Ultrasonic Phased Array Evaluation of the Integrity of Polyethylene Piping Systems

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Abstract. Polyethylene (PE) is a widespread material for the manufacturing of gas and water distribution pipelines and a large number of PE electrofusion pipe joints can be found over the thousands of kilometres of PE pipelines all over the world, thus generating an increasing interest in checking the quality of both these pipes and joints.

Within the last few years it has been proved that - among the available concepts - the Ultrasonic Phased Array Technique (PAUT) was one of the most promising candidates for Non Destructive and Non Intrusive Analysis of PE welds and pipes.

No current operational Non Destructive Examination (NDE) Technique to date has been adapted to inspect the small diameter electrofusion joints (OD from 20 to 63 mm) which are frequently encountered in particular on the French gas distribution networks.

The acuity of PAUT to detect both poor weld quality (e.g. cold weld) and calibrated faults has been evaluated on 63 mm electrofused joints by ENGIE Research & Technologies Division and Institut de Soudure Industrie.

Moreover the results of the PAUT evaluation and those of the destructive tests have been confronted in order to evaluate the degree of correlation between both techniques according to the acceptance requirements of the ISO 13956 standard.

The high level of reliability of PAUT in terms of Probability Of Detection (POD) and False Call Rate (FCR) gave way to field experimentations.

In parallel to an in-depth evaluation of this technique applied to the characterization of the PE welds, ENGIE Research & Technologies Division and Institut de Soudure Industrie have joined forces in the evaluation of PAUT to detect and measure defects - either artificial or natural - located within pipes (OD from 20 to 110 mm), focusing on Slow Crack Initiation and Growth.

In the same manner as for the joints, the results of the PAUT evaluation have been confirmed by indirect measurements (i.e. imprint techniques).

A specific PAUT setup (i.e. scanning mode, transducer, wedge and scanner) has been designed in order to match each different geometrical configuration.
INTRODUCTION

Over the last twenty years, a lot of studies have been devoted to the possible applicability on polymer materials - and especially polyethylene (PE) - of the classical non-destructive techniques (NDT) designed initially for metallic materials. But given the particular structure of PE with respect to metals the most promising ND techniques for PE reveal to be very limited in terms of both applicability and measuring capacity. Since a few years it has been demonstrated that - among the available concepts - the ultrasonic Phased Array (PAUT) technique was one of the most promising candidates for Non Destructive and Non Intrusive analysis of PE and especially PE welds realized by both electrofusion (EF) and butt fusion (BF) [1-19].

In this context ENGIE Research & Technology Division (formerly GDF SUEZ) has launched an in-depth evaluation of the PAUT on two levels. Firstly the evaluation was focused on the PE EF joints aiming at detecting the poor welds generally referred to as “kissing bonds” or “cold welds”. This work was initiated through a test program with Italian companies ISOTEST Engineering and ITALGAS focusing on the evaluation of the Korean system AIM33 [20-22]. Then the work was pursued partly within the European Gas Research Group [23][24] and partly with the NDE company Institut de Soudure Industrie focusing not only on welds but also on plain pipes [25-27]. Thus the capability of the PAUT was tested on both the welded assemblies and the PE pipes, with the aim of detecting and measuring the defects - artificial or natural - located both at the welded interface and in the pipe wall thickness. The range of diameters studied is mainly 20 to 200 mm.

One of the major issues is to be able to detect and measure accurately the defects produced by the squeeze-off operation especially on the oldest pipes. The other important issue is to be able to detect the slow crack initiation time in the pipe wall during its overall lifetime. This issue - once validated - could give way to a possible tool for detecting the initiation time for SCG and - beyond - could bring input data for the validation of the 6-parameter thermo mechanical model designed by ENGIE R.& T. Division aiming at describing the SCG (Slow Crack Growth) process in different loading conditions including over stresses [28-35]. The first issue is studied by applying the PAUT on a PE pipe with calibrated notches machined at the inner surface either in the transverse direction - to simulate the presence of an excess flow valve system - or in the longitudinal direction to simulate the well-known “squeeze-off” ears damage. The second issue is studied by applying PAUT on “old” PE pipes damaged either artificially - by internal notching - or naturally by overstresses.

