RESEARCH AND DEVELOPMENT ACTIVITIES IN QUALITY ASSURANCE OF WELDED COMPONENTS AT INDIRA GANDHI CENTRE FOR ATOMIC RESEARCH,
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1. INTRODUCTION

Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, India, is engaged in multidisciplinary R&D efforts in welding technology relevant to Fast Breeder Reactor Programme of the Country. R&D efforts initiated in the year 1974 have matured into groups with strong scientific and technological base in areas of design, processes and characterisation through complementary use of destructive and non-destructive test techniques. Dr. Placid Rodriguez, Head, Metallurgy and Materials Programme, delivered Keith Hartley Memorial Lecture on Welding Research and Development for the Fast Breeder Reactor Programme during the 20th National Welding Seminar 1986 at Madras. The manuscript of the lecture was latter published in Indian Welding Journal [1]. The paper by Dr. Rodriguez gives comprehensive information about our efforts at IGCAR, Kalpakkam, in the area of welding technology. The present paper is restricted in scope and aims to describe R&D efforts at IGCAR in the areas of quality assurance and non-destructive evaluation of weldments. Though the work is related mainly to the nuclear programme, the results are relevant to many of those industries such as petrochemical, space, defence etc. which are interested in achieving high levels of quality (preservice and in-service) through non-destructive evaluation (NDE). The paper attempts to generate awareness among the welding technologists and NDT professionals regarding the capabilities of NDE techniques for high sensitivity and reliable examination and evaluation of weldments.

Welding is an important means to fabricate structures and components, from a wide spectrum of materials, of varied complexity and thickness ranges. Welds can be designed and made with properties appropriate for service conditions. The requisite quality can be achieved based on adequate and appropriate testing, quality control and quality assurance of welds.

It is to be realised that no weld is completely perfect. Welds are small castings except that weld metal often cools much more rapidly. Microstructural variations due to heat input and thermal stresses may lead to deterioration of the material. The deterioration depends primarily on the material and welding processes and qualification of welding personnel.

Quality assurance in welded components is a specialised area meriting R&D efforts of basic and applied nature. Defects beyond permissible levels can be the cause of premature failure of the weld in service. Hence the need for appropriate R&D in testing of welded components becomes essential and crucial.

2. IMPORTANCE OF QUALITY ASSURANCE OF WELDED STRUCTURES AND COMPONENTS

Quality Assurance (QA) is a term related to the efforts of manufacturer in order to create confidence with the client that the manufactured product will perform intended service satisfactorily over the period of designed life. Thus, quality assurance ensures fitness-for-purpose and reliability of the component or plant on cost-effective basis. Planning, sequence of testing, evaluation of results and recording are recognised important aspects of quality assurance. Quality assurance of critical components requires multidisciplinary approach and the exploitation of developments in related disciplines such as materials, instrumentation, robotics and computers. New techniques and developments must be carefully analysed for advantageous implementation for quality assurance programmes. Quality assurance has considerable scope for contributions to improved design, reduction in cost of future plants, enhancing evaluation performance and enabling good failure analysis. However, these benefits of QA programmes are exploited to a limited extent only, in our country. Work related to quality assurance at Indira Gandhi Centre for Atomic

Research is significantly important as conscious efforts are made to improve the existing techniques, evolve methodical application of available experience and introduce new techniques for assessment of quality for enhanced safety and reliability.

Fast Breeder Test Reactor (FBTR) at IGCAR, Kalpakkam, is a sodium cooled reactor and uses uranium-plutonium carbide fuel. Various components of the reactor required different levels of QA. The stringent requirements were arrived at strictly as per the performance requirements: Fuel pins and sub-assemblies required application of complimentary techniques for ensuring fitness-for-purpose.

In pursuance of QA in the fabrication of welded structures and components for Fast Breeder Test Reactor the following QA programme was implemented.

1. Approval of detailed design
2. Approval of raw materials and consumables
3. Calibration of testing equipment
4. Qualification of welding procedures and welderperformance (through non-destructive and destructive testing)
5. Quality control during production welding (control of welding process, dimensional control, etc.)
6. Non-destructive testing of welds
7. Quality control during post-weld heat treatment
8. Non-destructive testing after post-weld heat treatment
9. Hydraulic pressure testing or load testing of welded structures
10. Leak testing of welds
11. Documentation.

The details of this elaborate but essential QA programme are reported in a comprehensive manner [2].

Subsequent sections highlight the importance of NDE techniques in quality assurance (during preservice and in-service inspection) of welded components. A few select case studies from the work done at Indira Gandhi Centre for Atomic Research are described to focus attention of concerned professionals in the Country and abroad regarding the possibilities of current technology levels in NDE. It is hoped that exploitation of the work mentioned in this paper would lead to more applications in other industries.

3. IMPORTANCE OF NON-DESTRUCTIVE TESTING (NDT)

NDT methods are required to obtain necessary information for evaluating welds which are to be placed in service. The primary advantage of the NDT methods is that the product can be examined without destroying its usefulness. Non-destructive evaluation can be conveniently applied for ensuring that the weldments are fit for the purpose.

Quality characteristics of welds such as cracks, inclusions, porosities, lack of penetration, lack of fusion, lack of bond, undercut, alloy identification, alloy composition, etc. can be evaluated by NDT methods. Present range of NDT techniques and evolved capabilities of NDT techniques promise evaluation of weld joints for the most stringent service condition. However, proper choice of materials, welding processes, etc. is a necessity to ensure building the quality in the product. Choice of a technique or complementary techniques should be carefully selected to ensure structural integrity during designed life of welded structures.

