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ULTRASONIC IN-SERVICE INSPECTION OF MAIN COOLANT PUMP BOWL WELDS

PART 1 - EXAMINATION TECHNIQUE

PART 2 - FIELD IMPLEMENTATION

Fourth International Workshop on Main Coolant Pumps - EPRI

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ULTRASONIC IN-SERVICE INSPECTION OF MAIN COOLANT PUMP BOWL WELDS
PART 1 - EXAMINATION TECHNIQUE

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INTRODUCTION

The paper reports on a new ultrasonic testing technique that permits volumetric examination of PWR Main Coolant Pump casing welds from the outside of the pump bowl. The following describes the past and current evolution of the in-service inspection practice, in the light of the ASME Code requirements, and outlines the main features of the ultrasonic technique, which is based on large diameter focused beam probes. A review of the tests applied to qualify the method is also given.

Part 2 deals with the associated automatic equipment, and with the practical conditions of field implementation.

PUMP CASING MANUFACTURING

In most Pressurized Water Reactors, the pressure-retaining bowls of main coolant pumps (MCP) are made from statically cast austenitic stainless steel (SA-351 CF8, CF8A, CF8M). The wall thickness, which ranges typically from 180 to 200 mm, is overdesigned to limit vibration effects and dimensional variations.

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Because of the pump size, the casings were previously constructed of three separately built-up sections, which were then assembled using the electroslag welding process. Later improvements in the casting technology enabled the manufacturers to eliminate progressively the two welds.

BASIC REQUIREMENTS OF ASME CODE

Section XI of the ASME Code (1) requires, during each interval, a volumetric examination of all casing welds of one pump among the loops of the reactor coolant system. In addition, visual testing (VT3) of the inner surface is to be conducted to the same extent and frequency ; from the 1989 edition however, this requirement holds only when a pump is disassembled for maintenance, repair, or volumetric examination.

Either ultrasonic testing (UT) or radiography may be used to perform the volumetric examination, and the maximum dimensions of allowable planar flaws are defined for pre-service and in-service inspections.

BACKGROUND OF IN-SERVICE INSPECTION PRACTICABILITY

If, at first glance, ultrasonic testing may seem to be the most suitable NDE technique to perform a volumetric examination, particularly because radiography is generally not ideal on thick components, reality turns out to be more complex : indeed, austenitic cast and welded materials are known to exhibit very coarse metallurgical textures, created by the epitaxial growth of long grains along the heat dissipation lines, during the solidification of the material. Columnar, equiaxed or mixed structures can result, depending on the chemical content and cooling process of the component (2).

If conventional UT-techniques are experimented, the large size of the anisotropic grains, relative to the acoustic pulse wavelength, generates strong disturbances in the pulse propagation. Among those phenomena, which have been detailed in several references (3,4), clearly the most drastic one is the rapid extinction of the signal with depth, due to attenuation and energy scattering. Twin-crystal search units emitting heavily damped low frequency compression waves have been developed to improve the signal/noise ratio, but, in practice, the inspectable depth range is limited by the probe size for which efficient coupling can be maintained (5). In MCP bowl steel, depth ranges of no more than 25 mm have been reported (6).

Such difficulties have encouraged the development of a miniaturized linear accelerator in the USA (7). A series of field examinations of MCP casing welds has been conducted, including two ten-year in-service inspections in Belgium, in 1985 and 1986. The examination sensitivity was in compliance with the ASME requirements, and flaw growth due to service has not been evidenced in the inspected zones.

The basic reproaches that can indeed be directed at X-ray MCP casing weld examination lie in the high cost of pump disassembly and drainage, which in turn require core defuelling, and in the associated radiation doses endorsed by personnel. In addition, it must be realized that those operations are most frequently not requested for other purposes, such as pump maintenance or repair.

Consequently, a study was undertaken to establish a strictly technical standpoint on the justifiable examination periodicity (8). The results showed that, for the types of pump considered, the intervals can be safely extended to 15 or 20 years. This provided to utilities a basis for seeking, and obtaining, deferral of ten-year inspection. Furthermore, an ASME Working Group has been dealing with that matter in the last years, and a code case (9) issued in 1990 suggests to perform, in lieu of the volumetric examination, various visual testing examinations and an evaluation to demonstrate the safety and serviceability of the casing.

Basically however, the need for adequate inspection techniques remains, until it would be demonstrated that no material degradation mode can develop, over the life of the component, to such a point that the structural integrity may be jeopardized.

ULTRASONIC TECHNIQUE DEVELOPMENT

As the design of the Tihange 1 (900 MWe Westinghouse PWR) reactor coolant pump volutes (Fig. 1) practically precluded using radiography, a feasibility study was initiated to find out an ultrasonic alternative, that would not involve pump disassembly.

