.

Decades of maintenance and NDE experience accumulated from existing commercial reactors should be used as a basis for the development of OLHM systems. When new reactor designs are developed, it is important to take advantage of this experience proactively in order to advance new nuclear power system safety and economy.

In [4] the authors propose the design-for-inspectability concept, which consists of two steps:

1. Identify the potential failure modes for each of the critical reactor components,
   and then
2. either affect the design itself or place monitoring devices at critical locations so that any component degradation can be reliably detected and mitigated before it reaches the critical stage.

The authors explain their approach using as an example the design of International Reactor Innovative and Secure (IRIS) from the International Near-Term Deployment (INTD). First, they identified key IRIS in-vessel components for which an on-line NDE would have the greatest benefit. They also began to conceive an on-line monitoring systems that could address the monitoring needs, using NDE methods based on electromagnetic, ultrasonic, and radiation detectors that are potentially feasible for on-line use in the reactor environment. Results of their investigation is summarized in Table 2.1 and Fig. 2.4.

Operational experience has shown that among the reactor pressure vessel (RPV) components listed in Table 2.1, the integrity of steam generator (SG) appears to be critical for long-term safe operation of the reactor. For the IRIS design, magnetite deposit may build-up on the inner-diameter (ID) tube surface. Eddy current (EC) inspection and guided-wave ultrasonic testing (UT) are concerned as effective tools for the deposit detection.

Component	Monitoring needs	NDE method
Steam generators	Magnetite deposits Tube/header attachment Tube integrity	EC, EMAT UT EMAT UT EC, EMAT UT
Coolant pumps	Coolant flow Structural attachment	$^{16}N/\gamma$-ray detector EMAT UT
Penetration welds	Degradation	EMAT UT

Table 2.1: Candidate IRIS components for on-line monitoring and applicable on-line NDE methods: EC – eddy current, UT – ultrasonic inspection, EMAT – electromagnetic acoustic transducer.

UT guided waves are also applicable for monitoring the attachment of the tubes to the headers, which is another defect-prone area. The EC and UT methods may also apply to monitoring of tube integrity itself. Note, that since control rod drive mechanisms (CRDMs) are located inside RPV in IRIS, upper head penetrations for the CRDM guidelines have been eliminated. However, the technique may be applied to some smaller thin-sleeve penetrations that may still remain in IRIS (e.g., for instrumentation tubes).

Another critical area for rector safety is coolant pump performance anomaly that could result in disturbance of the primary coolant flow through the steam generator. For the detection of such anomaly the on-line flow rate monitoring using the radioactive ^{16}N concentration in the SG volume is proposed.

It is worth noting that according to the authors of [4], **guided waves** emitted using EMAT are particularly compatible to the active reactor

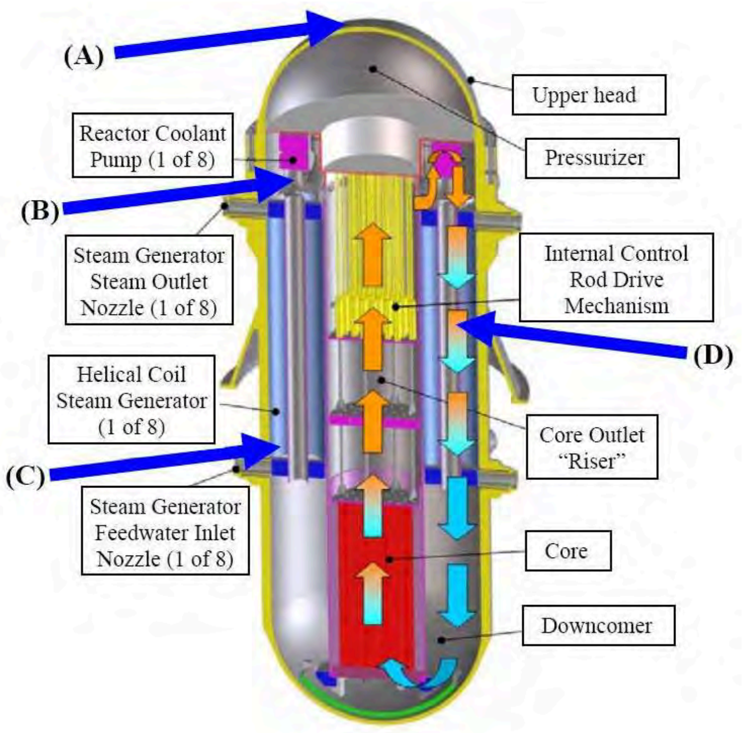
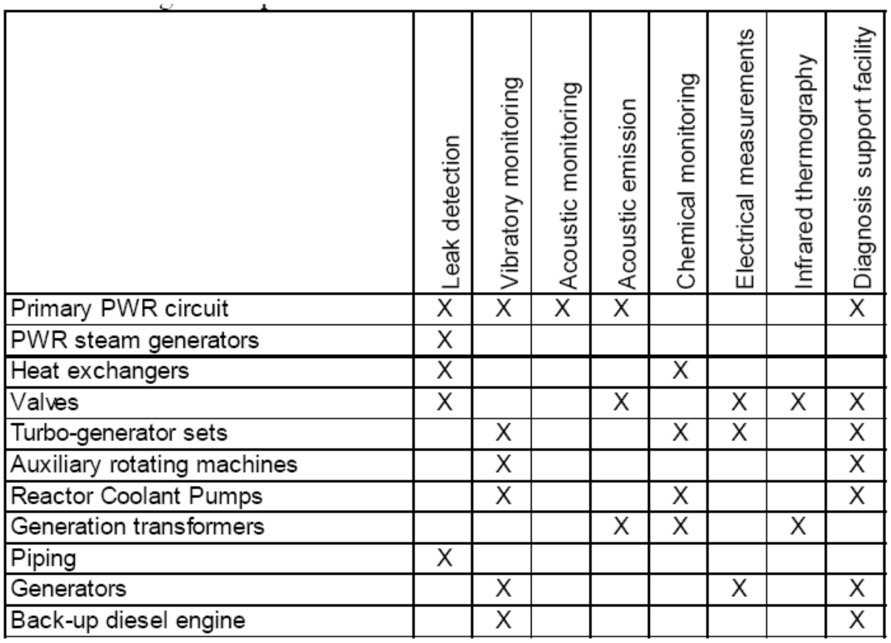


Figure 2.4: Components inside integral RPV and potential areas for online NDE: (A) upper head penetration welds (EMAT UT), e.g., instrumentation tubes, (B) pump attachment (EMAT UT), (C) steam generator tubes and tube attachment (EC, EMAT UT), and (D) primary coolant flow ($^{16}N/\gamma$-detection), [4].

environment and feasible for the on-line monitoring of different parts of SG. The authors advocate for their novel 3-phase AC EMAT emitting torsional waves in tubing. They also propose a special solution to EC inspection for magnetite deposit detection on boiler tubes, [3].

2.4.2 EDF's experience

EDF uses the main existing monitoring techniques listed in the table in Fig. 2.5 and applies these techniques to most of the equipment in the nuclear power plants, Annex IV [2]. These techniques may be used continuously, periodically or sporadically before a shutdown.



	Leak detection	Vibratory monitoring	Acoustic monitoring	Acoustic emission	Chemical monitoring	Electrical measurements	Infrared thermography	Diagnosis support facility
Primary PWR circuit	X	X	X	X				X
PWR steam generators	X							
Heat exchangers	X				X			
Valves	X			X		X	X	X
Turbo-generator sets		X			X	X		X
Auxiliary rotating machines		X						X
Reactor Coolant Pumps		X			X			X
Generation transformers				X	X		X	
Piping	X							
Generators		X				X		X
Back-up diesel engine		X						X

Figure 2.5: Monitoring techniques used by EDF [2].

Although leak monitoring is shown separately in the first column of the table in Fig. 2.5 the main measurement techniques used to detect leaks are acoustic measurements (overhead acoustics, acoustic emission), temperature measurements (especially infrared thermography), pressure, hygrometry and the physical-chemical analysis methods.

3

Guided-wave based inspections

Most effort concerning the safety of nuclear power plants is focused on reactors, boilers and turbines. Piping that acts as a hose-pipe to convey flow from one component to another is in most cases assumed to be less critical since it has no obvious moving parts. Over the years some utilities realized that the piping may be a critical component. In many cases piping failure would result not only in massive loss of revenue, but the consequences of a violent failure would be devastating and could result in potential loss of life. Despite the common opinions, piping is far from being passive, it is subjected to a severe temperature changes and it usually operates well into the creep range. Cyclic operation of the plant subjects the piping to mechanical and thermal fatigue mechanisms and poor or defective support assemblies can impose massive loads onto the structure.

Common strategy used in the Swedish plants is *leak before break* (LBB), which relies on monitoring leaks from the pipelines as indications of possible pipe break. The LBB technique is not capable of providing any detailed answers concerning break occurrence and localization, it provides only an indication that pipe break may occur in the future.

Significant parts of piping systems are partly or entirely inaccessible for the NDE inspectors, which complicates the use of proactive strategies. Moreover, majority of the conventional NDE techniques are characterized by a very limited range of detection and their application to piping systems is costly and time-consuming. A natural solution to the problem would be implementing OLM systems, possibly capable of monitoring tubes over a long range. The method, which shows much promise in such applications is the UT based on *guided waves*.

3.1 Guided-wave principles

If the wavelengths of elastic waves are comparable with or larger than typical dimensions of the structure (e.g., tube or plate thickness) the waves are called *guided waves* (GW). Due to the boundary conditions imposed by the structure, those waves are *guided* within the volume of a tube or plate. Due to their complex character, GWs have been used for NDE in very special applications only.

The first feature, which complicates potential GW applications is the existence of several wave modes that can propagate simultaneously with different velocities. Three basic modes occurring in cylindrical shells are, longitudinal, torsional and flexural modes. The first two are axisymmetric while the latter is non-axisymmetric one. Each of those modes, depending on frequency appears in a number of orders. Undesired modes can be attenuated by designing special transducers and/or by choosing certain frequency band.

The second feature is the fact that GWs are dispersive, i.e., their velocity is a function of frequency. Moreover, two different velocities are are defined, the *group velocity* and the *phase velocity*. Group velocity applies to pulses and phase velocity to *sine* components of a pulse. For isotropic media with known geometry, dispersion curves can be calculated theoretically and plotted as phase respective group velocity in function of frequency.

The main consequence of those features is that in order to avoid the confusing influence of higher-order modes in the pipe, it is reasonable to use for long-range OLM purposes lower order modes in the relatively small frequency band in the range of some tenths of kHz to a couple of hundreds kHz. Only in this frequency band wave propagation seems to be manageable and the number of modes is reduced to two or three fundamental modes.

