

DNV GL AUT QUALIFICATION DNVGL-ST-F101

General Qualification of the Applus+ RTD Rotoscan AUT System

Röntgen Technische Dienst Holding B.V.

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Objective:

The Applus+ RTD Rotoscan AUT system, as operated according to General Procedure for Automated Ultrasonic Testing No PIPL-06.01.0001 and Specific Procedure for Automated Ultrasonic Testing No. PIPL-06.01.0002, has been subjected to an evaluation of detection and height sizing performance according to requirements of DNVGL ST-F101. AUT performance of the Rotoscan system with multi probe and phased array probe setups have been evaluated separately, both for J and V-preparation weld bevels. The qualification program was performed in line with DNVGL-RP-F118 (2017) guidelines.

The Rotoscan AUT system is in general qualified for all carbon steel offshore pipeline girth weld inspection according to the requirements set forth in DNVGL-ST-F101, given certain prerequisites are met and the applied acceptance criteria are fulfilled.

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1 EXECUTIVE SUMMARY

The Applus+ RTD Rotoscan AUT system, as operated according to General Procedure for Automated Ultrasonic Testing No PIPL-06.01.0001 and Specific Procedure for Automated Ultrasonic Testing No. PIPL-06.01.0002, has been subjected to an evaluation of detection and height sizing performance according to requirements given in DNVGL-ST-F101. The basis of this evaluation is verification and qualification data from 47 different pipelaying projects, acquired and supplied by Applus+ RTD. The evaluation included repeatability trials on reference blocks and temperature sensitivity trials. The full scope of this qualification includes the trials and tests required for qualification according to DNVGL-ST-F101, Appendix E. The system is well documented from the supplied data and the tests performed and operational aspects have been found satisfactory. All qualification activities as described in DNVGL-RP-F118 May 2017 Section 4 are successfully performed and documented. The Rotoscan AUT system is therefore found qualified according to DNVGL-ST-F101 for pipelaying projects where certain prerequisites are met, and the applied acceptance criteria are fulfilled.

The Qualification data includes a wide range of weld configurations. The range of validity for this qualification is from 3" OD and above, and for pipe wall thicknesses above 6 mm.

The performance is related to all included functionality of the Rotoscan system being PE (Pulse Echo) channels, Tandem PE Channels TOFD and mapping channels. The results for vertical defect heights at 90% POD at 95% confidence and height sizing accuracy are given in the table below. The system performance is well documented from the tests performed. In summary, the performance can be described as follows (for details see main text):

- The Applus+ RTD Rotoscan AUT procedures, both Multi Probe and Phased Array setups, have demonstrated acceptable performance in terms of repeatability and when operating at elevated temperatures up to 70°C, while the reference block is kept at ambient temperature.
- The AUT system is documented to reliably detect imperfections down to 0.8 mm in vertical height for J-bevel configuration. Reliable detection is defined by a 90% POD value at 95% confidence level. The results are valid for imperfections of lengths down to 4 mm.
- Corresponding results for different parts of the weld are summarized in the Table 1-1 below.

Table 1-1: Rotoscan 90%|95% POD imperfection heights

Rotoscan System	Bevel Prep.	90% 95% Height [mm] at Different evaluation levels		
		40% FSH	30% FSH	20%FSH
Multi Probe	J	2.2	1.6	0.8
	V	2.2	1.2	0.9
Phased Array	J	1.7	1.4	1.1
	V	2.2	1.9	1.3

Evaluation of imperfection height sizing accuracy shows that in general a margin of 1.0 mm on height sizing to account for uncertainty is sufficient to achieve less than 5% probability of under-sizing for J-bevel and V-bevel. The observed mean over-sizing is below 0.8 mm. The results from the qualification regards height sizing accuracy are summarized in the Table 1-2 below.

Table 1-2: Rotoscan Height Sizing Accuracy

Rotoscan System	Bevel Prep.	Mean [mm]	Standard Deviation [mm]	95% limit against under-sizing [mm]
Multi Probe	J	0.0	0.59	-1.0
	V	0.1	0.65	-1.0
Phased Array	J	0.2	0.53	-0.7
	V	0.0	0.60	-1.0

These results are regarded valid for all future pipeline girth weld inspection projects for the Applus+ RTD Rotoscan AUT system where the welds used in this qualification are found relevant, provided that project specific acceptance criteria and certain prerequisites given in section 8.3 of this report 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.

2 INTRODUCTION

A general qualification according to requirements within DNVGL-ST-F101, Appendix E has been performed for the Applus+ RTD Rotoscan AUT system. The qualification is mainly based on qualification and verification data acquired for pipelaying projects in the past. These data have been supplemented by new trials in order to comply with the requirements. The qualification data used covers performance of the Rotoscan system, both with multi probe and with phased array probe setups.

DNV has reviewed all historical data with importance for the qualification, including available macro sectioning evidence, AUT scan files, radiographs and radiographic testing results of defective welds, AUT procedures and compliance with formal requirements.

Performance is evaluated as mainly detectability and vertical height sizing uncertainty. The purpose for this general qualification has been to document independently the performance of the Applus+ RTD Rotoscan AUT system for pipeline girth weld inspection applications. The results presented in this report are intended to be used as historical background data for further AUT verification, or as complete documentation of AUT performance according to DNVGL-ST-F101 for future pipelaying girth weld inspection projects.

Revision 02 of this report was issued in August 2015, in order to clarify compliance with DNV-RP-F118 (2010) and DNV-OS-F101 (2013). This was regarded necessary due to the considerable changes in requirements of DNV-OS-F101 Appendix E between the 2007 edition and the 2013 edition. The former revision of this report was issued prior to these documents, but with the intention to be in line with the upcoming DNV guideline on AUT qualification. The DNV-RP-F118 was therefore partly based on the experiences gained through the present qualification program.

Revision 03 was issued in February 2019, to clarify and ensure compliance with DNVGL-RP-F118 (2017) and DNVGL-ST-F101 (2017), which superseded the former DNV-RP-F118 (2010) and DNV-OS-F101 (2013). Depth and 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 with the Applus+ RTD Rotoscan AUT system, i.e. AFLS, Z-shaped guidance band and 4G hardware platform.

3 BASIS

The basis for this qualification work has been: DNVGL-ST-F101 [1] and DNVGL-RP-F118 2017 edition [2]. Further, the guidance given in the Nordtest TechReport 394 [3] is followed, as far as applicable. The Rotoscan system has been operated according to the Applus+ RTD General Procedure for Automated Ultrasonic Testing No PIPL-06.01.0001 and Specific Procedure for Automated Ultrasonic Testing No. PIPL-06.01.0002 [4,5]. Further details were given on witnessing and guidance during the qualification work.

4 OBJECTIVES

The main objective of the qualification work was firstly to document the Applus+ RTD Rotoscan AUT system performance according to DNVGL-ST-F101 [1].

Since this is 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 specifications, and the results should therefore be directly applicable for relevant pipeline girth weld inspection applications with specific acceptance criteria.

According to DNVGL-ST-F101 the basic requirements for documentation of an AUT system's performance are:

- A POD of 90% at a 95% confidence level (a 90%|95% POD) has to be documented for a defect height smaller or equal to the smallest allowable defect height, as derived by ECA, in the group of defects in question.
- The 5% limit against under-sizing of vertical height has to be established.
- Any over-sizing on average shall be below 0.8 mm
- As an alternative to the two above steps, evaluation of the 85%|95% POR defect height may serve the same purpose.
- Additional operational tests to check repeatability shall show variations not more than ± 2 dB.

5 REFERENCE DOCUMENTATION

- [1] DNVGL Standard DNVGL-ST-F101: Submarine Pipeline Systems, edition October 2017
- [2] Guidelines for NDE Reliability Determination and Description, Nordtest TechReport 394, Nordtest, Espoo, Finland, Approved 1998-04
- [3] DNVGL Recommended Practice DNVGL-RP-F118: Pipe girth weld automated ultrasonic testing system qualification and project specific procedure validation, May 2017
- [4] General Procedure for Automated Ultrasonic Testing No PIPL-06.01.0001
- [5] Specific Procedure for Automated Ultrasonic Testing No. PIPL-06.01.0002

6 DESCRIPTION OF QUALIFICATION PROCESS AND CONTENTS

6.1 Rotoscan AUT System Setup

The Applus+ RTD Rotoscan AUT system as operated according to the general AUT procedure PIPL-06.01.0001 [4] has been qualified. The general AUT procedure is a part of the quality assurance system of Applus+ RTD, and is not modified on a project basis. Any project specific documentation of the AUT setups are captured in a specific procedure. In this report, references for the specific procedure are given to a generic (template) document number PIPL-06.01.0002, the content in this procedure will vary between the different setups. The Rotoscan AUT system is designed for pipeline girth weld inspection, the basic functionality is pulse echo, mapping and TOFD (time of flight diffraction). Rotoscan pulse echo inspection is based on zonal discrimination. The zone height depends on the applied weld bevel configuration, and varies from 1.0 mm in root and up to 5.0 mm for fill zones in heavy wall thicknesses. It should be mentioned that recommended maximum zone height (embedded zones) according to DNVGL-ST-F101 Appendix E, paragraph B103 is 3.0 mm. The probe beam spot attributed to each channel is confirmed to cover the full zone height when overtrace signals are seen in adjacent channels. In addition there are volumetric channels to cover the interior of the weld. Specific transducer setup is determined by the parameters of the girth weld to be inspected, for instance wall thickness and weld bevel angle. When required by the Client, the Rotoscan

system can be enhanced with specific probes for transverse imperfection detection, or with specific creep wave probes for near OD surface inspection.

In a multi probe setup, individual ultrasonic probes are focused on each inspection zone. A phased array probe consists of several transducer elements, which allows manipulation of both angle and focus of the sound beam by the single probe.

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 6 MHz
ToFD 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

For a pulse-echo setup, the same probe is used as transmitter and receiver. In a tandem setup there are two separate probes working in pair, one is transmitting and one is receiving the signal. The setup to choose will be determined by the optimal conditions for reflection by imperfections at the weld bevel. For the Rotoscan system, tandem setup is generally used for embedded zones in narrow angle bevel welds, typical J-preparation. A wide weld bevel angle will favour the PE setup. In general, PE is the only method used for zones at root (0.5 skip) and cap (full skip), and for volumetric channels.

6.1.1 Adapted Focal Law Settings

The most recent Rotoscan AUT procedure includes possibility to use Adapted Focal Law Settings (AFLS) if the wall thickness variation of the inspected pipeline welds deviates outside the standard requirement ranges from the nominal wall thickness. This is an option with phased array probe setups only. For DNVGL-ST-F101 the wall thickness variations shall be within ± 1.5 mm from nominal wall thickness for low installation strain and ± 1.0 mm for high installation strain applications. The reference block will always be made with the nominal thickness. AFLS allows for inspections using the same reference block also when the wall thickness is outside these wall thickness variation ranges through model AUT setups. A model AUT setup for a given wall thickness is calculated from the set of focal laws established with the physical reference block, assuming a shift in position of weld bevel position and zone location when the wall thickness varies. Upon weld scanning, the wall thickness is continuously measured and the Rotoscan software applies automatically the relevant AUT setup for the scan presentation.

In practice, the AFLS functionality extends the wall thickness range that can be inspected by Rotoscan from one single reference block. With the reference block manufactured with the nominal wall thickness, the ranges are extended as follows:

- For applications where nominal installation strains $< 0.4\%$: AFLS can cover a maximum wall thickness range of nominal WT ± 4.5 mm, corresponding to a 9.0 mm wall thickness variation ($3 \times \pm 1.5$ mm). It is a prerequisite that all ultrasonic beams will fit within the footprint of the applied

PA probe footprint/array, and the setups has to provide coverage for the full range without any gaps (i.e. every AUT setup within AFLS has to comply with the validity of ± 1.5 mm).

- For applications where nominal installation strains $\geq 0.4\%$: AFLS can cover a maximum wall thickness range of nominal WT ± 3.0 mm, corresponding to a 6.0 mm wall thickness variation ($3 \times \pm 1.0$ mm). It is a prerequisite that all ultrasonic beams will fit within the footprint of the applied PA probe footprint/array, and the setups has to provide coverage for the full range without any gaps (i.e. every AUT setup within AFLS has to comply with the validity of ± 1.0 mm).

6.2 Qualification Data Background

This qualification is mainly based on historical data from various AUT qualification and validation trials performed by the Applus+ RTD Rotoscan AUT system. The AUT testing has been carried out by Applus+ RTD, while trial welds have been supplied by various Contractors and Pipeline Owners for the many different projects included.

A summary of the data included in the analyses is given in the Table 6-2 below.

Table 6-2: Qualification Data Summary for Rotoscan AUT General Qualification

Rotoscan System	Weld Bevel Geometry	Weld Method	Material	# Projects	# Observations
Multi Probe	J: 2°, 3°, 4°, 6°	GMAW	API 5L X60 and X65	12	248
Multi Probe	V, 30°	GTAW, SMAW, GSFCAW	API 5L X60 and X65	7	158
Phased Array	J, 3°, 4°, 5°, 6°, 7°, 10°	GMAW	API 5L X52, X60, X65, X70	10	160
Phased Array	V, 25° and 30°	SMAW	API 5L X52, X60, X65, X70	18	172
Phased Array (AFLS)	J7	GMAW	API 5L X60	1	34

Wall thicknesses were down to 6 mm. The outer pipe diameters (OD) were down to 3". A full overview of the included configurations is provided in Appendix 1.

It is made a distinction for qualification requirements of wide and narrow gap welds, denoted V and J bevel preparation welds throughout the report. This distinction is mainly motivated by the need for different AUT inspection setup philosophy in the two cases; Wide gap V-preparation (bevel angle $\geq 20^\circ$) requires inspection by pulse echo while narrow gap J-preparation (bevel angle $< 20^\circ$) requires tandem setup to

provide adequate inspection coverage for planar imperfections. This distinction corresponds for most cases to the application of AUT on distinct parts of the full welding scope within pipeline projects: Wide gap V-bevel preparation are typically in use for manual welding procedures, narrow gap J-bevel preparation are typically in use for automated welding procedures. It should be noted that the terminology of J and V bevel used within this report should not be regarded as strictly restrictive for future use with weld preparations and weld geometries that not falls directly within the definitions for J and V bevel mentioned above. It is the bevel angle and not necessary the weld geometry that dictates the optimal AUT setup, and the scope of this AUT qualification covers the full range of weld bevel angles 0° to 45°. This means for instance that a weld configuration denoted "V-bevel" but with bevel angle <20° will still be considered as covered by this qualification, provided that tandem setups as qualified within the J-bevel setup qualification will be applied. Likewise, weld configurations denoted "J-bevel" but with bevel angle ≥20° will find its relevant documentation in the results of V-bevel welds, provided that pulse echo technique setups as qualified within the V-bevel scope of the qualification will be applied.

For J-preparation welds, the used welding method has been GMAW for all projects. Some different steel grades are seen among the projects. For V-preparation welds, several welding methods are used. These are SAW, GSFCAW, GTAW and SMAW.

For the majority of the data included, the procedure for calibration of the system specifies Ø3 mm FBHs for embedded channels and 1 mm notches for surface channels, all set to 80% FSH, which resulted in the POD analysis results throughout the report. The evaluation threshold for pulse echo varied between 20% FSH and 40% FSH. Some of the AUT data acquired with multi probes, both at J and V weld bevel preparation, were recorded using a more sensitive calibration with reference reflectors of Ø2 mm FBHs for embedded channels and 1 mm surface notches for surface channels, all set to 80% FSH. Data attributed to Ø2 mm FBH calibration procedure can be used in the same POD analysis providing that a correction factor for the different sensitivity is applied on the reported amplitudes.

Supplementary radiographic testing has been performed on a regular basis for the qualification welds included in the analysis. In general, no significant imperfections were indicated by radiographs as missed by AUT.

6.3 Analysis Extent

6.3.1 Repeatability and Temperature Trials

DNVGL-ST-F101 requires verification scans of a reference block reference scan, where the amplitude deviations in any channel over 10 consecutive scans shall be within ±2dB. Fulfilment of this requirement indicates acceptable repeatability of the system. DNVGL-RP-F118 requires series of 10 consecutive scans with the centre of the reference block at 12 o'clock in 5G and 6 o'clock position in 5G. If regarded as relevant, scanning series with reference block in 2G position and 6G position shall also be performed.

In addition, 3 scans each shall be performed with band offset 1 mm to DS side and 1 mm to US side. This can be performed on the reference block or a defective weld, and possible deviations in imperfection sizing due to the band offset should be evaluated.

Furthermore, DNVGL-ST-F101 requires temperature sensitivity tests on one trial defective weld with at least 6 imperfections included. Temperature sensitivity trials are performed to guarantee that the inspection performance will not be influenced by large temperature changes between reference block and weld. The temperature sensitivity trials includes 15 consecutive scans of the same weld, heated to the elevated temperature for the AUT system to be qualified for upfront each scan. For this system, elevated temperature trials were performed at 70 °C. Before and after one scan, there shall be a scan on the reference block kept at ambient temperature (cal in-cal out). The time period between the start of scanning of two consecutive scans is denoted one cycle, and includes time used for scanning of one weld, mounting scanner off the weld and on the reference block, achieving acceptable calibration scan, mounting scanner back on the weld and in between; heating the weld to 70 °C. Deviations in maximum amplitude of the imperfections between the scans shall be within ±2dB. As an alternative, deviations in height sizing for selected imperfections shall not exceed overall sizing tolerances.

6.3.2 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], and is based on the method of the maximum likelihood estimator (MLE) where so called hit-miss AUT detection data are fitted to a statistical model. 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 a 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 maximum likelihood estimator (MLE) is found by selecting of 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 of the 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 also be calculated using the MLE, assuming that the estimates for b and x_0 are both average values and 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.

6.3.3 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 6.3.2 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 criteria 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.

