GENERAL QUALIFICATION OF THE APPLUS+RTD ROTOSCAN CRA AUT SYSTEM

Applus+RTD Rotterdam

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

Objective:

The Applus+RTD Rotoscan CRA AUT procedure for offshore pipeline girth weld configurations have been subjected to qualification trials according to DNVGL-ST-F101[2] and DNVGL-RP-F118[3], in order to document general performance for clad and lined pipe applications. The qualification trials covered in total 20 defective girth welds. 4 welds were of 12.75" OD, 25.6 mm WT + 3 mm metallurgical bonded CRA J5 and 4 welds were of 12.75" OD, 19.8 mm WT + 3 mm weld overlay CRA J5. For both configurations, the pipe material was DNV MWP 450 PDC grade steel, the weld, clad and overlay weld was UNS S31603. 7 welds were of configuration V30 10.75" nominal OD diameter, 19.2 mm WT + 3 mm metallurgically bonded clad with Inconel 625 in both weld, and clad layer while backing pipe was of API 5L X65 grade carbon steel. 5 were partial welds (only root and hot pass weld) 9.6" OD, 18.5 mm WT + 3.0 mm metallurgically bonded clad, J6 bevel, Material API X65 + Inconel 825.The qualified configurations are representative for wall thicknesses above 10 mm, and for pipes of diameter of 6" and above. A total of 288 AUT observations were added to the analysis through macro section examination. DNV GL has witnessed trials, and the qualification has been implemented according to the requirements set forth in the applied code and guideline. The qualification is valid for all CRA pipeline applications, on the condition that a consistent and sufficient signal to noise ratio can be demonstrated.

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1	2016-01-25	Revised POD analysis, several evaluation levels	HASTI	SALVE	PEH
2	2017-01-04	Revised Dataset, Additional POD analysis included	HASTI	KHO	PEH
3	2017-01-30	Remove typos	HASTI	SALVE	PEH
4	2017-02-20	Included Partial Weld Data and application	HASTI	SALVE	PEH
5	2019-03-28	Clarify compliance with DNVGL-ST-F101	HASTI	KHO	PEH

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1 EXECUTIVE SUMMARY

The Applus+RTD Rotoscan CRA AUT system inspection procedure for CRA applications (Doc No. PIPL-06.02.0001) has been subjected to qualification trials in order to evaluate the general performance of the system applied on pipe girth weld configurations with CRA weld and an inner layer of either metallurgical bonded clad CRA or weld overlay. The qualification work has been done under agreement between Applus+RTD and DNV GL AS, to follow the requirements of DNVGL-RP-F118 [3] and DNVGL-ST-F101 [2]. The qualification trials covered in total 20 defective girth welds. 4 welds were of 12.75″ OD, 25.6 mm WT + 3 mm metallurgical bonded CRA J5. 4 welds were of 12.75″ OD, 19.8 mm WT + 3 mm weld overlay CRA J5. The pipe material was DNV MWP 450 PDC grade steel, the weld, clad and overlay weld was UNS S31603. 7 welds were of configuration V30 10.75″ nominal OD diameter, 19.2 mm WT + 3 mm metallurgically bonded clad with Inconel 625 in both weld, and clad layer while backing pipe was of API 5L X65 grade carbon steel. In addition, 5 were partial welds to a minimum ID ligament of 6 mm, 9.6″ OD, 18.5 mm WT + 3.0 mm metallurgically bonded clad, J6 bevel, Material API X65 + Inconel 825. Performance is evaluated as stability upon repeated scans, detectability and vertical height sizing accuracy. The scope of the qualification includes trials for reliability, repeatability, macro sectioning and data analysis for POD evaluation and sizing accuracy evaluation. In total 288 observations were investigated for reliability analysis through macro sectioning.

POD and vertical height sizing accuracy have been evaluated for imperfection groups at different vertical positions in the weld, denoted Region A (OD surface), Region B (Buried) and Region C (ID surface). The results for vertical imperfection heights at 90% POD at 95% confidence and height sizing accuracy are given in the table below. The system performance is well documented and, in summary, the result can be described as follows (for details see main text):

- The system will in general reliably detect imperfections ≥0.3 mm in vertical height.
- Corresponding results for different parts of the weld are summarised in the table below.
- Evaluation of imperfection height sizing accuracy shows that a general addition of a margin of 0.92 mm on height sizing to account for uncertainty is sufficient to achieve less than 5% probability of under sizing. The results from the qualification regards height sizing accuracy are summarised in the table below.
- Application of the Rotoscan CRA AUT procedure on partial welds with a minimum ID ligament of 6 mm is demonstrated to cause no significant impact on the inspection performance. Therefore the general results presented in this report are also valid for partial weld examinations.

Table 1-1: Main result summary, Vertical Imperfection Height sizing accuracy and POD

	General	Region A	Region B	Region C	Region C*
Imperfection Height, 90% POD at 95% confidence	0.3 mm[a]	0.7 mm[b]	0.7 mm[a]	0.6 mm[b]	0.6 mm[b]
Imperfection Height Mean value	0.4 mm	0.4 mm	0.2 mm	0.4 mm	0.5 mm
5% Probability Under Sizing	-0.9 mm	-0.9 mm	-0.7 mm	-1.0 mm	-1.0 mm

* Only includes 3 mm CRA layer

[a] Value estimated with 10% FSH evaluation level

[b] Value estimated with 15% FSH evaluation level (i.e. no indications with response below 10% FSH present in data)

These results are regarded as valid for all future girth weld projects for the Applus+RTD Rotoscan-system where the welds used in this qualification are found relevant, provided project specific prerequisites and certain prerequisites attributed to the AUT procedure given in section 9.4 of this report are met. Provided that a consistent and sufficient signal-to-noise level is demonstrated for all channels, the results are valid for all wall thicknesses ≥10 mm, outer pipe diameters ≥6”, for all types of weld bevels and for all types of CRA materials. However, it is emphasized that due to the unpredictable conditions for sound propagation and attenuation in CRA materials, project specific validation trials are required for use on specific projects as described in section 9 of DNVGL-RP-F118[3].

It can also be noted that compliance according to DNVGL-ST-F101 ensures compliance with all previous revisions of DNV-OS-F101 which includes requirements to AUT, i.e. the 2000, 2007, 2010, 2012 and 2013 editions.

2 INTRODUCTION

The Applus+RTD Rotoscan automated ultrasonic testing (AUT) system for CRA pipeline welds operated according to the procedure No. PIPL-06.02.0001 [1] has been subjected to qualification trials in order to establish the general performance of the system applied on the corrosion resistant alloy (CRA) pipe girth weld configurations. Performance is evaluated as stability upon repeated scans and operational factors as elevated temperature and guidance band positioning inaccuracy, detectability and procedure AUT scan interpretation robustness, including vertical height sizing accuracy. The purpose for this general qualification has been to independently document the performance of the Applus+RTD Rotoscan CRA AUT system for offshore CRA pipeline girth weld inspection, according to requirements in DNV OS-F101 [2]. Inspection reliability data is gathered for inspection of pipeline girth welds on lined pipes with weld overlay CRA, metallurgically bonded clad and for partial CRA weld inspection (i.e. to a minimum ID weld ligament of 6 mm). The results presented in this report are suitable for use as pre-qualification data for further CRA AUT verification, or as complete documentation of CRA AUT performance according to DNVGL-ST-F101 pipe laying girth weld inspection projects.