For illustration, we show in Fig. 3.1 the dispersion curves calculated for a steel pipe with diam. 3" and 12" [9]. The $T(0,1)$, $L(0,1)$ and $L(0,2)$ modes are axially symmetric while the $F(m,n)$ modes ($m \neq 0$) are termed flexural modes that have m wavelengths around the circumference of the pipe. From Fig. 3.2, where the propagation of the corresponding axisymmetric guided waves is shown, it can be seen that the two longitudinal modes $L(0,1)$ and $L(0,2)$ propagate with different velocities. Propagation of the non-axisymmetric GW modes in pipes is even more complicated since, for instance, the waves generated by a point-like source propagate along helical curves around the longitudinal axis. For details see, e.g. [10] where the simulations performed for a steel pipe with diameter 406 mm and wall thickness 9 mm are presented.

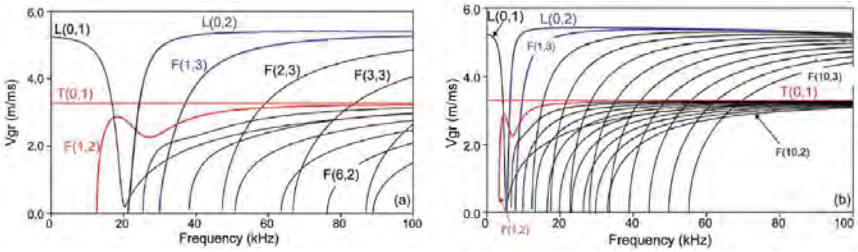


Figure 3.1: Dispersion curves for a steel pipe, diam. 3 inch (left) diam 12 inch (right) Note frequency scaling with increasing pipe diameter. (reprinted from [9]).

The $L(0,2)$ and $T(0,1)$ modes are the most useful modes in practical pipe inspection. From Fig. 3.1 it can be seen that the $T(0,1)$ mode is non-dispersive at all frequencies, while the $L(0,2)$ mode is practically

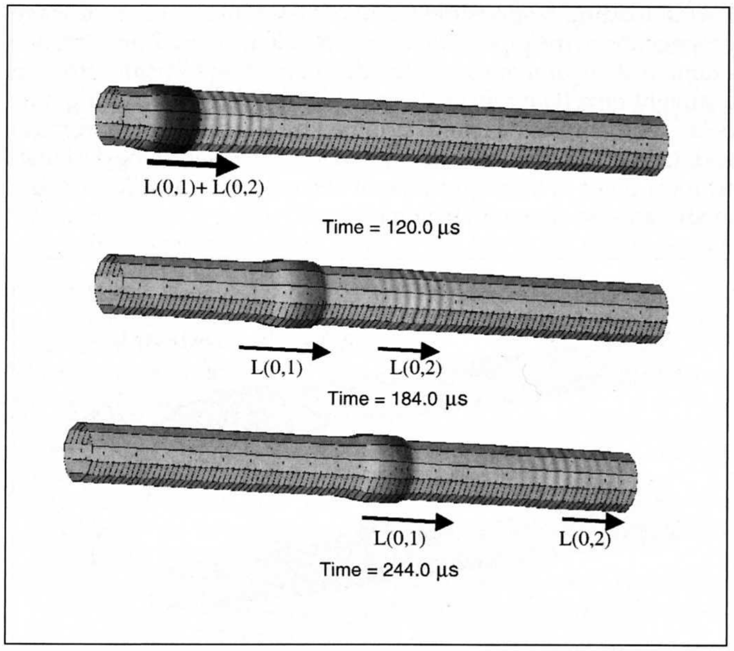


Figure 3.2: Simulation of guided waves in a straight pipe showing two axisymmetric waves with different velocities. For details see [11].

non-dispersive over a wide frequency band. They can be excited in a pure form without producing any flexural waves by applying uniform excitation over the circumference of the pipe, either by a ring of piezoelectric transducers or an electromagnetic system using a coil wrapped round the pipe.

The propagating wavefront will interact with any change in acoustic impedance in pipe wall caused by a change of thickness, for instance, a weld or a thinning due to corrosion. A portion of the energy will be reflected and will propagate back to the transducer. Mode conversion will also occur that will convert the incident axially symmetric mode to a combination of axially symmetric and flexural modes. The size of the reflector, expressed in terms of percent of thinning, can be often inferred form the amplitude of the returning echo. In many cases, an information concerning the shape and location of a reflector can be extracted by distinguishing between the reflected axially symmetric and flexural modes.

The above presented short review of GWs includes evidence that explains why those waves are not commonly used in NDE applications. Their main advantage, which is the possibility of long range inspection of several meter long piping sections can be used at the price of their complex physical nature. This means that a great deal of know-how is required and extensive preparations have to be made before each new project is launched.

It is worth mentioning, however, that based on extensive theoretical studies in the UK and USA, commercial instruments for the GW NDE applications have been developed. In most practical studies concerned with the detection of pipe wall damage the investigators launched a GW on the pipe and then let it propagate a long distance along the pipe before the wave was detected and analyzed. Received signal strengths are generally found to be different for the defect-free and defective pipes. Thus comparing the received signal from a defect-free pipe one can conclude if the inspected pipe is defective.

3.2 Guided wave instruments

The UK company *Guided Ultrasonics Ltd.* claims that it is the world leader in the development and manufacture of GW inspection equipment and training. Their *Wavemaker Pipe Screening System* uses low frequency guided ultrasonic waves to inspect tens of meters of pipe from a single remote location. The *Wavemaker*, shown in Fig. 3.3 is designed for rapid screening of long lengths of pipe to detect external or internal corrosion as well as axial and circumferential cracking. The system is composed of three primary components, the transducer ring, the *Wavemaker G3* instrument, and the controlling computer.

Figure 3.3: The Wavemaker instrument from *Guided Ultrasonics Ltd.* (left) and multiple transducer ring (right).

Another UK company *Plant Integrity Ltd.* (a subsidiary of TWI Ltd) offers an instrument very similar to Wavemaker which they market as *Teletest Focus*®. *Teletest* is a battery operated, computer controlled unit provided with transducers in the form of air-inflated collars, see Fig. 3.4.

Southwest Research Institute (SwRI) in USA has developed the magnetostrictive sensor (MsS^{TM}) technology, [12]. The *MsS* instrument generates and detects guided waves electromagnetically in ferromagnetic materials. With *MsS* technology, a pulse of relatively low frequency GWs of a certain wave mode (typically, longitudinal with frequency under 200 kHz) is launched along a structure from a fixed test location. When the propagating guided-wave pulse encounters welds or defects some part of the waves is reflected back to the original test location where they can be detected by the same sensor and analyzed for structural conditions. Operation principle of the *SwRI*'s instrument is illustrated by Fig. 3.5.

Figure 3.4: The *Teletest* instrument from *Plant Integrity Ltd.*

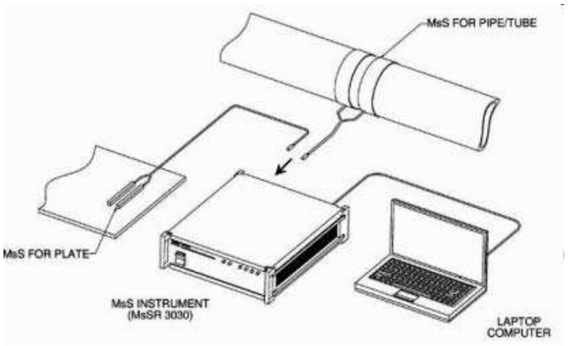


Figure 3.5: Operation principle of the MsS instrument from *SwRI*.

Figure 3.6: The MsSR3030 instrument from *Guided NDE LLC, USA*.

A commercial version of the MsS instrument the MsSR3030, shown in Fig. 3.6 is available from *Guided NDE LLC, USA*.

3.2.1 Guided wave transducers

A robust and efficient transducer, which does not require acoustic coupling is a vital part of an industrial GW test system. GWs are generated in pipes using either piezoelectric or magnetostrictive transducers.

Piezoelectric transducers available from the UK companies are in the form of rings or collars housing multiple piezoelectric elements arranged around tube circumference as shown in Fig. 3.7.

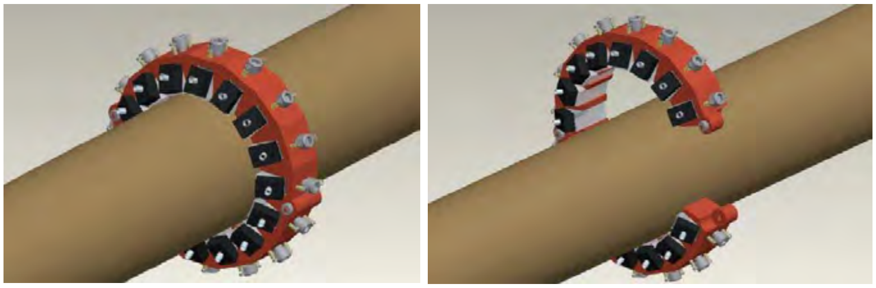


Figure 3.7: Transducer ring (reprinted from [13]).

Horizontal movement of the piezoelectric elements is transported to the pipe by hard pads that are mechanically pressed to the pipe surface using claws or air cushions. No coupling agent is required since low frequency (below 100kHz) torsional or longitudinal GWs are used for the test. A single transducer ring coupled to a tube generates GWs that propagate in both directions (left and right) along the tube. Multiple transducer rows in the rings, as shown in Fig. 3.8, are used to identify echoes from the reflectors located at each side of the ring and to separate different propagation modes. The signals from the transducers in various rows are summed coherently (phased) to enhance the desired side or mode.

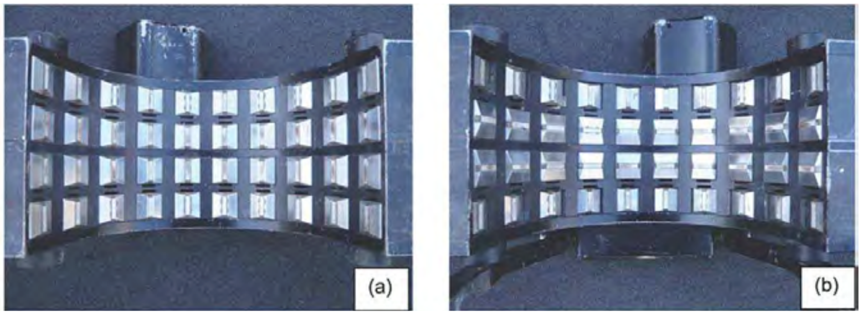


Figure 3.8: Example of transducer rings from *Guided Ultrasonics Ltd.* (a) longitudinal mode: all four rows used; (b) torsional mode: central two rows only used, outer rows pulled back (reprinted from [9]).