The POR can be used in practice when there is a clear set of acceptance/rejection criteria defined for the AUT procedure. These can for instance be a defined critical flaw height, applied with AUT height sizing based on a mixture of information from pulse echo, mapping channel data and TOFD. One example of application would be data from AUT evaluation of CRA material, where the correlation between amplitude and



imperfection height is severely influenced by the anisotropic nature of the CRA material. With these criteria applied, the actual sizes of the accepted and rejected flaws are assessed through POR. POR should be used to evaluate the imperfection size that needs to be rejected in order to ensure that the critical flaw height according to applicable acceptance criteria is consistently rejected. Usually, some probability of under-sizing should be expected, so the outcome of a POR study will normally suggest that flaws with an AUT size smaller than the critical flaw size shall be rejected. On the other hand side, since POR assess actual performance of interpretation which incorporates sizing accuracy, no sizing allowance needs to be added to the critical flaw sizes in the acceptance criteria. This is a benefit with POR, that it assesses the performance of AUT at the relevant flaw sizes. It should be noted that in order to ensure representativeness, POR should in theory be calculated specifically for each project.

6.3.4 Imperfection Height Sizing

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.

In addition to evaluation of allowance for under-sizing, the average over-sizing including all observations shall not exceed 0.8 mm.

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

6.3.6 Adapted Focal Law Settings

A functional demonstration of the Adapted Focal Law Settings (AFLS) was performed for the Phased Array Rotoscan AUT configuration. The demonstration included 2 series of scans of 3 12" OD reference blocks with AUT setup for the same welding procedure but with 3 wall thicknesses: One at nominal wall thickness and blocks with wall thicknesses ± 1.5 mm from nominal thickness. The test blocks are summarised in the Table 0-3 below.

Table 0-3: Reference Block Summary AFLS Demonstration


	Reference block ID	Wall thickness [mm]
Light Wall	Low WT	18.0
	Mid WT	19.5
	High WT	21.0
Heavy Wall	Low WT	29.5
	Mid WT	31.0
	High WT	32.5

The Rotoscan AUT setups were performed using the mid WT reference block, and the AUT setups for high and low wall thicknesses were modelled with AFLS. The high and low wall thickness reference blocks were scanned with AFLS, applying the modelled setups. Reference reflector responses for the high and low wall thickness reference block scans were evaluated with the same criteria as used for repeatability trials, paragraph 6.3.1, i.e. variations should be within ± 2 dB.

In addition, function of AFLS was documented with a limited validation including AUT scanning and macro sectioning of 3 defective welds and in total 34 imperfection locations. The welds were of configuration 16" OD x 28.4 mm WT, J7 bevel. The AUT setup was made for a reference block with the same configuration, except for a nominal wall thickness of 26.9 mm. AFLS modelled setups of WT-L of 25.4 mm and WT-H of 28.4 mm were applied on the weld scans.

6.3.7 Hardware units

The Applus+ RTD Rotoscan AUT system was initially qualified with the PA128 hardware platform, and the data presented in this report has been acquired on this platform. The next generation Applus+ RTD hardware platform, denoted 4G, was introduced for the pipeline girth weld AUT application in relation to the development of the Applus+ RTD IWEX system, and the 4G hardware platform has the same capabilities for



use in the Rotoscan system as the PA128. The main practical difference between the two hardware platforms for this application is considered to be more powerful electronics introduced with the 4G platform. A capability trial has been performed in order to document that the Rotoscan system can equally use the PA128 and the 4G hardware platforms without any degradation in performance. This trial was designed to be in accordance with DNVGL-ST-F101 requirements, with the objective to document that inspection performance with regards to sensitivity and stability can be maintained through a change of the hardware platform as the only variable. In practice, the trials consisted of 2 sets of repeated scans of a reference block and a defective weld, done with 2 almost identical Rotoscan setup where the hardware unit (i.e. PA128 and 4G) was the only difference. The following tests were performed:

- 10 consecutive scans of a reference block with Rotoscan equipped with the PA128 hardware unit.
- 10 consecutive scans of a reference block with Rotoscan equipped with the 4G hardware unit.
- 3 consecutive scans of a defective weld with Rotoscan equipped with the PA128 hardware unit.
- 3 consecutive scans of a defective weld with Rotoscan equipped with the 4G hardware unit.

All scans were done after each other, the same scanner, AUT setup and software was used for all scans. Between the series with different hardware units, the hardware unit was changed on the scanner. This changing operation was done within 10-15 minutes.

The scan results were evaluated for deviations in reference reflector responses, overtrace signal response deviations and reference reflector transit distance deviations. Both hardware platforms should provide the same signal responses and transit distances, within AUT technology inherent fluctuations, with the identical AUT setup. The AUT technology inherent fluctuations of reference reflector responses are ± 2 dB for amplitude responses and ± 0.5 mm for transit distance, in line with DNVGL-ST-F101 requirements.

6.3.8 Guiding band

The Applus+ RTD Rotoscan 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. However, 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 the Rotoscan system can equally use this Z-shaped band and 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 Rotoscan AUT scanner mounted on the Z-shaped band, details are provided in paragraph 6.3.1.

6.3.9 Analysis Considerations

Positions for macro sectioning were chosen at areas within the AUT weld scan files with imperfection indications. Some indications with low pulse-echo response were included in order to evaluate detectability. The qualification data includes a sufficient range of imperfection sizes and imperfection types.

Both the 95% confidence limit for the POD analysis and the 95% limit against under sizing for height sizing evaluation reflects the uncertainties in the analysis. The important uncertainties regarded to influence on the detection performance are briefly mentioned here.


Depth and ligament estimate accuracy have been evaluated from buried imperfections only. Surface breaking ID surface (root) imperfections have in principle no uncertainty in depth estimate accuracy. Surface breaking OD surface (cap) imperfections has depth estimate accuracy identical to the height sizing accuracy. Accuracy in surface ligament estimate is considered as irrelevant for surface breaking imperfections.

For the POD evaluation, a limited number of hit-miss detection data is a main uncertainty factor. As the POD-curve aims to evaluate detection for a range of imperfection heights, data from all of the parts of the height range in question should be present in the analysis. DNVGL-ST-F101 specifies that at least 29 imperfections are required in order to do an independent evaluation, however a higher number might be required if there is a spread in the hit miss data when compared to the model. In principle, the analysis will have more confidence when more hit-miss data is added.

It is important to include some height sizes of disregarded imperfections to the analysis. This is necessary since the imperfection sizes not reported by the NDT-method are evaluated through the POD-analysis. For AUT, the main approach to collect information about these small imperfections is to measure and do macro sections of small imperfections detected with ultrasonic response below the evaluation threshold. It might be challenging to find representative imperfections with response below the lowest evaluation threshold of 20% FSH. This might cause a bias towards the type of imperfections showing large response within the data of small imperfections, which in turn can add uncertainty to the POD-estimate for the smallest imperfection sizes. This applies in particular to analyses of small data samples. At least, for larger imperfections, with heights > 1 mm, the "hit-miss" data and the analysis results are regarded representative for the performance of the system. Some smaller imperfections occasional identified on macro section images, but at the borderline of detection and reporting by AUT, have been included in the POD analysis. As a consequence, the number of observations included in POD analysis and height sizing accuracy evaluation might slightly differ.

It is worth mentioning that imperfection length will influence the POD, as the area of the imperfection surface is the important measure when it comes to reflection of ultrasonic energy. In general, imperfections with a length of less than 4 mm are not included in the analyses.

The analysis is performed as follows: For each weld bevel preparation, a general POD and a height sizing accuracy-figure is shown. The general figure is regarded valid for all parts of the weld. This is the standard approach according to DNVGL-RP-F118 and DNVGL-ST-F101, Appendix E requirements. The analysis is based on a review of each single observation by comparison between AUT and destructive testing/macro results.



The analysis data contains inspection results from several different projects with different parameters on for instance pipe wall thickness, material, transducers etc. In addition, there are different sensitivity in calibration between the channels in the AUT system, for instance through different calibration reflectors at surface and embedded. For this general study, it is therefore not possible to quantify exactly the uncertainties described above. In general, the main part of uncertainty is regarded attributed to POD estimates for imperfection sizes < 1 mm.

It should be noted that issues mentioned above is about analysis and analysis data, and are attributed to the fact that this study is mainly focused on the general, overall performance of the AUT system. When trials and analysis are focused on performance of specific parts of the weld or on specific imperfections, reliable POD estimates can be made for imperfection heights far below 1 mm.

Beside the inherent uncertainties in a limited sample of data, there are some uncertainty attributed to the ultrasonic testing in general. In particular in assessment of imperfections with not optimal orientation or surface for easily interpretable ultrasonic response. These type of imperfections will account for some spread in height sizing measurement, and will influence the POD as well. Furthermore, there is some uncertainty attributed to the reference imperfection heights measured at macro sections. This is mainly uncertainty in picking the correct position at the physical weld, that correspond to the maximum amplitude response of the AUT scan. Several macro sections are usually made in order to account for this uncertainty.

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

7 MULTI PROBE ROTOSCAN AUT RESULTS

7.1 Analysis prerequisites

The analysis is based on information acquired by the Applus+ RTD Rotoscan system with multi probe setup. Some of the trials have been witnessed by DNV. The information includes original AUT weld scans and reports, and macro sectioning images.

In total 406 independent imperfection observations are included in the analysis for the multiple probe system. The data is further broken down on main weld bevel preparation. The observations are distributed as 248 observations on J-bevel welds and 158 on V-bevel welds.

Purely volumetric imperfections are not included in the analysis, which only covers imperfections detected in inspection channels directed on weld bevel. Volumetric imperfections amounts to 18 observations in J-bevel data and 8 observations in the V-bevel data. In addition, disregarded imperfections are usually not sized, and have therefore not been included for height sizing accuracy evaluation. Due to this, the number of observations differs between the POD and the height sizing accuracy analysis. This amounts to 6 observations in J-bevel data and 10 observations in the V-bevel data.

The total number of observations included in analysis on J-bevel welds with volumetric indications not included is 230. 150 independent observations are included for V-preparation welds.

AUT system documentation, including procedures with technique descriptions and reference block drawings, have been reviewed and found satisfactory.

7.2 Detectability (POD) Summary

For each analysis, the POD for the different evaluation thresholds at 20% FSH, 30% FSH and 40% FSH is presented.

Results of general 90%|95% imperfection heights from the analysis for both J- and V-preparation welds are tabulated in Table 7-1 below. Corresponding POD-curves are given later in this section.

Table 7-1: Summary Results Multi Probe 90%|95% POD imperfection heights

AUT Configuration	# Observations	90% 95% Height [mm] at Evaluation threshold		
		40% FSH	30% FSH	20%FSH
J-Bevel	230	2.2	1.6	0.8
V-Bevel	150	2.2	1.2	0.9

7.3 Height Sizing Accuracy Summary

The results are tabulated in Table 7-2 below for J and V bevel preparation welds.

Table 7-2: Summary Results Multi Probe J-Prep Height Sizing Accuracy

AUT Configuration	No. imperfections	Systematic Error / Mean sizing error [mm]	95% limit against under-sizing [mm]
J-Bevel	224	0.0	-1.0
V-Bevel	140	0.1	-1.0

7.4 J Weld Bevel Preparation Multi Probe General Detectability

The general Probability of Detection (POD)-curves reported here is valid for J-type weld bevel preparation at the given evaluation threshold for all the observations, where a calibration against 3 mm Ø FBH for embedded imperfections and 1 mm surface notch at root and cap are used.

POD-curves for detection thresholds at 20%, 30% and 40% are separately reported.

7.4.1 General POD J-Preparation at 40% FSH Evaluation Threshold

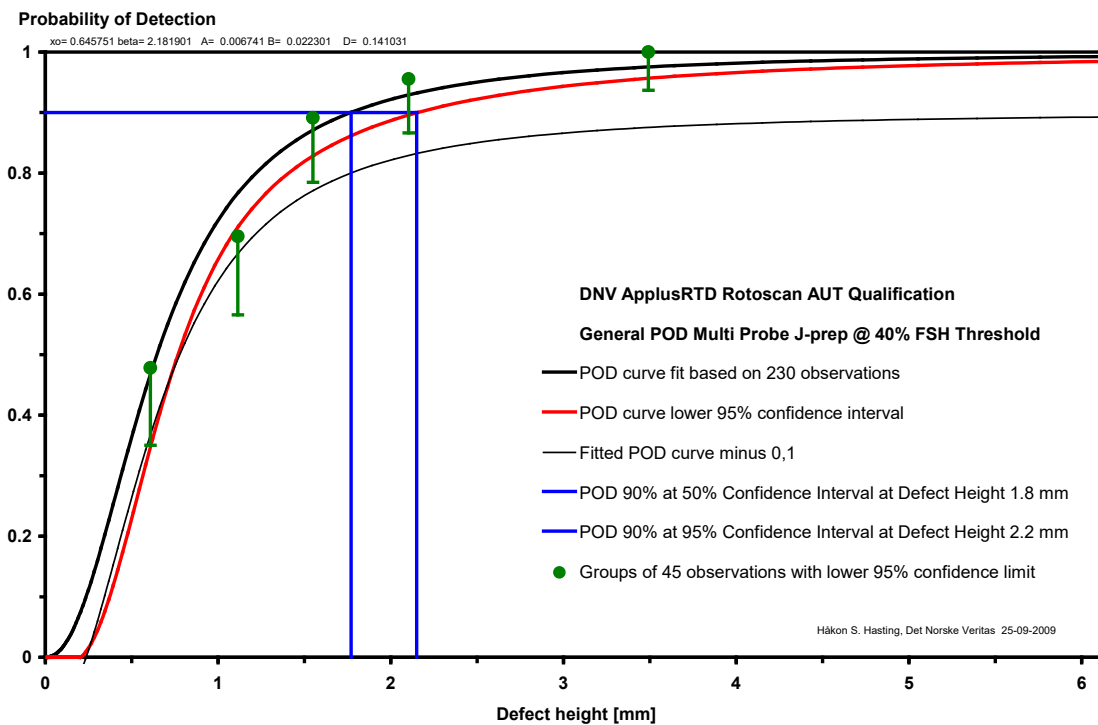


Figure 7-1: General POD Multi Probe J-preparation, 40% FSH detection threshold

With a 40% FSH evaluation threshold applied, the analysis shows a 90% POD with 50% confidence (confidence on average) at 1.8 mm, which is identical to the actual fit to the present results. The 90% POD height with 95% confidence is at 2.2 mm, which can be regarded as the conservative estimate of imperfection height of guaranteed reliable detection.

7.4.2 General POD J-Preparation at 30% FSH Evaluation Threshold

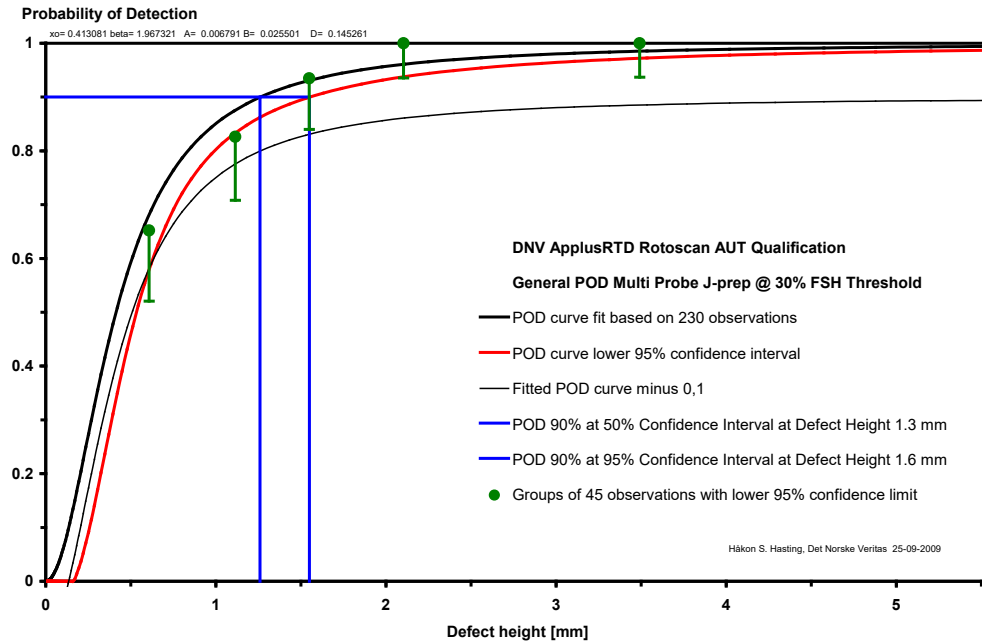


Figure 7-2: General POD Multi Probe J-preparation, 30% FSH detection threshold

With a 30% FSH evaluation threshold applied, the analysis shows the 90% POD with 95% confidence at 1.6 mm. The 90% POD height with 50% confidence is at 1.3 mm.

7.4.3 General POD J-Preparation at 20% FSH Evaluation Threshold

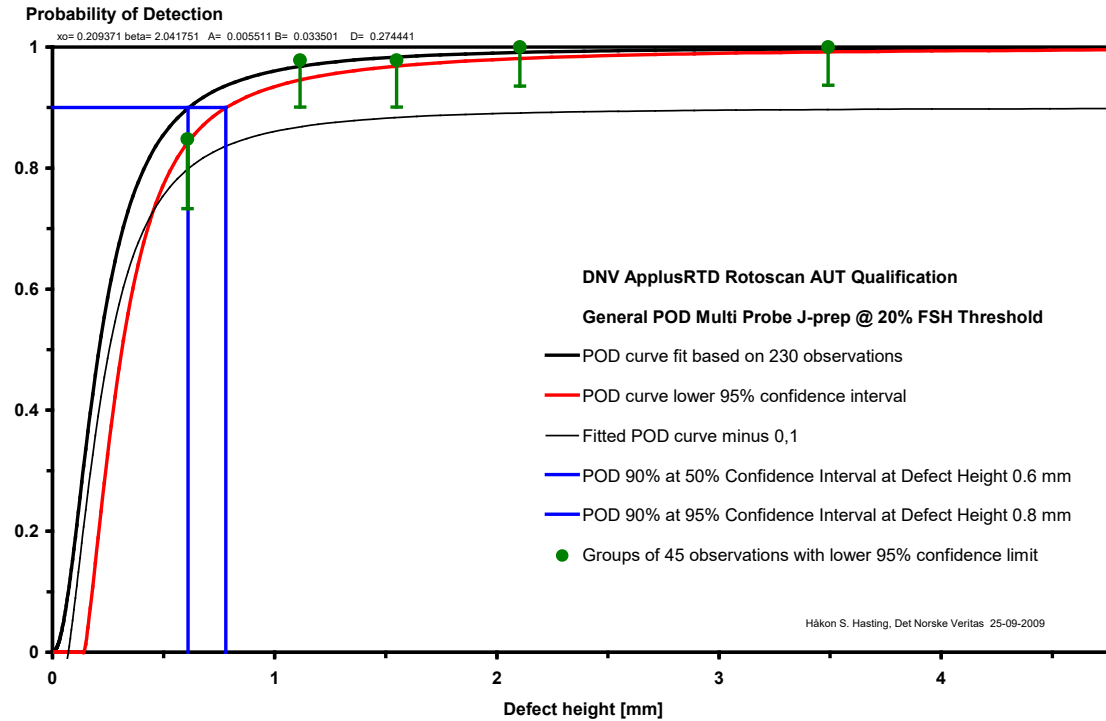


Figure 7-3: General POD Multi Probe J-preparation, 20% FSH detection threshold

With a 20% FSH evaluation threshold applied, the analysis shows the 90% POD with 95% confidence at 0.8 mm. The 90% POD height with 50% confidence is found at 0.6 mm.