3 BASIS

The basis for this qualification work has been: DNVGL-ST-F101 [2], Appendix E. In addition, the qualification has been done fully in accordance with DNVGL-RP-F118 [3]. Further, the guidance given in the Nordtest Tech Report 394 [4] is followed for data analysis. Further details were given on witnessing and guidance during the qualification work.

4 OBJECTIVES

The main objective of the qualification work has been to document the Applus+RTD Rotoscan CRA AUT system procedure [1] for CRA offshore pipeline girth weld inspection applications including full weld and partial weld inspection according to DNVGL-RP-F118 [3] and the requirements of DNVGL-ST-F101 [2]. The results are attributed to the general Applus+RTD AUT procedure used upon the qualification trials [1], which is given in Appendix D. As a general qualification of the system, no girth weld acceptance criteria are involved in the evaluation of the performance. The performance is measured according to the methods attributed to the different requirements given in the specifications, and the results should therefore be directly applicable for all relevant applications with specific acceptance criteria.

According to DNVGL-ST-F101[2] the basic requirements are:

- A POD of 90% at a 95% confidence level (a 90%|95% POD) has to be documented for a imperfection height smaller or equal to the smallest allowable imperfection height in the group of imperfections in question. As an alternative, performance of rejection of weld imperfections can be evaluated using a rejection threshold based on AUT reported height, so called probability of rejection (POR). Corresponding to the POD requirement, for the applicable rejection height a POR of 85% at a 95% has to be documented for the smallest allowable imperfection height of the imperfections in question.
- The 5% limit against under-sizing of vertical imperfection height has to be established
- Imperfection length and depth sizing performance has to be evaluated.
- Maximum variation of ±2 dB for amplitude in repeated calibration scans with the reference block in 5G 12 o’clock and 6 o’clock positions, in 2G position.

- For repeated scans on a defective weld with band offset of ±1 mm and elevated heat trials, maximum variation of ±2 dB for amplitude or variations in sizing within general tolerances for the system in repeated scans.

Beside the requirements of DNVGL-ST-F101[2], the objective was witnessing of the main qualification activities on site.

Inspection of partial welds are considered as another application of the same Rotoscan CRA AUT procedure as applied on full weld inspection. A clear distinction has therefore not been made between full and partial weld data in the analysis and results. However, evaluation of consistent performance upon full weld and partial weld examination was a clear objective during qualification, this is reported in separate chapters in this report.

5 ABBREVIATIONS

AUT – Automated Ultrasonic Testing
AFLS – Adapted Focal Law Settings
CCW – Counter Clock Wise
CRA – Corrosion Resistant Alloy
CW – Clock Wise
DS - Downstream
ECA – Engineering Criticality Assessment
FBH – Flat Bottom Hole
FSH – Full Screen Height
HP – Hot Pass
ID – Inner Diameter
MLE – Maximum Likelihood Estimator
OD – Outside Diameter
PA – Phased Array
POD – Probability of Detection
POR – Probability of Rejection
SDH – Side Drilled Hole
TOFR – Time of Flight Reflection
TRL – Transmit Receive Longitudinal
US – Upstream
WT – Wall Thickness

6 DESCRIPTION OF QUALIFICATION PROCESS AND CONTENTS

6.1 UT Inspection of CRA material

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

6.2 Applus+RTD Rotoscan CRA AUT System Setup

The Applus+RTD Rotoscan CRA AUT system has been qualified as operated according to the AUT procedure with document number PIPL-06.02.0001 [1]. For each AUT setup, it follows in addition a configuration specific procedure, which details the AUT setup parameters and project specific requirements.

The Applus+RTD Rotoscan CRA AUT system is designed for inspection of corrosion resistant pipeline girth weld based upon Phased Array or TRL probe generated longitudinal waves supplemented by creeping waves, Time of Flight Reflection (TOFR) and sectorial scan groups. The qualified CRA pipe configuration is a configuration of pipes with a thin inner layer of a corrosion resistant alloy, either metallurgically bonded to the pipe or as a liner pipe sealed to the pipe at the ends with an overlay weld. For the lined pipe configuration, good sound penetration between the clad and the backing pipe is ensured by an extended weld overlay area at the pipe ends in the area around the girth weld. Welding is performed with a CRA weld metal. The Applus+RTD Rotoscan CRA AUT system is designed to overcome the specific challenges attributed to UT CRA inspection, and the set-up differs substantially from typical AUT set-ups used on carbon steel pipes. The presentation of scan results has similarities to conventional carbon steel zonal discrimination set-ups, with strip charts and mapping channels. An essential difference are that the gates cover the full weld volume from both sides of the weld in the CRA AUT setup, while they are restricted to weld center line with carbon steel AUT. The strip chart presentation is also different in the CRA AUT setup, where the strip charts are all channel mapping images. For conventional zonal discrimination AUT for carbon steel only maximum amplitude and corresponding time of flight is presented.

The qualified Applus+RTD Rotoscan AUT inspection philosophy includes use of either phased array probes or TRL probes, or a combination of these in order to provide full coverage of the weld. Phased array probes and TRL probes are considered to provide equivalent inspection performance when properly set up. As the setup is based on use of direct beams of longitudinal waves, the use of PA-probes in the Rotoscan CRA AUT setup is not restrictive to focal law stand-off distances within the setup, different to carbon steel application zonal discrimination setup. This is considered the main reason that separate qualification programs are requested for phased array and multi probe setups for carbon steel application zonal discrimination setup. Use of phased array probes or TRL probes has to be considered separately for each weld configuration, based on what is the more beneficial. Sufficient penetration and signal-to-noise ratio is demonstrated by using a reference block with a weld or a transfer measurement block as per Applus+RTD's guideline document [6]. The Rotoscan CRA AUT system can hold up to 4 pairs of focused TRL probes for enhanced sensitivity inspection. The creeping wave probes provide coverage at the near OD surface area.

For AUT setups applying phased array probes, the zonal discrimination setup with focused beams of direct longitudinal waves is enhanced with groups of sectorial scans to enhance detection and interpretation capabilities as depth sizing and position accuracy. Sectorial scans are generated within the range of angles of 40°-80°. As an option to phased array setups exclusively, sectorial scans are considered to provide supplemental information about the weld condition to support the interpretation.

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
ToFR probe frequency:	6 MHz to 15 MHz
PA probe element pitch:	0.85 mm to 1.5 mm
PA probe height (passive aperture):	15 mm to 25 mm

6.2.1 Adapted Focal Law Settings

The Rotoscan AUT procedure includes the possibility to apply 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[2] 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.

6.3 Reference Block Design

A project specific reference block is made from the same pipe as the production pipe. The relevant reference reflectors for the different groups were: 1.0 mm surface notch at inner and outer surfaces, and 3 mm FBH positioned either at the theoretical weld bevels at both sides of the weld. The FBH reflectors were angled to reflect direct beams in the range of maximum 50°-80°. The level of the reference reflector responses were set to 80% FSH.

The Applus+RTD Rotoscan CRA AUT setup procedure includes the options to manufacture the reference block from a piece of project pipe material either with or without a representative weld. A reference block including a weld is considered to provide conditions for attenuation which is fully representative to production welds. The AUT setup can therefore be applied directly on production welds after calibration on the reference block. When applying a reference block not including the weld, a transfer correction (i.e. adjustment of gain) shall be applied upon production weld scanning in order to account for the differences in attenuation due to the CRA weld. The transfer correction shall be determined for each focal law using a transfer measurement block made of project material including a production weld and suitable and corresponding reflectors in the weld section and the bare pipe section of the block. Suitable reflectors would be surface notches at ID and OD surfaces, and SDHs or FBHs for the embedded parts. The reflectors should be positioned at the weld bevel fusion face equally spread through the pipe thickness, i.e. the surface notches are located at fixed positions compared to the weld center line and the buried reflectors should be along the weld bevel. The weld is considered to mainly affect the ultrasonic attenuation compared to the bare clad/weld overlay pipe with the Applus+RTD Rotoscan CRA AUT inspection concept, therefore the inspection is considered to be equivalent when reference blocks with or without a CRA weld is included. The philosophy to consistently select weld coupons and how to perform the transfer correction is captured in Applus+RTD's guideline document [6].