4. R&D IN NDE AT IGCAR, KALPAKKAM

4.1. Radiography

It is well known that source size contributes to radiographic quality, influences the geometry of the inspection and sets resolution and image definition limits. In microfocal x-ray systems, the focal spot size is less than 100 µm compared to the focal spots of 0.4-5 mm in conventional units. This leads to the possibility of projective magnification and thus observation of finer structural details and microdefects. Further, a microfocal radiograph has better resolution and contrast due to reduced scatter radiation from the sample. It also provides a uniform depth of focus compared to conventional radiographs. Outlined below are some of the examinations carried out on welded samples using the microfocal unit at the Division for PIE & NDT Development (DPEND), IGCAR.

4.1.1 Examination of tube to tubesheet welds of heat exchanger assembly of Prototype Fast Breeder Reactor[3]

This work pertains to the development of welding method and quality assurance procedures and techniques for the integrity of the tube to tubesheet welds of the steam generator of Prototype Fast Breeder Reactor (PFBR). This joint is very critical and needs a high quality non-destructive testing method to detect the defects such as cracks and porosities since any leak of sodium into water can lead to an explosive reaction. The configuration of this assembly is such that conventional radiography is not suitable as the desired position for the x-ray source is not accessible. Gamma radiography using isotopic sources as thulium could be done but the resultant resolution would be poor. Microfocal radiography with rod anode is the only option for the NDE of such welds.

A backward throw probe with a diameter of 10mm and with a beam spread of 55° x 360° was inserted into the tubesheet and the radiography of the weld was carried out with a projective magnification of 3x. Typical radiographic parameters employed are given in Table 1.

Table 1. Typical Radiographic Parameters

Wall thickness of the tube	: 2.3 mm
Radiographic technique	: Single Wall Single Image
Source to Object Distance	: 2 mm
Object to Film Distance	: 6 mm
Film	: AGFA Geveart D2
Penetrameter	: Wire type
Voltage applied	: 80 KV
Exposure	: 100 micro ampere minutes
Processing	: Manual, Standard
Projective magnification	: 3X
Sensitivity achieved	: A 30 - 40 micrometer diameter steel wire could be seen
Defects observed	: Porosities, Undercuts

Results on the trial welds of these tubes have shown that it is possible to resolve a 30 - 40 micron diameter steel wire placed on the inside of the tube. This corresponds to 1.3% - 1.6% of the wall thickness of the tube. Radiographs taken during the developmental stage of the orbital welding method indicated the following features :

i) Too many minute gas porosities, the extent of which need to be reduced by reducing the pressure of the inert gas used

ii) Weld joint line wavy due to non-perfect tie-up

iii) Uneven reinforcements

iv) Significant weld ripple

These observations were communicated to the designers for suitable corrective actions. This work has shown how microfocal radiography can be effectively used in coordination with the welding method for ensuring quality of heat exchanger assembly.

4.1.2 Radiography of endplug welds of the fuel pins of Fast Breeder Test Reactor [3]

This is a typical case demanding better resolution than achievable by conventional radiography. Thus microfocal radiography was employed. For the examination of end plug welds of thin walled cylindrical elements containing nuclear fuel pellets, it was necessary to provide a shape correction block. A hollow cylindrical shape correction block was designed in which upto ten end plug welds could be radiographed. A radial probe having a beam spread of 30° x 360° was used. A 50 μm diameter steel wire could be resolved through 5.1 mm of steel which corresponds to 13.5% wall thickness of FBTR cladding tube. The definition achieved by this technique is twice compared to conventional radiography. The sensitivity also compares well with the sensitivities achieved by eddy current and ultrasonic test methods employed to assess cladding tubes.

4.1.3 Examination of endplug weld of neutron source pin of FBTR [4]

One of the frequently encountered problems in radiography as a post-irradiation examination technique is gamma fogging. Examination of radioactive materials such as endplug welds of neutron source pins, irradiated fuel elements, etc. are often complicated by the fact that the film is exposed to the gamma rays from within the material. The effect of these gamma rays are similar to and in addition to scattered radiations from the specimen.

Radiography of the endplug weld of the neutron source pin for FBTR was carried out in hot cells at DPEND. Since the activity of the pin was very high (≃ 4.8 x 10^{13} Bacquerels), precautions were taken to minimise the fogging due to gamma radiations from antimonyoxide pellets as far as possible. A special lead enclosure was made, around the intercell transfer port, to provide shielding. This had a narrow opening for the source pin to project out. The source pin was kept in the adjacent cell with a provision to bring the endplug weld of the pin out of the opening only when the exposure is to be taken. To ensure alignment of the region to be radiographed with the source and the film, the shape correction block was provided with an end stopper. A 420 kv x-ray source was employed. The x-ray source was kept just above the neutron source pin. The entire operation of radiography was carried out remotely. To reduce film fogging, a very short exposure time of the order of 15 seconds and a fine grained slow film (D2) was used. The exposure parameters employed were 390 KV and 10 mA for 15 seconds.

However, due to the high strength of the source, the fogging intensity was quite significant. Since the endplug region of the source pin was radiographed, the fogging encountered was non-uniform. Background subtraction and filtering, was attempted. There was a significant improvement in the image quality. A sensitivity of 2 - 4 T was obtained.