TECHNICAL BACKGROUND OF PAUT APPLIED TO POLYETHYLENE

Polyethylene is a particular material with some specific acoustic characteristics which can turn it into a difficult material to inspect using ultrasonic waves. It has been already demonstrated throughout the literature that PE is a highly attenuative material. This means that special care shall be taken when selecting the frequency of the ultrasonic phased array transducer and also that only longitudinal waves (LW) are to be used for the evaluation of the integrity of PE components; shear waves (SW) cannot be used in PE since they are attenuated much more rapidly than LW. The velocity of LW has been evaluated on various calibration blocks from different PE grades (see Figure 1); the value commonly used is around 2200 m/s. The sensitivity of the examination, depending on the application, has
been set using appropriate reference blocks (see Figure 1) containing adequate reflectors such as side-drilled holes (SDH), flat-bottom holes (FBH) or notches. The nature, location and dimensions of those reference reflectors are usually determined by the performance of the examination looked for. The ultrasonic technique used for the examination of different types of PE components - PAUT [36-44] - suffers from the same hurdles as those encountered with conventional ultrasonic techniques but those can be easily overcome by the flexibility of PAUT. Indeed, essential inspection parameters like component geometry (pipe-sleeve, pipe-saddle, spigot-fitting or pipe), surface condition or inspection target area may require the use of phased array transducers with small or large footprints, specific wedges with curvature adapted to pipes (typically pipe OD values of 63, 90, 110 and 160 mm) or specific phased array settings (beam steering and/or focusing, filtering, display).

Figure 1 - Example of calibration blocks (Left - V2 type) and reference block (Right - Plate with FBHs)

Table I gives details of which PAUT scanning mode to be used depending on which type of component to be examined (within the range of pipe OD values from 20 to 160 mm).

<table>
<thead>
<tr>
<th>PAUT Scanning Mode</th>
<th>Type of examined component</th>
<th>Fitting</th>
<th>Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pipe-sleeve</td>
<td>X</td>
</tr>
<tr>
<td>Linear 0° LW</td>
<td></td>
<td>Pipe-saddle</td>
<td>X</td>
</tr>
<tr>
<td>Linear 45° LW</td>
<td></td>
<td>Spigot fitting</td>
<td>X</td>
</tr>
<tr>
<td>Sectorial 0°/+55° LW</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Sectorial -30°/+30° LW</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

ACUITY OF PAUT APPLIED TO PE ELECTOFUSED JOINTS

Assemblies exhumed from the field

Expertise of a 160 mm pipe-sleeve EF assembly: The examination of the assembly has been carried out by using a 0° LW linear scan. A 64-element PA transducer with a frequency of 5 MHz has been applied in direct contact (without any wedge) with the sleeve surface with an active aperture of 29.4 mm. The coupling agent between the surface of the probe and the test piece was a thixotropic gel. The whole surface of the sleeve has been inspected with the exception of the area near the connectors. A wheel encoder did allow the scanning of the whole circumference of the sleeve (X-axis, see Figure 2) whereas its total length has been covered by putting the PA transducer along the Y-axis at different incremental positions (see Figure 2).
The results of the PAUT examination are displayed in Figure 3 as amplitude C-Scans. The first C-Scan - which represents the amplitude signal over the whole thickness of the sleeve - enlightens the inner structure of the sleeve with both the positions of the wires and the central cold zone. The second C-Scan - which represents the amplitude signal at the exact depth of the pipe to sleeve interface - highlights five major defects more or less extended.

Figure 3 - Amplitude C-Scans of the whole 160 mm sleeve and the pipe to sleeve interface

Figure 4 gives as way of an example the cross-sectional view of the sleeve where the defect No 3 has been encountered. This defect is located on both sides of the last wire before the central cold zone.