Electromagnetic acoustic transducers (EMAT) based on magnetostrictive effect can also be used for generation and detection of GWs in pipes. The EMATs used in practical applications operate on two physical principles: magnetostrictive effect for the generation, and inverse-magnetostrictive effect for the GW detection. The magnetostrictive effect refers to a small change in the physical dimensions of ferromagnetic materials (in the order of several parts per million in carbon steel) caused by externally applied magnetic field. The inverse-magnetostrictive effect refers to a change in the magnetic induction of ferromagnetic material caused by mechanical stress (or strain).

The *SwRI's* (MsS^{TM}) sensor for cylindrical objects (such as rod, tube, or pipe) takes the form of a ring-shaped winding that encircles inspected object as shown in the right part of Fig. 3.6. It is configured to apply a time-varying magnetic field to the material under test and to pick up changes of the magnetic induction in the material caused by the GW. The guided wave is generated in the ferromagnetic strip and coupled to the structure through epoxy bonding (in monitoring application) and dry coupling by pressure (in inspection application). In some applications, MsS probes are directly operable on structures made of ferrous materials, such as carbon steel or alloyed steel. Examples of direct operation are the inspections using longitudinal mode in pipe, tube, anchor rod, and bridge cable.

Recently, the EMAT approach was further developed by the IHI Southwest Technologies Inc and resulted in the MsT transducer based on the AC winding wrapped through the short dimension of the strip. The main advantage of the MsT transducer is that it is more powerful comparing with (MsS^{TM}) sensor (6 - 15 dB depending on the method of coupling, the transducer size and the operation frequency). Figure 3.9 illustrates the major difference in the conceptual design of the MsS sensor (left) and the MsT transducer (right).

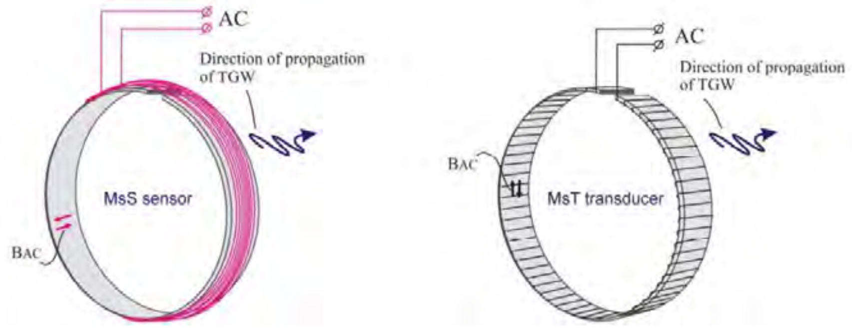


Figure 3.9: Designs of the EMAT senors from *SwRI*: MsS sensor (left) and the MsT transducer (right).

To operate the *MsS* or *MsT*, the material under testing needs to be in a magnetized state. This is achieved by applying a DC bias magnetic field to the material using either permanent magnet, electromagnet, or residual magnetization induced in the material. The DC bias magnetization is necessary to enhance the transduction efficiency of the sensor (from electrical to mechanical and vice versa) and to make the frequencies of the electrical signals and guided waves the same. The operating wave mode of the *MsS* is controlled by the relative alignment between the DC bias magnetic field and the time-varying magnetic field produced by the *MsS*. For longitudinal wave modes in cylindrical objects and Lamb wave modes in plates, a parallel alignment illustrated in Fig. 3.6, is used. *SwRI* has got a number of patents protecting their *MsS* configuration.

3.3 Pipe inspection using guided waves

Long range ultrasonic testing (LRUT) using guided wave has been successfully used for some years as a screening technique for corrosion in piping capable of detecting corrosion in pipes in different conditions, e.g., under insulation, road crossings, buried pipes and offshore risers. GW inspection is a remote inspection technique: in typical industrial pipe with general surface corrosion (e.g. in refinery or chemical plant) it is possible to test around 30 m in each direction from a single transducer location. Transducer ring located at one location on the pipe excites guided waves along the pipe and receives returning echoes from pipe features, such as welds, tees and defects. The test is therefore much quicker than conventional inspection that requires access to each test point to perform ultrasonic thickness gauging, see Fig. 3.10.

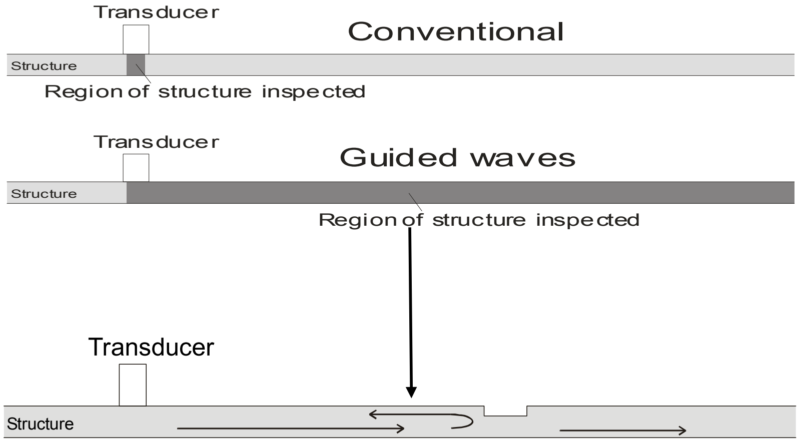


Figure 3.10: Comparison of a local pipe inspection using bulk waves with a long range inspection using guided waves. Guided waves propagate over a long distance and are reflected from welds or loss in wall thickness.

Modern instruments from the UK enable using two wave modes for tube inspection: the $T(0,1)$ and the $L(0,2)$, cf Fig. 3.1. The $T(0,1)$ mode, which is completely non-dispersive and exists at all frequencies, can be used at very low frequencies. This can be advantageous in the cases where the attenuation is very high, for instance, for burred pipes. Therefore, the Wavemaker system from *Guided Ultrasonics Ltd* primarily employs the $T(0,1)$ mode, though the $L(0,2)$ mode may be a better choice in some circumstances. The current model from *Plant Integrity Ltd* system, *Teletest Focus*®, uses both modes as a standard option.

Inspection results are presented in the form of graphs showing amplitudes of echoes received from each side of the transducer ring (A-scans).

Distance amplitude correction (DAC) curves corresponding to the attenuation in the inspected pipe are also plotted in the graph, as showni in Fig. 3.11. Signal processing technique has been developed that enable an approximate localization of a reflector at the tube circumference by appropriate summation of signals corresponding to different wave modes. This technique is based on the observation that wave modes differ in the magnitude and direction of displacements, details can be found in [14]. With this technique an unfolded 2D image of defect responses can be generated as shown in Fig. 3.12.

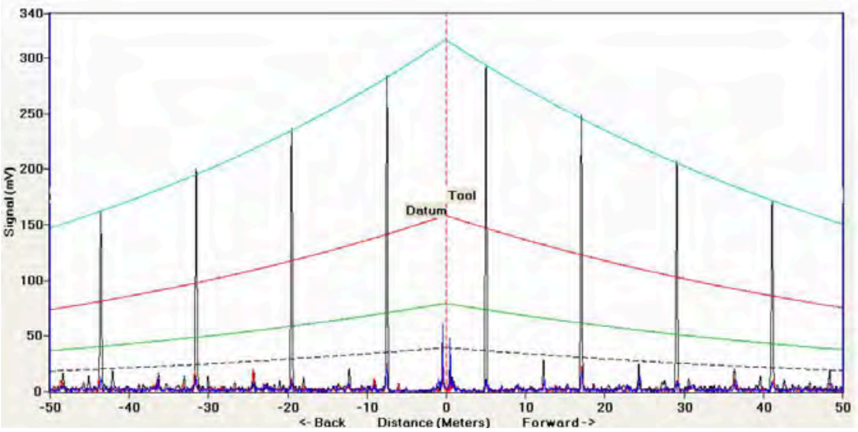


Figure 3.11: Amplitude graph illustrating result of GW inspection. Regular weld signals give highly repeatable amplitudes that can be used for calibration of the distance amplitude correction.

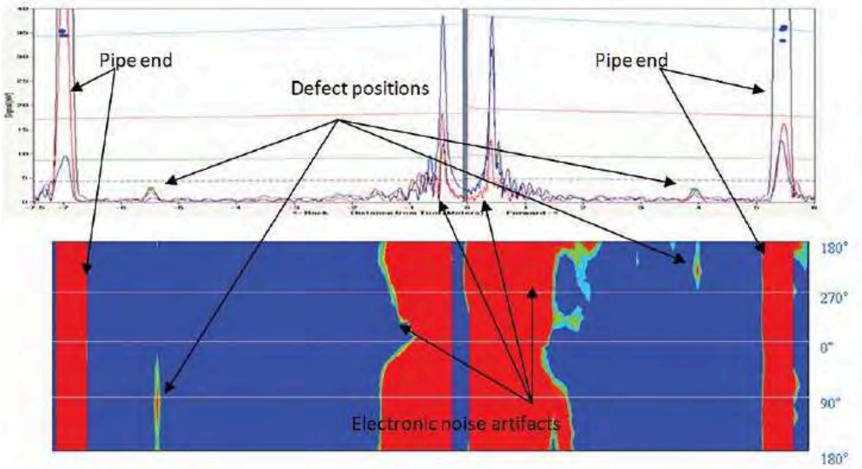


Figure 3.12: Amplitude graphs illustrating result of GW inspection. A-scan presentation of results showing distance from transducer against time (top). 2D B-scan presentation using the circumferential defect positioning method (bottom), (reprinted form [14]).

3.3.1 Focusing guided waves

Very recently, a more advanced defect characterization technique, using Flexural Mode Focusing (FMF) concept has been developed and practically implemented [14, 15]. This digital processing technique enables enhancement of the detected defects by focusing guided waves at certain distance from the transducer ring and a certain circumferential position. The FMF concept can be implemented using several rows of transducer sections shown in Fig. 3.13 and arranged in in a transducer collar of the type shown in Fig. 3.14. Theoretical presentation of the phased array focusing technique for guided waves in application to tubes can be found in [14, 16].

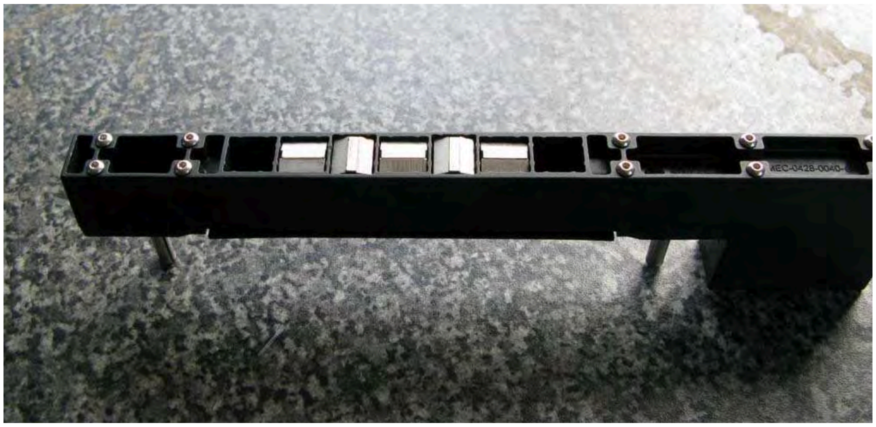


Figure 3.13: Example of a transducer section from *Plant Integrity Ltd.*

Figure 3.14: Example of a transducer collar from *Plant Integrity Ltd.*

The transducers are electronically divided into individual groups around the circumference that are capable of separating different wavemodes propagating in the inspected tube. A suitable combination of the wavemodes using the phased array FMF method can enhance a target (flaw) located at a given distance from the transducer collar at a certain angular location on tube. The factors required for focusing are calculated for each focal position using numerical modeling for each specific pipe diameter and thickness, see Fig. 3.15.