4.2. In-situ Metallography

Metallographic examination is normally classified as a destructive test technique however this can be treated as a non-destructive technique by use of in-situ metallographic examination methods. In this method, an area of interest is selected on the surface of the object to be examined and this area is then subjected to grinding, polishing and etching, with a view to do microscopic examination to study the microstructural features. The object may be a pipe line, a vessel, or a weld in a component or any other object from which a sample can not be cut. As the preparation often takes place on an actual component far from the laboratory, this part of the preparation utilises portable apparatus. The apparatus consists of flexible shaft grinders used for grinding and polishing with suitable interchangeable wheels. The polished surfaces are etched using chemical etchants or portable electrochemical etching apparatus. A small light weight portable microscope is used to examine the etched surfaces directly. In some cases where direct examination is not feasible due to site constraints or the disposition of the object to be examined, replications technique is used. A combination of plastic tape and chemicals such as cellulose acetate tapes with acetone is used for preparation of the replica. The plastic strip is softened with acetone solvent and is applied over the etched surface and allowed to harden, which will then replicate the surface features, and this can be examined under a microscope in the laboratory.

This technique was successfully used in a number of cases, for e.g. (a) in the examination of large dish ends to detect sensitisation and intergranular corrosion cracks, (b) examination of weld regions in a ball valve used in Heavy Water Plant, Tuticorin, to detect cracks adjacent to the weld region, (c) in the examination of a section of pipe and weldments to assess the microstructure after a sodium fire accident.

4.3. Ultrasonic Testing

4.3.1 Estimation of ultrasonic beam skewing in thick austenitic stainless steel weldments

It is well known that ultrasonic testing of thick austenitic stainless steel weldments poses unique problem. Low thermal conductivity and absence of phase transformations give rise to epitaxial growth of grains during subsequent weld passes. Thus, very coarse dendritic grain structures are obtained in thick weldments. The basic anisotropic nature of austenitic stainless steel weld structure is reflected in coarse dendritic morphology. Since both ultrasonic velocity and attenuation are strong functions of the orientation of the dendrites, the following phenomena take place. The beam travels with different velocities in different crystallographic directions and the beam has a tendency to bend due to successive refractions at grain boundaries. This phenomena results in beam skewing. Moreover, the method of defect location by ultrasonic technique is based on the presumption that ultrasonic beam travels in a straight line in the test material, and therefore, the location of defect as detected in thick austenitic weldments is quite different from the actual location.

A study was undertaken by fabricating 50 mm thick austenitic stainless steel weldments with single "U" configuration [5]. Artificial defects were introduced in the weld. The mislocation of the artificial defects were determined by using ultrasonic longitudinal wave angle probes (45°, 70° and frequency 2 & 4 MHz) and the results were compared with the theoretical estimates. The theoretical estimation was based on an idealised grain structure and orientation derived from the micro etched cross section of actual weldments. A geometrical model was developed. The top region of the idealised triangular weld was divided into vertical grains. Below this region, two vertical lines were extended upto the bottom area of the weld. In the weld/parent metal interface, trapezoidal grains were interposed with oblique grains. The angle at the vertices of the oblique grains were kept equal. With this arrangement, a continuous grain orientation was developed for model calculations.

The essence of the estimate was to find the possible beam path and the time to reach a particular defect. For tracing the path of ultrasonic beam after it crosses the parent metal/weld boundary, computation method was developed taking into account angle of probe in steel, angle of weld, plate thickness, velocity of sound in grains of different orientations and total angular variation of the axis of the grain between the top and bottom edge of the weld. The time taken by the beam to reach defect was calculated. This is the time which would be shown by the oscilloscope as the time taken for travelling the straight beam path to the phantom defect. The number of trapezoidal and oblique grains have been suitably varied in the framework of the geometrical model. We obtained success in accurate and reliable estimation of defect location in thick weldments using this model.

4.3.2 Detection of defects (such as cracks, porosities, etc.) in austenitic stainless steel welds by ultrasonic techniques based on signal analysis

The difficulties posed by thick austenitic stainless steel weldments for ultrasonic testing of defects are amply described in section 4:3.1. With this background, we shall now describe means to detect defects such as lack of fusion, line defects and porosities in an austenitic stainless steel weld pad, using signal analysis techniques [6]. Signal analysis techniques augment the capabilities of conventional ultrasonic testing for enhanced reliability and better sensitivity.

Both natural and artificial defects in stainless steel weld were studied for this purpose. Two plates having thicknesses of 10.0 mm and 16.5 mm with natural defects and a plate having thickness of 14.0 mm with artificial defects were used in this study. To simulate natural defects, artificial defects were incorporated in an austenitic stainless steel weldment. They include 5%, 3%, 2% and 1% of plate thickness (14.0 mm) notches, single holes of diameter 1.0 mm and 0.5 mm and a cluster of holes of approximate diameter 0.5 mm each, spread over a circular area of 10.0 mm in diameter. These artificial defects were machined using spark erosion technique.

In the plate with artificial defects, conventional ultrasonic examination could reliably detect 5% of thickness notch and cluster of holes with a margin of approximately 4 dB. However, other defects of smaller sizes could not be detected. Hence, ultrasonic signals were acquired for all these defects (both natural and artificial). The following parameters were extracted from these signals.

(a) Demodulated autocorrelation function

(b) Scalar mean peak power (SMPP) and

(c) Normalised mean deviation vector (NMDV).

Method (a) is basically a pattern recognition approach, whereas the other two methods use cluster analysis principles. Only the elements that form the clusters differ in methods (b) and (c).

In method (a), the log of the square of the autocorrelation function forms different patterns for different defects and noises. Visual examination of these patterns and pattern recognition principles applied to these patterns are able to differentiate and characterise noise and defect signals.

