FINAL REPORT

WP5: summarizing evaluation of the APR-technique

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1 Introduction

This report is directed to the Joint Industry Project aimed at the evaluation of the so-called APR-technique (Acoustic Pulse Reflectometry [1]) which has been developed by Acoustic Eye, Tel Aviv, Israel).
The project has been undertaken in the period from September 2012 till July 2013.

The objective of this project was to determine the capabilities and limitations of the APR-technique for the purpose of inspecting heat exchanger bundles.
This has been achieved through a combination of desk studies and experimental validations, as outlined in the various work packages WP 1 till WP 4, viz:

- WP1: evaluation of the physics of the APR-technique;
- WP2: evaluation of past inspection projects;
- WP3: validation through experiments with heat exchangers after service;
- WP4: validation through experiments with a mock-up.

In Reference [2] till [5], the results of the above mentioned work packages have been reported.
In sections 2 till 5 the results from the various WP's are summarized. In section 6 the results from the experimental work packages WP 3 and WP4 are evaluated to arrive at overall results. Subsequently, in section 7 a number of specific topics are addressed. Finally, the conclusions are presented in section 8.

Acknowledgement
This Joint Industry Project was initiated by the Dutch foundation KINT Onderzoeksprojecten.
Besides, it has been conducted as part (work package 3A) of the joint industry project "CWD" under auspices of the Foundation KPOT. The CWD project has been undertaken within the framework of the so-called IPC-regulation (Innovatie Prestatie Contracten) through which subsidy was provided by the Dutch Ministry of Economic Affairs.
HIS Consult B.V. (J.H.A.M. Heerings) was contracted to conduct and to manage the project.

The participating companies listed below have provided financial contributions in addition to contributions in kind and have taken part in the working group:
NAM, MCI, Sound Tube Testing, Total E&P Nederland, Quality Inspection Services (QIS) and VECOM.

2 Summary of WP1: evaluation of the physics of the APR-technique

The physics of the APR-technique are based on emitting a wideband acoustic pulse in the air enclosed within the tube. The frequency range is about in the range of 10 Hz - 10 kHz. If a discontinuity is encountered in the form of a change of cross section, reflected waves are created, which propagate back up the tube. Upon recording the acoustic reflections by a microphone, they are analyzed automatically. Schematically, the reflections will appear as shown in Figure 1.

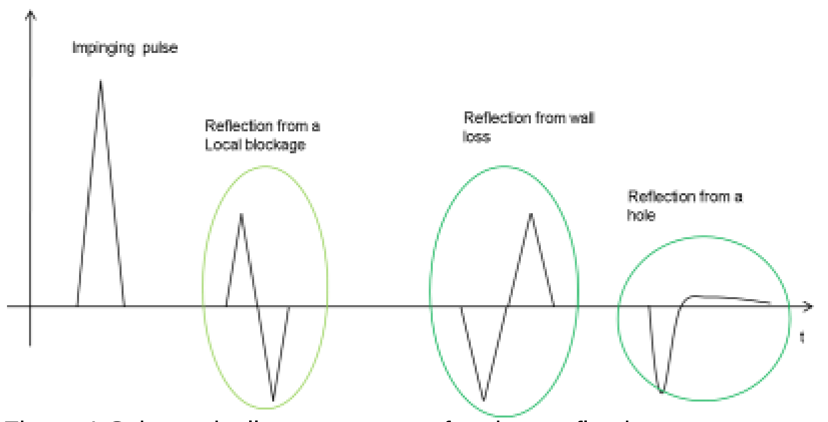


Figure 1 Schematically appearance of various reflections

The modern computing power at the end of the 20th century has enabled the effective use of the APR-technique for industrial purposes. The computer power is needed for the data processing. The algorithms used in the data treatment are complex, but in general well known although some aspects of the data processing have not been disclosed.

As with all instruments, the performance depends on the obtainable signal-to-noise ratio (SNR). In industrial applications the detection requirements are very stringent on the one hand, but the noise level can be high on the other hand. A very efficient technique for increasing SNR is the maximum length sequence technique. This comes down to replacing the single pulse excitation by multiple pseudo random pulse excitations. The advantage of this excitation is the increment of the signal-to-noise ratio. The disadvantage of this type of excitation is the more complicated data treatment needed to retrieve the signal.

Based on these considerations, a theoretical model was initially developed, to predict probability of detection depending on the tube radius and length and defect type and size. This model gives a defect size threshold as shown in Figures 2 and 3. It should be noted that different type of defects can give similar responses. These figures apply to the situation that the defect is present along the whole circumference of the tube. If only a fraction of the circumference contains the defect, the effective 'h' will be diminished by the same fraction.

The theoretically derived probability of detection can only be used to demonstrate the dependence of the probability of detection as function of defect sizes and tube parameters. The actual probability of detection depends on instrumental settings and noise contribution. If for a certain defect type and size the actual probability of detection is measured, then this dependence can be used to predict the probability of detection for other defect sizes and geometries.

For this theoretically derived probability of detection the conservative condition was assumed that the signal-to-noise ratio obtainable for a maximum length sequence is limited to the number of pulses in the sequence and that the spatial resolution over the complete length of the tube should be constant.

The actual signal-to-noise ratio can be larger and must be experimentally determined or released by the manufacturer.

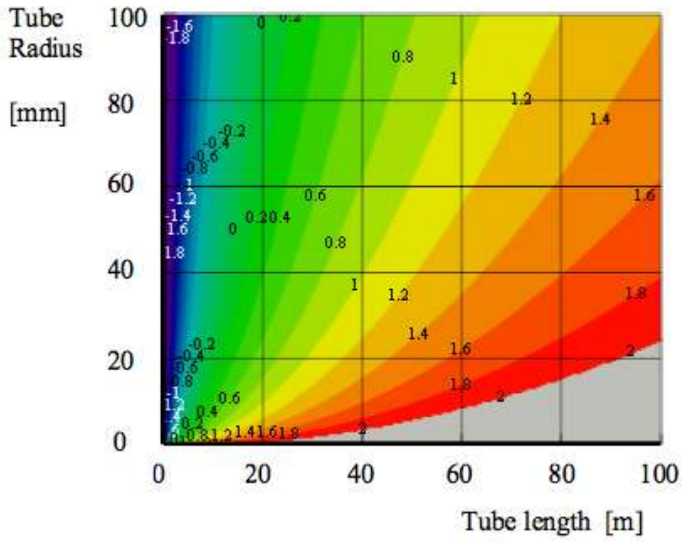


Figure 2 Defect size threshold (unit log(hd [cm2]) where h = effective defect height in cm. and d = effective defect length in cm.) as function of tube length and tube radius. For example, the yellow region between values 1 and 1.2 corresponds to values of the hd between 10 and 16 cm^2 whereas the number '0' means a detection threshold equal to a defect with hd=1 cm^2 and the number '-1' means a detection threshold equal to a defect with hd=0.1 cm^2.

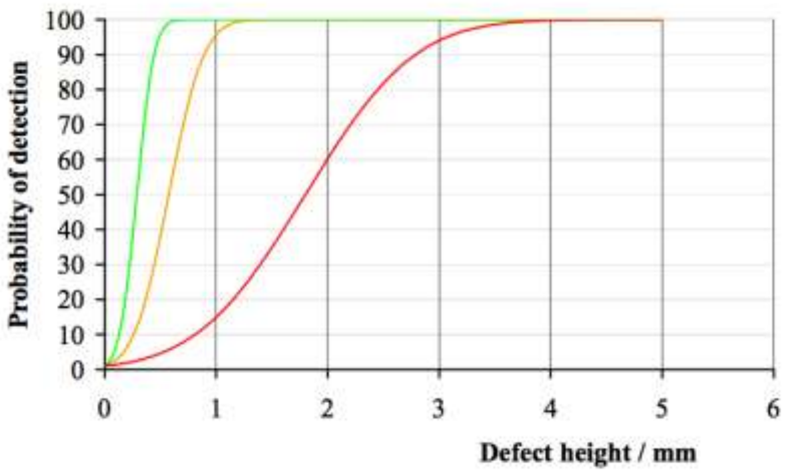


Figure 3 Theoretical probability of detection as function of effective defect height for 3 types of defect in a tube with radius 2 cm. Green line: defect length 2 cm; tube length 2 m; Orange line: defect length 4 cm; tube length 2 m; Red line: defect length 4 cm; tube length 5 m.
Note that these values are derived for a theoretically optimized APR system using maximum length sequence for the excitation of the sound waves.

In conclusion, this desk study has shown that the propagation and reflection of sound waves as used in the APR-technology is well understood and has a sound physical basis.
More details about WP1 are reported in [2].

3 Summary of WP2: evaluation of past inspection projects

Since the introduction of the APR-technique, a significant number of inspection projects have been performed worldwide so that experience has been gained for a variety of bundle configurations, tube sizes, materials and inspection conditions like fouling. A number of inspection reports have been made available with the aid of Sound Tube Testing. From these inspection reports, the resulting inspection performance has been identified.
The available results have been evaluated, predominantly on their significance from a verification point of view. Verifications have been performed through various ways, i.e.:

- A second comparative inspection (Eddy Current technique);
- Visual inspection or endoscopic inspection on a piece of tube which has been removed;
- Destructive examination followed by visual inspection;
- In cases where holes were detected, verification is also possible through the confirmed absence of leakage upon plugging.

It should be noted that most verification results originate from reporting by Sound Tube Testing or Acoustic Eye without technical documentation from a third independent party.
Most results appear to be related to the detection of holes and blockages whereas verification is based on visual inspection or the confirmed absence of leakage upon plugging.

Because of the limited number of available verification results, it was only possible to provide a qualitative estimate of the capability of the APR-technique rather than defining a POD-curve or quantifying the accuracy of localisation and sizing.
Clearly, the capability to detect holes, blockages and bulging has been quite high (without giving any quantitative measure) in the inspected cases whereas the capability to localise and to size these defects have also been fairly good. The capability to detect, localise or size the other defects (pitting, erosion and EOT erosion) has shown to be lower or is still unknown, even qualitatively.

In 2011 a extensive validation program was conducted by SouthWest Research Institute [6], using a mock-up containing artificial defects. The mock-up consisted of 36 straight aluminum tubes of 12 m total length (composed of 2 tubes of 6 meter) with an inner diameter of 19.1 mm and 2 mm wall thickness. In total 73 defects were machined, viz. thru-holes, pits, grooves, erosions, blockages and so-called End-Of-Tube erosions. A number of 3 – 5 defects were available for each type of defect combined with a certain size. The testing programme has been carried out with the latest version of the inspection device, type G3.
The dimensions of the artificial defects are given in table 1.

Table 1 Typical dimensions of artificial defects in SwRI-program [6]

	Length (in axial direction)	**Width (in circumferential direction)**
Groove	100 mm.	4.75 mm.
Pit	Diameter is 4.75 mm	
Hole	Diameter ranging from 0.5 mm to 3.0 mm	
End Of Tube erosion	50 mm.	Full circumference = 59.97 mm.
Blockage	50 mm.	No width defined, but expressed in % of cross sectional area
Erosion	300 mm.	Full circumference = 59.97 mm.