7.5 Multi Probe J-Type Weld Bevel General Height Sizing Accuracy

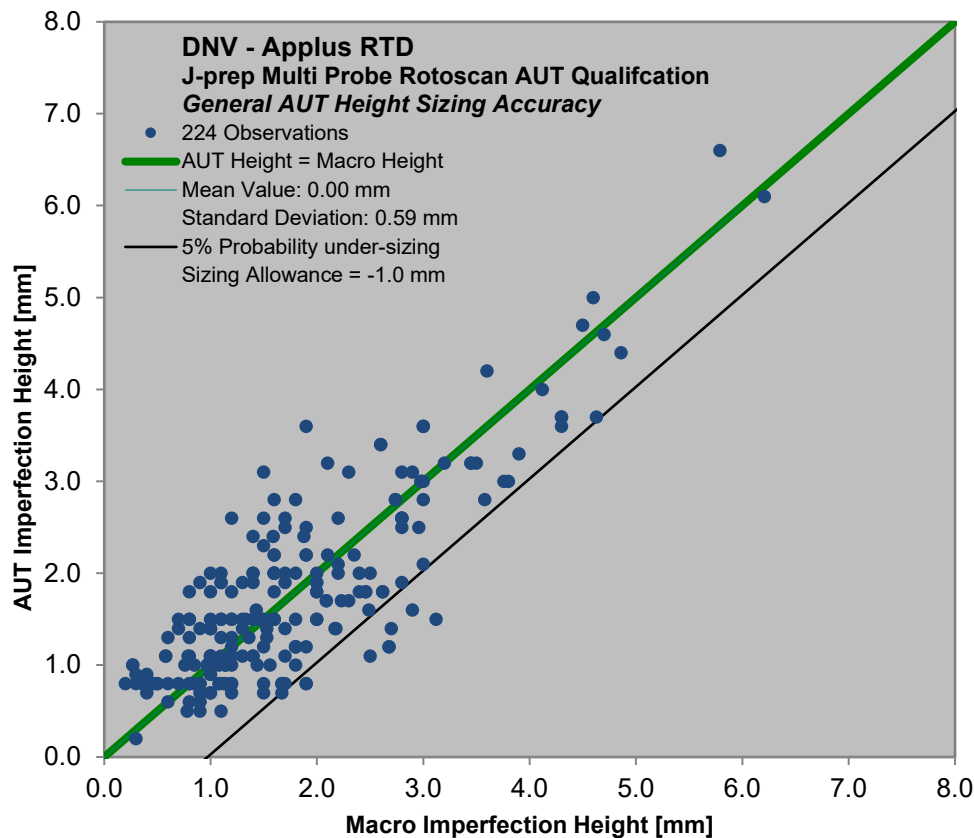


Figure 7-4: General height sizing accuracy, Multi Probe J-preparation

In general for the Multi Probe Applus+ RTD Rotoscan AUT system no systematic under or over sizing is found, and the 95% limit against under-sizing are found at -1.0 mm under sizing. This is the main result attributed to imperfection height sizing for J bevel preparation welds for the Multi Probe Rotoscan AUT system when applied according to DNVGL-ST-F101.

7.6 Depth and Ligament Position Accuracy, J-bevel

The inaccuracy in depth position estimate is on average 0.48 mm, with a standard deviation of 1.43 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 +2.8 mm and -1.9 mm, as shown in Figure 7-5. The results are valid for buried imperfections in general.

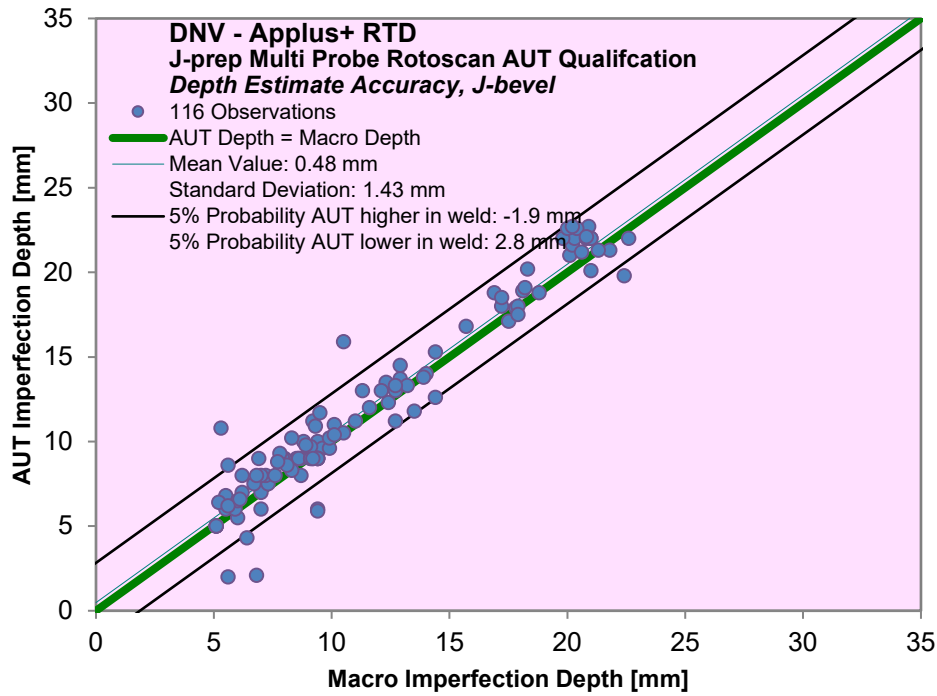


Figure 7-5: Depth estimate accuracy plot

The inaccuracy in surface ligament estimate for buried imperfections is on average -0.25 mm, with a standard deviation of 1.58 mm. The Rotoscan AUT reported surface ligament is mainly estimated at accuracy within +2.4 mm and -2.9 mm, as shown in Figure 7-5. 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.

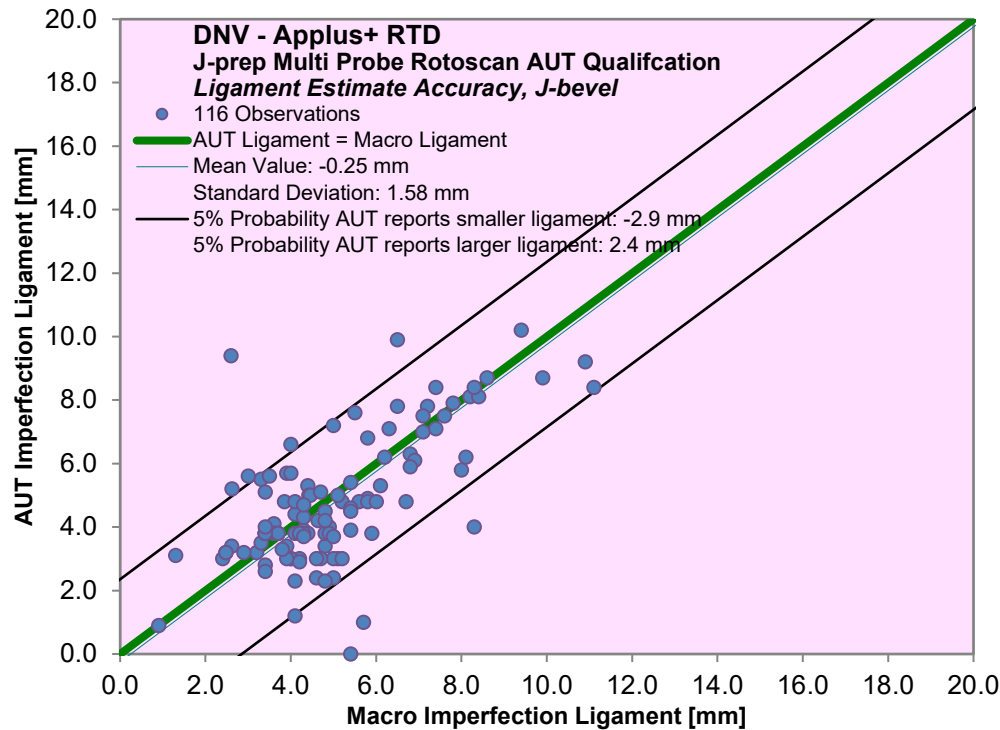


Figure 7-6: Buried imperfections ligament estimate accuracy, J-bevel

7.7 Detection of Volumetric Imperfections, J-Bevel

Volumetric imperfections are properly detected by the AppusRTD Rotoscan Multi Probe AUT system, applied for J bevel preparation welds. Detection of purely volumetric imperfections is not included in the general POD. This is due to the sensitive and complementary detection abilities for this kind of imperfections by TOFD and mapping channels, and to a need of a breakdown to position and type of imperfections in order to give a fair description. It might be hard to locate imperfections disregarded by the sensitive ToFD and mapping channels when the signal in the pulse-echo channels are low.

The detection limit for volumetric imperfections appears to be at small and short imperfections, typically small pores.

7.8 V Weld Bevel Preparation Multi Probe General Detectability

The general Probability of Detection (POD)-curves reported here is valid for V-type weld bevel preparation at the given evaluation threshold for all the observations where a calibration against 3 mm Ø FBH for embedded imperfections and 1 mm surface notch at root and cap are used.

POD-curves for evaluation thresholds at 20% FSH, 30% FSH and 40% FSH are separately reported.

7.8.1 General POD V-Preparation at 40% FSH Evaluation Threshold

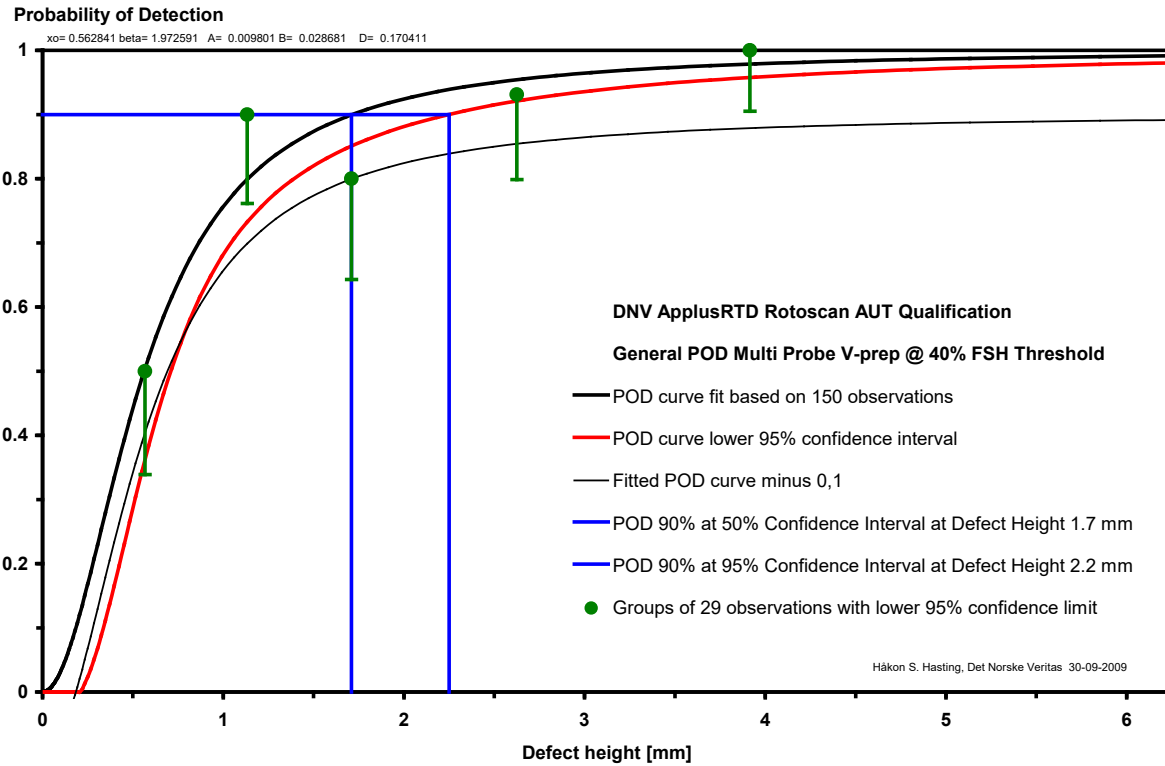


Figure 7-7: General POD Multi Probe V-preparation, 40% FSH detection threshold

With a 40% FSH evaluation threshold applied at inspection, the analysis shows a 90% POD with 50% confidence (confidence on average) at 1.8 mm, which is identical to the actual fit to the present results. The 90% POD height with 95% confidence is at 2.7 mm, which can be regarded as the conservative estimate of imperfection height of guaranteed reliable detection.

7.8.2 General POD V-Preparation at 30% FSH Evaluation Threshold

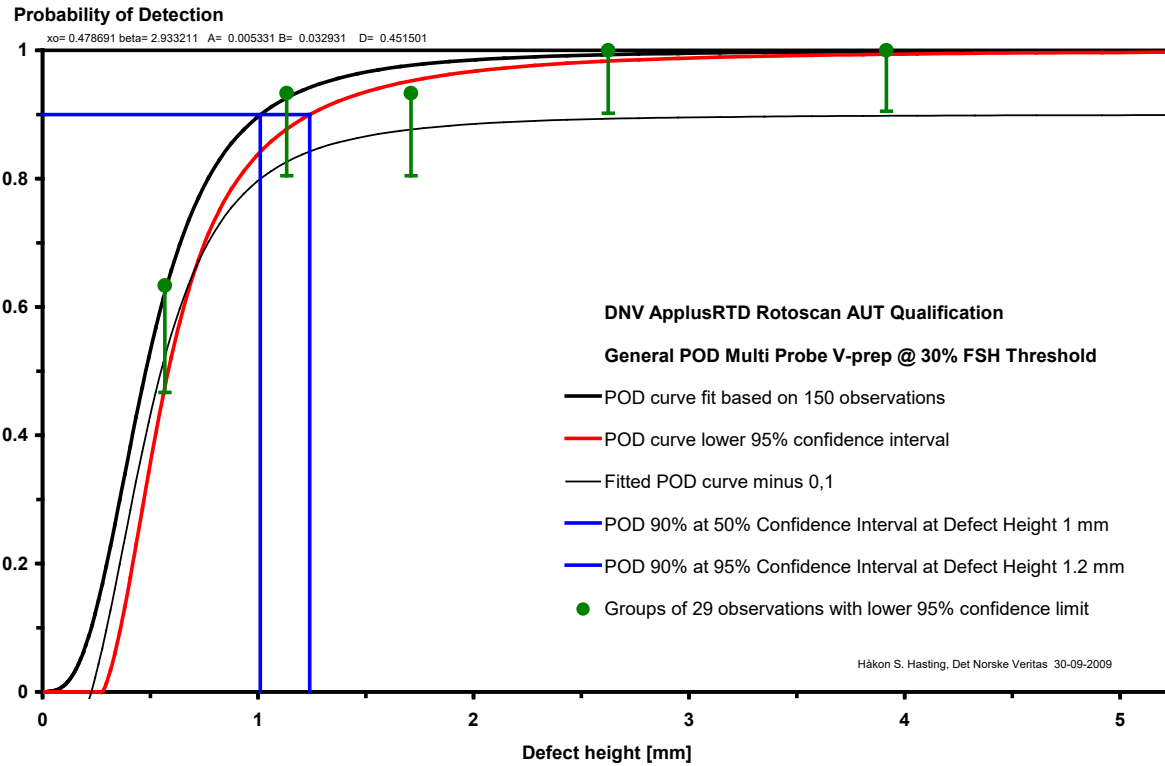


Figure 7-8: General POD Multi Probe V-preparation, 30% FSH detection threshold

With a 30% FSH evaluation threshold applied at inspection, the analysis shows the 90% POD with 95% confidence at 1.2 mm. The 90% POD height with 50% confidence is at 1.0 mm.