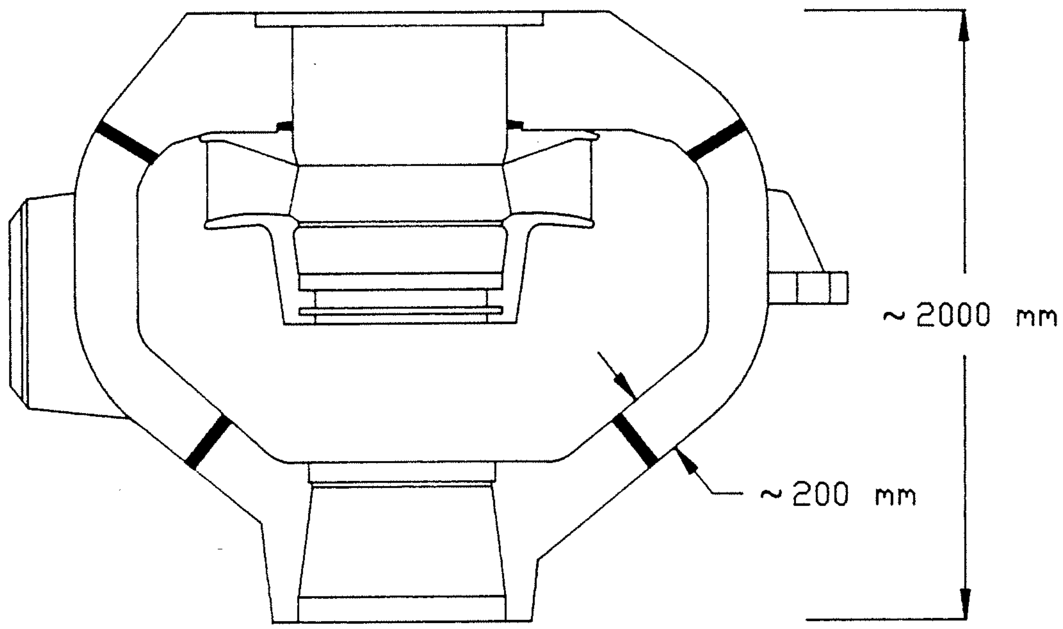

Fig. 1. Tihange 1 Pump Casing

An excrescence of one of the Tihange 1 casing sections, and a portion of a casing lower weld zone, were made available for the development of an examination method. The first specimen is a 200 mm thick cuboïd, containing ASME and other artificial reflectors, the representativeness of which was assessed through metallurgical and acoustical measurements of the pump material ; the second specimen contains simulated defects and is realistically shaped, but has a higher ferrite content.

Acoustic behavior experiments showed that proper propagation of sound pulses can be achieved only with low frequency (0.5 MHz or lower) compression waves. The first layer, in the through-wall direction, can be conveniently examined by contact TRL transducers refracting 0.5 MHz compression waves at 45° in steel (Fig. 2). A commercial search unit with the same frequency is selected for the straight beam examination.

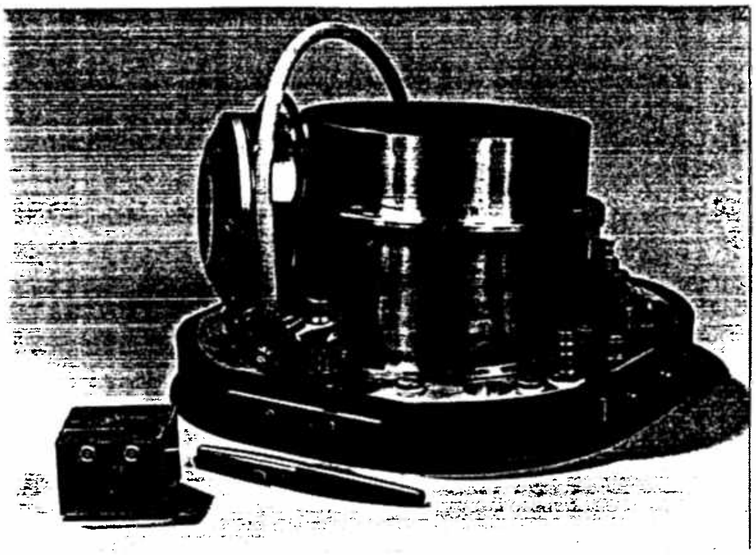

Fig. 2. Ultrasonic Probes

As however the efficiency of the TRL technology is limited in depth, focused beam transducers were specifically developed for the 60-200 mm depth range (Fig. 2). The required focal characteristics led to 0.5 MHz piezoelectric elements with a diameter of 140 mm, backed by a heavy damping material. The transducer is mounted on a local immersion chamber, which provides for efficient coupling and minimizes leakage.