The SwRI report gives a quantitative, indicative impression of the capabilities of APR, see Appendix A for a summary of the results regarding detection performance. In Appendix A two presentations are given: one in which the defect size is expressed in terms of percentage of wall thickness (which is more practice oriented) and one in which the defect size is expressed in terms of percentage of cross sectional area (which is more sound from a physics point of view because the magnitude of the acoustic reflection is determined by the change in cross sectional area of the air filled inner space of the tube).
The quantity of data (for each combination of defect type and defect size) is far too small in order to conclude on a so-called 'POD-curve' from a sound statistical background. Nevertheless, in table 2 a summary is given of the detection performance in terms of the 50% hit rate and 90% hit rate.

Table 2 Detection performance for the defects tested in the SwRI-program [6]

	Detection performance		
	Overall indicative Qualitative rating	**The 50% hit rate**	**The 90% hit rate**
Groove	Moderate	18% wall thickness	62% wall thickness
Pit	Moderate, but less than for grooves	32% wall thickness	80% wall thickness
Hole	Good	0.3 mm diameter	0.8 mm diameter
EOT erosion	Good	12% wall thickness	17% wall thickness
Blockage	Good	5% of cross sectional area	9% of cross sectional area
Erosion	Good	5% wall thickness	9% wall thickness

The above table clearly shows that blockages, erosions and thru-hole defects were the easiest to detect. Grooves were detected reasonably well whereas pits appeared more difficult to detect
In addition, the accuracy of sizing for holes appeared to be relatively high whereas the accuracy for pits was lowest and all other defects somewhere in between. The size of blockages and erosions were consistently over-estimated (measured larger than actual). As far as positional accuracy is concerned, it turned out that the majority of defects were found with less than 50 mm. deviation from their actual positions along the tube length.

Lastly, it should be noted that the results from the SwRI program apply to a situation of perfectly clean, dry and smooth tubes so that all results represent the highest achievable performance.

More details about WP2 are reported in [3].

4 Summary of WP3: validation through experiments with heat exchangers after service

Inspections with APR have been conducted on tubes from three heat exchangers, which will be referred to as the Tronox bundle, the NAM bundle and the Fuji bundle.

4.1 Tronox bundle

Retubing of the bundle was considered necessary because of the bad condition of the tubes measured through ET so that the heat exchanger was taken out of service. The size of the tubes is 38 x 2 mm. Length of tubes is 6 meters. The material of construction is stainless steel (SS 316).
APR inspections were conducted in 2 sessions, viz. on the tubes before retubing (session 1) and on a number of removed tubes (session 2).

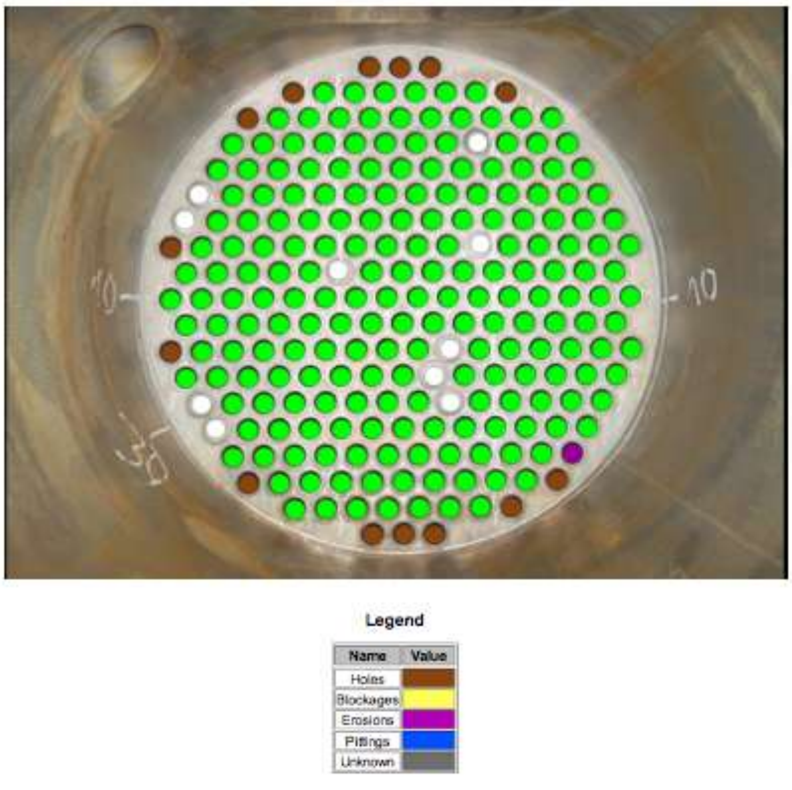


Figure 4. APR results of session 1; projected in South tube sheet

An interesting result of the APR inspection is the detection of holes as shown in Figure 4, see the brown coloured tubes. In the ET inspection wall reduction in the range of 80%-100% was detected, but not in the specific tubes which contain holes according the APR inspection. This deviation can be explained by the fact that ET inspection is capable of detecting smooth wall reductions in contrast to APR whereas APR is capable of detecting holes with very small diameter in contrast to ET.
In order to verify the presence of the holes detected by APR, examinations have been conducted including both PT (dye penetrant testing) and visual examination (both outside with naked eye and inside with endoscopy). However, the presence of holes could not be confirmed. The explanation for this is most likely the fact that the removed tubes were cut behind the inner tube sheets and therefore

missed the most severely attacked section in between the inner and outer tube sheet (at the North side). In conclusion, it was not possible to verify the detected holes due to improper sampling in the retubing workshop.

A second APR inspection was conducted on a number of tubes which were removed from the bundle. Before the execution of the APR inspection, the tubes were cut in two pieces of each 2.5 meters, see Figure 5. A number of through wall holes (1 mm and 2 mm diameter) was machined to have included known defects.
Through the APR inspection a number of holes, blockages and wall losses were reported. After the APR inspection destructive examination was conducted to verify the APR results.

Figure 5 Stack of 30 tube sections of each 2.5 meter length from Tronox bundle

The internal surface of the tubes appeared to be either very smooth or some pitting was present consisting of a multitude of pits up to 0.5 mm diameter and depth, see Figures 6a and 6b.

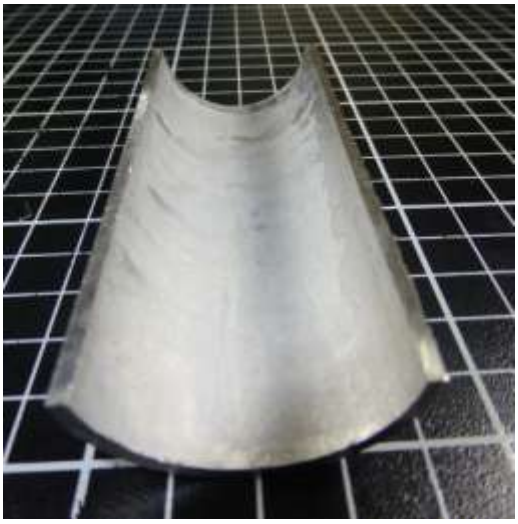


Figure 6a Smooth surface

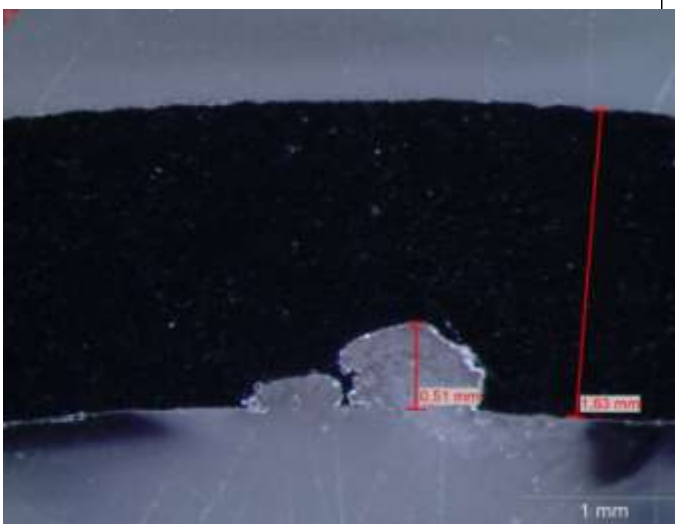


Figure 6b Isolated pitting

The detection capability for through-wall holes with 1 mm and 2 mm diameter turned out to be very high. No False call was reported. However, the detection capability for these small diameter holes appeared very dependent on covering effects.
Blockages appeared quite vulnerable to False Calling: especially blockages with a small size up to 3% turned out to be falsely reported. The False Calls are possibly caused by roughness of the corroded surface in case of pitting.
The reported wall losses in the range of 10 – 30% wall thickness (0.2 – 0.6 mm) could not be confirmed by destructive examination. For that reason they must also be considered as False Calls.
Because no actual blockages and no actual localised wall losses were present in the tubes, no indication of the detection performance for these type of defects could be generated.
The detected pittings were not reported in the APR inspection. Apparently, their sizes (diameter: < 1mm; depth: < 0.5 mm) were too small to be detected.

4.2 NAM bundle

In 2010 and in 2011, IRIS inspection was conducted and demonstrated severe attack along the entire tube length so that the heat exchanger was taken out of service in 2012.
The size of the tubes is 25.4 x 2.77 mm. Length of tubes is 130 cm. The material of construction is carbon steel. The tubes are finned tubes. Figure 7 presents a view of the bundle.

Figure 7a View from outside of bundle
The 19 tubes are positioned on the left hand part

Figure 7b View on top row of finned tubes

APR inspection were conducted in 2 sessions, viz. on the tubes as mounted in the bundle (session 1) and on a number of removed tubes (session 2). In both sessions tubes were inspected from both the left hand compartment of the bundle (referred to as the bottom part by the asset owner) and the right hand compartment.

The internal surface of the tubes appeared to have a pitting morphology which is different for the left hand compartment and right hand compartment due to the difference of fluid and operating conditions. The pitting in the left hand compartment is more severe, as can be seen in Figure 8.

Figure 8a Surface in left hand compartment

Figure 8b Surface in right hand compartment

The detection capability for through-wall holes with 1 mm diameter turned out to be somewhat ambiguous in contradiction to the very high detection capability found with the Tronox bundle. The rough internal surface seemed to have reduced the capability of detecting holes with 1 mm diameter.

From the results of session 1 it appeared that no conclusion was possible whether or not a correlation exists between results from APR and IRIS. In some tubes APR inspection did not detect a wall loss whereas IRIS inspection reported a certain pit depth, varying from 0.6 – 1.3 mm. No explanation for this difference could be given. For that reason, the actual wall reductions were measured through destructive examination. It turned out that again no correlation could be identified, neither:

- between IRIS results and the second APR results, nor
- between IRIS results and the actual, measured wall thicknesses, nor
- between APR results and the actual, measured wall thicknesses.

This means that the absolute value of the wall thickness as measured through none of the inspection methods IRIS and APR could be confirmed. Possibly the destructive examination was too limited for such a confirmation because of the local nature of detected wall reductions, apart from the fact that the locations of the maximum pit depth measured by IRIS was not known. Another explanation may be that the inspection results (both from IRIS and APR) has no meaning in terms of a absolute value of the local wall thickness.
The final conclusion as far as detection of wall loss is concerned is that no evidence was found that supports a positive expectation about the capability of APR (and IRIS).

4.3 Fuji bundle

An APR inspection was conducted on a heat exchanger in service with Fuji, upon their request. The inspection revealed a number of blockages, some holes and pitting. After completion of the inspection a verification was undertaken by means of endoscopy.