The reference reflectors are positioned such as each beam or focal law will hit and reflect on both a reflector at the closest weld bevel positions (primary reflector) and the weld bevel at the opposite side of the weld (coincidence reflector). Full coverage is confirmed in calibration scans by over trace in adjacent channels. In addition, gates are set to capture the full weld body when both primary and coincidence reflectors are within. Furthermore, the procedure has focused attention to the ID surface area, with detection either with focused focal laws or dedicated focused TRL probe.

Trials performed to demonstrate consistent performance using both approaches to manufacture reference block has been demonstrated upon DNV GL witnessing. This trial included scanning and comparison of reflector responses with two references blocks from of identical design except that one of them included a weld. Pipe configuration was 25.6 WT + 3 mm J5 bevel with metallurgically bonded clad. Also, a demonstration of the transfer correction as per Applus+RTD's guideline document [6] has sufficiently been demonstrated upon DNV GL witnessing. Pipe configuration for this demonstration was 9.6" OD x 17.6 mm WT + 3 mm J6 bevel with metallurgical bonded clad. Based on the results from this comparison and guideline demonstration, it was concluded that the reference block designs including a weld and made from bare pipe provides the same inspection sensitivity and ensures the same performance.

6.4 Trial welds and induced imperfections

The full qualification scope includes two different configurations, one with metallurgically bonded clad and one with overlay weld CRA. Each configuration demanded 2 AUT setups, for J and V bevel. The configurations of defective welds used for reliability trials were as follows:

- 4 welds 12.75" OD, 25.6 WT + 3 mm Metallugically bonded clad, J5 bevel, Material DNV MWP 450 PDC + UNS S31603
- 4 welds 12.75" OD, 19.8 WT + 3 mm weld overlay, J5 bevel, Material DNV MWP 450 PDC + UNS S31603
- 6 welds 10.75" OD, 19.2 WT + 3 mm Metallurgically bonded clad, V30 bevel, Material L450MQOS + 625 inconel
- 1 weld 10.75" OD, 19.2 WT + 3 mm Metallurgically bonded clad to 22.3 mm WT carbon steel pipe (dissimilar), Material L450MQOS + 625 inconel to L450MQOS
- 5 partial welds 9.6" OD, 18.5 mm WT + 3.0 mm Metallurgically bonded clad, J6 bevel, Material API X65 + Inconel 825 (minimum ID weld ligament 6.0 mm)

The aimed numbers of artificial imperfections were 80 in total for the 12.75" OD configurations and 100 for the 10.75" configurations. The aimed number of imperfections in the partial welds was 38.

Reference block repeatability trials have been sorted out on reference blocks with a different configuration than the defective welds, 12.75" OD x 25.5+5 mm WT, both J-bevel and V-bevel configurations with weld overlay CRA. These reference blocks were of material API 5L X65 + UNS N06625. The temperature trial has been performed using a defective weld of corresponding 12.75" OD x 25.5+5 mm WT V-bevel configuration.

Imperfections were induced by running intentionally wrong welding parameters and mechanically introducing imperfections in the weld upon welding. The latter imperfections were made using techniques including EDM notching.

6.4.1 Weld Region Categories

DNVGL-RP-F118 [3] Appendix A gives guidelines of the recommended numbers of imperfections at different parts of the welds. The weld is divided into three or four parts, root, (hot pass), fill and cap, with a recommended number of 29 imperfections within each part. For cap, the selection of imperfections shall include both surface breaking imperfections and sub-surface imperfections. A sub-surface cap imperfection is defined as an embedded imperfection with the bottom part maximum 5 mm from the surface.

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

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

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

The Region C category includes the CRA layer of 3.0 mm + the area up to 1.5 mm above clad/line thickness. This is based on the DNVGL-ST-F101 [2] Appendix E Table E1, which specifies acceptance criteria for root imperfections in the area up to 3 mm from ID surface and up to 1.5 mm above clad/line thickness. This means that acceptance criteria for root applies for the area up to 4.0 to 4.5 mm from the ID surface, depending on the CRA layer thickness, since the thinnest allowable CRA layer thickness according to DNVGL-ST-F101 is 2.5 mm. Region C* category includes only the CRA layer without the 1.5 mm area above. With regards to the Region A, DNVGL-ST-F101 [2] Appendix E Table E1 note 7 gives the requirement for surface interaction. Surface interaction is assessed based on ligament and imperfection height. In order to cover the area where surface interaction is expected to occur, taking basis in a 3 mm weld pass height, the Region A is defined as the uppermost 5 mm of the weld. Imperfections are assigned to the Region A category when the macro sections documents that the lowermost part of the imperfection is within 5 mm from the OD surface. Furthermore, a particularity with the Applus+RTD Rotoscan CRA AUT system is the inspection by creeping wave probes at the OD surface area. The creeping waves channels are considered as a main source of information from the weld area close to the OD surface down to about 5 mm.

6.5 Imperfection Types

A total of 176 weld positions in full welds were subjected to macro sectioning for further analysis. The 10.75” OD welds accounted for 102 of these indications, the 12.75” OD welds accounted for 74 indications. The macro sectioning plan included 74 positions for indications in the Region C (both surface breaking and in CRA layer region), 38 positions of indications Region B in the weld and 64 positions for indications in the Region A area.

For analysis purpose, both data from the clockwise (CW) and the counter clockwise (CCW) scans were included for the 12.75″ OD AUT qualification data. The number of observations from the 12.75″ dataset therefore amounted to 148, with a total number of observations within the full weld dataset of 250.

In total 38 weld positions in the partial weld were macro sectioned, all within Region C. Both data from the clockwise (CW) and the counter clockwise (CCW) scans were included in the analysis, which cause the total number of observations in the analysis to be 76.

Upon review of the macro sections for the actual position of the imperfections in the weld, some of the observations were excluded for analysis, other re-categorised to reflect actual position and type. 31 observations were excluded due to various reasons, the considerations have been assessed and accepted by DNV GL.

7 volumetric observations are kept out of the evaluation for POD and sizing accuracy evaluation. 2 of the observations in Region B was selected for macro sectioning based on results from supplemental radiographic testing. Since these were not AUT sized, they have been disregarded from the sizing accuracy evaluations. The number of observations in the POD analysis amounts to 288, for sizing accuracy evaluation it amounts to 286. The distribution in categories is presented in the Table 6-2 below:

Table 6-2 Total number of observations in the analysis

	Region A	Region B	Region C	Region C*	Volumetric
POD Observations	80	54	154	131	7
Sizing Accuracy Observations	80	52	154	131	7

Positions for macro sectioning were marked up on the weld using the AUT scanner, to recognize the precise position. The position of maximum height according to AUT was selected for all observations. For all type of imperfections, at least 3 salami slices were done for each macro section position, at 2 mm distance between each macro. All imperfections chosen for macro sectioning were identified by the weld number and the indication number from the official scan interpretation report. These imperfections are also attributed to a macro position, which is given in mm from the defined scanning start point.