Method (b) involves finding the norm (magnitude) of the cross power (noise*noise and defect*noise) at each frequency, over the entire frequency range, and the mean of these values is used to form the clusters. In method (c), position vectors, whose components are the cumulative positive and negative real and imaginary values of the cross power spectrum are used in a four dimensional orthogonal vector space and clusters of (noise*noise) and (defect*noise) cross power signals are formed.

Clusters formed by method (b) are analysed for their mean, standard deviation etc. and for each signal, the probability that it could originate from a defect cluster was computed. In method (c), the distribution of the position vectors and the normalised mean deviation vectors of defect (or unknown) signal with respect to the noise cluster are studied to differentiate between noise and defect signals. Typical results are shown in Tables 2 and 3.

For conventional ultrasonic testing of austenitic stainless steel for fast breeder reactor applications, Section XI (Division-3) of ASME standard has stipulated 10% of wall thickness notch as a standard reference defect. Results of the present study show that these three methods of analysis are able to differentiate between all the defect signals and noise signals effectively, i.e., a defect sensitivity of the order of even 1% of wall thickness can be achieved. This approach, offering higher sensitivity, provides an opportunity for the early detection of defects in in-service inspection.

Table 2. Natural Defects

Defect Type	Probability (in %) that the Signal is from a Defect	
	SMPP	NMDV
Noise 1	15.1	58.1
Noise 2	33.2	53.4
Lack of fusion 1	95.2	100.0
Lack of fusion 2	99.0	100.0
Porosities	70.0	93.4

Table 3. Artificial Defects

Defect Type	Probability (in %) that the Signal is from a Defect	
	SMPP	NMDV
Noise 1	9.2	67.6
Noise 2	10.3	48.4
5% Notch	83.0	99.0
1% Notch	78.4	95.0
Cluster Defect	69.7	95.0
Hole Defect	94.0	99.0

4.3.3 Detection of fatigue cracks in maraging steel weldments by ultrasonic signal analysis approach

This work relates to the application pursued at IGCAR for space programme. Load bearing capacity of any structure for a given dimension can be increased by improving the reliability of detection of smaller defects in weldments this is highly desirable in aeronautical and space industries where the overall weight of the structure is a major constraint as it decides the pay-load capacity.

Maraging steels are widely used in space industries for fabrication of rocket motor casings. Conventional ultrasonic pulse-echo technique is applied for defect detection in the weldments. However, the top mid-section of the maraging steel weldments, which is acoustically noisy poses problems for reliable detection of defects of size 3 mm long x 1 mm deep in 8 mm thick weldment, which was a design requirement for a specific application. This is because of small amplitude difference of echo signal (2dB) between the noise and defect signals. Reliability of detection of such defects can be improved by adopting advanced signal processing and pattern recognition techniques.

Developmental work was undertaken for reliable detection of small defects in maraging steel weldments. For this purpose, fatigue cracks of 3mm x 1mm size were created in top mid-section of the maraging steel weldments representing expected weld defects formed during fabrication.

Conventional ultrasonic testing was carried out using a 45° shear wave probe having frequency of 4 MHz. The data acquired during this testing from defects, noise due to scatter from the weld and defect signal accompanied with noise were analysed by applying advanced signal analysis technique like shape of the reflected signal, autocorrelation, demodulated autocorrelation function (DAC) and cross power cluster analysis. Cross power cluster analysis yielded the desired reliability for the detection of the fatigue cracks [7]. It was concluded that this approach of doing conventional ultrasonic testing in conjunction with signal analysis would result in considerable enhancement of reliability in detecting fine defects which may result in increase in the pay-load of space vehicle.

4.3.4 On-line structural integrity assessment of a carbon dioxide absorber vessel in a fertilizer plant

The CO_2 absorber vessel examined for structural integrity has four beds. Perforated rings are placed in each of the beds to moderate the flow and to effect maximum absorption. The rings are held in a tray which were supported by a ring, beam and stool arrangement. The ring which supports the tray is welded into the vessel circumferentially and also, is supported by 16 cleats which are joined with the vessel inner surface by fillet welds.

Periodic dye-penetrant and magnetic particle inspections were carried out by the plant personnel. During one of the inspections, it was observed that 9 out of 16 cleat fillet welds showed crack like indications. The main concern was that whether the defects observed as cracks were penetrating into the shell thickness or not.

Artificial defects of various sizes and depths were made in a mockup weld pad having similar cleat fillet weld configuration to establish capabilities of ultrasonic testing technique for reliable detection of surface, sub-surface or propagating type defects and to ensure that desired sensitivity in location could be achieved in this difficult geometry. After establishing the sensitivity level, on-line UT was done on the vessel. The data collected during this testing was taken as primary baseline data. Repeat UT after four months of operating the vessel showed extension of defects observed in the earlier testing.

Complementary acoustic emission monitoring carried out for four months (when the vessel was in operation) subsequent to the initial ultrasonic testing showed a good correlation with the UT results. The above study established the merit of using ultrasonic and acoustic emission techniques in a complementary fashion. It was concluded that the defects were propagating in the fillet weld and not in the thickness of the vessel based on defect evaluation and sizing by ultrasonic technique. This evaluation [8] helped to give the safety clearance that the vessel can continue its service.