The presence of blockages could be confirmed. For holes and pitting the findings with the applied endoscope were not conclusive possibly due to the poor detection capability of the applied endoscope.
Therefore, the only possible conclusion is that APR appeared very well capable of detecting the blockages.

4.4 Conclusion

The various results achieved through the experiments with the three bundles from service lead to the conclusion described in table 3, as far as the detection performance is concerned.

Table 3 Conclusion on detection performance from bundles which have been in-service only

	Performance
Holes	Very high for holes with 1 mm. and 2 mm. diameter provided that the inner surface is clean, smooth and not severely attacked by pitting. The detection performance is hampered by severe pitting / surface roughness, especially if the diameter is small. Holes covered by internal or external residues are not detected. No False Calls.
Blockages	High for fairly large obstacles (as present in Fuji bundle). No findings are available for other sizes. Detection is susceptible to small sized False Calls, viz. < 3 % cross sectional area which have no practical meaning (3.5% corresponds to 3 matches as shown in figure B.4).
Wall reductions	Only very few findings about detection of wall reductions are available. Detection is susceptible to False Calls suggesting wall reductions up to 30 % wall thickness.

More details about WP3 are reported in [4].

5 Summary of WP4: validation through experiments with a mock-up

5.1 Test set-up

The mock-up consisted of 2 parts (so-called boxes) which contained 38 tubes each. The tubes were made from carbon steel, with a diameter of 25 mm and a wall thickness of 2 mm. They have not been in service before but have been purchased as seamless precision tube. The length of the tubes is 2.5 meter in each box but the two boxes are connected to each other in order to generate a total length of 5195 mm. The connection was realised with a tube piece with a total length of 295 mm which was positioned 50 mm inside the tube (without permanent jointing) in both boxes and thereby resulted an additional length of 195 mm. The overall construction is illustrated in Figure 9.

Figure 9a Front view of the mock-up

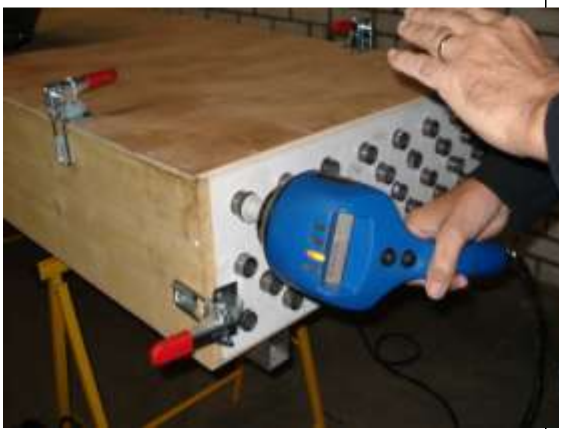


Figure 9b Inspection using type G3 tool

Various types of artificial defects have been realised on the internal surface of the tubes:

- Holes with diameters of 0.5, 1.0 and 2.0 mm. which were produced by drilling; total number of 64.
- Wall reductions with different shapes, sizes including the depth, see table 4; total number of wall reductions is 48. The diameter is 10 mm. for all wall reductions whereas the values of the depth are 0.6 mm, 1.1 mm or 1.6 mm., representing 30% (0.60 mm), 55% (1.10 mm) and 80% (1.60 mm.) of the wall thickness.

The wall reductions were manufactured by making use of machined inserts which were made from aluminium. The inserts were positioned and glued in a machined through wall slot in the tube, see Figure 10.

Figure 10. Example of an insert containing a defect

Table 4 Description of wall reductions

Flat bottom pits with rectangular shaped bevel				
Depth pit	Diameter	Volume pit	Delta CSA (*)	Number
0.6 mm	10 mm	47.1 mm^3	6 mm^2 = 1.7 %	3
1.1 mm	10 mm	86.3 mm^3	11 mm^2 = 3.2 %	3
Row of 4 pits (**) with a depth of 1.1 mm	10 mm	86.3 mm^3 for each pit	11 mm^2 = 3.2 % for each pit	3 rows of 4 pits = 12
Flat bottom pits with S-shaped bevel				
Depth pit	Diameter	Volume pit	Delta CSA (*)	Number
0.6 mm	10 mm	Ca. 47 mm^3	6 mm^2 = 1.7 %	3
1.1 mm	10 mm	Ca. 86 mm^3	11 mm^2 = 3.2 %	3
1.6 mm	10 mm	Ca. 125 mm^3	16 mm^2 = 4.6 %	3
Cup shaped pits				
Depth pit	Diameter	Volume pit	Delta CSA (*)	Number
0.6 mm	10 mm	Ca. 28 mm^3	Ca. 3.6 mm^2 = 1.0 %	3
1.1 mm	10 mm	Ca. 52 mm^3	Ca. 6.6 mm^2 = 1.9 %	3
1.6 mm	10 mm	Ca. 75 mm^3	Ca. 9.6 mm^2 = 2.8 %	3
Axial flat bottom pits with S-shaped bevel				
Depth pit	Diameter	Volume pit	Delta CSA (*)	Number
1.1 mm	10 mm	Ca. 306 mm^3	11 mm^2 = 3.2 %	3
1.6 mm	10 mm	Ca. 445 mm^3	16 mm^2 = 4.6 %	3
Reference defects				
Depth pit	Diameter	Volume pit	Delta CSA (*)	Number
20% = 0.4 mm	4.75 mm	7.1 mm^3	1.9 mm^2 = 0.55 %	3
80% = 1.6 mm	4.75 mm	28 mm^3	7.6 mm^2 = 2.2 %	3

(*): Delta in Cross Sectional Area, both expressed in "mm^2" and in "%" relative to the inner air space
(**): the 4 pits were distributed over a length of about 200 cm.

- Different types of blockages were produced, viz:
    - Wooden pieces having a length: 90 mm, width: 7 mm, thickness: 3 mm.
    - Pasting a layer of gypsum on the inner surface. The size of the gypsum layer is about an average thickness of 1 mm.
    - Gluing (regular) matches. The size of the matches is: length: 40 mm., width and thickness of 2 mm.

The morphology of the various defects is outlined in Appendix B.
All defects have been positioned at predefined locations along the tube. In course of the various measurement sessions, some changes have been made implying that certain defects (holes and blockages) have been added or removed whereas the wall reductions were not changed. The exact situation regarding the presence of certain defects and their location for each session is not presented in this report but is available in [5].

All inspections have been conducted by the same experienced operator from Sound Tube Testing.
No information was made available about the defects present, viz. the number of defects, the type of defects, the dimensions and the wetting or drying conditions. The tubes were covered in boxes so the

operator could not observe any indication of the presence of the defects, nor did he know which defects could possibly be present.
The analysis of the inspection data was performed in a few days period after the inspection. It was carried out by experienced analysts from Acoustic Eye and Sound Tube Testing. Because of the importance of these inspections, it can be assumed that the quality of the analysis was maximised. Also, the analyses were carried out without any information about the defects. In addition, the data analyses of the various inspection sessions were conducted without any feedback about the detection or presence of the defects. Therefore, the inspections can be considered as fully blind.

In order to simulate a realistic situation, all inspections have been performed from only one side of the mock-up.
The mock-up has been installed in a shop and has been inspected during the period November 2012 – March 2013, implying an environmental temperature of 5 – 10 ˚C.

In between the separate inspection sessions, some changes in the tube configuration and or the defects were realised. Besides, in cases that defects were missed, visual examination was conducted to verify the presence of those missed defects or to understand the cause of missing and a repeat inspection was undertaken in the next session.

5.2 Results and conclusions

The conclusive results of the validation program are summarized in the tables below. They are based on measurements of 64 holes, 48 wall reductions and 9 blockages whereby each specific type was produced in threefold.

5.2.1 Detection performance

Table 5 Conclusion on detection performance

	Performance
Holes	Very high (1), even for the smallest holes with 0.5 mm. diameter provided that the hole is not covered. Holes covered by contaminants or pooled water are not detected.
Blockages	High: 8 out of 9 were detected for sizes of > 3% cross sectional area whereas the False Call rate was 6 out of 24 and the assigned defect dimension of these False Calls was only small, viz. < 4% which is without practical meaning (3.5% corresponds to 3 matches as shown in Figure B.4).
Wall reductions	Very high (1) for all shapes for the range of defect dimensions and shapes used in this testing program. Note that wall reductions covered by pooled water are not detected. Further, no or only limited effect of the presence of multiple defects.

(1): The term ‘very high’ expresses that the hit rate found in the validation programme is 100% for 64 holes and also 100% for the 48 wall reductions whereas the False Call rate was: 0 out of 64, and 2 out of 98 for holes and wall reductions respectively taking account of the small sizes (assigned defect dimension) of the False Calls for wall reductions, viz. < 9% wall thickness.

Obviously, the 100% hit rate for wall reductions is valid for the range of applied defect dimensions, which means a diameter of 10 mm. whereas the range for the depth was 0.6 mm – 1.6 mm., representing 30% - 80% of the wall thickness. The corresponding delta in Cross Sectional Area that resulted from these defects was 0.55% – 4.6%.
Because of the 100% hit rate, no dependency was observed as function of the range of shapes and edge roundness which were used. In addition, this 100% hit rate applies to the specific measurement condition, viz. clean and dry tubes. In order to determine the effect of the number of preceding defects, a row of 4 defects (coded 4R) was included in the testing program. The delta in cross sectional area of each individual wall reduction was 3.2% whereas the distances in between was about 50 cm. All wall reductions were detected, so no effect was observed. On the other hand, certain shadowing effects were observed in cases where defects were located more closely resulting in a loss of detection performance. Only 2 False Calls were reported out of 98 reported wall reductions. These False Calls were sized to maximum 9% wall reduction which is relatively small compared to the size of the artificial wall reductions. The dimensions of the so-called 'reference defects', coded as 20R (depth = 20%) and 80R (depth = 80%) as outlined in table 4, is chosen equal to certain defects from the testing program with SwRI [6] to enable comparison with the results from this program. In the SwRI-program the hit rate was 30% and 90% (out of 5 defects) for the 20R and 80R respectively. The 30% hit rate is clearly lower than the 100% hit rate from this validation program although it should be recognized that this conclusion has no statistically sound basis. The difference is probably resulting from the improvement which has been realized in the inspection tool (model G3): in the SwRI-program an early prototype of the inspection tool was used.

5.2.2 Sizing performance

Table 6 Conclusion on sizing performance

	Performance
Holes	Reasonable: underestimation of 10% - 30%.
Blockages	Reasonable: the deviation was small for Cross Sectional Area below 20%.
Wall reductions	Poor: a quite large spread, so quite uncertain and too limited to enable trend analysis.

The conclusion is based on data which is presented in Appendix C.

5.2.3 Characterisation performance

Table 7 Conclusion on characterization performance

	Performance
Holes	Fully correct: all holes were characterised as holes.
Blockages	Fully correct: all blockages were characterised as blockages.
Wall reductions	Fully correct: all wall reductions were characterised as wall reductions.

5.2.4 Localization performance

Table 8 Conclusion on localization performance

	Performance
Holes	Good: underestimated, usually < 1% but occasionally up to 2% (*)
Blockages	Good: underestimated, usually < 1% (*)
Wall reductions	Good: underestimated, from less than 1% up till 3% (*)

(*): relative to the distance between a given defect and the inspection tool.