Weld macro cross sectioning were prepared and measured by independent metallurgical laboratories Exova for both the 10.75″ configuration and partly South West Research Institute and Element for the 12.75″ and 9.6″ partial weld configurations. Prior to macro sectioning, the ID-number for the macro and the position for each macro section were hard stamped on the material at US side close to the weld. Section slices were cut, ground, etched and photographed.

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

6.6 Applus+RTD Rotoscan Partial Weld CRA AUT

6.6.1 Partial Weld CRA AUT Setup

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

- The AUT setup includes only channels covering the ID surface are up to 1^{st} fill channel
- A shear wave overskip channel, with reference reflector 1.0 mm notch at theoretical partial weld OD surface. Channel is added to aid in positioning of imperfections, to determine of they are within or outside of Region C.

6.6.2 Partial Weld Trial considerations

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

The part of the trials including the partial weld AUT setup was focused on inspection performance in Region C only. The possible impact of the un-fused bevel in the partial welds was considered to mainly be for buried imperfections, in particular above the CRA layer. Therefore, the seeded defect welds were designed to include mainly buried imperfections within Region C. In order to capture inspection performance in the full Region C, including the area within 1.5 mm above the CRA layer, intended imperfections were located minimum 1.5 mm above the CRA layer upon welding. Some of these indications were macro sectioned. The trials were designed to fulfil the requirements for a full AUT validation according to DNVGL-RP-F118[3] and DNVGL-ST-F101 [2], i.e. minimum 29 independent observations in Region C.

6.7 Extent of Qualification Activities and DNV GL witnessing

The extent of qualification activities was agreed between Applus+RTD and DNV GL upfront qualification, and included full witnessing repeatability and temperature trials on 12.75” OD x 33.5 mm WT weld configuration and reliability trials of 12.75” OD x 25.5+3 mm WT weld configuration and 9.6” OD x 18.5+3 mm WT partial weld configuration. In addition, it was accepted to allow use of historical data (the 10.75” configuration) for the analysis based on DNV GL involvement in earlier qualification programs with the Rotoscan CRA setup [6], upon a thorough review of the data. The following activities have been performed by Applus+RTD, and witnessed by DNV GL:

- Repeatability scans on reference block in 5G position, 10 scans each with reference block center at 12 and 6 o’clock positions.
- Band offset trials
- Elevated Temperature trials.
- Capability scanning of 8 seeded defect welds of 12.75” OD configuration and 5 partial welds of 9.6” configuration, both CW and CCW directions with 2 operators.

- AUT scanning of Rotoscan setup including sectorial scans and reference blocks of bare pipe CRA material.
- Interpretation of AUT scans.
- Stamping of selected imperfection's macro section locations.

6.8 Analysis Extent

6.8.1 Repeatability and Temperature Trials

DNVGL-ST-F101[2] 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[3] 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 should be performed on a defective weld, and possible deviations in imperfection sizing due to the band offset should be evaluated.

Furthermore, DNVGL-ST-F101[2] 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 ºC. 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 ºC. 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.

6.8.2 90% POD at 95% Confidence

Probability of Detection (POD) analysis has been performed to comply with the requirements in DNVGL-ST-F101[2]. 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 [4], 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 [4]:

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

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 a 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 a 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 a 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:

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

For this expression, k is the total number of observed imperfections, n_j is the number of observed imperfections at imperfection 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 xj 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.

6.8.3 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 and equations as presented in paragraph 6.8.2 to evaluate the qualification data. The difference between POD and POR is the threshold applied for hit and miss. For POR the threshold is set for AUT reported imperfection height rather than amplitude. When applied in qualification trials, the criterion for the smallest allowable imperfection size is at least an 85% POR at a 95% confidence level, according to DNVGL-ST-F101[2]. The 85% POR accounts for both a

90% POD and a 95% probability of avoiding under-sizing. The 85%|95% POR imperfection height will represent the actual imperfection height rejected consistently assuming the used rejection threshold. The imperfection height at 85% POR at 95% confidence level shall be equal to or below the smallest “allowable” imperfection height in the acceptance criteria. POR will thus not necessarily say anything about the smallest imperfection that is possible to detect with the system at a certain set-up.

6.8.4 Imperfection Height Sizing Accuracy

In DNVGL-ST-F101[2] 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 this case, the sizing inaccuracy is calculated as $\mu \pm 1.65\sigma$, where μ is the mean sizing inaccuracy and σ is the standard deviation. In cases where the sizing data does clearly not follow normal distribution, the observed 5% percentile might be used instead.

Regards the workmanship type acceptance criteria introduced in DNVGL-ST-F101 [2], the requirement on height sizing accuracy is within ±1 mm, calculated as described above.

6.8.5 Imperfection Length Sizing Evaluation

Imperfection length sizing accuracy has been evaluated on reference block reference reflectors. The fixed length of the reference reflectors has been compared with the length measured on the AUT calibration scan, using both 20% FSH and 40% FSH reporting thresholds. The length has been measured as the difference between the first position in the AUT scan that exceeds the threshold to the first position that goes below the threshold at the other side of the reflector peak. The mean over-sizing in length at each imperfection end has been reported as the measure of length sizing accuracy, this indicates the tendency of length sizing performance of the AUT procedure.

Length sizing accuracy performance should not be assessed statistically through a calculation of the 5% probability of under-sizing. It is regarded as not practical to capture a sufficient number of reliable observations within the scope of the AUT qualification according to DNVGL-RP-F118[3]. Length sizing accuracy is considered as far less critical as height with regards to criticality for weld integrity, therefore the scope of the AUT qualification is focused on providing high quality data on height sizing accuracy. A length sizing accuracy within ±5 mm is anticipated for AUT in general, and observations in length sizing accuracy should in general fall within that range.

6.8.6 Imperfection Depth Sizing Evaluation

For CRA welds, depth sizing accuracy is considered as most relevant near the ID surface as a measure that surface ligament and sizes are sufficiently well assessed to confirm that the integrity of the CRA layer is ensured. For the present report, the mean inaccuracy in imperfection AUT depth sizing when compared with macro imperfection depth has been reported as the measure of depth sizing accuracy. This indicates the tendency of depth sizing performance of the AUT procedure.

The 5% probability of depth estimate accuracy is calculated using same methodology as for height sizing accuracy for depth estimate imperfections lower and higher in the weld. Depth estimate inaccuracy is defined as the reference imperfection depth from the macro subtracted from the AUT measured imperfection depth. A negative depth estimate inaccuracy will then indicate that AUT tend to estimate imperfection position higher up in the welds than the actual position (i.e. macro depth is closer to ID surface than AUT depth).

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

6.8.7 POD and Height Sizing Accuracy in Use

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

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

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

The results of this general qualification are applicable to workmanship style acceptance criteria as well. The workmanship approach is a bit different than the fitness-for-purpose approach offered by ECA, as the workmanship acceptance criteria are attributed to requirements to the AUT procedure, according to applicable standards and specifications. Conservatism is in principle ensured by the requirements according to the standard rather than the demonstrated performance at the qualification. Therefore, subtraction of sizing error is not necessary to workmanship acceptance criteria, as uncertainty in principle is accounted for by the requirements to sound operation of AUT.

AUT used in combination with workmanship style acceptance criteria is recommended to be performed with a 40% FSH evaluation threshold [2]. All indications with response above the evaluation threshold shall be evaluated against the acceptance criteria on both height and length. This means that a imperfection that exceeds the acceptance criteria in length shall be rejected regardless of its AUT height and vice versa. Concerning POD, the AUT system shall be capable to detect the largest allowable imperfection according to the workmanship acceptance criteria, at a 90% POD at a 95% confidence level. Concerning vertical height sizing accuracy, the inaccuracy should not exceed ±1.0 mm.

