

**ADVANCED PROCEDURES FOR THE ULTRASONIC EXAMINATION OF
NARROW GAP WELDS CONNECTING THE STEAM GENERATOR TO THE RCS PIPING.**

G. Maes, AIB-Vinçotte, Brussels, Belgium

M. Lepière, Tractebel Energy Engineering, Brussels, Belgium

Abstract

Steam generator replacement is a current topic in the nuclear industry worldwide. In Belgium, steam generators have already been replaced in three units. In all three cases, entirely automated narrow gap welding was performed to connect the primary nozzles of the new steam generators to the reactor coolant system piping.

Narrow gap welds present a specific metallurgical grain structure. In spite of the limited quantity of weld metal deposited this structure can drastically affect the capability of conventional ultrasonic examination techniques.

In the framework of its effort to comply with the requirements of Appendix VIII of Section XI of the ASME Code concerning the qualification of UT procedures for in-service inspection, Electrabel (the utility) and Tractebel (the A/E) initiated within the ASME XI Steering Committee, involving also AVN (the regulatory body) and AIB-Vinçotte (the AIA), the preparation of advanced procedures for the examination of such narrow gap welds.

To provide a solid technical foundation for these procedures, an experimental study was conducted on several types of narrow gap welds used in Belgian plants. This paper shall present results concerning the influence of important examination parameters such as wave type, frequency, and refracted angle on the propagation of ultrasound through the considered welds.

Realistic crack-like flaws in representative test blocks were used to assess the detection and sizing capability of newly developed, twin-crystal transducers. The enhanced performance in terms of signal-to-noise ratio and height sizing accuracy, obtained through customized design using focusing crystals, is clearly illustrated.

To conclude, the paper shall forward guidelines as to the selection of examination techniques for both manufacturing and in-service inspection of steam generator narrow gap welds, in relation with the specific geometry and the metallurgical structure of the considered components. As an example, an outline shall be presented of the examination procedures applied during the steam generator replacement of the Tihange 1 plant in August 1995.

1. Introduction

Steam generator replacement is a current topic in the nuclear industry worldwide. Indeed, steam generator tubes are known to be susceptible to corrosion. After some time, microcracks may appear in the tubes, and eventually cause leaks. Tube plugging or repairing methods, such as sleeving, can be used to maintain the structural integrity of the component. However, if too many tubes have to be plugged, the heat exchange capacity from the primary to the secondary circuit will deteriorate, and affect the power output and the efficiency of the unit as a whole. Depending on the repair which might be needed in the long term, replacement of the steam generator can prove to be the most cost-effective strategy and should enable the maintaining of a higher availability of the unit (1). Moreover, replacement of the steam generators may offer a unique opportunity to uprate the power of a nuclear plant.

At the replacements performed in three Belgian plants, Tihange 1, Doel 3 and Doel 4, fully automated GTAW (gas tungsten arc welding) narrow gap welding was used to connect the new steam generator to the existing reactor coolant system. Compared to conventional submerged arc welding using a double-angle chamfering, the amount of welding material and thus the welding time is drastically reduced. In addition, a low dose rate can be achieved.

2. Ultrasonic propagation in narrow gap welds

A typical primary piping narrow gap weld configuration is shown schematically on figure 1 : after welding, the width is about 10 mm and the bevel angle is reduced to almost 0°. The successive weld runs are parallel to the pipe surface.

The considered welds present a specific metallurgical structure, characterised by a large change in grain orientation across the weld. Such a structure is known to affect the propagation of acoustic energy. Numeric simulations using ray-tracing models have shown that considerable distortion of both straight and angle beams occurs when crossing the weld . Amplitude losses of about 40 dB have been predicted for conventional shear wave probes, compared to 6 dB for compression waves (2).

Additional difficulties are introduced by the variety of base materials to be welded : wrought and cast austenitic piping, statically cast elbows.