5.2.5 Effect of wetting and subsequent drying

Wetting by pooled water results in a tremendous reduction of the detection capability. This has been observed for holes and wall reductions but will probably also apply to obstacles. Besides, False Calls of blockages will show up caused by the pooled water.

Subsequent drying has a restoring effect. Nevertheless, it will not always restore the dry situation in case of holes. This is cause by a remaining film of contaminations. Obviously this effect is stronger the smaller the size of the holes.

5.2.6 Effect of multiple defects

Observations show that in certain cases the effect of the presence of nearby defects on the detection capability of individual defects may be absent or negligible. However in other cases it may lead to missing defects or to wrong characterisation of defects. It is understandable that the effect cannot be expressed in general terms but is very dependent on the size and distances in between the defects.

5.2.7 Representativeness of the results

It should be noted that the results from the experiments on the mock-up are not representative for tubes which have been in service because of the roughness and possible contamination of the internal surface that may occur during service. The internal surfaces of the newly purchased tubes were clean and smooth. Especially the effect of covering or contaminating holes has been proven to be strong. Therefore, the results from the mock-up should be considered as a non conservative, somewhat too positive result.

The results are valid for the specific types and dimensions of the defects which have been included in the experiment. This implies that no conclusions can be drawn for other types of defects, especially for uniform (more smooth) wall reduction.

All results are related to the specific type of the inspection device used in the experiments which is referred to as “model G3”.

6 Evaluation

In this section the results of the experimental validations are combined to overall conclusions with a general meaning rather than a specific application.
The results from WP4 are very well documented and quantified because of the nature of the mock-up validation. However, these results are not representative for tubes which have been in service because of the surface roughness and possible contamination of the internal surface that may occur during service. For the purpose of evaluation of the detection performance, the mock-up experiment (WP4) forms the basis whereas the results from the bundles which have been in-service (WP3) are used to correct and complement in order to arrive at overall conclusions.
To formulate the overall conclusion regarding sizing performance, characterization performance and localization performance only the results from the mock-up experiment are available.

6.1 Detection performance and capability

Table 9 Copy of table 5: Conclusion on detection performance from only the mock-up (WP4)

	Performance
Holes	Very high (1), even for the smallest holes with 0.5 mm. diameter provided that the hole is not covered. Holes covered by contaminants or pooled water are not detected.
Blockages	High: 8 out of 9 were detected for sizes of > 3% cross sectional area whereas the False Call rate was 6 out of 24 and the assigned defect dimension of these False Calls was only small, viz. < 4%.
Wall reductions	Very high (1) for all shapes for the range of defect dimensions and shapes used in this testing program. Note that wall reductions covered by pooled water are not detected. Further, no or only limited effect of the presence of multiple defects.

(1): The term 'very high' expresses that the hit rate found in the validation programme is 100% for 64 holes and 48 wall reductions whereas the False Call rate was: 0 out of 64, and 2 out of 98 for holes and wall reductions respectively.

As stated before, the performance outlined in table 9 applies to the situation of new tubes, implying a smooth and clean inner surface. Therefore, the results from the bundles which have been in-service should be added, see table 10.

Table 10 Copy of table 3: Conclusion on detection performance from only the bundles (WP3)

	Performance
Holes	Very high for holes with 1 mm. and 2 mm. diameter provided that the inner surface is clean, smooth and not severely attacked by pitting. The detection performance is hampered by severe pitting / surface roughness, especially if the diameter is small. Holes covered by internal or external residues are not detected. No False Calls.
Blockages	High for fairly large obstacles (as present in Fuji bundle). No findings are available for other sizes. Detection is susceptible to small sized False Calls, viz. < 3% cross sectional area which have no practical meaning.
Wall reductions	Only very few findings about detection of wall reductions are available. Detection is susceptible to False Calls suggesting wall reductions up to 30% wall thickness.

Combining the results including those from WP2 leads to the overall conclusion in table 11.

Table 11 Overall conclusion on detection performance

	Performance
Holes	Very high, even for the smallest holes with 0.5 mm. diameter provided that the hole is not covered and the inner surface is not too rough resulting from pitting for example. Holes covered by contaminants or pooled water are not detected. Obviously, the effect of surface roughness is smaller for larger holes. No False Calls. Summarizing rating: Highly to fairly reliable (high detection rate, low False call rate) dependent on the surface condition.
Blockages	High (for sizes of > 3% cross sectional area in clean, smooth surface) whereas detection is susceptible to False Calls dependent on surface condition suggesting blockages up to 4 % cross sectional area which have no practical meaning (3.5% corresponds to 3 matches as shown in Figure B.4). Summarizing rating: Highly to fairly reliable (high detection rate, susceptible to small sized False Calls) dependent on surface condition.
Wall reductions	High to very high in case of smooth and clean surface and applicable to the shapes in the range of defect dimensions and shapes used in this testing program, see section 2.2.2. Wall reductions covered by pooled water are not detected. Susceptible to False Calls suggesting wall reductions up to 30 % thickness (so-called large sized False Calls). No data is available regarding the detection performance in case of other surface conditions as well as the effect of the shape gradient. The gradient effect will be strong above a given threshold, see also 7.5. Summarizing rating: Highly to poorly effective dependent on surface condition and shape gradient.

In the abovementioned tables separate ratings have been given to the detection performance (or hit rate) and the False Call rate. However, the quality of a given inspection method is determined by the combination of both parameters. The combined quality indicator is referred to as ''Detection capability''. In the table 12 below, the various ratings for the detection capability are defined as function of the rating for the detection performance and the rating of the False Call.

Table 12 Rating terminology

Conclusion on Detection capability	**Detection performance (only the Hit Rate)**	**False Call rate (*)**
Highly reliable	High	Between zero and low number of False Calls or only small sized False Calls
Fairly reliable	High	Low number of large sized False Calls
Poorly reliable	< High	Fairly number of large sized False Calls
Highly effective	High	Few small sized False Calls
Fairly effective	High	Fairly number of large sized False Calls
Poorly effective	< High or No data	Fairly number of large sized False Calls

(*) 'small sized False Call' means: they have no practical significance, e.g. size < 4% for blockages.

Applying this qualification system to the results as given in table 11 leads to the summarizing rating for the detection capability presented in table 13.

Table 13 Overall summary on 'detection capability' which is the combined quality of 'Hit Rate' (detection performance) and 'False Call rate'.

	Summarizing rating
Holes	Highly reliable (high detection rate, low False call rate); capability dependent on the surface condition.
Blockages	Highly reliable (high detection rate, susceptible to small sized False Calls only); capability dependent on surface condition.
Wall reductions	Between highly and poorly effective for defect dimensions and shapes used in this testing program (high detection rate, susceptible to large sized False Calls) dependent on surface condition. No data regarding the effect of the shape gradient is available. In summary, a large spread has to be assumed varying between highly effective to poorly effective.

The above summary represents all the results achieved in the project as far as detection performance is concerned.

6.2 Sizing performance

The sizing performance has only been assessed in the experiments with the mock-up, so the final conclusion given in table 14 is a copy of table 6.

Table 14 Copy of table 6: Conclusion on sizing performance

	Performance
Holes	Reasonable: underestimation of 10% - 30%.
Blockages	Reasonable: the deviation was small for Cross Sectional Area below 20%.
Wall reductions	Poor: a quite large spread, so quite uncertain and too limited to enable trend analysis.
The above conclusion is based on the experiments with the mock-up. No information is gained from bundles which have been in-service. So the above rating applies to clean, smooth surfaces whereas no data are available for other surfaces.	

6.3 Characterization performance

The characterization performance has only been assessed in the experiments with the mock-up, so the final conclusion given in table 15 is a copy of table 7.

Table 15 Copy of table 7: Conclusion on characterization performance

	Performance
Holes	Fully correct: all holes were characterized as holes.
Blockages	Fully correct: all blockages were characterized as blockages.
Wall reductions	Fully correct: all wall reductions were characterized as wall reductions.
The above conclusion is based on the experiments with the mock-up. No information is gained from bundles which have been in-service. So the above rating applies to clean, smooth surfaces whereas no data are available for other surfaces.	

6.4 Localization performance

The localization performance has only been assessed in the experiments with the mock-up, so the final conclusion given in table 16 is a copy of table 8.

Table 16 Copy of table 8: Conclusion on localization performance

	Performance
Holes	Good: underestimated, usually < 1% but occasionally up to 2% (*)
Blockages	Good: underestimated, usually < 1% (*)
Wall reductions	Good: underestimated, from less than 1% up till 3% (*)
The above conclusion is based on the experiments with the mock-up. No information is gained from bundles which have been in-service. So the above rating applies to clean, smooth surfaces whereas no data are available for other surfaces.	

(*): relative to the distance between a given defect and the inspection tool

6.5 Effect of wetting and subsequent drying

Wetting by pooled water results in a tremendous reduction of the detection capability. This has been observed in the mock-up experiments for holes and wall reductions but will probably also apply to obstacles. Besides, False Calls of blockages have showed up caused by the pooled water.

Subsequent drying has a restoring effect. Nevertheless, it will not completely restore the dry situation in case of (small) holes. This is caused by a remaining film of contaminations which remains in the small sized holes. Obviously this effect is stronger the smaller the size of the holes.

6.6 Effect of multiple defects

Observations show that in certain cases the effect of the presence of nearby defects on the detection capability of individual defects may be absent or negligible. However in other cases it may lead to missing defects or to wrong characterisation of defects. It is not possible to determine the magnitude of the effect in general because this is very dependent on the size and distances in between the various defects.

6.7 Representativeness of the results

All results are related to the specific type of the inspection device used in the experiments which is referred to as “model G3”.

7 Discussion

In this section a number of specific topics are addressed.

7.1 Comparison to physics model

In WP1 an evaluation of the physics of the APR-technique has been conducted resulting in a theoretical model for the defect size threshold and probability of detection shown in Figure 2 and 3 respectively. Quite a number of assumptions were made to establish the model and thereby the model cannot be used to determine the probability of detection in an absolute meaning. Nevertheless, the results from the experiments with the mock-up can be compared with the theoretical model. This comparison shows clearly that the model is too conservative / pessimistic about the detection performance. For instance, for wall reductions with a depth of 0.6 mm, the effective ‘defect height’ (averaged along the entire circumference) is 0.076 mm. According to the model the detection performance would be extremely low, even after correction of the given Figures 2 and 3 for the correct tube radius. However, in the mock-up experiment **all** wall reductions with a depth of 0.6 mm were detected !

7.2 Nature of validation

Evaluation of non-destructive techniques can be undertaken in varying degrees of detail, form very qualitatively to an extensive quantitative testing program. In Article 14 of ASME Section V, the so-called level of rigor is described to express the level and extent of quantitative data. The document explains that three levels of rigor can be defined, viz:

a) Low Rigor: only a technical justification is required, no performance demonstration.
b) Intermediate rigor: in addition to a technical justification, the performance should be demonstrated through testing with a limited number of tests (blind or non-blind)
c) High rigor: a sufficient number of test specimens shall be evaluated to estimate sizing error distributions and determine an accurate POD (Probability Of Detection) for different defect sizes. In this case a statistical analysis should support the evaluation.

The nature of the current validation project meets the requirement of the level of intermediate rigor.