7.8.3 General POD V-Preparation at 20% FSH Evaluation Threshold

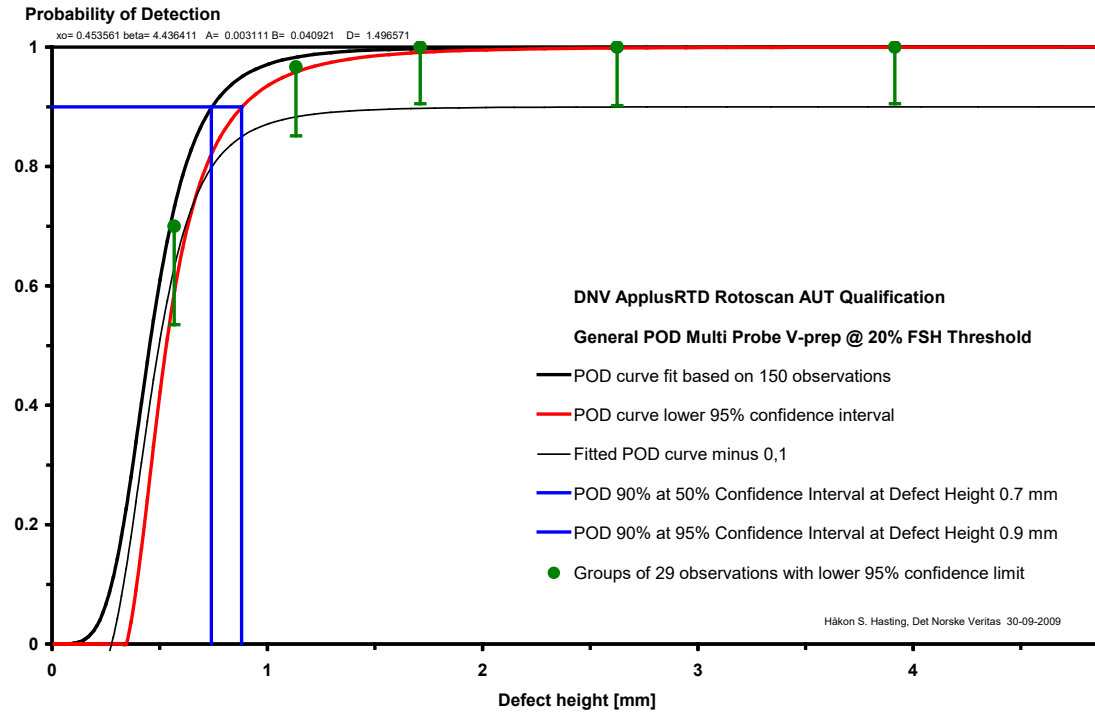


Figure 7-9: General POD Multi Probe V-preparation, 20% FSH detection threshold

With a 20% FSH evaluation threshold applied at inspection, the analysis shows the 90% POD with 95% confidence at 0.9 mm. The 90% POD height with 50% confidence is found at 0.7 mm.

7.9 Multi Probe V-Type Weld Bevel General Height Sizing Accuracy

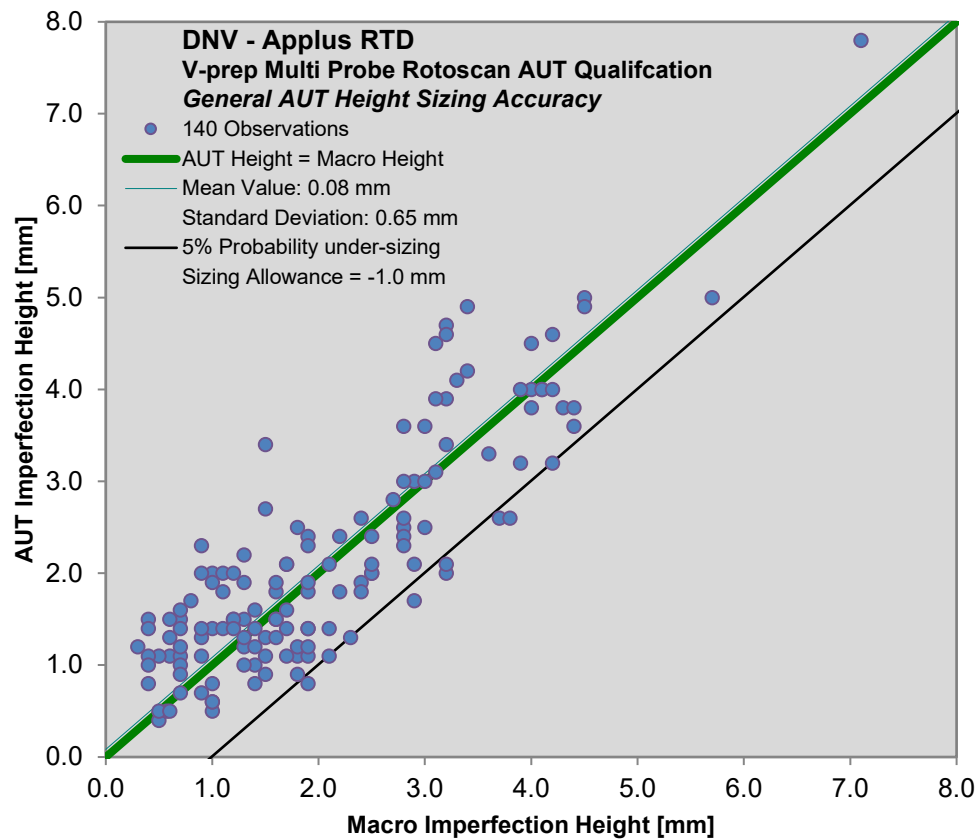


Figure 7-10: General height sizing accuracy, Multi Probe V-preparation

In general for the Multi Probe Applus+ RTD Rotoscan AUT system no significant systematic under or over sizing is found, and the 95% limit against under-sizing are found at about -1.0 mm under sizing. This is the main result attributed to imperfection height sizing for V bevel preparation welds for this AUT system when applied according to DNVGL-ST-F101.

7.10 Depth and Ligament Position Accuracy, V-bevel

The inaccuracy in depth position estimate is on average -1.7 mm, with a standard deviation of 2.07 mm. The positive average value means that AUT tends to indicate the defect position lower in the weld than the actual position. The AUT reported defect depth is mainly estimated at accuracy within +1.7 mm and -5.1 mm, as shown in Figure 7-11. The results are valid for buried imperfections in general.

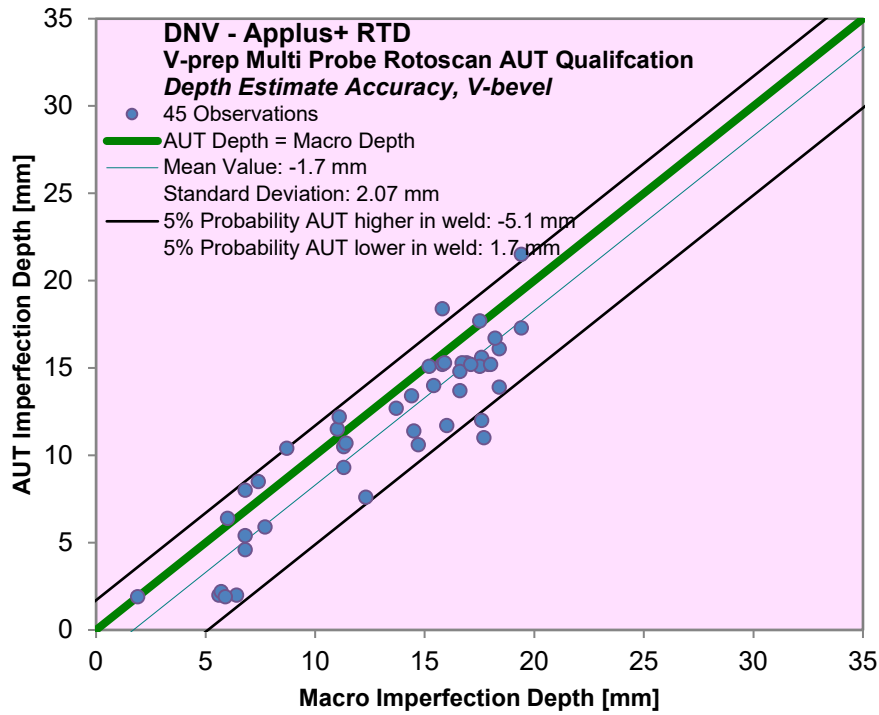


Figure 7-11: Depth estimate accuracy plot, V-bevel

The inaccuracy in surface ligament estimate for buried imperfections is on average 0.85 mm, with a standard deviation of 2.50 mm. The Rotoscan AUT reported surface ligament is mainly estimated at accuracy within +4.9 mm and -3.3 mm, as shown in Figure 7-12. 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.

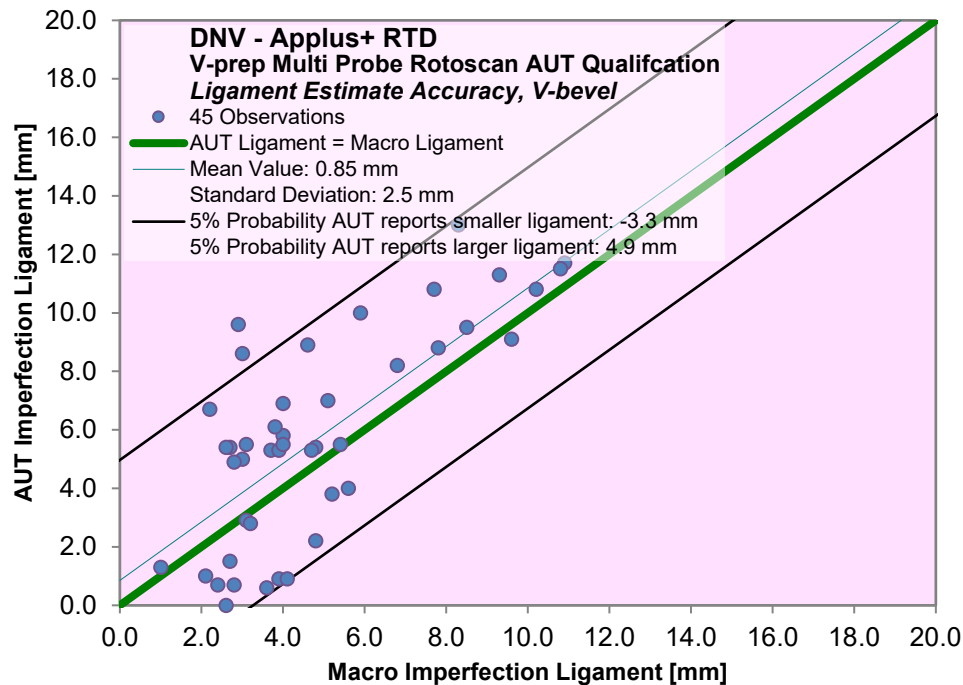


Figure 7-12: Buried imperfections ligament estimate accuracy, V-bevel

7.11 Detection of Volumetric Imperfections, V-Bevel

Volumetric imperfections are properly detected by the Appus RTD Rotoscan Multi Probe AUT system, applied for V bevel preparation welds.

The detection limit for volumetric imperfections appears to be at small and short imperfections, typically small pores.

7.12 Multi Probe Length Sizing Accuracy, J&V Bevel

The figure below shows the results of length sizing accuracy by the multi probe Rotoscan system, valid for both J and V Bevel setups. Among in total 30 imperfections with length measured by macro sectioning, 16 of them were AUT sized with a evaluation threshold of 20% FSH and 14 with a 40% FSH evaluation threshold, for imperfection end location. The majority of the imperfections investigated were between 10 and 60 mm long.

For further length sizing accuracy evaluation, the data with 20% FSH and 40% FSH threshold settings were analysed separately. The result show a tendency of some systematic over sizing with 1.8 mm of imperfections with length evaluated at 20% FSH, while the same magnitude of under sizing, -1.9 mm, is systematically found for 40% FSH length evaluation threshold. The tendency of a higher occurrence of under

sizing when using a higher threshold for length sizing is as expected. It is worth mentioning that only a limited number of imperfections have been evaluated, and one outlier of the length measurements might have been given a disproportionately weight in the analysis for 40% FSH. However, if this measurement is removed, the tendency of under sizing at 40% FSH is still maintained.

It is observed a less than 5% probability of having an under sizing of more than 3 mm for a imperfection length with an applied length sizing threshold of 20 % FSH.

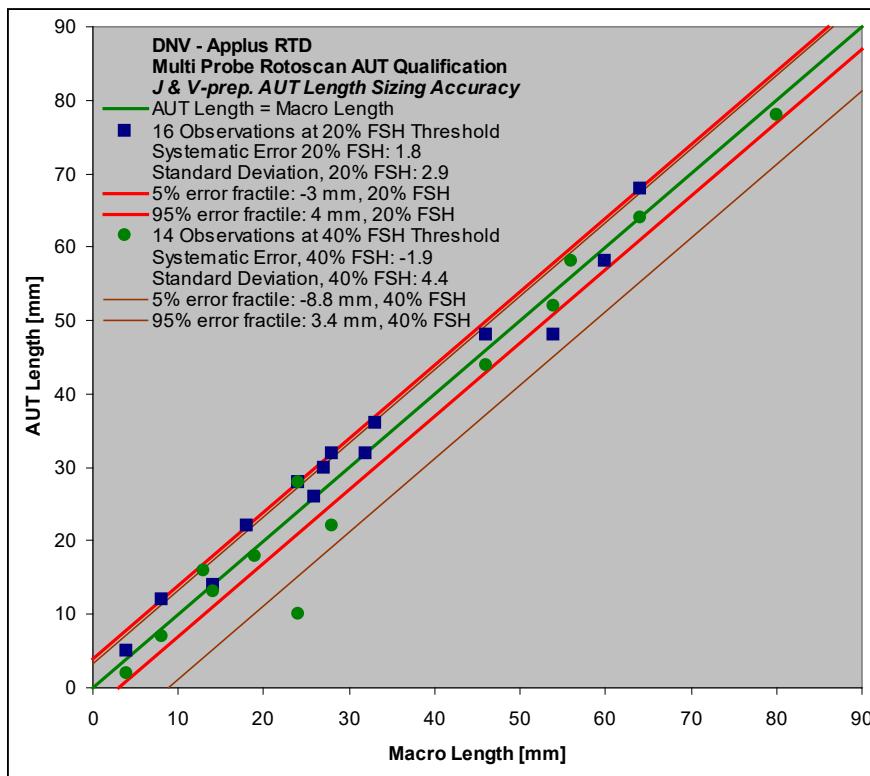


Figure 7-13: Multi Probe length sizing accuracy

7.13 Probability of Rejection Analysis

POR is calculated from the same set of observations as the POD analysis, as described in chapter 7.1. The figure below shows how the estimated POR-values at 50% and 85%, both at 95% confidence level, vary with increasingly set POR threshold. The 50% POR-value is the imperfection size that will be rejected on average, which might serve as a useful benchmark on how the system performs compared to the threshold AUT height. POR can be presented the same way as POD, as a curve for POR vs real imperfection height. In the figures below, the results at 85%|95% POR and 50%|95% POR are given for varying AUT imperfection height rejection thresholds at both J and V bevel preparation. For instance, according to the figure for J-bevel preparation, if all imperfections with reported AUT height of 2 mm are rejected, one can expect to reject imperfections with height of 2.8 mm on average. Here, the X-axis denoted AUT height rejection limit

is attributed to the AUT reported height. The results on the 50%|95% POR values suggests that AUT rejection threshold shows good accordance with the real imperfection size on average.

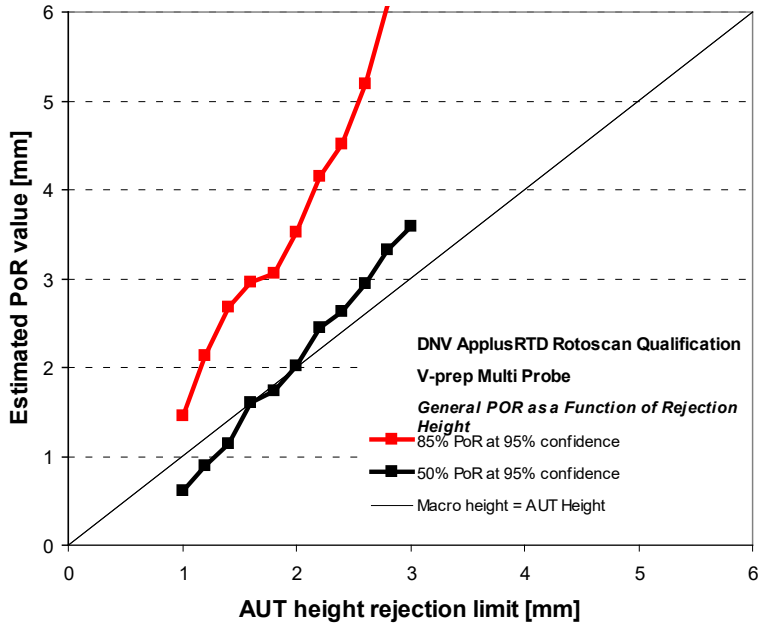


Figure 7-14: Multi Probe V-preparation results of POR-analysis, varying rejection limits of AUT reported height.

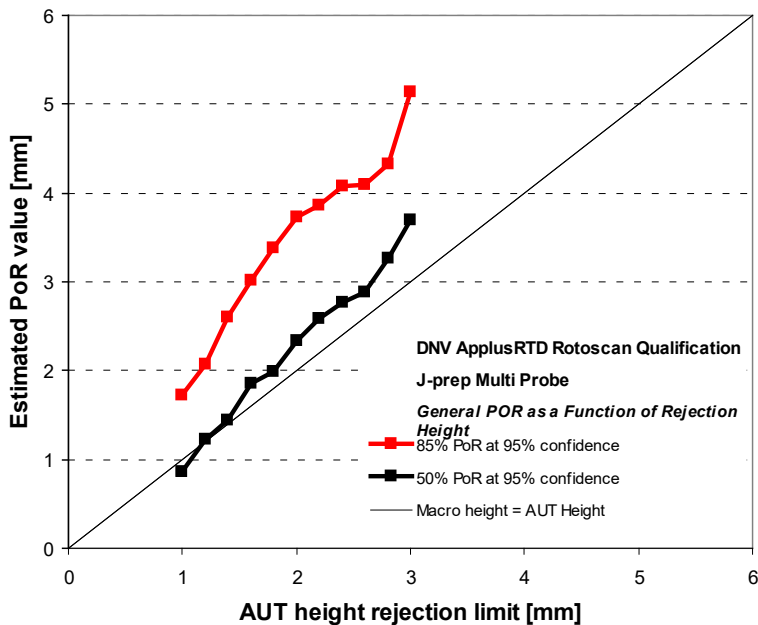


Figure 7-15: Multi Probe J-preparation results of POR-analysis, varying rejection limits of AUT reported height.

7.14 Repeatability

7.14.1 Reference block repeated Scans

The pre-examination repeatability test scans on calibration blocs show sufficient consistency for repeated scans, with no deviation from initial scan more than ± 2 dB. In general, the test scan series are found to give deviations well within ± 1 dB. No evident differences in repeatability are seen between the scan series of different conditions, e.g. 12 o'clock, 6 o'clock, vertical (2G) or 45 degree (6G) positions. The same applies for the 1mm offset scans performed. Some results of these trials can be found in Appendix 3.