4.3.5 Effect of compressive stress on the detection of weld cracks during ultrasonic testing

In pulse-echo ultrasonic test techniques, it is customary to regard the presence of a signal in the form of an echo pulse as indicative of the existence of a flaw and the amplitude of the signal as related to flaw-size. The reliability of this method of sizing is dependent on many factors including for example, the operational procedure used, the material in which the defect is present, the geometry of the object being tested, the nature of the crack surface, the surface finish of the object and the amount of crack opening. The amount of crack opening depends among others, on the compressive stress present around the crack faces. These factors combine to cause variations in the simplified probability of detection.

It has been shown that the ultrasonic response from a crack is significantly influenced by the application of compressive stress on the face of the crack. The generation of compressive stress in a welded joint can occur in many cases. For example, in long butt weld joined pipe line, supported on either side of the weldment, and when the pipe line carries hot fluids, there is a possibility for compressive stress to develop at the weldment. It is also reported [9] that a drop of 10 dB can occur in the signal amplitude from fatigue cracks in austenitic steel weldments at compressive stress of 100 MN/m^2. There is therefore some risk of underestimating the size of a flaw or even missing it altogether. The reflectivity of a crack is thus a decisive factor in estimating the size of defect. The above mentioned problems were investigated by testing a simulated crack in a welded specimen subjected to varying compressive stress [10]. Shear wave angle beam examination was employed for the study using angle probes of 35°,45°,60° and 70° in pulse-echo and in tandem modes. From the investigations, the following observations were made :

For pulse echo mode, the value of compressive stress beyond which defect detectability reduces significantly was found to be 180 MN/m^2.

For tandem mode, defect detectability decreases appreciably beyond 85-90 MN/m^2.

Shear probe of 45° shows lack of sensitivity to applied compressive stress upto 180 MN/m^2 in pulse-echo mode. Thus it is preferred over other probes.

Tandem mode of testing is not a preferred method for defect sizing, under compressive load using maximum amplitude method.

Since the compressive stress value during service conditions is expected to be appreciably higher than 180 MN/m^2 in some instances, standardisation is essential for the use of ultrasonic testing for evaluating defect serverity in such applications.

4.3.6 Development of ultrasonic pipe scanner system for evaluating pipe weldments of FBTR

The safety of modern industrial plants and installations such as pressure vessels, high pressure piping systems, offshore structures and pipelines etc. depends to a great extent on fully reliable non-destructive weld inspection systems. Significant efforts have therefore been made to develop ultrasonic weld inspection systems capable of meeting the most stringent quality requirements during preservice and in-service.

High reliability, precision, reproducibility and clear permanent documentation are indispensable requirements which can only be met by operator independent automatic inspection and recording systems.

Keeping the above points in view, an ultrasonic probe manipulator has been developed in collaboration with Division for Remote Handling and Robotics, BARC, to test the welded pipes in the secondary system of Fast Breeder Test Reactor. Ultrasonic evaluation has to be carried out as a part of the in-service inspection during annual shut down of the reactor. It is possible to do simultaneous observations in four different orientations using four probes so that correct idea of any defect in any orientation is immediately obtained. These probes are placed at mutually right angles.

Each probe held in a housing is mounted on the piston of small air cylinder, the force of which keeps the probes positively in contact with pipe with constant pressure. Four such setups are mounted at right angles in a plane and pressed on a pipe line thus balancing the reaction and dead weight. Oil is used as couplant as water may evaporate since the temperature of FBTR pipe lines will be 430K due to molten sodium in the pipe line even during shut down.

The octagonal ring with four probes is held concentric with pipe line. The axial motion is obtained by a pair of pneumatic cylinders 25 mm diameter and 100 mm stroke, placed diametrically opposite to maintain vertical orientation of the probes. The frame body of the cylinders is mounted on a circular cage which rotates on four sets of two rollers kept at right angles on a guide fixed on pipe line. All the rollers are provided with ball bearings. A geared air motor (0.33 HP, 300 rpm) rotates the cage through self propelling roller assembly. All the rings, cages, octagonal frame, etc. are in a split construction to facilitate in-situ installation on running pipe line. Since the air cylinders cannot be moved in steps, monitoring is executed in small circumferential steps and full length axial strokes.

The manipulator has an axial movement of 100 mm from the centre of the weld convering the weld and the heat affected zone (HAZ). At the end of the axial movement, it provides a circumferential shift of 12° and further axial movements take place. This operation is repeated till the entire volume of the weldment to be tested is covered. This can be accomplished in short time with better reliability and repeatability. Whenever any defect indication is observed, the exact probe position indicating its axial position as well as circumferential position can be recorded with the help of the microprocessor based analysis system attached to the manipulator. The manipulator is used in conjunction with a multiplexed multichannel ultrasonic test system.

4.3.7 Ultrasonic testing of endcap welds in thin walled fuel elements of Pressurised Heavy Water Reactor (PHWR)

In PHWRs, the fuel is encapsulated in thin walled zircaloy tubes. The ends of the fuel elements are closed with end caps welded to the cladding tube by resistance welding. Each power reactor (235MWe) uses nearly 3670 bundles of 19 elements each. The quality of these elements has to be of the highest standard to ensure requisite performance level.

Resistance welding process leaves a material upset on both inside and outside of the joint. The outside upset is machined off leaving only a tiny step between end cap and the cladding tube. The manufacturing industry at present follows stringent controlled process conditions and helium leak test to ensure the quality of the welded end caps. The helium leak test has the capability to reveal only through and through defects with high sensitivity.

A feasibility study on the use of ultrasonic testing for the detection of defects in the end cap welded region was taken up at Division for Post-Irradiation Examination and NDT Development, IGCAR, Kalpakkam.