Several such straight beam and angle beam (30°) compression wave probes were manufactured to cover the required depth range, with respect to the various surface curvatures to be considered. Acoustic beam dimensions have been measured in steel to be from 15 to 25 mm in the focal depth range.

Figure 3 shows two angle probe sensitivity curves, which are the references actually used for the examination of the lower weld zone. The curves result from data collected on 9.5 mm diameter (4 mm for the TRL) holes drilled in the reference steel specimen, and compensated for the curvature difference. The diagram also displays the peak amplitudes obtained from a 4 mm deep milled notch and from a 20 mm deep spark-eroded slot. Figure 4 illustrates data generated by the latter reflector : the upper tip signal can be clerly be distinguished from the corner reflection, allowing for accurate sizing.

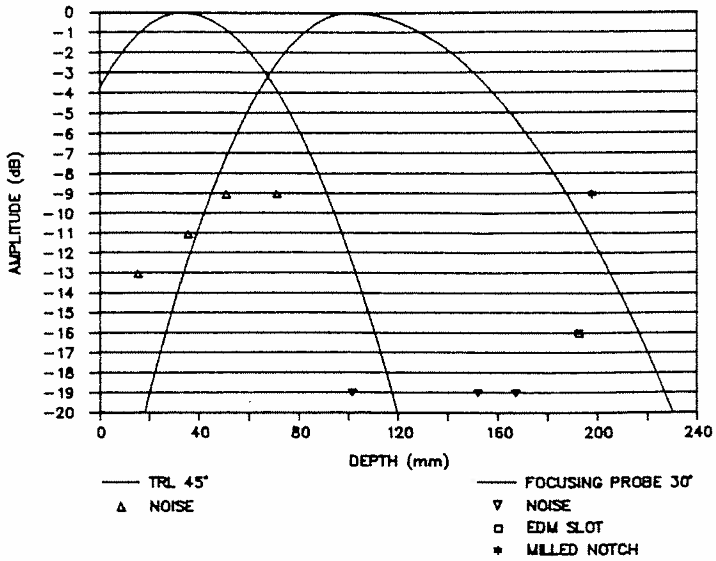

Fig. 3. Depth Sensitivity Curves

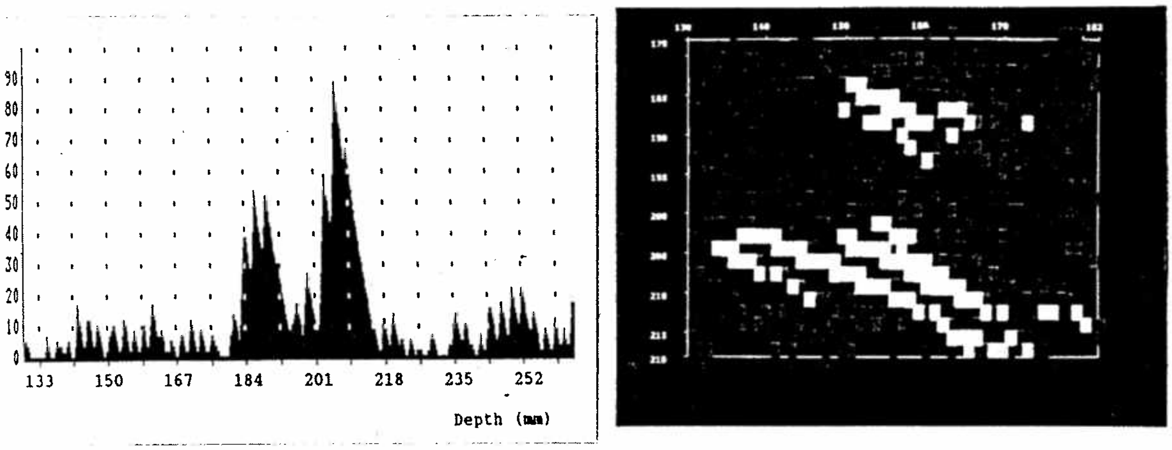

Fig. 4. Signal from Spark-Eroded Slot (left : A-scan ; right : B-scan)

However, the figure also shows that, near to the inner surface, it may be difficult, particularly in a material featuring high metallurgical noise and acoustic velocity variations, to discriminate between crack tip signals, corner reflections and specular echoes from volumetric flaws, whereas the relevance of those reflectors as to the component integrity is quite different. Therefore, a pitch-catch mode configuration , with two focusing probes, can be implemented to scan the far-surface region. As the distance between emitter and receiver is set manually, wide areas cannot be examined conveniently, but nevertheless the pitch-catch setup can be very helpful locally, where pulse-echo data call for further characterization of indications.