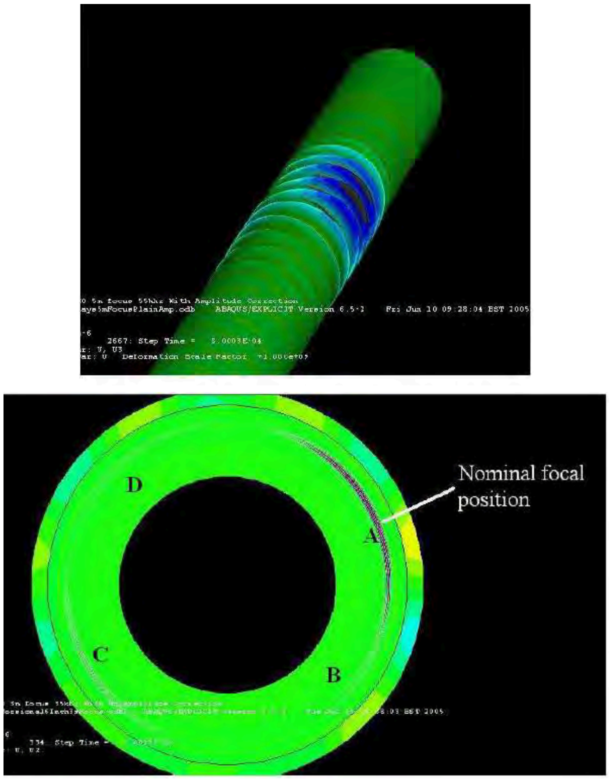


Figure 3.15: Numerical simulation of focusing result. Localized energy concentration at pipe length (left) and at its cross section (right) (reprinted from [15]).

The accuracy of defect size determination may be improved using the FMF technique; weak response from a local defect can be amplified in this way, as shown in Fig. 3.16.

The FMF focusing capability has been implemented in the *Teletest Focus®* instrument available from the *Plant Integrity Ltd.*

3.4 Capability of the GW LRUT

The GW technology is a NDE method suitable for inspecting pipelines for metal loss caused by mainly corrosion and erosion. The GW technology was originally developed for the inspection of corrosion under insulation in petrochemical plant piping but it is equally suited for application to pipelines including road crossings, bridge piers and poorly accessed pipework generally.

There are many advantages of using the GW pipe screening systems

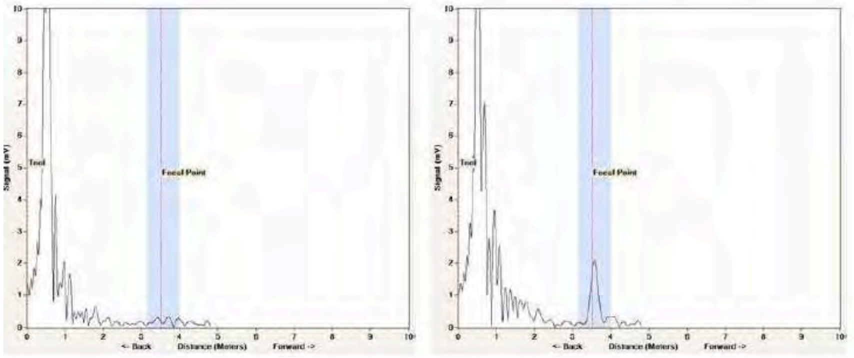


Figure 3.16: Signals received from a GW focusing test. Focal spot at other angular position than defect (left). Focal spot centered at defect (right) (reprinted from [15]).

for LRUT:

- Global inspection, 100% of the pipe can be rapidly inspected (within the diagnostic length of a test).
- Pulse echo type operation provides information on feature position and severity.
- Ultrasonic contact agent is not needed.
- Ability to detect external or internal metal loss and planar defects at long range (typically 10th of meters).
- Sophisticated analysis tools have been developed for interpretation of results.
- Sensitivity can be as good as 1% loss of cross-section in ideal conditions (but is typically set at 5%).

It should be noticed, however, that LRUT is a screening technique that cannot replace or eliminate conventional UT used for local inspection. When the pipe is accessible, it is frequently recommended that a detailed inspection (using complementary techniques) is performed at any identified corrosion areas. Among the LRUT's limitations the most important are:

- It cannot detect low volume defects such as cracks, pinholes.
- Detection result depends greatly on design and condition of the inspected pipeline and it can be greatly reduced by the presence of bitumen, plastic or cement coating, T-connections, bows, welded supports, etc.
- Transducer ring has a dead zone of approx. 0.5 m.
- It requires well-skilled operators.

Pipe diameters and thickness. GW instruments and transducer rings are today suitable for testing all pipe diameters (ANSI/ASME nominal bore) from 1.5 to 48 inches. Other sizes both smaller and larger (based upon standard pipe diameters) are available to order. Pipe wall thickness affects the frequency-thickness product, so it affects the dispersive behavior of the waves as a function of frequency. The most difficult to inspect is a small diameter, thick walled pipe.

Access. Access is required to 0.5m of bare pipe in order to mount the transducer ring. The ring also needs to be located at least 1m from the nearest girth weld.

Pipe material. Piezoelectric transducers operate properly on all materials such as steel, stainless steel, aluminum, plastic. Even tubes mad of high damping metal (e.g. centrifugally casted steel) can be successfully inspected due to the long wavelength of guided waves used (for details see Table 3.1).

Application	**Pipe type**	**Pipe material**	**Pipe size**	**Pipe temperature**
Standard	Seamless Longitudinally or spiral welded	Steel Other metals	1-72 inches	-40C to 180C (following specific procedures)
Advanced (custom made equipment or procedure)	Duplex	Plastic	½ to 110 inches	

Table 3.1: Material and pipe range that can be inspected using LRUT according to *Guided Ultrasonics Ltd.*

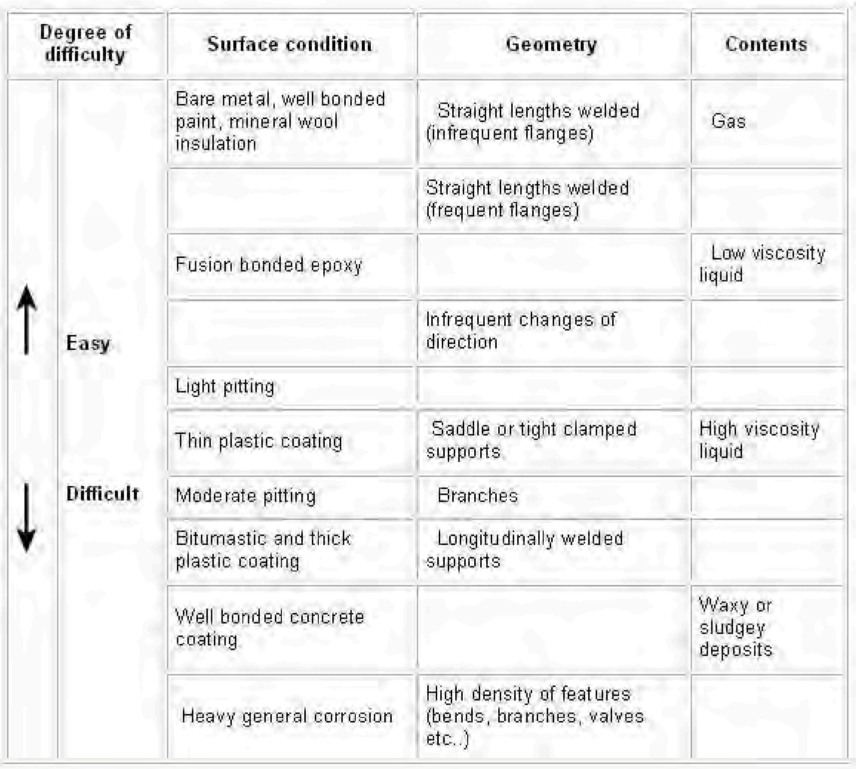
Pipe condition. LRUT works by detecting echoes from corroded regions of the pipe. Each corroded region, however, acts as a reflector in turn attenuating the intensity of the ultrasound traveling beyond it. On piping exhibiting general heavy corrosion regions, guided waves will be reflected from all the corrosion, effectively reducing the inspection range.

Temperatures. Pipe surface temperatures can be in the range of +5°C to +125°C.

Test range. Transducer ring sends guided waves in both sides from its location. Typically ranges of $\pm 30m$ are achieved. Under ideal conditions the range up to $\pm 180m$ was achieved. However, it can be less than 30 m, if conditions are unfavorable.

LRUT capability is summarized in Tables 3.2 and 3.3 .

Proven applications. LRUT instruments have been used commercially for almost a decade. There is a long list of their successful industrial applications including: road and wall crossings, insulated lines (mineral wool and polyurethane foam), buried pipelines, spirally welded pipe, stainless steel pipe, high temperature lines (<+125°C).



Degree of difficulty		Surface condition	Geometry	Contents
		Bare metal, well bonded paint, mineral wool insulation	Straight lengths welded (infrequent flanges)	Gas
			Straight lengths welded (frequent flanges)	
		Fusion bonded epoxy		Low viscosity liquid
↑	Easy		Infrequent changes of direction	
		Light pitting		
		Thin plastic coating	Saddle or tight clamped supports	High viscosity liquid
↓	Difficult	Moderate pitting	Branches	
		Bitumastic and thick plastic coating	Longitudinally welded supports	
		Well bonded concrete coating		Waxy or sludgey deposits
		Heavy general corrosion	High density of features (bends, branches, valves etc..)	