The ultrasonic inspection of the weld area is based on angle beam tests with line focused beam using the immersion technique. Ultrasonic flaw detector model Echograph 1030 Multiplex system with a 10 MHz frequency line focus probe was used for the experimental study. Indigenously developed, manually operated immersion probe manipulator with provisions for precise X, Y and Z axis movements and tilting the probe to a maximum angle of 50° in two perpendicular directions was utilised.

Taking into account the shear wave velocity in zircaloy material as 2360 m/sec, the transducer was made inclined at an angle of 26° with the vertical, so that the beam enters the zircaloy material at an angle of 45°

For laboratory investigations, artificial defects were incorporated by spark erosion machining. Two radial holes of 0.4 mm and 0.2 mm diameter having 0.375 mm depth (through and through hole) and one radial hole of 0.15 mm diameter with 0.185 mm depth (half the wall-thickness) were made on the welded region of the fuel cladding tube. The holes of different diameters and depth were made in order to ensure the possibility of achieving higher sensitivity of detection of defects by the method. Suitable test parameters like height of water column, testing range, gain (dB) etc. were optimised.

The study has revealed the following :
The end of the endcap provides a good reference point from which the position of the weld can be scaled. Though this end point acts as a reflector point, it was possible to resolve clearly the echo from the end of the endcap and the scatter noise signal from the weld. It was possible to detect clearly all the three standard artificial defects.

4.3.7.1 Evaluation of endcap welds having natural defects

Based on the success in detecting the artificial defects, further evaluations were carried out on tubes with endcaps which were rejected in helium leak test. The leak rate observed was 3 x 10^{-6} std. cc/sec. Ultrasonic immersion testing carried out on these specimens at the standard sensitivity level (level of artificial defects) showed that it was possible to get a clear echo with higher amplitude (60%) at regions where natural defects were present compared to the background scatter noise signal amplitude of 20% from the weld region with no defects.

Though this has indicated, that it is possible to evaluate the quality of the endcap welds by observing the change in amplitude of the echo pattern during ultrasonic testing, an attempt was made to adopt signal analysis approach in order to get reliable defect detectability and develop ability to differentiate signals obtained from noise and actual defect signals.

Two types of signals were obtained from the endcap welds during ultrasonic testing: (1) signals having contribution from both defects and geometry (2) signals having contribution from the geometry alone. These signals were subjected to various analysis procedures i.e., (a) autopower spectrum (b) total energy content (c) demodulated autocorrelation function.

Overall frequency contribution to the signals or the contribution of energy in various frequency components of the signal showed good variation for signals from defective part of the endcap and signals whose contribution comes from the geometry factor. Generally, autopower of signals from the defective part had single peak showing that the contribution comes from a certain band of frequencies. For the signals from the geometry, there was a distribution of energy over a few narrow frequency bands. Total energy content for these signals too showed a good variation. Signals from the defective part had an energy value over 100 arbitrary units whereas for the signals from the geometry, this value was less than 50 arbitrary units.

Envelopes of demodulated autocorrelation functions showed a good detectable variation, thus indicating the possibility that a pattern recognition approach can be followed for quality assurance at shop floor with high reliability.

4.4 Application of Acoustic Emission Technique for In-service inspection of Pressurised Heavy Water Reactors

This section discusses the use of acoustic emission technique for assessing the structural integrity of some components of the primary coolant systems of Pressurised Heavy Water Reactors (PHWRs). Frequency domain analysis of AE for detection of leaks in a tube sheet of the end shield and pressure tube of operating reactors is highlighted in this section.

For PHWRs (the type which is the mainstay of the Indian Nuclear Power Programme), pressure tubes (PT), calandria tubes (CT) and the end shields are important nuclear components. Regular in-service inspection of these components are of utmost importance to assess their structural integrity. There are 306 coolant channels in a 235 MWe reactor. Each channel is an assembly of a zircaloy-2 (a zirconium alloy) pressure tube (PT) surrounded by a zircaloy-2 calandria tube (CT). The coolant channel consists of PT rolled into the end fitting at either ends and it is 9.220 metres long. The PTs are 5.400 metres long, 82.6 mm inner diameter and 4.0 mm wall thickness. The coolant channels are positioned horizontally and pass through the lattice tubes of the two end shield assemblies. Each end shield assembly consists of a calandria side tube sheet (CSTS), a fueling machine side tube sheet (FSTS) and lattice tubes which are welded to the tube sheets.

4.4.1 In-service inspection of the end shield

In one of the end shields of a pressurised heavy water reactor at Rajasthan Atomic Power Station-Unit One (RAPS-I), light water leakage was observed from the south end shield. Helium leak detection technique was applied to detect the region of leakage. Subsequently, AET was applied to locate the leak paths present on calandria side tube sheet (CSTS) by placing the acoustic emission (AE) sensor on fueling machine side tube sheet (FSTS) [11]. The end shield system was pressurised with air upto 1.26 kg/cm^2 and the AE signal due to air leakage through the leak paths was analysed in time domain. Locations of the leak paths were later confirmed by both ultrasonic and visual examination techniques after removing the identified channels. These leak paths were plugged and the reactor was made operational.

After a few months of reactor operation, again light water leakage was noticed from the same end shield system. Water level in the end shield was found to be stable at the level above the earlier repaired region. This indicated that there is/are new leak path(s).

In the earlier instance when AET was used [11], time domain analysis of the AE signal was applied. The end shield had been pressurised with air to 1.26 kg/cm^2 which could give a strong AE signal due to air leak. However, in the present investigations [12], it was felt that time domain analysis would not be feasible because the maximum pressure that could be applied on to the end shield system was restricted to below 0.35 kg/cm^2 due to structural considerations. The weak signal due to leakage at low pressure would get masked in the presence of high background noise due to running of primary heat transport pumps.

