AUT QUALIFICATION OF APPLUS+ RTD IWEX SYSTEM

General DNV GL Qualification of Applus+ RTD IWEX for Carbon Steel Pipeline Girth Weld Applications

Applus+ RTD Rotterdam

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Applicable contract(s) governing the provision of this Report:

Objective:

The Applus+ RTD IWEX (Inverse Wave field Extrapolation) automated ultrasonic testing (AUT) procedures have been subjected to qualification trials in order to establish the general performance of the system applied on carbon steel pipeline girth weld applications. The qualification work has been done under agreement between Applus+ RTD and DNV GL AS, and follows the requirements of DNVGL-ST-F101 and DNVGL-RP-F118.

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1	2019-05-14	Clarify compliance with DNVGL-ST-F101	HASTI	KHO	DAWPAM
2	2020-03-20	Added compliance for 10MHz Probe	HASTI	KHO	DAWPAM

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1 EXECUTIVE SUMMARY

The Applus+ RTD IWEX™ (Inverse Wave field Extrapolation) automated ultrasonic testing (AUT) procedures have been subjected to qualification trials in order to establish the general performance of the system applied on carbon steel pipeline girth weld applications. IWEX is an ultrasonic imaging technique, which is presently a non-conventional ultrasonic technique for the pipeline girth weld inspection application. The qualification work has been done under agreement between Applus+ RTD and DNV GL AS, and follows the requirements of DNVGL-ST-F101 [1] and DNVGL-RP-F118 [2].

DNV GL has witnessed all trials and all scan interpretation, and has been invited to comment on all relevant documentation for IWEX and the qualification program. The system performance is well documented from the tests performed. It is documented that IWEX is capable of operating in accordance with DNVGL-ST-F101 requirements. It has been further documented that IWEX is capable of identifying imperfection dimensions, sizes, shapes and positions at consistent accuracies independent of weld bevel geometry, welding method, wall thickness and band settings. Sizing accuracy and POD has been derived in accordance with DNVGL-ST-F101 for general applicability for carbon steel applications. The conclusions of the qualification program are summarized as follows:

- The Applus+ RTD IWEX system is concluded to be in compliance with DNVGL-ST-F101 requirements.
- The IWEX procedure has demonstrated consistent performance with regards to repeatability and when operating at elevated temperatures up to 80°C, while the reference block is kept at ambient temperature. Repeatability refers to consistency in height estimates upon repeated scans.
- Variations in band offset and probe separation distance have no significant impact on inspection performance.
- Variations in wall thickness have been documented to have no significant impact on detection and sizing performance.
- Individual imperfections, i.e. stacked defects, with a separation distance of 2 mm in any direction can be resolved.
- It is demonstrated that imperfection shape and orientation within a margin of 5° are accurately determined by IWEX.
- Surface ligament of sub-surface imperfections has been determined with accuracy of ±0.5 mm.
- Root and cap reinforcement heights are demonstrated to be determined with an accuracy of about ±0.5 mm.
- ID and OD surface misalignment are demonstrated to be determined with an accuracy of ±0.5 mm.
- No significant difference in sizing and detection performance has been observed for inspection with 4 MHz, 7.5 MHz and 10 MHz probes.
- The signal-to-noise levels achieved with both 4 MHz, 7.5 MHz and 10 MHz setups and thin/thick wall thicknesses are not limiting carbon steel inspection.
- The AUT system is documented to reliably detect any imperfection, regardless of length, down to 0.66 mm in vertical height, defined by a 90% POD value at 95% confidence level. This assumes a recording level of 20%.
- Imperfections with vertical heights below 0.5 mm and lengths above 10 mm have consistently been observed to be clearly detected.
- Vertical height sizing accuracy is observed within the range -0.76 mm to +1.0 mm, defined as the 5% probability of under- and over-sizing. Mean over-sizing is calculated to be 0.13 mm.
- Imperfection through thickness depth estimate has been observed within the range -1.83 mm to +1.44 mm.

The qualification program has been designed to document insensitivity with regards to detection and sizing performance to weld geometry, imperfection orientation, positioning both in depth and horizontally, shape and type and band offset. The program has covered 16 girth welds, all of different configurations: 5 J-bevel narrow gap welds with bevel angles of 3°-8° and wall thicknesses of 21 mm and 41 mm, 5 V-bevel welds with bevel angles of 15°-30° and wall thicknesses of 21 mm and 41 mm, 5 small diameter (5.5” OD) V-bevel welds with bevel angles of 25° and nominal wall thickness of 8.4 mm and 1 weld with 24” outer diameter and WT varying between 22.0 mm and 24.6 mm The defective welds and corresponding reference blocks have been subjected to trials for reliability, repeatability and heat influence. In total 189 observations were included for further reliability analysis through macro sectioning. All scanning was witnessed by DNV GL and DNV GL decided from which locations macros were made. DNV GL performed the analysis presented in this report based on reporting by Applus+ RTD and macro sectioning reports by BKW.

Evaluation of qualification trials results have first of all been focused on demonstration of compliance with the requirements of DNVGL-ST-F101. POD and vertical height sizing accuracy have been evaluated for general applicability. In addition, a set of additional trials and data evaluation exercises were performed in order to assess the capabilities of IWEX which are considered to be improvements from conventional zonal discrimination AUT.

These results are regarded valid for all future carbon steel girth weld projects, provided project specific prerequisites and certain prerequisites given in section 8.4 of this report are met. The qualified configurations are representative for a range of wall thicknesses from 6.0 mm up to 42.0 mm, and for pipes of diameter of 4” and above. It can also be noted that compliance according to DNVGL-ST-F101 ensures compliance with all previous revisions of DNV-OS-F101 which includes requirements to AUT, i.e. the 2000, 2007, 2010, 2012 and 2013 editions.

2 INTRODUCTION

The Applus+ RTD IWEX (Inverse Wave field Extrapolation) automated ultrasonic testing (AUT) procedures have been subjected to qualification trials in order to establish the general performance of the system applied on carbon steel pipeline girth weld applications. IWEX is based on a presently non-conventional ultrasonic technique for the pipeline girth weld inspection application. With IWEX the inspection data is presented as images, either as 2D cross sections through the weld or as real tomographic 3D images. All data interpretation is performed from the images, using for instance extent, position and intensity of the imperfection responses. The purpose for this general qualification has been to independently establish and document the performance of the Applus+ RTD IWEX AUT system procedure according to requirements of DNVGL-ST-F101 [1]. The full qualification program has been performed in two phases. The present report documents the final results from phase 2 of the program, which is a full-blown qualification in accordance with DNVGL-RP-F118 [2] as far as applicable. IWEX performance is evaluated as stability upon repeated scans, stability upon elevated temperature, detectability and vertical height sizing uncertainty. The principles outlined in both the applicable standard and the RP documents are written for zonal discrimination AUT mainly, so some considerations have been made to accommodate tests to the distinctly different IWEX inspection concept. However, DNV GL will consider amendments to DNVGL-ST-F101 Appendix E and DNVGL-RP-F118 for ultrasonic imaging techniques on the basis of the experiences and results presented in this report.

DNV GL has witnessed all trials and all scan interpretation, and has been invited to comment on all relevant documentation for IWEX and the qualification program.

The results presented in this report are intended to be used as pre-qualification data for further AUT verification, or as complete documentation of AUT performance according to DNVGL-ST-F101 for future pipeline girth weld inspection projects upon pipeline owners discretion.

Revision 01 was issued in March 2019, to clarify and ensure compliance with DNVGL-RP-F118 (2017) and DNVGL-ST-F101, which superseded the former DNV-RP-F118 (2010) and DNV-OS-F101 (2013). Ligament estimate analysis have been included to provide compliance with updated requirements in DNVGL-ST-F101. Also, paragraphs have been included to document coverage for recent developments in hardware, i.e. the Z-shaped guidance band.

3 BASIS

The basis for this qualification work has been: DNVGL-ST-F101 [1], Appendix E. In addition, the qualification has been completed in accordance with DNVGL-RP-F118 [2]. The guidance given in the Nordtest Tech Report 394 [3] is followed, as far as applicable. Further details were given on witnessing and guidance during the qualification work.

4 OBJECTIVES

The main objective of the qualification work has been to document the Applus+ RTD IWEX AUT system procedure performance for carbon steel pipeline girth weld inspection applications according to DNVGL-RP-F118 [2] and the requirements of DNVGL-ST-F101 [1]. The results are attributed to the Applus+ RTD IWEX AUT procedures used during the qualification trials [4,5]. As a general qualification of the system, no girth weld acceptance criteria are involved in the evaluation of the performance. The performance is measured according to the methods attributed to different requirements given in the code, and the results should therefore be directly applicable for relevant applications with specific acceptance criteria.

The basic requirements of DNVGL-ST-F101 are:

- A POD of 90% at a 95% confidence level (a 90%|95% POD) has to be documented for an imperfection height smaller or equal to the smallest allowable defect height in the group of imperfections in question. As an alternative, performance of rejection of weld defects can be evaluated against rejection criteria for AUT reported height, so called probability of rejection (POR). Corresponding to the POD requirement, for the applicable rejection height a POR of 85% at a 95% confidence level has to be documented for the smallest allowable defect height of the defects in question.
- The 5% limit against under-sizing of vertical defect height and the mean sizing inaccuracy have to be established.
- Defect length sizing accuracy has to be established.
- Stability at elevated temperature shall be demonstrated.
- Maximum variation of ±2 dB for amplitude in repeated calibration scans with the reference block in 5G 12 o'clock and 6 o'clock positions, 6G and 2G positions, and for repeated scans on a defective weld with band offset of ±1 mm have to be demonstrated.

Beside the requirements of DNVGL-ST-F101, the objective was witnessing of the critical qualification activities on site.

5 ABBREVIATIONS

AUT – Automated Ultrasonic Testing

CW – Clock Wise

CCW – Counter Clock Wise

IWEX – Inverse Wave Field Extrapolation

POD – Probability of Detection

POR – Probability of Rejection

TOFD – Time of Flight Diffraction

FBH – Flat Bottom Hole

FSH – Full Screen Height

OD – Outside Diameter

ID – Inner Diameter

WT – Wall Thickness

MLE – Maximum Likelihood Estimator

ECA – Engineering Criticality Assessment

HP – Hot Pass

SDH – Side Drilled Hole

SPA – Sampling Phased Array

TFM – Total Focusing Method

6 DESCRIPTION OF QUALIFICATION PROCESS

6.1 IWEX AUT Particularities

The Applus+ RTD IWEX concept is distinctively different from the conventional zonal discrimination AUT or AUT based on mechanised inspection utilising electronic scanning with phased array probes. While the latter techniques are basically based on assessments of A-scans and amplitude signals in relation to beam angle and time of flight for single probes or focal laws, IWEX is an ultrasonic imaging technique. The technical details of the IWEX technique are described in the literature [6,7,8]. In short, ultrasonic imaging takes benefit from the capability of array probes to measure the main part of the complete wave field of scattered ultrasound at the pipe surface for each element separately. Images are constructed through back-calculation of the positions of the scattering features with basis in the captured wave field. The Applus+ RTD IWEX technique has similarities with techniques known as TFM (Total Focusing Method) [9] and SPA (Sampling Phased Array) [10].

Full coverage of the weld can be acquired if wave fields with origin from all parts of the weld are captured and processed. With IWEX this is ensured by back-calculation of up to 10 modes, which represent different beam paths of scattered signals. Inclusion of sufficient relevant modes makes IWEX insensitive to weld bevel configurations, since imperfections of all possible orientations can be detected in any scan as long as the relevant mode is processed upon scanning.

A notable feature of IWEX compared with zonal discrimination AUT is the presentation of data as images, either as a 2D cross section of the weld or as real tomographic 3D images. Although software views can be configured to resemble similarities, imaging provides a different approach to sizing and interpretation of signals in scans.

IWEX provides an alternative approach to ultrasonic inspection than conventional pulse echo inspection, as it combines insensitivity to angle and imperfection orientations by applying wide, unfocused beams with synthetic focusing of beams at high spatial resolution. The combined angle insensitivity and spatial resolution in the IWEX image is ensured by use of relevant modes, which together are capable of capturing the full angular spectrum from 0° to 180° in one scan. Furthermore, modes are overlapping in efficient angle ranges, and indications are normally captured in several modes. As a result of this, the IWEX AUT setup philosophy is identical regardless welding process or weld bevel angle. Due to this insensitivity and lack of attention to angle and bevel orientations with IWEX, welding process and weld bevel type and are not considered as essential variables for IWEX.

Furthermore, IWEX introduces a slightly different approach to sensitivity than conventional pulse echo UT, in terms of gain and reference levels. Optimal gain is not mainly determined by the response of a reflector of known shape, position and size. Nevertheless, the resulting image will have a dynamic range as the intensity of each indication in the image will be determined by how well any scattered signals captured by the entire range of array elements coincide. The gain to provide contrast and intensity in the image presented to the operator has to be optimised in order to provide the best detection upon scanning. It was found that response of reference reflectors in a reference block is still suitable for this purpose.

6.1.1 Reference block

A new reference block design has been developed for IWEX, which accommodates the modal concept of the imaging methods. This design includes one reference reflector for each of the 10 processed modes, in addition to reflectors to document coverage. The reflector responses are upon calibration used to align the gain settings for the modes relative to each other, and to set the contrast scale in the images upon scanning. The combination of IWEX modes makes the orientation of indications non-essential to detection and sizing. However, the individual modes are more sensitive to orientation of indications. Therefore, the reference reflectors will be oriented such that an optimised response can be achieved, in order to ensure a uniform and directly comparable sensitivity distribution between the different IWEX modes in the scan. The optimised angle for the reflectors can be obtained by using the dedicated Reflector Angle Calculator software functionality.

For production scanning, the reference block is necessary to confirm a stable setup. The IWEX reference block design includes the following reference reflectors:

Table 6-1: IWEX reference reflectors

Mode	Number	Reflector Orientation Towards the Array	Comment
IWEX-0	2 (US/DS)	3 mm FBH, at depth 4 mm from ID Surface	Direct mode
IWEX-1	2 (US/DS)	3 mm FBH, 0° at depth 2/3 WT, or 0.5 mm ID notch (for small WT pipes)	Tandem mode, half skip
IWEX-2	2 (US/DS)	3 mm FBH, at depth 1/3 WT	Skip mode
IWEX-3	2 (US/DS)	3 mm FBH, 0° at depth 1/3 WT	Tandem mode, over skip
IWEX-0C	1	3 mm FBH, +90° at depth 2 mm from ID Surface	Direct Cross mode
IWEX-2C	1	3 mm FBH, -90° at depth 2 mm from OD Surface	Skip cross mode

The reference block also includes surface notches in HAZ at both ID and OD to document coverage in the HAZ, and through drilled holes (TDH) to document sensitivity along the full vertical direction of the weld cross section. In addition, the reference blocks used for the qualification included reflectors for conventional pulse echo channels intended to be used in the setup, i.e. TOFD and notches in the transverse direction.

6.2 Extent of Qualification Activities and DNV GL Witnessing

The extent of qualification activities was agreed upon upfront, in accordance with DNVGL-RP-F118. The activities summarised in Table 6-2 have been performed by Applus+ RTD, and entirely witnessed by DNV GL:

Table 6-2: Qualification Trial Summary

Trial	Content
Repeatability, 5G	41.3 mm WT reference block in 5G position, 10 scans each with reference block centre at 12 and 6 o'clock positions.
Repeatability, 2G & 6G	41.3 mm WT reference block in 2G and 6G positions, 3 scans each with reference block centre at 12 o'clock position (only applicable to 6G).
Band offset trials, 21.3 mm WT	One nominal scan in 5G position with no band offset, 3 consecutive scans with band offset -3 mm and 3 consecutive scans with band offset +3 mm.
Band offset trials, 41.3 mm WT	One nominal scan in 5G position with no band offset, each 3 consecutive scans with band offsets of ±3 mm, ±2 mm and ±1 mm.
Temperature trials, 21.3 mm WT	15 cycles of a calibration scan on a reference block at ambient temperature followed by a scan of one defective trial weld heated to above 80ºC.
Temperature trials, 41.3 mm WT	3 cycles of a calibration scan on a reference block at ambient temperature followed by a scan of one defective trial weld heated to above 80ºC.
Reliability trials, 4 MHz	Scanning of 8 defective welds of 21.3 mm WT and 2 defective welds of 41.3 mm WT, both clockwise (CW) and counter-clockwise (CCW). Reference block scans upfront and after each weld scan.