Table 3.2: Factors affecting *Wavemaker* performance according to *Guided Ultrasonics Ltd.*

Degree of difficulty		Surface condition	Geometry	Contents
		Bare metal		
		Smooth well bonded paint	Straight lengths	Gas
↑		Mineral wool insulation		
	Easy	Fusion bonded epoxy	Infrequent swept/bends	Low viscosity liquid
		Light pitting	Attachments/brackets	
	Difficult	Heavy pitting		High viscosity liquid
		Plastic coating		
↓		Bitumastic coating		
		Concrete coating	Branches	Waxy or sludgey deposits
			Many bends	

Table 3.3: Factors affecting *Teletest* performance according to *Plant Integrity Ltd.*

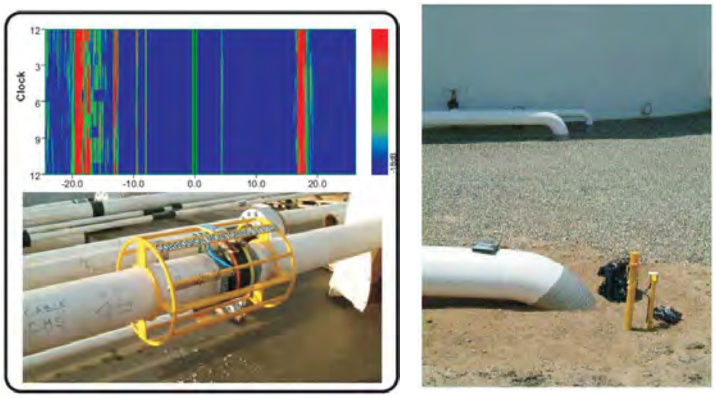
3.5 Pipe screening and monitoring using guided waves

A complete OLM system for piping systems should include two monitoring levels, a global and a local one. Monitoring at the global level should be capable of detecting abnormal states of the overall piping system. At the local level a number of units should be used for monitoring crucial error-prone parts of the system. The most feasible solution seems to be the GWs based OLM system, possibly integrated with vibration analysis. The respective sensor and hardware parts in such a system would have a common software for generating diagnosis and decisions concerning factors limiting the performance and service life of the entire pipeline.

Below, we present three examples of OLM systems, the first two are already commercially available and the third has been developed as a result of EU project *SAFE PIPES*.

3.5.1 Industrial OLM systems offered by *Guided Ultrasonics Ltd.* and by *Plant Integrity Ltd.*

Guided Ultrasonics Ltd. offers Permanently Installed Monitoring Systems (PIMS) for pipelines and piping systems. The company claims that PIMS have already been installed on around 100 buried pipes. One of them had been installed on a subsea pipe and then lifted back to platform (see Fig. 3.17a).



(a) (b)

Figure 3.17: PIMS unit installed on a subsea line and cabled back to platform and a C-scan produced by PIMS (a). PIMS connection point for buried section of pipeline mounted on yellow post (right).

PIMS transducers can be installed on the buried sections of pipelines between the ground entry points as shown in Fig. 3.17b.

PIMS transducers are encapsulated in polyurethane to protect them from most environments allowing results to be obtained from buried, subsea, sleeved or pipes in contaminated areas (see Figs 3.17 and 3.18).

The manufacturer claims that due to the high repeatability and time stability of the results PIMS are capable of detecting changes in pipe cross-section of less than 1%.

Figure 3.18: Encapsulated transducers used in PIMS.

Guided Ultrasonics Ltd. offers Permanently Installed Monitoring Systems (PIMS) for pipelines and piping systems. The company claims that PIMS have already been installed on around 100 buried pipes. One of them had been installed on a subsea pipe and then lifted back to platform (see Fig. 3.17a).

Very similar solutions, called *Teletest Perm-A-Mount*^{TM} are also offered by the *Plant Integrity Ltd.* An example of their permanently installed collars for LRUT is shown in Fig. 3.19. Perm-A-Mount is a low-cost, long-life tool installation intended for regular monitoring of piping systems in environmentally hostile, safety critical or difficult to access areas. An application of an installation developed in collaboration with Electric Power Research Institute EPRI on a underground 24" (610mm) diameter emergency cooling water pipe at a nuclear power plant is shown in Fig. 3.20.

Figure 3.19: Example of an encapsulated transducer ring developed by *Plant Integrity Ltd.*

Figure 3.20: Teletest installation on a 24” emergency cooling water pipe at a nuclear plant.

3.5.2 OLM system developed by *SwRI*

The *MsS* instruments from *SwRI* are commercially available from the American company *Guided NDE LLC*, San Antonio, TX. According to the company, the long-range guided wave monitoring using the *MsS* offers the following benefits:

- *MsS* probes are much cheaper than piezoelectric ring probes. (The cost of *MsS* probe for monitoring 24-inch-OD pipe is about \$150).
- The system is easy to install in various structures for monitoring. The probe is light (less than 0.5 kg for 24-inch-OD pipe), so that the installation work is easy. Only a 25-mm clearance is needed around the pipe in permanent monitoring (see Fig. 3.21).
- No limitation of pipe size exists because the MsS probes are directly made on site using ribbon cables (see Fig. 3.21).
- MsS probes work well at high temperature pipe up to 300°C.

The monitoring includes a few simple steps: when the *MsS* probe is permanently installed at a corrosion-sensitive region of the inspected structure the baseline data is obtained. Then the structure is periodically tested and the periodic data is compared with the baseline data to identify structural changes with time.

3.5.3 The OLM system developed by *IzFP-D* in Dresden

The complete system concept concept outlined in the introduction to this section has been proposed and developed within the EU project *SAFE PIPES*, see [17]. The global level of the OLM system proposed

Figure 3.21: Instalation of *MsS* on a pipeline (left). Magnetostrictive bands (middle). Encircling coil formed of a ribbon cable (right).

in the project employs a model-based vibration analysis. Its main objective is the detection of condition changes that influence the life-cycle of a piping system. The method is based on the fact that changes in system's stiffness and boundary conditions result in significant changes of the experimentally detectable natural frequencies in the range up to several tens of Hz as well as changes of the related mode shapes. At the global level, changes in the stiffness of supporting constructions should be detected, e.g., the loss of load bearing capacity of aged spring hangers, the increase of hysteresis with spring and constant hangers, the load rearrangement due to heating and cooling processes of piping systems or the failure of pipe clamps due to fatigued bolts.

For crucial error-prone parts of a structure, the global vibration monitoring can be efficiently supplemented by a number of locally installed units using GWs in the kHz frequency range. The GWs have a shorter active range but are more sensitive to smaller defects and thus, can serve as an early-warning system evoking an alarm long before the critical damage occurs.

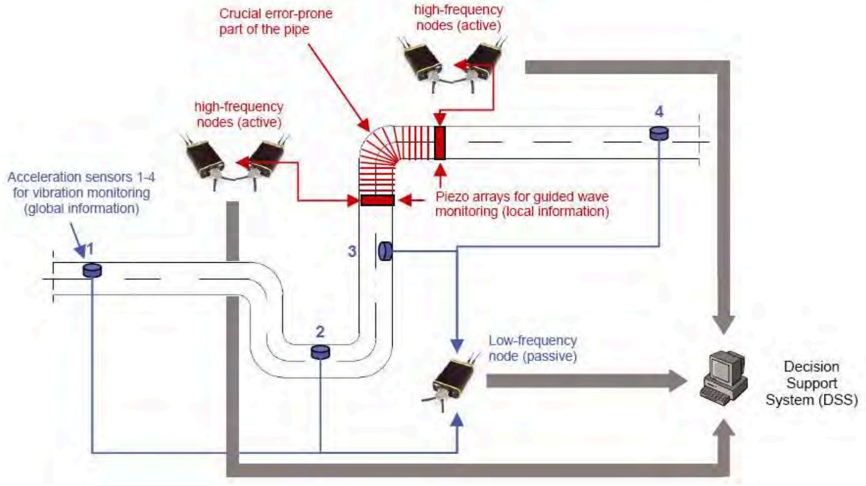


Figure 3.22: Combination of low- and high-frequency monitoring proposed by IZFP-D.

A schematic diagram of such system, developed and verified by the Fraunhofer-Institute for Nondestructive Testing *IzFP* in Dresden is shown in Fig. 3.22 (for details see [17]). The global part of the OLM system consists of four accelerometers for vibration monitoring. The local GW based system is installed on an elbow representing the error-prone part of the piping.

The preliminary results reported in [17] indicate that both global vibration monitoring and the local GW monitoring of industrial piping systems provide complementary information about the structure under investigation. While vibration monitoring is able to characterize the global condition of the structure due to supports and dampers, the guided wave module is able to find smaller defects, like corrosive material degradation, in crucial error-prone parts of the components.

The following information was received in April 2009 from Dr.-Ing. Frank Schubert from *IzFP* Dresden, concerning the SAFE PIPES system: *'The IzFP-D Institute is mainly responsible for the exploitation process of the core SAFE PIPES system. The system is ready for exploitation but the process is not far advanced up to now'.*

3.5.4 Summary

OLM of piping in industrial and nuclear systems using GW appears to be a feasible and mature technique. There are serious industrial companies offering commercial instruments and transducers for long-term monitoring of surface installed pipelines, as well as those buried underground and submersed in water.

Those installations consist of GW piezoelectric or magnetostrictive sensors mounted permanently on the pipelines and provided with connectors accessible on the surface. The specially designed test instruments are used for the acquisition of the GW waveforms that are later compared to the baseline acquired at a healthy state of the pipeline. The method is capable of detecting circular defects, such as, corrosion, wall-loss or cracks at the distance of several meters from the transducers.

Based on the available literature references we have identified the following main actors in this area:

Organization	Technology	Instrument
Guided Ultrasonics Ltd., UK	GW	*Wavemaker G3*
Plant Integrity Ltd., UK	GW	*Teletest Focus*®
Guided Wave NDE LLC, USA	GW	*MsSR3030*
IzFP-D Dresden	GW & vibr.	*unavailable*

Table 3.4: Organizations offering GW based OLM.

4

Experimental demonstrations of GE instruments

4.1 Demonstration of the *Wavemaker G3* operation

Performance of the *Wavemaker G3* was demonstrated in the demo-test performed at Imperial College in London (*Guided Ultrasonics Ltd.* is a spin-off company of the Imperial College). A pipe mockup, shown in Fig. 4.1, consisting a number of welded pipes, bends and flanges with total length approx. 16 m, was used in the test. The pipes' diameter was 3" and their wall thickness 3.2 mm. A transducer ring, matching the pipe diameter was attached to the mockup without using ultrasonic contact agent at approx. 4 m from its left end (see Fig. 4.2). The transducers mounted in two half-rings were connected to the *Wavemaker G3* instrument using two separate cables.

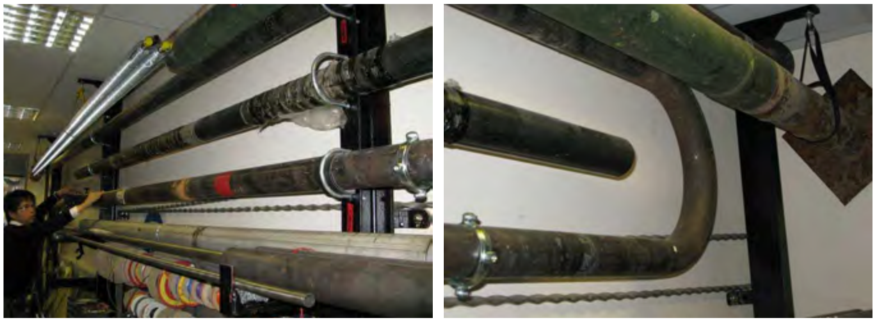


Figure 4.1: Pipe mockup used in the demo-test. Two long tubes welded of several parts (left). Curved part of the tube (right).