The huge weight of the focusing probes (about 14 kg), the need for accurate and reliable examination data, and the obvious concern as to staff dosimetry, all call for mechanization. The automated system developed to perform field inspections is described in Part 2 of the paper (10). The scanning manipulator can be seen on Figure 5 in the pitch-catch configuration, on a polyester full scale mockup in which windows were made to permit the insertion of the reference specimens. The mockup was used to test the proper operation of the equipment under fairly realistic conditions, to calibrate it dynamically, and to qualify the examination method.

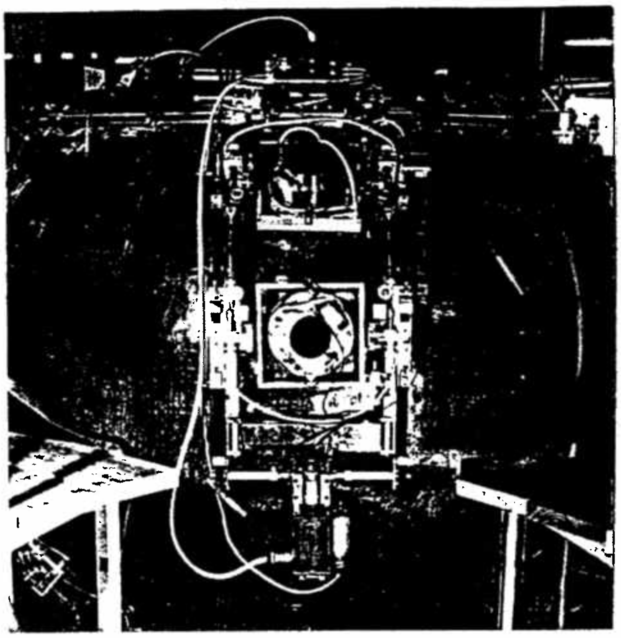

Fig. 5. Pitch-Catch Mode Configuration on Pump Mockup

METHOD QUALIFICATION

In order to qualify the examination method and the associated equipment, the capability of calibration on the reference block cannot reasonably be seen as a satisfactory assessment. On the other hand, an extensive validation exercise with realistic samples and flaws cannot be afforded, since large amounts of proper steel material are not available. The approach eventually selected identifies all basic parameters which can affect the flaw location and sizing capability (except those relating to the defect morphology or to the particular sizing method) ; the maximum magnitude of each soure of error is either measured experimentally, where possible, or postulated conservatively, and the various contributions are then combined to yield global error estimates.

Some results of the analysis are shown in Fig. 6, where the ideal conditions designate, by way of reference, a carbon steel planar component, and where the two scanning step values (4 and 1 mm) are those specified respectively for basic detection scanning and for indication characterization (with locally resumed scanning). It can be seen that, for a reflector point close to the far surface, a location error of about 10 mm and a sizing error of 2.5 mm can be achieved, with a 99% confidence level, in the through-wall direction.

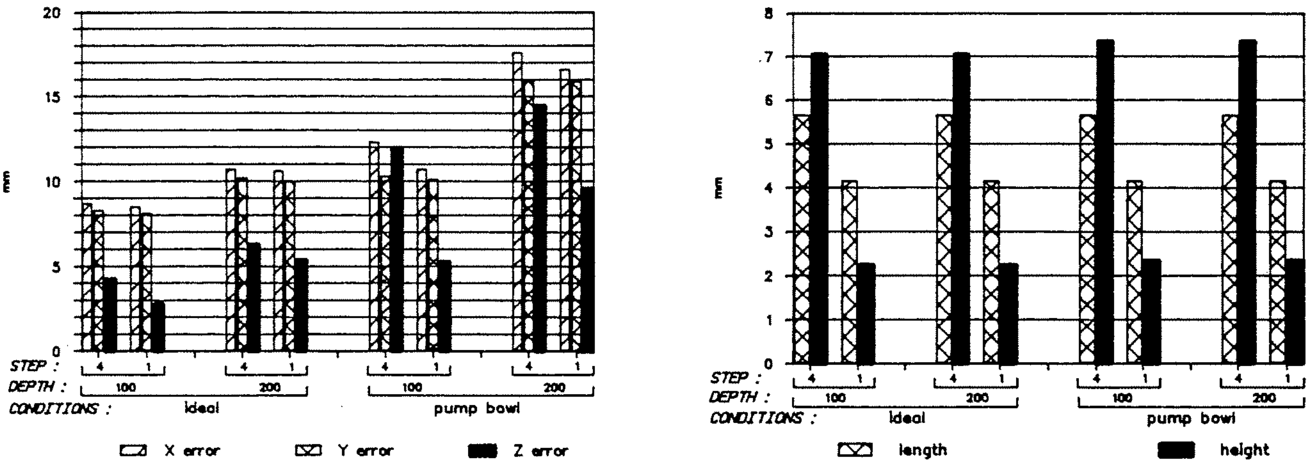

Fig. 6. Error Estimates (left : reflector location ; right : reflector sizing)