POR is applicable for combined criteria, as it is at the same time taking into account that there is a probability of under sizing and disregarding imperfections. Furthermore, it captures that the POD and sizing inaccuracy will vary with imperfection size. This means that it is unnecessary to subtract the allowance for sizing inaccuracy from the ECA derived acceptance criteria. For instance, if the smallest allowable ECA (or otherwise) imperfection size is 1.0 mm, the qualification has to demonstrate an at least 85%|95% POR for 1.0 mm imperfections. Imperfections are rejected based on AUT reported height so in order to achieve this, one have to identify which AUT reported imperfection sizes that needs to be rejected in order to comply with the 1.0 mm criteria of real imperfection sizes. Since there usually is a risk of under sizing imperfections, one should expect that imperfections of a somewhat lower AUT reported size than the criteria size has to be rejected in order to comply with the requirement.

6.8.8 Adapted Focal Law Settings

A functional demonstration of the Adapted Focal Law Settings (AFLS) was performed for the Phased Array Rotoscan CRA AUT configuration. The demonstration included a scan of one 16" OD reference block with wall thickness 20.4 mm including a weld with dissimilar material on each side of the weld. One side was with pipe of metallurgical bonded clad, the other side of the weld was carbon steel material. The actual weld to be inspected with the demonstrated AUT setup included a nominal wall thickness of 17.4 mm + 3.0 mm CRA clad layer, however the WT on the carbon steel side was nominal 19.8 mm WT. The AFLS was applied in order to ensure an acceptable scan within the wall thickness tolerances with one reference block.

AFLS modelled AUT CRA setups and scans for high and low WT (i.e. nominal WT ±1mm) were reviewed. Reference reflector responses for the high and low wall thickness reference block scans were evaluated, and shifts in amplitude responses and time of flight within the gate from reference reflector signals were confirmed to be reasonable and according to expectation. The focal laws of the modelled high and low WT setups were reviewed and confirmed to be acceptable. The focal laws within Rotoscan CRA AUT procedure is not considered as very demanding for AFLS, as the beam paths are direct. Most of the adjustments in modelled setups consists therefore of modest shifts in index point of the focal laws. For the reviewed setup this amounted mainly to shifts in focal law of 1-2 elements along the array. The Rotoscan CRA AUT procedure[1] is regarded as well suited for use with AFLS.

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 (3x±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 ≥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 (3x±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).

6.8.9 Hardware units

The Applus+ RTD Rotoscan CRA 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 was performed on a carbon steel setup of the Applus+ RTD AUT system 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 provided the same signal responses and transit distances, within AUT technology inherent fluctuations, with the identical AUT setup. The fluctuations of reference reflector responses were confirmed to be within ±2dB for amplitude responses and ±0.5 mm for transit distance, in line with DNVGL-ST-F101 requirements. The PA128 and 4G acquisition unit is confirmed to produce identical results with the same scanner and probes through these trials.

These conclusions are equally valid and applicable for the present Applus+ RTD Rotoscan CRA AUT setups, as the carbon steel and CRA setups will cause no difference in performance for the applied hardware platform. 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.

6.8.10 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. Howewver, Applus+ RTD has developed a Z-shaped guiding band to be applied on pipes with shorter distance of coating cut-back, where parts of the band is located over the coating.

A capability trial was performed carbon steel setup of the Applus+ RTD AUT system 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.

The repeatability trials with the Z-shaped guiding band consisted of the following trials:

- 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.
- Series of 3 consecutive scans of the reference block in 2G orientation with the Z-shaped guiding band.

The Z-shape band is confirmed to produce stable and repeatable results with target responses all confirmed to be within ±2dB. This is identical to results derived through using the standard band through the same 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].

These conclusions are equally valid and applicable for the present Applus+ RTD Rotoscan CRA AUT setups, as the carbon steel and CRA setups will cause no difference in performance when standard or Z-shaped guiding bands are used. 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.

6.8.11 Analysis Considerations

Reference block repeatability trials have been sorted out on reference blocks with 12.75" OD x 25.5+5 mm WT, both J-bevel and V-bevel configurations with weld overlay CRA. These reference blocks were of material API 5L X65 + UNS N06625.The temperature trial has been performed using a defective weld of corresponding 12.75" OD x 25.5+5 mm WT V-bevel configuration.

Inspection and detection involves a combination of the available information in the scanning data. Direct mode pulse echo, mapping channels, Time of Flight reflection (TOFR), creeping wave and head waves. Indirectly, tip and back diffraction techniques are applied. In addition, for creeping wave channels and partly root channels, pattern recognition in B-scans is vital to distinguish real indications from noise. This presentation enhances the visibility of the time of flight information. All channels in the setup have wide gates that cover the weld, and are displayed as mapping channels in the software. Active use of mapping channels is a prerequisite for the most sensitive detection with this AUT procedure. The procedure specifies a low reporting threshold down to 9% FSH for some channels (fill), in order to capture the weak responses provided by diffraction signals. It should be mentioned that even lower signal amplitudes down to noise level are used during interpretation, as secondary responses. Typically, the lowest signals are used with pattern recognition for instance with coincidence responses. So, for the confirmation signals, there were applied no lower reporting threshold on the signals used for evaluation. A typical imperfection indication is observed to have a significant response in at least one channel, with confirming signals in other channels. The creeping wave channels can catch up response from imperfections quite deep in the weld, due to reflections of the head wave. Response from indications around 5 mm below the

OD surface was observed in the data. Due to this, information in the creeping wave channel needs to be evaluated connected with the response of the other channels in order to determine the imperfection height and depth. For indications only detected by the creeping wave channels, the height is set to 1.0 mm.

For the Region C, it has been observed that it might be challenging to distinguish between a surface breaking imperfection and a sub-surface imperfection buried in the overlay weld area. This applies for lack of fusion type of imperfections with a small ligament to the ID surface, where the main response is found in the root channels. It has been observed and confirmed that addition of sectorial scans improves the imperfection detection and depth positioning significantly in AUT setups including phased array probes, in particular in Region C.

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

Volumetric imperfections with main detection by volumetric channels and TOFR have been omitted for the analysis, this includes in total 7 buried porosity clusters. This is based on considerations with regards to height sizing. The ultrasonic response and height sizing principles of porosity clusters differs significantly from planar flaws and it is considered as challenging to accurately confirm the vertical height of a porosity cluster by macro sectioning. These imperfections are considered to not make any impact to the general POD results as they are all well detected. They are still kept outside the general analysis in order to keep the similar imperfection sample for POD and sizing accuracy analysis.

In order to be able to estimate a POD, some information about the imperfection sizes at the detection border line has to be included in the analysis. Imperfections with vague responses and appearance in the scan were intentionally picked for macro sectioning for this purpose. In order to more accurately estimate the POD, these will be considered as "missed observations". In order to further expand on the POD estimation the detection border line of the system has been denoted as "non-reported" even if it was in fact detected by the system. This has been done to be able to provide some conservative estimates of the overall POD performance. The criteria used to denote an observation "border line" has been insignificant or no response in the pulse echo and volumetric channels. No amplitude rejection threshold has been used for the general POD analysis due to the use of pattern recognition and low amplitudes upon scan interpretation. The presented POD curves should be considered as representative to inspection at a high sensitivity level, i.e. low rejection thresholds.

