

APPLUS+ RTD IWEX CRA QUALIFICATION

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

Applus+ RTD Rotterdam

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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 corrosion resistant alloy (CRA) 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-F101:2017 and DNVGL-RP-F118:2017.

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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 corrosion resistant alloy (CRA) pipeline girth weld applications. CRA in this context means all kinds of alloys that improve corrosion resistance of the pipeline, but at the same time this introduces additional challenges for ultrasonic inspection due to anisotropy for ultrasonic wave propagation caused by coarse grain sizes. 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 carried out under agreement between Applus+ RTD and DNV GL AS, and follows the requirements of DNVGL-ST-F101:2017 [1] and DNVGL-RP-F118 [2].

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[1] for future pipeline girth weld inspection projects upon pipeline owners discretion.

The programme has covered 19 girth welds, and includes application of Applus+ RTD IWEX on pipeline girth weld configurations with metallurgical bonded clad, weld overlay, narrow gap J and manual V weld bevel preparations, and applications on both full weld and partial welds. The weld configurations included in the programme are summarised in the Table 1-1 below, the analysis included a total of 161 independent observations of weld imperfections.

Table 1-1: Applus+ RTD IWEX CRA AUT Qualification defective weld details

Weld OD	WT [mm]	No. welds	CRA Material	CRA type	Bevel configuration	No. Intended Imperfections	No. Confirmed Imperfections
12.75"	19.8+3	4	UNS S31603	Weld overlay	J5	38	36
12.75"	25.6+3	4	UNS S31603	MB	J5	36	35
14"	20.6+3	1	625	MB	J5	6	6
9.6"	17.9+3	5	825	MB	J5	42	41
9.6"	18.5+3	5	316L	MB	V30	48	43

DNV GL has witnessed all trials and all scan interpretation. POD and vertical height sizing accuracy have been evaluated for all captured data, valid for all imperfection groups at different vertical positions in the weld. Weld imperfections has been categorised based on type and position in the weld as Region A (OD surface), Region B (Buried) and Region C (ID surface). The results for vertical imperfection heights at 90% POD at 95% confidence and height sizing accuracy are given in the table below. Sizing accuracy and POD has been derived in accordance with DNVGL-ST-F101:2017 [1] for general applicability for CRA applications. The conclusions of the qualification programme are summarised as follows:

- The Applus+ RTD IWEX system is in compliance with DNVGL-ST-F101:2017 [1] requirements.
- The IWEX procedure has demonstrated consistent performance with regards to stability and when operating at elevated temperatures up to 90°C, while the reference block is kept at ambient temperature. Repeatability refers to consistency in height estimates upon repeated scans.
- Consistency upon repeated scans has been documented, with variations in sizes of reference reflectors over 10 scans < ±0.5 mm.
- The AUT system is documented to reliably detect any imperfection down to 0.9 mm in vertical height in general, defined by a 90% POD value at 95% confidence level. The main results of the POD analysis are summarised in Table 1-2 below.

- Vertical height sizing accuracy is observed within the range -0.7 mm to +1.2 mm, defined as the 5% probability of under- and over-sizing. The main results of the POD analysis are summarised in Table 1-3 below.
- Imperfection through thickness depth estimate has been observed within the range -1.3 mm to +2.1 mm.

Table 1-2 Vertical imperfection heights of 90% POD at 95% confidence result summary

Evaluation Level	General
10% FSH	0.9 mm

Table 1-3 Vertical Imperfection Height sizing accuracy result summary

Category	# Observations	5% Probability Under Sizing	Mean	Standard Dev.
General	159	-0.7 mm	0.2 mm	0.59 mm
Region A	40	-0.8 mm	0.2 mm	0.61 mm
Region B	31	-0.4 mm	0.3 mm	0.44 mm
Region C	88	-0.8 mm	0.2 mm	0.62 mm
Region C*	76	-0.9 mm	0.2 mm	0.65 mm

* Only includes 3 mm CRA layer

Evaluation of qualification trials results have first of all been focused on demonstration of compliance with the requirements of DNVGL-ST-F101:2017 [1]. POD and vertical height sizing accuracy have been evaluated for general applicability.

These results are regarded valid for all future corrosion resistant alloy (CRA) girth weld projects, provided project specific prerequisites and certain prerequisites given in section 9.4 of this report are met. The qualified configurations are representative for a range of wall thicknesses up to 42 mm, and for pipes of diameter of 6" 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 corrosion resistant alloy (CRA) pipeline girth weld applications. CRA in this context mean all kind of alloys that improve corrosion resistance of the pipeline, but at the same time this introduces additional challenges for ultrasonic inspection due to anisotropy for ultrasonic wave propagation caused by coarse grain sizes. IWEX is an ultrasonic imaging technique, which is presently a 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 example the 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 the requirements of DNVGL-ST-F101:2017 [1]. The qualification programme is in full compliance with DNVGL-RP-F118 [2]. IWEX performance is evaluated as stability upon repeated scans, stability upon elevated temperature, detectability and vertical height sizing uncertainty. 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 programme.

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 [1] for future pipeline girth weld inspection projects upon pipeline owners discretion.

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 and discussion was undertaken during witnessing of the qualification work.

4 OBJECTIVES

The main objective of the qualification work has been to document the Applus+ RTD IWEX AUT system procedure [4,5] performance for CRA pipeline girth weld inspection applications according to DNVGL-RP-F118 [2] and the requirements of DNVGL-ST-F101 [1]. 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-F101:2017 [1] 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.

- Defect depth estimate 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.

Besides the requirements of DNVGL-ST-F101, the objective was to witness all the critical activities of qualification on site.

5 ABBREVIATIONS

AUT – Automated Ultrasonic Testing

CRA – Corrosion Resistant Alloy

CW – Clock Wise

CCW – Counter Clock Wise

EDM – Electrical Discharge Machining

FMC – Full Matrix Capture

IUT – Immersion Ultrasonic Testing

IWEX – Inverse Wave field EXtrapolation

POD – Probability of Detection

POR – Probability of Rejection

RT – Radiographic Testing

TOFD – Time of Flight Diffraction

TOFR – Time of Flight Reflection

FBH – Flat Bottom Hole

FSH – Full Screen Height

OD – Outside Diameter

ID – Inner Diameter

WT – Wall Thickness

MLE – Maximum Likelihood Estimator

ECA – Engineering Critical Assessment

HP – Hot Pass

SDH – Side Drilled Hole

SPA – Sampling Phased Array

6 DESCRIPTION OF QUALIFICATION PROCESS

6.1 UT Inspection of CRA material

Corrosion resistant alloys (CRA) are well known to impose specific challenges for ultrasonic inspection due to heterogeneous and anisotropic material grain structure playing an important role on the ultrasonic propagation at normal frequencies used upon inspection. The anisotropy is mainly related to a coarser grain structure than found in conventional carbon steel for pipelines. Anisotropy due to material grain size and preferential orientation is known to appear when the grain size is of similar dimension as the sound wave length (stochastic and geometric domains), and will cause effects such as ultrasonic wave scattering and beam skewing. Also the interface between Carbon Steel and CRA welding material forms a barrier, producing intrinsic reflections. As a result, inspection will be hampered by attenuation and a high noise level. Transversal waves (shear waves) are known to be less suitable for CRA inspection than longitudinal waves because of the wavelengths at useful frequencies for imperfection inspection. It should be emphasized that grain size and structure of CRA welds and layers will differ between different pipe configurations. Therefore, the material is regarded to be a critical parameter that influences the ultrasonic inspection performance, different from conventional carbon steel applications.

6.2 Applus+ RTD IWEX CRA AUT System Setup

The Applus+ RTD IWEX is an ultrasonic imaging technique. The technical details of the IWEX technique are described in the literature [5,6,7]. In short, IWEX 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 Full Matrix Capture (FMC) [8,9].

Full coverage of the weld is achieved when wave fields with origin from all parts of the weld are captured and processed. With IWEX this is ensured by back-calculation of several modes in parallel, which represent different beam paths of scattered signals. The application of ultrasonic testing on anisotropic CRA welds has inherent restrictions that applies equally to IWEX as for other ultrasonic testing methods like pulse echo UT. With IWEX, these restrictions determine which modes that can carry useful information for inspection. Direct modes, cross modes and tandem modes will always be included in a setup. Furthermore, since the ultrasonic anisotropy is material dependent, additional modes might provide useful information depending on applications of the procedure. Inclusion of these modes might improve the inspection for the specific cases, and this needs to be determined prior to use. For instance, there might be a difference in added value of inclusion of shear wave modes between pipe weld configurations with metallurgical bonded clad and configurations with weld overlay clad.

IWEX introduces a 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. The main limitation for applied sensitivity with the CRA materials is normally the signal-to-noise level, and the sensitivity of the different IWEX modes is set using the bare noise level as the reference. In practice, the background noise level is set to 10% in the presentation of the results. This ensures that the different modes are applied at the highest practical sensitivity, without compromising the inspection with an impractically high level of noise. As a result of this, the reference reflector responses might vary between the modes. Further details with reference block is provided in paragraph 6.2.1.

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 the response of reference reflectors in a reference block is still suitable for this purpose.

The procedure is restricted to the AUT setup parameters provided in the Table 6-1 below. These are also essential parameters for the results presented in this report.

Table 6-1: Qualified Probe Range

Parameter	Range
PA & Conventional probe frequency:	1 MHz to 7.5 MHz
ToFR probe frequency:	6 MHz to 15 MHz
PA probe element pitch:	0.85 mm to 1.5 mm
PA probe height (passive aperture):	15 mm to 25 mm

6.2.1 Reference block

A project specific reference block has to be made from the same pipe as the production pipe, with or without a project specific weld. This qualification covers both cases. The reference block design has been specifically developed for IWEX and accommodates the modal concept of the imaging methods. This design includes one dedicated reference reflector for each of the processed modes in the setup. The reflector responses are used to align the sensitivity 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 as 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. For production scanning, the reference block is utilised to confirm a stable setup. The IWEX reference block design includes the following reference reflectors:

Table 6-2: IWEX CRA reference block reflectors. Modes apply for both longitudinal and shear waves, or a combination of these.

Mode	Side	Reflector Orientation Towards the Array	Comment
IWEX Direct	US/DS	3 mm FBH at depth ~4 mm from ID Surface	Direct mode
IWEX Skip	US/DS	3 mm FBH at depth ~1/3 WT	Skip mode
IWEX Tandem	US/DS	3 mm FBH at depth ~2/3 WT	Tandem mode, half skip
IWEX Tandem round trip	US/DS	3 mm FBH at depth ~1/3 WT	Tandem mode, over skip
IWEX cross	1	3 mm FBH at depth 2 mm from ID Surface	Direct Cross mode
IWEX cross skip	1	3 mm FBH at depth 2 mm from OD Surface	Skip cross mode
Creep Weld bevel		1 mm x 10 mm notch OD surface	at weld bevel position
Creep Weld Toe	US/DS	1 mm x 10 mm notch OD surface	at weld toe position

In addition, the reference blocks used for the qualification included reflectors for time-of-flight reflection (TOFR). These were 5 mm OD surface notch at weld centreline position and 3 mm ID surface tip notch (60° nose angle) at weld centreline position.

Other reference block designs were used for some of the trials within this qualification. These were all based on the reference block design for the Applus+ RTD Rotoscan CRA AUT setup and included a substantially larger number of reflectors than indicated in Table 6-2 above, to comply with zonal inspection. The available reflectors were used to evaluate sensitivity for direct modes. Additional reflectors were included in these blocks in order to provide applicable reflectors for all modes, i.e the skip modes, tandem modes and cross modes.

Reference blocks were made from the same pipe material as the welds to be inspected, with and/or without a weld which was/is purely based upon Company preference. Both are considered qualified by DNV GL.

6.3 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 6-3 have been performed by Applus+ RTD, and fully witnessed by DNV GL:

Table 6-3: Qualification Trial Summary

Trial	Content
Repeatability, 5G	25.6 mm+3 mm metclad WT reference block in 5G position, 10 scans each with reference block centre at 12 and 6 o'clock positions.
Repeatability, 2G & 6G	25.6 mm+3 mm WT metclad 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	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. Scanned weld of configuration 12.75" OD and 25.6 mm+3 mm WT metclad.
Temperature trials	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 90°C. Scanned weld of configuration 12.75" OD and 25.6 mm+3 mm WT metclad.
Reliability trials, J-bevel	Scanning of 4 defective welds J5 of 12.75" OD x 19.8+3 mm WT weld overlay CRA, both clockwise (CW) and counter-clockwise (CCW). Scanning of 4 defective welds J5 of 12.75" OD x 25.6+3 mm WT metallurgical bonded clad, both clockwise (CW) and counter-clockwise (CCW). Reference block scans prior to and after each weld scan.
Reliability trials, J-bevel	Scanning of 2 defective welds of 355.6 mm OD x 20.6+3 mm WT metallurgical bonded clad, both clockwise (CW) and counter-clockwise (CCW). 1 weld J5 and 1 weld V-bevel configurations. Reference block scans prior to and after each weld scan.
Reliability trials, Partial welds	Scanning of 5 defective partial welds (Root and hot pass) J6 of 9.6" OD x 17.9+3 mm WT metallurgical bonded clad, both clockwise (CW) and counter-clockwise (CCW). Reference block scans prior to and after each weld scan.
Reliability trials, V-bevel	Scanning of 5 defective welds V30 of 9.6" OD x 18.5+3 mm WT metallurgical bonded clad, both clockwise (CW) and counter-clockwise (CCW). Reference

block scans prior to and after each weld scan.