In order to determine a POD-curve, a minimum of 30 samples are needed as a rule of thumb. These samples should be spread over the range of defect sizes where the POD-curve is positioned (this is the range where the POD values vary from 0% to 100%).
The selected sizes and morphologies for the holes as well as wall reductions were apparently too large (and easily detected) so that 100% hits were found and no single defect was missed. This clearly resulted in to the lack of required data (hits and misses) to establish a POD-curve.
A statistical evaluation was possible for the sizing performance regarding holes. This is elaborated in table C.1 of Appendix C.

7.3 POF guideline

In the field of pipeline operators, the so-called POF-guideline (Pipeline Operators Forum) [7] is commonly used to describe the approach for the evaluation of pig inspection techniques. In this guideline a scheme is included for the definition of defects (named ‘metal loss anomalies’). In appendix D, the graphical presentation from this guideline is given. The sizes of the various artificial defects from the mock-up program have been plotted in this graph in order to clarify which types of defects were used according to the definition of the POF-guideline.

7.4 Comparison with other inspection methods

No extensive experimental comparison has been undertaken between APR and other techniques. Nevertheless, some considerations can be given in general.

Comparison to Electromagnetic techniques

Electromagnetic Testing has different types, of which the main types are.:

- ET: conventional Eddy Current applied to non ferromagnetic materials.
- FSEC: Fully Saturated Eddy Current applied to steel in pre-service inspection.
- RFT / RFEC: Remote Field Eddy Current applied to steel in in-service inspection.

The various techniques are in essence capable of detecting and sizing wall loss, pitting and cracking. An overview of general advantages and shortcomings relative to APR is given in table 17.

Table 17 Overview of advantages and shortcomings of Eddy Current techniques relative to APR

Technique & application	Typical features	Advantages relative to APR	Shortcomings relative to APR
ET Non ferromagnetic metals; Pre-service and In-service inspection	Very high detection performance for pitting, cracks and wall loss.	Sizing possible, Uniform corrosion detection possible due to absolute wall measurement mode, Detection of axial cracks possible, Also detecting wall loss on outside surface is possible.	Less fast, Cannot pass narrow bends, No detection of blockages possible behind first blockage. Measurement is unreliable near support and tube plates. Edge effect: no capability near tube ends.
FSEC Steel; pre-service inspection	High detection performance for pitting, cracks and wall loss.	Sizing possible, Uniform corrosion detection possible due to absolute wall measurement mode. Detection of axial cracks possible, Also detecting wall loss on outside surface is possible.	Less fast, Cannot pass bends, Not transportable, only for pre-service inspection. No detection of blockages possible behind first blockage. Edge effect: no capability near tube ends.
RFT / RFEC Steel; in-service inspection	Medium detection performance for pitting, cracks and wall loss.	Uniform corrosion detection possible, Detection of circumferential cracks possible, Also detecting wall loss on outside surface is possible.	Less fast, Cannot pass narrow bends, No discrimination possible between outside or inside defects, Low performance for holes. No detection of blockages possible behind first blockage. Measurement is unreliable near support and tube plates. Edge effect: no capability near tube ends.

Comparison to IRIS
In case of uniform corrosion without local wall reductions, it is to be expected that IRIS is capable of detecting wall loss and sizing it more effectively than APR. Both techniques require sufficient cleaning. APR is appropriate for the detection of blockages in contrast to IRIS. Further, APR is capable of detecting holes whereas small holes under 2 mm. will not be detected through IRIS. Lastly, IRIS is time consuming and slower than electromagnetic inspection, even more so relative to APR.

7.5 Effect of defect morphology

In the mock-up experiments no dependency was demonstrated for the range of shapes and roundness of the edges which was used in the various wall reduction, see table 4 and Appendix B.
From the modelling work in WP1 as well as from general experience it is known that the detection performance is dependent on the gradient of the wall reduction in direction of the tube length. Apparently, the applied gradients in the artificial defects were too steep to determine this effect. No conclusion can be drawn on the threshold value due to the lack of data but also because of the fact that the threshold will depend very strongly on the surface condition.

7.6 Detection threshold

In the mock-up experiments wall reductions were detected with a diameter of 10 mm. whereas the range for the depth was 0.6 mm – 1.6 mm., representing 30% - 80% of the wall thickness. The corresponding delta in Cross Sectional Area that resulted from these defects was 0.55% – 4.6%, as described in table 4. Note that the Cross Sectional Area is expressed relative to the inner air space that corresponds to the tube size.
Similar to the defect morphology, no conclusion can be drawn on the detection threshold value because of the lack of data but also because of the fact that the threshold will depend very strongly on the surface condition.

7.7 Working conditions

From various sources information is collected regarding the optimum working conditions to be met for effective application of the APR-technique:

- Required minimum number of tubes for a proper statistical processing to achieve the reference signal. The required number is dependent on the type of defect that is to be detected: for holes it could be only one, whereas for blockages and wall reductions the minimum number of tubes is 5, when defects are large. The manufacturer specifies a minimum number of 50 [8].
- Required minimum length of tubes: 1 meter.
- Required maximum length of tubes: 35 meters
- Dry inner surface of tubes: no pooled water or moisture.
- As clean as possible. APR needs more cleaning than electromagnetic techniques. Holes or pits that are covered by any fouling material won't be detected, and can appear as multiple small blockages that add noise to the signal. IRIS needs cleaning down to the bare metal, so relative to IRIS, APR needs a lower level of cleaning.

8 Conclusions

A validation program was conducted to evaluate the performance of the APR-technique for the purpose of inspecting tubes in heat exchangers. The validation was carried out on one specially constructed mock-up, and three bundles taken out of field service.

Table 18 below demonstrates clearly that APR is very well capable of detecting holes (from 0.5 mm diameter) as well as distinguishing them from pits. It also demonstrates a high detection of blockages for all surface conditions. The APR technology also proves to deliver relatively high accuracy in sizing for both holes and blockages.

On the other hand it demonstrates that the effective detection of wall reductions will strongly depend on the given application and associated surface condition. In addition, it must be noted that detection of wall reductions is only possible if the gradient of the wall reduction is sufficiently steep. No threshold value for the gradient could be determined due to lack of data. Therefore, the detection capability has a large spread varying between highly effective to poorly effective.
The finding that the sizing performance for wall reductions is poor, implies that APR is not suitable for the purpose of trending corrosion or erosion. It has been demonstrated in this validation program that all included wall reductions were detected (in the presence of a smooth and clean surface).

Table 18 Summary of detection capability and sizing performance for APR

	Detection Capability	Sizing performance
Holes	Highly reliable	Reasonable
Blockages	Highly reliable	Reasonable
Wall reductions	Large spread	Poor

The ratings used for the detection capability are defined in table 12, whereas the ratings for the sizing performance are based on table 14.

The detection capability shows a certain reduction which is caused by the strong effect of the surface condition. The magnitude of the effect is dependent on a number of factors, viz. the surface roughness caused by pitting, the presence of pooled water, covering of holes and pits due to scaling and contamination.
Therefore, a higher level of cleaning is recommended in case of a contaminated surface. Obviously, the magnitude of the effect also depends on the defect size relative to the surface effect: the larger the defect size, the smaller the effect.

The evaluation of the physics of the APR technique have confirmed that the propagation and reflection of sound waves as used in this technology is well understood and has a sound physical basis for tube and pipe inspection applications.

In summary, the findings of this study indicate that APR can be considered superior to other techniques regarding the detection and sizing of small holes as well as blockages, while not performing as well on wall loss detection in pipes with rough surfaces, nor in wall loss sizing.

9 References

[1] general description of the APR-technique:
http://www.acousticeye.com/en-us/technology/overview.asp

[2] Principle of Acoustic Pulse Reflectometry applied to tubular heat exchangers; Dr. Ir. Ing.V.O. de Haan; March 2012

[3] Evaluation of inspection reports; ir. J.H.A.M. Heerings; January 2012

[4] Validation with heat exchangers after service; ir. J.H.A.M. Heerings; June 2013

[5] Evaluation through experiments with a mock-up; ir. J.H.A.M. Heerings; June 2013

[6] Evaluation and Characterization of the Acoustic Eye Technology; Report from SouthWest Research Institute (SwRI), San Antonio, Texas; August 2011

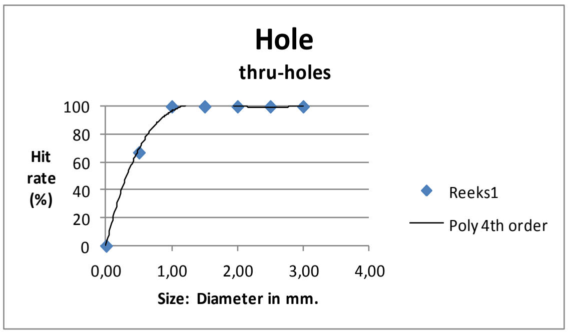
[7] POF: Specifications and requirements for intelligent pig inspection of pipelines; version 3.2, January 2005

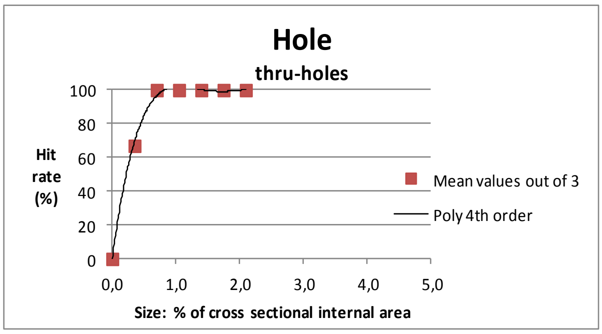
[8] Private communication with Sound Tube Testing, kick-off meeting 7th October 2011.

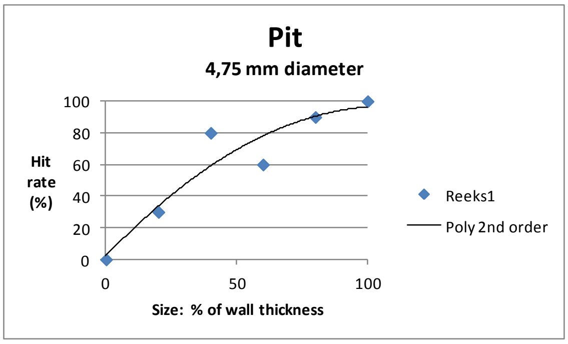
Appendix A Results from SwRI-program

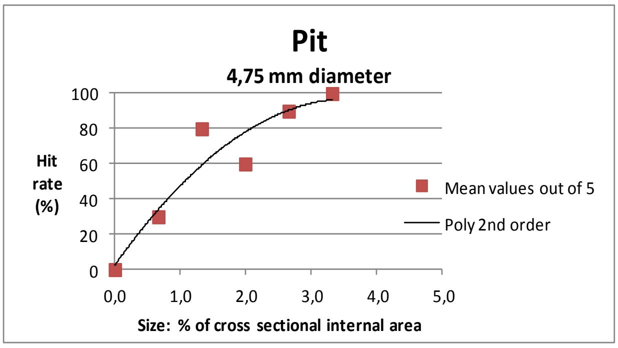
Table A.1 Detection performance (hit rate) as function of defect size from SwRI-program [6]

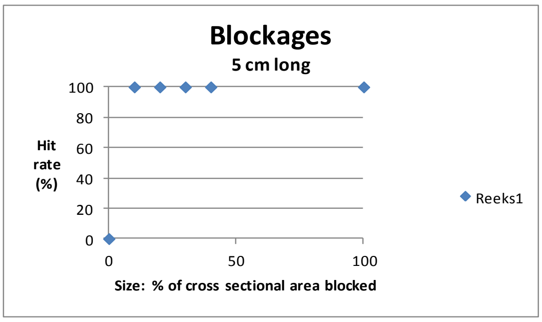
In this column the defect size is expressed in terms of % of wall thickness for a pit, blockage and erosion.	In this column the defect size is expressed in terms of % of cross sectional area for all defects.