If there were any leak paths above/below water level, air/water would leak out. The signals due to air and water leaks are expected to have different frequency components. Hence in order to find out whether AE due to the air leak and water leak could be discriminated in frequency domain, experiments were conducted on a mock up end shield assembly with artificial cracks. The results indicated that water and air leak signals could be discriminated

The experimental set up consisted of a Biomation 1010 Transient Data Recorder (TDR) which acquired the AE signal picked up by the broadband (100 KHz - 2 MHz) AE sensor placed on FSTS. A magnetic spring loaded (for maintaining constant contact pressure) gadget was developed to keep the sensor on FSTS. The signals thus recorded were analysed subsequently for obtaining frequency distributions of the signal.

A strong signal having a dominant frequency component at 250 KHz was acquired at a leak location on FSTS. This frequency component got reduced when the probe was kept at the more distant locations. This confirmed the applicability of frequency domain analysis approach for detection and location of leak paths on CSTS by probing from FSTS side.

Another strong signal having a dominant frequency range 175-200 KHz was also observed at the next adjacent ligament towards west side. This signal also got reduced when the probe was kept at distant locations. This indicated the presence of another leak path on the CSTS. The variation in the frequency of the signal due to various leak paths is attributed to the size, shape and morphology of the leak paths. These frequency components disappeared when water level was raised above the suspected ligament. This confirmed the presence of an additional leak path.

The results of the above test indicated the presence of additional leak path which was later confirmed by visual examination after cutting a few channels in the suspect region of leakage.

4.4.2 Acoustic Emission Testing of Coolant Channels of MAPS-I[13]

Though this study does not pertain to welded component, it has significance as the inaccessible welded components can be evaluated by the same technique without any modifications.

Heavy water leakage was observed in the calandria vault of Madras Atomic Power Station - Unit One (MAPS-I). Signals were acquired from all the 306 channels keeping pressure (80 kg/cm^2) and temperature constant. Analysis was carried out on the time signal waveform and the power spectrum.

It was thought that the leaking channel should be one among the 15 channels which had high frequency components 700 - 1000 kHz. In order to further narrow down the number of suspect channels, test was carried out on these channels at a lower pressure of 60 kg/cm^2. The autopower spectrum could not give any further information in identifying the leaky channel(s). Additional signal parameters namely spectral ratios S1 and S2, (at two different pressures P1 and P2) and the value S1/S2 (which is a measure of the effect of pressure change on the spectral ratio) were computed from the autopower spectra of the signals and six channels were identified as suspect channels based on the significant variation in the spectral ratio with pressure (Table 4).

Table 4. Signal parameters derived from the autopower spectrum of AE signals acquired from suspect channels of MAPS - I

Channel S.NO.	Energy in the Band (700-100 kHz) / Energy in the Band (39-175 kHz)			Remarks
	S1 (80 kg/cm^2)	S2 (60 kg/cm^2)	S1/S2	
1.	2.70	1.40	1.930	Suspect
2.	0.89	0.74	1.200	
3.	1.20	4.70	0.260	
4.	1.30	7.40	0.175	Possibly seal plug leak
5.	1.05	9.20	0.114	
6.	0.42	7.30	0.060	

It was thought that the increase in spectral ratio with increase in pressure viz, (S1/S2)>1, should have resulted due to the increased AE activity of the leak as a result of rise in pressure.

It may be seen from Table 4 that for channel serial nos.1 and 2, S1/S2 is >1. Hence they were suspected for leak and conventional tests were carried out on these two channels after defuelling.

The channel with serial no. 1 did not indicate presence of any leakage when vacuum and hydrotests were carried out. Subsequently, when channel with serial no.2 was vacuum tested, there was no change in vacuum level. However, when hydrotest was carried out, the pressure dropped indicating the presence of leak. This was further confirmed when eddy current test was carried out which indicated the presence of leak paths.

4.5. Thermography for Modeling Temperature Distribution

Infrared imaging camera has been employed at IGCAR to study the temperature distribution during welding for ratifying weld heat flow simulation model and estimation of heat affected zone. Detailed studies in accurate comparison of the theoretically predicted and the experimentally determined temperature distribution across the weld could lead to the development of microstructure and residual stresses prediction.

Initial studies were conducted by taking thermograms of the welds during the welding process. External filters were used to bring down the intense infrared radiation to the acceptable levels of the thermovision camera used. Thermocouples were placed at suitable points for calibrating the intensity with temperature. It was observed that temperature profile across the weld region would give the heat affected zone and temperature profile along the weld gives information about the welding parameters in real time.

4.6 Barkhausen Noise Analysis Method for Assessment of Post-weld Heat Treatment

A magnetic method based on Barkhausen noise analysis is being developed for the assessment as to whether Post-weld Heat Treatment (PHWT) has been adequately carried out or not in Cr-Mo steel tube to tube weld and tube to tube sheet weld joints of steam generator of Fast Breeder Reactor. The technique is based on the fact that PWHT removes the internal strain at the weld joint and reduces the hardness of weldment and HAZ. These changes cause significant increase in the Barkhausen noise activities. The PWHT is necessary for one or more of the following reasons :

a) to prevent distortion in service by removing some or most of residual stress
b) to avoid the possibility of stress corrosion cracking in service
c) to reduce the risk of brittle fracture during commissioning or in service
d) to develop optimum weld joint properties following welding.