SUMMARY

A new ultrasonic testing method has been developed for the volumetric examination of the welds of MCP casings, on the basis of the ASME requirements.

The method relies on large focusing transducers, which are capable of inspecting the full thickness from the outside of the casing, thereby canceling the need for pump draining and disassembling.

The capability of the method has been assessed with all available means, and satisfactory figures were obtained.

Further details on field operation are to be sought in Part 2.

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ULTRASONIC IN-SERVICE INSPECTION OF MAIN COOLANT PUMP BOWL WELDS
PART 2 : FIELD IMPLEMENTATION

D. Verspeelt, J. Cermak, F. Pinto *

INTRODUCTION

Part 1 of the paper described the ultrasonic technique newly developed to examine volumetrically the casing welds of PWR main coolant pumps.

The following deals with the field implementation of that alternate ultrasonic technique, which is carried out from the outer surface only, and thereby reduces significantly the inspection cost as well as the radiation doses incurred by personnel.

EXAMINATION EQUIPMENT

General description

Figure 1 represents the main parts of the equipment. Beside the data analysis workstation, all units are located in the controlled zone of the nuclear power plant. Their function is detailed hereafter :

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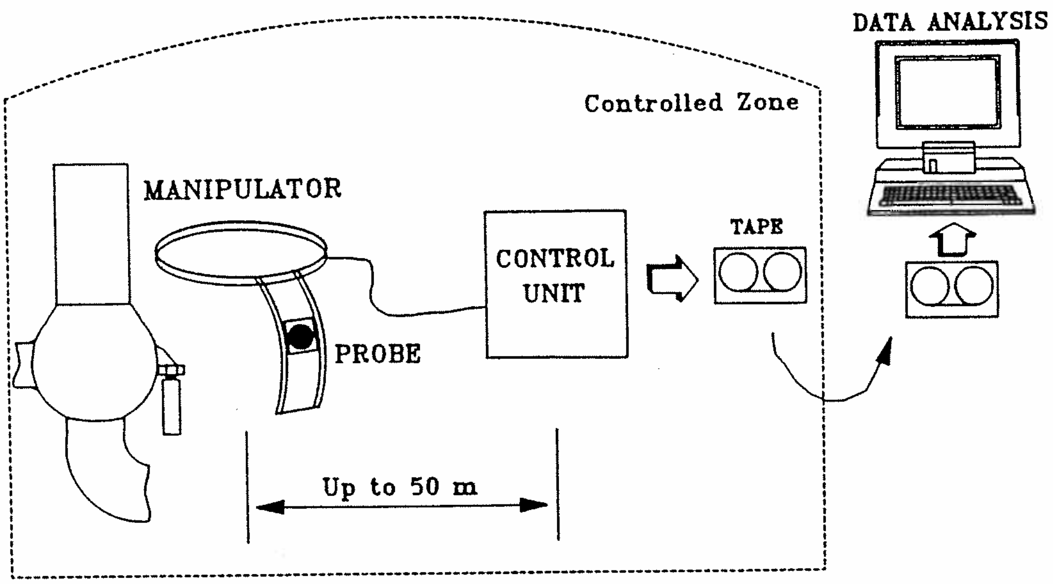
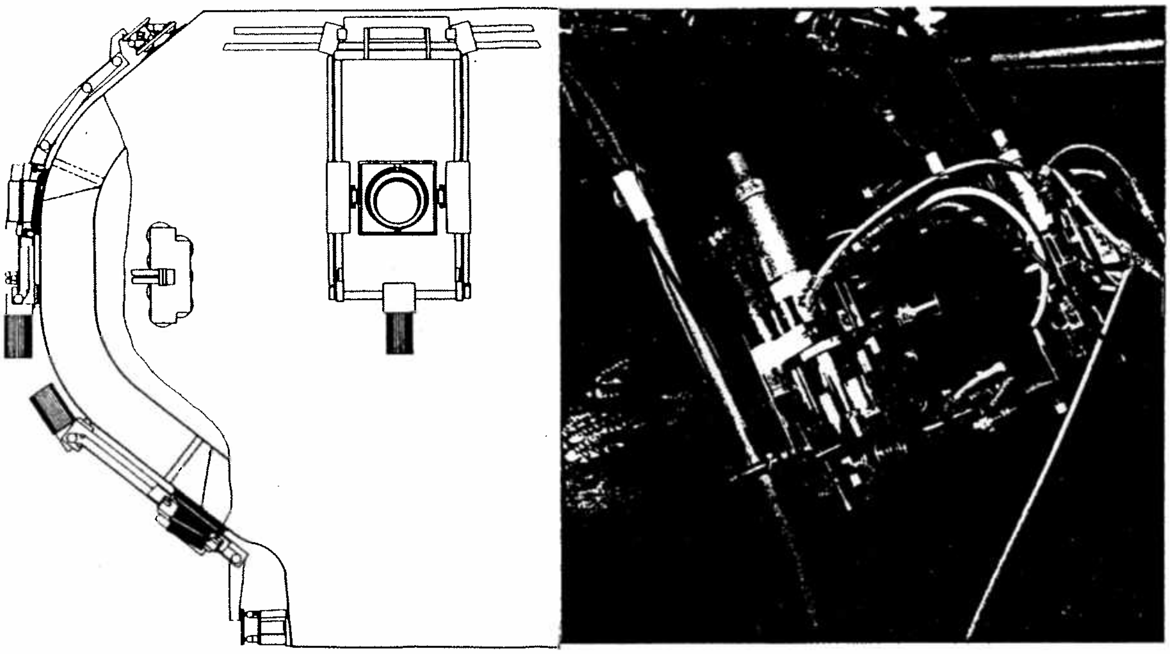


