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Developments in Ultrasonic Inspection I

Influence of Crack Networks on the Ultrasonic Inspection of a Propagated Defect

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SUMMARY

Thermal fatigue in the mixing zones of pressurized water reactor pipings can potentially lead to the appearance of crack networks. Ultrasonic detection and characterization of a propagated defect in such a network is then a challenge.

To study the influence of these secondary crack networks on the ultrasonic inspection of a propagated defect, a mock-up was produced. The innovative manufacturing process must allow, according to the supplier, to propagate cracks with realistic and controlled characteristics, in terms of position, sizing, opening, residual stresses and fracture surface roughness.

The selected configuration deals with the inspection of various crack networks of 2 millimetres depth, with various inter-crack spaces (from 1 to 4 millimetres), propagated in a mock-up thickness of 38 millimetres. Two deeper notches were established afterwards in these crack networks.

Experimental tests were then carried out and we present and discuss here the various results obtained.

1. CONTEXT

Simulation is used more and more for Non Destructive Testing (NDT), to design or qualify an application, or to contribute to the expertise of an inspection result.

Modelling tools are now available to simulate the ultrasonic inspection of an isolated defect, according to its descriptor parameters [LON][MAH], but all the cases encountered on sites are not covered. Indeed, the inspection of the mixing zones results in studying the cases of zones potentially subjected to thermal fatigue. The awaited damage resulting from this mechanism consists of a crack network. Under specific loading conditions, one particular crack could propagate in this network. From a mechanical point of view, the critical defect corresponds to the propagated one, which has to be correctly characterised by NDT.

In order to study the abilities of the codes for simulate the ultrasonic inspection of this type of damage, some preliminary experimental reference tests were necessary. Consequently, a representative mock-up was produced and this paper synthesizes the main experimental results obtained.

2. STUDIED MOCK-UP

The experimental tests were carried out on a mock-up taken in a 38 mm rolled sheet of austenitic stainless steel (316L type).

A crack network, representative of thermal crackling, was first established in this mock-up by Trueflaw Company (Finland). Then, to study the influence of this network on the detection of a propagated defect, we chose to machine two notches of 30 mm length, 8 mm height and 0.2 mm thickness.

2.1 Manufacturing process

The initiation and the growth of the thermal fatigue damage are based on the stress cyclic repetition, inducing microscopic plastic deformations. The cracks created by these repeated stresses depend on the material properties and the characteristics of the fatigue cracks are directly related to the temperatures and the rates of loading. Consequently, by controlling the heating and cooling, the accumulated damage can be controlled.

The mock-up is thus subjected to thermal fatigue cycling, by applying successive heating and cooling periods. High frequency induction is used as the heating method, while water and gas spray are used for cooling. With this method, sufficient amplitude of temperature is obtained quickly, which makes it possible to accelerate cracking. In addition, the cycles are selected so that no unwanted change of the microstructure occur (grain size, phase transformation, etc) [KEM].

2.2 Dye penetrant inspection

The first NDT consists of a dye penetrant inspection, with the objective of visualizing the network and the crack morphology in the emerging side.

Figure ***1*** presents the result of dye penetrant inspection. This test was prolonged on the left side of the image, to reveal the fine crack network at this extremity. Three networks are thus revealed whose characteristics are detailed below (see next paragraph).