Reliability trials, 7.5 MHz	Scanning of 8 defective welds of 21.3 mm WT, both clockwise (CW) and counter-clockwise (CCW). Reference block scans upfront and after each weld scan.
Reliability trials, 10 MHz	Scanning of 5 small diameter (5.5”) defective welds of 8.4 mm WT, both clockwise (CW) and counter-clockwise (CCW). Reference block scans upfront and after each weld scan.
Wall thickness range trials	Scans on machined block and defective weld with considerable wall thickness variations with and without correction for wall thickness variations.
Evaluation capability trials	- Demonstration of detection and evaluation performance in terms of remaining flaw surface ligament - Misalignment measurement accuracy evaluation - Cap and root height measurement accuracy evaluation - Imperfection orientation and shape evaluation performance - Indication horizontal position determination performance - Performance with regards to discrimination of stacked flaws
Probe separation distance trials	Scans of the same weld with two different probe separations

In addition, the following activities were also a part of the scope, and have been witnessed by DNV GL:

- Demonstration of integration of conventional probes with the IWEX setup
- Interpretation of IWEX scans.
- Selection of macro section positions based on official interpretation of scans.
- Monitoring of macro location identification and mark-up by hard stamping on welds

6.3 AUT Qualification Design

6.3.1 General Considerations

The qualification program has been designed to demonstrate full compliance with DNVGL-ST-F101, Appendix E requirements, and to follow DNVGL-RP-F118. This means that all required trials have been performed, for documentation of stability upon repeated scans, elevated temperature, band offset, production and scans of defective welds and destructive testing of the required amount of imperfections.

Ultrasonic imaging and IWEX is a new ultrasonic method for the application, and it has been clear that some of the requirements in the standard have been written with zonal discrimination AUT in mind. As a result, some of the required trials or criteria in the standard might be regarded as irrelevant for IWEX. These are still included in the program, in order to provide the required documentation of compliance with the standard. Furthermore, some additional trials have been included in the program in order to evaluate the impact of essential parameters specific to ultrasonic imaging techniques. The considerations made to get this qualification program in line with the overall principles and formal requirements of DNV-OS-101 are given below.

It should be mentioned that the qualification program has aimed for documentation of the most accurate sizing and detection possible within what is regarded as reasonable production rate. This means for instance that high sampling rates to provide optimal resolution have been selected at the expense of scanning speed.

6.3.2 Defocusing

Ultrasonic imaging introduces a different concept to control and measure quality of the inspection setup, compared to conventional zonal discrimination AUT. With conventional AUT, an optimal setup is largely dependent on the reference block design that represents the anticipated weld flaws as accurate as possible. Instabilities in the setup are characterised by variability in amplitude responses upon repeated scans. With IWEX, inspection quality is more related to image sharpness. While imaging at optimal conditions will provide sharp images, a sub-optimal setup will be characterised by a defocusing of features in the image. The imaging algorithm is based on a linear approximation, and anticipates tight control of the physical parameters of the probes, wedges and weld material and configuration. Any deviations from the assumptions in the imaging model will add to the defocusing. Some defocusing is inevitable, since it in practice is impossible to avoid inhomogeneities in material, surface and coupling conditions, probes etc. Essential parameters of ultrasonic imaging of materials that have an impact on defocusing are regarded to be:

Probe characteristics

Wedge characteristics

Material wall thickness

Material sound velocity

Material surface

Pulse bandwidth

Probe separation distance (i.e. distance between the front of the separate wedges)

Temperature

The extent of defocusing can be assessed by the point spread function, which is the spatial intensity distribution of the defocused image of a sharp point. The point spread function should be as narrow and well defined as possible to provide the best conditions for accurate sizing. This is most notable if the amplitude drop method is applied for height sizing. It has been observed that a wide point spread function will cause over-sizing in height as the signal becomes increasingly stretched. One way to bypass this issue is to perform height sizing using tip diffracted signals from the imperfections. For this reason, sizing based on tip diffractions is the preferred method, with the amplitude drop-off method being a fallback option. Diffracted signals have the benefit that they mainly become defocused in a different direction than the imperfection height direction. On the other hand, diffracted signals are weaker than the reflected signals so a sharp image is a prerequisite to resolve these signals.

6.3.3 Defective Welds

The full DNVGL-RP-F118 scope of minimum 122 flaws was performed with 8 welds of 24” OD 21.3 mm WT pipes. Performance of IWEX is regarded insensitive to weld bevel configuration, bevel angle and welding procedure in carbon steels in terms of anticipated imperfection orientations and occurring imperfection types. To cover this within the qualification program, it was decided to have 4 welds of V-bevel and 4 welds of J-bevel configuration with different bevel angles. In addition, validity of the results of the full qualification scope was validated for a heavy wall thickness pipe configuration. This included a full DNVGL-RP-F118 validation scope of minimum 29 flaws within 2 welds of 24” OD 41.3 mm WT, 1 weld of V-bevel and 1 weld of J-bevel configuration. Details of all welds are provided in the Table 6-3 below. The number of confirmed indications refers to the number of imperfections reported in the weld with IWEX, useful for qualification purpose.

The study has been supplemented with data from small diameter low wall thickness pipeline girth welds, to extend the range of validity of this qualification to include the IWEX setup using high frequency probes (10 MHz) for inspection of low wall thickness pipes. This included a full DNVGL-RP-F118 validation scope of minimum 29 flaws within 5 welds of 5.5” OD 8.4 mm WT.

Table 6-3: Defective weld details, 24” OD 21.3 mm WT and 24” OD 41.3 mm WT

Weld No.	OD	WT [mm]	Bevel configuration	No. Intended Imperfections	No. Confirmed Imperfections
1	24”	21.3	J4	16	18
2	24”	21.3	J4	16	15
3	24”	21.3	J6	16	16
4	24”	21.3	J8	17	15
5	24”	21.3	V15	17	21
6	24”	21.3	V20	17	19
7	24”	21.3	V25	17	16
8	24”	21.3	V30	16	13
9	24”	41.3	V20	15	14
10	24”	41.3	J3	15	21
A-1	5.5”	8.4	V25	6	11
A-2	5.5”	8.4	V25	6	9
A-3	5.5”	8.4	V25	6	9
A-4	5.5”	8.4	V25	6	7
A-5	5.5”	8.4	V25	6	6

The pipe wall thickness and fit-up of the pipes were tightly controlled, and the misalignment due to pipe out-of-roundness or wall thickness variations is considered to be minimal. The effect of pipe misalignment was investigated with a separate trial that address the effect of wall thickness variations, which is described in paragraph 6.3.9.

Intentional imperfections were planned in each weld in order to comply with the requirements of DNVGL-RP-F118 [2] with regards to the number of imperfections spread over the full depth range and categories (root, cap and fill). Artificial flaws were induced either by manipulation of welding parameters or by careful EDM notching to desired flaw height, orientation and at desired depth along the weld bevel. Upon review of the macro sections, the artificial lack of fusion type of imperfections was in general confirmed to be relevant with regard to position, orientation and shape.

Positions for macro sectioning were marked up on the weld using the IWEX scanner, to recognize the precise position. It might be a bit time consuming to identify the maximum height position from the IWEX scans, as it implies assessments of information in several modes. During mark-up with the scanner, the position was therefore identified through a direct comparison with the image in the offline IWEX scan used to identify the positions. For most selected imperfections, 3 salami slices were done for each macro section position, at 2 mm distance between each macro. A few indications with observed stable shape and vertical height over the full length were sectioned with 1 slice. All imperfections chosen for macro sectioning have been given unique ID-numbers, containing the imperfection weld number and the imperfection number as reported in the IWEX report.

Weld macro cross sections and attributed reporting were prepared by BKW in Bremen. Prior to macro sectioning, the ID-number for the macro and the position for each macro section were hard stamped in the material close to the weld. Section slices were cut, ground and etched before they were photographed. DNV GL has monitored all parts of the macro sectioning process.

6.3.4 Probes

The IWEX procedure can be operated with a range of phased array probes. As with conventional UT, the probe is regarded as an essential parameter for ultrasonic imaging. Notably, higher frequencies allow for higher resolution images. However, this will be on the expense of scan speed as higher frequencies will require higher spatial sampling for generating the pixels in the image. The restriction is in the capacity of the hardware and computational power. Probe frequency might also be restricted by the size of the inspection area of the same reason. This was observed with heavy wall thickness pipes and with wide welds.

In order to cover inspection and sizing performance for a range of frequencies, all welds within the full qualification scope (21.3 mm WT) were scanned with both 4 MHz and 7.5 MHz probes. The heavy wall thickness pipes (41.3 mm WT) were inspected with 4 MHz probes only, due to the large size of the weld.

The qualification program is mainly focused to assess performance with the 4 MHz probe, since this is regarded to be the optimal frequency for the weld dimensions included in the qualification program. Furthermore, lower frequency probes are more feasible for field application of IWEX providing reasonable inspection speed. Higher frequency probes might be an option for thin wall pipes.

The qualification also covers IWEX setups for smaller wall thicknesses (WT) and pipe outer diameters (OD), i.e. WT between 15.0 mm and 6.0 mm, and OD between 4” to 6”. Inspection setups for these dimensions applies a reduced size probe with higher frequency compared with the larger pipes and welds, including a 10 MHz probe with a small pitch (0.32 mm) and a smaller wedge. This philosophy accommodates for the shorter beam paths when the wall thicknesses decreases.

The procedure is restricted to the AUT setup parameters provided in the Table 6-4 below. These are also essential parameters for the results presented in this report.

Table 6-4: Qualified Probe Range

Parameter	Range
PA & Conventional probe frequency:	1 MHz to 10.0 MHz
ToFR probe frequency:	6 MHz to 15 MHz
PA probe element pitch:	0.30 mm to 1.5 mm
PA probe height (passive aperture):	10 mm to 25 mm

6.3.5 Signal-to-noise

The signal-to-noise ratio can be derived directly from the IWEX images, when assessing the background intensity compared to the reference level. The appearance of images can be manipulated through adjustments on the color slider. The color slider provides the conversion from intensity (%FSH) to color in the image. It also provides the possibility to set the interval where the color palette is active within the full dynamic range in the images from 0%-400% FSH. This is a useful tool for scan interpretation, as it offers the possibility to exaggerate relevant indications and suppress noise in images. For the latter, all scans were evaluated to establish the color slider settings useful to remove general noise in the images. In principle, this done by adjustment of the lower level in the interval, which has to be set above the noise level in order to remove all signals below in the presentation. Saturation of signals shall per default be on reference level, i.e. 80% FSH. It should be noted that manipulation of the color slider will not manipulate the scan data itself, it will only affect how the data is presented on the screen.

For general information, all IWEX images presented in this report are captured with a color slider range of 5%-80% FSH.

6.3.6 Repeatability Consistency Trials

Consistency trials with repeated scans on reference block were performed with 5G, 2G and 6G pipe positions as required in DNVGL-ST-F101 Appendix E. The reference block for the 41.3 mm WT pipe was used for this trial. The heaviest wall thickness reference block in the program was selected, since it is regarded as the most challenging configuration in terms of stability upon repeated scans.

Ultrasonic imaging is not considered as amplitude-based the same way as pulse echo or pitch-catch UT setups. A robust setup will indeed give stable intensities in the image of reflector responses upon repeated scans with IWEX. However, the meaning of the intensity in the IWEX image is not fully equivalent to amplitude response with angled ultrasonic beams. A ±2dB criterion has therefore potentially another meaning within an IWEX image, and is considered as less relevant than with conventional UT. Regardless of this, the ±2dB criteria was employed for this qualification with the maximum intensity of reference reflector image upon repeated scans to document compliance with DNVGL-ST-F101 requirements. The gain was set such that the reference reflectors showed up with an intensity of 80 %FSH in the image, with a dynamic range of intensity in the image of 0-400 %FSH.

A more relevant measure of a stable and well controlled setup might be a stable point spread function upon repeated scans. This is regarded to impact the ability to consistently size the same imperfections upon repeated scans using the -6dB drop method. All reference reflectors in the consistency trial scans were also evaluated on size in addition to intensity. A ±0.5 mm sizing variation criterion was introduced for this purpose, and applied to all consistency trial series. In addition, imperfection sizing in clockwise (CW) and counter-clockwise (CCW) scans of a defective weld was compared to assess the consistency in vertical height sizing.

6.3.7 Band Offset Trials

Band offset trials were performed with both 4 MHz and 7.5 MHz probe setups, with V-bevel defective welds of 41.3 mm and 21.3 mm wall thickness respectively. Furthermore, band offsets of ±3 mm were investigated. Band offsets of ±2 mm and ±1 mm were also tested with the 4 MHz setup. The effect of band offset was assessed as deviations within the repeated scans in measured flaw height of 6 selected flaws.

The nominated weld for this trial was weld number 9, with V20 bevel preparation. The weld configuration with a wide bevel combined with a heavy wall thickness was considered as the most conservative configuration for this trial, and represents an extreme case with regards to probe separation and sampling rates. Imperfections for evaluation were selected to cover all parts of the weld, i.e. OD and ID surface area and embedded parts of the weld. 6 imperfections are taken from a representative range of imperfection heights, listed in the Table 6-5 below.

A validation trial series of 3 scans with ±3 mm band offset was performed with the 7.5 MHz probes and 21.3 mm WT V25 defective weld number 8. The intention with this scan series was to document validity of results for the 7.5 MHz probe. Details of the included imperfections for evaluation are provided in Table 6-6.

Table 6-5: Imperfections Included in Band Offset and Elevated Temperature Trials, Weld 9

ID	Scan Position	Length [mm]	Depth [mm]	Height [mm]
1	98.2	11.3	2.3	2.5
2	518.6	47	42.2	2.8
3	885.7	33.6	18.3	3.1
4	967.7	37.3	30.1	2.8
5	1332.4	20.6	10.1	2.6
6	1472.3	81.4	42	1.6

Table 6-6: Imperfections Included in Band Offset and Elevated Temperature Trials, Weld 8

ID	Scan Position	Length [mm]	Depth [mm]	Height [mm]
1	41.4	92.9	20.9	5.2
2	311.2	12.2	3.6	1.9
3	596.7	20.8	5	2.3
4	1058.2	1.5	16	2.9
5	1233.5	46.6	15.1	3.4
6	1309	10	7.7	2.3
7	1711.5	29.2	8.6	4.6

Band offset is regarded as insignificant and irrelevant for IWEX inspection performance, since a horizontal shift of the probe arrangement over the weld will cause nothing more than a horizontal shift of the captured image. The two probes will stay positioned on each side of the weld with any band offset, so full coverage is ensured. The trial was still performed in order to demonstrate compliance with the present standard requirements.

With IWEX, probes should be positioned on each side of the weld with an as small as possible separation in order to ensure that as much as possible of the wave field at the surface is captured. An unnecessary large probe separation distance will therefore cause loss of information, which might have an impact on image sharpness (defocusing). Due to this, there is no risk of considerable band offset upon scanning with a good setup, as there is limited space available between weld cap and the probes.

A related and more relevant test for IWEX is to investigate the impact on excess probe separation distance. This test was performed within the qualification program, more details are provided in paragraph 6.3.10.

6.3.8 Temperature Trials

The elevated temperature trial was performed with a pipe temperature of 80 °C, 4 MHz probe setup and with the V-bevel defective weld of 21.3 mm wall thickness. The effect of elevated temperature was assessed as deviations within the repeated scans in measured flaw height of 6 selected flaws. The nominated weld for this trial was weld number 8, as with the band offset trial. The imperfections used for evaluation are given in Table 6-6.

Elevated temperature is regarded as a critical parameter to ultrasonic imaging due to the potential impact on sound velocities in both pipe and wedge material. Following the same reasoning as for the consistency trials, paragraph 6.3.6, the impact on imperfection response during upon elevated temperature has been evaluated as deviations in sized imperfection heights.

A small validation trial of 3 cycles of scan on ambient temperature reference block followed by a scan on a heated weld was performed on the heavy wall setup with 4 MHz probes and 41.3 mm WT V-bevel defective weld number 9. Details of the included imperfections for evaluation are provided in Table 6-5. This weld was not used for the full trial for practical reasons, as both heating and scanning were impractically more lengthy than with 21.3 mm WT setup.

6.3.9 Wall Thickness Variation

In principle, an Applus+ RTD IWEX image is calculated from time and amplitude compensation factors that are pre-programmed and stored in so called propagation matrices, which can be compared to a set of delay times or ‘delay laws’ of a phased array beam. For the calculation of each Applus+ RTD IWEX mode, a dedicated propagation matrix is required. The calculation of the propagation matrices is done during the set-up phase where all the parameters of tuned and optimised for adequate focusing and positioning of indications. Once the propagation matrices are calculated, they are stored in the internal memory of the Applus+ RTD IWEX system.

In case the WT deviates from the nominal, in principle a new propagation matrix must be calculated that corresponds with the actual WT. The internal memory of the Applus+ RTD IWEX system is large enough to store a significant number of propagation matrices. Principle of the Applus+ RTD IWEX wall thickness variation software module is to pre-calculate propagation matrices that correspond to different wall thicknesses and all stored in the internal memory of the Applus+ RTD IWEX system, the Applus+ RTD IWEX wall thickness variation software module enables an assessment of expected maximum wall thickness coverage by a theoretical single Applus+ RTD IWEX system setup configuration. Based on the actual wall thickness, obtained through measurement during scanning for each probe / side independently, the corresponding propagation matrices are selected and used to generate the image.

The resulting Applus+ RTD IWEX image will now be in focus and indications are positioned correctly due to the correct propagation matrix was applied to generate the image.

A separate demonstration was performed to evaluate the effect of wall thickness variations on imaging, sizing and detection. This trial is not a requirement of DNVGL-ST-F101, neither a part of the DNVGL-RP-F118; however performed to determine the proper functioning of the Applus+ RTD IWEX wall thickness variation software module. The trial included one scan on a test block of nominal wall thickness 19.5 mm with an open J4 bevel and with the outer surface machined to give varying wall thickness of 19.5 mm ±3 mm, i.e. in the interval 16.5 mm and 22.5 mm on both sides. Furthermore, one defective weld of 24” OD and nominal wall thickness 23.1 mm including highly variable wall thickness was scanned. Wall thickness variations in this weld were within 23.1 mm -0.6/+0.9 on US and 23.1 mm -1.1/+1.5 DS.