The mockup had a number of distinct features, such as welds, flanges, bends, an artificially made notch and a flat bottom hole. One of the tube sections had severely corroded zone and another section was covered with an outside bitumen layer (see Fig 4.3).

Directly after mounting the transducer the test could be started. The test was performed automatically by the instrument's software that controlled the electronic part of the Wavemaker. During the test the transducers were excited using sine bursts with variable frequencies and the received waves were acquired and processed.

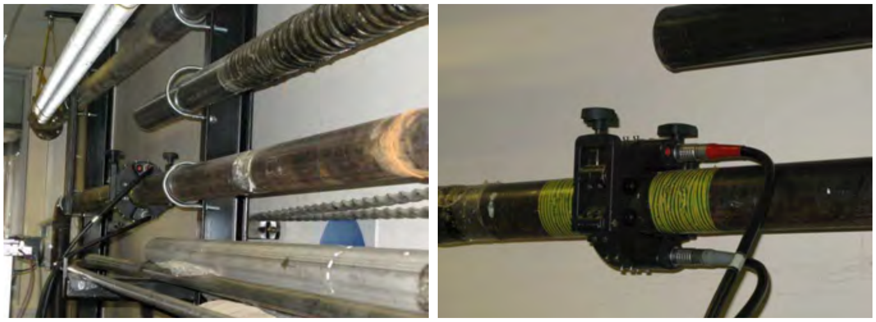
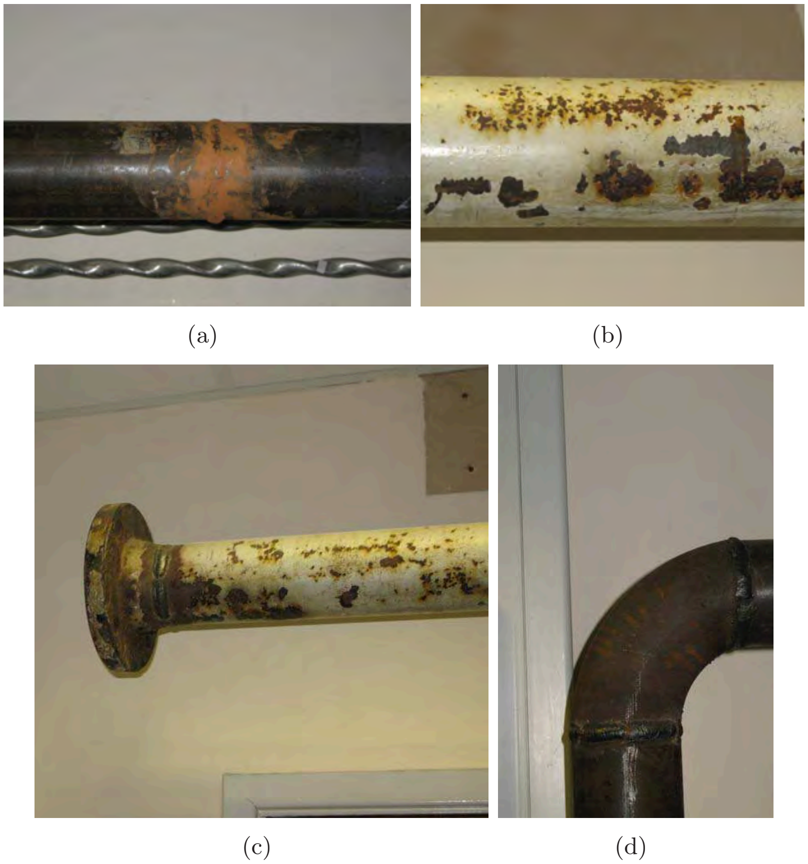


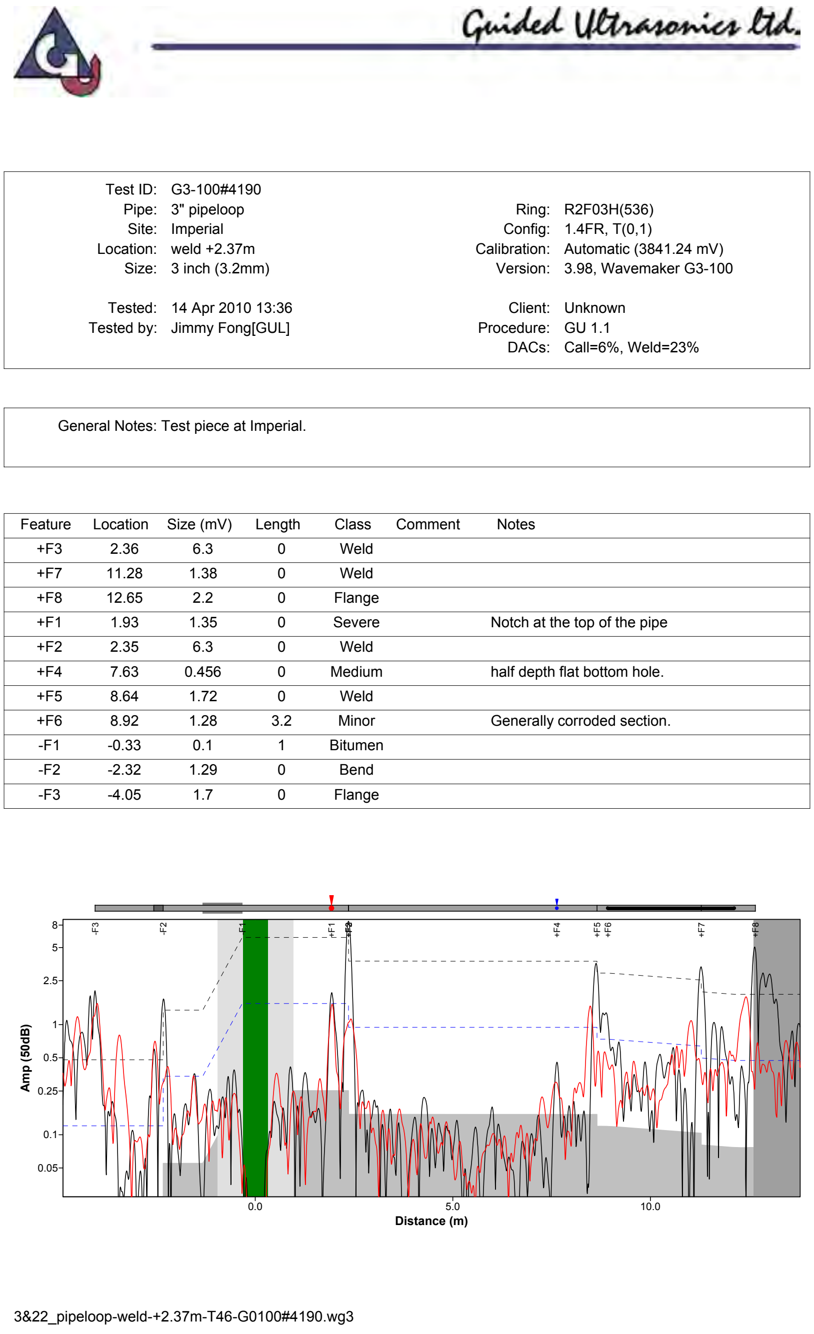
Figure 4.2: Transducer ring installed on the pipe mockup used in the demo-test (left). Transducer half-rings attached in mechanical contact with the tube wall (right).



(a) (b)

(c) (d)

Figure 4.3: Examples of the features detected in the demo-test. Weld (a), extensive corrosion damage (b), flange (c), and bend (d).



Guided Ultrasonics ltd.

Test ID:	G3-100#4190		
Pipe:	3" pipeloop	Ring:	R2F03H(536)
Site:	Imperial	Config:	1.4FR, T(0,1)
Location:	weld +2.37m	Calibration:	Automatic (3841.24 mV)
Size:	3 inch (3.2mm)	Version:	3.98, Wavemaker G3-100
Tested:	14 Apr 2010 13:36	Client:	Unknown
Tested by:	Jimmy Fong[GUL]	Procedure:	GU 1.1
		DACs:	Call=6%, Weld=23%

General Notes: Test piece at Imperial.

Feature	Location	Size (mV)	Length	Class	Comment	Notes
+F3	2.36	6.3	0	Weld		
+F7	11.28	1.38	0	Weld		
+F8	12.65	2.2	0	Flange		
+F1	1.93	1.35	0	Severe		Notch at the top of the pipe
+F2	2.35	6.3	0	Weld		
+F4	7.63	0.456	0	Medium		half depth flat bottom hole.
+F5	8.64	1.72	0	Weld		
+F6	8.92	1.28	3.2	Minor		Generally corroded section.
-F1	-0.33	0.1	1	Bitumen		
-F2	-2.32	1.29	0	Bend		
-F3	-4.05	1.7	0	Flange		

3&22_pipeloop-weld-+2.37m-T46-G0100#4190.wg3

Figure 4.4: Report from the demo-test generated by the *Wavemaker G3*.

During the processing the echoes arriving from both sides of the transducer ring are identified and their amplitude were plotted in the form of A-scan shown in Fig. 4.4. Transducer position in the A-scan is indicated with a green strip-line and the echoes arriving from both transducer sides are presented separately at each side of that line. The highest echoes originate from welds, which are strong circumferential reflectors. Those echoes are used for the calibration of the attenuation curve and wave velocity adjustment. Black and red solid lines in the A-scan show echoes received for different wave modes. The features detected by the software are marked by the symbol F with an index; negative sign indicates the features detected at the left side from the transducer. Harmful features are indicated with color arrows and the explanations of all recognized echoes are summarized in the table included in the test report, Fig. 4.4.

The most severe damage detected in the demo-test was the notch on the top of the pipe (*+F1*) and a half depth flat bottom hole (*+F4*). The size of the corroded area (*+F6*) was under the alarm level.

4.1.1 Summary of the Wavemaker test

Summarizing the demo-test, the Wavemaker G3 was capable of detecting welds and damage in the 3" pipe at the distance up to 12 m from the transducer ring. It should be noted, however, that the mockup was a well known object, which facilitated identification of the detected features. Generally, using guided wave technique requires rather high skills, an appropriate training is provided by the company in relation to the procurement of an instrument.