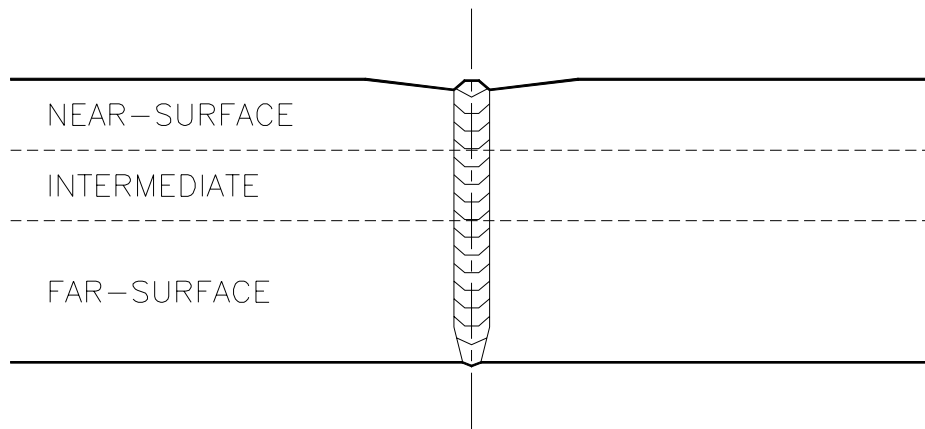


Fig. 1 : Schematical representation of typical primary piping narrow gap weld.

3. Experimental study

In the framework of its effort to comply with the requirements of Appendix VIII of Section XI of the ASME Code concerning the qualification of UT procedures for in-service inspection, the Belgian utility Electrabel initiated the preparation of advanced procedures for the examination of austenitic welds of the reactor coolant system.

As few relevant data on the capability of ultrasonic examination techniques for primary piping narrow gap welds were available, an experimental study on representative test specimens was deemed necessary to provide a solid technical foundation for the new examination procedures. The study aimed at assessing the influence of important inspection parameters, such as wave type, frequency, and refracted angle on the propagation of ultrasound through narrow gap welds.

3.1. Test specimens

Six test specimens were made available by the Belgian utility, all of them representative of narrow gap weld configurations encountered in Belgian plants. All specimens have external diameters of about 900 mm, and wall thicknesses of 75 or 90 mm.

Table 1 provides further details on the specimens and on the reflectors. In two of the test blocks the narrow gap weld connects a cast to a wrought base material, while in all other blocks two wrought base materials are welded together. Series of side-drilled holes are present both in the various base materials and in the welds. To simulate far-surface cracks, both rectangular and circular slots of different heights and orientations were machined at realistic positions in the weld and the HAZ. The circular slots are identical to the smooth and sharp defects commonly used in the PISC III exercise (type A flaws), and were manufactured at the JRC Petten of the CEC.

3.2. Equipment

Manual ultrasonic examination of the specimens was performed using a standard Krautkrämer USK7D flaw detector. Measurements for detection and sizing of crack-like reflectors were also performed by automated ultrasonic testing, using a Tomoscan data acquisition system and a motorized scanning device.

An extensive set of ultrasonic probes was applied during the experimental study. Table 2 lists the different models, with their nominal characteristics (measured in carbon steel) and the depth zone(s) for which they have been tested. Conventional shear wave transducers were used as well as twin-crystal compression wave (TRL) probes.

The so-called focusing TRL transducers are designed with curved piezoelectric elements instead of the more common planar elements. This yields an "optical" focusing, in addition to the pseudo-focusing effect generated by the overlap of transmitter and receiver beams. Thus, a very narrow acoustic beam can be obtained in a limited depth range, improving both the signal-to-noise ratio (SNR) and the lateral resolution. Figure 2 illustrates the detection and sizing capability of the TS45 1 635 transducer (45°TRL, 1 MHz) on a sharp spark-eroded slot at the far-surface in cast austenitic base material : the clearly resolved tip diffraction signal allows for accurate height sizing.