A further note is given on use of amplitude responses in POD analysis. A basic assumption with the applied POD model is that reflected amplitude from an imperfection has some kind of relation with imperfection size. The relation between size and amplitude response is regarded to be weak for the applied AUT procedure for several reasons. Mainly due to the unpredictable anisotropic material properties, but also since normal incident to plane imperfection surface cannot be expected in all cases and since amplitude responses from different type of techniques (i.e. creeping wave, pulse echo and mapping) are mixed. Another thing to mention with regards to interpretation is that quite low amplitude signals are utilised during operator interpretation, for instance as pattern recognition within all channel mapping. For POD, analysis has therefore been focused on low reporting thresholds in order to capture the full range of signals that are utilised with the procedure.

Height sizing inaccuracy 5% probability against under-sizing has been calculated as μ-1.65σ.

Tendency in depth sizing inaccuracy and length sizing accuracy have been assessed from observed trends in the data.

7 RESULTS

7.1 General Observations

Noise is a well-known issue with the coarse and preferentially oriented grain structured CRA welds. The signal to noise level is in general found to be good for all channels, regardless of this noise level is observed to vary between the different channels within the setup. Most prominent noise is found within Region C of the weld and for the creeping wave and head wave channels at Region A. It is emphasized that all channels in the AUT setup are presenting information from the whole weld in all mapping channels (B-scans) and sectorial scans (S-scans). This information is fully available and actively used by the operators, according to the AUT procedure [1]. Using this information, the signature of a flaw can be identified at even low amplitudes when it stands out from the more random distributed noise.

The root and fill channels are observed in general to have a noise level in general not more than 10% FSH, which is seen for root channel and the lowest fill channel. This corresponds to a signal to noise ratio of consistently >18 dB. For the rest of the fill channels and the head beam channel the signal to noise ratio is consistently >20 dB. The creeping wave channel was observed to have in general higher noise levels, mainly observed within 20% FSH. This corresponds to a signal to noise ratio of consistently >12 dB. Care should be taken during AUT setup, to provide a good calibration scan in order to achieve optimal signal to noise ratio.

7.2 Repeatability

The pre-examination repeatability test scans on a reference block show good consistency for repeated scans, with no deviation from initial calibration sensitivity at 80% FSH more than ±2 dB. The deviations are in general found within ±1 dB. This is regarded to be stable.

The results of the repeatability trials for J-bevel reference block are presented in the Figure 7-1, Figure 7-2, Figure 7-3 and Figure 7-4 below. The x-axis represents the different reference reflectors used to set sensitivity in the setup. The same trials are performed on V-bevel reference block, with similar results. The full results of these tests can be found in Appendix A.

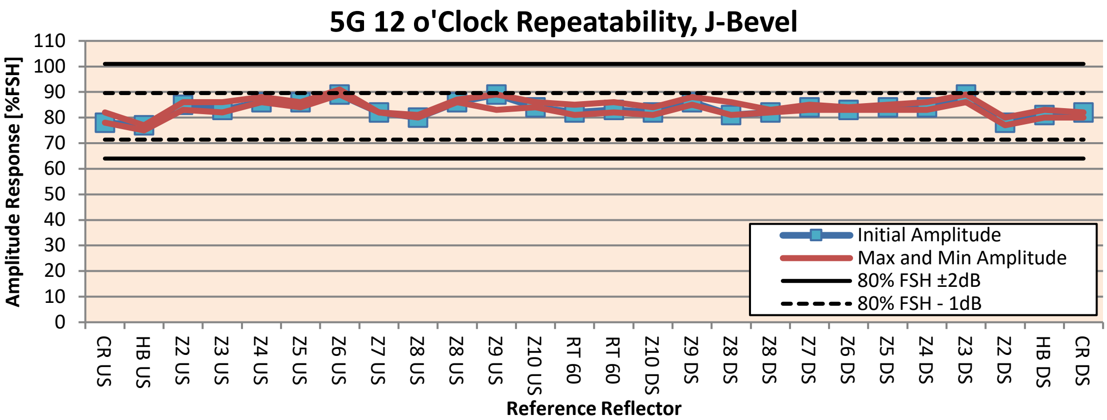

Figure 7-1: Reference block repeatability for both US and DS side for 10 scans with the reference block at 5G position with 12 o'clock start position.

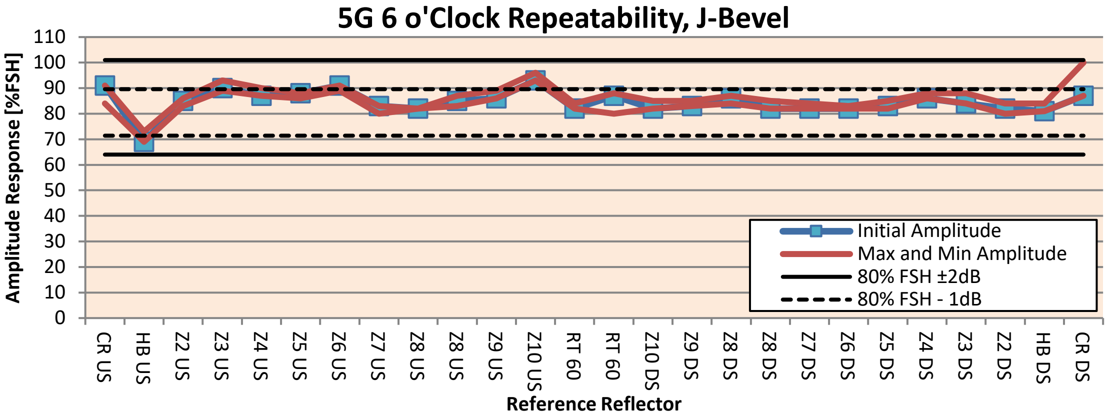

Figure 7-2: Reference block repeatability for both US and DS side for 10 scans with the reference block at 5G position with 6 o'clock start position.

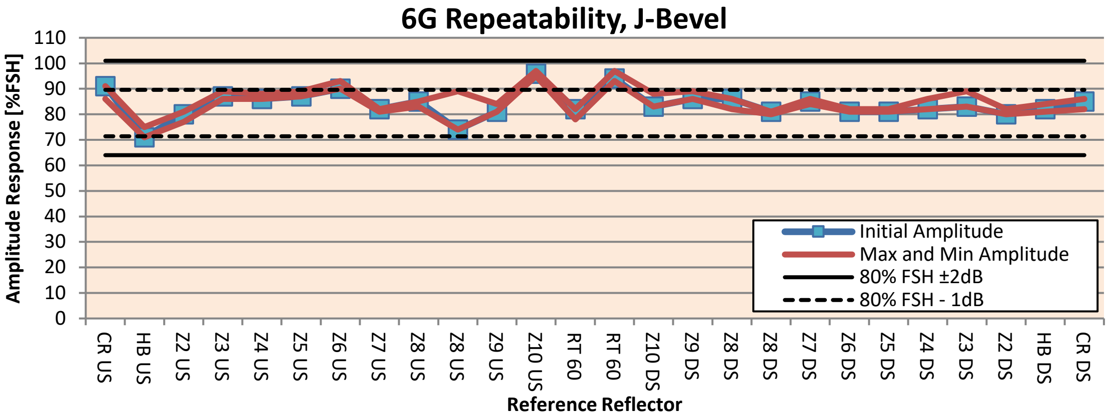

Figure 7-3: Reference block repeatability for both US and DS side for 10 scans with the reference block in 6G position.