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

- 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

6.4 Trial welds and induced imperfections

6.4.1 Defective Welds

The full DNVGL-RP-F118 scope was performed with 19 welds of various wall thicknesses, material and weld configurations. The programme was executed over a long period with 4 separate trial sessions in order to be able to include the different weld configurations. The following considerations were made for the full scope:

- Performance of IWEX is regarded insensitive to weld bevel configuration and bevel angle in terms of anticipated imperfection orientations and imperfection types. The main part of the programme was focused towards narrow gap J-bevel weld configurations (mainline welds), as this is considered as the main application for the procedure.
- Both weld configurations with metallurgical bonded clad and weld overlay were included in the scope in order to document validity for different material configurations. The number of observations is >29 for both configurations.
- To cover the full variation of weld bevel configurations within the qualification programme, 5 V-bevel welds were included with >29 observations.
- The qualification scope was designed to qualify IWEX as a stand-alone method for inspection of partial welds in addition to full weld inspection, i.e. inspection of only root and hot pass. 5 partial welds with in total >29 observations have been included in the scope for this purpose.

Details of all welds are provided in Table 6-4 below. The number of confirmed indications refers to the number of imperfections reported in the weld with IWEX, that were found to be useful for qualification purpose.

Table 6-4: Defective weld details

Weld OD	WT [mm]	No. welds	CRA Material	CRA type	Bevel configuration	No. Intended Imperfections	No. Confirmed Imperfections
12.75"	19.8+3	4	UNS S31603	Weld overlay	J5	38	36
12.75"	25.6+3	4	UNS S31603	MB	J5	36	35
14"	20.6+3	1	625	MB	J5	6	6
9.6"	17.9+3	5	825	MB	J5	42	41
9.6"	18.5+3	5	316L	MB	V30	48	43

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.

6.4.2 Weld Region Categories

DNV-RP-F118 [3] Appendix A gives guidelines of the recommended numbers of imperfections within different parts of the welds. The weld is divided into three or four parts, root, (hot pass), fill and cap, with a recommended number of 29 imperfections within each part. For the cap, the selection of imperfections shall include both surface breaking imperfections and sub-surface imperfections. A sub-surface cap imperfection is defined here as an embedded imperfection that is restricted to 5 mm from the outer surface (cap), i.e. the lower extremity of the imperfection is equal to or less than 5 mm from the outer surface.

DNV-RP-F118[3] includes no direct requirements for imperfections in CRA pipeline girth welds. The division into four categories is regarded relevant to CRA welds as well with regards to recommendation of imperfections selected for macro sectioning. The need for the corrosion resistance layer adds criticality to the weld root area, which results in tighter requirements for critical imperfection heights in this area than for conventional carbon steel pipelines. According to the criteria of the 2017 edition of DNVGL-ST-F101[2], the system shall demonstrate detection of imperfections of 1 mm height in this area.

For data analysis, the weld has been categorised in 4 regions for independent analysis to allow the results to be applied independently for surface area and buried parts of the weld. The categories used for the analysis are as follows:

- Region A: Area within 5 mm from OD surface
- Region B: Area of buried parts of the weld between category A and C
- Region C: Area within 4.5 mm from ID surface
- Region C*: Area within 3.0 mm from ID surface (i.e. only CRA layer)

The Region C category includes the CRA layer of 3.0 mm + the area up to 1.5 mm above clad/line thickness. This is based on the DNVGL-ST-F101:2017[2] Appendix E Table E-1 and Table E-2, which specifies acceptance criteria for root imperfections in the area up to 3 mm from ID surface and up to 1.5 mm above clad/line thickness. This means that acceptance criteria for the root applies to the area up to 4.0 to 4.5 mm from the ID surface, depending on the CRA layer thickness, since the thinnest allowable CRA layer thickness according to DNVGL-ST-F101 [1] is 2.5 mm. Region C* category includes only the CRA layer without the 1.5 mm area above. With regards to the Region A, DNVGL-ST-F101[1] Appendix E Table E-1 note 6 gives the requirement for surface interaction. Surface interaction is assessed based on ligament and imperfection height. In order to cover the area where surface interaction is expected to occur, assuming a 3 mm weld pass height, the Region A is defined as the uppermost 5 mm of the weld. Imperfections are assigned to the Region A category when the macro sections documents that the lowermost part of the imperfection is within 5 mm from the OD surface.

With regards to inspection at the OD surface, useful modes will depend on attenuation in the CRA layer. For cases where use of shear wave over skip mode is restricted, the inspection in the OD surface area will be ensured by the creeping wave probes. For these cases the creeping wave channels can be

considered as a main source of information from the weld area close to the OD surface down to about 5 mm.

6.4.3 Induced Imperfections Summary

The macro sectioning plan included 96 positions for indications in the Region C (both surface breaking and in CRA layer region), 34 positions of indications Region B in the weld and 40 positions for indications in the Region A area.

In addition, a total of 42 weld positions in the partial weld were macro sectioned, 39 of them within Region C and 3 considered to be within Region B.

Upon review of the macro sections for the actual position of the imperfections in the weld, some of the observations were excluded for analysis, other re-categorised to reflect actual position and type. 5 observations were excluded due to reasons specific to the affected observations, the considerations have been assessed and accepted by DNV GL. 6 observations were added to the dataset upon macro section review as detection borderline indications, relevant for the POD analysis. These 6 observations have not been included in any evaluation of height sizing accuracy.

2 volumetric observations were removed from the evaluation for POD and sizing accuracy evaluation, both from Region B. This has been justified by the fact that the height sizing of larger porosity clusters or cavities buried in the weld is not necessarily fully representative to height sizing of planar flaws. The detection is confirmed for these indications. The number of observations in the POD analysis amounts to 165, 159 for sizing accuracy evaluation. The distribution in categories is presented in the Table 6-5 below:

Table 6-5: Total number of observations in the analysis

	Region A	Region B	Region C	Region C*	Volumetric
POD Observations	41	35	89	77	2
Sizing Accuracy Observations	40	31	88	76	2

Positions for macro sectioning were marked up on the weld using the IWEX scanner, to identify 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 taken 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 various laboratories for different weld configurations (Exova Houston, Element Rotterdam, BKW Bremen). Prior to macro sectioning, the ID-number for the macro and the position for each macro section were hard stamped on 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.

A compilation of the qualification data can be found in the appendices.

6.5 Applus+RTD IWEX Partial Weld CRA AUT

6.5.1 Partial Weld CRA AUT Setup

The IWEX CRA AUT procedure for partial weld inspection is designed to provide intermediate inspection of the root and hot pass of the weld, i.e. Region C. The procedure is identical to the full weld procedure described in paragraph 6.2, except for the following modifications:

- The AUT setup includes only modes covering the ID surface up to the first fill welding passes above the CRA layer. This means that the round trip tandem mode and cross over skip mode are not included, the same applies to the creeping wave probes.

6.5.2 Partial Weld Trial considerations

Except for the weld design and removal of irrelevant channels in the partial weld AUT setup, all other essential variables for the IWEX CRA AUT procedure remain the same as with full weld inspection, including reference block design, all AUT hardware and general AUT procedure. The qualification programme has been focused on providing results in height and depth sizing accuracy and POD, to document adequacy for stand-alone AUT inspection of partial welds.

The part of the trials including the partial weld AUT setup was focused on inspection performance in Region C only. The possible impact of the un-fused bevel in the partial welds was considered to mainly be for buried imperfections, in particular above the CRA layer. Therefore, the seeded defect welds were designed to include mainly buried imperfections within Region C. In order to capture inspection performance in the full Region C, including the area within 1.5 mm above the CRA layer, intended imperfections were located a minimum of 1.5 mm above the CRA layer upon welding. Some of these indications were macro sectioned. The trials were designed to fulfil the requirements for a full AUT validation according to DNVGL-RP-F118[2] and DNVGL-ST-F101:2017[1], i.e. minimum 29 independent observations in Region C.

6.6 Analysis Extent

6.6.1 Repeatability Consistency Trials

Consistency trials with repeated scans on the reference block were performed on 5G, 2G and 6G pipe positions as required in DNVGL-ST-F101:2017 [1] Appendix E. The reference block for the 12.75" OD x 19.8 + 3 mm WT Weld overlay pipe was used for this trial. The weld overlay configuration was selected in preference to a configuration with metallurgical bonded clad as it is regarded as the most challenging configuration in terms of stability of repeated scans.

Ultrasonic imaging is not considered as amplitude-based in 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 ± 2 dB criterion has therefore potentially another meaning within an IWEX image, and is considered as less relevant than with conventional UT. Regardless of this, the ± 2 dB criteria was employed for this qualification with the maximum intensity of reference reflector image upon repeated scans to document compliance with DNVGL-ST-F101:2017 [1] requirements. The sensitivity 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.

6.6.2 Band Offset Trials

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 a 12.75" OD x 25.6+3 mm WT metallurgical bonded clad (UNS S31603) weld, weld number 3 with J5 bevel preparation. 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 6-6 below.

A validation trial series of 3 scans with ± 3 mm band offset was performed.

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

ID	Scan Position	Length [mm]	Depth [mm]	Height [mm]
1	51	4.8	10.3	1.9
2	92	47.8	30.2	2.6
3	203	47.4	30.2	2.3
4	428	22.3	2.9	1.6
5	576	20.3	14.7	2.6
6	936	25.6	6.3	2.0

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.

6.6.3 Temperature Trials

The elevated temperature trial was performed with a pipe temperature of 90 °C, with the same nominated weld as with the band offset trials of configuration; 12.75" OD x 25.6+3 mm WT metallurgical bonded clad (UNS S31603), weld number 3 with J5 bevel preparation. The imperfections used for evaluation are thus given in Table 6-6. The effect of elevated temperature was assessed as deviations within the repeated scans in measured flaw height of the 6 selected flaws.

Heating was performed by gas heaters. Temperature was confirmed on the weld and pipe prior to scanning.

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 6.6.1, the impact on imperfection response at elevated temperature has been evaluated as deviations in sized imperfection heights.

6.6.4 Wall thickness Variations

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 are 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.

The functioning of the Applus+ RTD IWEX wall thickness variation software module was successfully demonstrated and documented as a part of the qualification programme for the Applus+ RTD IWEX applied for carbon steel applications [10]. These results are equally valid when IWEX is used on CRA applications. The wall thickness variation software module was also applied upon all scanning within the scope of the present qualification.

6.6.5 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:

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

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 in 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.

6.6.6 85% POR at 95% Confidence

The 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 6.6.5 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 as the 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.

6.6.7 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. The straight forward calculation with this approach gives tolerances of $\sim \mu \pm 1.65\sigma$, where μ is the mean value sizing inaccuracy, and σ is the standard deviation. 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.

6.6.8 Imperfection Depth Position Estimate Accuracy

The accuracy in the AUT reported depth estimate compared to imperfection depth measured on the macros has been evaluated the same way as for defect height sizing. For the present analysis the tolerance for less than 5% "under-sizing" is determined assuming the normal distribution. In AUT reports, the reported imperfection depth is the vertical distance from the outer surface to the lowest part of the imperfection. It is not considered as fully correct to use terms like "under-sizing" and "over-sizing" about depth estimate accuracy. A negative value of the tolerance indicates that imperfection location is deeper in the weld than AUT reports (i.e. macro depth is closer to ID surface than AUT reported depth). The opposite applies for a positive value.

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 $\sim \mu \pm 1.65\sigma$.

6.6.9 Imperfection Length Sizing Evaluation

Imperfection length sizing accuracy has been evaluated on reference reflectors in reference block scans, and is presented as beam spread. Scans of the reference block of 9.6" OD x 18.5 mm + 3 mm 316L metallurgical bonded clad (for V-bevel configuration) have been used for this evaluation, as this block was designed for IWEX exclusively with dedicated reflectors for the various applied modes. Beam spread has been evaluated at a fixed reporting level of 20%, according to the specific procedure [4].

The results of this analysis is indicative of how indications appear in the IWEX scans, and does not necessarily indicate the accuracy of length sizing of imperfections in welds. Possible over-sizing due to beam spread is taken into consideration in the procedure [4]. Furthermore, it should be noted that the procedure [4] specifies that length sizing shall be with either 6dB drop method or with a fixed recording threshold. The different modes might show up with different sensitivities in the scans due to physical limitations and the way the sensitivity is set, so variations in beam spread among the different modes might happen.

6.6.10 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 $1.0\text{mm} - 0.3\text{mm} = 0.7\text{mm}$. 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 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. For IWEX, compliance with best workmanship approach of DNVGL-ST-F101 should be related to the results in this report, to ensure compliance to requirements of DNVGL-ST-F101, sub-chapter E.5.4 and Table E-1. Vertical height sizing accuracy shall be within $\pm 1\text{ mm}$. With regards to 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.