7.14.2 Band Offset Trials

The ± 1 mm band offset scans on reference blocks show in general consistency for repeated scans with band offset. With the V-bevel configuration, the observations are found within ± 2 dB, with J-bevel, some of the observations exceed ± 2 dB. The observed deviations within the J-bevel configuration are considered to be attributed to the specific setup used for the trial, and shall not be regarded as an inherent property of the Rotoscan equipment. Results of these trials can be found in Appendix 3.

8 PHASED ARRAY ROTOSCAN SYSTEM RESULTS

8.1 Analysis prerequisites

Positions for macro sectioning were chosen at areas within the AUT weld scan files with imperfection indications. Some indications with low pulse-echo response were included in order to evaluate detectability. The qualification data includes a sufficient range of imperfection sizes and imperfection types. In total 332 independent imperfection observations are included in the analysis for the AUT phased array system. The data is further broken down on main weld bevel preparation. The observations are distributed as 160 observations on J-bevel welds and 172 on V-bevel welds.

Purely volumetric imperfections are not included in the analysis, which only covers imperfections detected in inspection channels directed on weld bevel. Volumetric imperfections amounts to 11 observations in J-bevel data and 15 observations in the V-bevel data. In addition, disregarded imperfections are usually not sized, and have therefore not been included for height sizing accuracy evaluation. Due to this, the number of observations differs between the POD and the height sizing accuracy analysis. This amounts to 12 observations in J-bevel data and 5 observations in the V-bevel data.

The total number of observations included in analysis on J-bevel welds with volumetric indications not included is 149. 157 independent observations are included for V-preparation welds. In total for both J and V bevel this amounts to 306 indications.

AUT system documentation, including procedures with technique descriptions and reference block drawings, have been reviewed and found satisfactory.

8.2 Detectability

For each analysis, the POD for the different evaluation levels at 20% FSH, 30% FSH and 40% FSH. In case that the results from the POD analysis find insufficient support in the data material, the general POD figure is recommended valid. This is seen to concern evaluation of detectability at cap, where there are few imperfections within the data sets.

For J-preparation welds, general phased array POD including data from both J and V-preparation welds are regarded as valid. This is because of similarities seen between the J and V types of data, and is done in order to strengthen the POD analysis for J-preparation. This is the reason for the difference in number of imperfections used for POD and height sizing accuracy evaluation reported.

Results of 90%|95% imperfection heights valid for both J- and V-preparation welds are tabulated in Table 8-1 below. Corresponding POD-curves are given later in this section.

Table 8-1: Summary Results Phased Array J-Prep 90%|95% POD imperfection heights

AUT Configuration	# Observations	90% 95% Height [mm] at Evaluation threshold		
		40% FSH	30% FSH	20%FSH
J-Bevel	306	1.7	1.4	1.1
V-Bevel	157	2.2	1.9	1.3

8.3 Height Sizing Accuracy

The results are tabulated below for J and V bevel preparation welds in Table 8-2.

Table 8-2: Summary Results Phased Array J-Prep Height Sizing Accuracy

AUT Configuration	No. imperfections	Systematic Error / Mean sizing error [mm]	95% limit against under-sizing [mm]
J-Bevel	137	0.2	-0.7
V-Bevel	152	0.0	-1.0

8.4 J Bevel Phased Array General Detectability

The general Probability of Detection (POD)-curves reported here is valid for J-type weld bevel preparation at the given evaluation level for all the observations where calibration against 3 mm Ø FBH for embedded imperfections and 1 mm notches for surface imperfections are used. PE-response from reference reflectors was set to 80% FSH. Due to few imperfections showing ultrasonic response below threshold, detectability (POD) has been evaluated from data from both V and J-preparation welds. Although the results appears as reasonable, it is recommended to add more data from small imperfections for J-preparation welds inspected by the Rotoscan system with phased array probes.

The general POD-curve is regarded as valid for the system for the whole weld, and is the main result for the Phased Array Rotoscan system when it comes to detectability of the J-bevel.

POD-curves for detection thresholds at 20%, 30% and 40% are separately reported.

8.4.1 General POD J-Preparation at 40% FSH Evaluation level

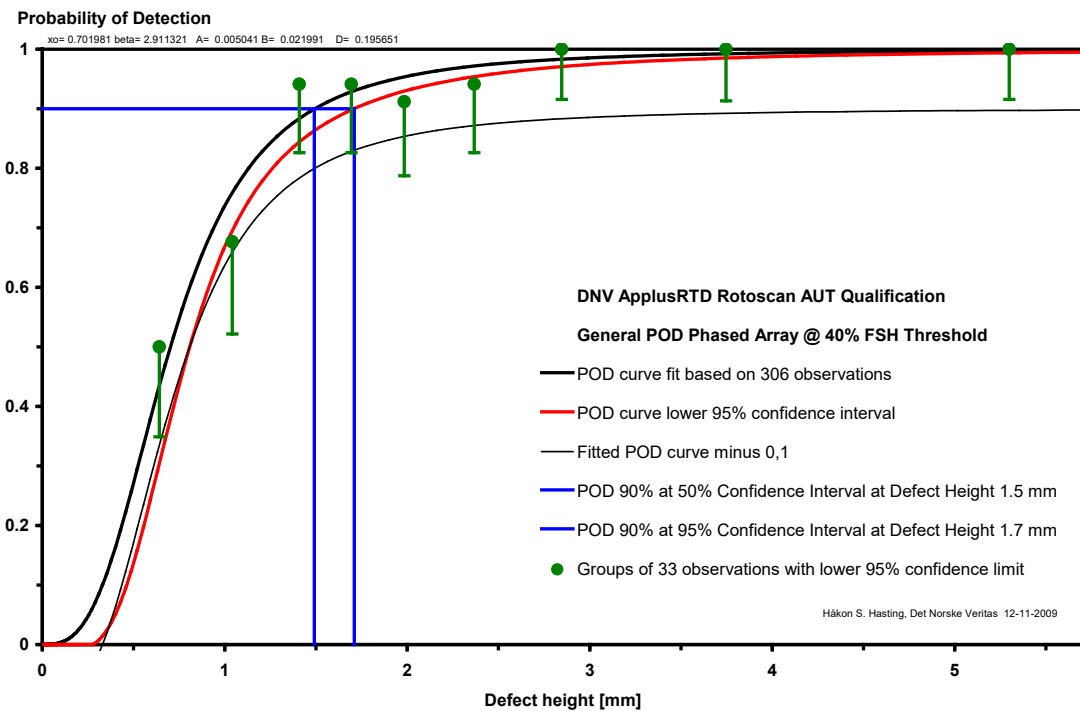


Figure 8-1: General POD Phased Array, 40% FSH detection threshold

With a 40% FSH evaluation level applied, the analysis shows a 90% POD with 50% confidence (confidence on average) at 1.5 mm, which is identical to the actual fit to the present results. The 90% POD height with 95% confidence is at 1.7 mm, which can be regarded as the conservative estimate of imperfection height of guaranteed reliable detection.

8.4.2 General POD J-Preparation at 30% FSH Evaluation level

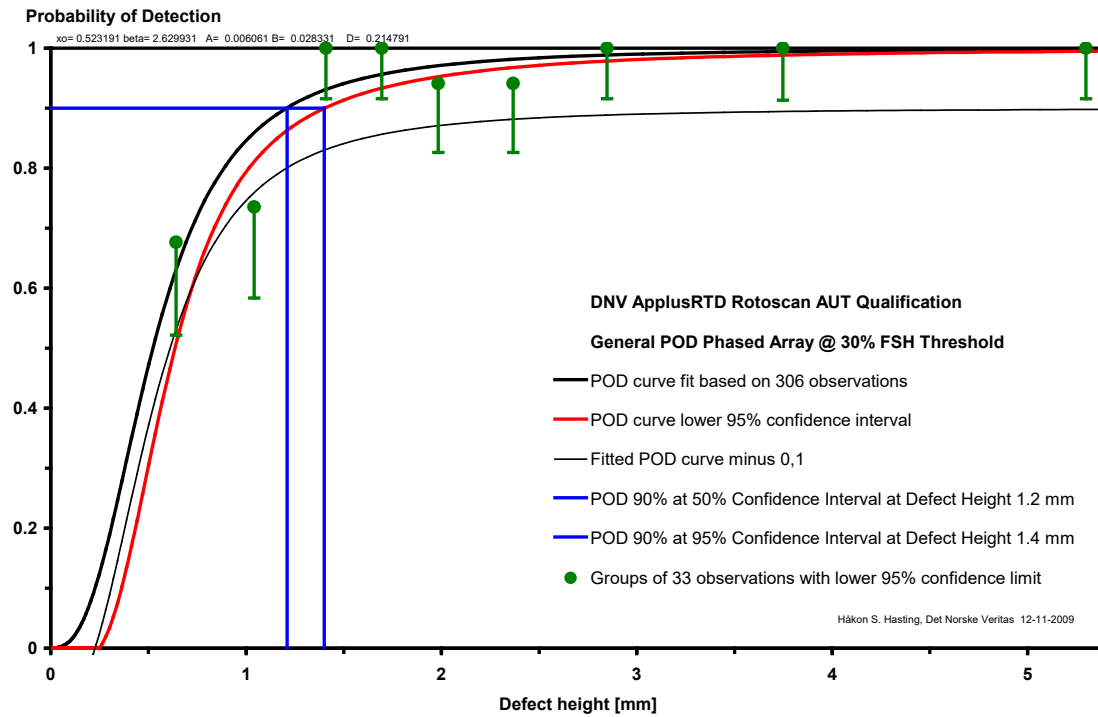


Figure 8-2: General POD Phased Array, 30% FSH detection threshold

With a 30% FSH evaluation level applied, the analysis shows the 90% POD with 95% confidence at 1.4 mm. The 90% POD height with 50% confidence is at 1.2 mm.

8.4.3 General POD J-Preparation at 20% FSH Evaluation level

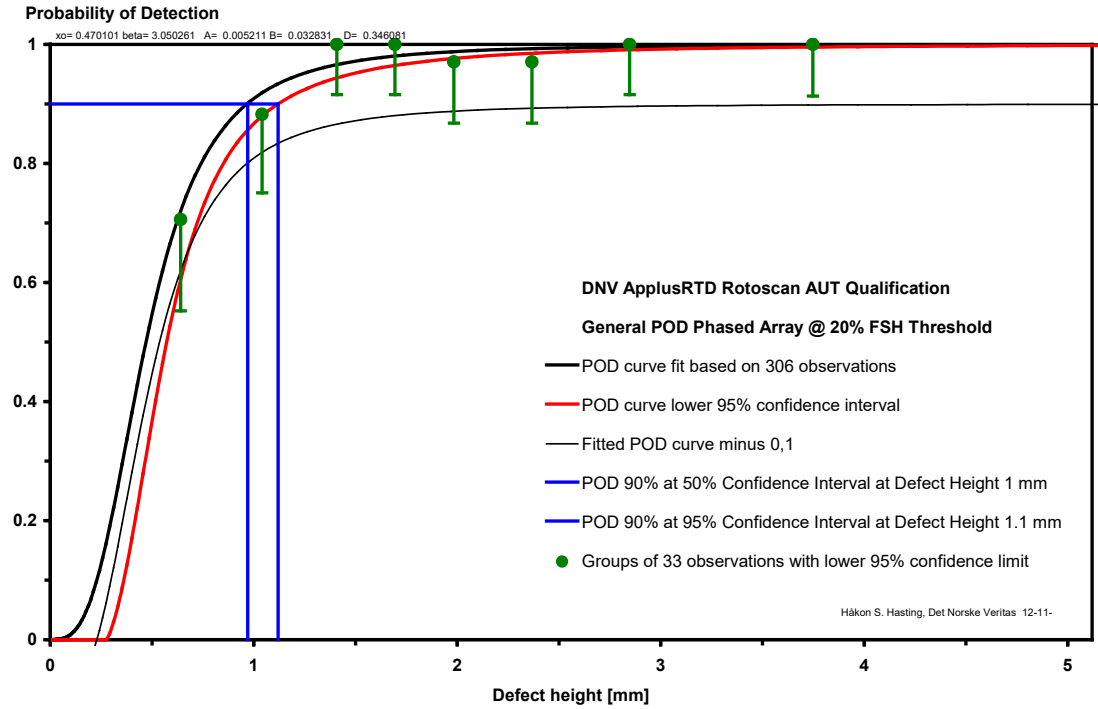


Figure 8-3: General POD Phased Array, 20% FSH detection threshold

With a 20% FSH evaluation level applied, the analysis shows the 90% POD with 95% confidence at 1.1 mm. The 90% POD height with 50% confidence is found at 1.0 mm.

8.5 Phased Array J-Type Weld Bevel General Height Sizing Accuracy

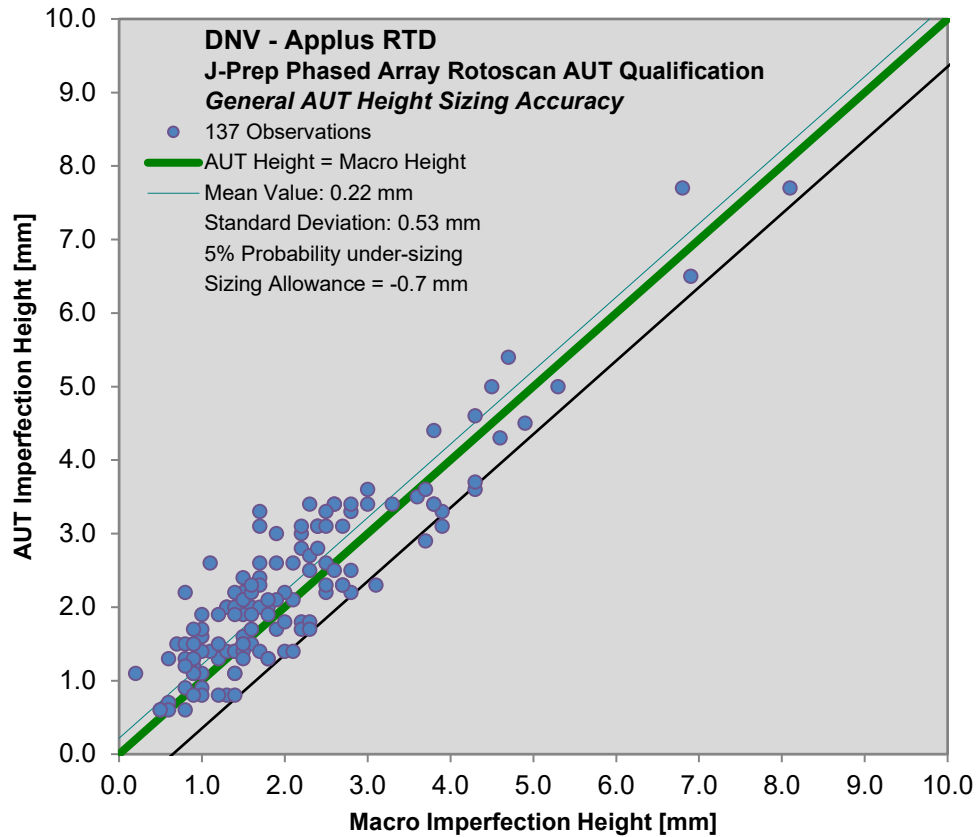


Figure 8-4: General height sizing accuracy, Phased Array J-preparation.

In general for the Phased Array Applus+ RTD Rotoscan AUT system a systematic over sizing of 0.2 mm is found, and the 95% limit against under-sizing are found at -0.7 mm under sizing. This is the main result attributed to imperfection height sizing for J bevel preparation welds for this AUT system when applied according to DNVGL-ST-F101.

8.6 Depth and Ligament Position Accuracy, J-bevel

The inaccuracy in depth position estimate is on average 0.46 mm, with a standard deviation of 0.98 mm. The positive average value means that AUT tends to indicate the defect position lower in the weld than the actual position. The AUT reported defect depth is mainly estimated at accuracy within +2.1 mm and -1.2 mm, as shown in Figure 7-5. The results are valid for buried imperfections in general.

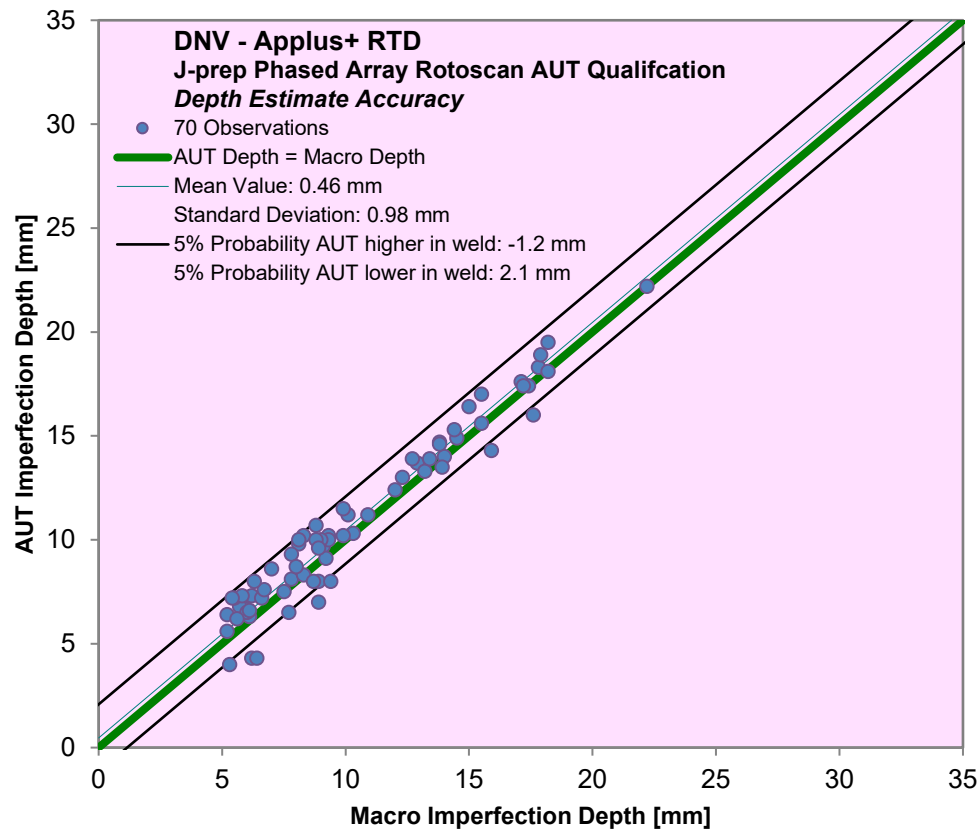


Figure 8-5: Depth estimate accuracy plot

The inaccuracy in surface ligament estimate for buried imperfections is on average -0.15 mm, with a standard deviation of 1.11 mm. The Rotoscan AUT reported surface ligament is mainly estimated at accuracy within +1.7 mm and -2.0 mm, as shown in Figure 7-5. 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.