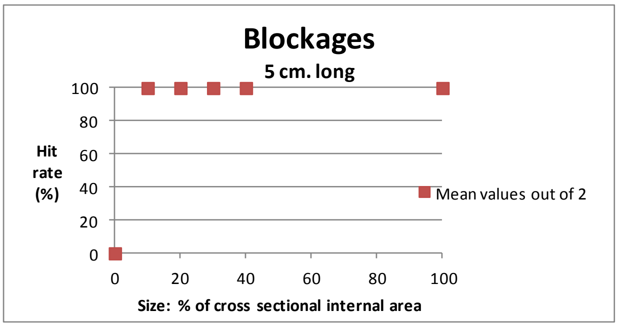


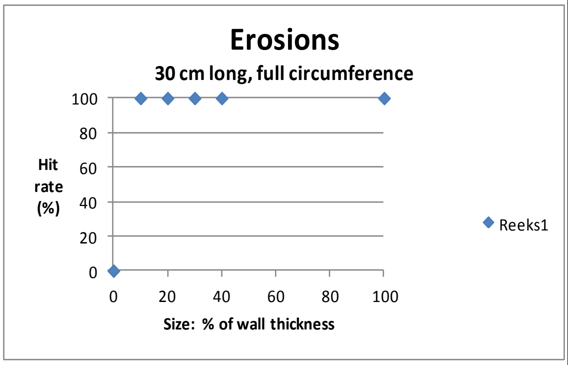


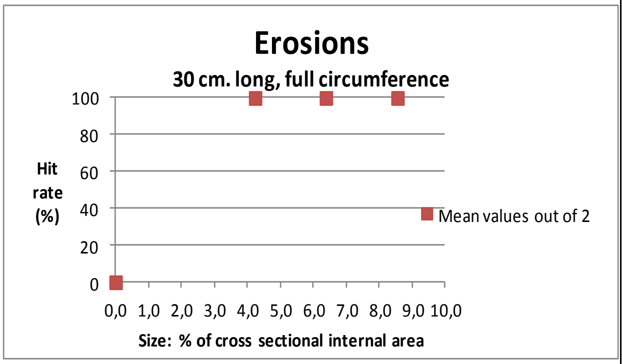












Appendix B Morphology of wall reductions and blockages in mock-up

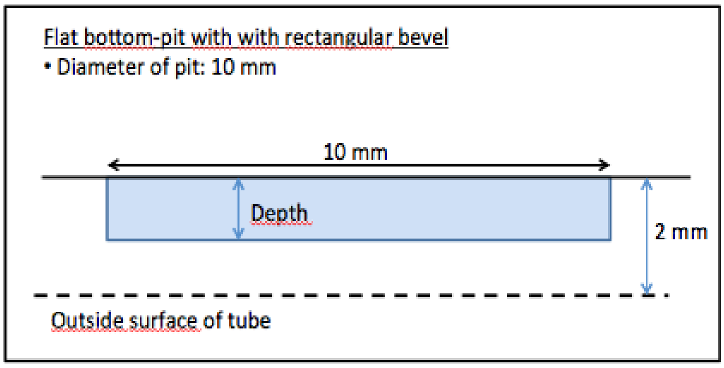
1. Flat bottom pit with rectangular shaped bevel

Table B.1 Description of flat bottom pits with rectangular shaped bevel

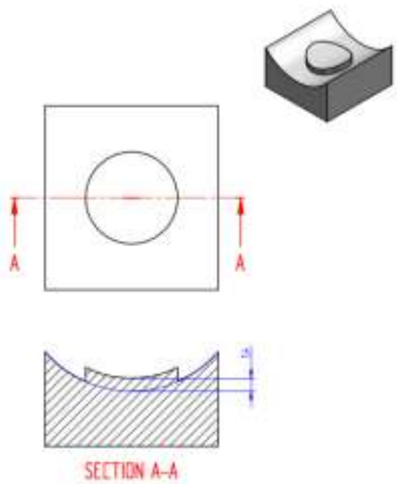
Depth pit	Diameter	Defect code	Volume pit	Delta CSA (*)	Number
0.6 mm	10 mm	FS	47.1 mm^3	6 mm^2 = 1.7 %	3
1.1 mm	10 mm	FM	86.3 mm^3	11 mm^2 = 3.2 %	3
Row of 4 pits (**) with a depth of 1.1 mm	10 mm	4R	86.3 mm^3 for each pit	11 mm^2 = 3.2 % for each pit	3 rows of 4 pits = 12

(*): Delta in Cross Sectional Area, both expressed in "mm^2" and in "%" relative to the inner air space
(**): the 4 pits were distributed over a length of about 200 cm.

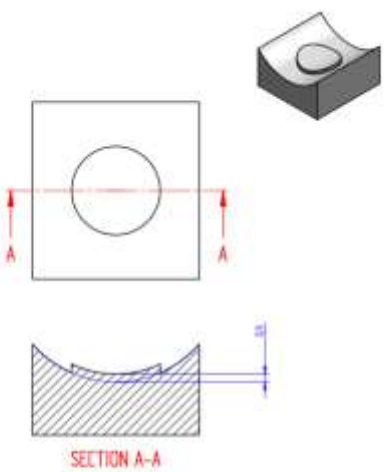
Definition of defect morphology



Resulting defect



Type FS: Depth = 0,6 mm



Type FM: Depth = 1,1 mm

2. Flat bottom pit with S-shaped bevel

Table B.2 Description of flat bottom pits with S-shaped bevel

Depth pit	Diameter	Defect code	Volume pit	Delta CSA (*)	Number
0.6 mm	10 mm	SS	Ca. 47 mm^3	6 mm^2 = 1.7 %	3
1.1 mm	10 mm	SM	Ca. 86 mm^3	11 mm^2 = 3.2 %	3
1.6 mm	10 mm	SL	Ca. 125 mm^3	16 mm^2 = 4.6 %	3

(*): Delta in Cross Sectional Area, both expressed in "mm^2" and in "%" relative to the inner air space

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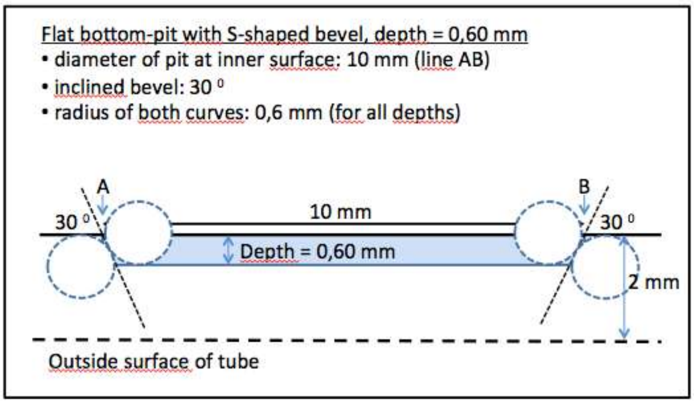

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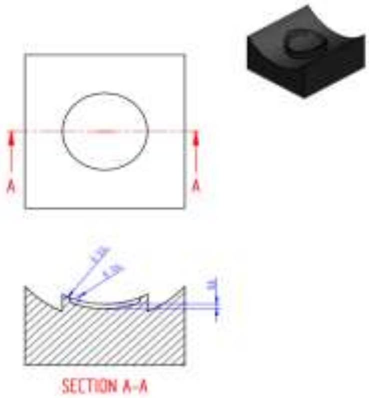

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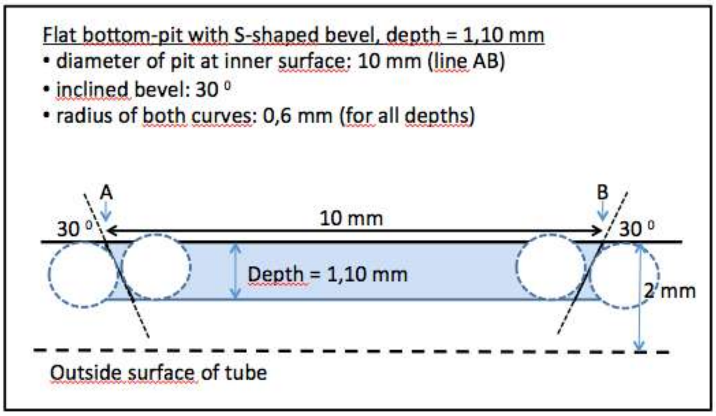

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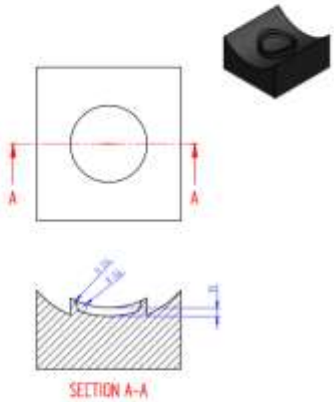

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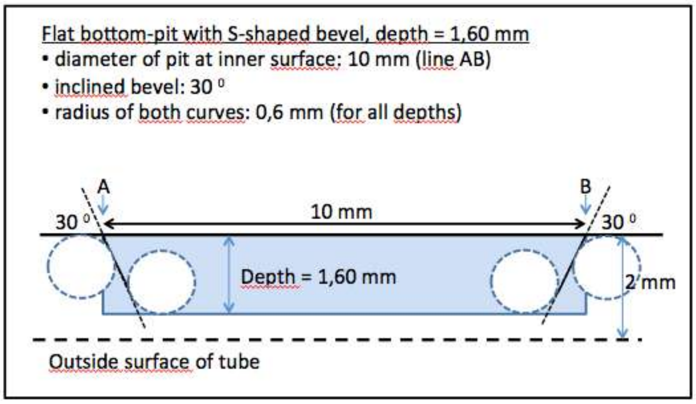

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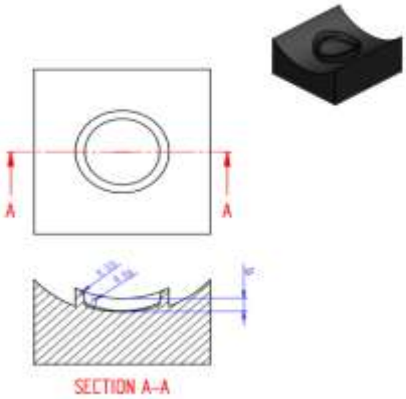