6.7 Analysis Considerations

Inspection and detection involves a combination of the available information in the scanning data.



Height sizing has been performed according to the procedure [4]. The order of the modes to be used for sizing is specified, and the preferred method is based on tip diffractions. If tip diffracted signals cannot be identified, height sizing will be performed by amplitude method (6 dB drop-off). Information captured on both sides of the weld (US/DS) usually needs to be applied for interpretation. It was observed that responses from an imperfection appeared stronger in the relevant mode (usually direct) at the opposite side of the weld, i.e. after inspection through the weld.

The modes included in the IWEX setup varied between the different weld configurations. This was done in order to ensure as efficient an inspection as possible. In principle, all modes with possible value for CRA inspection could have been included for scanning in general, however this will be at the expense of scanning speed. The option to only include modes in the setup that demonstrates added value to the inspection performance needs to be available in order to allow the most efficient inspection. For the IWEX scans within this qualification differences apply to weld configurations with weld overlay and metallurgical bonded clad. For configurations with welded overlay, it was confirmed that the overlay weld restricted use of shear wave modes over skip due to excessive attenuation. Due to this, the number of modes used for the weld overlay configuration was lower than with configurations with metallurgical bonded clad. It can be noted that the restriction in use of shear wave inspection over skip in overlay welds applies to ultrasonic inspection in general, and is not restricted to IWEX inspection of these welds.


Use of shear skip longitudinal tandem mode was observed to be a valuable addition for inspection of weld configurations with metallurgical bonded clad with regards to height sizing capabilities. This mode was confirmed to provide coverage in Region A, in addition to the creeping wave channels. For weld configurations with weld overlay CRA, Region A will be covered by creeping wave channels for the ~3 mm area closest to the OD surface.

For the analysis specific for Region C, results are derived from a merged dataset with both full weld observations and partial weld observations. This approach is considered justified by the corresponding results observed for the full weld and partial weld data sets.

The full set of data has been split for evaluation of IWEX performance of inspection of partial weld. Only observations from partial welds has been evaluated for this analysis, i.e. configuration 9.6" OD x 17.9 mm + 3 mm WT, metallurgical bonded clad. As a reference for direct comparison, the same analysis have been done for all the Region C indications in the full welds.

Volumetric imperfections with main detection by volumetric channels and TOFR have been omitted for the analysis, this includes 1 buried porosity cluster and 1 large pore/cavity (Region B). This is based on considerations with regards to height sizing. The ultrasonic response and height sizing principles of porosity clusters differs significantly from planar flaws and it is considered as challenging to accurately confirm the vertical height of a porosity cluster by macro sectioning. These imperfections are considered to not make any impact to the general POD results as they are all well detected. They are still kept outside the general analysis in order to keep the similar imperfection sample for POD and sizing accuracy analysis.

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 the general noise level in the images (when disregarding artefacts), i.e. 10%. The reasoning for using the general noise level for POD evaluation has been to be able to capture the full range of signals that are utilised for detection with the procedure [4]. Recording levels of intensity/amplitude levels down to 20% has also been applied for analysis, however it was confirmed that the dataset includes very few



indications within the range 10%-20%. The distinction between detected (hit) and disregarded (miss) has been done by evaluation of the intensity in the strongest mode against the recording threshold.

Furthermore, in order to be able to estimate a POD using the applied model, some information about the imperfection sizes at the detection border line has to be included in the analysis. Imperfections with vague responses and appearance in the scan were identified upon review of macro section reports for this purpose. In order to more accurately estimate the POD, these will be considered as "missed observations". In order to further expand on the POD estimation the detection border line of the system, these have been denoted as "non-reported" even for instances where these in fact were detected by the system. This has been done to be able to provide some conservative estimates of the overall POD performance. The criteria used to denote an observation "border line" has been insignificant or no response in any of the applied inspection modes.

A generic POR analysis has been performed for the range of rejection imperfection heights from 0.8 mm to 1.8 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 even up to 4.0 mm rejection size, however the analysis results above the evaluate range appeared to be obscured by some systematic over-sizing of certain types of imperfections in the height size range 2.0~2.5 mm. The analysis results appear as excessive and misleading due to this, and are therefore not presented in this report.

A majority of the qualification data has been interpreted independently by two operators, in order to confirm robustness in Applus+RTD IWEX interpretation rules and to ensure compliance with DNVGL-RP-F118 section 4.3 requirements. This applies to all welds with the 12.75" configuration and all welds with the 9.6" V-bevel configuration. The second operator has not been the same person for both the 12.75" and 9.6" configurations.

Height sizing and depth estimate inaccuracy 5% probability against under-sizing has been calculated as $\mu-1.65\sigma$.

7 QUALIFICATION RESULTS

7.1 Elevated Temperature Trial Results

The elevated temperature trial scans show good consistency between scans at ambient temperature and scans at elevated temperature. This is illustrated in Figure 7-1, which includes the AUT measurements of height of the selected imperfections in the nominated test weld 3 at an elevated temperature at above 90°C. 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. More details about the trials are found in Appendix B.

The time for each cycle, including heating of the pipe with a gas burner, one calibration scan and one weld scan, was kept at about 6.5 minutes on average (pipe dimension 12" OD x 28.6 mm WT)

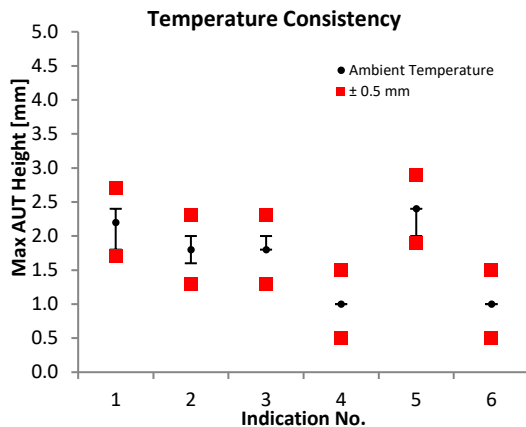


Figure 7-1: Elevated temperature repeatability and ambient scan, defective welds. Indication number refers to Table 6-6.

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.

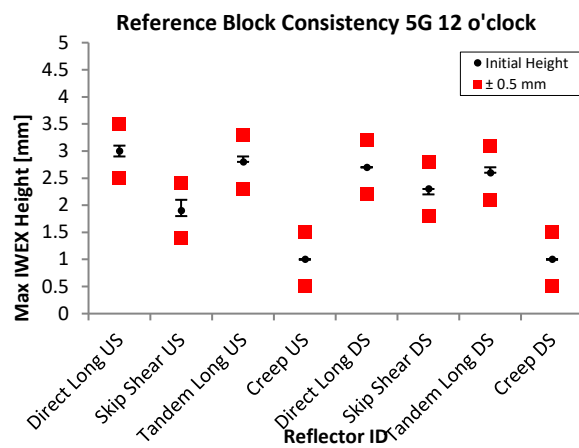
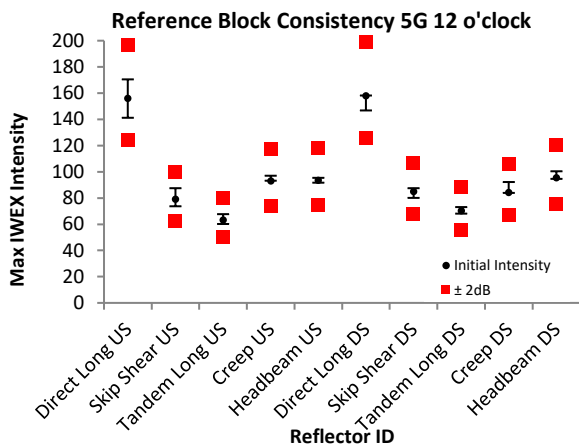


Figure 7-2: Consistency trial results, 10 scans with the reference block at 5G position, 12 o'clock start position.

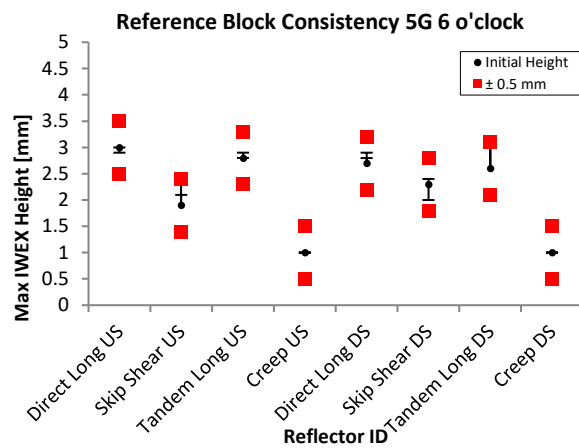
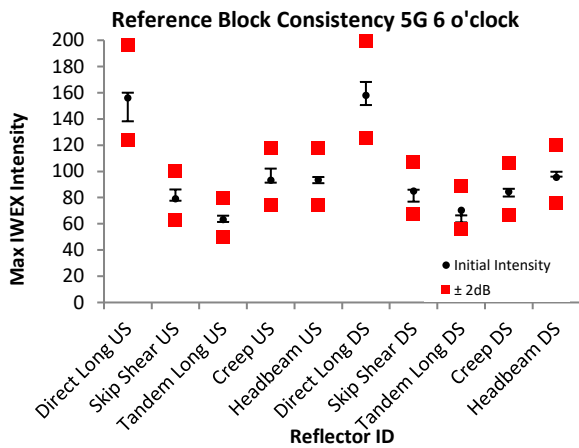


Figure 7-3: Consistency trial results, 10 scans with the reference block at 5G position, 6 o'clock start position.

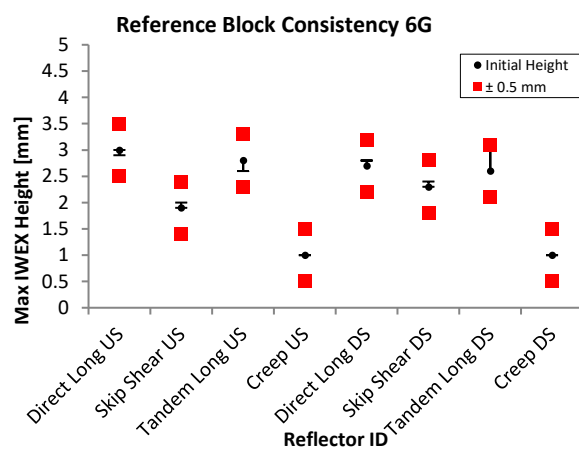
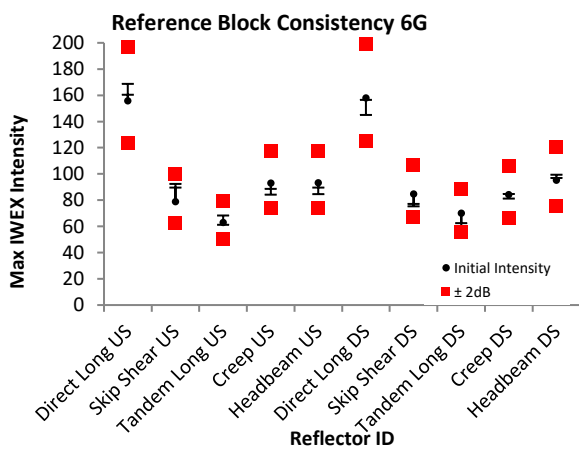


Figure 7-4: Consistency trial results, 3 scans with the reference block at 6G position.

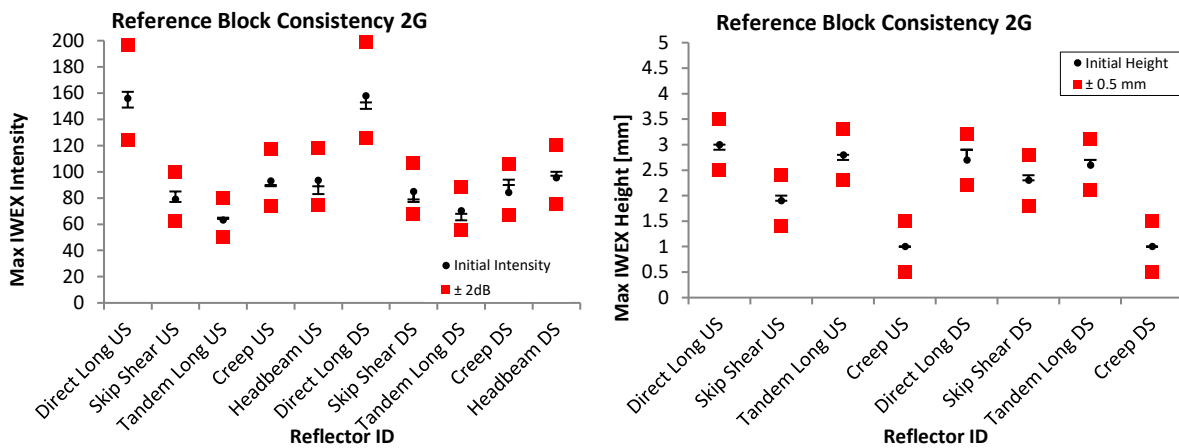


Figure 7-5: Consistency trial results, 3 scans with the reference block at 2G position.