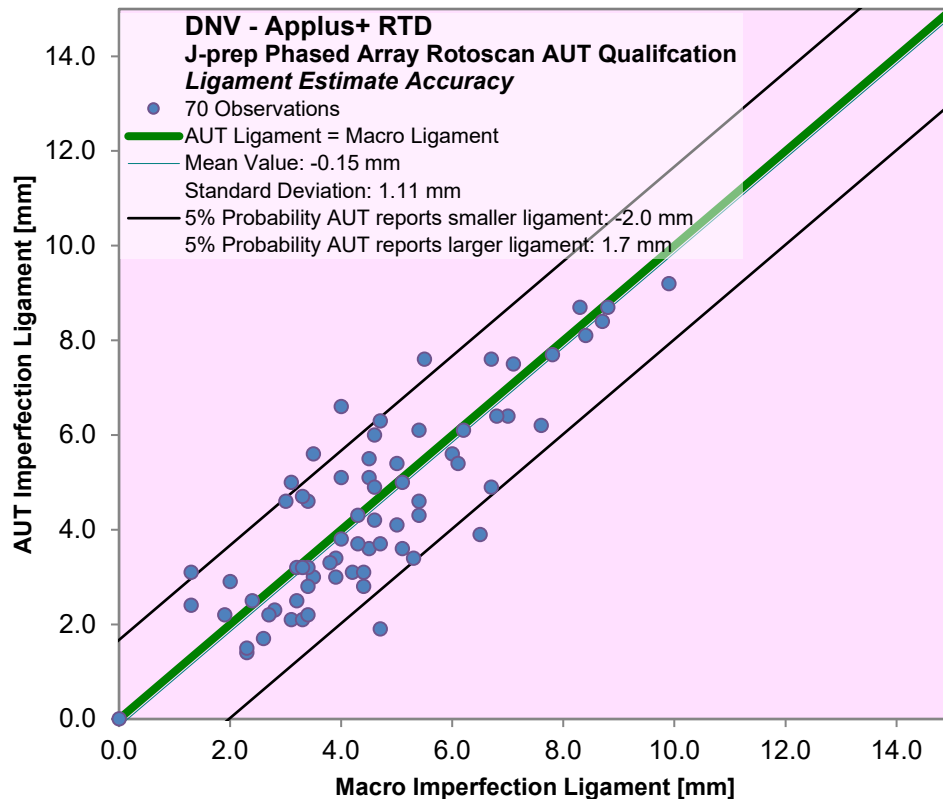


Figure 8-6: Buried imperfections ligament estimate accuracy, J-bevel

8.7 Detection of Volumetric Imperfections

Volumetric imperfections are properly detected by the AppusRTD Rotoscan Phased Array AUT system, applied for J bevel preparation welds. Detection of purely volumetric imperfections is not included in the general POD. However, a POD for the volumetric imperfections is probably irrelevant to make. This is due to the sensitive and complementary detection abilities for this kind of imperfections by TOFD and mapping channels, and to a need of a breakdown to position and type of imperfections in order to give a fair description.

The detection limit for volumetric imperfections appears to be at small and short imperfections, typically small pores. Detection of Cu-inclusions has not been evaluated specifically, but in general this type of imperfection is observed to be well detected by mapping channels and TOFD channel in the Rotoscan AUT system.

8.8 V Weld Bevel Preparation Phased Array General Detectability

The general Probability of Detection (POD)-curves reported here are valid for V-type weld bevel preparation at the given evaluation level, for inspection where a calibration against 3 mm Ø FBH reflectors for embedded

channels and 1 mm surface notches are used. The general POD-curve is regarded as valid for the system for the whole weld, and is the main result for the Phased Array Rotoscan system when it comes to detectability of the V-bevel.

POD-curves for detection thresholds at 20%, 30% and 40% are separately reported.

8.8.1 General POD V-Preparation at 40% FSH Evaluation level

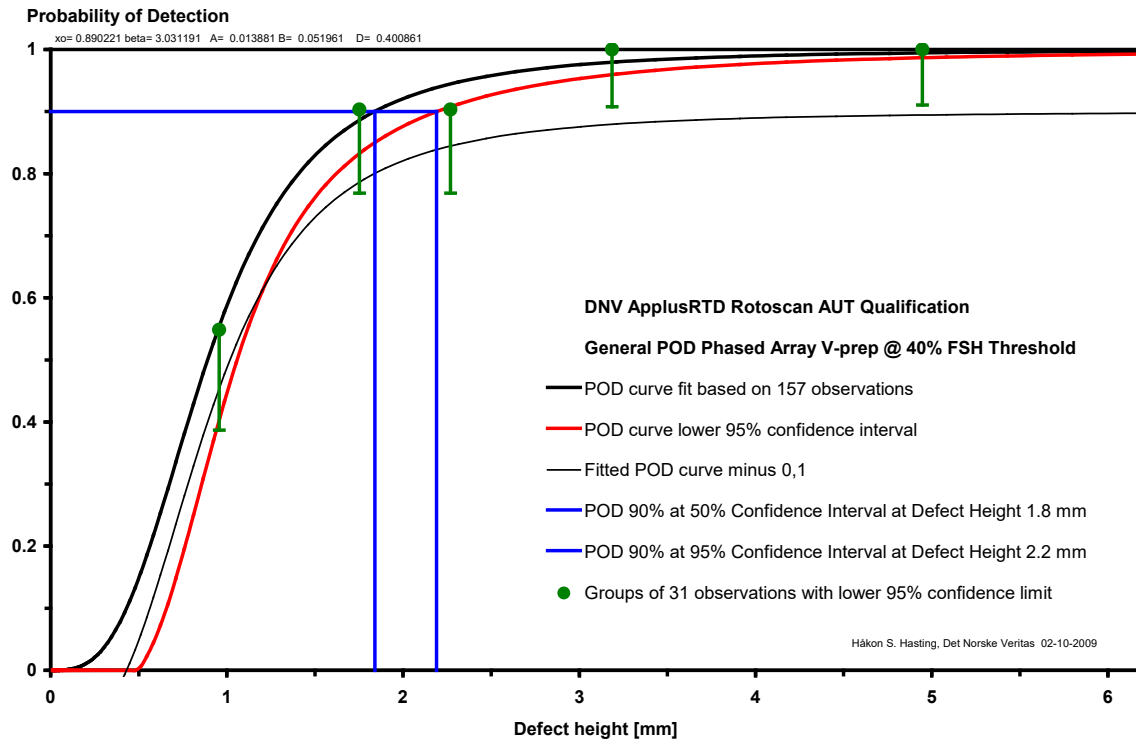


Figure 8-7: General POD Phased Array V-preparation, 40% FSH detection threshold.

With a 40% evaluation level applied at inspection, the analysis shows a 90% POD with 50% confidence (confidence on average) at 1.8 mm, which is identical to the actual fit to the present results. The 90% POD height with 95% confidence is at 2.2 mm, which can be regarded as the conservative estimate of imperfection height of guaranteed reliable detection.

8.8.2 General POD V-Preparation at 30% FSH Evaluation level

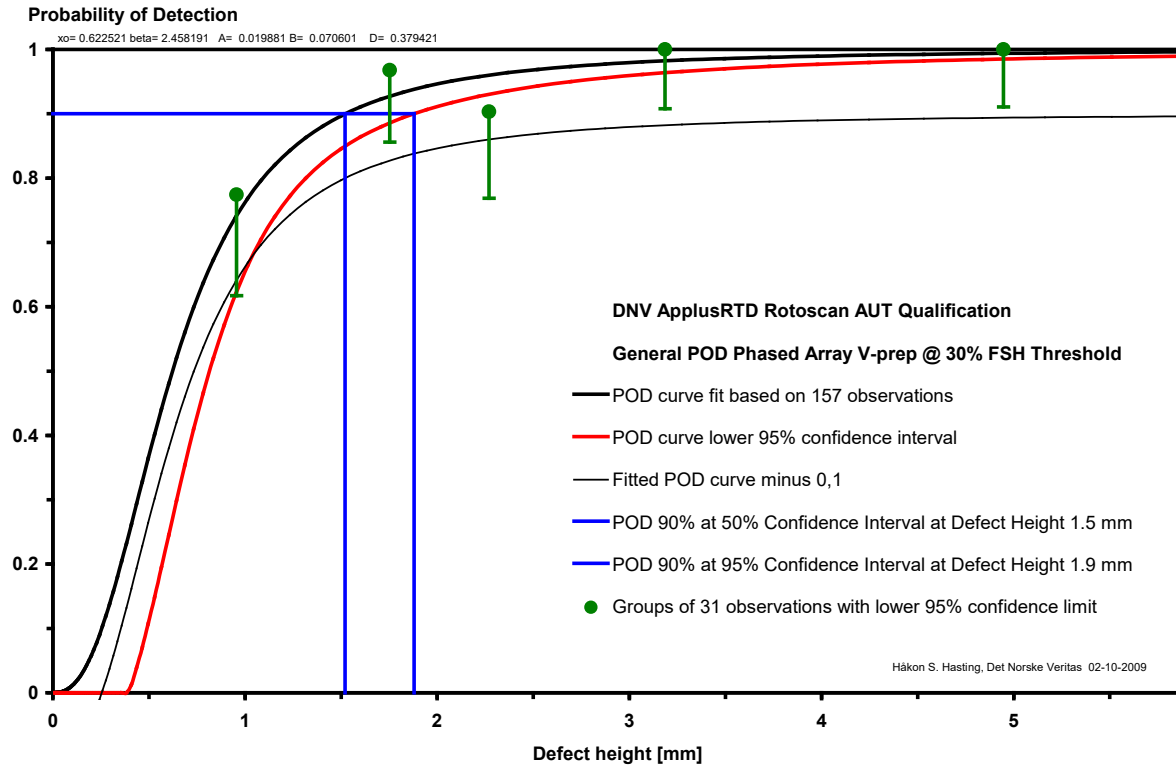


Figure 8-8: General POD Phased Array V-preparation, 30% FSH detection threshold.

With a 30% evaluation level applied at inspection, the analysis shows the 90% POD with 95% confidence at 1.9 mm. The 90% POD height with 50% confidence is at 1.5 mm.

8.8.3 General POD V-Preparation at 20% FSH Evaluation level

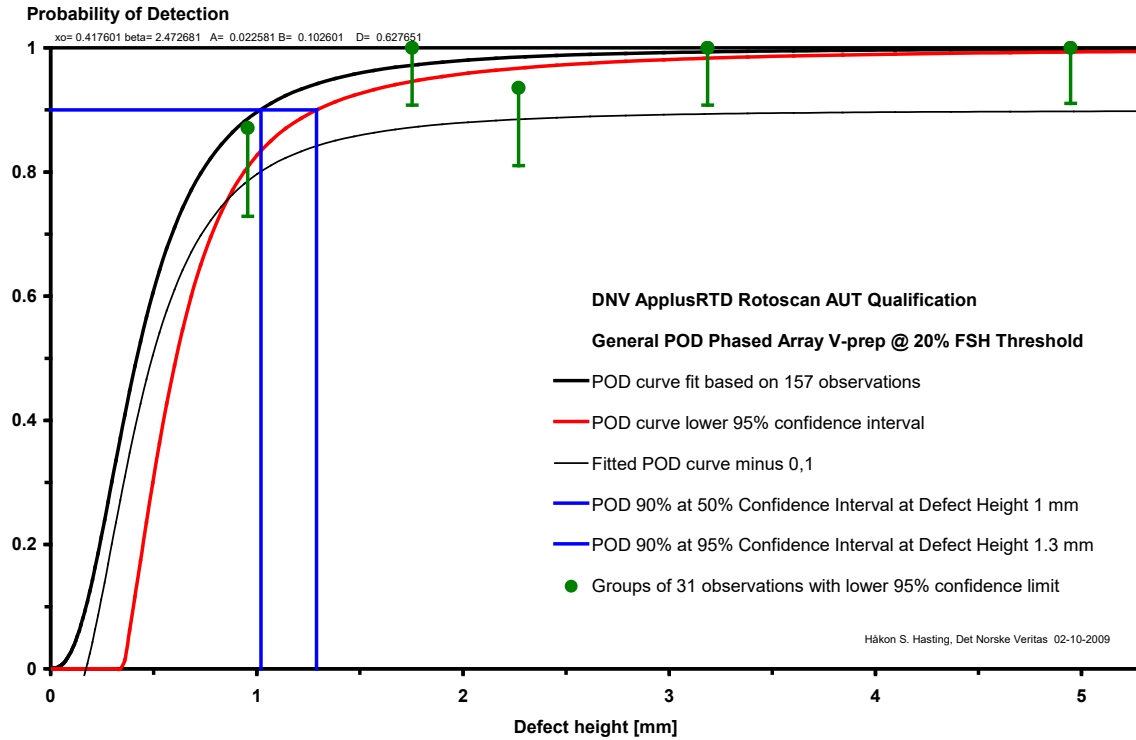


Figure 8-9: General POD Phased Array V-preparation, 20% FSH detection threshold.

With a 20% evaluation level applied at inspection, the analysis shows the 90% POD with 95% confidence at 1.3 mm. The 90% POD height with 50% confidence is found at 1.0 mm.

8.9 Phased Array V-Type Weld Bevel General Height Sizing Accuracy

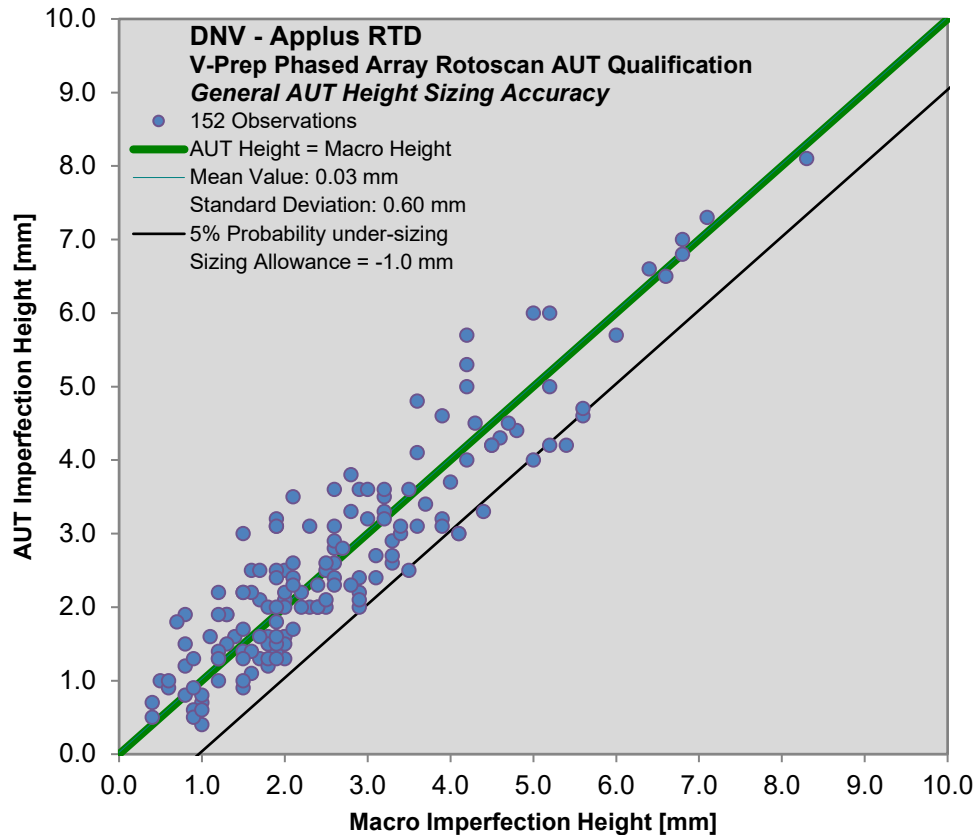


Figure 8-10: General height sizing accuracy, Phased Array V-preparation.

In general for the Phased Array Appus+ RTD Rotoscan AUT system applied for V-preparation girth weld inspection, no systematic over or under sizing is found. The 95% limit against under sizing is found at -1.0 mm under sizing. This is the main result attributed to imperfection height sizing for V bevel preparation welds for this AUT system when applied according to DNVGL-ST-F101.

8.10 Detection of Volumetric Imperfections

Volumetric imperfections are properly detected by the AppusRTD Rotoscan Phased Array AUT system, applied for V bevel preparation welds. Detection of purely volumetric imperfections is not included in the general POD. However, a POD for the volumetric imperfections is probably irrelevant to make. This is due to the sensitive and complementary detection abilities for this kind of imperfections by mapping channels and TOFD, and to a need of a breakdown to position and type of imperfections in order to give a fair description.

The detection limit for volumetric imperfections appears to be at small and short imperfections, typically small pores. Detection of Cu-inclusions has not been evaluated specifically, but in general this type of

imperfection is observed to be well detected by mapping channels and TOFD channel in the Rotoscan AUT system.

8.11 Phased Array Length Sizing Accuracy

The figure below shows the results of length sizing accuracy by the phased array Rotoscan system. The evaluation level used was 20% and 24% FSH for imperfection end location, the majority of the imperfections investigated were between 10 and 30 mm long. The analysis shows a systematic over sizing of the imperfection length of 2.3 mm. It is observed a less than 5% probability of have an under sizing of more than 3 mm for a imperfection length. Only welds with V type bevel preparation were included in the analysis.