Fig 1. General Setup of Ultrasonic System
for Main Coolant Pump Bowl Inspection

Ultrasonic Probes. Due to the coarse structure of the pump bowl material, only heavily damped low-frequency focussed beam transducers are suited to perform the volumetric examination. To ensure efficient coupling with the pump outer surface, each transducer is mounted on a local immersion chamber. Further details are to be found in Part 1 of the paper [1].

A miniaturized pulser/preamplifier fixed on the transducer provides for efficient probe excitation : matching problems induced by the very low impedances of the large piezoelectric elements (140 mm diameter) and signal losses in long cable lines are eliminated.

Manipulator. The huge size and weight (about 14 kg) of the probes request mechanized scanning. Therefore, two dedicated manipulators (one for the upper and one for the lower weld) are used (Fig. 2). They are fixed on the pump body by means of suction discs. The global design has confined the manipulator within a clearance of 150 mm around the pump body, which is usually slightly more than the space occupied by the thermal isolation shield.



a b

Fig 2. Dedicated Manipulator for Upper and Lower Weld Inspection (a). Scanning of the Pump Bowl Upper Weld during Field Examination (b)

Two motions, a horizontal rotation and a vertical translation, are actuated by stepping motors. Scan speeds up to 50 mm/s can be achieved. Radiation safe synchro-resolvers are used to measure the probe position.

The whole manipulator is composed of different low-weight parts, which are assembled in the controlled zone nearby the pump. This modular structure provides the required transportation flexibility in the controlled zone, and eliminates additional charge (time scheduling) of the power plant cranes. The currently existing manipulator allows the inspection of one-weld and two-weld pump casings in 900 MWe three-loop PWR's of Westinghouse or Framatome design. Adaptation to other geometries are possible : a manipulator fitted to a two-weld, two-loop 400 MWe PWR coolant pump will be available in Fall 1991.

Control unit. The main tasks of the control unit (Fig. 3) are the powering of the manipulator motors and the acquisition, processing and visualization of the ultrasonic data.

Fig 3. Remote Control System during
Field Examination at Tihange 1

Due to the high ultrasonic noise caused by the coarse structure of the pump material, the system has to face a huge amount of raw ultrasonic data : an inspection of a two-weld pump bowl generates about 20 Gbytes of raw data. To permit convenient data storage, processing and analysis, those raw data must be dramatically reduced. The implementation of commonly used ultrasonic gates does not yield a valid solution because of the risk of relevant data elimination. For this reason, the digitized ultrasonic data is on-line processed with, beside a spike elimination and spatial averaging procedure, an original peak-detection algorithm, which can extract, from the original A-scan, a virtually unlimited number of peak amplitudes and associated times-of-flight. To achieve fast data handling, that on-line process is implemented on transputer technology, which has an architecture that is extremely well suited to perform parallel processing [2]. This results in a remarkable data reduction, without jeopardizing the inspection speed and the availability of significant signals : with a data stream of 100 kbytes/s, the initial raw data (20 Gbytes) are reduced to about 200 Mbytes.