Figure 4 - S-Scan of defect No 3 (Cross-sectional view of the sleeve) 160 mm pipe-sleeve EF assembly

In every other instance the defects are located at the edge of the last wire before the central cold zone. The location and dimensions of the defects detected by PAUT are given in Table II.
Table II - Location and dimensions of the defects detected by PAUT in the 160 mm pipe-sleeve EF assembly

<table>
<thead>
<tr>
<th>Defect No</th>
<th>Location and dimensions of the defects</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X (mm)</td>
<td>Length along X-axis</td>
</tr>
<tr>
<td>1</td>
<td>22</td>
<td>104</td>
</tr>
<tr>
<td>2</td>
<td>66</td>
<td>334</td>
</tr>
<tr>
<td>3</td>
<td>334</td>
<td>130</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>536</td>
<td>79</td>
</tr>
</tbody>
</table>

The resistance of the weld has been evaluated by means of the peel test according to the ISO 13955 standard [45], as illustrated in Figure 5.

Figure 5 - Peel test on the 160 mm pipe-sleeve assembly and resulting failure pattern

Figure 6 - Brittle zones revealed after the peel test corresponding to the defect #1 detected by PAUT

The PAUT evaluation of the sleeve allows one to catch five defect indications. These defects appear to be aligned on an internal “ring” located near the last internal wire in the border of the internal cold zone of the sleeve, which could be expected regarding the asymmetrical thermal environment of this wire.

The destructive peel test results confirm the PAUT non-destructive evaluation.
Assemblies produced with calibrated faults/defects

**Preparation of samples:** Two experimental campaigns were designed to assess for acuity of the PAUT for detecting faults at the interface of 63 mm-electrofused assemblies [26]. The first one included a set of 56 assemblies welded with the nominal heating time and the second one included a set of 28 assemblies welded with a reduced (0.8) heating time. For both sets of samples, deliberate faults were created in the weld plane by integrating discrete surface non-welded zones at the interface pipe-saddle, comprising adhesive coated paper strips placed regularly at the theoretical weld zone of the saddles in order to design three different configurations, as illustrated in Figure 7.

![Figure 7 - Application of adhesive strips at the theoretical weld zone for the saddle ("Cross" configuration T1 (a); "Cross" configuration T2 (b); “Mass” configuration (c)](image)

The density and location of the strips were calculated so that they fall on either side of the criteria recommended with respect to standard ISO 13956, as illustrated in Table III.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>(L/Y_{\text{nom}})</th>
<th>(A/A_{\text{nom}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross T1 and T2</td>
<td>9.1% 1.8%</td>
<td>13.6% 2.7%</td>
</tr>
<tr>
<td>Mass</td>
<td>22.7% 9.1%</td>
<td>22.7% 18.2%</td>
</tr>
</tbody>
</table>

The results of the PAUT inspection were then compared to the destructive test results obtained afterwards by means of the ISO standardized peel test [46], as illustrated in Figure 8.

![Figure 8 - Destructive peeling of an EF saddle revealing the calibrated non-welded zones](image)

In order to quantify the non-welded zones, a mapping of the peeled surfaces has been done by means of a specific mechanical device installed on a microscope associated with an image processing system.
Non-destructive PAUT of the welded assemblies: The inspection was performed via a 16-element PA probe with a frequency of 10 MHz in direct contact with the test piece. Multiple beams using LW of incidence angles varying by steps of 1° within a range of -30° to +30° have been generated and displayed in an S-Scan sector image. A thixotropic gel ensured the coupling between the surface of the probe and the test piece. The small size of the sensor (around 5 mm x 5 mm of active surface) made it possible to inspect nearly the entire welded zone without contact problems. The electrofusion fitting was inspected by sweeping the part as evenly as possible. Regularity was better for a sleeve fitting than for a saddle, due to the more complex geometry of the latter, linked to the presence of connectors, outlet, fusion indicators, and stamps, as illustrated in Figure 9.

Detection and sizing of the defects in the welded assemblies: Within the framework of the first test campaign (56 assemblies welded with the nominal heating time), 256 strips and 160 strips were researched respectively for the “mass” configuration and for the “cross” configuration. For “mass” faults, the 256 strips are detected by PAUT, hence a POD of 100% and an FCR of 0. However, for a gain increased by +6 dB (normal conditions +6 dB), the surface condition of the saddles influences the PAUT response, specifically the presence of striations or the presence of the fusion indicator or the existence of local instances of excess thickness. In this case, the grinded saddle presents a better foundation for the analysis of the welded assembly, as illustrated by way of example in Figure 10.