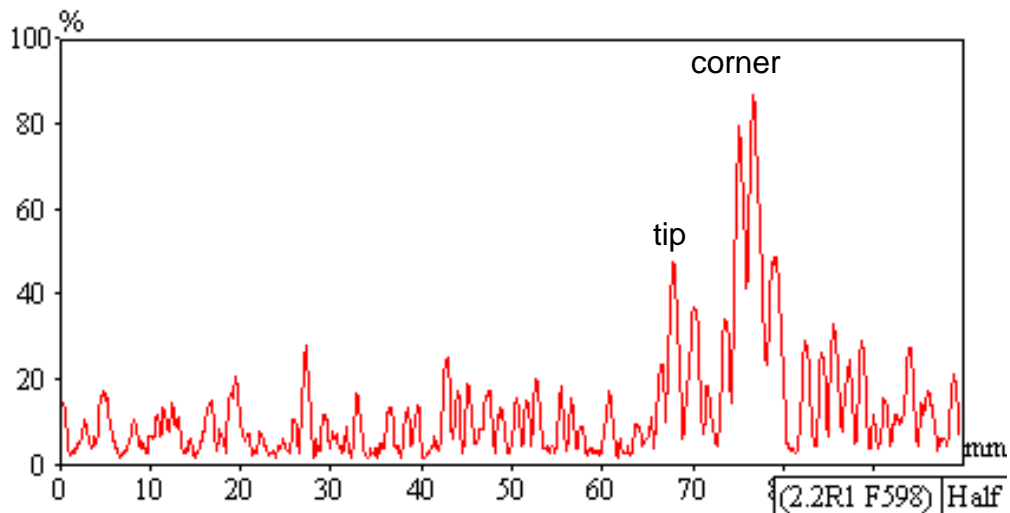


Fig. 2 : A-scan signal obtained with focusing 45°TRL, 1 MHz search unit on far-surface breaking crack-like flaw (h = 10 mm) in CCSS test specimen.

3.3. Data recording

All examinations of the test specimens were conducted from the outside surface, scanning perpendicular to the weld axis.

A flaw is considered detected if the peak echo amplitude exceeds the noise level estimated in a flawless zone of the test specimen, at the same depth range. The SNR was determined for each reflector. Measurements on side-drilled holes were performed to evaluate the influence of the propagation through different materials on the performance of the examination, while the detection capability for service-induced defects was assessed on simulated crack-like defects.

Flaw height measurements for planar surface breaking defects were recorded whenever the tip diffraction method was applicable.

4. Data exploitation

4.1. Influence of the narrow gap weld

To assess the influence of the weld structure and of the interfacing fusion lines, side-drilled holes in the heat affected zone were insonified through wrought base material on the one hand and through a narrow gap weld on the other hand (see figure 3). The signal-to-noise ratio values obtained with the considered examination techniques are presented in table 3, under insonification modes "A" and "B". All values are averages resulting from data recorded on different test specimens.

Even at a low excitation frequency, the detection capability of shear wave transducers is drastically affected by the crossing of the weld : several reflectors cannot be detected, and amplitude losses of at least 10 dB are observed on the others. This confirms the predictions of theoretical modelling (2).

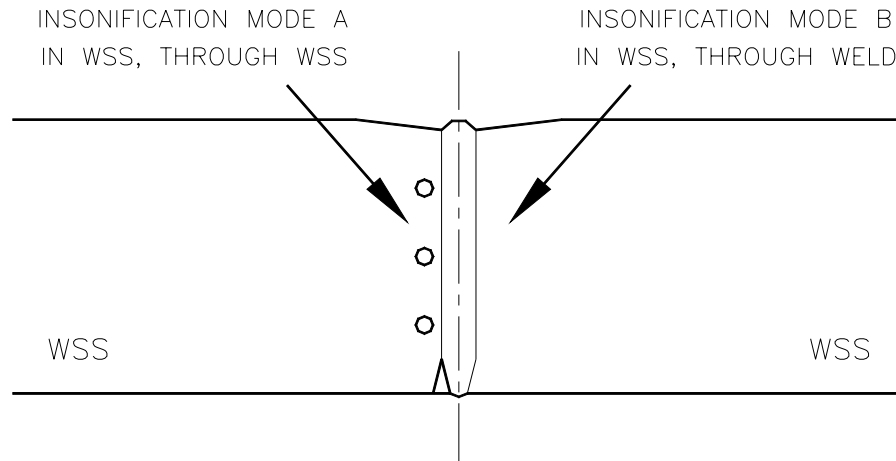


Fig. 3 : Insonification modes for the assessment of the influence of the narrow gap weld on ultrasonic capability

Compression wave probes detect all reflectors for both insonification modes. The amplitude loss while crossing the weld varies from 4 to 9 dB. When only 1 MHz focusing TRL transducers are considered, a SNR of at least 22 dB is observed for insonification through the weld. The improvement of the detection capability compared to standard TRL probes is in the range from 4 to 15 dB.

4.2. Influence of the base material

Side-drilled holes located at the weld centre line were insonified from two different base materials, as shown schematically on figure 4, to assess the influence on acoustic energy propagation and detection capability. The signal-to-noise ratio values obtained with the considered examination techniques are mentioned in table 3, under insonification modes "C" and "D". The detection capability in cast austenitic base material is equally presented (insonification mode "E").