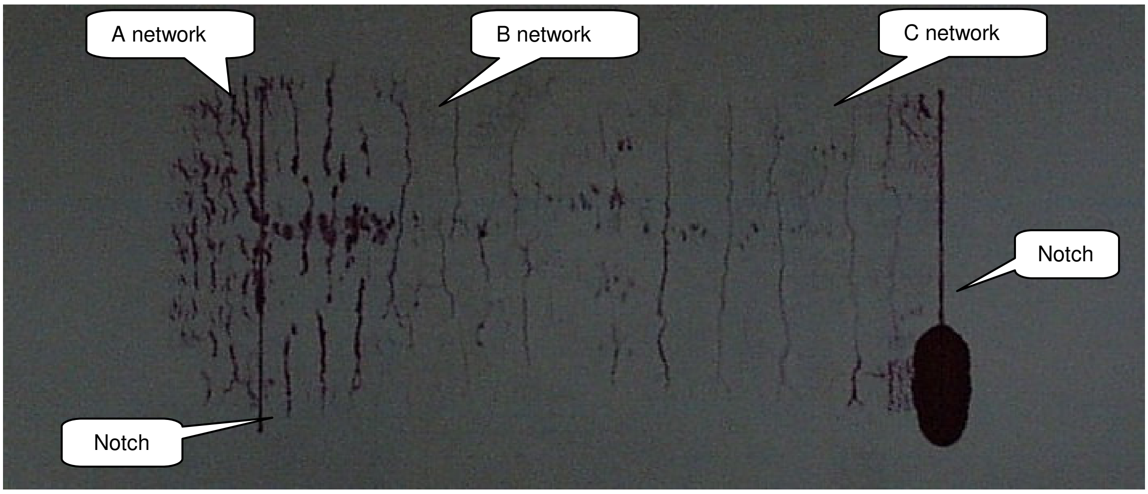

Figure 1 - Dye penetrant test of the crackled mock-up in the presence of the electro-eroded notches

2.3 Destructive examination

To complete the dye penetrant inspection, we also carried out destructive examination of the mock-up. These exams make it possible to characterize precisely the crack networks. Figure 2 schematically presents how the mock-up could be modelled (see prospects), while Table 1 gives the principal characteristics of each of the three networks.

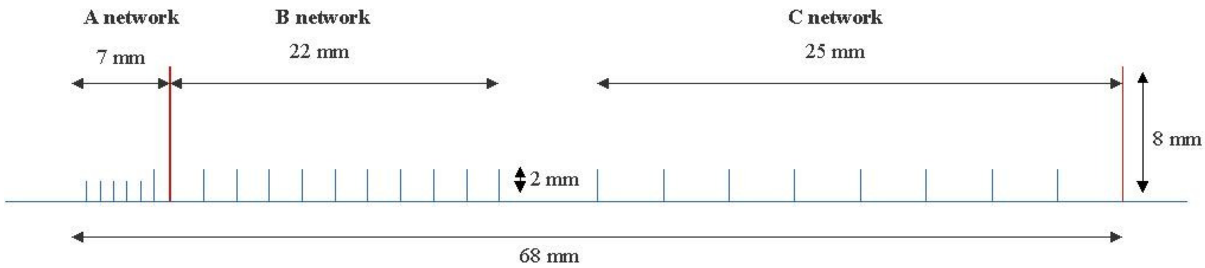

Figure 2 - Schematic representation of the three networks obtained (blue) and of the two notches (red)

Table 1 - Characteristics of the three networks studied

	Average distance between cracks (mm)	Extend of the network (mm)	Opening at flaw mouth (µm)	Average height and standard deviation (mm)	Max height (mm)
A network	1	7	<30 to 50	0.9 +/- 0.5	1.8
B network	2.5	22	50 to 90	1.8 +/- 0.8	2.5 to 2.8 locally
C network	5	25	80 to 110	2.1 +/- 1.0	3.5

Concerning the morphology of crack networks, the observations are presented below:

- For network A., the cracks are very parcelled out (length not exceeding a few millimetres) and discontinuous, with local disorientations, which can be significant.
- Network B. presents discontinuous but less parcelled out cracks and each one is longer (from 10 to 20 mm) and more rectilinear.
- Lastly, the cracks of network C. are relatively rectilinear and continuous, with a length of approximately 30 mm.

Taking into account the results of open measurements carried out at flaw mouth and the presence of small craters in internal wall, we can consider that the loading was relatively important. Moreover, the loading was certainly more significant for C network (more important openings at flaw mouth) [VIR].

The crack openings measured at flaw mouth and observed along the crack height indicate that we are in the presence of open cracks, therefore favourable to UT inspection [VIR][PIT].

3. TRANSDUCERS

In order to study the influence of the inspection configuration, we used a wide range of probes. The studied parameters are the wave type (longitudinal and shear), the frequency (1 MHz and 2 MHz), the propagation angle (45 and 60°) and the probe type (single or dual).

UT inspections with pulse echo mode, in the two directions, make it possible to study the influence of each network. In addition, inspection in direction 2 also makes it possible to obtain reference for the isolated defect.

4. RESULTS

The mock-up was inspected with the selected probes, before and after notch implantation, to facilitate the result interpretation.

4.1 Detection by corner echo

The detection of an emerging plane defect requires obtaining a corner echo, on the dihedron formed by the defect itself and the component internal wall. In the presence of a crack network, the amplitude of this echo is more or less affected by shade phenomena and multiple rebounds, according to the inspection configuration (probe, height of the cracks, distance between cracks, etc).
To highlight the influence of the inspection configuration and the distance between cracks, we analyse first the impact of the various networks on the corner echo amplitude. Table 2 shows the results obtained.