7.2.2 Band Offset

The series of band offset scans shows that deviations in maximum AUT measured height from 6 imperfections in 12.75" OD x 25.6 + 3 mm WT test weld 3 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 ± 3 mm. It is concluded that band offset has no impact on IWEX performance. The results are illustrated in Figure 7-6. Details of the trials are provided in Appendix A.

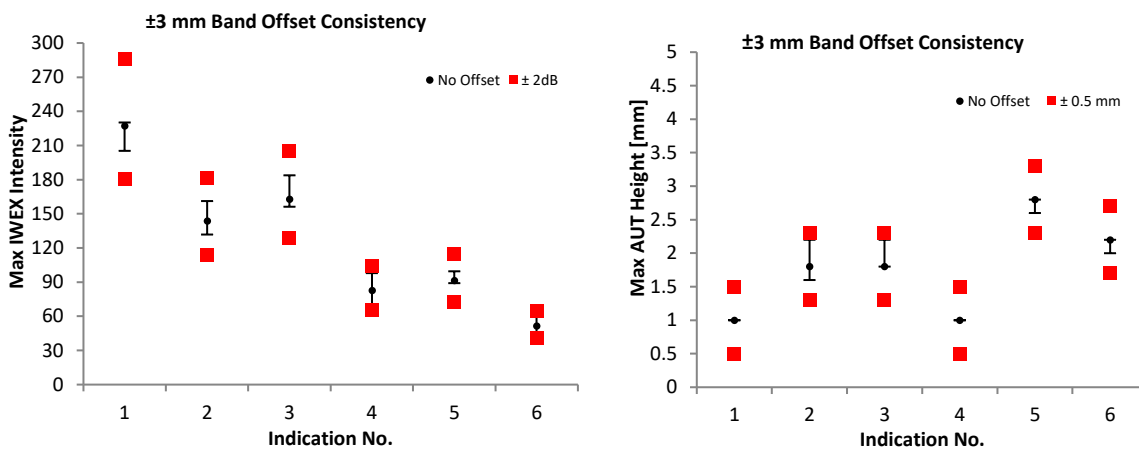


Figure 7-6: Band offset trials results for band offset of ± 3 mm.

7.3 Detectability (POD and POR)

The results from the detectability analysis for general applicability are summarised in Table 7-1 below. Further details and curves are provided further below.

Table 7-1: Summary of 90%|95% POD Analysis Results

Evaluation Level	General
10% FSH	0.9 mm
20% FSH	1.0 mm

Figure 7-7 shows the general Probability of Detection (POD)-curve for imperfection observations at all depths of the weld as accounted for in paragraph 6.4.3. In total 165 independent observations are included.

The analysis shows the imperfection height corresponding to a 90% POD at 50% confidence level at 0.8 mm, which is the actual fit to the present results. The 90% POD imperfection height with 95% confidence is at 0.9 mm. The results are valid and applicable for all parts of the weld, i.e. Region A, Region B, Region C and Region C*.

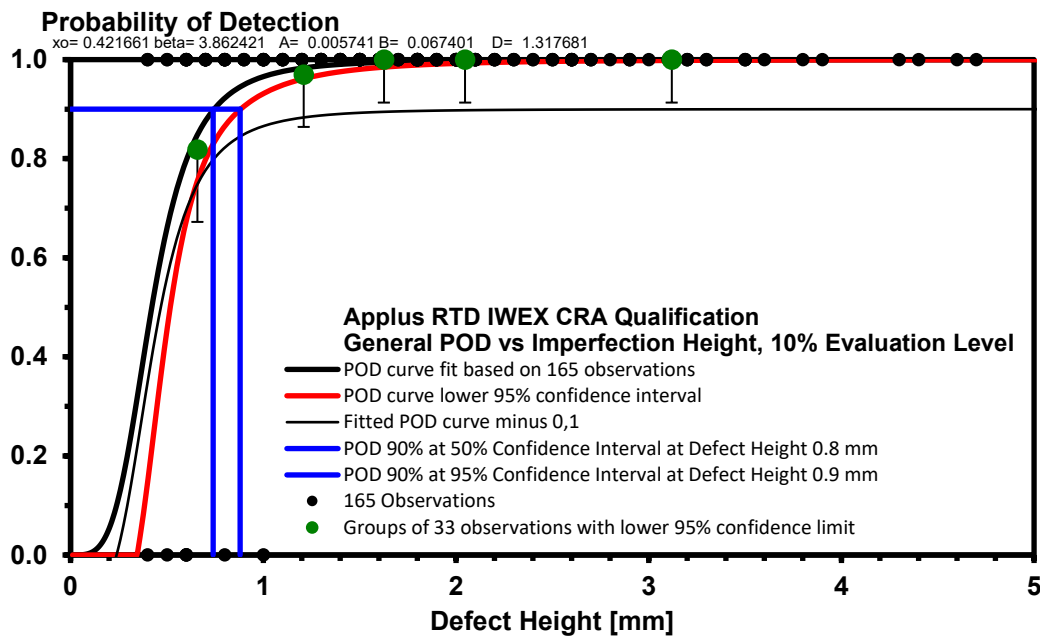


Figure 7-7: POD-curve, general detection. 90%|95% POD indicated.

Figure 7-8 shows the POR curve corresponding to a 1.0 mm rejection threshold of IWEX AUT reported imperfection height for all parts of the weld. The 85% POR imperfection height with 95% confidence is estimated to be 0.9 mm.

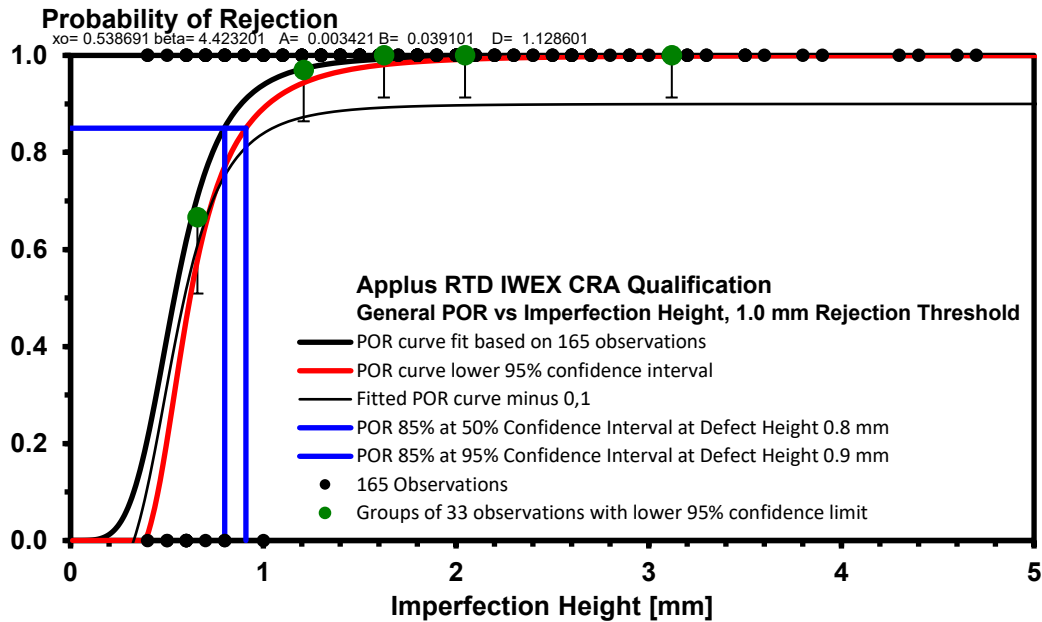


Figure 7-8: POR-curve, general detection with a 1.0 mm imperfection height rejection threshold. 85%|95% POR indicated.

POD analysis has been performed at several evaluation levels, the results are summarised in Table 7-1. The calculated 95% confidence bands for evaluation levels of 10% and 20% are plotted in Figure 7-9 below.

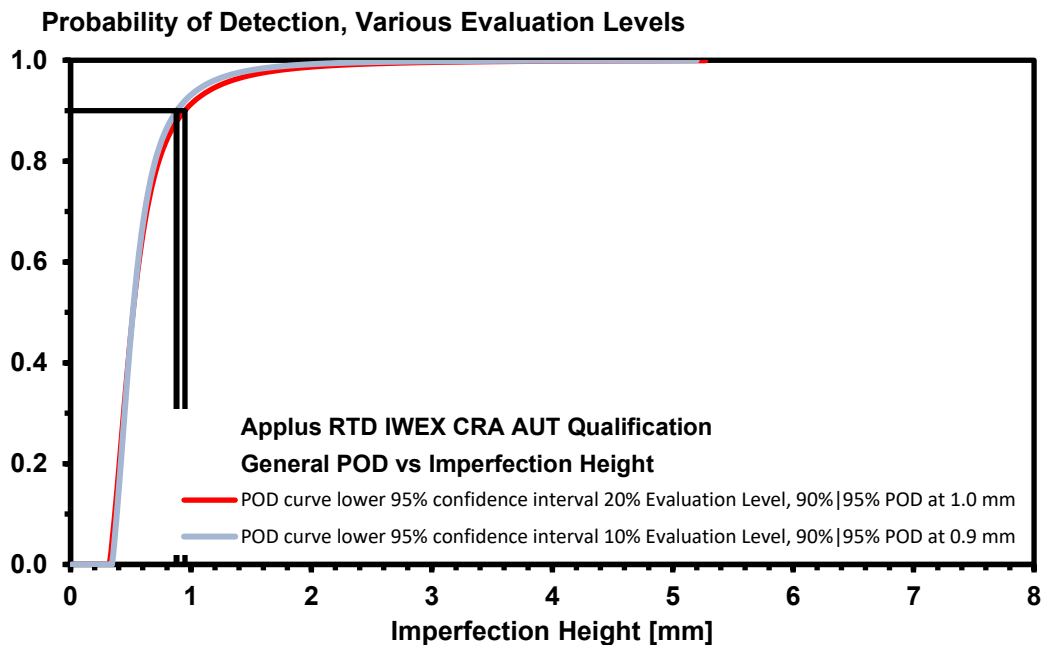


Figure 7-9: The general 90% POD height at 95% confidence for different evaluation levels.

7.4 Imperfection Height Sizing Accuracy

The imperfection height sizing results are summarised in the Table 7-2 below.

Table 7-2: Summary of height sizing accuracy analysis results

	General	Region A	Region B	Region C	Region C*
5% Probability Under Sizing	-0.7 mm	-0.8 mm	-0.4 mm	-0.8 mm	-0.9 mm

The overall distribution of imperfection sizes within the data is showed in Figure 7-10 below.

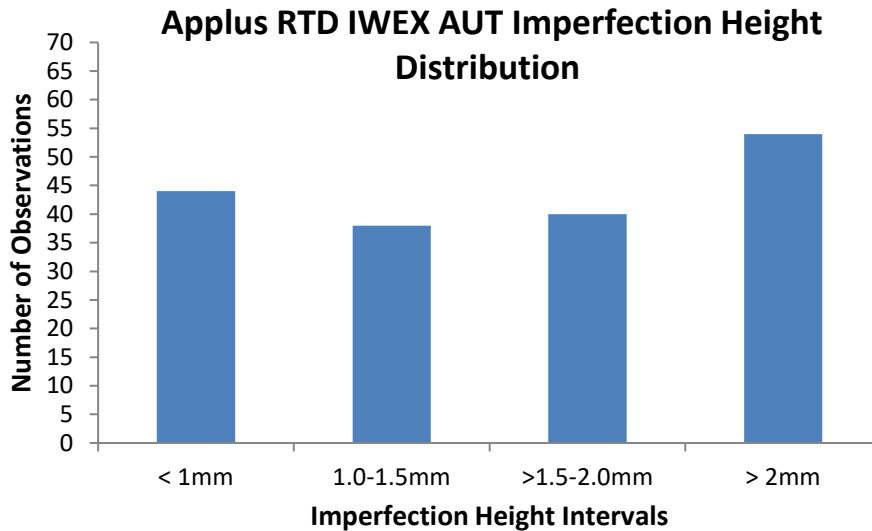


Figure 7-10: Imperfection height distribution in general for the imperfections included in the analysis.

7.4.1 General Height Sizing Accuracy

The general height sizing accuracy (the 95% limit against under-sizing) is estimated to -0.7 mm, Figure 7-11. The mean height sizing error is estimated to 0.2 mm over sizing, with a standard deviation of 0.59 mm. The same sample of imperfections as used in the POD analysis is included in the height sizing accuracy evaluation.