As generally known, shear wave probes are not suited for propagation through cast austenitic material : none of the reflectors could be detected. Even for insonification through wrought base material, poor SNR values are achieved on reflectors in the narrow gap weld : 15 dB for the near-surface range, and 10 dB for the intermediate and the far-surface range.

The performance of low-frequency TRL transducers is only slightly affected by the difference in base material : the cast base material generates an average SNR reduction of 8 dB. The focusing 45°TRL search unit for the far-surface range still allows for a SNR of 18 dB through cast material.

No clear influence of the refracted angle could be observed for either compression or shear waves.

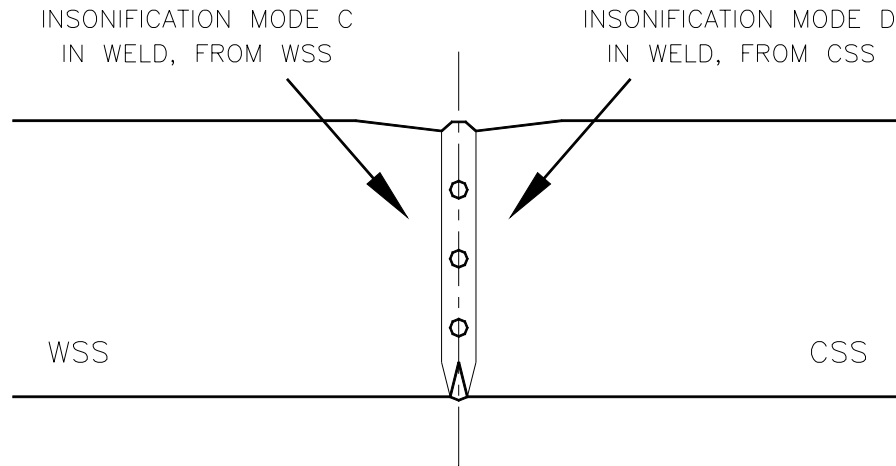


Fig. 4 : Insonification modes for the assessment of the influence of various base materials on ultrasonic capability

4.3. Detection and sizing of far-surface breaking flaws

Detection results obtained on simulated crack-like defects for different insonification modes are presented in table 4. For a surface breaking defect located in the heat-affected zone, the focusing TRL probe detects the corner reflection with a SNR of 17 dB through wrought base material, and 10 dB through the narrow gap weld. A reflector in the weld is detected with a SNR of 19 dB when insonifying through wrought base material and only 7 dB when insonifying from the cast side. In general, it is observed that the SNR on defects located near the weld is affected by the presence of ultrasonic noise generated by the fusion lines.

Low-frequency shear waves at 45° were observed to provide excellent detection capability on far-surface breaking flaws in the weld or in the heat-affected zone, but only for insonification through wrought base material. Indeed, shear waves at 45 degrees are known to generate a more efficient corner reflection than compression waves.

Accurate height sizing of crack-like flaws can only be achieved in the presence of clearly resolved tip diffraction signals. The capability of focusing TRL probes to generate these signals was demonstrated on both cast and wrought stainless steel base material. However, for flaws located in the heat-affected zone or in the weld material, no diffraction signals could be resolved from the obviously broadened corner echo, an effect most probably caused by the weld structure.

4.4. Detection capability of straight beam probes

Under certain conditions, the narrow gap welding technique can generate lack of interrun fusion defects, parallel to the external surface. As such defects cannot be detected by radiographic testing, there is a need for an effective ultrasonic straight beam examination during manufacturing inspection (3). Using the two straight beam probes mentioned in table 1, SNR values higher than 15 dB were obtained over the complete depth range on 3 mm diameter side-drilled holes located in the weld. The detection capability of the probe for the intermediate and the far-surface range is clearly illustrated on figure 5.