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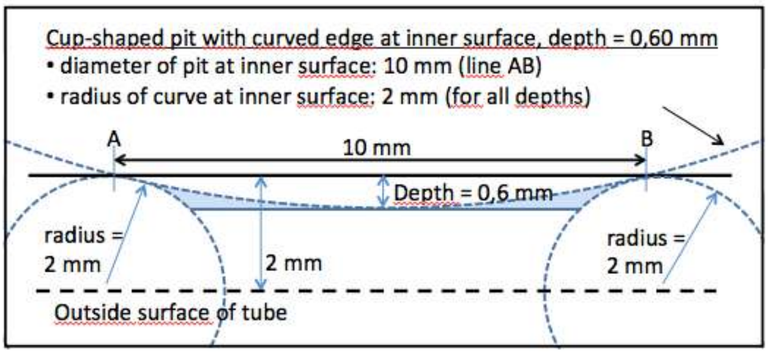
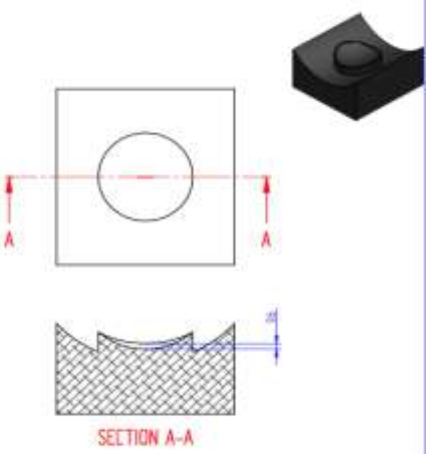
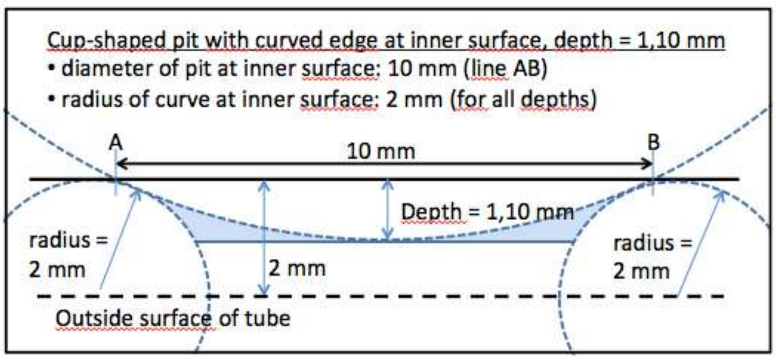
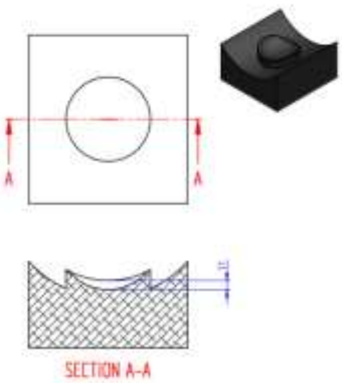
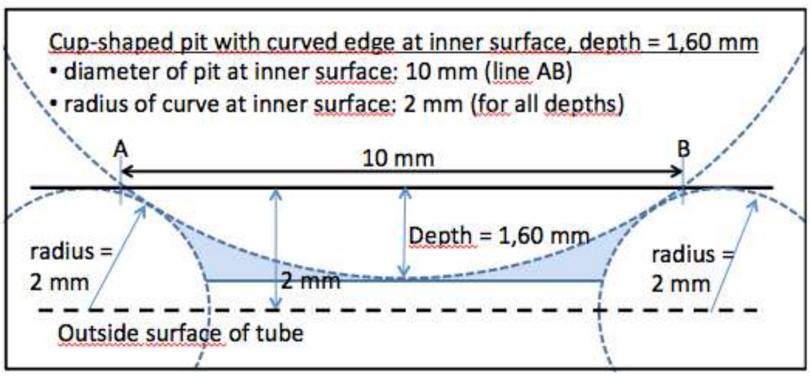
3. Cup shaped pit

Table B.3 Description of cup shaped pits

Depth pit	Diameter	Defect code	Volume pit	Delta CSA (*)	Number
0.6 mm	10 mm	CS	Ca. 28 mm^3	Ca. 3.6 mm^2 = 1.0 %	3
1.1 mm	10 mm	CM	Ca. 52 mm^3	Ca. 6.6 mm^2 = 1.9 %	3
1.6 mm	10 mm	CL	Ca. 75 mm^3	Ca. 9.6 mm^2 = 2.8 %	3

(*): Delta in Cross Sectional Area, both expressed in "mm^2" and in "%" relative to the inner air space

Definition of defect morphology	Resulting defect
 Type CS, definition of curvatures	
 Type CM, definition of curvatures	
 Type CL, definition of curvatures	No drawing available

4. Flat bottom pit with S-shaped bevel AND with axial length of 30 mm.

Table B.4 Description of axial flat bottom pits with S-shaped bevel

Depth pit	Diameter	Defect code	Volume pit	Delta CSA (*)	Number
1.1 mm	10 mm	ASM	Ca. 306 mm^3	11 mm^2 = 3.2 %	3
1.6 mm	10 mm	ASL	Ca. 445 mm^3	16 mm^2 = 4.6 %	3

(*): Delta in Cross Sectional Area, both expressed in “mm^2” and in “%” relative to the inner air space

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<tr><th>Definition of defect morphology</th><th>Resulting defect</th></tr>
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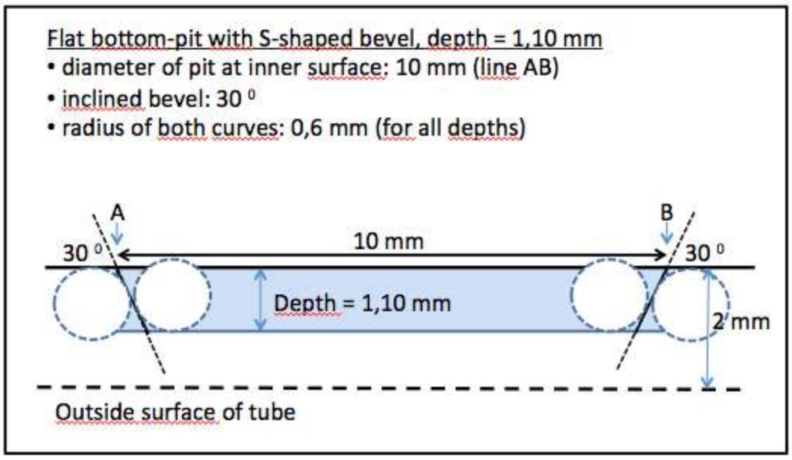
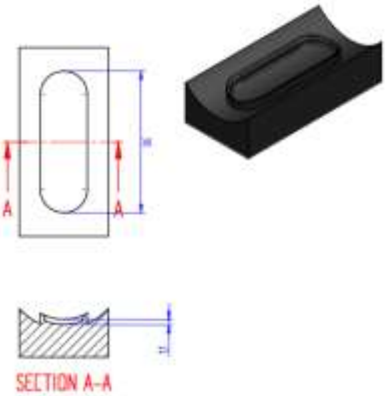


Type ASM, definition of curvatures
</td><td>


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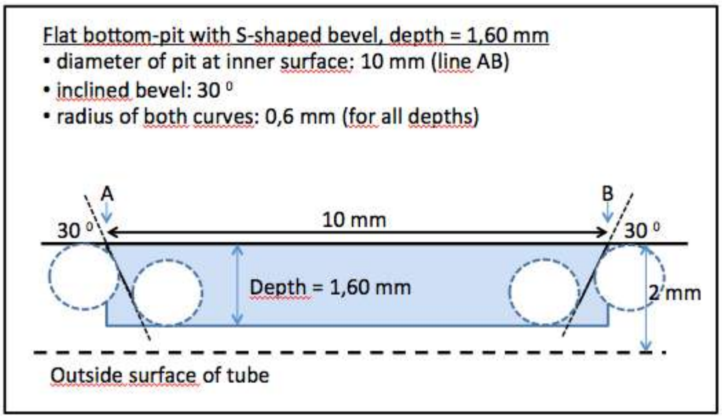

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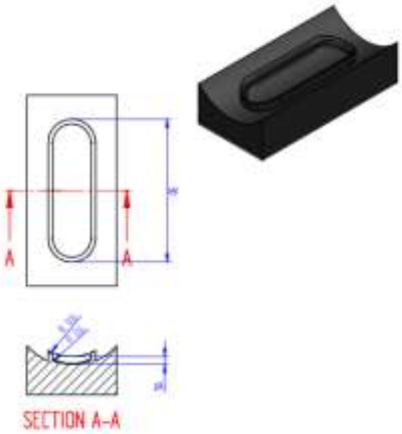

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</table>

5. Reference defects: Flat bottom pit with rectangular shaped bevel

The dimensions of the so-called 'reference defects' is chosen equal to certain defects from the testing programme with SwRI [2] to enable comparison with the results from this programme. The defect morphology is similar to the flat bottom pit with rectangular shaped bevel, as used for the defects with codes FS, FM and 4R. However, the diameter is 4,75 mm.

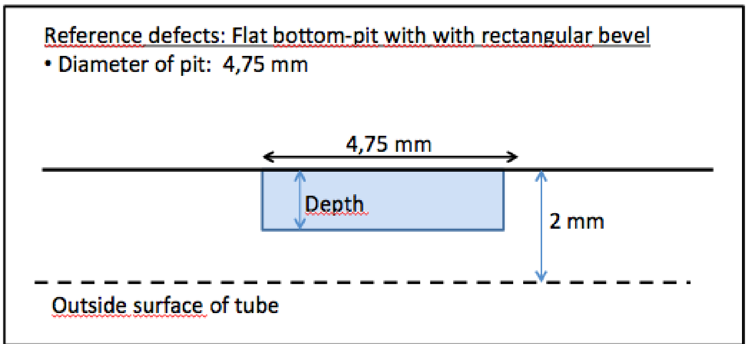
Table B.5 Description of reference defects

Depth pit	Diameter	Defect code	Volume pit	Delta CSA (*)	Number
20% = 0.4 mm	4.75 mm	20R	7.1 mm^3	1.9 mm^2 = 0.55 %	3
80% = 1.6 mm	4.75 mm	80R	28 mm^3	7.6 mm^2 = 2.2 %	3

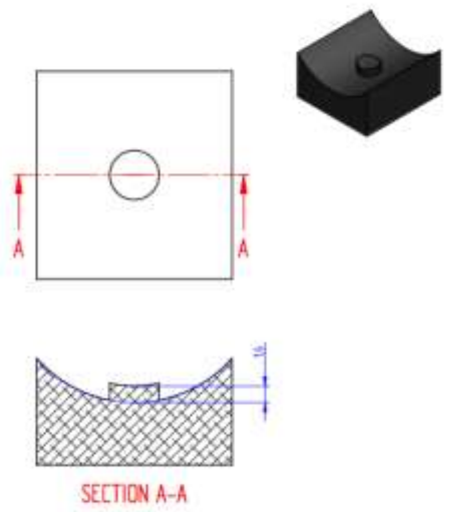
(*): Delta in Cross Sectional Area, both expressed in "mm^2" and in "%" relative to the inner air space

The morphology of the reference defects is identical to those of the flat bottom pits with rectangular shaped bevel.