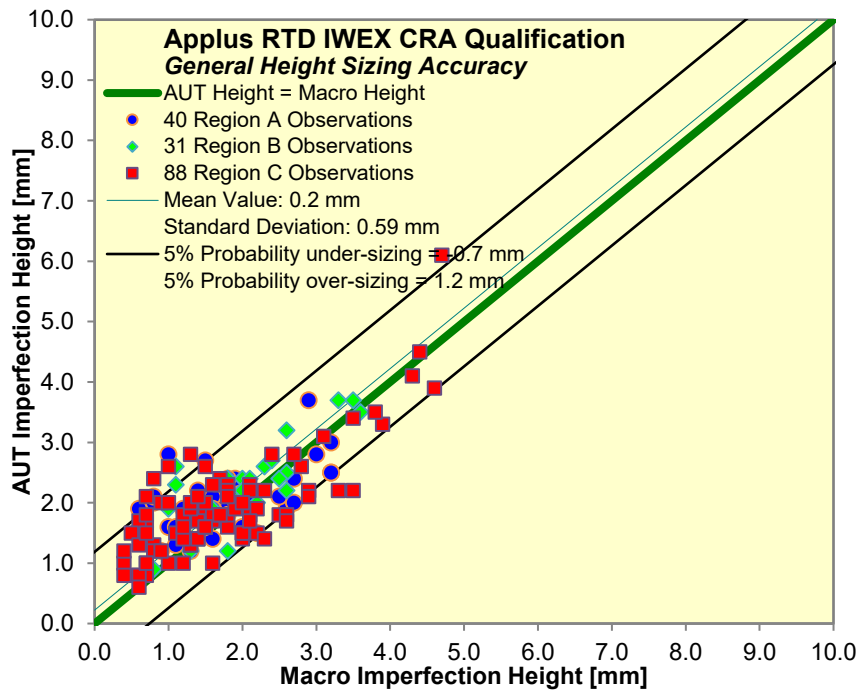


Figure 7-11: General height sizing accuracy plot.

7.4.2 Region A Height Sizing Accuracy

In total 40 independent imperfection observations have been included in the analysis for sizing accuracy in the OD surface area. For the OD surface imperfections investigated, a mean height sizing error of 0.2 mm over sizing, with a standard deviation of 0.61 mm were calculated. The 95% limit against under sizing is estimated to -0.8 mm, Figure 7-12.

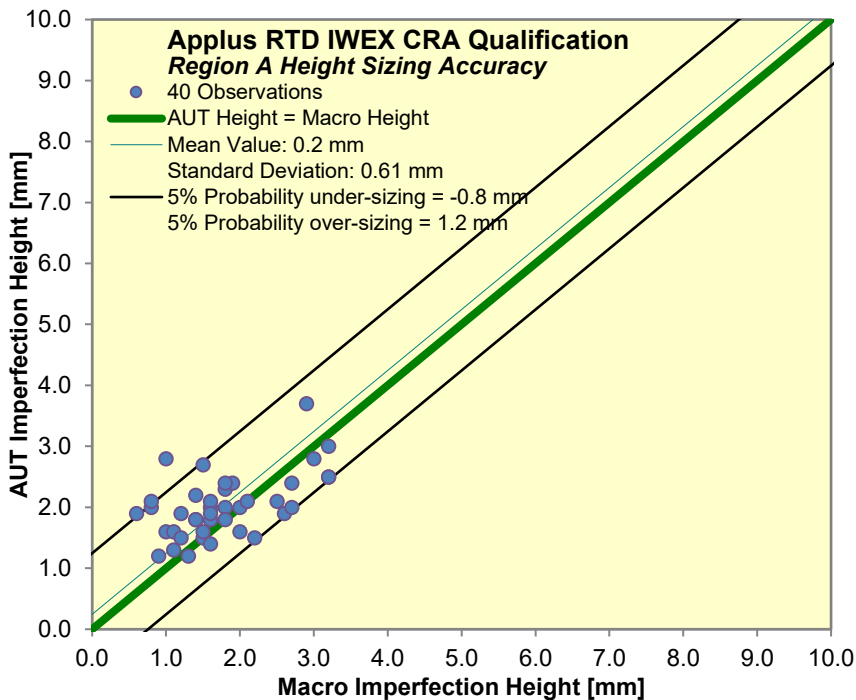


Figure 7-12: Height sizing accuracy for Region A.

7.4.3 Region B Height Sizing Accuracy

The buried category comprises of 31 independent imperfection observations detected at the buried parts of the weld. For the buried imperfections investigated, there is observed a mean height sizing error of 0.3 mm, with a standard deviation of 0.44 mm. The 95% limit against under-sizing is estimated at -0.4 mm, Figure 7-13.

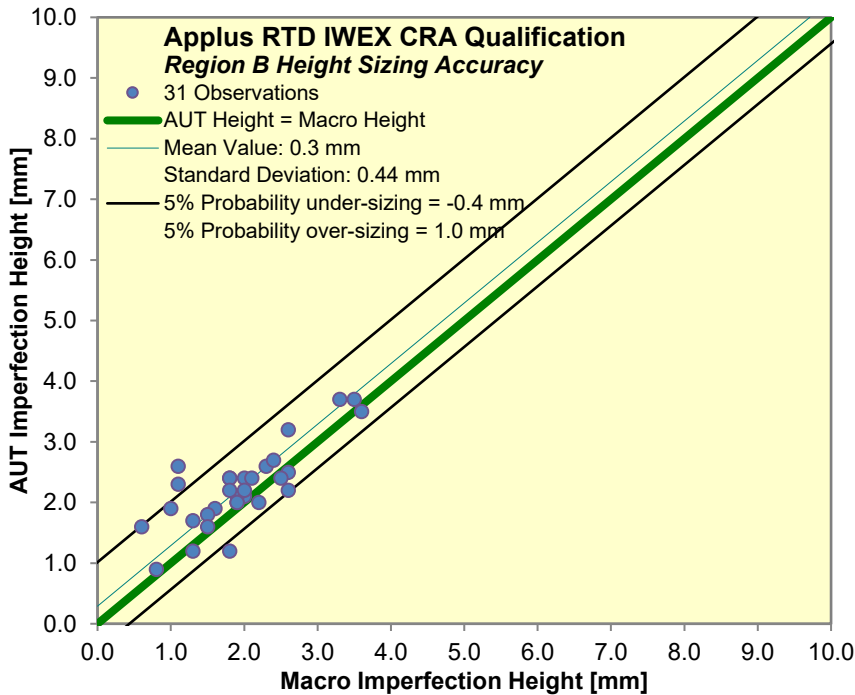


Figure 7-13: Height sizing accuracy for Region B.

7.4.4 Region C Height Sizing Accuracy

The Region C category includes 88 independent imperfection observations, both surface breaking and buried in the CRA layer area. A mean height sizing error of 0.2 mm was observed, the standard deviation was 0.62 mm. The 95% limit against under-sizing is estimated to -0.8 mm under-sizing, Figure 7-14.

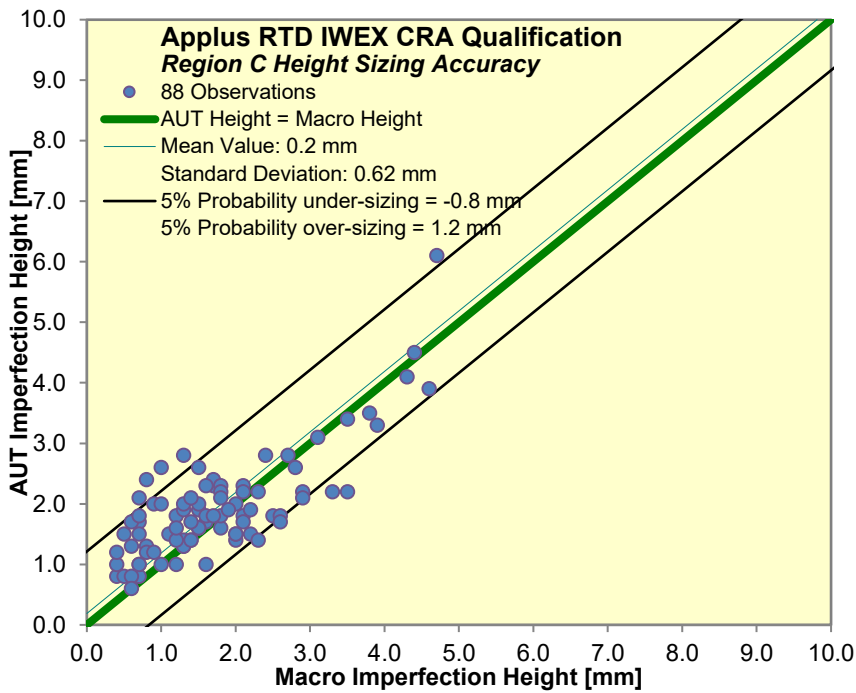


Figure 7-14: Height sizing accuracy plot for Region C.

7.4.5 Region C* Height Sizing Accuracy

The Region C* category includes 76 independent imperfection observations, both surface breaking and buried in the CRA layer area. A mean height sizing error of 0.2 mm was observed, the standard deviation was 0.65 mm. The 95% limit against under-sizing is estimated to -0.9 mm under-sizing, Figure 7-15.

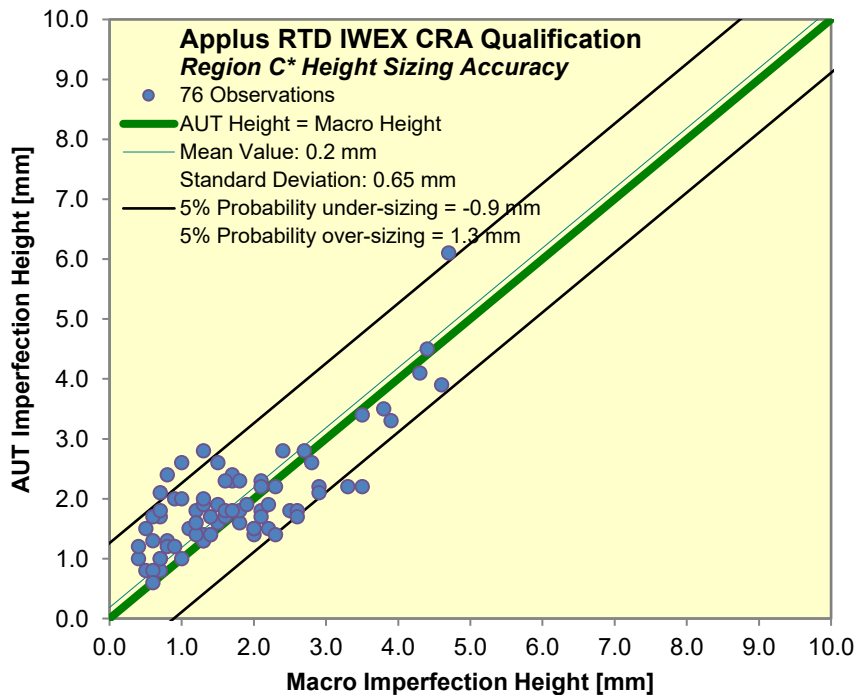


Figure 7-15: Height sizing accuracy plot for Region C*.

7.5 Length Sizing Accuracy

Accuracy in length sizing has been evaluated as observed beam spread for reference reflectors. Beam spread has been evaluated at an evaluation threshold of 20%. The observed beam spreads are presented in Table 7-3.

Table 7-3: Observed values, reference reflector beamspread

Mode	Observed beamspread
Direct Longitudinal	4.4 mm
Skip Longitudinal	3.1 mm
Tandem Longitudinal	2.2 mm
Direct Shear	1.3 mm
Skip Shear	4.0 mm

It shall be noted that this beam spread will be taken into account upon length sizing, according to the inspection procedure [4].

7.6 Probability of Rejection Analysis

Figure 7-16 shows how the estimated POR-values at 50% and 85%, both at 95% confidence level, vary with increasingly set defect height rejection thresholds from 0.8 mm to 1.8 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%).

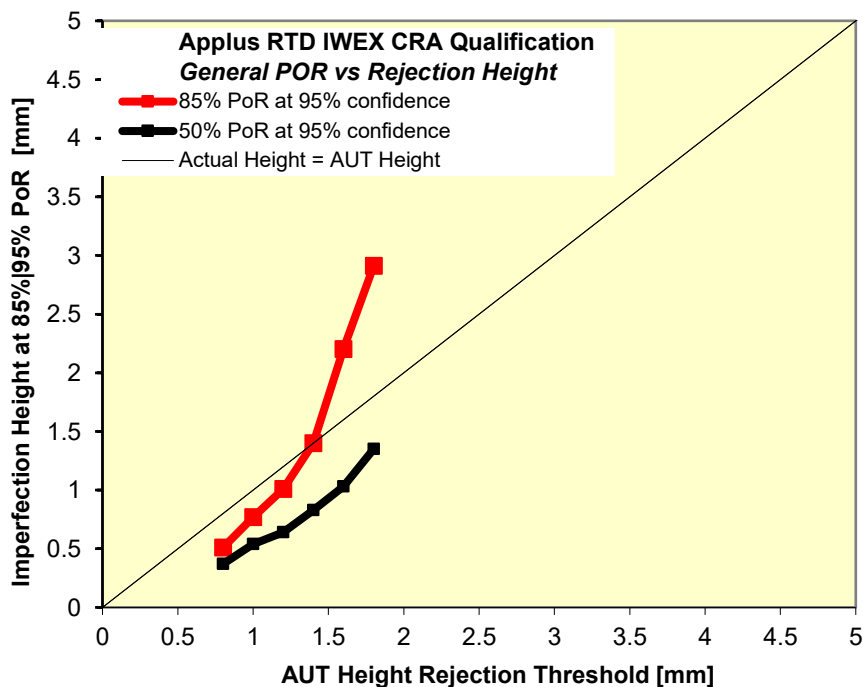


Figure 7-16: POR results of 85%|95% POR and 50%|95% POR for AUT height rejection thresholds from 0.8 mm to 1.8 mm.