Table 2 - Influence of the various networks on the corner echo amplitude* of the propagated defect

Configuration		A network Step of 1 mm	B network Step of 2.5 mm	C network Step of 5 mm
SW	45° 2MHz	-4.3	-6.2	-4.8
	60° 2MHz	-1.2	-1.5	-2.1
	45° 1MHz	-3.2	-5.9	-7.6
	60° 1MHz	-1.0	-2.8	-2.0
LW	45° 2.25MHz	-0.8	-1.3	-2.0
	60° 2.25MHz	-0.6	-5.6	-2.4
	TRL60° 2MHz	0.1	-5.0	-6.9
	TRL45° 1MHz	0.6	0.7	0.1

*: Amplitude losses on the corner echo (dB) compared to the reference defect: isolated notch of 8 mm height.

The experimental results show that the more penalizing configurations involve an amplitude loss of approximately 7 to 8 dB, while certain inspection configurations, more favourable, are less influenced (less than 2 dB) by the presence of the studied crack networks (LW45 at 1 MHz or 2 MHz and SW60 at 2 MHz).

In addition, with SW, inspections at 60° are less sensitive to the presence of a small crack network than inspections at 45°, while in LW the effects are reversed.

Lastly, the results obtained at 1 and 2 MHz are comparable (SW or LW). Indeed, the differences observed between these two frequencies remain lower than 2 dB most of the time.

These results highlight the least influenced inspection configurations by the presence of a crack network (LW45 and SW60) and the most impacted configurations (LW60 and SW45).

On the other hand, taking into account the amplitude variations obtained between reference defect and crack networks (10 to 14 dB in SW and only 3 to 7 dB in LW), the most adapted configuration for detection is not necessarily the one whose corner echo remains the most stable in the presence of a network. Table 3 shows the results obtained in terms of signal to noise ratio (the noise includes the echoes obtained on the crack networks).

The results indicate that the most favourable configuration for the detection of a propagated defect of 8 mm height, within the studied crack networks, is the one using a SW60° probe (RSB > 10 dB).

Table 3 - Influence of the various networks on the SNR of a propagated defect

Configuration		Isolated defect	A network Step of 1 mm	B network Step of 2.5 mm	C network Step of 5 mm
SW	45° 2MHz	12.4	6.8	6.2	6.3
	60° 2MHz	14.3	11.6	12.8	10.8
	45° 1MHz	9.5	7.0	3.6	2.6
	60° 1MHz	13.5	12.5	10.7	11.6
LW	45° 2.25MHz	6.6	5.8	5.3	4.6
	60° 2.25MHz	2.7	2.3	-2.8	0.6
	TRL60° 2MHz	5.8	7.5	0.8	0.5
	TRL45° 1MHz	2.7	4.4	3.4	3.9

*: SNR (dB) of the corner echo of the propagated defect compared to the max level of the network echoes.

4.2 Height sizing

Height sizing of a plane defect requires obtaining a diffraction echo on the top of the defect. Table 4 shows the results obtained in terms of height measurement of the propagated defects (8 mm height) according to the crack network studied. The measurement method takes into account the position of the diffraction echo and the component thickness.

Table 4 - Influence of various networks for height sizing of a propagated defect of 8 mm

Configuration		Isolated defect	A network Step of 1 mm	B network Step of 2.5 mm	C network Step of 5 mm
SW	45° 2MHz	8.3	7.5	7.8	7.4
	60° 2MHz	7.1	7.1	7.2	7.9
	45° 1MHz	8.3	6.6	ND	ND
	60° 1MHz	7.3	8.3	6.4	11.0
LW	45° 2.25MHz	7.8	7.6	7.7	7.7
	60° 2.25MHz	8.9	8.9	8.7	8.9
	TRL60° 2MHz	8.2	8.2	6.7	7.6
	TRL45° 1MHz	7.8	8.1	8.2	6.4

ND: diffraction echo not detected.

On the isolated defect, the measurement method selected involves an intrinsic sizing error lower than 5%, with an atypical configuration for the L60-2 MHz transducer for which the maximum error is 11%.

Generally, the presence of a 2 mm crack network does not disturb (or little) height sizing by the diffraction echo of a propagated defect. Diffraction echo remains quite distinct from the network echoes.

However, in the presence of a network, we can observe under sizing of 20% (SW-1 MHz and TRL45° at 2 MHz), but also over sizing of almost 40% in SW60° at 1 MHz.