There is a strong necessity for developing a routine NDT test to ascertain the adequacy of PWHT. The chances of not carrying out PWHT adequately in one or more weld joints is higher when the number of weld joints involved is higher such as in large steam generator assemblies.

Barkhausen Noise Signal : Both magnetic perturbation signals (known as Barkhausen effect signals) and acoustic emission (known as magneto-mechanical acoustic emission) are generated when an induced magnetic field in a ferromagnetic material is swept in a hysterisis loop. Both the signals are strong functions of the microstructure and internal strain.

At the Division for PIE and NDT Development, analysis of the magnetic perturbation signals with suitable frequency filtering has shown that significant variation in the signals takes place before and after PWHT of 2.25 Cr-1Mo butt welded tube joints. High pass filtering allows consideration of the changes in the stresses taking place due to PWHT in the subsurface region instead of the change in the stress pattern throughout the wall thickness. Since in the equilibrium, the net overall stress is either small or zero, the values of the change in the Barkhausen activities in the case where no high pass filtering is carried out will be small. On the other hand, since the change in the stress levels in the subsurface region before and after PWHT is significant, change in the Barkhausen noise activity is evident when high pass filtering is carried out.

5. FUTURE DIRECTIONS

At IGCAR, we are engaged in developing quality assurance methodologies and procedures and techniques (destructive and non-destructive) to achieve Fitness-for-Purpose in a reliable manner for the components of Prototype Fast Breeder Reactor (500 MWe). Real time X-ray imaging with adequate sensitivity, on-line assessment of austenitic stainless material degradation in heat affected zone of weldments using thermal imaging techniques, time of flight diffraction ultrasonic technique for quantitative assessment of linear defects, phased array and synthetic aperture ultrasonic imaging with high sensitivity are the areas recognised for R & D specific to meet non-destructive testing requirements of PFBR components. We are also developing automated device for remote in-service inspection of weldments of the main and safety vessels of PFBR using visual examination, eddy current testing and ultrasonic techniques in a complementary way. Data recording, evaluation and displays for automated inspection system will be implemented using state-of-the-art software and computers.

6. CONCLUSIONS

This paper has attempted to focus the importance of quality assurance. Application of conventional and advanced NDT techniques for achieving Fitness-for-Purpose (preservice and in-service inspection) of welded components is a necessity. A few select examples of our work are described for the purpose ofhighlighting the capabilities of non-destructive evaluation expertise developed in-house for specific difficult applications. Future directions are briefly mentioned. Organisational information about the groups carrying out non-destructive inspection and developmental work is given in Annexe 1 and 2. Confidence and expertise gained during last fifteen years is being strengthened continuously to meet future needs. It is vital that the expertise and information generated at IGCAR is disseminated in a most effective way to all the concerned professionals for successful exploitation towards obtaining realistic solutions, and indeed this is the objective of presenting this paper.

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Annexure - 1

ORGANISATIONAL CHART OF QUALITY ENGINEERING SECTION, IGCAR WITH RESPECT TO QUALITY ASSURANCE OF WELDED COMPONENTS

METALLURGY & MATERIALS PROGRAMME
(Head : Dr. Placid Rodriguez)

QUALITY ENGINEERING SECTION
(Head : Shri G. Mallikrjunan)

QUALITY CONTROL ENGINEER
PROJECTS
(Shri B.S.C. Rao)

QS WORKS OF VARIOUS PROJECTS REGARDING WELDED COMPONENTS

SITE QC AND WELDING DEVELOPMENT WORKS

NO OF PERSONS :
11 Engineers,
4 Supervisors and
Auxiliary staff

QUALITY CONTROL ENGINEER
NDT AND FABRICATION
(Shri M. Palaniappan)

NDT SERVICES

PRESERVICE AND IN-SERVICE INSPECTION OF FAST REACTOR COMPONENTS

NO OF PERSONS :
9 Engineers,
3 Supervisors and
Auxiliary staff

Annexure - 2

ORGANISATIONAL CHART OF DIVISION FOR PIE AND NDT DEVELOPMENT, IGCAR WITH RESPECT TO NDT DEVELOPMENT OF WELDED COMPONENTS

METALLURGY & MATERIALS PROGRAMME
(Head : Dr. Placid Rodriguez)

DIVISION FOR PIE AND NDT DEVELOPMENT
(Head : Shri. Baldev Raj)

R & D SECTION (Head : Shri D.K. Bhattacharya)	SIGNAL PROCESSING, ELECTRONICS AND CONTROL SECTION (Head : P. Kalyanasundaram)
R & D IN NDT OF WELDED COMPONENTS USING ULTRASONIC TESTING, RADIOGRAPHY, MICROFOCAL RADIOGRAPHY, HOLOGRAPHY, ACOUSTIC EMISSION, INSITU-METALLOGRAPHY, EDDY CURRENT TESTING AND THERMOGRAPHY	APPLICATION OF SIGNAL ANALYSIS TECHNIQUES ON ULTRASONIC SIGNALS FOR DEFECT DETECTION & CHARACTERISATION
PRESERVICE AND IN-SERVICE INSPECTION OF WELDED COMPONENTS	ANALYSIS OF ACOUSTIC EMISSION SIGNALS FOR DETECTION OF DEFECTS
QUALIFICATION OF NDT PERSONNEL	
FAILURE ANALYSIS	
NO OF PERSONS : 11 Engineers, 4 Supervisors and Auxiliary staff	NO OF PERSONS : 9 Engineers, 3 Supervisors and Auxiliary staff