In general precise height sizing by IWEX is found to provide good conditions for accurate POR analysis. The results in Figure 7-16 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 for rejectable sizes up to about 2.0 mm. The dataset did not include sufficient information to evaluate larger rejection thresholds.

7.7 Depth and Ligament Position Accuracy

The inaccuracy in depth position estimate is on average 0.4 mm, with a standard deviation of 1.06 mm. The positive average value means that AUT tends to indicate the defect position slightly lower in the weld than the actual position. The AUT reported defect depth is mainly estimated at accuracy within +2.1 mm and -1.3 mm, as shown in Figure 7-17. The results are valid for all imperfections in general.

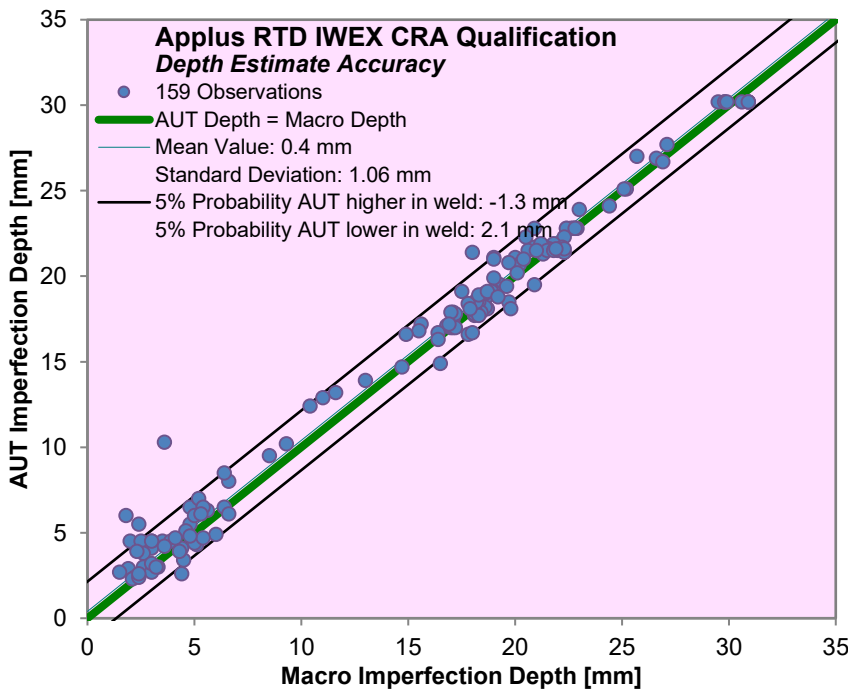


Figure 7-17: Depth estimate accuracy plot

The inaccuracy in surface ligament estimate at the ID surface is on average -0.2 mm, with a standard deviation of 0.85 mm. The IWEX reported surface ligament is mainly estimated at accuracy within +1.2 mm and -1.6 mm, as shown in Figure 7-17. With regards to surface ligament at the ID surface, the minus sign indicates that the actual imperfection ligament is smaller than estimated by AUT. Only sub-surface imperfections are included in this analysis. These results are strictly valid imperfections in Region C.

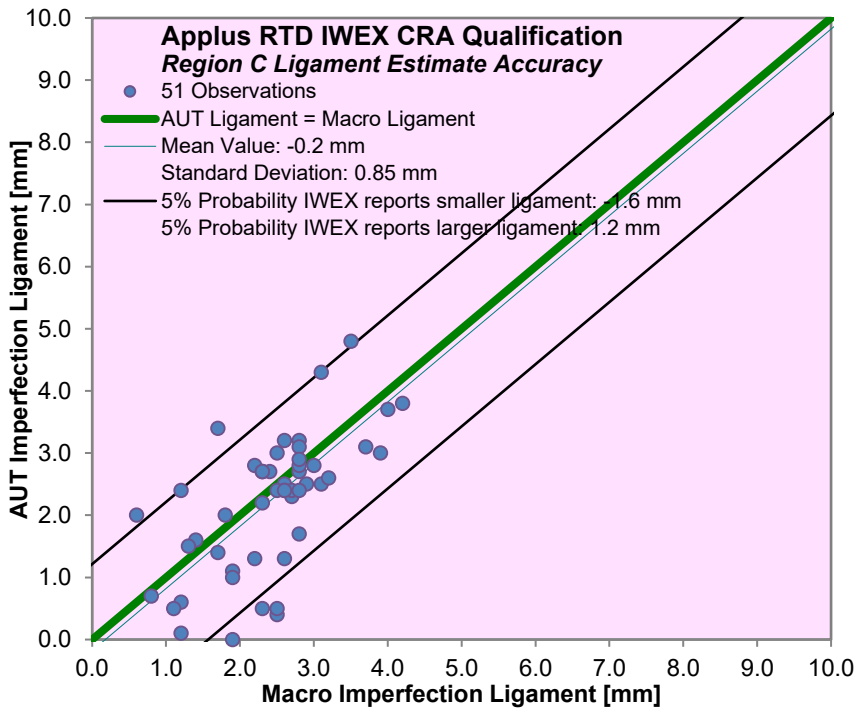


Figure 7-18: Region C (ID Surface) ligament estimate accuracy

The corresponding inaccuracy in surface ligament estimate at the ID surface for Region C* is on average -0.1 mm, with a standard deviation of 0.84 mm. The IWEX reported surface ligament is mainly estimated at accuracy within +1.3 mm and -1.4 mm, as shown in Figure 7-19. Only sub-surface imperfections are included in this analysis.

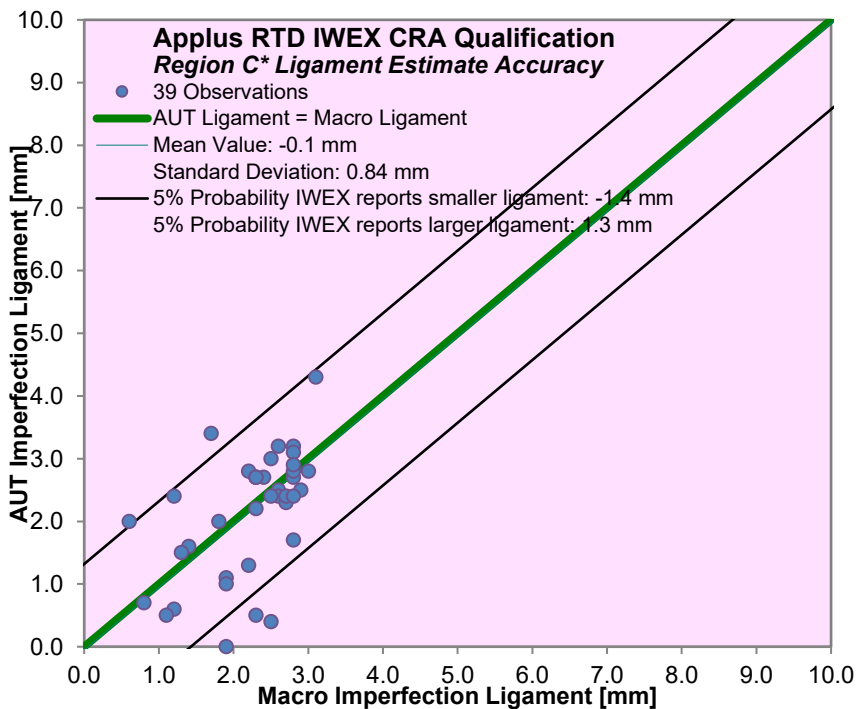


Figure 7-19: Region C* (ID Surface) ligament estimate accuracy

The inaccuracy in surface ligament estimate at the OD surface is on average 0.6 mm, with a standard deviation of 1.38 mm. The IWEX reported surface ligament is mainly estimated at accuracy within +2.8 mm and -1.7 mm, as shown in Figure 7-17. With regards to surface ligament at the OD surface, the minus sign indicates that the actual imperfection ligament is smaller than estimated by AUT. These results are strictly valid imperfections in Region C.

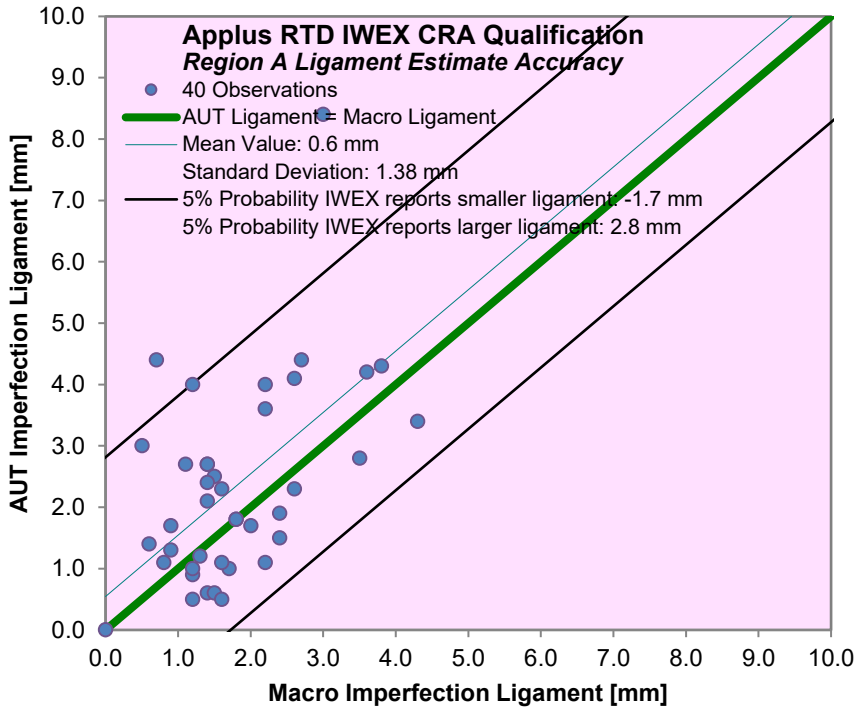


Figure 7-20: Region A (OD Surface) ligament estimate accuracy

7.8 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.

7.9 Interpretation Consistency, Clockwise (CW) and Counter-clockwise (CCW) Scans

Results of consistency in weld scan interpretation upon repeated scans are presented in the Table 7-4 below. This table details sizing accuracy results from clockwise (CW) and counter-clockwise (CCW) scans of the same dataset as used for the analysis presented in chapter 7.4, interpreted by the same operator. The results are presented with 2 decimals in order to provide the most accurate comparison between CW and CCW scan results.

Table 7-4 Comparison CW and CCW scan results

Category	<5% Probability undersize/oversize	Mean (μ)	Standard Deviation (σ)
General, CW	-0.74/-1.19	0.22	0.59
General, CCW	-0.72/1.18	0.23	0.58
Region A, CW	-0.76/-1.25	0.25	0.61
Region A, CCW	-0.69/1.23	0.27	0.58
Region B, CW	-0.43/-1.02	0.29	0.44
Region B, CCW	-0.42/0.99	0.29	0.43
Region C, CW	-0.84/-1.21	0.19	0.62
Region C, CCW	-0.83/1.22	0.20	0.62
RegionC*, CW	-0.89/-1.26	0.19	0.65
Region C*, CCW	-0.89/1.25	0.18	0.65
Depth General, CW	-1.34/-2.15	0.40	1.06
Depth General, CCW	-1.39/2.21	0.41	1.10

For single indications, it is observed that height and depth estimates are consistent upon repeated scans CW and CCW, with deviations well within ± 0.5 mm. This is well reflected in the overall results presented in **Table 7-4** above.

The data also includes interpretation of the same scans by a second operator. Consistent reporting between the two operators has been confirmed for these scans, in terms of similar interpretation and sizing. Results are presented for these weld scan data in Table 7-5 with 2 decimals, in order to provide the most accurate comparison between first operator and second operator results.

Table 7-5: Comparison CW and CCW scan results

Category	<5% Probability undersize/oversize	Mean (μ)	Standard Deviation (σ)
General, First Operator	-0.79/1.06	0.14	0.56
General, Second Operator	-0.87/1.06	0.10	0.58

7.10 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. Furthermore, IUT was performed on the 12.75" OD pipe configurations, which was also used to identify positions for macro section locations. Reporting was confirmed to be consistent between IUT and IWEX.

8 APPLUS+RTD IWEX PARTIAL WELD CRA AUT RESULTS

8.1 Height sizing accuracy

The height sizing accuracy evaluation results are summarised in Table 8-1. Results from a dataset consisting of only the partial weld observations are compared with results from a dataset of only the full weld observations from Region C.