The staff of *Guided Ultrasonics Ltd.* as well as *Force Technology AB* declared their willingness to demonstrate their technique on an unknown object in Sweden.[1]

4.2 Demonstration of the *Teletest Focus*® operation

Performance of the *Teletest Focus*® was demonstrated in the demo-test performed at TWI in Great Abington, UK (*Plant Integrity Ltd.* is a spin-off company of the TWI). A pipe mockup with reference TL01, shown in Fig. 4.5 was inspected using the *Teletest Focus* instrument. The mockup consisted of welded pipeline with flange and bows that was placed on supports. The pipe diameter was 8" and its wall thickens 8.18 mm. The *Teletest Focus* instrument, shown in Fig. 4.6 that was located approx 18m from the flange on eastern end of line of the TL01 was set to inspect 50 m of the pipeline (18 m to the flange end and 32 m to the second bow.

There were two artificial defects made in the pipe shown in Fig. 4.7:

- 10mm drilled hole at a distance of approx. 13 m from the flange, and

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[1] Three Wavemaker instruments are in possession of Force Technology and two others have been purchased by INSPECTA.

- welded plate at the distance of approx. 28 m from the flange.

There was also a permount collar mounted on the pipe at the distance of approx. 5.5 m from the flange (see Fig. 4.6).

Teletest Focus® instrument was operated remotely from a laptop located at a distance of approx 30 m from the test collar. There was cable connection between the laptop and instrument. After setting the tube parameters, test frequencies and wave velocity were calculated by the Teletest software. Before the signals could be acquired the transducer collar was pressurized automatically from the instrument compressor to provide mechanical contact between the transducer segments and the inspected tube.

Figure 4.5: TL01 pipeline tested in the TWI demo-test (left). Flange on eastern end of line (upper right) and one od the supports (lower right).

In the first step after acquiring the data tube attenuation was adjusted using large echoes from tube welds (signal amplitude drops with several dBs after each weld). Then the echoes from tube supports were identified manually at the laptop's screen shown in Fig. 4.8. When this was done the initial part of the test was completed and the schematic diagram shown in Fig. 4.9 was generated. Besides echoes from the welds and supports there are two indications in the diagram marked as Cat.1 and Cat.1 (green dots in Fig. 4.9). Cat.1 denotes for indications of category 1, with an amplitude exceeding the black dotted line indicating threshold level.

In the second step two separate wave modes, longitudinal and torsional, were analyzed. The diagram shown in Fig. 4.9 was generated, where echoes of both modes are plotted in different colors together with the 2D scan indicating the extend of defects on the tube circumference.

Teletest's focusing ability was demonstrated by pointing on the in-

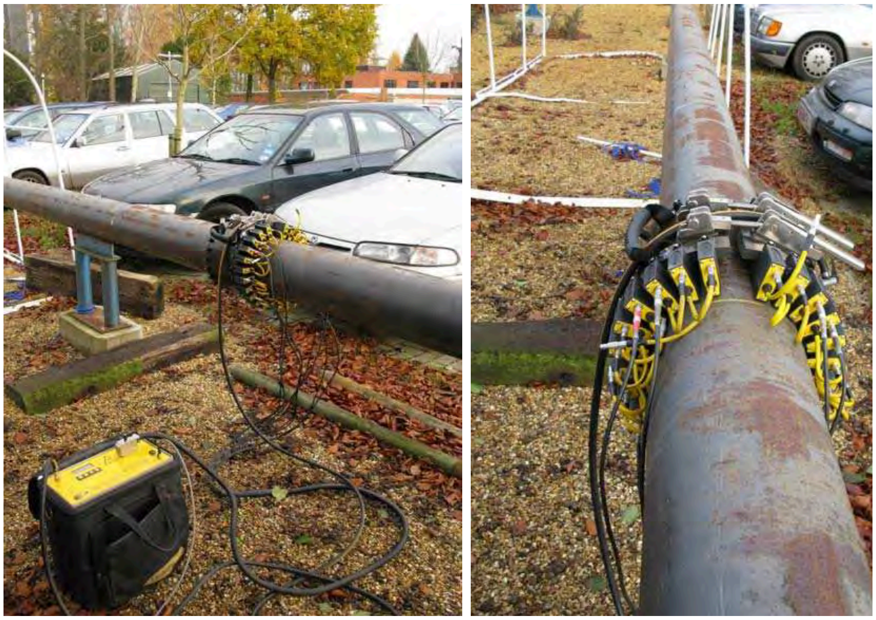
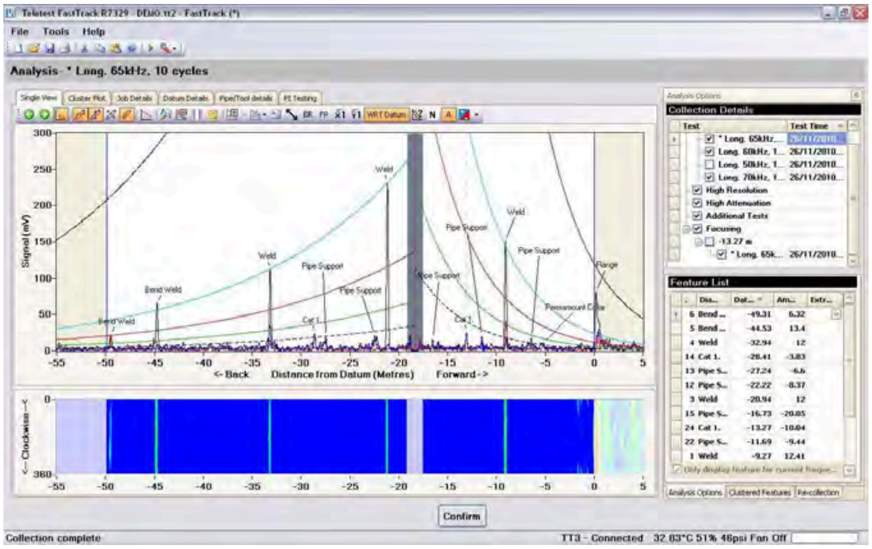


Figure 4.6: *Teletest Focus* instrument and the transducer ring installed on the pipe.

Figure 4.7: Artificial defects in TL01 pipeline tested in the TWI demo-test. Drilled hole in the upper part of tube (left). Welded plate on the lower part of tube (upper right) and a permaunt transducer collar. (lower right).



Analysis- * Long. 65kHz, 10 cycles

Collection Details

Test	Test Time
☑ * Long. 65kHz...	26/11/2010...
☑ Long. 60kHz, 1...	26/11/2010...
☐ Long. 50kHz, 1...	26/11/2010...
☑ Long. 70kHz, 1...	26/11/2010...
☑ High Resolution	
☑ High Attenuation	
☑ Additional Tests	
☑ Focusing	
☐ -13.27 m	
☑ * Long. 65k...	26/11/2010...

Feature List

Dis...	Dat...	Am...	Extr...
6 Bend ...	-49.31	6.32	
5 Bend ...	-44.53	13.4	
4 Weld	-32.94	12	
14 Cat 1.	-28.41	-3.83	
13 Pipe S...	-27.24	-6.6	
12 Pipe S...	-22.22	-8.37	
3 Weld	-20.94	12	
15 Pipe S...	-16.73	-20.05	
24 Cat 1.	-13.27	-10.04	
22 Pipe S...	-11.69	-9.44	
1 Weld	-9.27	12.41	

☑ Only display features for current freque...

Collection complete

TT3 - Connected 32.83°C 51% 46psi Fan Off

Figure 4.8: Screenshot of the *Teletest Focus* display during the test.

dication Cat.1 at the distance of -13.27 m (gray dotted line in Fig. 4.9). The result of focusing is shown symbolically in the lower part of Fig. 4.9).

4.2.1 Summary of the Teletest test

The *Teletest Focus*® was capable of detecting welds and damage in the 8" pipe at the distance up to 32 m from the transducer ring. Artificial defects in the form of drilled hole and welded plate were detected at a distance of 13 m from the transducer collar and classified as Cat. 1 indications. Pipeline supports were clearly visible in the generated A-scans. Focusing ability using different modes was also successfully demonstrated.

It should be noted, however, that similarly to the Wavemaker test, the mockup was well known to the operator, which facilitated identification of the detected features. Generally, using guided wave technique requires rather high skills, an appropriate training is provided by the company in relation to the procurement of an instrument.

The staff of *Plant Integrity Ltd.* declared their willingness to demonstrate their technique at one of the Swedish nuclear power plants.[2]

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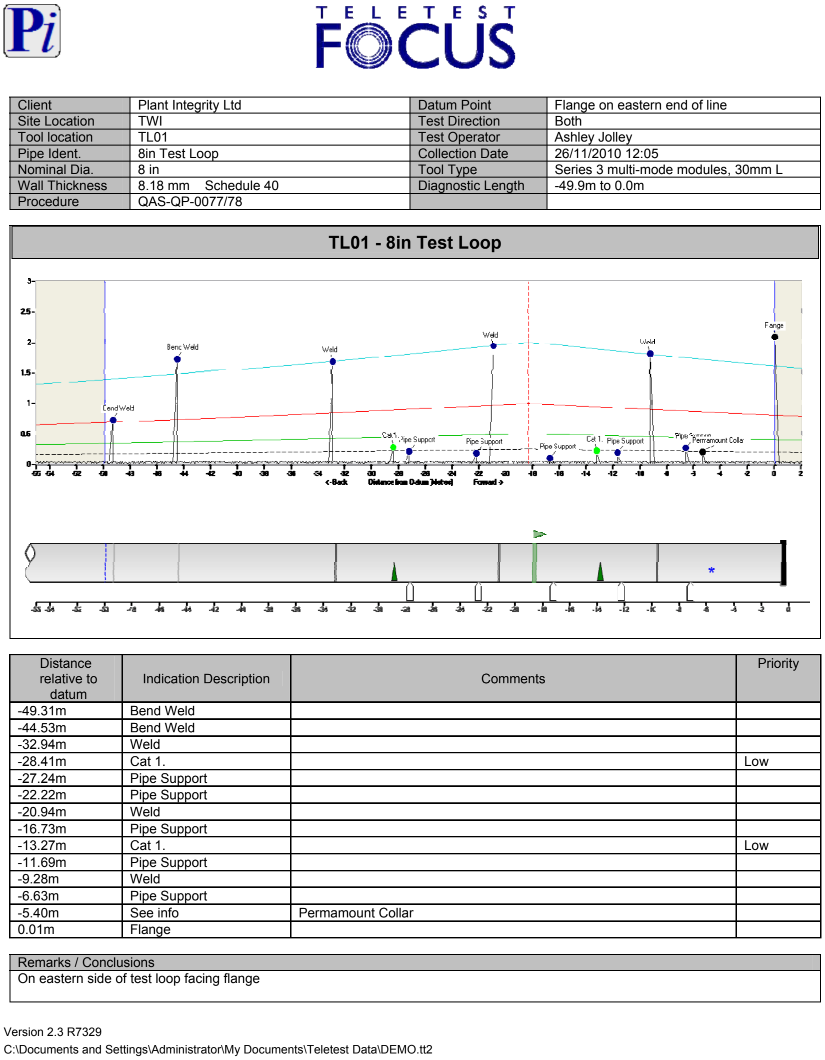
[2] According to Plant Integration Ltd no *Teletest Focus*® instruments were sold in Sweden