Wall thickness is a parameter for beam path calculation, and variations from nominal thickness will affect the various modes differently. For instance, it will have no impact for the mode without skip in the back wall. Contrary, it will disturb the focusing for the tandem mode. Since most of the modes are considered to be affected by wall thickness variations only to a limited extent, imperfection characterisation and height sizing have been considered to be only marginally affected as well. The effect was disregarded for the full qualification scope by machining of the wall thickness of pipes for the defective welds.

The trials included a test of the Applus+ RTD IWEX wall thickness variation software module that compensates the influence of wall thickness variation. This software module was demonstrated on the weld sample with variable wall thickness described above. Scan results derived from corrected and un-corrected images were compared. Height sizing was performed according to the AUT procedure on all indications in the defective weld with WT variations for both WT corrected and un-corrected scans. In addition, 4 of the indications were macro sectioned for reference.

6.3.10 Probe Separation Trial

A separate demonstration was performed to evaluate the effect of variations in probe separation over the weld cap on imaging, sizing and detection. This trial is neither a requirement of DNVGL-ST-F101, nor a part of the DNVGL-RP-F118. The trial included two scans on the V15 defective weld, one with a setup including a probe separation of 30 mm and one with a separation of 40 mm.

6.4 Additional IWEX Interpretation Capability Assessment Trials

A series of additional trials were included in the program to specifically assess capabilities with regards to accurate evaluation and interpretation of images. These trials included specific reporting of identified features in the scan, and subsequent macro sectioning. Results of these trials are provided in section 7.14.

6.4.1 Stacked Flaws

5 locations with stacked flaws identified in the same image cross section were selected for careful individual interpretation of all indications at the exact location. The positions were subject to subsequent macro sectioning. IWEX capability of resolving individual indications in case of stacked flaws was assessed by a comparison between reported imperfections from the ultrasonic images and macro sections.

The capability to better discriminate between individual flaws at the same location is claimed to be one of the benefits of IWEX compared to zonal discrimination AUT. This trial was included in the qualification program in order to ensure that this issue would be covered by the macro sectioning.

6.4.2 Imperfection Orientation

5 locations with planar flaws of distinctively different orientations were selected for evaluation of flaw orientation. The positions were subject to subsequent macro sectioning. IWEX capability with regards to evaluation of imperfection orientation was assessed by a comparison between reported indications from the ultrasonic images and macro sections.

The capability to provide fairly accurate information about flaw orientation is claimed to be one of the benefits of IWEX compared to zonal discrimination AUT. This trial was included in the qualification program in order to ensure that this issue would be covered by the macro sectioning.

6.4.3 Imperfection Characterisation (Shape and Horizontal Positioning)

5 locations of various flaw types with different position in the horizontal direction of the weld cross section were selected for evaluation of capability of flaw characterisation and horizontal positioning. This included positions clearly on US and DS side, in addition to indications close to the weld center line. Characterised flaw types included volumetric flaws and copper inclusions. The positions were subject to subsequent macro sectioning. IWEX capability with regards to flaw characterisation was assessed by a comparison between reported imperfections from the ultrasonic images and macro sections.

The capability to more accurately determine imperfection type, aided by more precise information about the exact position in the weld is claimed to be a benefit of IWEX compared to zonal discrimination AUT. This trial was included in the qualification program in order to ensure that this issue would be covered by the macro sectioning.

6.4.4 Cap and Root Reinforcement Heights and Misalignment Estimate

Cap and root height and any present hi-lo were evaluated on 5 locations selected for macro sectioning. In addition, misalignment (hi-lo) was measured on ultrasonic images and compared with macro sections from one of the welds used in phase 1 of the qualification program. This weld had ID number DW02, pipe configuration was 24” OD x 19.1 mm WT. Evaluation of misalignment was not considered for phase 1, and pipe misalignment was avoided for the welds of phase 2.

The capability to measure cap and root height and hi-lo directly from the ultrasonic image, is thought to be a benefit of IWEX compared to zonal discrimination AUT. This trial was included in the qualification program in order to assess this capability.

6.4.5 Surface Ligament Measurement

5 locations each of indications either close to the ID surface or the OD surface were selected for evaluation of remaining ligament to the surface. The positions were subject to subsequent macro sectioning. IWEX capability with regards to measurement of surface ligament of sub-surface indications near the ID and OD surfaces was assessed by a comparison between reported indications from the ultrasonic images and macro sections.

The capability to provide more accurate measurement of surface ligament is claimed to be one of the benefits of IWEX compared to zonal discrimination AUT. This trial was included in the qualification program in order to ensure that this issue would be covered by the macro sectioning.

6.5 Induced Imperfections Summary

Intended and non-intended observations were selected for macro sectioning, to comply with the requirements of DNVGL-ST-F101 with regards to distribution in size, type and positions. The actual distribution of observations in the POD and sizing accuracy evaluation were confirmed through the macro sectioning.

The amount of planned and confirmed number of imperfections within the initial 10 trial welds are provided in Table 6-3. The initial welds were made with a target of 162 imperfections in total, which were evenly distributed at all depths. The IWEX scans showed clear indications of 167 imperfections. In addition, there was observed considerable unintended scattered porosity in some of the welds, in particular for the V-bevel weld configurations. For the 5 supplemental small WT welds, the amount of planned imperfections was 30, while 42 indications were reported.

167 confirmed imperfections were selected for macro sectioning within the initial scope and 33 imperfections were selected in the supplemental scope, in total 200 imperfections. 12 of the positions had 2 indications at the same location, so the number of macro section locations was 188. Among the 12 positions with 2 indications, one target indication was selected and macro sectioned at maximum. The secondary indication was height sized at the same location as the primary maximum, regardless of its own maximum location.

Upon macro sectioning, 9 locations were not confirmed by macro sectioning. These are considered to be due to inherent inaccuracy in mark-up for macro sectioning on short indications. 1 indication of Cu inclusion was disregarded for further analysis. Ultrasonic testing is in general not suitable for this imperfection type, as the ultrasound cannot distinguish between copper and steel. Among the 12 positions with double indications, 1 of the secondary indications was considered as questionable and disregarded for analysis. The total number of observations for the analysis was therefore 189.

The intended imperfections were distributed evenly along the vertical axis of the weld, i.e. at different depths, in order to evaluate consistency in AUT reporting with depth. An evaluation of imperfections at and near the surfaces was performed after macro sectioning. ID surface and OD surface areas were defined as the areas within 2 mm from the surface.

6.6 Analysis Extent

6.6.1 Repeatability and Temperature Trials

DNVGL-ST-F101 requirements for reference block consistency trials is that all deviations shall be within ±2dB upon repeated scans.

For band offset and elevated temperature trials, deviations in height sizing for selected imperfections shall not exceed overall sizing tolerances.

6.6.2 90% POD at 95% Confidence

Probability of Detection (POD) analysis has been performed to comply with the requirements in DNVGL-ST-F101. The main purpose of a POD analysis is to document reliable detection of critical imperfection heights, for instance as derived by ECA for project specific acceptance criteria. The imperfection height at 90% POD at the 95% confidence level is regarded as the reliably detected imperfection height by the AUT system. The method applied for the present POD-analysis is described in the Nordtest technical report 394 [2]. The statistical model used in the analysis was the one recommended in the Nordtest document [2]:

$$P(x; x_0, b) = 1 - \frac{1}{1 + \left(\frac{x}{x_0}\right)^b}$$

For the expression above, x is the imperfection size, and b and x_0 are the parameters to be fitted to the trial data. Hit-miss refers to the outcome of inspection of an imperfection with a certain size by the AUT system, the imperfection is either detected (hit) or not detected (miss). For instance for pulse echo detection, a "hit" corresponds to an imperfection signal response above the reporting amplitude threshold, while a "miss" corresponds to imperfections with signal below the threshold. For TOFD detection, a hit would typically be when an imperfection gives a defined signal at the scan, while a miss would be the opposite case. For the present POD analysis, hit and missed imperfections are each attributed to an imperfection height which is the reference imperfection height as measured at macro sections.

The parameters b and x_0 are fit to the statistical model through the method of the maximum likelihood estimator (MLE) using hit-miss AUT detection data. The maximum likelihood estimator (MLE) is found by selecting the parameters b and x_0 such that the total probability of the occurrence of the observed data is maximized, given the model for POD above:

$$L = \prod_{j=1}^{k} \binom{n_j}{i_j} p_j^{i_j} \times (1 - p_j)^{n_j - i_j}$$

For this expression, k is the total number of observed imperfections, n_j is the number of observed imperfections at flaw size x_j, i_j is the number of detected (hit) imperfections at the same flaw size x_j, p_j is the probability of detection for x_j as a function of the parameters b and x_0. For practical reasons it is preferable to calculate further with the logarithmic MLE:

$$\ln L = \sum_{j=1}^{k} \left[\ln \binom{n_j}{i_j} + i_j \ln p_j + (n_j - i_j) \ln(1 - p_j) \right]$$

The most optimal estimates for the parameters b and x_0 are then found by solving the expressions for the partial derivatives of L as functions of b and x_0 set equal to 0.

The confidence band can be calculated from the MLE, assuming L is normally distributed.

The statistical model allows POD to be evaluated as a function of the imperfection height, and presented as a curve. 90% POD at 50% confidence refers to the actual fit between the collected hit-miss data and the statistical model used. The 95% confidence interval includes the uncertainty referred to the amount of collected data and how well the data fits to the estimated POD. A larger amount of data together with a closer fit to the model will give a confidence band closer to the estimated POD-curve. There is usually a considerable amount of conservatism in the detectability requirement of 90% POD at 95% confidence level for the smallest acceptable imperfection height.

6.6.3 85% POR at 95% Confidence

So called Probability of Rejection (POR) is in principle the same approach to reliability evaluation as POD. POR involves hit-miss data and the same statistical model as presented in paragraph 6.6.2 to evaluate the qualification data. The difference between POD and POR is the threshold applied for hit and miss. For POR the threshold is set for AUT reported imperfection height rather than amplitude. When applied in qualification trials, the criterion for the smallest allowable imperfection size is at least an 85% POR at a 95% confidence level, according to DNVGL-ST-F101. The 85% POR accounts for both a 90% POD and a 95% probability of avoiding under-sizing. The imperfection height at 85% POR at 95% confidence level shall be equal to or below the smallest "allowable" imperfection height in the acceptance criteria. POR will thus not necessarily say anything about the smallest imperfection that is possible to detect with the system at a certain set-up.

6.6.4 Imperfection Height Sizing Accuracy

In DNVGL-ST-F101 height sizing accuracy is attributed to the project specific acceptance criteria which are derived by ECA. It is specified that the AUT system shall show reliable detection of the smallest "allowable" imperfections according to the acceptance criteria with less than 5% probability of under-sizing. Evaluation of imperfection height sizing accuracy is done by a comparison between the imperfection height as measured by AUT and the reference imperfection height measured on macro sections. The macro section with the highest measured indication will be used as the reference when there are more than 1 macro sections made at one imperfection position. Sizing inaccuracy is defined as the reference imperfection height from the macro subtracted from the AUT measured imperfection height. A negative sizing inaccuracy will then indicate under-sizing. The sizing inaccuracy is assumed to be normally distributed, and the 5% probability should in principle be found from the normal distribution. In cases where the sizing data does clearly not follow normal distribution, the observed 5% percentile might be used instead.

With regards to the workmanship type accept criteria of DNVGL-ST-F101 a prerequisite for use of these acceptance criteria are a documented sizing accuracy within ±1 mm, defined as the less than 5% probability of under- and over-sizing.

6.6.5 Imperfection Depth Position Estimate Accuracy

The accuracy in the AUT reported depth estimate compared to defect depth measured on the macros has been evaluated the same way as for defect height sizing. In AUT reports, the reported defect depth is the vertical distance from the outer surface to the lowest part of the defect. Depth sizing accuracy is only regarded to be relevant for embedded defects, as the depth of surface breaking defects at the inner surface is known to the operator. Surface breaking defects at the outer surface (OD surface) have been included in the analysis, difference in reported depth and macro result is usually identical to the height sizing accuracy for this type.

Ligament is calculated slightly differently, as calculations include the shortest distance between an imperfection and either ID or OD surface. Near ID surface ligament is calculated as measured imperfection depth to ID surface (i.e. WT minus Imperfection depth from OD surface). Near OD surface ligament is calculated as measured imperfection depth from OD surface minus imperfection height. For buried imperfections, ligament is always calculated to the closest surface. Accuracy in ligament estimate is calculated the same way as for depth estimate accuracy, i.e. as AUT ligament minus macro ligament, and tolerance calculated as $\sim\mu \pm 1.65\sigma$.

6.6.6 Imperfection Length Sizing Evaluation

Imperfection length sizing accuracy has been evaluated on one weld imperfection, which has been macro sectioned at both ends. A direct comparison of length estimated from IWEX scan and the actual length derived from destructive testing has been performed. The AUT procedure specifies that length sizing shall be performed by boxing of indications, using an evaluation threshold.

6.6.7 POD and Height Sizing Accuracy in Use

Both POD and height sizing accuracy are intended to be used with project specific acceptance criteria which are derived by ECA.

The POD is a statistical description of the AUT system's ability to reliably detect a flaw of a certain size. The purpose of a POD evaluation is to document that the AUT system is capable to reliably detect the imperfections of critical sizes according to applicable acceptance criteria with applied rejection thresholds. The important parameter in this context is that the imperfection height at 90% POD at 95% confidence level is equal or smaller than the smallest rejectable (ECA) imperfection size.

The purpose of the height sizing accuracy value, under-sizing allowance, is to adjust the ECA derived imperfection sizes of the acceptance criteria to assure that all flaws exceeding the smallest ECA allowable flaw are rejected. For instance, if the smallest rejectable ECA imperfection size is 1.0 mm and the under-sizing allowance is 0.3 mm, the smallest allowable imperfection size at AUT inspection has to be 1.0mm-0.3mm = 0.7 mm. When it comes to POD, the AUT system is qualified for use as long as the 90%|95% POD imperfection height is at most 1.0 mm, which is the smallest rejectable ECA imperfection size.

The results of this general qualification are applicable to workmanship style acceptance criteria according to DNVGL-ST-F101 Appendix E as well. The workmanship approach is a bit different than the fitness-for-purpose approach offered by ECA, as the workmanship acceptance criteria are attributed to requirements to the AUT procedure, according to applicable standards and specifications. Conservatism is in principle ensured by the requirements according to the standard rather than the demonstrated performance at the qualification. AUT used in combination with workmanship style acceptance criteria should not be performed with a higher than 40% FSH reporting threshold. All indications with response above the reporting threshold shall be evaluated against the acceptance criteria on both height and length. This means that a imperfection that exceeds the acceptance criteria in length shall be rejected regardless of its AUT height and vice versa. Concerning POD, the AUT system shall be capable of detecting the largest allowable imperfection according to the workmanship acceptance criteria, at a 90% POD at a 95% confidence level. For the qualified configuration the largest allowable imperfection height in Table E-1 of Appendix E, DNVGL-ST-F101 is 3 mm.

6.6.8 Guiding band

The Applus+ RTD IWEX AUT system was initially qualified with standard design guiding band, and all the data presented in this report has been acquired with the scanner mounted on this guiding band. Howewver, Applus+ RTD has developed a Z-shaped guiding band to be applied on pipes with shorter distance of coating cut-back, where parts of the band is located over the coating. A capability trial has been performed in order to document that this Z-shaped band can replace the standard band without any degradation in performance. This trial was designed to be in accordance with DNVGL-ST-F101 requirements, the possible impact with use of the Z-shaped band was considered to be mechanical stability of the AUT system. In practice, the trials consisted of a series of reference block repeatability trial in compliance with to DNVGL-ST-F101 requirements for the AUT scanner mounted on the Z-shaped band, details are provided in paragraph 6.6.1. The trials were performed with the Applus+ RTD Rotoscan hardware, however the results are equally applicable for IWEX.

6.7 Analysis Considerations

All kind of imperfection types and sizes are included in the full analysis, except for copper inclusions. The presented results should therefore be regarded as representative for all kind of imperfections at all different depth and lengths.

The POD analysis has been performed using a recording threshold on intensity in image. Detection is considered to depend on contrast in the image, which is provided by the intensity compared to the noise level in the image. The weakest indications used for detection and sizing have been identified at a level comparable to 6 dB above the general noise level in the images (when disregarding artefacts). Recording levels of intensity/amplitude levels down to 20% has been applied, in order to ensure observations of clear detection in the analysis. The distinction between detected (hit) and disregarded (miss) has been done by evaluation of the intensity in the strongest mode against the recording threshold. The detection borderline is considered to be at detection of single pores.