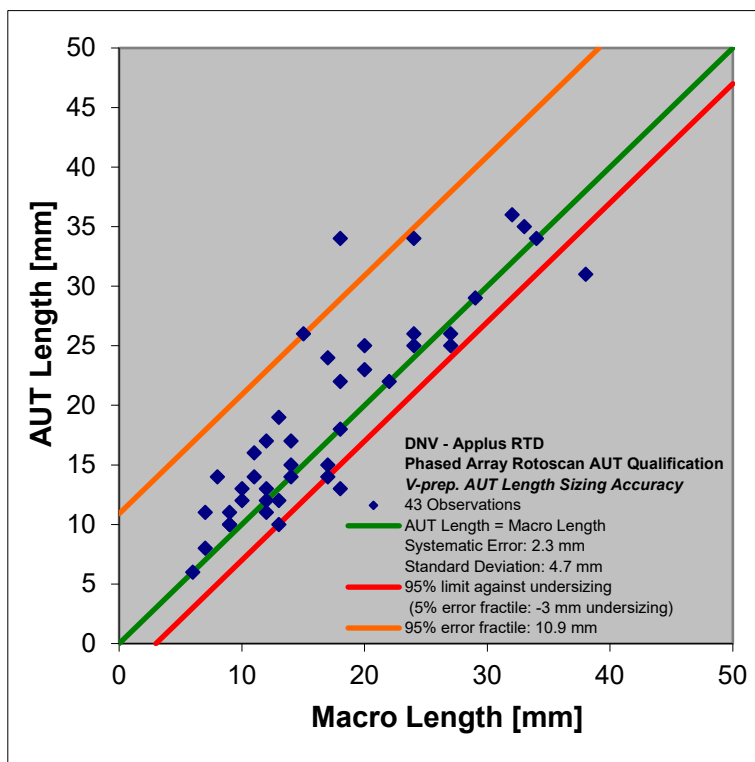


Figure 8-11: Phased Array length sizing accuracy

8.12 Depth and Ligament Position Accuracy, V-bevel

The inaccuracy in depth position estimate is on average 0.54 mm, with a standard deviation of 1.47 mm. The positive average value means that AUT tends to indicate the defect position lower in the weld than the actual position. The AUT reported defect depth is mainly estimated at accuracy within +3.0 mm and -1.9 mm, as shown in Figure 7-12. The results are valid for buried imperfections in general.

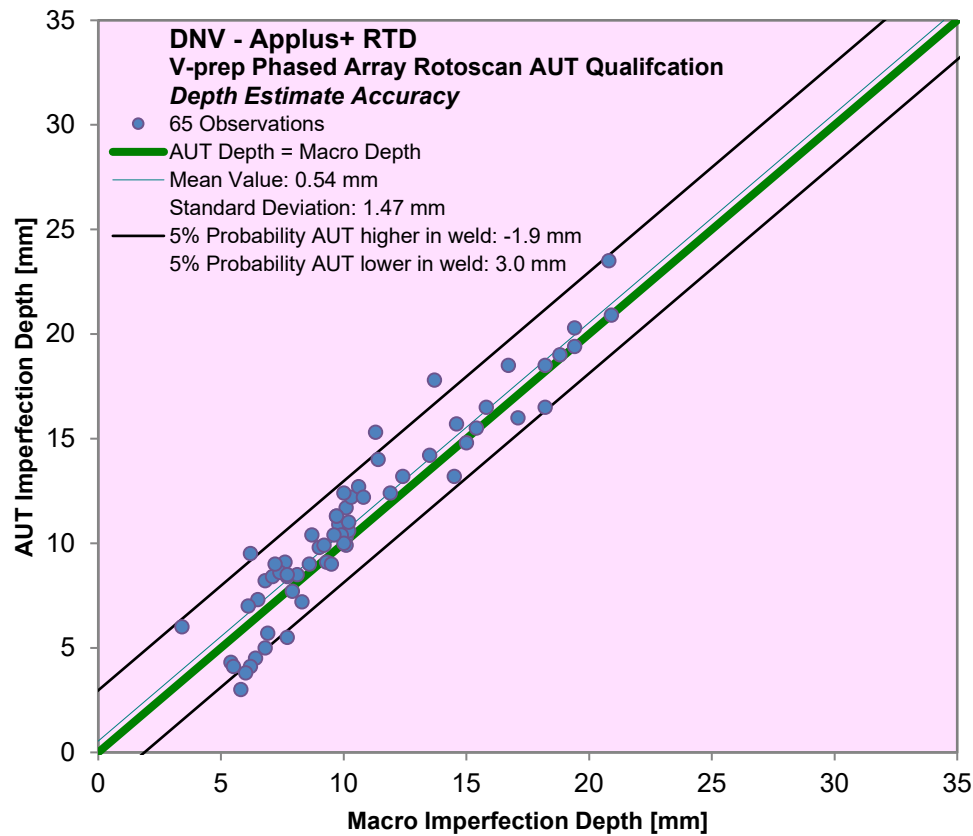


Figure 8-12: Depth estimate accuracy plot, V-bevel

The inaccuracy in surface ligament estimate for buried imperfections is on average 0.60 mm, with a standard deviation of 1.48 mm. The Rotoscan AUT reported surface ligament is mainly estimated at accuracy within +1.8 mm and -3.0 mm, as shown in Figure 7-12. 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.

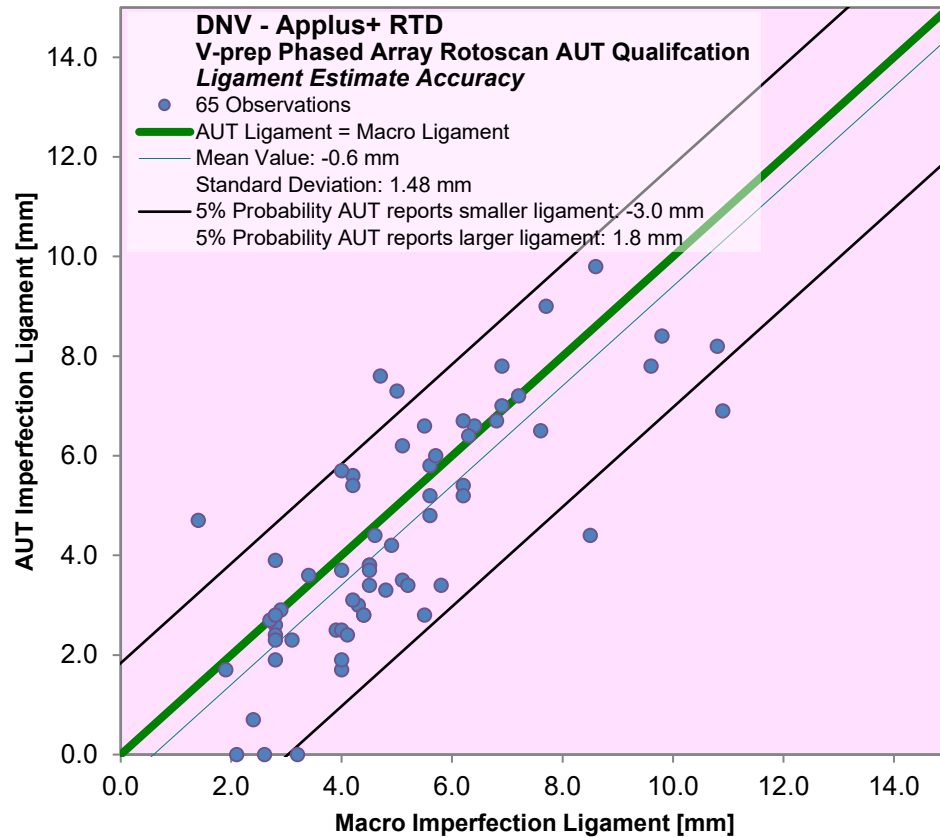


Figure 8-13: Buried imperfections ligament estimate accuracy, V-bevel

8.13 Probability of Rejection Analysis

The figure below shows how the estimated POR-values at 50% and 85%, both at 95% confidence level, vary with increasingly set POR threshold. The 50% POR-value is the imperfection size that will be rejected on average, which might serve as a benchmark on how the system performs in detecting imperfections with the threshold AUT height. POR can be presented the same way as POD, as a curve for POR vs. real imperfection height. In the figures below, the results at 85%|95% POR and 50%|95% POR are given for varying AUT imperfection height rejection thresholds at both J and V bevel preparation. For instance, according to the table for J-bevel preparation, if all imperfections with reported AUT height of 2 mm are rejected, the table below shows that the largest non rejected imperfection is expected to have a real height not larger than 2.8 mm. Here, the X-axis denoted AUT height rejection limit is attributed to the AUT reported height. The results on the 50%|95% POR values suggests that AUT rejection threshold shows good accordance with the real imperfection size on average.

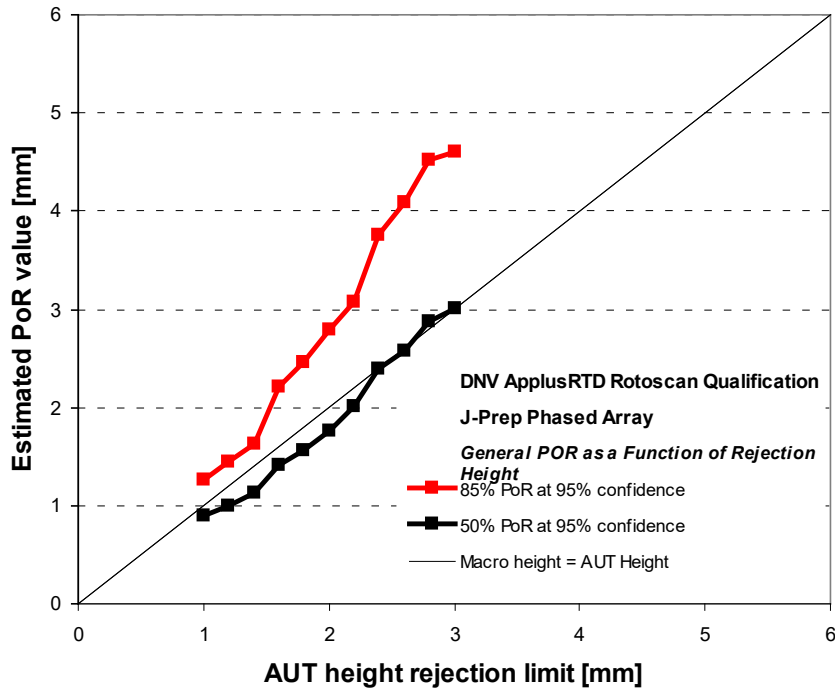


Figure 8-14: Results of POR-analysis for varying rejection limits of AUT reported height, valid for inspection by Rotoscan phased array AUT on J-preparation girth welds.

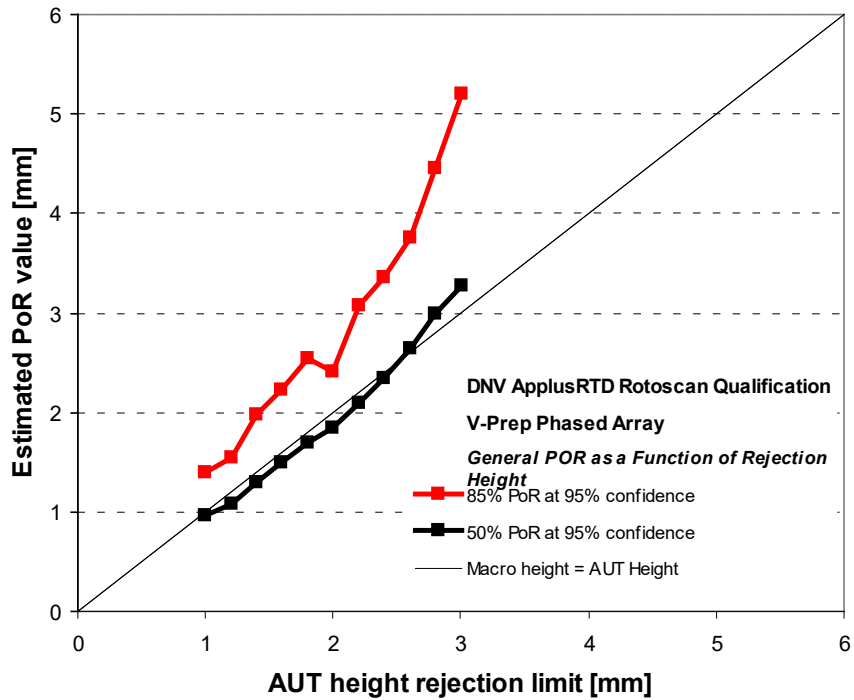
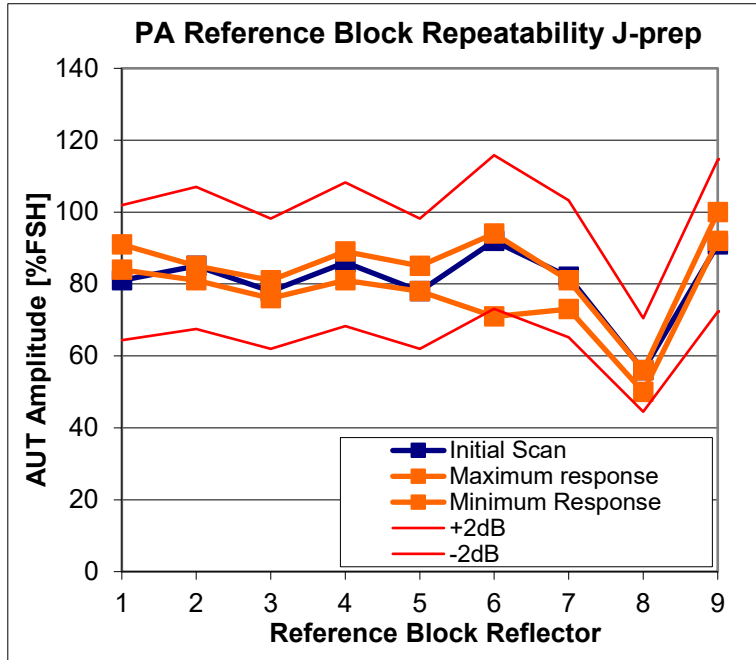


Figure 8-15: Results of POR-analysis for varying rejection limits of AUT reported height, valid for inspection by Rotoscan phased array AUT on V-preparation girth welds.

8.14 Repeatability

8.14.1 Reference block Repeated Scans

The repeatability test scans on reference blocks show sufficient consistency for repeated scans for both J and V-preparation reference block, with no deviation from initial scan more than ± 2 dB. Some results done at reference blocks oriented in 5G-position with scanner start position at 12 o'clock are shown in the figures below. Each series consist of 10 consecutive scans at ambient temperature. The full results of these tests can be found in Appendix 3.



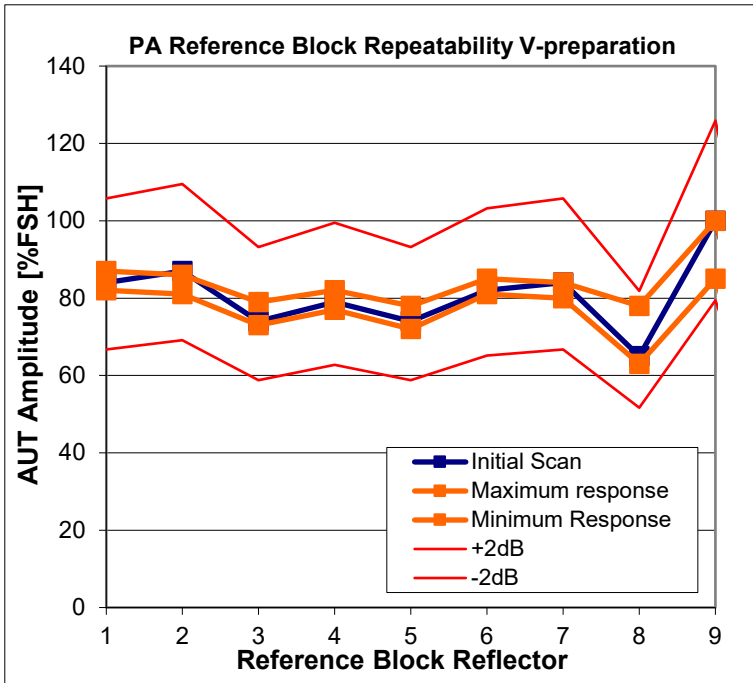


Figure 8-16: Reference block repeatability trials. X-axis represents different reference reflectors

8.14.2 Band Offset Trials

The ± 1 mm band offset scans on reference blocks show consistency for repeated scans with band offset. With both configurations, the observations are found within ± 2 dB.

Results of these trials can be found in Appendix 3.

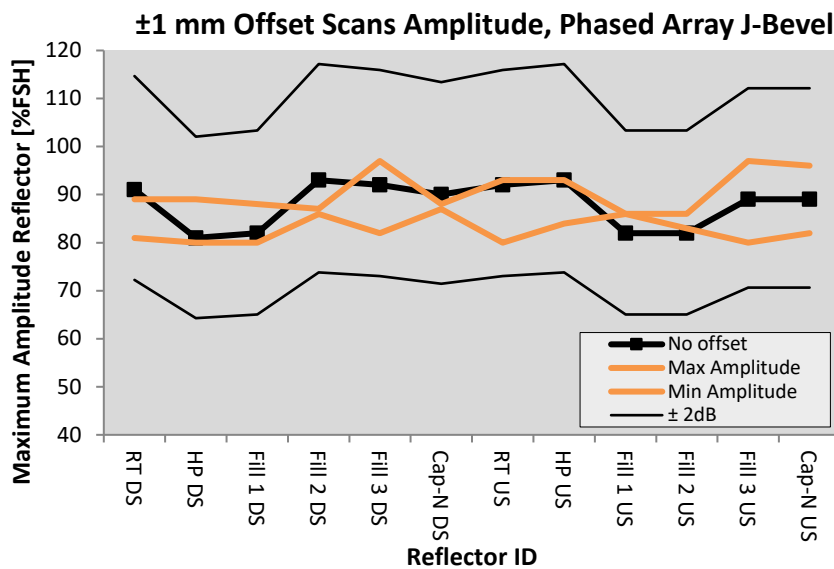


Figure 8-17: ± 1 mm band offset trial results, Phased Array J-bevel

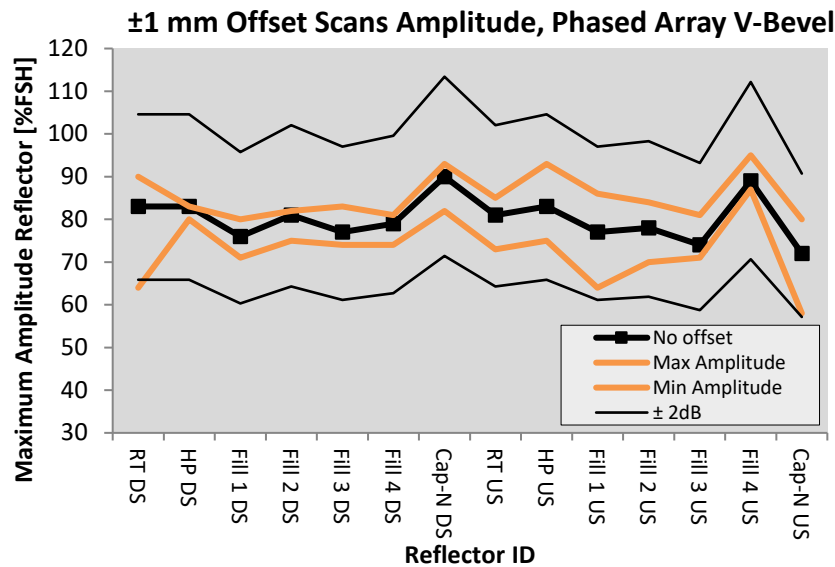


Figure 8-18: ±1 mm band offset trial results, Phased Array V-bevel

8.15 Temperature Sensitivity

Two elevated temperature sensitivity trials have been performed on actual welded sample with natural imperfections, witnessed by DNV.