Table 8-1: Applus+RTD IWEX CRA AUT Partial weld height sizing accuracy results

	No	5% under-sizing [mm]	Mean [mm]	Std.Dev [mm]
Partial Weld Region C	37	-0.6	0.4	0.64
Partial Weld Region C*	32	-0.6	0.5	0.65
Full weld Region C¹	51	-0.9	0.0	0.55
Full weld Region C*¹	44	-1.0	0.0	0.58

¹ Including only observations from full weld inspection

The height sizing accuracy results from the partial weld are confirmed to be similar to the results with full weld derived from the same Regions C and C*. Minor differences are observed in the results for mean value, while the standard deviations are close. The difference in mean values is identified to be due to a few indications of larger flaw heights in the full weld dataset (>3.0 mm vertical height), which shows a tendency of slight under-sizing. The partial weld dataset does not include any indications >3.0 mm in vertical height. A direct comparison of scatter plots from the full weld data and the partial weld data confirms the similar performance characteristics. It is therefore concluded that the IWEX CRA AUT procedure can be applied on partial welds as a stand-alone method with no impact on the height sizing performance. The slight differences observed in the results between the full weld and partial weld datasets are considered to be insignificant and due to the inherent uncertainties in AUT qualification design introduced by varying conditions with trial welds. The consistent results leave no indication of different AUT performance between full weld and partial weld setups.

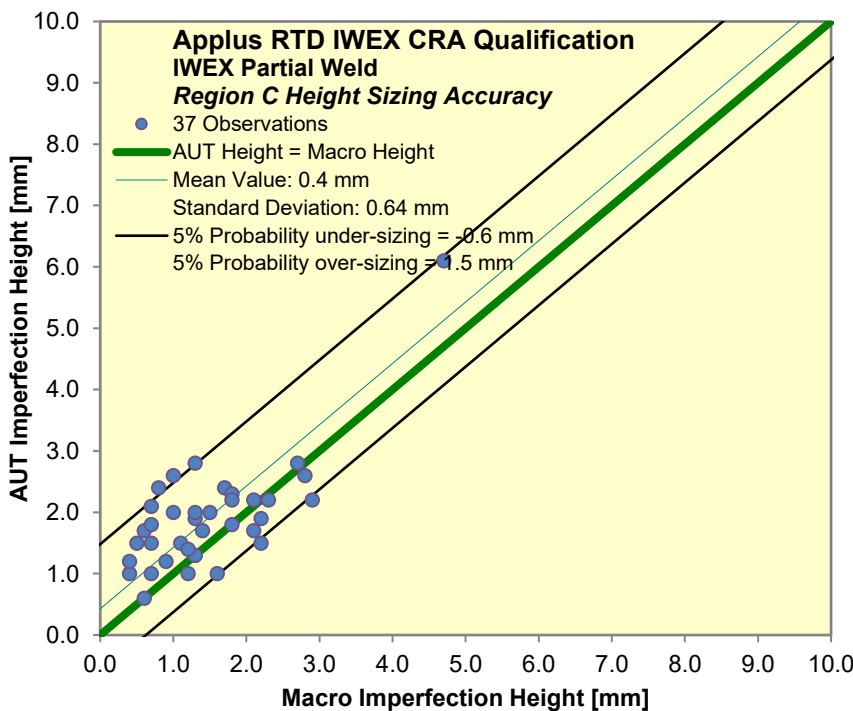


Figure 8-1: Partial weld AUT qualification data height sizing accuracy results, Region C.

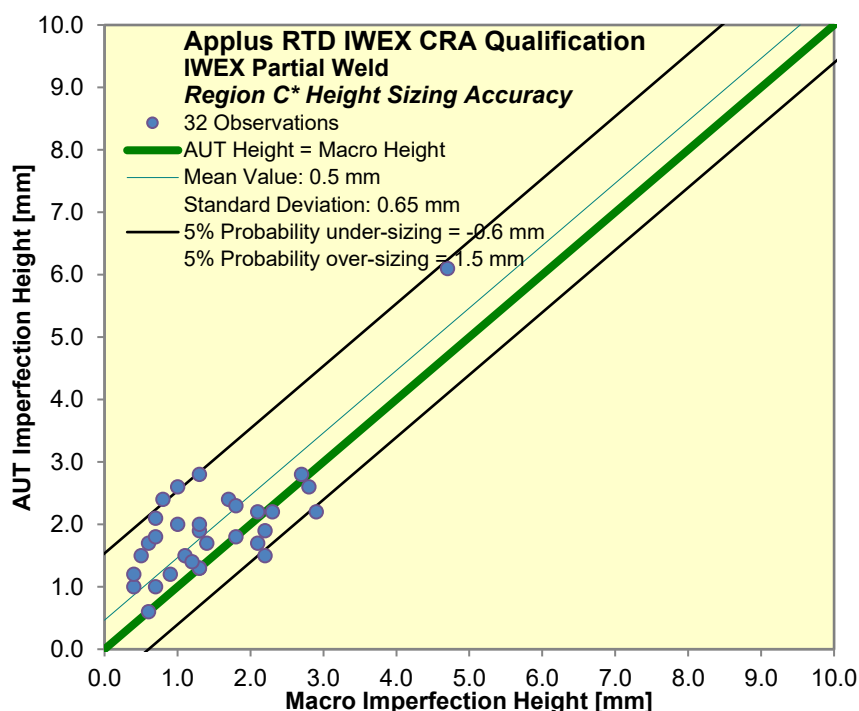


Figure 8-2: Partial weld AUT qualification data height sizing accuracy results, Region C*.

8.2 Depth Estimate Accuracy

The depth estimate accuracy evaluation results for partial weld and full weld datasets are summarised in Table 8-2.

Table 8-2: Applus+RTD IWEX CRA AUT Partial weld depth estimate accuracy results

	No	Mean [mm]	Std.Dev [mm]
Partial Weld Region C	37	0.1	0.75
Partial Weld Region C*	32	0.0	0.76
Full weld Region C¹	51	0.2	0.81
Full weld Region C*¹	44	0.1	0.77

¹ Including only observations from full weld inspection

The depth estimate accuracy results from the partial weld are confirmed to be similar to the results with full weld derived from the same Regions C and C*. The differences in results are considered to be insignificant. The results are considered as representative to also the accuracy in the remaining ligament estimate by AUT at the ID surface, since the imperfection depth is measured at the lowest part of the imperfection both by AUT and in macro reporting.

A direct comparison between scatter plots from the partial weld data and the full weld data confirms the similar performance characteristics. It is therefore concluded that the IWEX CRA AUT procedure can be applied on partial welds as a stand-alone method with no impact on the depth estimate performance. The consistent results leave no indication of different AUT performance between full weld and partial weld setups.

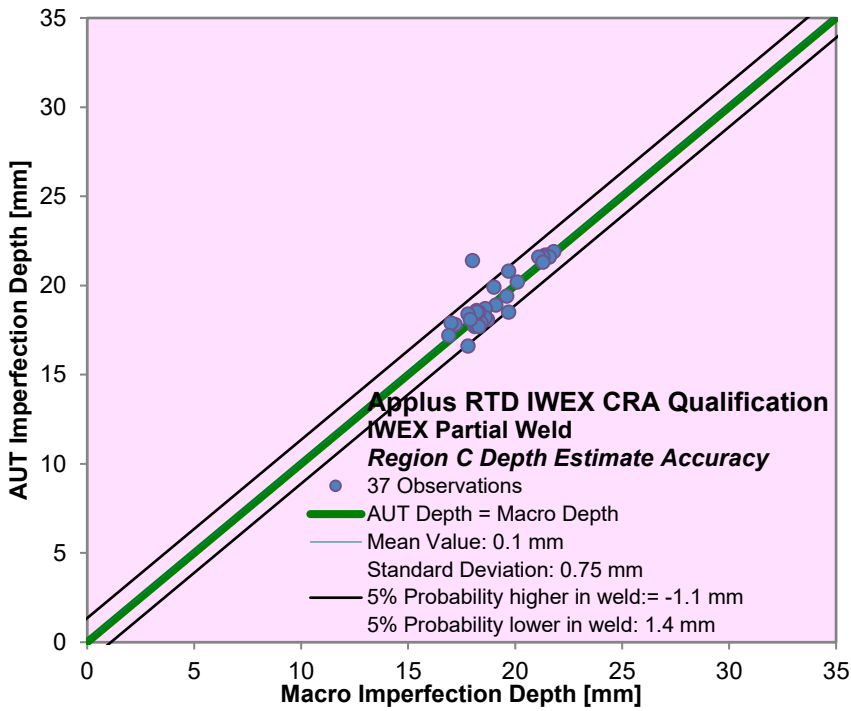


Figure 8-3: Partial weld AUT qualification data depth estimate accuracy results, Region C.

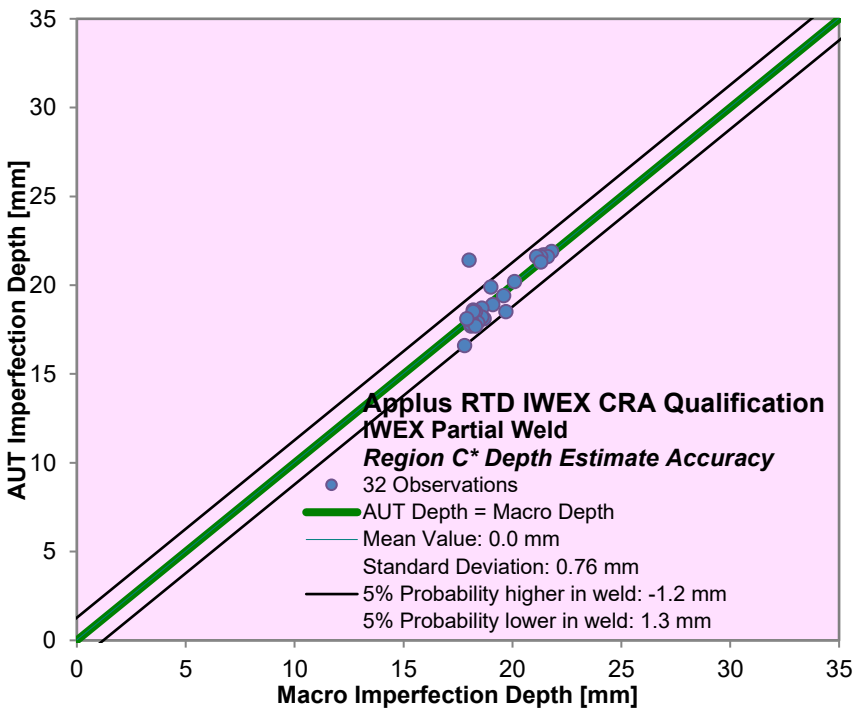


Figure 8-4: Partial weld AUT qualification data depth estimate accuracy results, Region C*.

8.3 Detectability

The probability of detection (POD) analysis results are summarised in Table 8-3. Reference results from the full weld qualification are also specified in the same table.

Table 8-3: Applus+RTD IWEX CRA AUT Partial weld POD evaluation results

	No	Evaluation Threshold [%FSH]	90% 95% POD Height [mm]
Partial Weld Region C	38	10	0.8
Partial Weld Region C*	33	10	0.8
Partial Weld Region C	38	20	0.8
Partial Weld Region C*	33	20	0.8
Full weld Region C ¹	52	10	0.8
Full weld Region C* ¹	45	10	0.8

¹ Including only observations from full weld inspection

The POD evaluation results with the partial weld are considered to be similar to the POD results for full weld. The differences in results are considered to be insignificant. Similar detection performance has been confirmed upon data review.

The POD curves for partial weld Region C and Region C* are provided below.

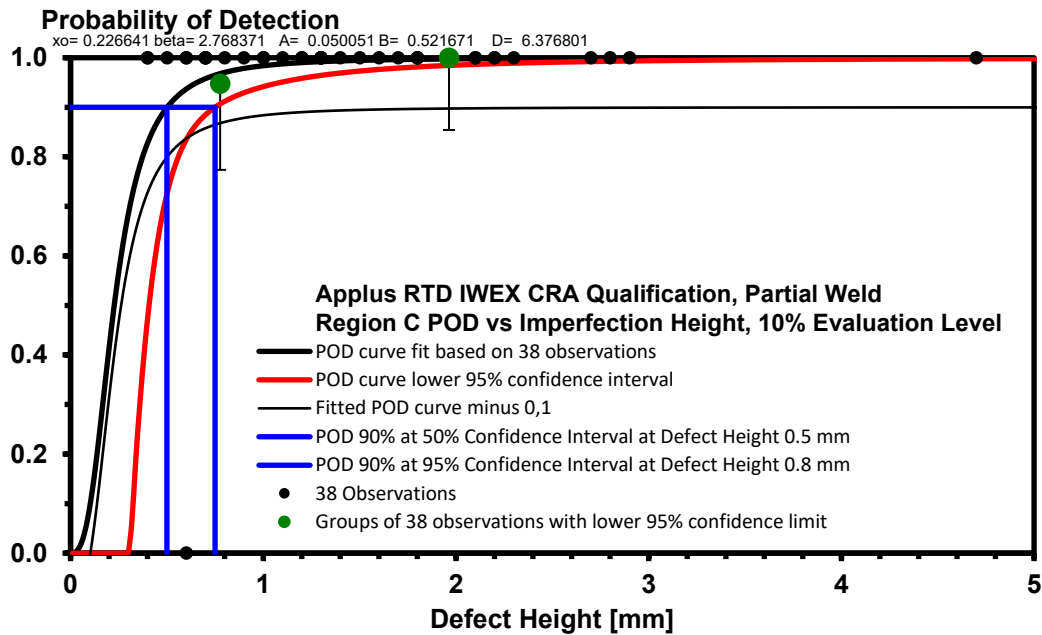


Figure 8-5: POD curve partial welds, Region C, 10% FSH evaluation level

POD analysis has been performed at several evaluation levels for Region C, the results are summarised in Table 8-3. The calculated 95% confidence bands for evaluation levels of 10% and 20% are plotted in Figure 8-6 below. Both curves are identical, so the red curve for the 20% FSH threshold is hidden behind the blue curve for the 10% FSH threshold.