For the studied propagated defect, the presence of a type C network is particularly unfavourable with SW45° transducer. Indeed, the diffraction echo is not detected at 1 MHz and is mixed with a network echo at 2 MHz (Figure 3).

In conclusion, the sizing of a propagated defect of 8 mm height is not called into question by the presence of network, more precisely when using a TRL60 - 2 MHz probe.

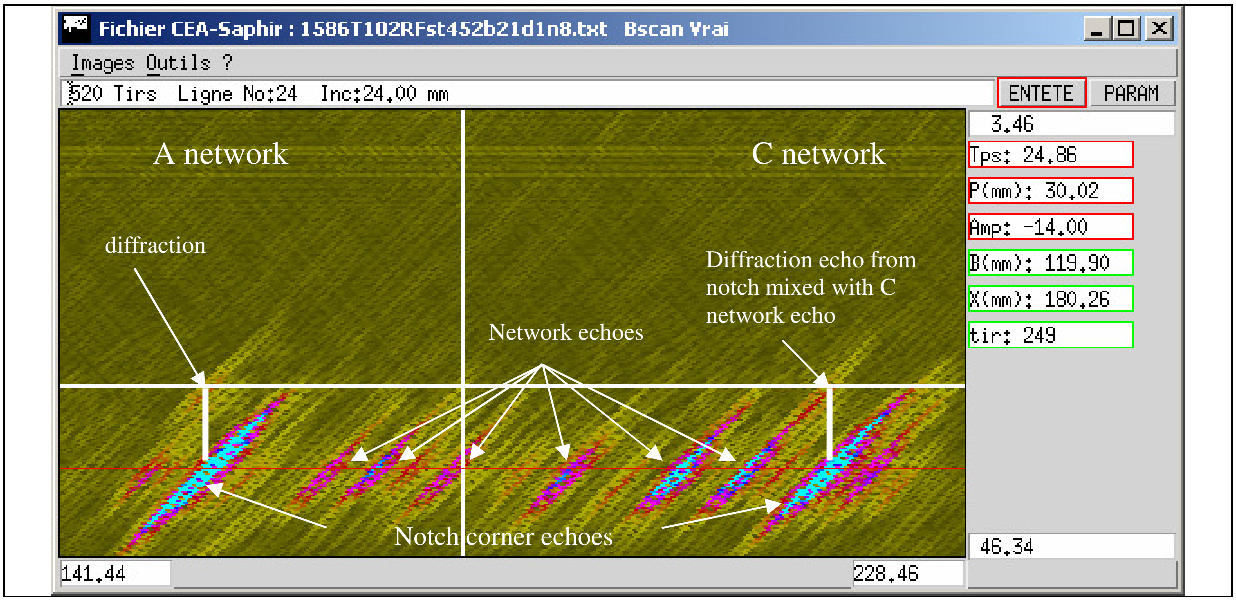

Figure 3 - SW45°-2 MHz probe (component internal wall in red, notches in white and white cursor at the top of the notches)

4.3 Contribution of mode conversion echoes for the characterization

The presence of mode conversion echoes (LLT, LTL or LTT) is useful to characterize a propagated plane defect. A previous study showed that the amplitude of LLT echo obtained with LW transducer by reflexion on the defect and mode conversion on the internal wall strongly depends on the defect height [DUP][BCS].

Table 5 presents the results obtained in terms of amplitude loss of this echo according to the crack network studied. Table 6 presents the evolution of the amplitude difference between the mode conversion and the corner echoes.

Table 5 - Influence of various networks on the amplitude of mode conversion echo*

Probe	A network Step of 1 mm	B network Step of 2.5 mm	C network Step of 5 mm
LW45° 2.25MHz	1.0	-6.0	-3.3
LW60° 2.25MHz	-2.3	ND	ND
TRL60° 2MHz	-1.7	-7.8	-7.5
TRL45° 1MHz	-1.1	-4.4	-3.7

*: Amplitude loss (dB) of mode conversion echo compared to that obtained on the isolated defect.

Table 6 - Influence of various networks on the amplitude ratio between mode conversion echo and corner echo (dB)

Probe	Reference defect	A network Step of 1 mm	B network Step of 2.5 mm	C network Step of 5 mm
LW45° 2.25MHz	-9.2	-7.4	-13.9	-10.4
LW60° 2.25MHz	-2.7	-4.4	/	/
TRL60° 2MHz	-1.5	-3.3	-4.3	-2.1
TRL45° 1MHz	1.0	-0.7	-4.1	-2.8

These results indicate that the presence of a crack network affects more the amplitude of the mode conversion echo than the corner echo. Indeed, in the presence of a B or C network, the amplitude loss of the mode conversion echo can reach 8 dB for an inspection at 60° and 6 dB at 45°. For memory, at 45°, the amplitude loss on the corner echo does not exceed 2 dB.