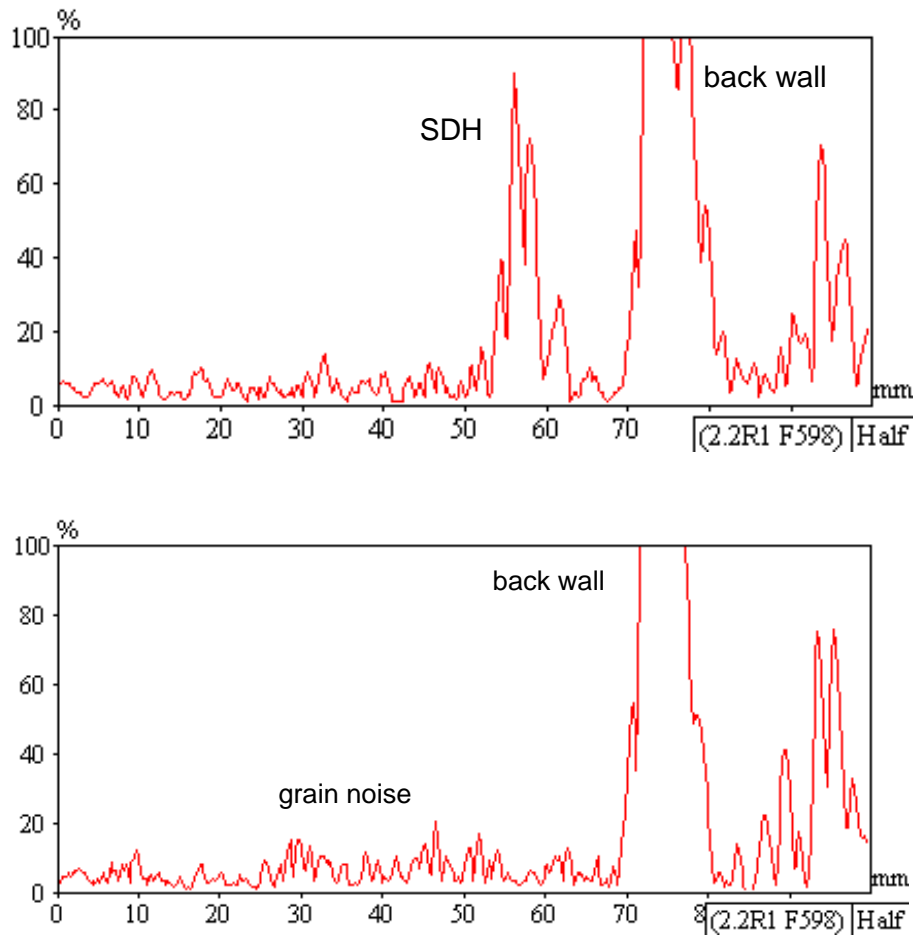


Fig. 5 : Ultrasonic signals obtained with focusing 0°TRL, 1 MHz search unit in primary piping narrow gap weld : A-scan signal on 3 mm diameter SDH at 55 mm depth (above), and on a flawless region (below).

5. Selection of examination techniques

In the framework of manufacturing inspections of primary piping welds, the transposition into the Belgian context of Section III of the ASME Code demands a full thickness ultrasonic examination of the weld in addition to the radiographic examination. The experimental study discussed above clearly demonstrates the superior performance of low-frequency focusing TRL probes, especially for detection of flaws through welded or cast material. However, the beam focusing technique only generates an increased examination sensitivity in a limited depth zone (4). Thus, in order to achieve constant examination sensitivity and sufficient signal-to-noise ratio over the complete depth range several transducers are required. This principle is illustrated in figure 6 for the angle beam examination of a primary piping weld.

Examination sensitivity

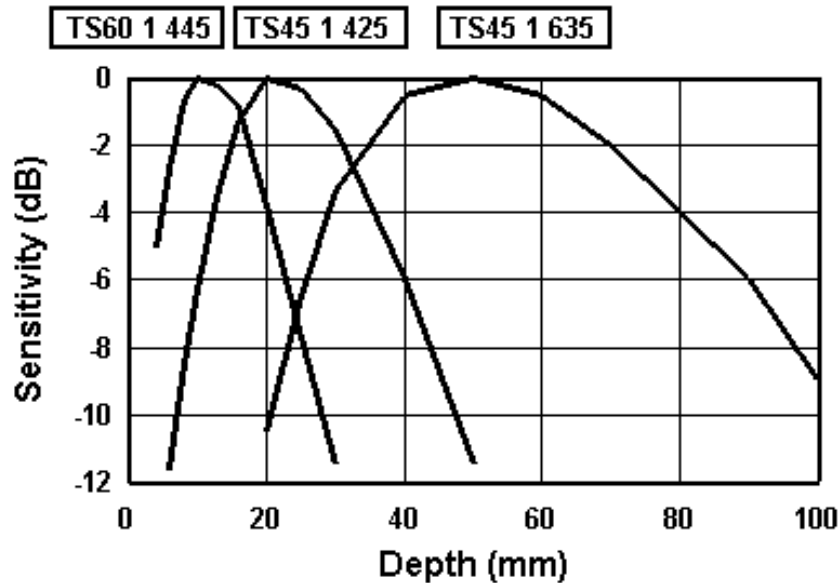


Fig. 4 : Sensitivity curves of angle beam twin-crystal search units covering the various depth ranges