Probability of Detection, Various Evaluation Levels

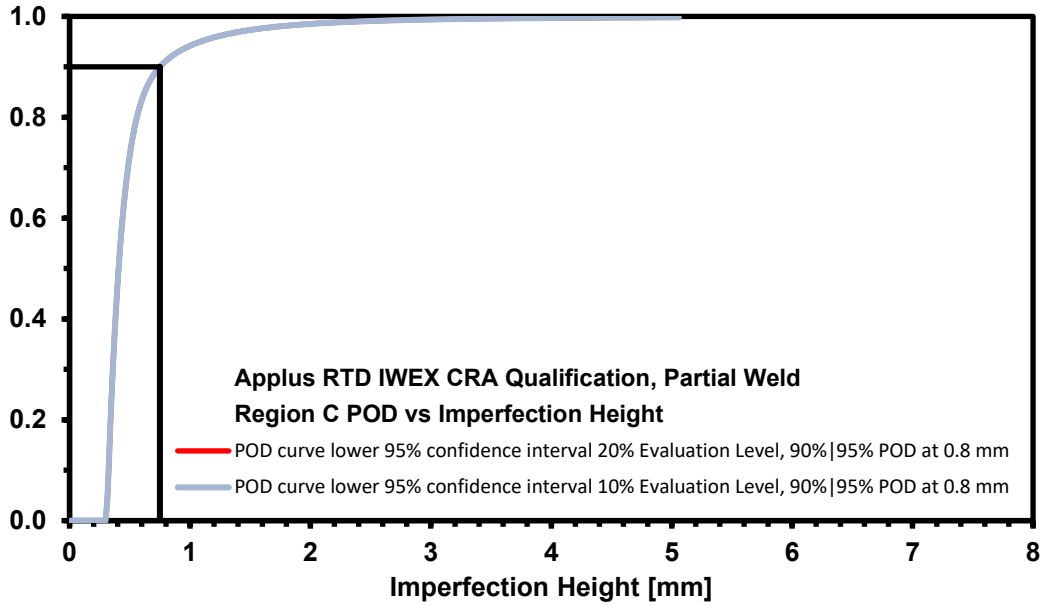


Figure 8-6: The general 90% POD height at 95% confidence for different evaluation levels.

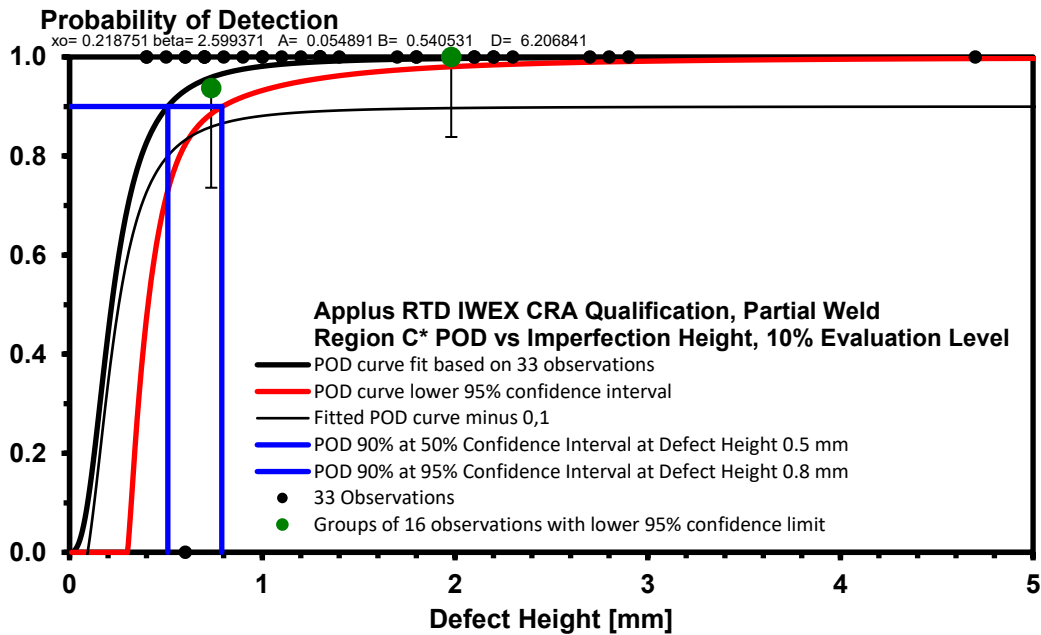


Figure 8-7: POD curve partial welds, Region C*, 10% FSH evaluation level

POD analysis has been performed at several evaluation levels for Region C*, the results are summarised in Table 8-3. The calculated 95% confidence bands for evaluation levels of 10% and 20% are plotted in Figure 8-8 below. Both curves are identical, so the red curve for the 20% FSH threshold is hidden behind the blue curve for the 10% FSH threshold.

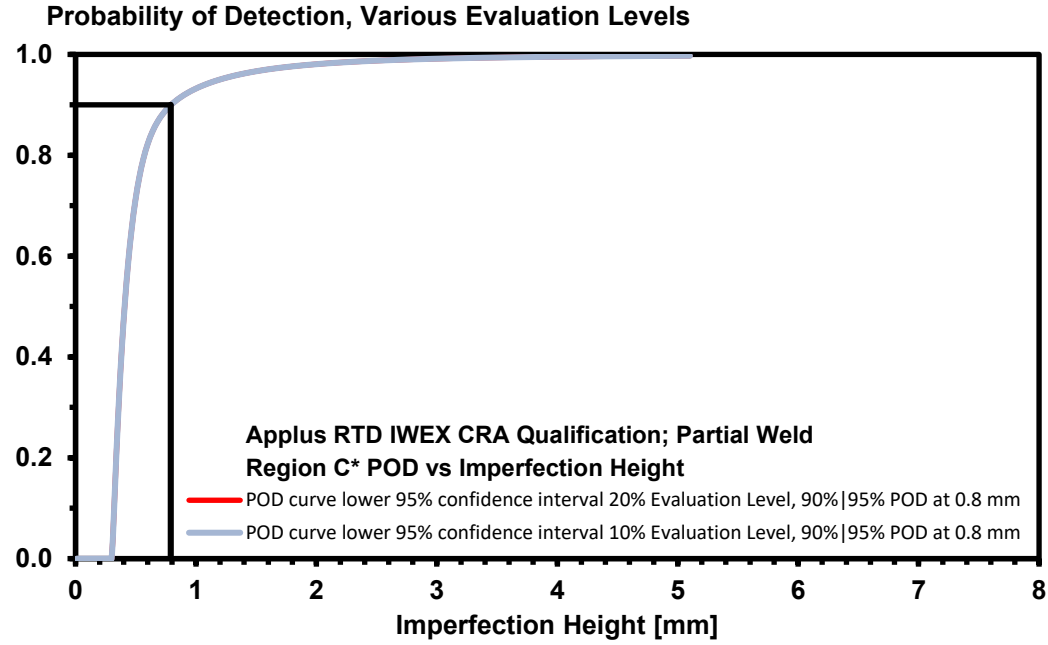


Figure 8-8: The general 90% POD height at 95% confidence for different evaluation levels.

9 CONCLUSIONS

9.1 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 corrosion resistant alloy (CRA) pipeline girth weld applications. The present qualification programme has documented that IWEX complies with the requirements of DNVGL-ST-F101, Appendix E [1].

DNV GL has witnessed all trials and all scan interpretation within the qualification programme.

The qualification work has been done under agreement between Applus+ RTD and DNV GL AS, and follows the requirements of DNVGL-RP-F118 [2]. The qualification trials have covered 19 welds of various configurations, as listed in Table 9-1.

Table 9-1: Applus+ RTD IWEX CRA AUT Qualification defective weld details

Weld OD	WT [mm]	No. welds	CRA Material	CRA type	Bevel configuration	No. Intended Imperfections	No. Confirmed Imperfections
12.75"	19.8+3	4	UNS S31603	Weld overlay	J5	38	36
12.75"	25.6+3	4	UNS S31603	MB	J5	36	35
14"	20.6+3	1	625	MB	J5	6	6
9.6"	17.9+3	5	825	MB	J5	42	41
9.6"	18.5+3	5	316L	MB	V30	48	43

In total 161 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 various independent laboratories.

9.2 Performance Results, DNVGL-ST-F101 Requirements

9.2.1 Repeatability

For reference block repeatability trials deviations in measured reference reflector size is documented to be well within ± 0.5 mm.

9.2.2 Band Offset Sensitivity

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

9.2.3 Temperature Sensitivity

Elevated temperature trials were performed as series of 15 scans on a defective weld of configuration 12" OD x 25.6 mm + 3.0 mm metallurgical bonded clad heated to a temperature of at least 90 °C, 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.

9.2.4 Detectability

Defect heights with documented reliable detection at 90% POD with 95% confidence valid for all weld imperfections (except volumetric inclusions) and for all imperfection lengths are provided in Table 9-2.

Imperfections with vertical heights below 1.0 mm have consistently been observed to be clearly detected.

Table 9-2 Vertical imperfection heights of 90% POD at 95% confidence result summary

Evaluation Level	General
10% FSH	0.9 mm
20% FSH	1.0 mm

9.2.5 Height Sizing Accuracy

Height sizing accuracy results for general use, valid for all weld imperfections (except volumetric imperfections) at all orientations, depths and types and for all imperfection lengths are provided in Table 9-3.

Table 9-3 Vertical Imperfection Height sizing accuracy result summary

Category	# Observations	5% Probability Under Sizing	Mean	Standard Dev.
General	159	-0.7 mm	0.2 mm	0.59 mm
Region A	40	-0.8 mm	0.2 mm	0.61 mm
Region B	31	-0.4 mm	0.3 mm	0.44 mm
Region C	88	-0.8 mm	0.2 mm	0.62 mm
Region C*	76	-0.9 mm	0.2 mm	0.65 mm

* Only includes 3 mm CRA layer

9.2.6 Length Sizing Accuracy

Beam spread was evaluated for reference reflectors. Beam spread was observed to vary between 4.4 mm and 1.3 mm among the different modes.

9.2.7 Imperfection Depth Estimate Accuracy

The IWEX defect through thickness depth measured from the outer surface to the bottom of each defect was found to be estimated in general within an accuracy of ± 2.1 mm. Imperfections are on average reported 0.4 mm lower in the weld by IWEX than the actual position. This applies to embedded imperfections. The results are summarised in Table 9-4 below.

Corresponding results from evaluation of accuracy in remaining ligament near the ID surface (Region C and Region C*) are summarised in Table 9-5.

Table 9-4: Depth Estimate Accuracy Result, General use

Area	5% probability, IWEX higher in weld [mm]	5% probability IWEX lower in weld [mm]	Mean depth inaccuracy [mm]	Standard deviation [mm]
General Depth	-1.3	2.1	0.4	1.06

Table 9-5: Region C Surface Ligament Estimate Accuracy Result, General use

Area	5% probability, IWEX reports smaller ligament [mm]	5% probability IWEX reports larger ligament [mm]	Mean ligament inaccuracy [mm]	Standard deviation [mm]
Region C	-1.6	1.2	-0.2	0.85
Region C*	-1.4	1.3	-0.1	0.84

9.3 Partial Weld IWEX AUT Performance Results

A direct comparison between the qualification of IWEX CRA AUT procedure on full welds and partial welds confirms similar performance characteristics. It is therefore concluded that the IWEX CRA AUT procedure can be applied on partial welds as a stand-alone method. It is considered as fully demonstrated that the partial weld cause no significant impact on sizing performance. Therefore, the results summarised in paragraph 9.2 of this report for Region C and Region C* are also valid for partial weld examinations by the IWEX CRA AUT procedure.

9.4 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 corrosion resistant alloy (CRA) pipeline girth weld applications.

The IWEX system shall include sufficient modes to provide full coverage of the weld, and as a minimum longitudinal direct, skip and tandem modes and in addition separated creeping wave probes included in the present qualification. Minimum 64 element phased array 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 (3 mm FBHs embedded) 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 wall thickness 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.

All modes that provides information useful for either sizing or detection purposes shall be included in the IWEX setup. Applied welding method or weld bevel type and angle are not essential variables. Validity for heavy wall thicknesses above 42 mm requires that the qualified setup can be maintained and shall be evaluated from case to case.



9.5 Validity

The qualification has unlimited validity, as long as the prerequisites in section 9.4 are met. 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.

10 REFERENCES

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