It has been observed a slight but significant improvement in POD for scans with higher frequency probes (i.e. 10 MHz) compared with lower frequency (i.e. 4 MHz). This is considered fully attributed to the higher resolution offered by the shorter wavelength, which allows smaller features in the scan to be resolved. Because of this, the POD analysis in this report has been made using data from 4 MHz probes solely, in order to provide the more conservative general estimate of the 90%|95% height. The number of observations in the POD analysis is therefore 156, while all 189 observations are included in all other analysis. The sizing capabilities are not considered to be affected by the change in probe frequency, so the full dataset has been included in all sizing accuracy analysis.

A generic POR analysis has been performed for the range of rejection imperfection heights from 0.4 mm to 4.0 mm. The analysis was carried out with a step size of 0.2 mm within the range. This range was selected since consistent 85%|95% results were documented within the full range. The data allowed for an extension to 5.0 mm rejection size, since 17 of the indications are above 4.0 mm. However, the analysis shows that the relatively low number of large observations causes considerable inaccuracies in POR estimates for rejection thresholds above 4.0 mm.

Height sizing has been performed according to the procedure [5]. The order of the modes to be used for sizing is specified, and the preferred method is based on tip diffractions. The clearest signals are often provided by the cross modes. If clear cross mode signals are not provided, height sizing shall be performed with tip diffracted responses observed from one side of the weld. Some decrease in sizing accuracy has been observed in this case.

An alternative method for sizing, which has been avoided during this qualification, is box-sizing of the vertical height by the 6 dB drop-off method in the strongest mode in which the imperfection is detected. The results presented in this report are therefore not applicable in general for drop-off sizing, which is more dependent on directly reflected responses.

For the analysis of depth and ligament estimate accuracy, all surface breaking indications at the ID surface have been disregarded from analysis. This has been done since these indications are automatically given the wall thickness as the depth, and are therefore irrelevant for the evaluation of depth estimate accuracy. The analysis therefore includes buried and OD surface indications, in total 154 observations.

For imperfection length sizing, a fixed reporting threshold has been used.

7 QUALIFICATION RESULTS

7.1 Elevated Temperature Trial Results

The elevated temperature trial scans shows good consistency between scans at ambient temperature and scans at elevated temperature. This is illustrated in Figure 7-1, which includes the measurements of maximum measured height of the selected imperfections in the nominated weld 8 at an elevated temperature at above 80°C. The results from the validation trial on the 41.3 mm WT weld 9 are given in the same figure.

Figure 7-1 shows the maximum AUT height for the same indications within the 15 scans, and a range in height of ±0.5 mm from the ambient scan. All measurements at the elevated temperature were found within ±0.5 mm from the scan at ambient conditions, which is within the same range of fluctuations in height sizing as documented in the consistency trials, paragraph 7.2. This result was validated for the 41.3 mm WT heavy wall setup. More details about the trials are found in Appendix B.

Heating was performed by gas heaters. Temperature was confirmed on at least 4 random locations on the weld and pipe. Spot checks of temperature during trials showed wedge temperatures not higher than 20°C.

The time for each cycle, including heating of the pipe with a gas burner, one calibration scan and one weld scan, was mostly kept below 15 minutes for the 21.3 mm WT setup, and around 25 minutes for the 41.3 mm WT. The conditions used are regarded as representative to the conditions at field inspections. Cycle times for the complete trial are tabulated in the Table 7-1 below.

Table 7-1 Cycle Times Elevated Temperature Trials

Scan No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cycle time [min]	-	15:24	14:46	13:55	13:17	13:41	14:35	15:23	14:01	14:47	14:26	14:11	16:12	15:38	14:38
Temperature [°C]	>80	>80	>80	>80	>80	>80	>80	>80	>80	>80	>80	>80	>80	>80	>80

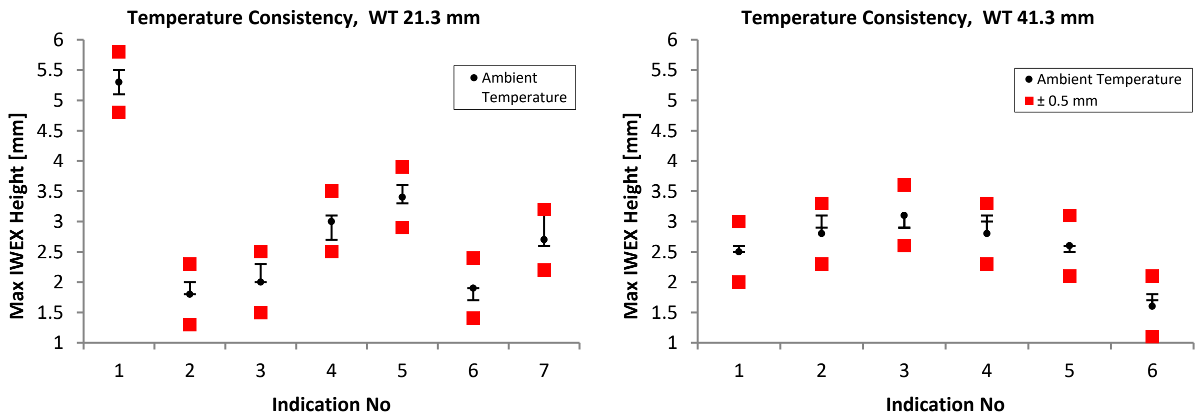

Figure 7-1: Elevated temperature repeatability and ambient scan, defective welds. Primary detection channel for indications indicated. Right: Full qualification series with 21.3 mm WT setup, Left: Validation series of 3 consecutive scans with 41.3 mm WT setup.

7.2 Repeatability Trial Results

7.2.1 Reference Block Repeated Scans

The pre-examination repeatability consistency test scans on reference blocks show good consistency for repeated scans with IWEX, with no deviation from initial calibration sensitivity at 80% FSH more than ±2 dB when considering the intensity level in the image. Sizing of the reference reflectors has been performed as well, and consistent sizing well within ±0.5 mm is observed. The results with both amplitude and height sizing are presented graphically in Figure 7-2, Figure 7-3, Figure 7-4 and Figure 7-5, details are provided in Appendix A. Please note that reflectors 0C and 2C are not height sized, as they have no vertical component.

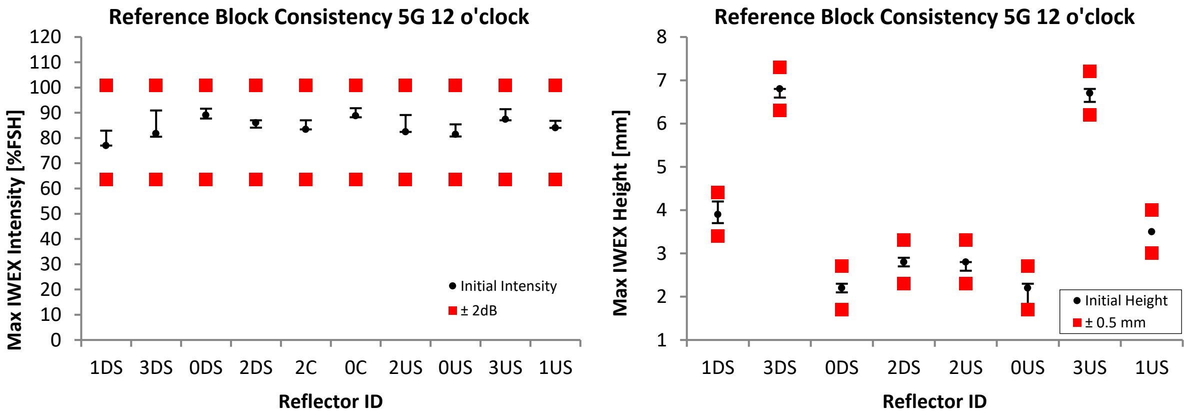

Figure 7-2: Consistency trial results, 10 scans with the reference block at 5G position, 12 o'clock start position.

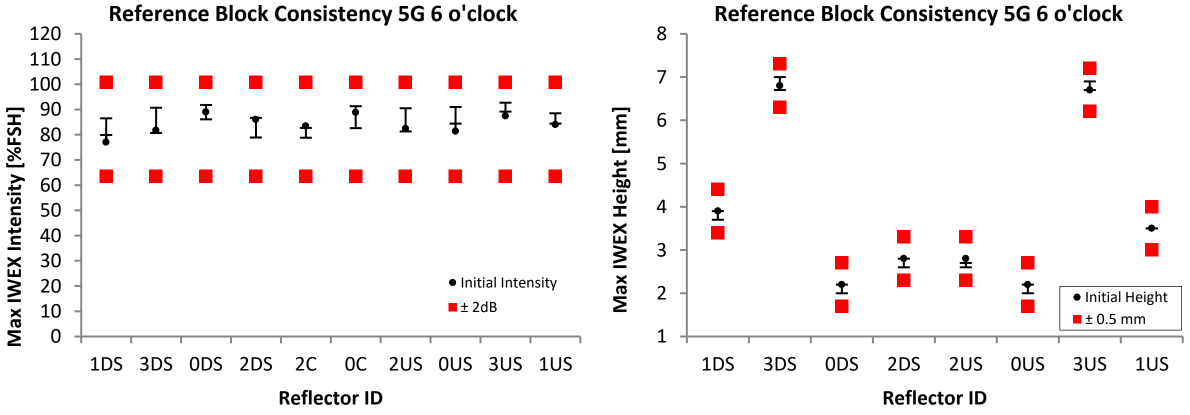

Figure 7-3: Consistency trial results, 10 scans with the reference block at 5G position, 6 o'clock start position.

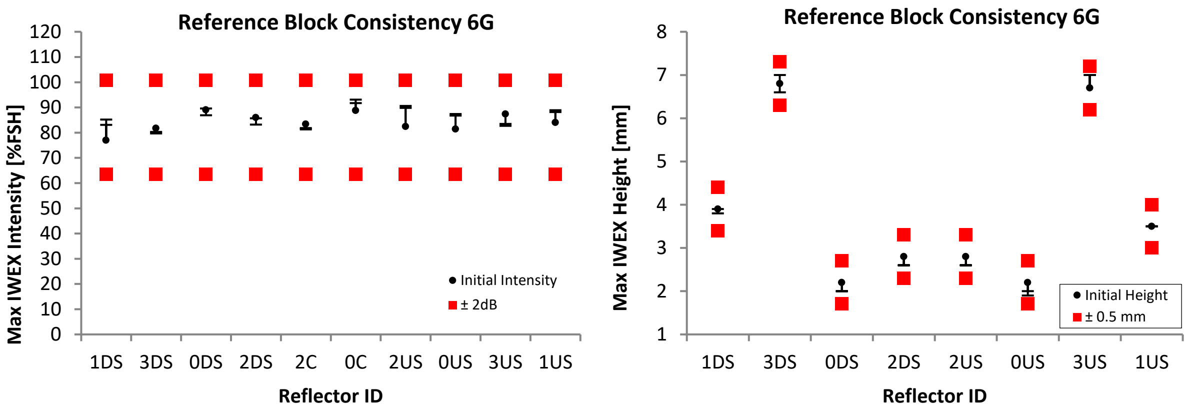

Figure 7-4: Consistency trial results, 3 scans with the reference block at 6G position.

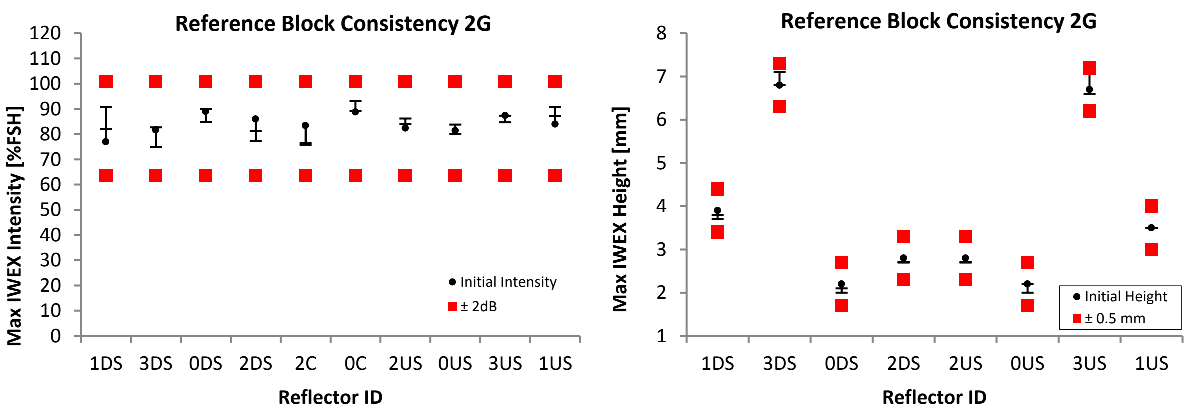

Figure 7-5: Consistency trial results, 3 scans with the reference block at 2G position.

7.2.2 Band Offset

The series of band offset scans shows that deviations in maximum AUT measured height from 6 imperfections in weld 9 are well within ±0.5 mm from the height measurement at no band offset. No significant differences are observed in results between series of band offsets of ±1 mm, ±2 mm and ±3 mm. It is concluded that band offset has no impact on IWEX performance. The results are illustrated in Figure 7-6.

These results are validated for a band offset of ±3 mm for the 7.5 MHz probe setup used on the 21.3 mm WT Weld Number 8, Figure 7-6. This also qualifies the setup with 4 MHz probe for the 21.3 mm wall thickness. Details of the trials are provided in Appendix A.

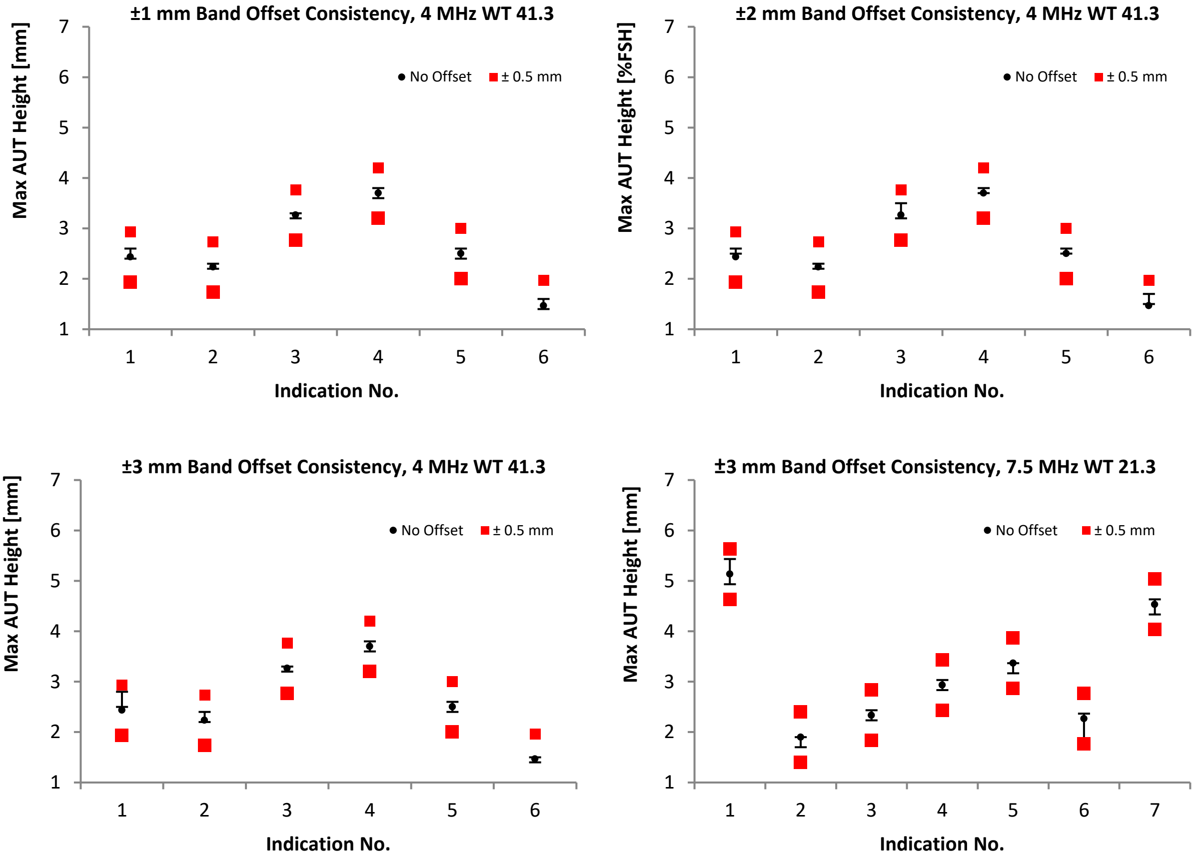

Figure 7-6: Band offset trials results for band offsets of ±1 mm, ±2 mm and ±3 mm for 4 MHz setup on 41.3 mm WT weld and ±3 mm for 7.5 MHz setup on 21.3 mm WT weld.

7.3 Detectability

The general Probability of Detection (POD)-curve includes imperfection observations of all types and at all depths of the weld, Figure 7-7. The analysis shows the imperfection height corresponding to a 90% POD at 50% confidence level at 0.51 mm, which is the actual fit to the present results. The 90% POD imperfection height with 95% confidence is at 0.66 mm. The recording level of 20% refers to the intensity set to 80% for reference reflectors. Selection of the recording level is further discussed in paragraph 7.9.

The general POD curve is regarded valid for all zones and areas (root, buried and cap) of the weld, all types of imperfections except Cu inclusions and all lengths of imperfections.