In Belgium, in-service inspections are performed according to section XI of the ASME code. For primary piping, only the inner third of the wall thickness is to be examined. This depth range is fully covered by the TS00 1 425 (straight beam) and the TS45 1 635 (angle beam) focusing TRL search units. In addition, for an enhanced detection probability of surface-breaking flaws in wrought base material, the use of a 45 degree shear wave probe is strongly recommended.

The selection of examination techniques, as presented hereabove, is appropriate for a standard pipe-to-pipe configuration, and needs to be adapted for real inspection configurations. First of all, the external surface of steam generator primary nozzles is conical. Therefore, to maintain the optimal 45 degree incidence angle between the acoustic beam and a surface-breaking planar defect, the nominal refracted angle of the far-surface transducers requires to be modified. Second, the mechanical matching of a new steam generator to the existing reactor coolant system may introduce particular external surface conditions in the narrow gap weld region. In such cases, alternative beam angles may be required for near-surface or intermediate zone, in order to increase the resulting inspected volume. In fact, an optimized scanning schedule is prepared for each weld configuration .

Examination procedures designed according to this principle have been applied during the Tihange 1 and Doel 4 steam generator replacements. During the qualification phase, the high detection capability of the examination method was clearly demonstrated on a representative test sample : a number of fairly small lack of interrrun fusion type indications were detected and confirmed afterwards by destructive examination of the sample.

6. Conclusions

An experimental study on ultrasonic examination capability in various primary piping narrow gap weld configurations led up to the following results :

- low-frequency (1 MHz) focusing TRL search units demonstrate an excellent general detection performance : the SNR is almost unaffected by the weld structure.
- all far-surface breaking flaws are reliably detected by TRL probes, while shear wave transducers are efficient through wrought base material only.
- focusing TRL probes can in some cases generate tip diffraction signals allowing for accurate height sizing of crack-like defects.

Industrial examination procedures were presented for manufacturing and in-service inspection of narrow gap welds, providing constant sensitivity over the complete depth range while scanning from the outside surface only. The considered procedures can be applied manually as well as by mechanised inspection.

7. Acknowledgements

Most of the work presented in this paper was sponsored by the ASME XI Steering Committee which involves Electrabel (the utility), Tractebel (the A/E), AVN (the regulatory body) and AIB-Vinçotte (the AIA).

8. References

1. Ph. Somville, P. Hernalsteen, R. Houben, "Steam Generator Replacement as a Part of a General Problem Management Process", Spec. Meeting on Operating Experience with Steam Generators, Brussels (Belgium), September 1991
2. J. A. Ogilvy, "The Influence of Austenitic Weld Geometry and Manufacture on Ultrasonic Inspection of Welded Joints", British Journal of NDT, May 1987
3. B. Brion, "Le Contrôle Ultrasons des Soudures TOCE des Tuyauteries Primaires", RGN, September-October 1994
4. G. Maes, M. Delaide, Ph. Dombret, "On the Use of the Ultrasonic Beam Focusing Technique", 11th Int. Conference on NDE in the Nuclear and Pressure Vessel Industry, Albuquerque (NM), April 1992
5. M. Lepièce, J-P. Liétard, "Belgian Response to ASME XI Requirements", BELGATOM, 2nd International Conference, Brussels (Belgium), May 1995

Table 1: Test specimens and reflectors.