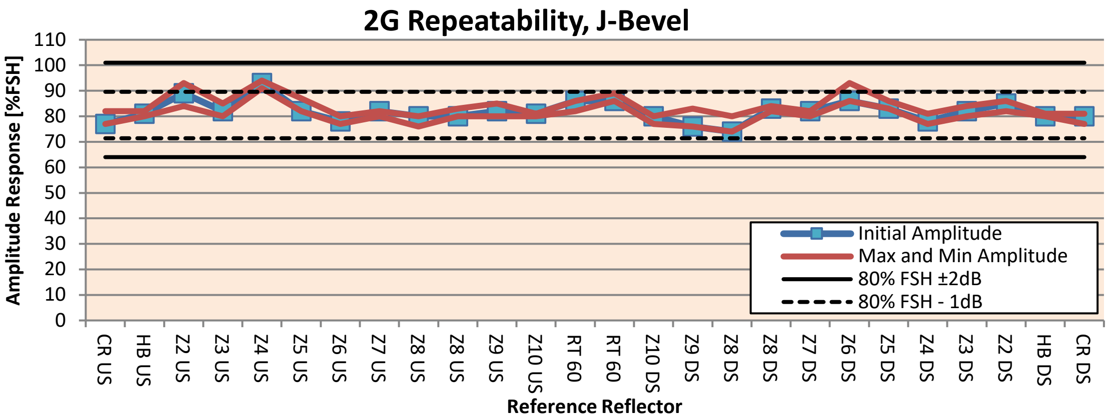

Figure 7-4: Reference block repeatability for both US and DS side for 10 scans with the reference block in 2G position.

7.3 Elevated Temperature

Temperature trials were performed on one nominated weld (weld G3-6), including 6 clearly identified flaws.

The high temperature test scans shows good consistency between scans at ambient temperature and scans at elevated temperature. This is illustrated in Figure 7-5, which includes measurements of maximum amplitude of 6 flaws in the trial weld V25 at an initial elevated temperature at around 70°C. The 6 flaws are taken from a representative range of flaw heights, listed in the Table 7-1 below.

Table 7-1 Imperfections Included in Elevated Temperature Trials

	Channel	Length [mm]	Depth [mm]	Height [mm]
Defect 1	CR US	30	2.5	2.5
Defect 2	HB DS	9	1.7	1.7
Defect 3	Z3 DS	21	8.1	1.7
Defect 4	Z3 US	20	8.3	2.2
Defect 5	RT60 US	31	33.5	3.2
Defect 6	Z10 US	35	31.5	2.2

The figure shows the maximum amplitude for the same flaws within the 15 scans, and amplitude response ±2 dB from the ambient scan. All measurements at the elevated temperature were found within ±2 dB from the scan at ambient conditions, which is within the height sizing accuracy documented in paragraph 7.5.1. More details about the trials are provided in Appendix B.

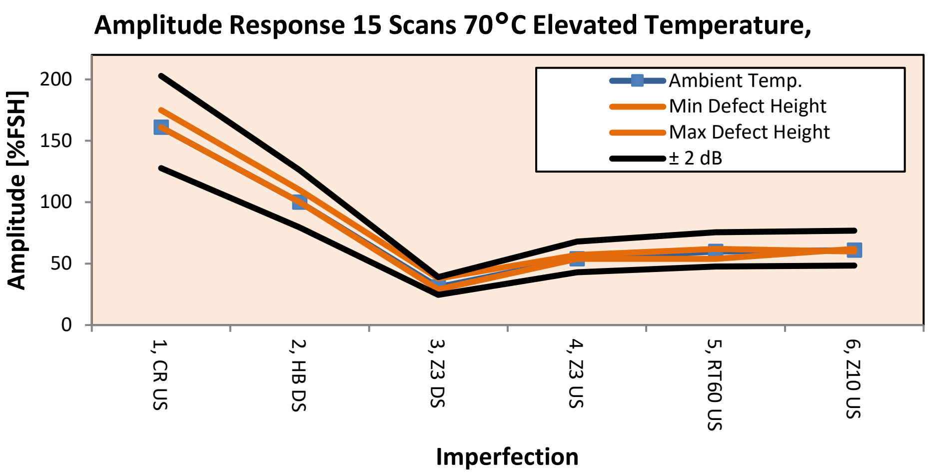

Figure 7-5: Elevated temperature trial, maximum amplitude measured for 6 imperfections in one defective weld, series of 15 scans with at least 70°C.

7.4 Detectability

The results from the detectability analysis are summarised in Table 7-2 below. Further details and curves are provided in the subsequent sub-chapters.

Table 7-2: Summary of POD Analysis Results

Evaluation Level	General	Region A	Region B	Region C	Region C*
10% FSH	0.3 mm	-	0.7 mm	-	-
15% FSH	0.6 mm	0.7 mm	1.5 mm	0.6 mm	0.6 mm
20% FSH	1.0 mm	0.8 mm	2.6 mm	0.9 mm	0.9 mm
25% FSH	1.5 mm	1.1 mm	2.6 mm	1.4 mm	1.5 mm
30% FSH	2.0 mm	1.4 mm	2.8 mm	1.9 mm	2.2 mm

* Only includes 3 mm CRA layer

7.4.1 General Detectability (POD and POR)

Figure 7-6 shows the general Probability of Detection (POD)-curve for imperfection observations at all depths of the weld as accounted for in paragraph 6.5. In total 288 independent observations are included.

The analysis shows the imperfection height corresponding to a 90% POD at 50% confidence level at 0.2 mm, which is the actual fit to the present results. The 90% POD imperfection height with 95% confidence is at 0.3 mm. The results are valid for all parts of the weld.

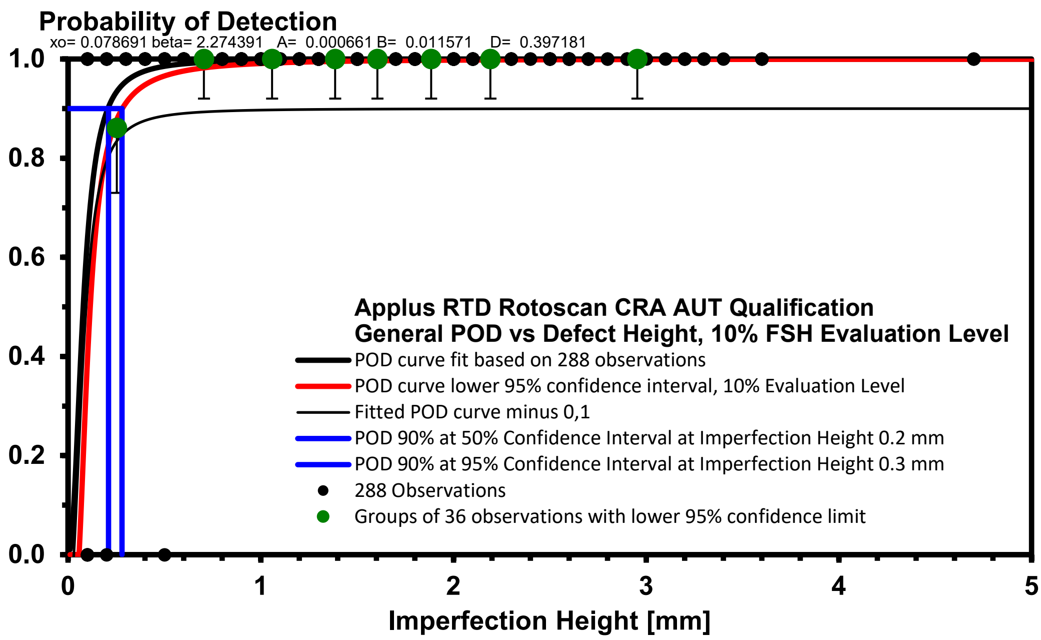

Figure 7-6: POD-curve, general detection. 90%|95% POD indicated.