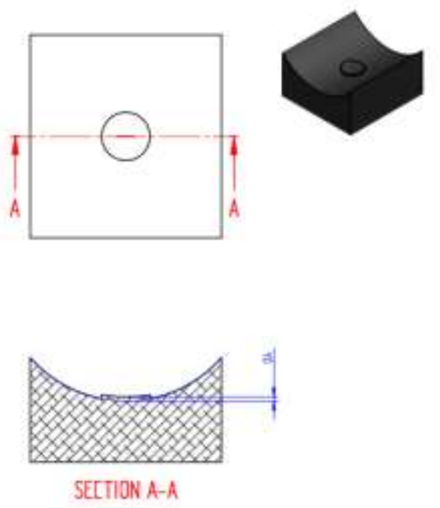
Definition of defect morphology



Resulting defect



Type 20R: Depth = 0,4 mm



Type 80R: Depth = 1,6 mm

Blockages

Different types of blockages were introduced in the tubes, see the figure below:

- Glueing wooden pieces.
  The size of the wooden pieces: length: 90 mm, width: 7 mm, thickness: 3 mm.
  The wooden pieces represent 7.9% of the cross sectional area.

- Pasting a layer of gypsum on the inner surface.
  The size of the gypsum layer could not be measured but is estimated to have an average thickness of 1 mm which resulting in to 18% reduction of the cross sectional area.

- Glueing (regular) matches
  The size of the matches is: length: 40 mm, width and thickness: 2 mm. The matches have been sharpened at both ends to create a smooth change in cross sectional area.
  The matches (3 matches in one tube) represent 3.5% of the cross sectional area.

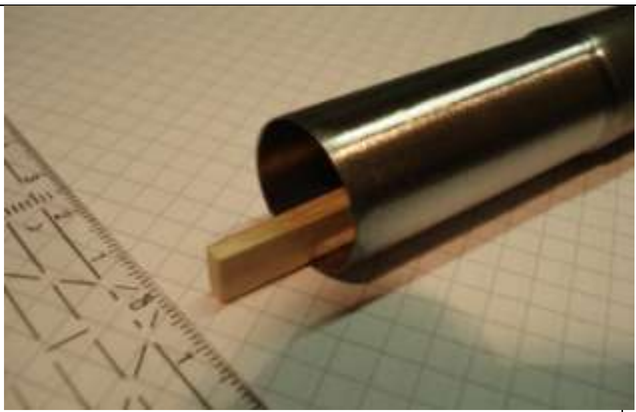


Figure B.1 Wooden piece

Figure B.2 Layer of gypsum paste

Figure B.3 Matches with sharpened ends

Figure B.4 Matches (3 pieces) glued in a tube

Appendix C Results regarding sizing performance from mock-up

Holes

A summary of the actual and measured sizes is given in table C.1.
All measurements show a diameter which is equal or less than the real diameter. The underestimation is globally 10% - 30%.
Quite a number (26 holes) of 1 mm diameter holes have been sized so that a statistical analysis could be conducted for this size resulting in an average size and a standard deviation. Also for the other sizes a statistical analysis has been conducted although the number of holes is much less (6 holes) which makes the analysis not very reliable.

Table C.1 Overview of sizes of the holes

Real diameter	Number of holes	Average measured size	Standard deviation
0.5 mm.	6	0.49 mm.	0.02 mm.
1.0 mm.	26	0.89 mm.	0.08 mm.
2.0 mm.	6	1.59 mm.	0.33 mm.

Blockages

A summary of the actual and measured sizes is given in the table C.2 below.
A good agreement between real and measured size is demonstrated.

Table C.2 Overview of sizes of the blockages

Type of blockage	Dimensions	Real size (1)	Measured size (1)
Wooden pieces	90 x 7 x 3 mm.	7.9 %	7 – 8 %
Layer of gypsum	Thickness: about 1 mm. (2)	18 %	15 – 25 %
3 matches	3 matches of each 40 x 2 x 2 mm.	3.5 %	3.5% - 7 %

(1): in terms of cross sectional area reduction
(2): the thickness could not be measured and is a rough guess.

Wall reductions

In [5] the measured depth values are presented for the different types of wall reductions. In Figure C.1 and in Figure C.2 these values are plotted..
Both plots demonstrate that a general trend exists between measured depth and real size (real depth or cross sectional area). However, quite a large spread generates a great uncertainty in case of individual measurements.

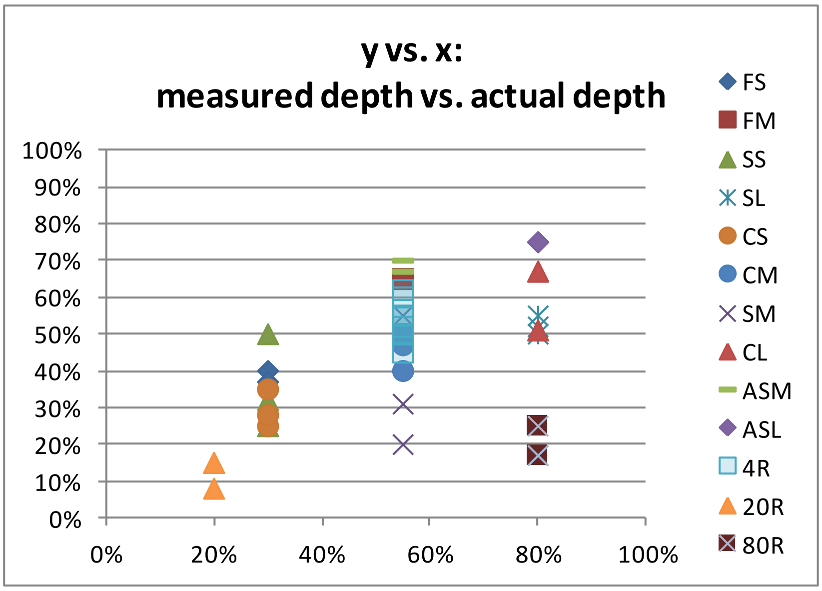


Figure C.1 Measured depth against actual depth of the wall reductions

Another way of evaluating these results is to plot the measured depth against the cross sectional area of the wall reduction in order to remove the effect of the axial dimension of the defect and to account for the shape of the defect. This plot is presented in Figure C.2.

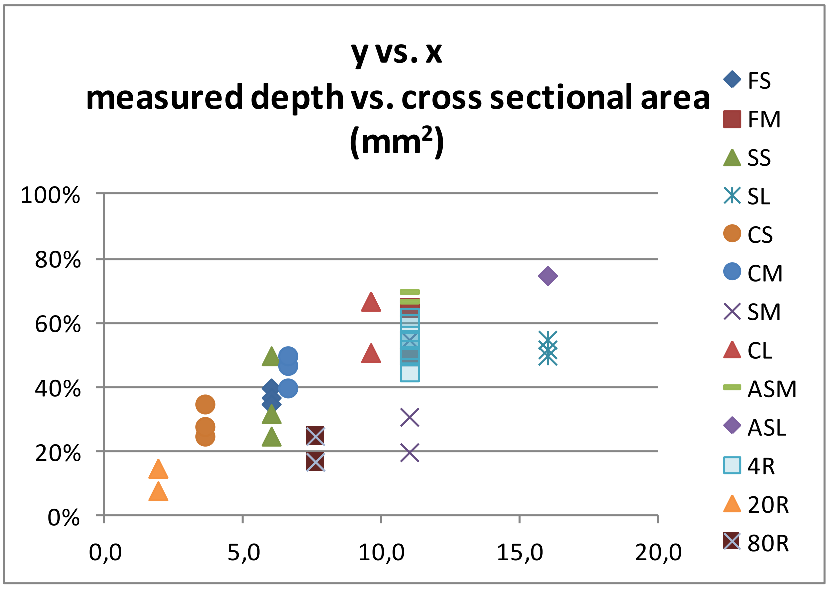


Figure C.2 Measured depth against the cross sectional area of the wall reductions

Appendix D Defect morphology according POF-guideline

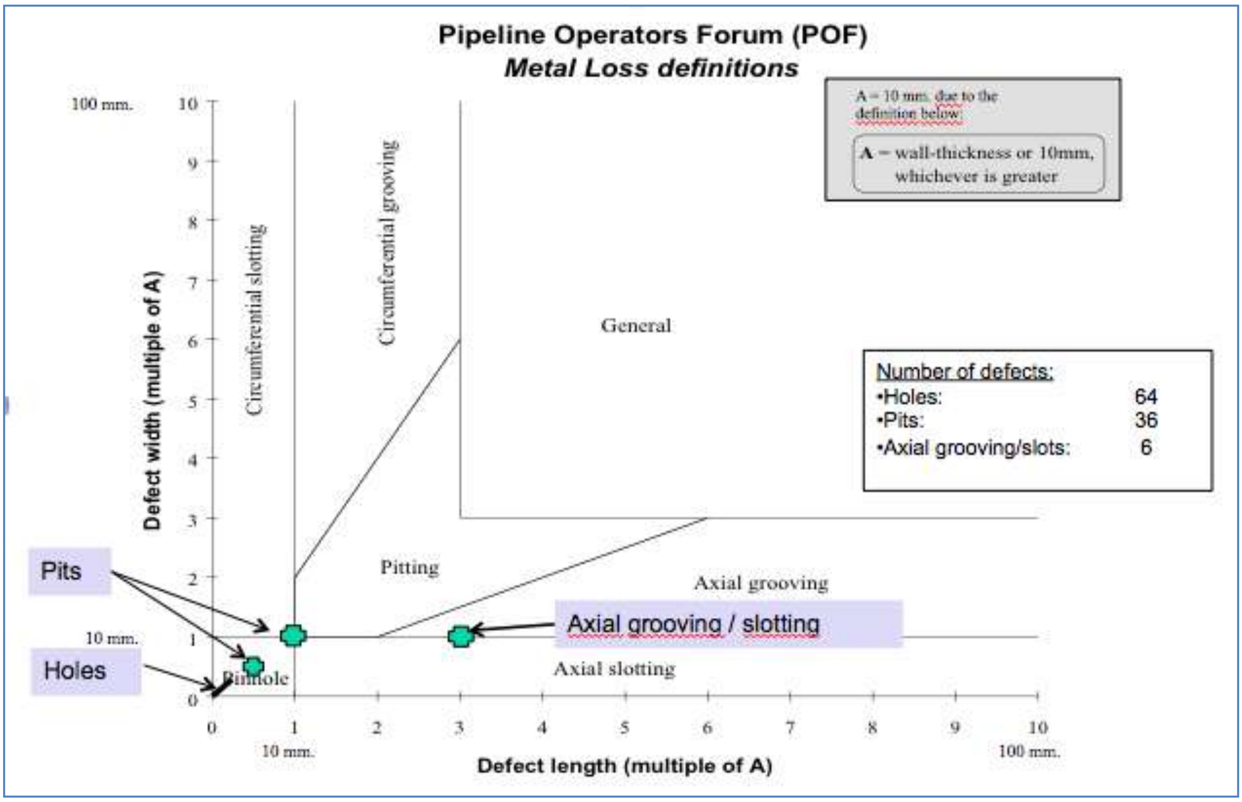


Figure D.1 Graphical presentation of metal loss anomalies from POF-guideline [7] including the position of the artificial defects from this validation program (see green coloured crosses).

In the application field of pipeline operators, the so-called POF-guideline (Pipeline Operators Forum) [7] is commonly used to describe the approach for the evaluation of pig inspection techniques. In this guideline a scheme is included for the definition of defects (named 'metal loss anomalies').
In above figure, the graphical presentation from this guideline is given.
The sizes of the various artificial defects from this validation program have been plotted in this graph in order to clarify which types of defects were used according to the definition of the POF-guideline.