The grinding of the saddle then leads to detection rates that always exceed those obtained from an as-received one. In addition, the transition to a gain augmented by +12 dB for
around 60 strips (i.e. around one quarter of the total number of strips implemented) makes it possible to refine detection.

An attempt to measure the dimensions of the strips detected was performed in four cases. The analysis of these results shows that while the width of the strip is hard to measure in 5 out of 7 cases, the estimate for the two remaining cases is relatively correct. With regard to the detected length, the PAUT estimate is overestimated in the 7 cases. For theoretical lengths less than 5 mm, the overestimate is very significant. On the other hand, it is quite accurate for strips bigger than 5 mm. The biggest overestimate observed in the case of small strips could be due to the dimensions of the focal spot of the ultrasonic beam, which are around 6 mm x 6 mm and therefore bigger than the faults encountered.

For applied “cross” faults, of the 160 strips implemented in T1 and T2 cross configurations, 129 are detected, resulting in a total POD of around 80.6% and an FCR of 0. The remaining 31 strips are not detected due to difficulties in the probe accessing areas of interest, especially when the strip dimensions are smaller. Figure 11 gives, by way of example, the PAUT detection of a strip placed in the interior periphery (T1) of the heating zone of saddles referred to as #28 (l/y = 13.6%) and #43 (l/y = 50%).

This figure shows the excellent probability of detection of two strips having very different dimensions (lengths of 3 mm and 11 mm) located at relatively inaccessible positions (near the saddle well). Detection is easier since the impact of the ultrasonic beam is maximal (saddle #43, strip 4). For the “cross” configuration, the grinding of the saddle does not improve detection for the various gains used. With a conventional gain of +6 dB it is possible to detect only 51 strips out of a total 129 remaining (160-31). It is then necessary to double or even quadruple the gain in order to be able to detect the 78 other strips and thus increase the individual PODs. If the cross configurations (T1 and T2) are below 27.3%, the POD does not reach 100%. On the other hand, once this experimental value is reached, the POD is close to 100%, enabling correct detection at the ISO standard requirement threshold transition (50% “cross”).

The second test campaign was complementary of the first one with a double objective:
- On a qualitative level, evaluate the POD of PAUT on both the calibrated defects and the zones improperly welded due to the insufficient heating time ;
- On a quantitative level, size the dimensions of both the calibrated defects and the zones improperly welded.
For this second campaign, 28 assemblies (welded at 0.8 times the nominal heating time) were implemented. In these welded assemblies, 128 strips and 80 strips were researched respectively for the “mass” configuration and for the “cross” configurations (T1 and T2). Figure 12 gives an example of the S-Scans obtained on saddles with calibrated faults in “mass” configuration.

Figure 12 - S-Scans of two saddles (#60 & #63) revealing the calibrated defects and additional anomalies

For “mass” faults, the 128 strips are detected, even for the lowest proportion (9.1%), hence a POD of 100%. Moreover, PAUT reveal additional anomalies with some saddles located mainly on the external “ring” materialized by the outermost strips. From the data obtained on 8 assemblies, an attempt for sizing the overall faults is presented in Table IV.

Table IV - Sizing of the faults (mm x mm) detected by PAUT in the welds with calibrated defects (*grinded saddle)