The detection limit is observed to be for single pores with diameters below 1.0 mm. It should be noted that planar indications with some length, measured down to 10 mm are consistently reported with documented vertical imperfection heights below 0.5 mm.

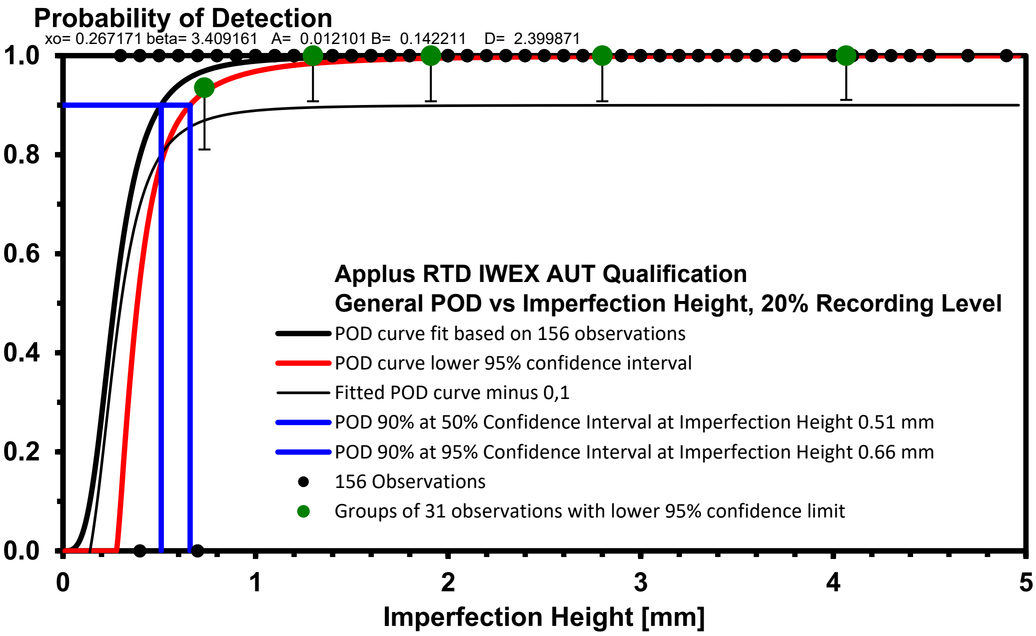

Figure 7-7: General POD curve

7.4 Height Sizing Accuracy

The general height sizing accuracy (the 95% limit against under-sizing) is estimated at -0.76 mm under-sizing, Figure 7-8. The mean height sizing error is found at 0.13 mm, with a standard deviation of 0.54 mm.

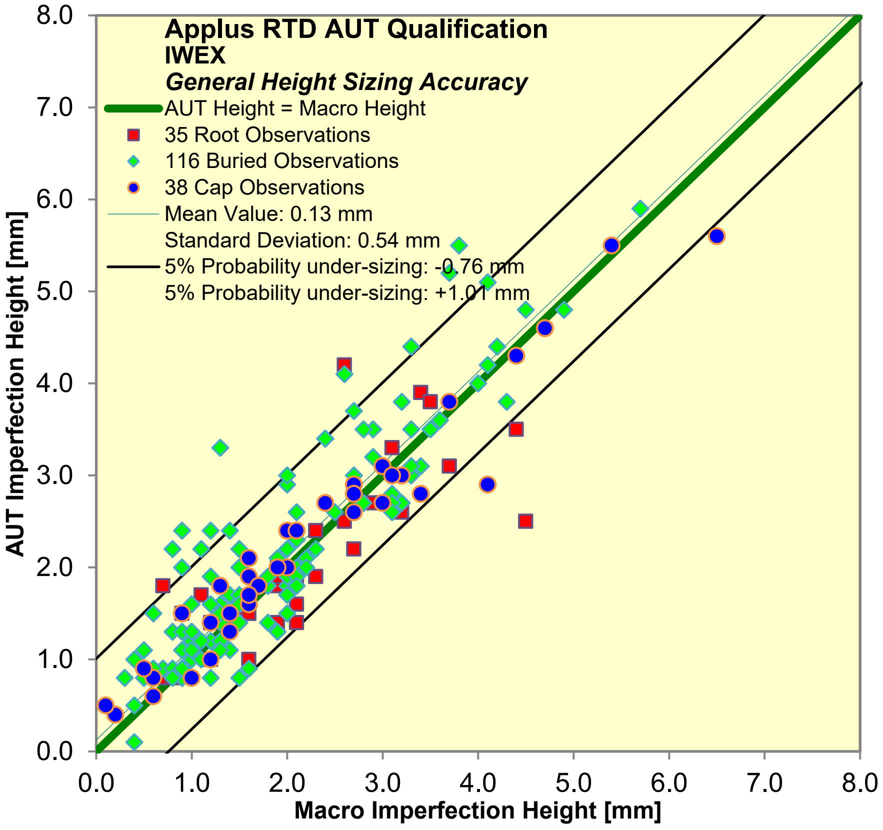

Figure 7-8: General height sizing accuracy plot.

7.5 Length Sizing Accuracy

Length sizing accuracy was evaluated with macro sectioning on two indications. This were 1) a surface breaking lack of penetration type of imperfection at the ID surface, indication M035 in weld 1 (21.3 mm WT) and 2) an embedded lack of fusion type of imperfection, indication M31 in weld A-6.

AUT reported length was 64.7 mm, while macro sectioning confirmed a length of 65 mm for the surface breaking imperfection. For the embedded lack of fusion imperfection, the AUT reported length was 18 mm which was confirmed to be 20 mm by macro sectioning.

7.6 Probability of Rejection Analysis

Figure 7-9 shows how the estimated POR-values at 50% and 85%, both at 95% confidence level, vary with increasingly set defect height rejection thresholds from 0.4 mm to 4.0 mm in steps of 0.2 mm. Each result is indicated with a dot. The X-axis keeps the values for the AUT rejection thresholds, while the Y-axis keeps the estimated defect heights at the specified POR (85% or 50%).

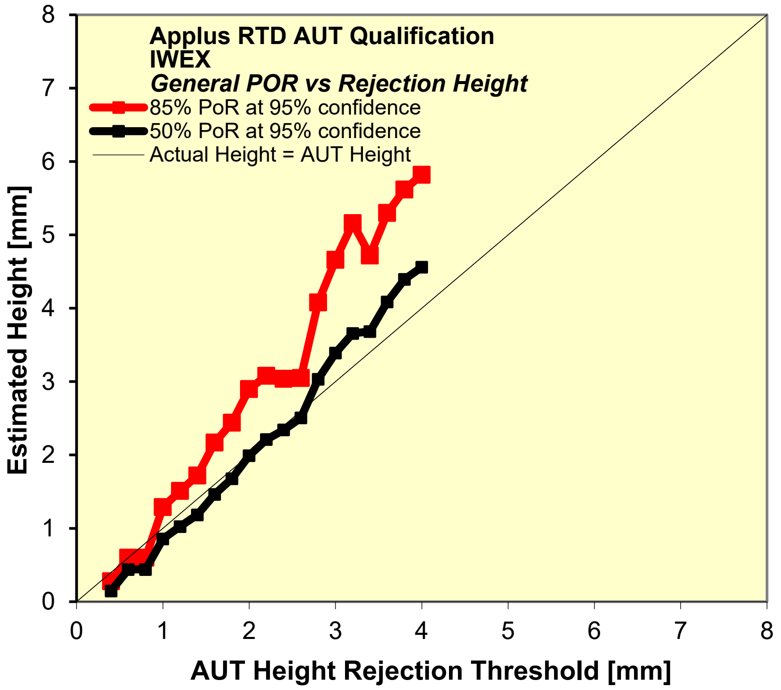

Figure 7-9: POR results of 85%|95% POR and 50%|95% POR for AUT height rejection thresholds from 0.4 mm to 4.0 mm.

The in general precise height sizing of IWEX is found to provide good conditions for accurate POR analysis. The results in Figure 7-9 show in general a good correspondence between rejected actual imperfection size and AUT rejection threshold. Roughly, it is documented that for a rejection threshold of 2.0 mm, imperfections larger than +0.5 mm (i.e. imperfections larger than 2.5 mm with 2.0 mm rejection threshold) are consistently rejected, while for larger rejection thresholds imperfections larger than +1.0 mm are consistently rejected.

7.7 Depth Position Accuracy

The inaccuracy in depth position estimate is on average at -0.20 mm, with a standard deviation of 1.00 mm. The negative sign of the average value means that AUT tends to indicate the defect position a bit higher in the weld than the actual position. The AUT reported defect depth is mainly estimated at accuracy within +1.44 mm and -1.83 mm, as shown in Figure 7-10. The results are valid for OD surface and buried imperfections.

In general, the depth position accuracy of the IWEX is considered as accurate, in particular when well resolvable responses are observed with the cross modes.

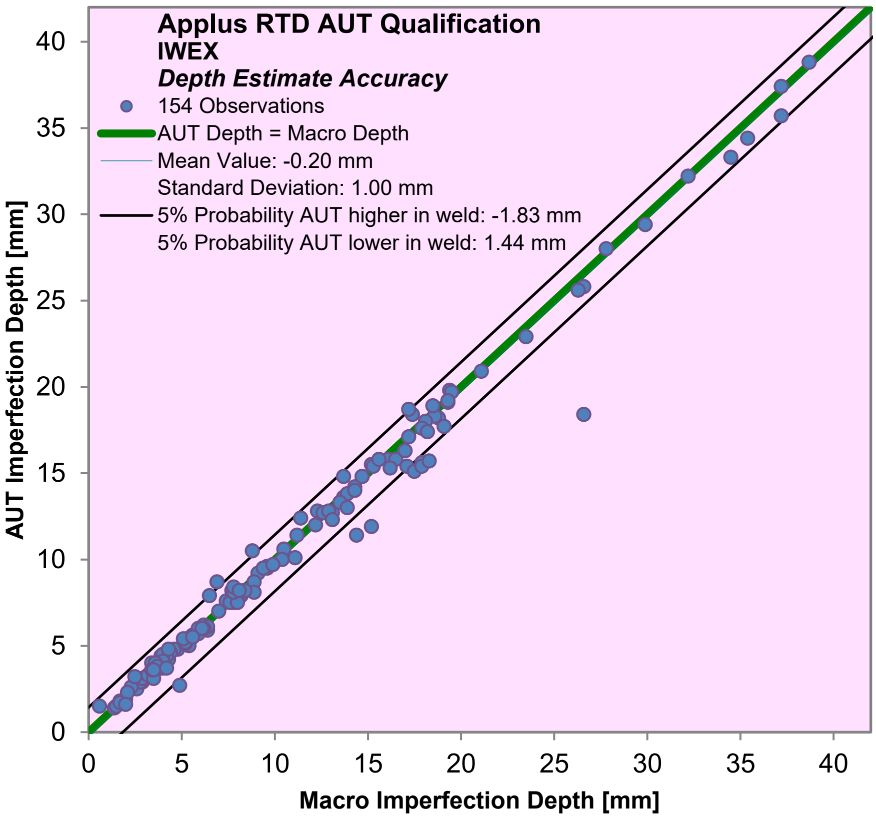

Figure 7-10: Depth estimate accuracy plot

The inaccuracy in surface ligament estimate for buried imperfections is on average 0.13 mm, with a standard deviation of 1.01 mm. The IWEX AUT reported surface ligament is mainly calculated at an accuracy within +1.78 mm and -1.53 mm, as shown in Figure 7-11. A minus sign indicates that the actual imperfection ligament is smaller than estimated by AUT, while the plus sign indicates that AUT estimates a smaller ligament than the actual value. Only buried imperfections are included in this analysis.

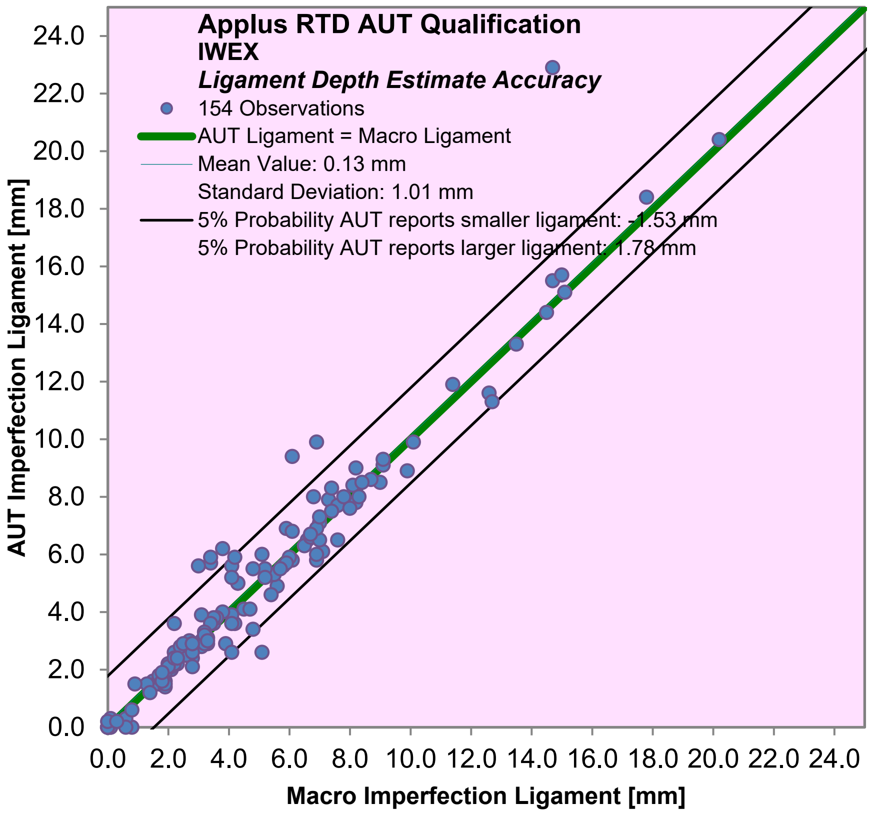

Figure 7-11: Buried imperfections ligament estimate accuracy.

7.8 Detection and Height Sizing at Different Parts of Weld

POD and height sizing accuracy have been evaluated for ID surface, buried and OD surface imperfections separately as well. The sizing performance and sensitivity of IWEX is observed to be consistent regardless of position in the weld. Most notable differences in sizing performance are observed between height sizing with different modes. This is either observed when the same imperfection is sized with different modes, or with comparison of distinct imperfection types which allows for sizing with different modes from the others.

In addition, it is observed that weld shrinkage can have a minor impact on height sizing accuracy. This was observed with a comparison between sizing of V-bevel and J-bevel welds for 21.3 mm WT, where the former configurations have some shrinkage.

These particularities are captured in the general figures for POD and height sizing accuracy presented in this report.

Due to this observation, results are not presented separately for ID surface, buried and OD surface imperfections in this report, as sizing and detection performance are considered unaffected by position in the weld.

7.9 Signal-to-noise

It has been observed that the signal-to-noise ratio of all 4 MHz, 7.5 MHz and 10 MHz is not limiting carbon steel inspection. The overall general noise level is observed to be in the area of 3-4 % FSH, and usually not higher than 5% FSH. The general noise level is observed to be insignificantly lower in the 7.5 MHz images than in the 4 MHz images.

The recording level of 20% FSH used for the POD analysis was selected based on the observations of signal-to-noise. The recording level shall be consistently higher than the noise level, to avoid spurious indications. Different color slider settings with the lower level varying between 0%-20% FSH are compared for macro M119 in Figure 7-12 below. It can be observed that the general noise disappears when the lower level is set at 5%. No considerable change in recorded signal used for interpretation is observed when the lower level is raised from 10% to 20%. Saturation is set to 80% for all images. Based on these observations, color slider set betwen 5%-80% FSH has been used for all images presented in this report.