On the other hand, disturbances due to the A network are weak. The weak extent of this network and the low depth of the first cracks can explain this result. In this case, the mode conversion on the internal wall is carried out in front of the network.

Taking into account these results, for sizing a propagated defect, it would be risky to limit the analysis to the amplitude of the mode conversion echo. Indeed, the defect height could be underestimated, more precisely if the diffraction echo were badly detected.

To illustrate these results, Figure 4 and Figure 5 present corrected Bscans, respectively obtained with LW45 and TRL60 probes at 2 MHz, on the reference notch (on the right) and on the notch propagated in the B network (on the left). These presentations make it possible to visualize the amplitude losses of the corner echo and of the mode conversion echo.

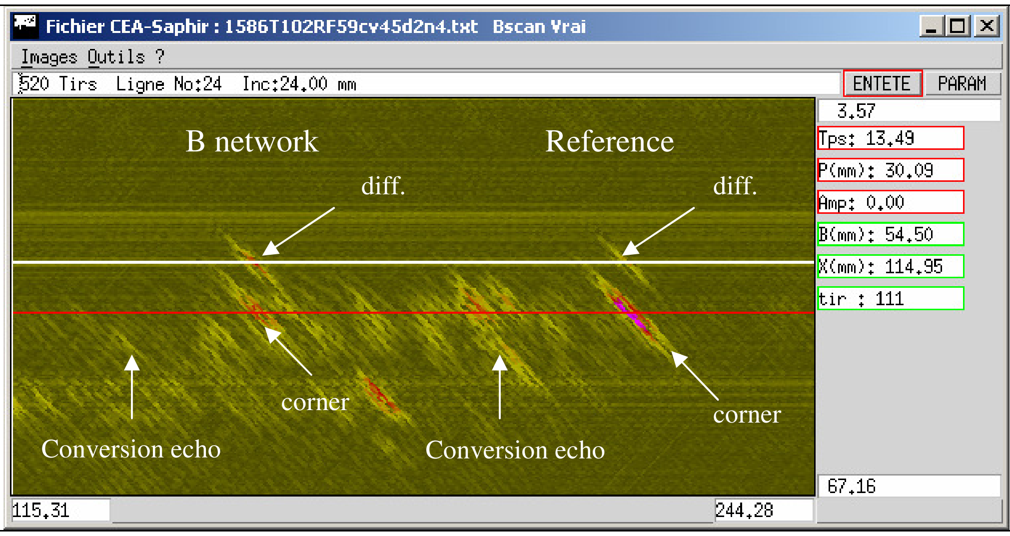

Figure 4 **-** LW45°-2 MHz probe
(component internal wall in red and white cursor at the top of the notches)

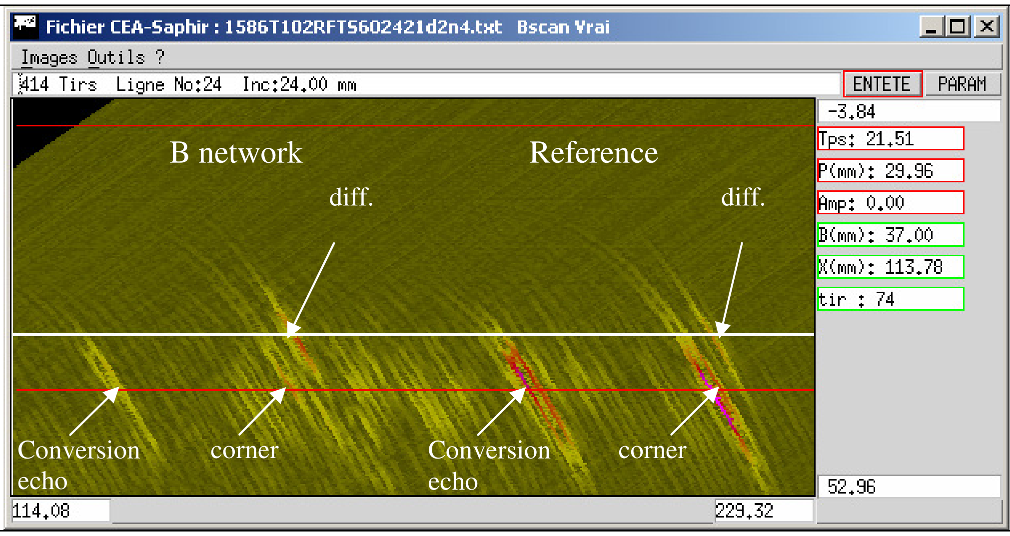

Figure 5 - LW60°-2 MHz probe
(component internal wall in red and white cursor at the top of the notches)