<table>
<thead>
<tr>
<th>Saddle No</th>
<th>No and position of the adhesive strip</th>
<th>External « ring »</th>
<th>Internal « ring »</th>
</tr>
</thead>
<tbody>
<tr>
<td>57</td>
<td>6x6 5x6 5x7 5x9 5x10 5x12 5x16 5x18</td>
<td>6x6 5x8 5x8 5x6 5x6 5x6 5x6 5x6</td>
<td>5x9 5x12 5x15 5x15 5x15 5x15 5x15 5x15</td>
</tr>
<tr>
<td>58*</td>
<td>6x6 5x9 5x15 5x16 5x16 5x16 5x16 5x16</td>
<td>5x12 5x14 5x14 5x14 5x14 5x14 5x14 5x14</td>
<td>5x16</td>
</tr>
<tr>
<td>59</td>
<td>6x7 5x9 5x17 5x17 5x18 5x18 5x18 5x18</td>
<td>5x7 5x15 5x15 5x15 5x15 5x15 5x15 5x15</td>
<td>5x19</td>
</tr>
<tr>
<td>60*</td>
<td>5x16 5x18 5x18 5x18 5x18 5x18 5x18 5x18</td>
<td>5x16 5x16 5x16 5x16 5x16 5x16 5x16 5x16</td>
<td>5x20</td>
</tr>
<tr>
<td>61</td>
<td>5x17 5x17 5x17 5x17 5x17 5x17 5x17 5x17</td>
<td>5x17 5x17 5x17 5x17 5x17 5x17 5x17 5x17</td>
<td>5x20</td>
</tr>
<tr>
<td>62*</td>
<td>5x17 5x17 5x17 5x17 5x17 5x17 5x17 5x17</td>
<td>5x17 5x17 5x17 5x17 5x17 5x17 5x17 5x17</td>
<td>5x20</td>
</tr>
<tr>
<td>63</td>
<td>5x16 5x18 5x18 5x18 5x18 5x18 5x18 5x18</td>
<td>5x16 5x16 5x16 5x16 5x16 5x16 5x16 5x16</td>
<td>5x36</td>
</tr>
<tr>
<td>64*</td>
<td>5x16 5x18 5x18 5x18 5x18 5x18 5x18 5x18</td>
<td>5x16 5x16 5x16 5x16 5x16 5x16 5x16 5x16</td>
<td>5x36</td>
</tr>
</tbody>
</table>

PAUT sizing is possible for 126 strips on 128 (98.5%). The estimated widths - between 4 mm and 6 mm - are very close to the real ones, even if these dimensions are also very close to the focal spot of the UT beam. The estimated lengths are greater than the real ones. Considering a 30% error on the measurement (as for the widths), it is possible to reveal about 50 cases for which additional disorders do exist (in red in Table IV). Figure 13 gives an illustration of such cases for the “mass” configuration.
Several other anomalies are not detected but lowering the error from 30% to 20% allows one to increase the oversizing level to 98 cases on 126. Consequently the zones improperly welded - excluding the surface of the calibrated defects - measured by PAUT stand between 14% and 53% of the overall surface improperly welded. Figure 14 displays the overall surfaces of the defects (calibrated strips in “mass” configuration + non-welded areas) for 8 welds. The gap between both measurements gives indication of the non-welded areas due to the insufficient heating time.

In the « cross » configurations, the POD stands between 25% and 100%, and the faults can be sized for only 45% of the welds but with a poor accuracy and a low reliability.
ACUITY OF PAUT APPLIED TO PE PIPES

Pipes exhumed from the field and retested

Characterization of damage in a 110 mm old pipe after Hydrostatic Pressure Testing: An excavated 110 mm old pipe (1978) was first tested under Hydrostatic Pressure conditions in 20 °C water at a hoop stress of 11 MPa. The pipe failed in a brittle way in ca. 5900 h \[25\]. Looking at the inside of the pipe after depressurization reveals several small cracks oriented along the pipe axis, as shown in the Figure 15.

![Figure 15 - Excavated old 110 mm pipe after 5886 h HPT in water 20°C at 11 MPa](image)

PAUT inspection from the outside of the failed pipe was implemented in order to test the acuity of this NDT technique for detecting the multiple cracks visually observed. A 64-element PA transducer with a frequency of 5 MHz has been used on a specific LW wedge. This wedge has been designed to adapt to the pipe curvature and produce an optimized 45° refraction angle on the inner surface of the pipe. Moreover a translation/rotation system was specially designed in order to locate precisely each of the detected cracks, as illustrated in the Figure 16. The coupling has been performed by water injection.