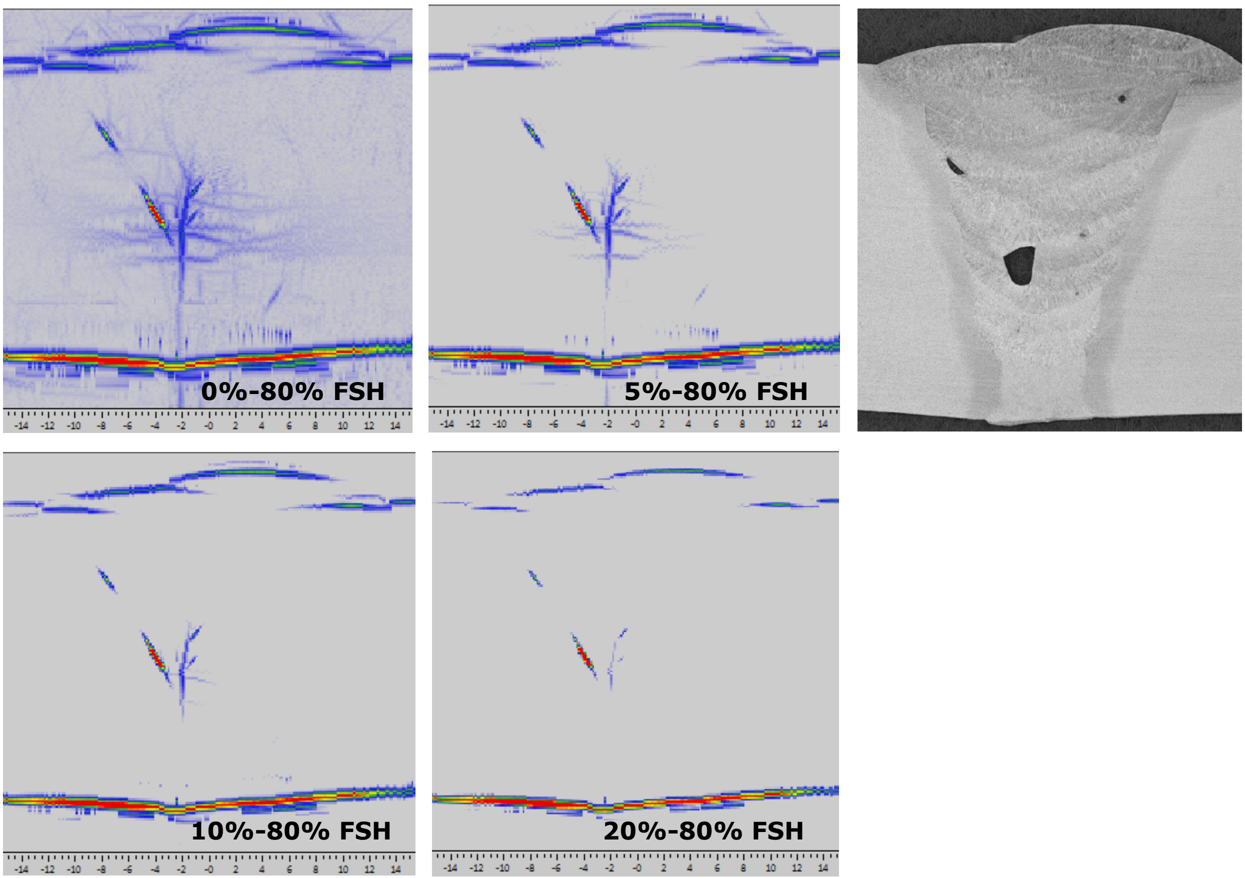

Figure 7-12: Example of scan presentation when color slide varies, indication M119. The general noise is removed with the color slider set between 5%-80% FSH.

7.10 Reported Imperfection Type

The imperfection types reported by AUT correspond well with the actual imperfections observed by macro sectioning. This includes root imperfection types (lack of penetration and lack of root fusion), embedded planar imperfections in general, cavities and cluster porosity indications.

One observed benefit with IWEX over conventional zonal discrimination AUT is the possibility to evaluate the actual shape of an imperfection from the responses of the different modes. This applies in particular to planar indications which provide responses in the tandem modes. It was in addition observed that a volume will provide stronger reflections for the cross modes and partly the direct/over skip modes. With the latter, a curved surface flaw might provide weaker or stronger response depending on which side the sound is approaching.

Due to the discussion above, some intentionally induced cavities and/or large pores were reported as Lack of fusion by IWEX. Further reference is given to paragraph 7.14.3. Below are some examples of IWEX imaging of different type of imperfections.

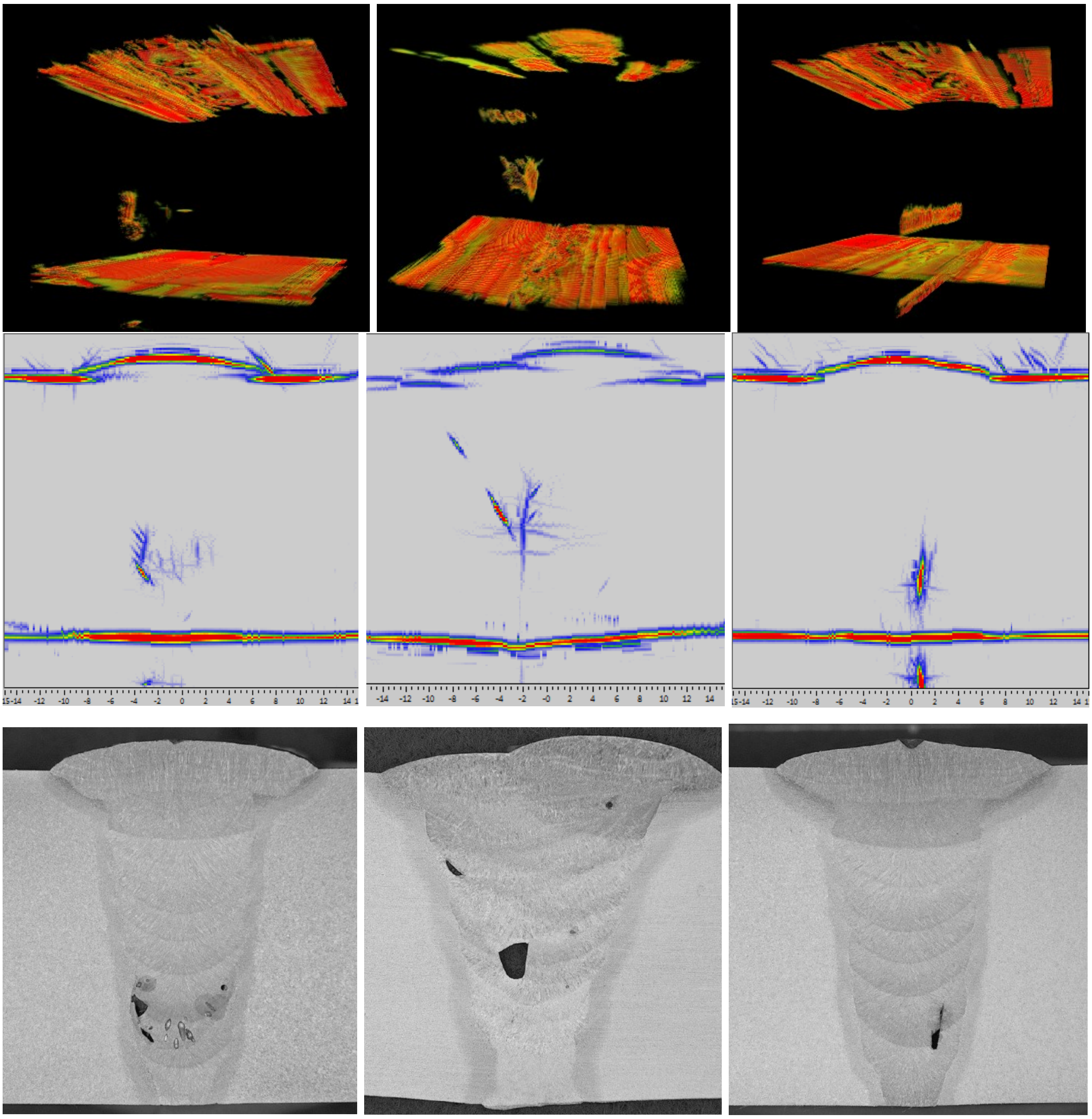

Figure 7-13: Examples of 3D and 2D imaging of different types of imperfections: Left: Porosity (M093), Middle: void/volumetric (M119), Right: Planar (M082)

7.11 Probe Frequency Impact

The height sizing and POD results for the 4 MHz and 7.5 MHz scans of the same weld are more or less identical, as listed in the Table 7-4 below. Differences in sizing are so low that they might be considered insignificant.

Table 7-2 Probe Frequency Trial Result, analysis of general dataset

Setup	5% probability under-sizing [mm]	5% probability over-sizing [mm]	Mean sizing inaccuracy [mm]	Standard deviation [mm]	90%|95% POD Height [mm], 20% Rec. Level
4 MHz	-0.8	1.1	0.2	0.57	0.66
7.5 MHz	-0.8	1.0	0.1	0.53	0.81

A direct comparison between 4 MHz and 7.5 MHz scans indicates that the improved resolution for high frequency is most useful to resolve individual indications located close to each other. Responses from the different modes are repeatedly documented to be comparable. One notable exception is for tandem modes IWEX1 and IWEX3, where the responses are stronger with the low frequency probe. This is considered to be due to the increased directivity with higher frequencies. Since tandem modes are hardly used for height sizing, this has no impact on IWEX reporting performance. The modes used for sizing evaluation appear to perform similar regardless of frequency. A comparison between 4 MHz and 7.5 MHz images for indication M089 where the discussed features are included is provided in Figure 7-14.

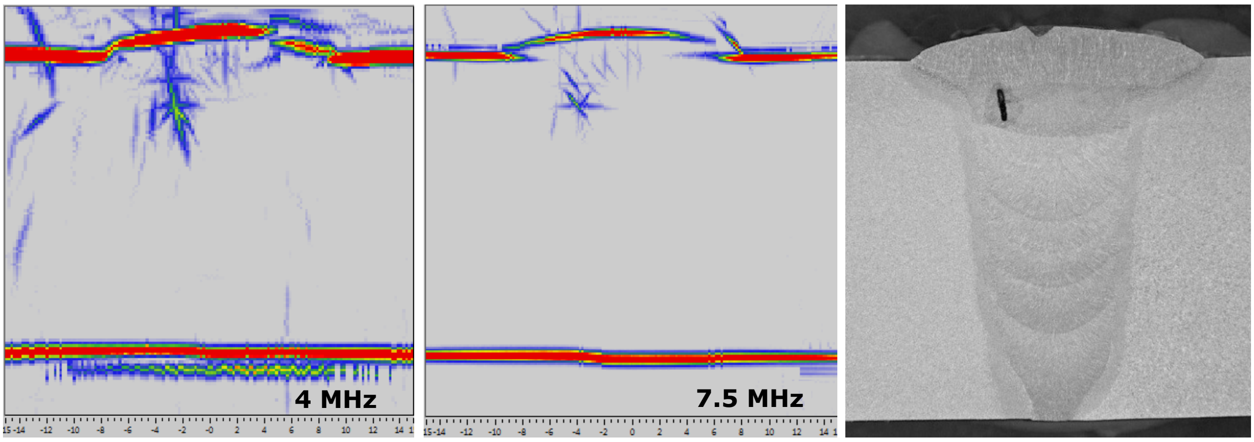

Figure 7-14: Comparison 4MHz and 7.5 MHz IWEX images with macro.

The study was supplemented with data and results from inspection with the 10 MHz IWEX setup for low wall thickness configurations. The dataset included in total 33 imperfections, the results from these data are listed in Table 7-3 below. The 90%|95% POD height has been calculated using the full dataset including observations with both 4MHz and 10MHz probe scans.

Table 7-3 10 MHz Probe Frequency Result, analysis of specific dataset

Setup	5% probability under-sizing [mm]	5% probability over-sizing [mm]	Mean sizing inaccuracy [mm]	Standard deviation [mm]	90%|95% POD Height [mm], 20% Rec. Level
10 MHz	-0.5	0.4	-0.1	0.28	0.45

The results from the 10 MHz data are concluded to be in line with the results listed in **Table 7-2** for 4 MHz and 7.5 MHz scans. Use of 10 MHz probe is therefore documented to provide a fully equivalent inspection as with 4 MHz probes, provided that it is used at relevant weld configurations. The observed deviations are small, and can be fully explained by the different set of welds and imperfections between the datasets.

A qualitative evaluation of the scans with the 10 MHz setup confirms the considerations made above with use of 7.5 MHz probes, that the increased resolution is clear in the IWEX images. It is furthermore observed an increased capability of accurate sizing and detection of small size imperfections (i.e. >1.0 mm vertical height) due to this, compared to the scans with lower frequency. The mentioned observations for the tandem channels with the 7.5 MHz does not apply for the 10 MHz setup, as the dimensions of the 10 MHz probe are scaled to match the frequency. The 4 MHz and 7.5 MHz probes were of the same dimensions. The use of the 10 MHz is in principle limited by attenuation when beam paths increases with increasing wall thicknesses, and the range of validity is set to maximum 15 mm WT for this qualification.

7.12 Wall Thickness Variation Impact

The results for the trials are summarised in Table 7-4 below, which includes depth, length and height sizing results of all indications in WT corrected and un-corrected scans of weld with variable wall thickness.

It has been demonstrated on weld sample with nominal WT 23.1 mm and variations -1.1 mm/+1.5 mm, corresponding to a wall thickness range between 22.0 mm – 24.6 mm.

Table 7-4 WT variation trial results

ID	Scan pos. [mm]	WT Un-corrected Length [mm]	WT Un-corrected Depth [mm]	WT Un-corrected Height [mm]	WT corrected Height [mm]	Macro Depth [mm]	Macro Height [mm]
1	92.9	64.6	23	1.9	1.7		
2	325.7	46	22.2	1.1	1.4	19.6	1.1
3	610.8	47.4	15.7	1.9	1.7	15.0	1.1
4	684.3	46.8	10.3	2.8	2.9	11.0	2.3
5	755.4	38.4	10.8	1	1.1		
6	846.5	35	10.9	2.5	2.5		
7	1021.2	22.8	8.3	2.6	2.8		
8	1247.3	18.1	7.2	4.3	4.5		
9	1305.9	11.2	4.1	3.9	3.8		
10	1520.4	27.4	2.2	4.4	4.3		
11	1646.2	12.8	3.1	0.7	0.7		
12	1810.8	12	8.4	5.8	5.9	9.5	6.2

The results from this trial indicate that wall thickness variations have no significant impact on imperfection height sizing. Results are within the documented natural variations in sizing between repeated scans of the same weld. This can be explained by the use of single modes in height sizing; when the signals at upper and lower extremes of the indications are equally affected by the wall thickness variation. The main impact by wall thickness variations in an un-corrected scan is observed to be on de-focusing on tandem modes IWEX 1 and IWEX 3 and on how the responses in the different modes are matching in image position. This is illustrated for indication M158 in Figure 7-15. This was clearly confirmed with the scans of the open bevel test block, Figure 7-16, which provides an extreme situation with regards to WT variation impact on tandem mode detection. In practice, WT correction is therefore considered to have most value for evaluation of imperfection type and shape, where tandem modes are of importance. For detection and sizing of imperfections, WT correction remains an optional step.

The wall thickness variation correction software was confirmed to perform correctly. It is regarded as fully documented that all indications within the weld with wall thicknesses in the WT range of nominal WT -1.1 mm / +1.5 mm were presented with similar sensitivity and position by IWEX. Use of the WT correction software module is therefore concluded to not affect the scope of this qualification.

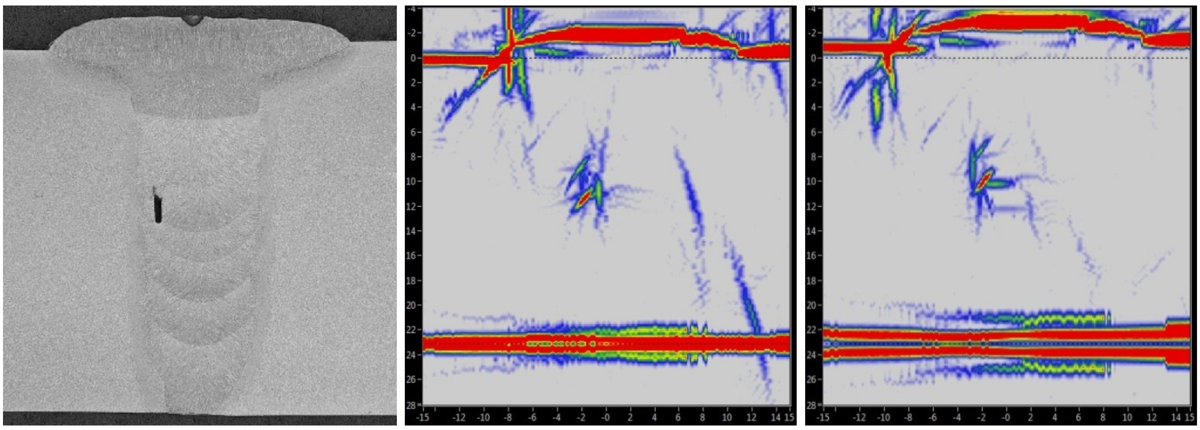

Figure 7-15: Comparison macro (left), WT corrected (middle) and WT un-corrected(right) of indication M158.

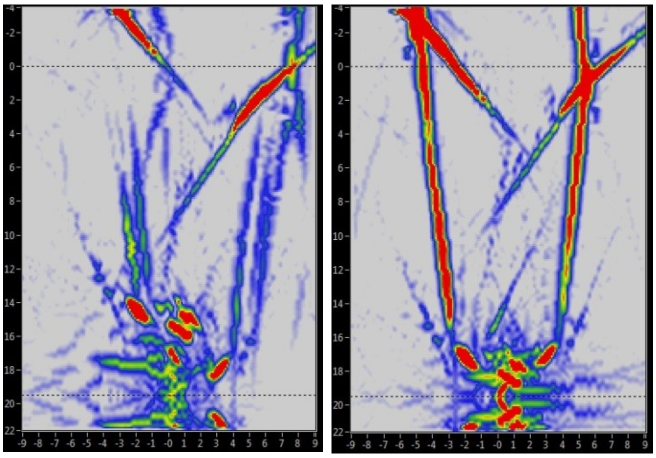

Figure 7-16: Examples of wall thickness correction impact on open bevel scan from same position with WT variation from nominal WT of +2.9 mm US and -0.9 mm DS. Nominal WT is 19.5 mm, US side is to the left in both images. Left: WT un-corrected scan, Right: WT corrected scan.