By means of the software package AIDA running on a UNIX operated system controller, the processed data are on-line displayed as B-, C- and D-scans views on a colour graphic screen. This allows the on-site crew to validate the inspection data.

Data analysis. Once the data have been captured, they are stored on tape and handed out of the controlled zone, for further analysis. The off-line part of AIDA is implemented on a workstation, to allow detailed analysis and graphic reporting.

FIELD IMPLEMENTATION

The implementation of a PWR reactor coolant pump bowl inspection is subdivided in two parts : a preliminary measurement exercise and the inspection itself. A time gap of a few 6 months should be planned between the two phases.

Preliminary measurements

Objectives. The coarse structure of the pump bowl material strongly influences the propagation behavior of the ultrasound. The first aim of the preliminary measurement is to characterize the pump material to verify the effectiveness of the inspection method and, if needed, to determine the calibration correction.

Additionnally, dimensional measurements are carried out, to make sure that the mechanism fits to the pump bowl geometry and to its environment.

Eventually, the percentage of inspectable weld volume can be inferred from the collected data.

Implementation. The one-week site intervention can be carried out during any planned shut-down of the reactor. It requires only the removal of the thermal isolation shield around the pump bowl.

By means of ferrite content measurements, the weld is located and marked. Time and frequency analysis of backwall echoes at several locations, on the weld and on the base material, provides the data requested to compare the material with the available reference samples.

The dimensions and profiles of the volute are determined by physical measurements. Such parameters are used to verify if any adaptation of the manipulator and of the focusing lenses of the transducers is required.

Any obstacle nearby the pump, which can hamper the use of the inspection mechanism, are also carefully documented.

Outcome. To date, four pump casings, three with two welds and one with one weld, have been examined in that way in four different units.

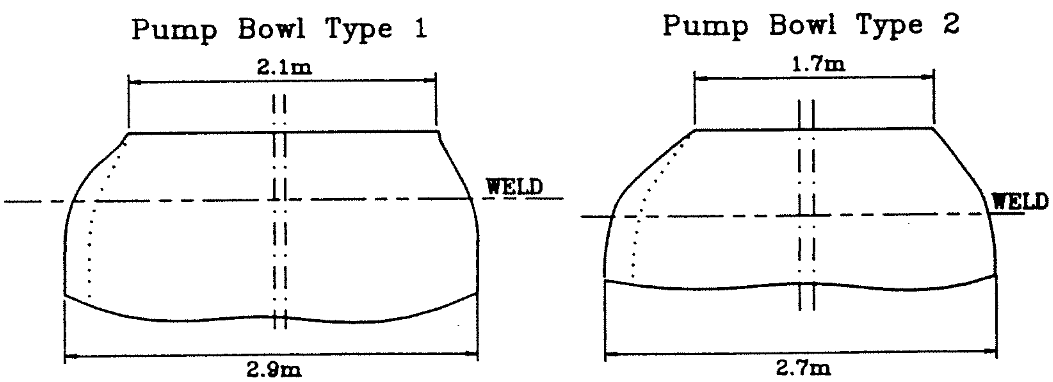


Fig 4. Volute Profiles of a 400 MWe, 2-Weld (type 1), and a 900 MWe, 1 or 2 Weld (type 2) pump bowl model

Figure 4 shows the variation of the volute profile of a given pump, as well as the variations between different pumps.

Table 1 compares the ultrasonic wave propagation properties with the reference block figures. The data indicated with brackets refer to measurements carried out with a prototype transducer, slightly different from the final probe used for the other pumps.

TABLE 1

ULTRASONIC PROPAGATION PROPERTIES
OF DIFFERENT PUMP BOWLS

Pump type	Mean Relative Attenuation [dB]		Mean Working Frequency [MHz]	
	Weld	Base	Weld	Base
900 MWe 3-loop 2 - weld	[-4 to 2]	[0 to 10]	[0.5]	[0.5]
900 MWe 3-loop 1 - weld	1 to 5	1 to 6	0.30	0.35
400 MWe 2-loop 2 - weld (1)	-4 to -8	-5 to 5	0.45	0.45
400 MWe 2-loop 2 - weld (2)	4			
Reference Block (SA-351 CF8A)		0		0.35

The figures are derived from measurements carried out on a number of points arbitrarily chosen on two parallel circumferences : one on the weld and one on the nearby base metal. This reduces the possible share of geometric influences (internal or external surface irregularities) in the assessment of the acoustical attenuation variation.

The analyzed backwall echoes are obtained with a highly damped focused beam probe. The effective working frequency depends on the material properties (grain size,...) which filter the initially broad frequency spectrum emitted by the probe. Figure 5 shows typical spectrum analysis data.