![Figure 16 - Experimental setup specially designed for the PAUT characterization of the 110 mm cracked pipe](image)

The C-Scan obtained through PAUT characterization on the multi cracked 110 mm pipe is displayed in Figure 17. A large population of longitudinal cracks more or less mature is detected easily by PAUT. Apart for the slit-like crack that has led to the failure (circled in red color) other cracks are clearly on the way to exit on the outer surface.
Samples produced with calibrated faults/defects

20 mm pipe with transverse calibrated defects: Artificial notches were designed on a 20 mm inner pipe surface by means of a specific bench equipped with micro blades with different heights. In order to make possible a reliable quantitative measurement of the depth of the transverse artificial notches put inside the PE pipes, a 4 mm-thick plane specimen on which were integrated calibrated notch depths was used, as shown in the Figure 18.

PAUT was implemented through the use of a LW sectorial scan from 0° to 55°. A 16-element PA transducer with a nominal frequency of 10 MHz (5 mm x 5 mm of active surface) has been used. Given the curvature of the 20 mm pipe, a specific flat wedge with a small footprint has been manufactured. Its geometry was well adapted for an optimized refraction of the LW according to the Snell-Descartes law (see Figure 19). A thixotropic gel was used as a coupling agent. The following physical phenomena are considered: specular reflection of the corner echo of the artificial notch and diffraction at the top of the artificial notch.

The 20 mm pipe had a thickness of 2.1 mm. The notch depth was first targeted to 0.5 - 0.6 mm.

Figure 20 displays the S-Scan obtained of the notch detected on the 20 mm. Table V presents the quantitative characteristics of the notch inside the 20 mm pipe.
The results show that the notch is well detected and can be positioned correctly on the pipe axes. The estimated value of the notch depth - 0.4 mm - is very close to the value measured afterwards - after destruction of the pipe - through an imprint procedure by means of the replica kit designed by ENGIE R. & T. Division for damage measurements on pipes, as shown in Figure 21 [47][48]. This value is of the order of 0.45 to 0.50 mm.

**110 mm pipes with longitudinal calibrated defects:** In order to generate the required database of defects to be detected, but also to be able to size the disorders detected in the walls of pipes and fittings, a test programme needed to be carried out on quantitative characterisation using PAUT, initially for pipes exhibiting calibrated defects. These calibrated defects, presenting four different geometries, were artificially implanted by machining on the internal wall of a PE pipe cut in four half-shells. Specific tools were designed in order to produce the defects. The defects are dubbed “V-shaped”, “half V-shaped”, “semi-elliptical” and “rectangular”, respectively.
They were machined at ten increasing depths on the internal wall of four half-shells from a PE100 pipe, as illustrated in Figure 22 and in Table VI.

![Figure 22 - Typology of the calibrated defects implanted on the internal wall of the pipe](image)

Table VI - Size characteristics of the calibrated defects
(NB: "target" heights correspond to the “theoretical” values to be achieved by machining; in reality they are often difficult to achieve, as demonstrated on several occasions by notching experiments performed on PE pipes of different degrees of “hardness”)

<table>
<thead>
<tr>
<th>Defect Type</th>
<th>Targeted height</th>
</tr>
</thead>
<tbody>
<tr>
<td>V-shaped</td>
<td>2 %e 0.2 mm</td>
</tr>
<tr>
<td>1/2-V-shaped</td>
<td></td>
</tr>
<tr>
<td>Rectangular</td>
<td></td>
</tr>
<tr>
<td>1/2-elliptical</td>
<td></td>
</tr>
</tbody>
</table>

In order to check the geometry of the implanted defects, replicas of these were cast using the impression-diagnostic method developed by CRIGEN in the early 1990’s to investigate damage caused to PE pipes by the directional drilling and tubing technique, and eventually for the measurement of damages incurred by PE pipes in general (scratches, notches, etc.) [47][48].

Figure 23 illustrates the different phases involved in the casting of the defect replicas machined on the inner wall of a pipe.

![Figure 23 - Sizing of calibrated defects based on replicas obtained using impression-casting](image)

The non-destructive evaluation of the artificially notched pipes has been carried out by PAUT. The implemented scanning mode was a LW angled linear scan.
The evaluation was carried out from the external wall of the pipe. The use of a specific wedge design has yielded LW angled beams with an incident angle of 45° relative to the internal wall of the pipe. The following physical phenomena have been considered: the specular reflection of the corner echo of the artificial notch on the inner surface of the pipe - considered a dihedral reflector - and the tip diffraction at the top of the artificial notch. Two examinations have been performed for each half-shell, positioning the PA transducer along two opposite directions (0° and 180°) in order to maximize the signal amplitude from the specular reflection of the corner echo, in particular for asymmetrical defects such as the “half-V” type, as illustrated in Figure 24.