7.13 Probe Separation Impact

Scans of weld 5 with probe separation of 30 mm and 40 mm provides almost identical results for height sizing of all indications in the weld. Deviations are within 0.3 mm, which is within the natural variations in sizing upon repeated scans of the same weld as for instance documented in paragraphs 7.2.1 and 7.2.2.

Table 7-5 Probe separation trial result

Scan Position [mm]	Wedge distance 29.8 mm height [mm]	Wedge distance 40.4 mm height [mm]
120	2.9	2.9
250	2.3	2.2
380	1.3	1.6
600	1.6	1.5
660	1.2	1.1
720	2.4	2.5
1150	1.8	1.6
1380	1.6	1.5
1470	US 0.9/DS 2.4	US 0.8/DS 2.3
1600	1.2	1.3
1630	1.9	1.9
1730	1.1	0.9
1800	US 0.7/DS 0.8	US 0.9/DS 0.8

It is concluded that there are considerable tolerances for probe separation with regards to sizing, and that at least 10 mm additional probe separation from optimal value (i.e. as close as possible) will not cause any decrease in sizing and detection capability.

7.14 Interpretation Capability

7.14.1 Stacked Flaws

The locations particularly selected for assessment of stacked flaw interpretation were all well reported, with documented accurate reporting in imperfection height, depth and horizontal position. These stacked flaws were spatially separated by at least 2.0 mm, either in depth or horizontal position. One example is provided in Figure 7-17.

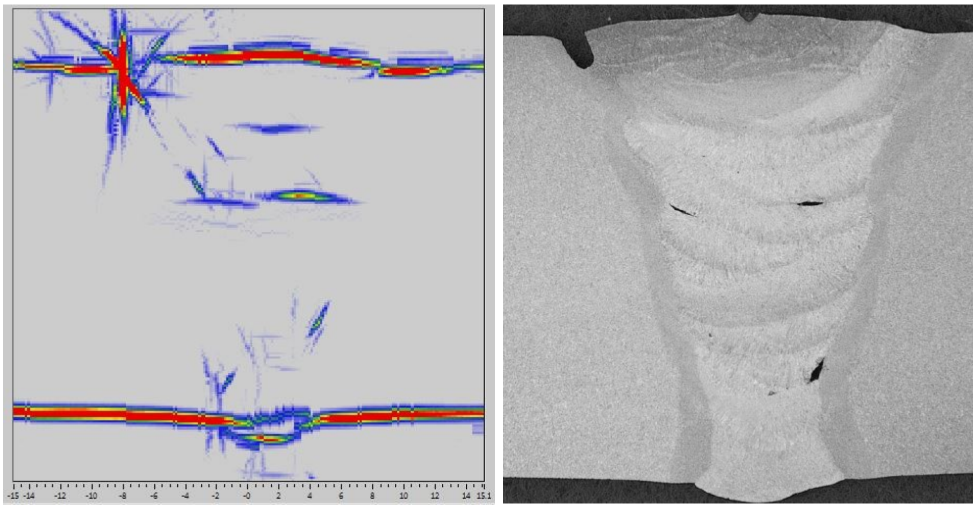

Figure 7-17: Examples of stacked defects of indication M099, clearly resolved in the IWEX images. Some indications in the IWEX image are not confirmed by the macrographs.

There were some observations among the full data set that are anticipated to be over-sized due to stacked flaws. Two of these observations were confirmed by macro sectioning. In both cases, the target imperfection had a satellite flaw located on the top with a separation of maximum 1.0 mm. It is considered as reasonable that there is a lower limit for stacked flaw separation distance where the two individual flaws cannot be resolved. The observations within the present qualification program suggest that this limit is for flaw separation somewhere between 1.0 mm and 2.0 mm.

7.14.2 Imperfection Orientation

The results are summarised in Table 7-6 below.

Table 7-6 Orientation trial result

Weld No	Bevel	ID	IWEX Angle	Macro Angle
3	J6	M071	-45°	-32.9°
4	J8	M080	-10°	-6.9°
6	V20	M120	20°	15.4°
6	V20	M127	-5°	-1°
8	V30	M150	5°	0°
01 first batch	J4	M156	-45°	-14.5°

The results suggest that determination of angle and shape by IWEX is accurate for low angles, ie when the imperfection is oriented not far off the vertical direction in angle. An example is provided in Figure 7-18. Accurate estimates of angle were determined for imperfections with orientations up to 20° from the vertical axis, except for one hot pass indication. It should be mentioned that the accuracy in angle estimate with IWEX is anticipated to be about ±5°, which is well confirmed for low angle planar indications.

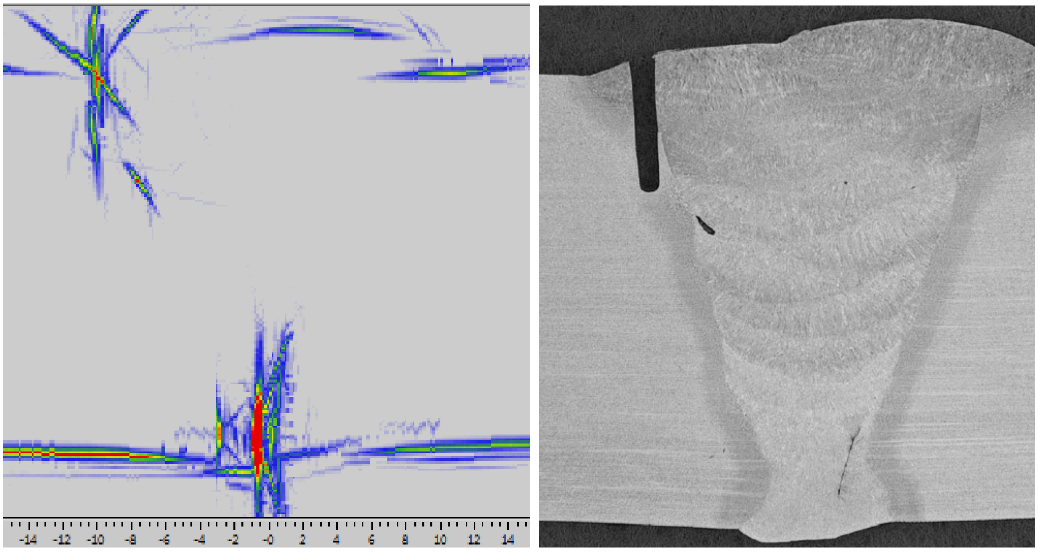

Figure 7-18: Examples of oriented indications of macro M120. Orientation angle of planar indication at the lower part of the weld is included in Table 7-6.

Two hot pass indications were included as high angle observations in the trial. It is observed that these have a shape that makes it challenging to measure an exact angle on the macro. Furthermore, deviations in results for these two indications can be explained by the lower height of the hot pass indications in comparison with the other flaws. For flaw sizes in the order of only 1 mm, the inaccuracy in the determined angle increases.

The documented capability to determine shape and orientation of weld imperfections is considered as a strong benefit with IWEX compared with inspection by conventional zonal discrimination setups.

7.14.3 Imperfection Characterisation (Shape and Horizontal Positioning)

The results are summarised in Table 7-7 below.

Table 7-7 Imperfection Characterisation Trial Result

Weld No	Bevel	ID	IWEX Lateral Position [mm]	Macro Lateral Position [mm]	Comment IWEX	Comment Macro
4	J8	M092	-3.2	-3.0	vertical OD surface-breaking	As described by IWEX
4	J8	M093	-3.1		cluster porosity/copper inclusion (shape)	Copper inclusion, width not reported
4	J8	M094	3.4	3.5	cluster porosity/copper inclusion	As described by IWEX
5	V15	M105	0.8	2.6	LOIRF	As described by IWEX. Macro lateral measured to middle of indication,
6	V20	M119	-2.0	-1.6	indication with width	Large volume, as described by IWEX
10	V20	M027	4.2	5.3	width	As described by IWEX

Most of the imperfections in this trial were confirmed by macro sectioning to have an orientation that differs substantially from the bevel orientation. The challenging cases of imperfection characterisation are observed to be well described by IWEX. It was demonstrated to have the capability to identify volumetric type, shape and position. Horizontal positioning in the weld cross section was observed to be within ±1 mm. One example is provided in Figure 7-19.

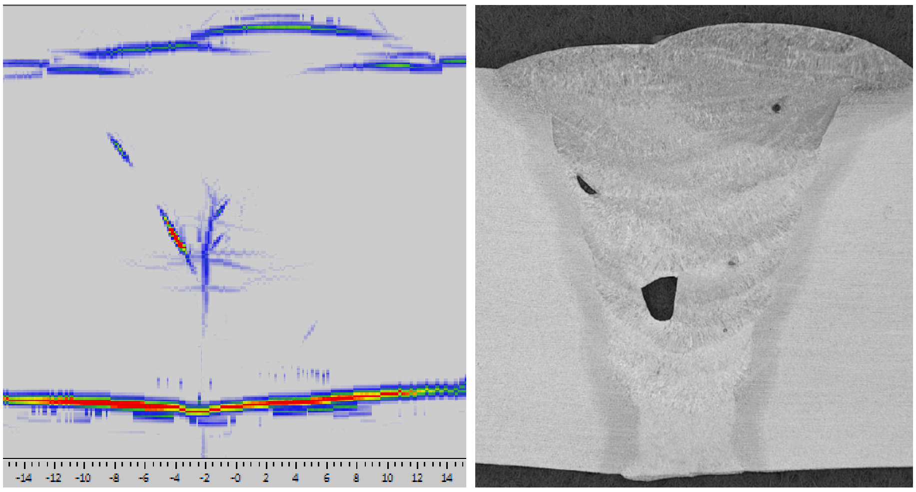

Figure 7-19: Example of large volumetric indication characterised by IWEX, macro M119.

7.14.4 Cap and Root Height

Cap and root height measurement accuracies are plotted in the figures below.

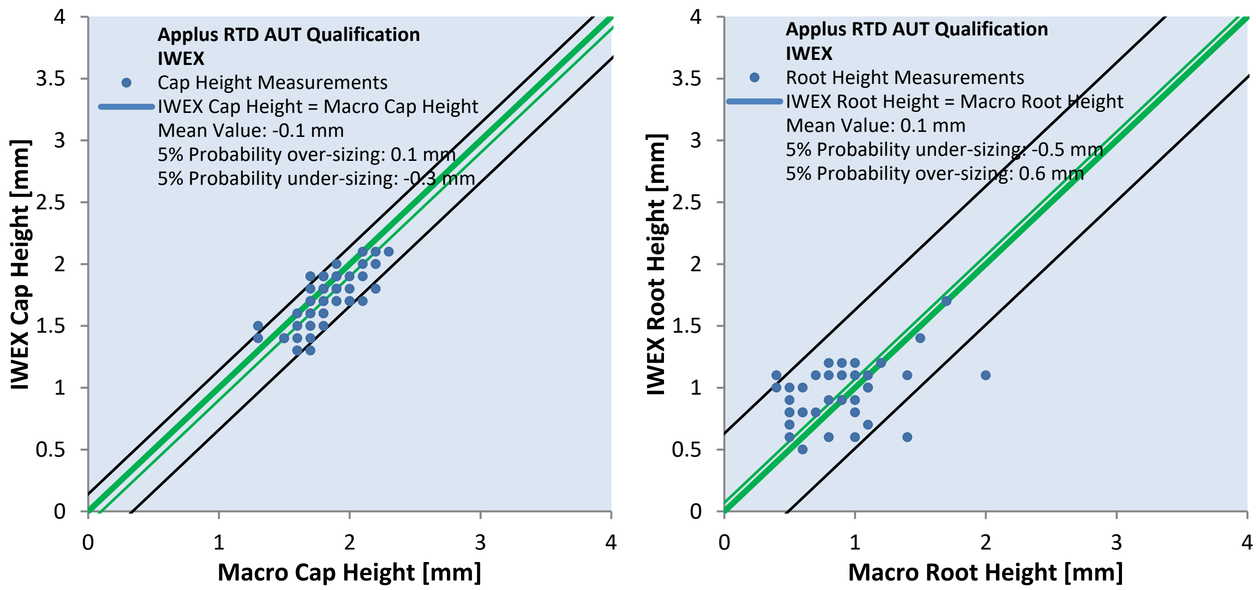

Figure 7-20: Sizing accuracy, left: Cap height, right: root height

The accuracy in cap height estimates is observed to be very accurate, with all observations in cap height within ±0.4 mm. Root height measurements are observed to be a bit less accurate, however still well within the general results for imperfection height sizing as presented in Figure 7-8. In principle there should not be any difference in sizing capabilities between root and cap heights, since sizing is performed relative to pipe surface with the similar modes. However, the width of the cap makes it easier to determine the height accurately, whereas the narrow root geometry provides fewer points for measurement of its vertical extent. The increased spread in root height sizing is considered to be also due to observed shrinkage in manual V-bevel welds number 5 and 10 used for this trial. Shrinkage has been observed to introduce some uncertainty in sizing of the V-bevel welds, due to unpredictable wall thickness variations around the root.

7.14.5 Misalignment (Hi-lo) Measurement

The results are summarised in Table 7-8 below. Misalignment was measured from both sides of cap or root reinforcement, at the points where the reinforcement starts.

Table 7-8: ID & OD Misalignment measurement trial results, weld DW02 (phase 1)

	IWEX		Macro			
Scan Position	OD misalignment [mm]	ID misalignment [mm]	OD misalignment [mm]	ID misalignment [mm]	Δ IWEX – Macro OD [mm]	Δ IWEX – Macro ID [mm]
19	1.6	0.6	1.2	0.6	0.4	0.0
230	0.9	0	0.8	0.4	0.1	0.4
611	-0.4	-0.2	-0.3	-0.2	0.1	0.0
662	0	0	0.0	0.1	0.0	0.1
783	-0.1	0.2	0.0	0.1	0.1	0.1
960	0.5	0.2	0.3	0.2	0.2	0.0
1062	0.3	-0.3	-0.1	0.0	0.4	0.3
1198	0.7	0.4	0.6	0.3	0.1	0.1
1245	0.8	0.5	0.5	0.4	0.3	0.1
1369	0.9	0.3	0.8	0.3	0.1	0.0
1382	1.1	0.3	0.7	0.3	0.4	0.0
1408	1	0.5	0.6	0.3	0.4	0.2
1823	0.5	0.2	0.3	0.1	0.2	0.1
1916	0.9	0.6	0.4	0.4	0.5	0.2

It is concluded that IWEX accurately determines and quantifies misalignment at both ID and OD surface. IWEX misalignment estimate and macro misalignment reference differs not more than 0.5 mm. In addition, it is observed that the IWEX image of the ID surface corresponds well to the real surface as documented in the macro sections. One example is provided in Figure 7-21.

The documented capability to quantify misalignment is considered as a strong benefit with IWEX compared with inspection by conventional zonal discrimination setups.

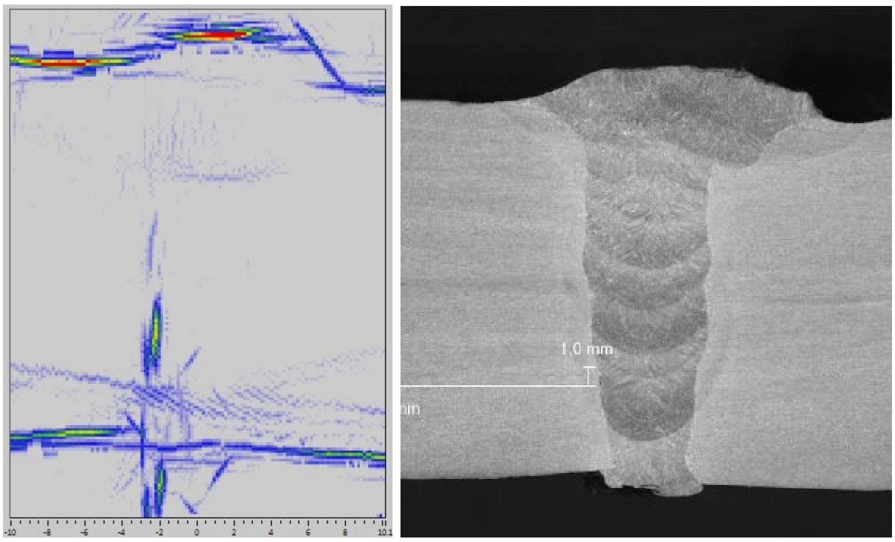

Figure 7-21: Example of misalignment appearance in IWEX image, corresponds to scan position 19 in Table 7-8.

7.14.6 Surface Ligament Measurement

The results are summarised in Table 7-9 below.