Client	Plant Integrity Ltd	Datum Point	Flange on eastern end of line
Site Location	TWI	Test Direction	Both
Tool location	TL01	Test Operator	Ashley Jolley
Pipe Ident.	8in Test Loop	Collection Date	26/11/2010 12:05
Nominal Dia.	8 in	Tool Type	Series 3 multi-mode modules, 30mm L
Wall Thickness	8.18 mm Schedule 40	Diagnostic Length	-49.9m to 0.0m
Procedure	QAS-QP-0077/78		

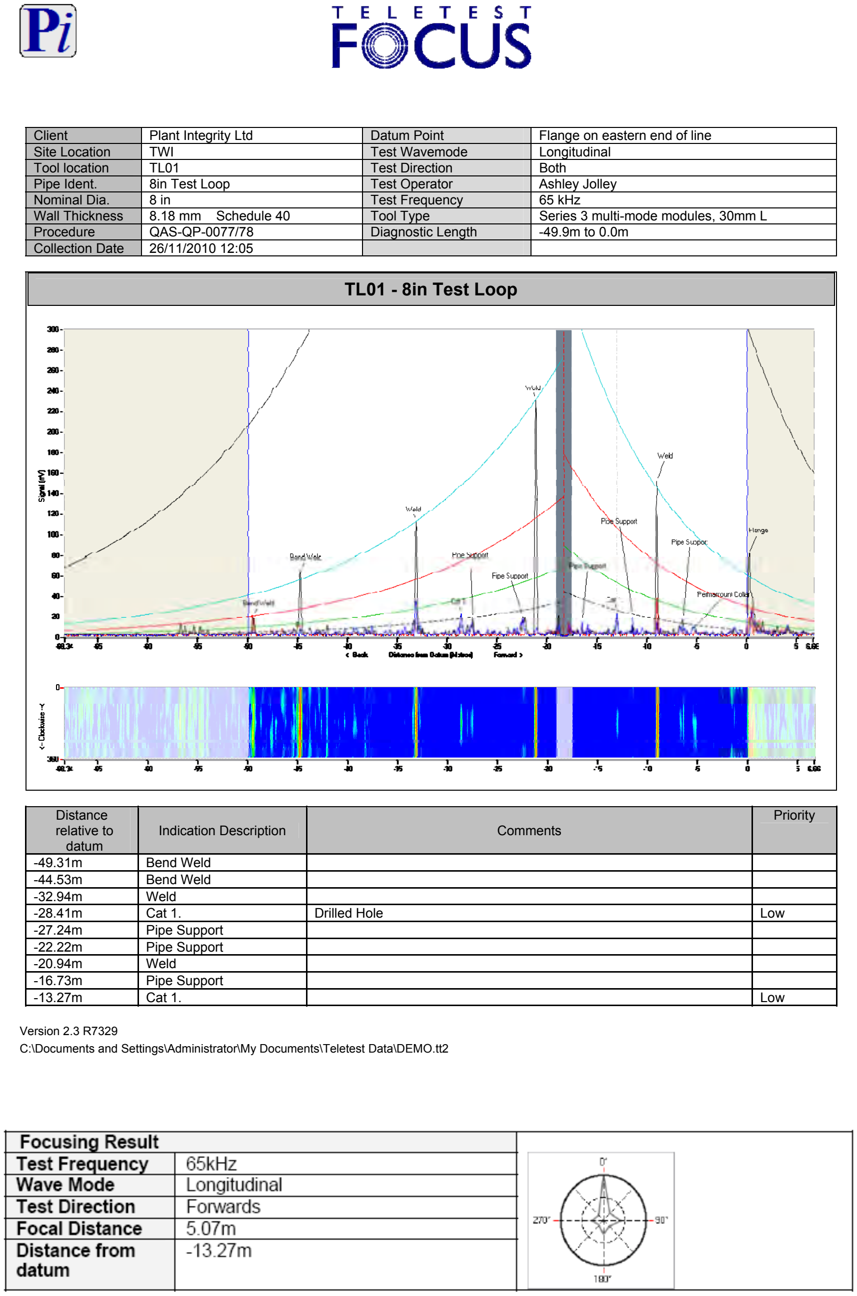
TL01 - 8in Test Loop

Distance relative to datum	Indication Description	Comments	Priority
-49.31m	Bend Weld		
-44.53m	Bend Weld		
-32.94m	Weld		
-28.41m	Cat 1.		Low
-27.24m	Pipe Support		
-22.22m	Pipe Support		
-20.94m	Weld		
-16.73m	Pipe Support		
-13.27m	Cat 1.		Low
-11.69m	Pipe Support		
-9.28m	Weld		
-6.63m	Pipe Support		
-5.40m	See info	Permamount Collar	
0.01m	Flange		

Remarks / Conclusions
On eastern side of test loop facing flange

Version 2.3 R7329
C:\Documents and Settings\Administrator\My Documents\Teletest Data\DEMO.tt2

Figure 4.9: Front page of the *Teletest Focus* report.



TELETEST FOCUS

Client	Plant Integrity Ltd	Datum Point	Flange on eastern end of line
Site Location	TWI	Test Wavemode	Longitudinal
Tool location	TL01	Test Direction	Both
Pipe Ident.	8in Test Loop	Test Operator	Ashley Jolley
Nominal Dia.	8 in	Test Frequency	65 kHz
Wall Thickness	8.18 mm Schedule 40	Tool Type	Series 3 multi-mode modules, 30mm L
Procedure	QAS-QP-0077/78	Diagnostic Length	-49.9m to 0.0m
Collection Date	26/11/2010 12:05		

TL01 - 8in Test Loop

Distance relative to datum	Indication Description	Comments	Priority
-49.31m	Bend Weld		
-44.53m	Bend Weld		
-32.94m	Weld		
-28.41m	Cat 1.	Drilled Hole	Low
-27.24m	Pipe Support		
-22.22m	Pipe Support		
-20.94m	Weld		
-16.73m	Pipe Support		
-13.27m	Cat 1.		Low

Version 2.3 R7329
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Focusing Result	
Test Frequency	65kHz
Wave Mode	Longitudinal
Test Direction	Forwards
Focal Distance	5.07m
Distance from datum	-13.27m

Figure 4.10: Second page of the *Teletest Focus* report. Note focusing result on Cat.1 indicating position of the hole drilled in the tube.

Bibliography

[1] On-line monitoring for improving performance of nuclear power plants, part 2: Process and component monitoring and diagnostics. Technical Report IAEA NP-T-1.2, International Atomic Energy Agency, 2008.

[2] Implementation strategies and tools for condition based maintenance at nuclear power plants. Technical Report IAEA-TECDOC-1551, International Atomic Energy Agency, 2007.

[3] N. Nakagawa, F. Inanc, A. A. Frishman, R. B. Thompson1, W. R. Junker, F. H. Ruddy, A. R. Dulloo, J. M. Beatty, and N. G. Arlia. On-line health monitoring for advanced reactor designs. *Fourth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls and Human-Machine Interface Technologies (NPIC&HMIT 2004), Columbus, Ohio*, 2004.

[4] N. Nakagawa, F. Inanc, A. A. Frishman, R. B. Thompson1, W. R. Junker, F. H. Ruddy, A. R. Dulloo, J. M. Beatty, and N. G. Arlia. On-line nde and structural health monitoring for advanced reactors. *Key Engineering Materials*, 321-323:234 – 39, 2006.

[5] J.W. Hines and E. Davis. Lessons learned from the U.S. nuclear power plant on-line monitoring programs. *Progress in Nuclear Energy*, 46(3-4):176 – 89, 2005.

[6] J.W. Hines and R. E. Uhring. Trends in computational intelligence in nuclear engineering. *Progress in Nuclear Energy*, 46(3-4):167 – 75, 2005.

[7] L. J. Bond, R.J. Meador, R.J. Jarrell, D.R. Sisk, T.M. Koehler, D.D. Hatley, K.S. Watkins, J. Chai, and W. Kim. On-line intelligent self-diagnostic monitoring system for next generation nuclear power plants. Technical Report PNNL-14304, Pacific Northwest National Laboratory (PNNL), 2003.

[8] F. H. Ruddy, A. R. Dulloo, J. G. Seidel, B. Petrovic, and W. R. Junker. Reactor coolant pump performance monitoring in IRIS using nitrogen-16 measurements. *Fourth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls and Human-Machine Interface Technologies (NPIC&HMIT 2004), Columbus, Ohio*, 2004.

[9] D. N. Alleyne, T. Vogt, and P. Cawley. The choice of torsional or longitudinal excitation in guided wave pipe inspection. *Insight: Non-Destructive Testing and Condition Monitoring*, 51(7):373 – 77, 2009.

[10] F. Schubert, B. Frankenstein, K.-J. Froehlich, and M. Kuettner. Guided wave based structural health monitoring of piping systems. *Proc. SPIE - Int. Soc. Opt. Eng. (USA)*, 6532, 2007.

[11] T. Hayashi and J.L. Rose. Guided wave simulation and visualization by a semianalytical finite element method. *Materials Evaluation*, pages 75 – 79, January 2003.

[12] Kwun. H., S.-Y. Kim, and G.M. Light. Magnetostrictive sensor guided-wave probes for structural health monitoring of pipelines and pressure vessels. *Proceedings of the 5th International Workshop on Structural Health Monitoring 2005*, pages 694 – 701, 2005.

[13] J.L. Rose, Jing Mu, Jia Hua, and S. Kenefick. Guided wave testing of burried pipe. *Materials Evaluation*, pages 1387 – 91, December 2009.

[14] P. Catton, P. Mudge, and W. Balachandran. Advances in defect characterisation using long-range ultrasonic testing of pipes. *Insight: Non-Destructive Testing and Condition Monitoring*, 50(9):480 – 84, 2008.

[15] P. J. Mudge and P. Catton. Quantification of defect size from long range guided wave ultrasonic tests on pipes. In D.O. Thompson and D.E. Chimenti, editors, *Annual Review of Progress in QNDE 2007*.

[16] Wei Luo and J.L. Rose. Phased array focusing with guided waves in a viscoelastic coated hollow cylinder. *J. Acoust. Soc. Am.*, 121(4):1945 – 91, April 2007.

[17] F. Schubert, B. Frankenstein, K.-J. Froehlich, and M. Kuettner. A multi-channel SHM framework for industrial piping systemns based on guided elastic waves and vibrations. *Proc. of the Fourth European Workshop on Structural Health Monitoring 2008*, pages 953 – 62, 2008.

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The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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