The elevated temperature test scans shows a fair consistency between scans at ambient temperature and scans at elevated temperature. The test was performed at one 12"OD, 17.5 mm WT J-preparation girth weld containing six different natural imperfection indications.,

The imperfections were distributed: 2 in the root, 1 in hot pass, 2 in fill and 1 in cap. The trial weld was scanned 16 cycles at a temperature of 90°C. The cycle time was well below 4 minutes for all scans, mainly between 3:00 and 3:30 minutes. The results are given in the figure below, where the amplitude response for weld imperfection indications are plotted, for ambient temperature scan and maximum and minimum values found within the elevated temperature scans. In addition, the ±2 dB limits are indicated.

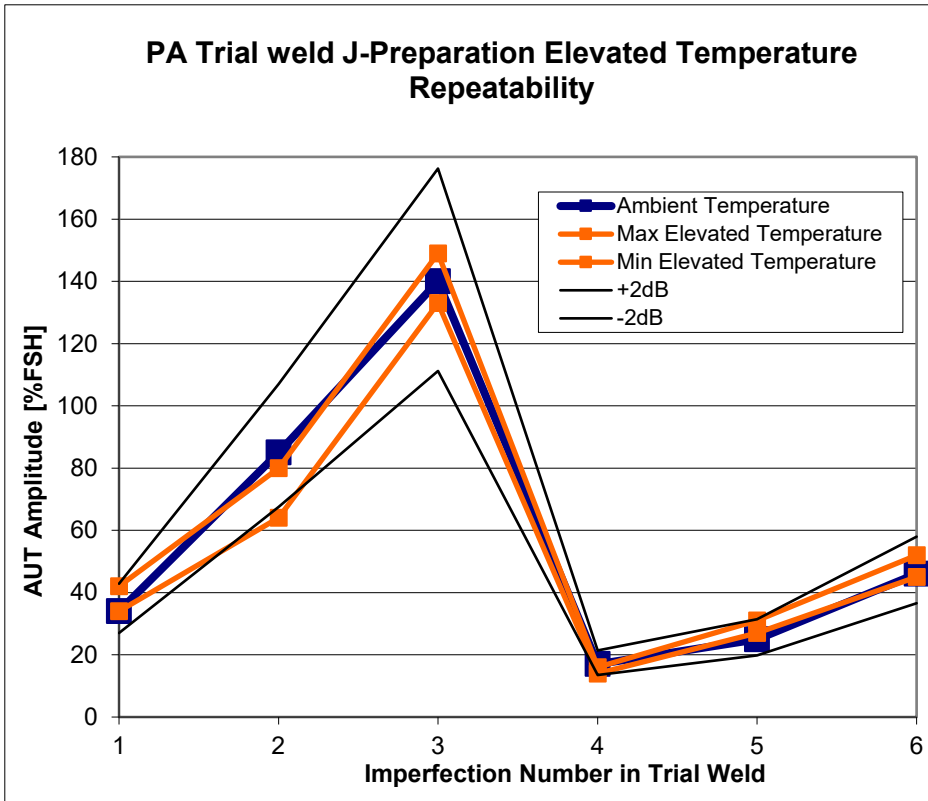


Figure 8-19: Repeatability at elevated temperature, phased array probes. Imperfection 1 and 2 are from root, imperfection 3 is from hot pass, imperfection 4 and 5 are embedded and imperfection 6 is from cap.

The variance in the amplitude readings is found outside ± 2 dB for one of the indications; this is slightly higher than seen for repeatability scans at ambient temperature. All variations in signal response are observed to stay within ± 2.5 dB. This indicates that the elevated temperature do have a slight influence on the repeatability on the Rotoscan AUT system with phased array probes, when the cycle time is kept ≤ 4 minutes.

Another series of 15 scans at elevated temperature of 70°C was carried out at similar conditions; 18" diameter pipe with a wall thickness of 22.2 mm. The cycle time was about 8 minutes, all scans were done within 8:30 min and 5:30 min after the previous scan. The results from this series are in line with the results presented above, however no measurements are found outside the ± 2 dB limits.

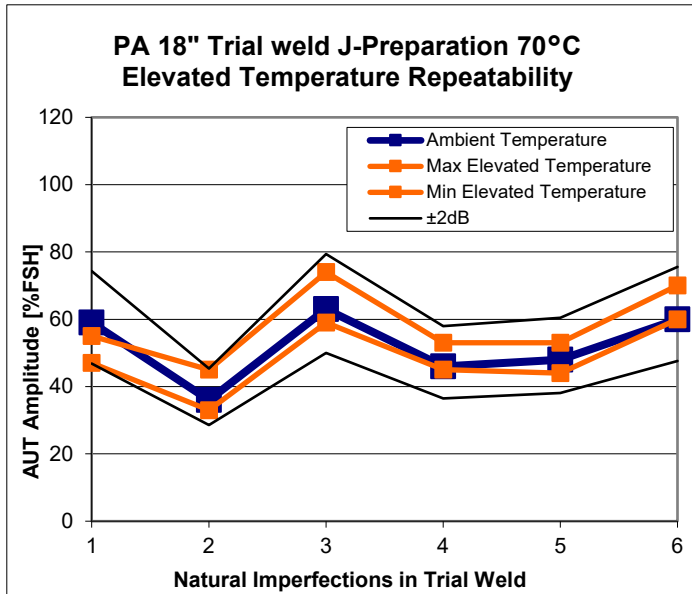


Figure 8-20. Repeatability at 70°C elevated temperature, phased array probes. Imperfection 1 is from root, imperfection 2 to 5 are embedded and imperfection 6 is from cap.

The stability upon heat build up appears to be good, with no observed tendency of changed detection behaviour over time.

For Rotoscan multi probe AUT system, the performance at elevated temperature of 70°C is regarded as acceptable based on historical data. No additional trials have been performed attributed to this qualification for the multi probe system.

8.16 Adapted Focal Law Settings (AFLS)

It was successfully demonstrated that AFLS generates AUT setups for three different wall thicknesses with one reference block, which are equivalent to separate setups on three different reference blocks. All reference reflector responses in scans of the physical reference block (high and low) with setups derived by AFLS were within the tolerance of ± 2 dB. It was observed some over-trace values outside the tolerance range between 40% FSH and 5% FSH from reference reflectors, all within 2 dB above 40% FSH. This was investigated, and it was concluded that there will always exist some natural variations in surface condition, material variance and machining tolerance between individual reference blocks. The minor deviations observed in the trials are concluded to reflect this, as the AFLS modelled setup assumes identical conditions as the mid WT reference block.

The results of the trials of the 3 welds with AFLS modelled setup active documented that the performance of AFLS with regards to POD and sizing accuracy was in line with the general performance of the Rotoscan AUT system documented in this report. This means that the qualification results remains valid also for AFLS software setups. It was confirmed on the scans that the software modelled WT-H setup (WT = 28.4 mm) was active for most of the scans, when the AUT setup was according to the reference block with WT=26.9 mm.

8.16.1 AFLS functionality demonstration

It is recommended to demonstrate AFLS functionality upfront use each time it is applied in projects, preferably as a part of the AUT validation activities. How this should be done is not detailed in the present revision of DNVGL-ST-F101 [1]. In order to demonstrate the ROTOSCAN AUT AFLS are adequately setup in view of focal laws, zone positions and L/H triggering based on WT measurements the following is proposed:

- Desktop study detailing the work preparation process of the project specific ROTOSCAN AUT AFLS setups
- Desktop study detailing the ROTOSCAN Work Preparation Module (RWPM) software, which is used during the work preparation process to ensure all ultrasonic beams of L/M/H ROTOSCAN AUT AFLS setups fit within the footprint of the applied PA probe footprint / array
- Physical demonstration of toggling between L/M/H ROTOSCAN AUT AFLS setups generated in the specific project calibration file within the ROTOSCAN System software, to demonstrate that the WTR view displayed is relevant to the actual WT

8.17 Hardware and scanner

8.17.1 Hardware platform

The comparative study between the PA128 and the 4G system units gave the following results:


- For the 10 consecutive scans of the same reference block with both the PA128 and the 4G units, target responses and overtrace values were confirmed to be within $\pm 2\text{dB}$, and transit distances were confirmed within $\pm 0.5\text{ mm}$.
- For the 3 consecutive scans of the same defective weld with both the PA128 and the 4G units, target responses and overtrace values were confirmed to be within $\pm 2\text{dB}$, and transit distances were confirmed within $\pm 0.5\text{ mm}$.

The PA128 and 4G acquisition unit is confirmed to produce identical results with the same scanner and probes through these trials. As a consequence, the results presented in this report is considered to be applicable for use of the Rotoscan AUT system including both PA128 and 4G hardware units.

8.17.2 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 $\pm 2\text{dB}$.
- For the serie 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 $\pm 2\text{dB}$.



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 Rotoscan AUT procedure [4]. As a consequence, the results presented in this report is considered to be applicable for use of the Rotoscan AUT system mounted on both standard and Z-shape band.

9 CONCLUSIONS

9.1 Introduction

The Rotoscan System in configurations with both multi probes and phased array probes as operated according to general AUT procedure No PIPL-06.01.0001 supplemented with specific procedure No. PIPL-06.01.0002, has undergone a performance evaluation on pipeline girth weld inspection according to the qualification programme described and required in DNVGL-ST-F101, Appendix E, and DNVGL-RP-F118 (2017). This general qualification has its main basis in data acquired and supplied by Applus+ RTD, on the performance of the Rotoscan system on mainline welds. The data spans over a wide range of pipelaying projects with different contractors, some of them witnessed by DNV. In addition, DNV has, specifically for the purpose of this general qualification, witnessed AUT scanning attributed to three AUT verification scopes on girth weld inspection included in the analysis. DNV has also witnessed trial activities to document function and performance of AFLS. In total 738 observations from 47 different projects are included in the analysis. AUT system documentation, including procedures with technique descriptions and reference block drawings, have been reviewed and found satisfactory and in compliance with the basic requirements in DNVGL-ST-F101 Appendix E, section E.2.

9.2 Performance data

9.2.1 Detectability

Reliably detected imperfection sizes, the imperfection heights showing 90% POD at a 95% confidence level, have been evaluated for different evaluation levels interpreted in accordance with the AUT procedure [4,5]. Interpretation includes use of information captured in pulse echo, mapping and TOFD channels. The results can be used directly with acceptance criteria derived by ECA if the prerequisites of section 8.3 are fulfilled, according to DNVGL-ST-F101.

9.2.1.1 Rotoscan Detectability

The 90%|95% POD imperfection heights valid in general for the Rotoscan system with both Multi probe and phased array probe setups at evaluation levels of 40% FSH, 30% FSH and 20% FSH, when responses from 3 mm FBHs and 1 mm surface notches are set to 80% FSH, are tabulated below for J and V weld bevel preparations separately.

Table 9-1: Rotoscan 90%|95% POD imperfection heights

Rotoscan System	Bevel Prep.	# Obs.	90% 95% Height at Evaluation Level [mm]		
			40% FSH	30% FSH	20%FSH
Multi Probe	J	230	2.2	1.6	0.8
	V	150	2.2	1.2	0.9
Phased Array	J	149	1.7	1.4	1.1
	V	157	2.2	1.9	1.3

9.2.2 Height Sizing Accuracy

Height sizing accuracy generally valid for the Rotoscan AUT system with both multiple and phased array probes is given in the Table 9-2 below.

In general, an under sizing allowance of 1.0 mm is recommended. Height sizing accuracy is generally found within ± 1 mm

The mean sizing error (systematic error) is in general close to 0.0 mm, and within ± 0.2 mm.

Table 9-2: Rotoscan Height Sizing Accuracy

Rotoscan System	Bevel Prep.	Mean [mm]	Standard Deviation [mm]	95% limit against under-sizing [mm]
Multi Probe	J	0.0	0.59	-1.0
	V	0.1	0.65	-1.0
Phased Array	J	0.2	0.53	-0.7
	V	0.0	0.60	-1.0

9.2.3 Length Sizing Accuracy

It is observed a systematic over sizing of imperfection length of about 2.0 mm, when a 20% FSH evaluation level is applied for length sizing.

Length sizing accuracy is in general observed to remain predictable regardless of AUT setups, provided that imperfections have amplitude responses above threshold for a considerable length (i.e. >10 mm). Also, the technique used for sizing of length is considerably different to sizing of height. Due to this, no allowance to

accommodate for inaccuracy in length sizing is considered as necessary when applied for the best workmanship acceptance criteria of DNVGL-ST-F101 Table E-1 and E-2.

9.2.4 Depth and ligament estimate accuracy

The results for depth and ligament estimate accuracies are summarised in Table 9-3 below.

Table 9-3: Rotoscan Depth and Ligament Accuracy

Rotoscan System	Bevel Prep.	Depth Estimate accuracy		Surface ligament Estimate accuracy	
		Mean [mm]	Standard Deviation [mm]	Mean [mm]	Standard Deviation [mm]
Multi Probe	J	0.5	1.43	-0.2	1.58
	V	-1.7	2.07	0.9	2.50
Phased Array	J	0.5	0.98	-0.2	1.11
	V	0.5	1.47	-0.6	1.48

9.2.5 Operation Repeatability


Operational uncertainties of the Rotoscan system with multiple and phased array probes cause no variations in signal response amplitudes outside ± 2 dB. A band offset of ± 1 mm is found to have modest impact on reference reflector responses in general, for scans on reference block.

9.2.6 Operation Temperature

For phased array probes; in general it is observed a good consistency between scans performed at ambient and elevated temperature, and is in general qualified for operation up to 70 °C. For 16 consecutive scans with short cycle times below 4:00 minutes, a temperature difference between ambient conditions (~ 25 °C) and 90 °C is observed to cause a slight influence on the inspection uncertainty upon scanning. It should be noted that the vast majority of the measurements are found within ± 2.0 dB. The observed influence of elevated temperature is regarded as minor; accordingly the heat resistance of the Rotoscan phased array probes is regarded as acceptable.

A scan series of 15 consecutive scans at 70 °C elevated temperature with cycle times mainly between 5:00 and 8:00 minutes gave observed variations in signal response within ± 2 dB.

The Rotoscan AUT system with phased array probes appears to operate stable upon heat build, with no observed tendency of changed detection behaviour over time.



For Rotoscan multi probe AUT setup, the performance at elevated temperature is regarded as acceptable based on historical data. No additional trials have been performed attributed to this qualification for the multi probe system.

9.3 Prerequisites

The performance documented in this report for the Applus+ RTD Rotoscan AUT system is attributed to the General AUT procedure, No PIPL-06.01.0001, and regarded relevant for general use on carbon steel pipeline girth welds.,

The Rotoscan system shall have a zonal discrimination set up with full coverage of the weld. Qualified probe setups are multiple probes and phased array probes, both with tandem or pulse echo arrangements for inspection of embedded zones. Tandem arrangement is qualified for use on weld bevels up to about 20°, while the pulse echo arrangement is qualified for weld bevels in the range between 20°-45°.

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. Care should be taken, and effects assessed, especially with respect to imperfection height sizing, when zone heights are changed.


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.

The same type of reference reflectors (2 mm to 3 mm FBHs embedded, 1 mm surface notch at ID and OD cap, 1.5 mm FBHs for volumetric channels) as during the qualification trials shall be used. Reflector sizes may be reduced, provided that necessary area focus and resolution is maintained.

Girth welds shall be made in carbon steel pipe material, with a mechanized or manual welding method that are producing the common/associated welding imperfections to those processes, as used during the AUT system qualification. Variations in the weld bevel configuration and welding method are not considered essential, as long as the probe set-up and calibration of the AUT system remains within the qualified range. Validity of the overall qualification for wall thicknesses below 6.0mm or for pipes having an outer diameter below 3" shall be evaluated from case to case to determine whether the qualified setup status can be maintained.

Hardware platform shall be PA128 or 4G. Guiding bands shall be either standard Rotoscan type or Z-shaped guiding band.

AFLS can be used to extend the wall thickness range for a single reference block through generation of H and L AUT setups. According to requirements of DNVGL-ST-F101, the applicable wall thickness range with AFLS is restricted to 9.0 mm (3x±1.5 mm) with nominal installation strain <0.4% and to 6.0 mm (3x±1.0 mm) with nominal installation strain ≥0.4%. It is a prerequisite that all ultrasonic beams will fit within the footprint of the applied PA probe footprint/array, and the AFLS setups have to provide coverage for the full range without any gaps.



Qualified personnel as according to DNVGL-ST-F101 requirements shall be used. In addition, adequate training and experience shall be documented. The Rotoscan AUT system shall be operated under the Applus+ RTD quality system.

9.4 Validity

The qualification has unlimited validity, given the prerequisites in section 9.3 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.