5. CONCLUSIONS AND PROSPECTS

In order to study the influence of a secondary crack network on UT inspection of a propagated defect, experimental tests were carried out. A specific mock-up was produced, and this paper presents the principal experimental results obtained.

As far as the influence of the studied crack networks is concerned, the principal conclusions for a propagated defect of 8 mm height are as follows:

- The distinction of the corner echo of the propagated defect, and even the detection, can in certain configurations, to be called into question by the presence of crack network. For detection, the use of a SW60° probe is recommended, with a SNR which is always higher than 10 dB. This SNR can fall 7 dB with other configurations, which are more influenced by the presence of a network. This conclusion is valid only for homogeneous and isotropic steels, but not for the austenitic stainless steel welds, in which SW are strongly disturbed [DUP2].
- The diffraction signal is always available, except with SW45° - 1MHz probe. Height sizing, when using the time of flight diffraction, is affected. The intrinsic error evaluated on an isolated defect, generally lower than 5%, reached 20% and even 40% in the most unfavourable case. Configuration TRL60° - 2 MHz seems to be a good compromise to size a propagated defect within a crack network.
- The diffraction echo can in certain cases, according to beam width, be confused with the network echoes, thus limiting the capacities of height sizing.
- The amplitude of the mode conversion echo can be strongly affected by network, even on a defect of 8 mm. This phenomenon would certainly be amplified for a more propagated defect. The contribution of this echo for the characterization of the propagated defect can thus be called into question.

In the future, simulations will be launched and compared with these experimental results. Simulation will also be used to analyse and understand the disturbing phenomena.

6. REFERENCES

[BCS] B. CHASSIGNOLE, E. ABITTAN, EDF R&D, France, O. PARIS, CEA/LIST/SYSSC, France, "Ultrasonic examination of a CVCS weld", 6^{th} ICNDE, Budapest, 2007.

[DUP] O. DUPOND, D. VILLARD, M. MAYOS, EDF, France, "Toward an improvement of ultrasonic examination of austenitic stainless steel welds", Proceedings of the third ICNDE, Seville, Spain, November 2001.

[DUP2] O. DUPOND, B. CHASSIGNOLE, L. DOUDET and C. BIRAC, EDF, France, "methodology for modelling ultrasonic inspection of an austenitic stainless steel weld", 6^{th} ICNDE, Budapest, 2007.

[KEM] M. KEMPPAINEN, Doctoral dissertation, "Realistic artificial flaws for NDE qualification – a novel manufacturing method based on thermal fatigue", Helsinki University of Technology, Finland, 2006.

[LON] S. LONNE, L. DE ROUMILLY, L. LE BER, S. MAHAUT, CEA/LIST/SYSSC, France, G. CATTIAUX, IRSN, France, "experimental validation of CIVA Ultrasonic simulation", Proceedings of the 5^{th} ICNDE, San Diego, May 2006.

[MAH] S. MAHAUT, L. DE ROUMILLY, S. LONNE, CEA/LIST/SYSSC, France, G. CATTIAUX, IRSN, France, "validation of CIVA simulation tools for ultrasonic inspection in realistic configurations", 9^{th} ECNDT, Berlin, September 2006.

[PIT] J. PITKANEN, POSIVA OY, Olkiluoto (Finland) ; M. KEMPPAINEN, I. VIRKKUNEN, Trueflaw, Espoo (Finland) ; A. LAUKKANEN, VTT Industrial Systems, VTT Espoo (Finland) ; "Effect of stress on ultrasonic response in detection and sizing of cracks" ; 9^{th} ECNDT, Berlin, September 2006.

[VIR] I. VIRKKUNEN, M. KEMPPAINEN, Trueflaw, Espoo (Finland) ; J. PITKANEN, POSIVA OY, Olkiluoto (Finland) ; "Effect of crack opening on UT response" ; 9^{th} ECNDT, Berlin, September 2006.