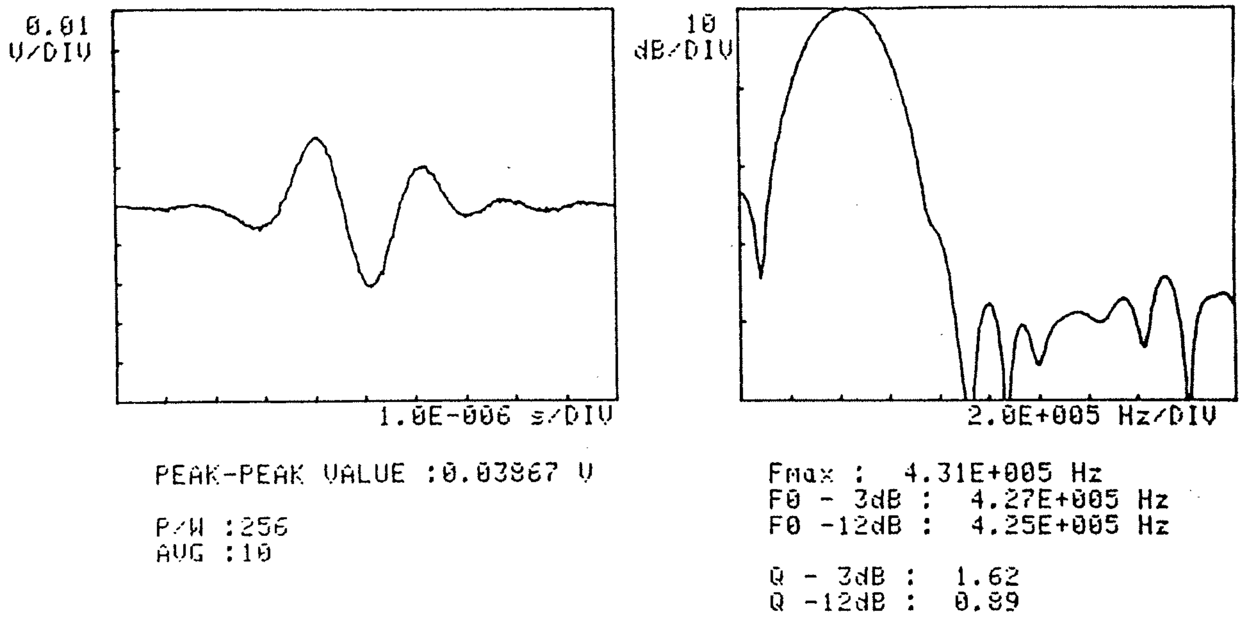


Fig 5. Typical Frequency Spectrum Analysis of a Backwall echo

Inspection

A first field inspection was achieved in Tihange 1, during a refuelling shutdown. It was carried out on a three-loop, two-weld Westinghouse design volute with a wall thickness ranging from 180 to 200 mm.

Examination techniques. Penetrant testing is applied on the outer surface of the pump bowl to detect possible near-surface flaws.

Volumetric examination of the two welds is achieved by ultrasonic testing. The 0-50 mm range beneath the outer surface is scanned manually with TRL contact probes, whereas the 50 to 200 mm range is scanned automatically with focusing transducers. According to the ASME Section XI requirements, angle beam scanning is conducted under four orthogonal directions ; defect characterization in pitch and catch mode could also be performed along the same orientations.

Inspection results. More than 70% of the weld was scanned automatically, the pump outlet nozzle and the supporting feet preventing from scanning some parts of the weld zones. Slight modifications of the manipulator are planned to increase that figure.

The examination revealed no reportable indication in the weld zones. However, some indications were detected well below the ASME reporting level.

Practical considerations. The inspection of a two-weld coolant pump, including the installation and the dismantling of the UT-equipment, was completed in two weeks, with continuous shift operation.

Driving the examination equipment requires two operators, with an appropriate training.

Data analysis is carried out off-line. A preliminary report, addressing the acceptability of the scanned zones, is made available a few days after the data acquisition.

In Tihange 1, the average ionizing radiation dose incurred by personnel was about 7000 microSievert per individual, with a maximum figure of 12000 microSievert.

CONCLUSION

An ultrasonic inspection system, based on focussed beam transducers, is available for the volumetric examination of PWR pump casing welds.

As the inspection is carried out from the external surface, draining and opening the pump to disassemble internal parts are not required, and, consequently, the inspection can be completed within the duration of a refuelling outage.

Preliminary field measurements must be conducted to ensure the proper operation of the equipment.

Field efficiency was demonstrated by the Tihange 1 performance.

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