SPECIMEN	BASE MATERIAL	WELD	REFLECTORS
064/SN2 Doel 3	WSS / WSS	narrow gap SIEMENS	side-drilled holes ($\varnothing = 3.0$ mm) in WSS rectangular slot (h = 2.5 mm) in weld
068/SN3 Doel 3	WSS / CSS	narrow gap SIEMENS	side-drilled holes ($\varnothing = 3.0$ mm) in WSS and CSS
DOEL4SGR Doel 4	WSS / CSS	narrow gap SIEMENS	side-drilled holes ($\varnothing = 4.8$ mm) in WSS, in CSS, in HAZ and in weld rectangular slot (h = 10.0 mm) in weld
TOCE1 Tihange 1	WSS / WSS	narrow gap FRAMATOME	side-drilled holes ($\varnothing = 3.0$ mm) in WSS and in weld milled notch (1.5 x 4 mm)
TOCE3 Tihange 1	WSS / WSS	narrow gap FRAMATOME	type A circular slots (h = 5.0, 7.5 and 10.0 mm) in WSS, in HAZ and in weld
TOCE5 Tihange 1	WSS / WSS	narrow gap FRAMATOME	type A circular slots (h = 7.5 and 10.0 mm) in WSS, in HAZ and in weld

Table 2 : UT transducers (note : characteristics are measured in carbon steel).

PROBE	WAVE TYPE	PROBE TYPE	HOUSING WxLxH	FREQ	ANGLE	DEPTH ZONE
MSEB-2E	L	TRL	$\varnothing 20 \times 45$ mm	2 MHz	0°	near-surface
TS00 1 425	L	TRL focused	50x40x38 mm	1 MHz	0°	intermediate / far-surface
ST70 2 121	T	Single crystal	17x29x22 mm	2 MHz	70°	near-surface
TS70 2 220	L	TRL	30x30x31 mm	2 MHz	70°	near-surface
TS60 1 445	L	TRL focused	50x40x38 mm	1 MHz	60°	near-surface
TS45 1 425	L	TRL focused	50x40x38 mm	1 MHz	45°	intermediate
TS60 1 520	L	TRL	50x50x38 mm	1 MHz	60°	intermediate / far-surface
WB45-N1	T	Single crystal	32x55x50 mm	1 MHz	45°	intermediate / far-surface
TS45 1 621	L	TRL	60x60x45 mm	1 MHz	45°	far-surface
TS45 1 635	L	TRL focused	60x60x45 mm	1 MHz	45°	far-surface
WB60-N1	T	Single crystal	32x55x50 mm	1 MHz	60°	intermediate / far-surface

Table 4 : Signal-to-noise ratio values of corner reflections obtained on realistic far-surface breaking planar flaws for various insonification modes (Remark : "ND" means that the reflector was not detected, whereas "-" means that no measurement was performed).

PROBE TYPE	INSONIFICATION MODE				
	A IN WSS (HAZ) THROUGH WSS	B IN WSS (HAZ) THR. WELD	C IN WELD FROM WSS	D IN WELD FROM CSS	E IN CSS THROUGH CSS
45°T, 1 MHz	24 dB	12 dB	19 dB	ND	ND
45°TRL foc., 1 MHz	17 dB	10 dB	19 dB	7 dB	10 dB

Table 3 : Signal-to-noise ratio values obtained for various angle beam transducers and insonification modes (Remark : "ND" means that the reflector was not detected, whereas "-" means that no measurement was performed).

		INSONIFICATION MODE				
DEPTH ZONE	PROBE TYPE	A IN WSS THROUGH WSS	B IN WSS THR. WELD	C IN WELD FROM WSS	D IN WELD FROM CSS	E IN CSS THROUGH CSS
NEAR-SURFACE (0 - 20 mm)	70°T, 2 MHz	26 dB	ND	15 dB	ND	ND
	70°TRL, 2 MHz	21 dB	12 dB	13 dB	ND	14 dB
	60°TRL foc., 1 MHz	34 dB	27 dB	34 dB	28 dB	28 dB
INTERMEDIATE (20 - 40 mm)	45°T, 1 MHz	28 dB	ND	10 dB	ND	ND
	60°T, 1 MHz	19 dB	ND	10 dB	ND	ND
	45°TRL foc., 1 MHz	26 dB	22 dB	18 dB	25 dB	26 dB
	60°TRL, 1 MHz	22 dB	18 dB	20 dB	11 dB	14 dB
FAR-SURFACE (40 - 90 mm)	45°T, 1 MHz	23 dB	10 dB	10 dB	ND	ND
	60°T, 1 MHz	23 dB	12 dB	9 dB	ND	ND
	60°TRL, 1MHz	21 dB	14 dB	16 dB	10 dB	13 dB
	45°TRL, 1 MHz	22 dB	20 dB	18 dB	13 dB	15 dB
	45°TRL foc., 1 MHz	35 dB	28 dB	28 dB	18 dB	22 dB