Figure 24 - Principle of the PAUT examination of the 110 mm half-shells (Cross-sectional view)

The mechanical encoding device (wire encoder) allows the recording of data along the length of the pipe. The wedge/transducer unit is slid lengthwise along the pipe, as illustrated in Figure 25.

Figure 25 - Implementation of the PAUT examination of the 110 mm half-shells

A preliminary sizing of the calibrated defects was performed on transversal cross-sections of the replicas using a specific magnifier with a measuring reticule calibrated to 1/10 mm (see Figure 21 and Figure 23). The deviation observed between the measured values on replicas and the “target” values for the four types of defects values are both very close and quite high for the “sharper” defects. Conversely, the sizing of rectangular defects appears quite accurate. Figure 26 is an example of PAUT rendition for semi-elliptical defects (E7 - position 180°), including an A-Scan (top left), an S-Scan (top right) and an amplitude C-Scan (bottom). The S-Scan in Figure 26 reveals the semi-elliptical geometry of the defect and clearly highlights the accidental imperfections induced by the blunt tool at the top of the notch.
All ten semi-elliptical defects (E1 to E10) are detected, which means a POD value of 100%. Figure 27 presents the PAUT measurements performed on the semi-elliptical defects with the “target” values superimposed.

Comparing the results shows that, first, the values measured by PAUT are moderately dispersed over the range of the measured values; second, the measured values by PAUT are in their majority lower than the “target” values, except for the defect with the smallest heights (E1, E2); third, the relative deviation between the PAUT and “target” values is around 40% on average, with a maximum of around 100% for the defect with the smallest depth (E1).

More generally, PAUT sizing deviations for the sharper defects (“V-shaped”, “half V-shaped” and “semi-elliptical”) are very close and moderately high on average but PAUT
sizing appears to be very inaccurate for the defects with the smallest heights. PAUT sizing of “rectangular” defects turns out to be the most accurate. 

The four series of measurements performed on replicas of the calibrated defects have been compared to the PAUT measurements. Figure 28 displays, as way of an example, the comparison between the values for the semi-elliptical defect. These data show that PAUT technique leads, in the majority of cases, to height values higher than those measured on the replicas for “targets” below 2 mm (20% of the pipe thickness), and to height values generally lower than their replica counterparts for “targets” above 2 mm.

The sizing of semi-elliptical defects using PAUT appears, therefore, to be more conservative in terms of safety for defect with heights below 20% of the pipe thickness.

Figure 28 - Comparison between sizing values obtained using replicas and those obtained using PAUT for the semi-elliptical calibrated defects

The 39 calibrated defects implanted in the pipe half-shells were detected by the PAUT examination, including those with the smallest heights corresponding to 2% of the pipe thickness which brings the POD to 100%. The irregularities created by machining of the different profiles have been “seen” by the PAUT examination. Consequently such irregularities have lowered the correlation between PAUT measurements and those obtained on replicas. In general, the measurement accuracy of PAUT relative to the target heights is quite acceptable with values between 5% and 40% on average, except for defect heights in the order of 2% of the pipe thickness, which is the limit for this technique.
CONCLUSIONS AND PERSPECTIVES

The very promising results obtained in laboratory using PAUT since the last five years have led the way to a confrontation with a field experimentation. Thus an urban worksite has been chosen on purpose in the centre of Paris. The experimentation focused on the PAUT scanning of 26 EF fittings (sleeves, saddles, repair collars, elbow) in the diameter range 20 mm to 63 mm. Figure 29 gives an illustration of the on-site experimentation.

Figure 29 - Field experimentation using PAUT on PE welded assemblies in the centre of Paris

The next step in developing PAUT for plastic piping systems requires the creation of an ambitious correlation of the dimensions and location of the defects with the residual lifetime regarding a “Remove / No Remove” decision.

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