Table 7-9 Surface ligament trial result

Weld No	Bevel	ID	Surface	IWEX Ligament [mm]	Macro Ligament [mm]	∆ IWEX – Macro [mm]
1	J4	M039	OD	3.8	4.1	-0.3
2	J4	M052	ID	1.5	1.8	-0.3
2	J4	M053	ID	2.3	2.7	-0.4
2	J4	M061	OD	2.9	2.9	0
2	J4	M062	OD	2.9	3	-0.1
2	J4	M063	OD	2.9	3.4	-0.5
4	J8	M090	OD	3.3	3.9	-0.6
4	J8	M091	OD	3.1	3.2	-0.1
7	V25	M141	OD	1.8	2.4	-0.6
9	J3	M002	ID	2.3	2.8	-0.5
9	J3	M003	ID	2.1	1.9	0.2

It is concluded that IWEX accurately determines ligament of sub-surface imperfections. IWEX ligament estimate and macro ligament reference differs in general not more than 0.5 mm. Furthermore, there is a tendency that the IWEX estimate is conservative, as the ligament is systematically measured smaller than the macro result (i.e. negative ∆ IWEX - Macro). One example is provided in Figure 7-22.

The documented capability to determine imperfection surface ligament is considered as a strong benefit with IWEX compared with inspection by conventional zonal discrimination setups.

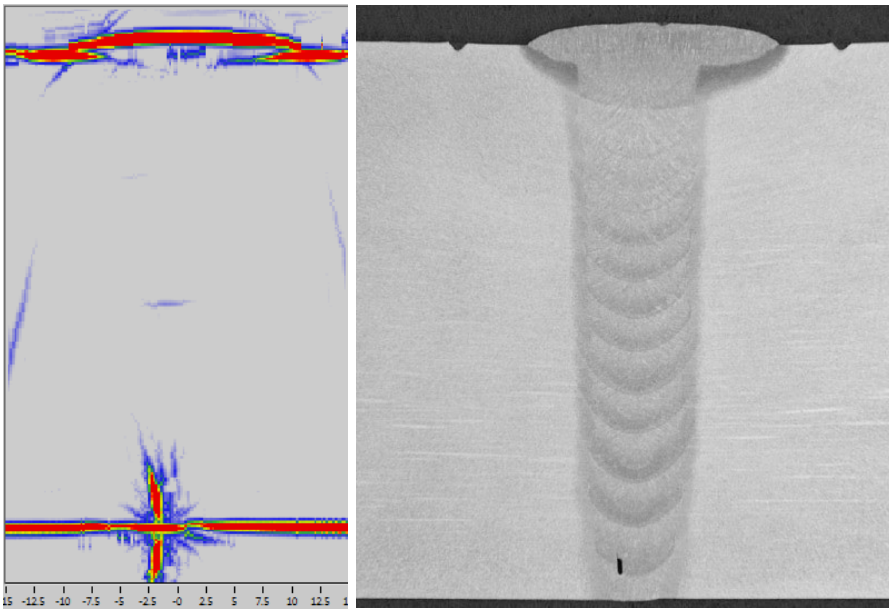

Figure 7-22: Example of sub-surface indication with measurable ligament, indication M003.

7.14.7 Interpretation Consistency, Clockwise and Counter-clockwise Scans

Results of consistency in weld scan interpretation upon repeated scans are presented in the Table 7-10 below, which details scan interpretation of clockwise (CW) and counter-clockwise (CCW) scans of weld No 9.

Table 7-10 Comparison CW and CCW scan interpretation

ID	Scan pos. CW [mm]	Depth CW [mm]	Height CW [mm]	Scan pos. CCW [mm]	Depth CCW[mm]	Height CCW [mm]	Δ Depth	Δ Height
1	0	28.3	0.6	1903.65	28.5	0.8	-0.2	-0.2
2	0	31.8	0.9	1902.15	31.9	0.9	-0.1	0
3	8.1	35.1	0.7	1893.05	35.3	0.8	-0.2	-0.1
4	88.5	1.6	3.1	1808.7	1.7	3.3	-0.1	-0.2
5	190.8	36.7	3.8	1710.6	36.6	3	0.1	0.8
6	291.5	4.1	5.4	1599.7	4.1	5.5	0	-0.1
7	499	9.8	1.7	1395.15	9.7	1.8	0.1	-0.1
8	715.2	17.4	1.9	1174.5	17.4	2.2	0	-0.3
9	750.9	10.3	0.7	1155.25	10.3	1.1	0	-0.4
10	825.7	21.2	2.9	1062.8	21.3	3.1	-0.1	-0.2
11	889.7	41.4	1.5	1016.85	41.4	1.5	0	0
12	961.4	41.5	1.6	946.15	41.3	1.6	0.2	0
13	1077	27.9	1.9	808.9	27.9	1.8	0	0.1
14	1197.7	32.3	1.2	683.5	32.3	1.3	0	-0.1
15	1277.6	25.5	0.9	627.6	25.7	1.3	-0.2	-0.4
16	1391.2	37.4	1.5	508.3	37.5	1.8	-0.1	-0.3
17	1531.5	39.6	1.2	342.9	39.6	1.1	0	0.1
18	1677.7	39.1	0.8	216.15	39.1	0.8	0	0
19	1749.2	41.6	2.9	134.45	41.3	2.5	0.3	0.4

It is observed that height and depth estimates are consistent upon repeated scans CW and CCW, with deviations well within ±0.5 mm. One minor exception is for indication 5. Deviation in vertical height sizing for this indication is due to different modes used for sizing for the two scans, which makes the results not directly comparable.

7.15 Guiding band

The repeatability trials with the Z-shaped guiding band gave the following results:

- For the series of 10 consecutive scans of the reference block in 5G orientation with center at both 12 o'clock and 6 o'clock positions with the Z-shaped guiding band, target responses were all confirmed to be within ±2dB.
- For the series of 3 consecutive scans of the reference block in 2G orientation with the Z-shaped guiding band, target responses were all confirmed to be within ±2dB.

The Z-shape band is confirmed to produce stable and repeatable results identical to use with the standard band through these trials. It is therefore documented that use of the Z-shape band has no impact on the inspection performance, when applied according to the applicable Applus+ RTD AUT procedure [4]. Therefore, the results presented in this report is considered to be applicable for use of the IWEX AUT system mounted on both standard and Z-shape band.

7.16 Supplemental NDT

The supplementary radiographic testing (RT) reports have been compared to the IWEX reports. The imperfections detected with radiography were found to correspond well to the results from AUT when it comes to position. Reported positions differ no more than a few mm between AUT and RT. The reported imperfection types appear in general to correspond well between AUT and RT.

Some imperfections were reported by IWEX and confirmed by macro sectioning, but disregarded by radiography. These were planar lack of penetration and lack of fusion imperfections, observed to be closed imperfections, i.e. without considerable volumetric components. RT was observed to disregard this type, regardless of imperfection height. The observed response with IWEX on this and all types of planar imperfections are observed to be very clear. An example is given with indication M139 from weld 7 (V25) in Figure 7-23.

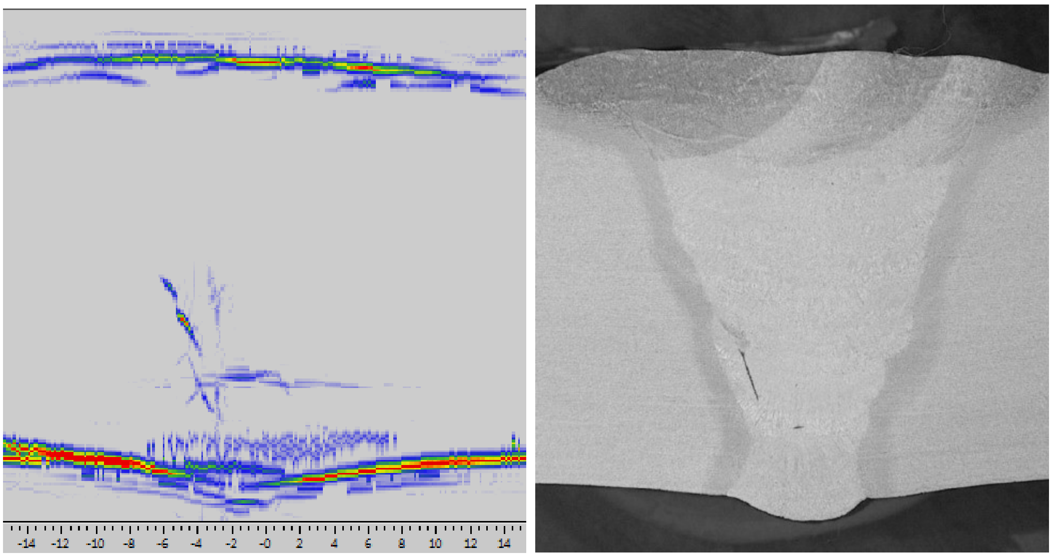

Figure 7-23: Example of closed planar imperfection disregarded by RT but with clear detection with IWEX.

7.16.1 Conventional channels

The IWEX hardware has the possibility to include conventional channels to the scanner, for instance creeping wave probes and TOFD. Applus+ RTD demonstrated this functionality, both with the probes mounted on the scanner frame and the integration with IWEX images in the software. Good correspondence between TOFD and IWEX images with regards to imperfection position and sizes were confirmed. The inclusion of conventional channels is regarded as useful to provide supplemental information for interpretation, perhaps in particular for volumetric imperfections.

The performance of the conventional channels was not evaluated, as this has been well investigated upon earlier qualification programs.

8 CONCLUSIONS

8.1 General

The Applus+ RTD IWEX (Inverse Wave field Extrapolation) automated ultrasonic testing (AUT) procedures have been subjected to qualification trials in order to establish the general performance of the system applied on carbon steel pipeline girth weld applications. IWEX is an ultrasonic imaging technique which differs substantially from conventional zonal discrimination AUT. The present qualification program has documented that IWEX complies with the requirements of DNVGL-ST-F101, Appendix E. Furthermore, IWEX capabilities with regards to benefits specific to ultrasonic imaging have been documented, where IWEX outperforms conventional zonal discrimination AUT. In particular, the abilities of IWEX to measure remaining surface ligament and flaw orientation are considered to be beneficial. The determination of the flaw position is also supported by the capability to measure hi-lo as well as cap and root reinforcement heights as detailed in section 8.3. The combination of these features enables improved flaw characterization.

DNV GL has witnessed all trials and all scan interpretation, and has been invited to comment on all relevant documentation for IWEX and the qualification program.

The qualification work has been done under agreement between Applus+ RTD and DNV GL AS, and follows the requirements of DNVGL-RP-F118 (2017). The qualification trials have covered 8 welds of 24” outer diameter and 21.3 mm nominal wall thickness, 2 welds of 24” outer diameter and 41.3 mm nominal wall thickness, 5 welds of 5.5” outer diameter and 8.4 mm nominal WT and 1 weld with 24” outer diameter and WT varying between 22.0 mm and 24.6 mm. The defective welds and corresponding calibration blocks have been subjected to trials for reliability, repeatability and heat influence. In total 189 observations were included for reliability analysis by macro sectioning. All scanning was witnessed by DNV GL, and DNV GL performed the analysis of this report based on AUT reporting by Applus+ RTD and macro sections by BKW.

8.2 Performance Results, DNVGL-ST-F101 Requirements

8.2.1 Repeatability

For reference block repeatability trials deviations in measured reference reflector size is documented well within ±0.5 mm, and mainly within ±0.2 mm.

8.2.2 Band Offset Sensitivity

A band offset of ±3 mm on a defective weld has no significant impact on sizing and detection performance.

8.2.3 Temperature Sensitivity

Elevated temperature trials were performed as a scan series of 15 scans on a heavy WT 41.3 mm V20 weld heated to a temperature of at least 80 ºC, with a scan of the calibration block kept at ambient temperature in between each scan of the weld. The scan series shows good consistency in detection, with the variation in maximum measured imperfection heights within ±0.5 mm.

8.2.4 Detectability

Defect heights with documented reliable detection at 90% POD with 95% confidence valid for all weld imperfections (except Cu inclusions) and for all imperfection lengths are provided in Table 8-1.

The detection borderline has been observed in the dataset to be for small single pores with diameter below 1.0 mm. Imperfections with vertical heights below 0.5 mm and lengths above 10 mm have consistently been observed to be clearly detected.

Table 8-1 Detectability (POD) result, general use

Setup	90%|95% POD [mm]
IWEX	0.66

8.2.5 Height Sizing Accuracy

Height sizing accuracy results for general use, valid for all weld imperfections (except Cu inclusions) at all orientations, depths and types and for all imperfection lengths are provided in Table 8-2. Consistency in the general results has been confirmed for all areas of the weld, i.e. for ID surface, buried and OD surface areas.

Table 8-2 Height Sizing Accuracy Results, General use

Setup	5% probability under-sizing [mm]	5% probability over-sizing [mm]	Mean sizing inaccuracy [mm]	Standard deviation [mm]
IWEX	-0.76	1.01	0.13	0.54

8.2.6 Length Sizing Accuracy

The macro sectioned indication for length sizing accuracy evaluation was accurately sized in length, within 2 mm.

8.2.7 Imperfection Depth and Ligament Estimate Accuracy

The IWEX defect through thickness depth measured from the outer surface to the bottom of each defect was found to in general be estimated within an accuracy of ±1.83 mm. Imperfections are on average reported 0.2 mm higher in the weld by IWEX than the actual position. This applies to embedded imperfections. The results are summarized in Table 8-3 below.

Table 8-3 Depth Estimate Accuracy Result, General use

Setup	5% probability, IWEX higher in weld [mm]	5% probability IWEX lower in weld [mm]	Mean depth inaccuracy [mm]	Standard deviation [mm]

IWEX	-1.83	1.44	-0.20	1.00

The inaccuracy in surface ligament estimate for buried imperfections has a mean value of 0.1 mm, with a standard deviation of 1.01 mm. The IWEX AUT reported surface ligament is calculated to have an accuracy within +1.8 mm and -1.5 mm.

8.3 Performance Results, Ultrasonic Imaging Specific

8.3.1 Signal-to-noise

The signal-to-noise levels achieved with 4 MHz, 7,5 MHz and 10 MHz setups and thin/thick wall thicknesses are not limiting carbon steel inspection. The overall general noise level is observed not higher than 5% FSH.

8.3.2 Stacked Imperfections

The capability to resolve individual imperfections which are separated by at least 2 mm in any direction has been documented.

8.3.3 Surface Ligament

It has been documented that IWEX consistently determines ligament of sub-surface imperfections within ±0.5 mm accuracy.

8.3.4 Imperfection Orientation

The capability to accurately determine orientation of planar imperfections, with an accuracy of ±5° has been documented.

8.3.5 Root and Cap Reinforcement Height Measurements

Root and cap reinforcement heights are demonstrated to be determined with an accuracy of about ±0.5 mm.

8.3.6 Misalignment Measurement

ID and OD surface misalignment are demonstrated to be determined with an accuracy of ±0.5 mm.

8.3.7 Probe Frequency Impact

No significant difference in sizing and detection performance has been observed for inspection with 4 MHz, 7.5 MHz and 10 MHz probes. It has been observed that higher frequency probes (i.e. 10 MHz) have better performance for WT < 15 mm.

8.3.8 Imperfection Characterisation

It has been documented that IWEX accurately and consistently detects and determines the various imperfection types that occur with pipeline girth welding. In addition, shape and horizontal positioning in the weld volume is accurately determined by the ultrasonic image.

8.3.9 Wall thickness variations

Wall thickness variations are observed to cause no impact on sizing performance. The module for wall thickness variation compensation was demonstrated to be working according to expectation within the demonstration range.

8.3.10 Impact of Probe Separation Distance

A change in wedge separation distance from 30 mm to 40 mm has been documented to cause no impact on inspection performance.

8.4 Prerequisites

The performance documented in this report for the Applus+ RTD IWEX AUT system is attributed to the General AUT procedure [4], and regarded relevant for general use on carbon steel pipeline girth welds.

The IWEX system shall include sufficient modes to provide full coverage of the weld, and as a minimum the 10 modes included in the present qualification for WT above 6 mm. For WT <15 mm the number of tandem modes might be reduced to 2, provided that coverage is demonstrated. Minimum 64 element PA transducers shall be used in the setup. The wedge calibration tool shall be used whenever a new probe and/or wedge is introduced to the system.

The same type of reference reflectors (2 mm to 3 mm FBHs embedded and at ID and OD cap, alternatively 0.5 mm notch at ID surface, 1.5 mm FBHs for volumetric channels) as during the qualification trials shall be used. Reflector sizes may be reduced.

It shall be ensured that de-focusing is controlled within the full range of WT variations in the inspection scope.

Detailed inspection technique documents, similar to the ones used during the qualification, shall be used for relevant welds in question, taking material thickness and variations, bevel preparation details and other relevant items into consideration.

Any changes to the system including hardware, software and operating manuals and procedure that will influence the performance of the system with respect to imperfection detection and sizing compared to what was achieved during the qualification, shall be assessed. This includes pulser unit.

Guiding bands shall be either standard type or Z-shaped guiding band.

Girth welds and pipe ends shall be carbon steel pipe material. Applied welding method or weld bevel type and angle are not essential variables. Validity for heavy WT above 42 mm requires that the qualified setup can be maintained and shall be evaluated from case to case.

8.5 Validity

The qualification has unlimited validity, as long as the prerequisites in section 8.4 are met.

9 REFERENCES

/1/ DNVGL Standard DNVGL-ST-F101: Submarine Pipeline Systems, edition October 2017

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/4/ AUT Procedure, Doc. No. PIPL-06.11.0001 Rev.1, General Procedure for RTD IWEX Automated Ultrasonic Testing

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