Figure 7-7 shows the POR curve corresponding to a 1.0 mm rejection threshold of AUT reported imperfection height for all parts of the weld. The 85% POR imperfection height with 95% confidence is estimated to be 0.6 mm.

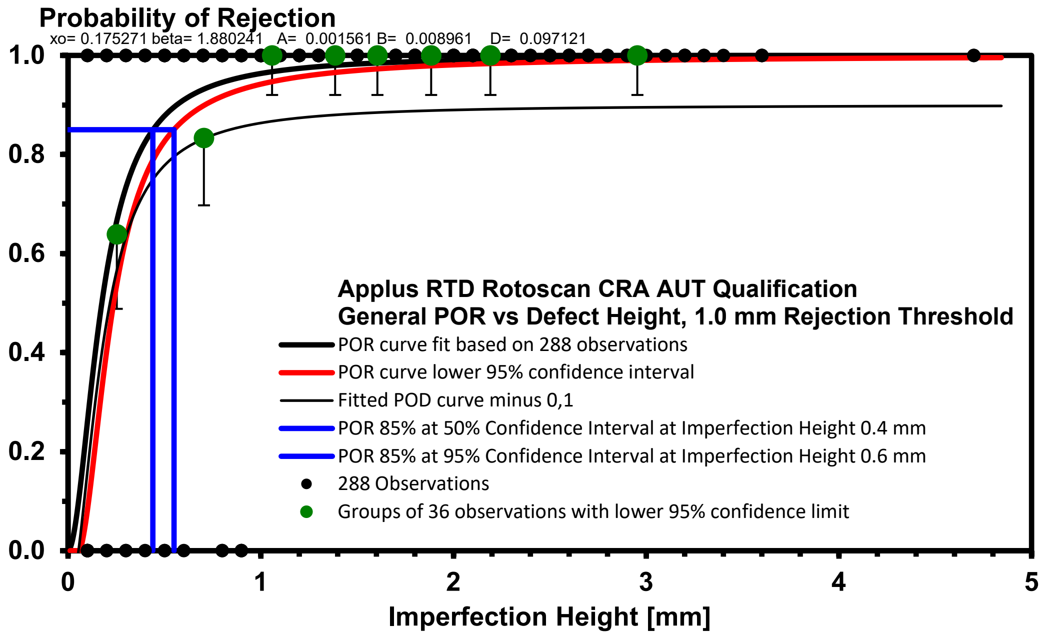

Figure 7-7: POR-curve, general detection with a 1.0 mm imperfection height rejection threshold. 85%|95% POR indicated.

POD analysis have been performed at several evaluation levels, the results are summarised in Table 7-2. The calculated 95% confidence bands for evaluation levels of 10%, 15%, 20%, 25% and 30% are plotted in Figure 7-8 below.

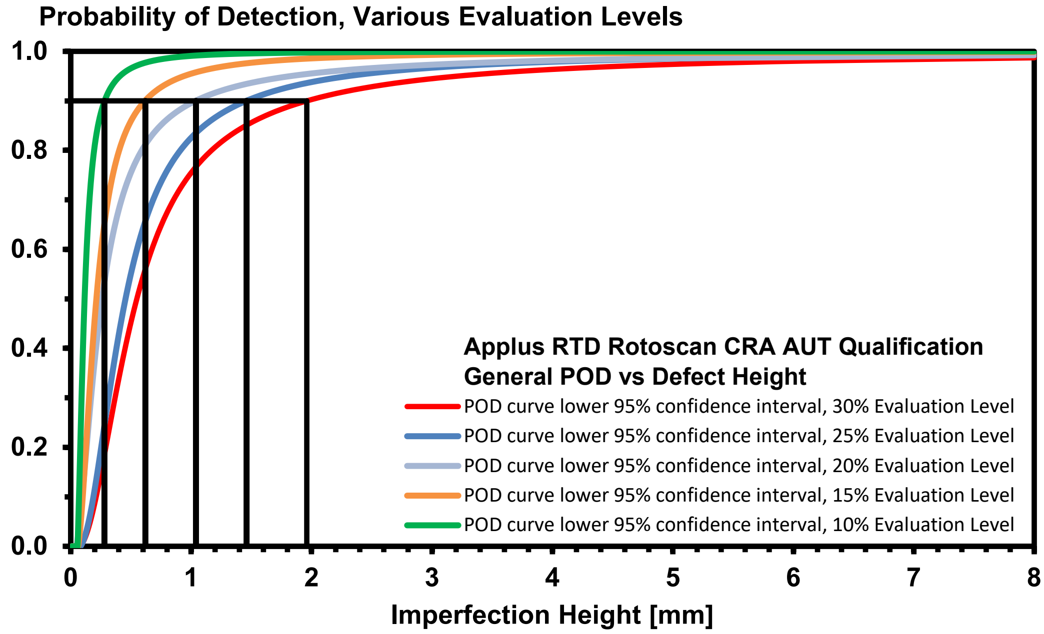

Figure 7-8: The general 90% POD height at 95% confidence for different evaluation levels.

7.4.2 Region A Detectability

POD analysis for Region A has been performed at several evaluation levels, the results are summarised in Table 7-2. The calculated 95% confidence bands for evaluation levels of 15%, 20%, 25% and 30% are plotted in Figure 7-9 below.

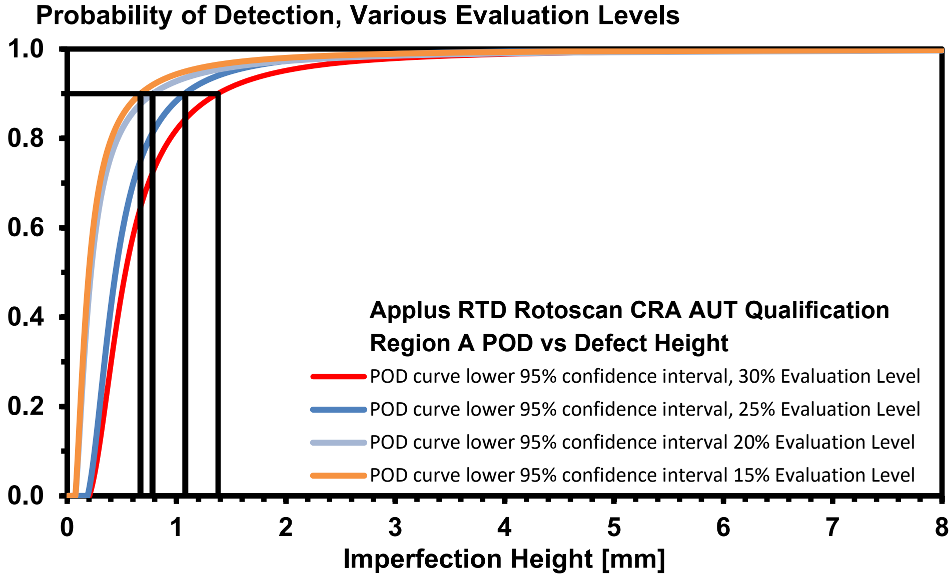

Figure 7-9: POD-curves at 95% confidence, Region A. 90%|95% POD indicated.

7.4.3 Region B Detectability

POD analysis for Region B has been performed at several evaluation levels, the results are summarised in Table 7-2. The calculated 95% confidence bands for evaluation levels of 10%, 15%, 20%, 25% and 30% are plotted in Figure 7-10 below.

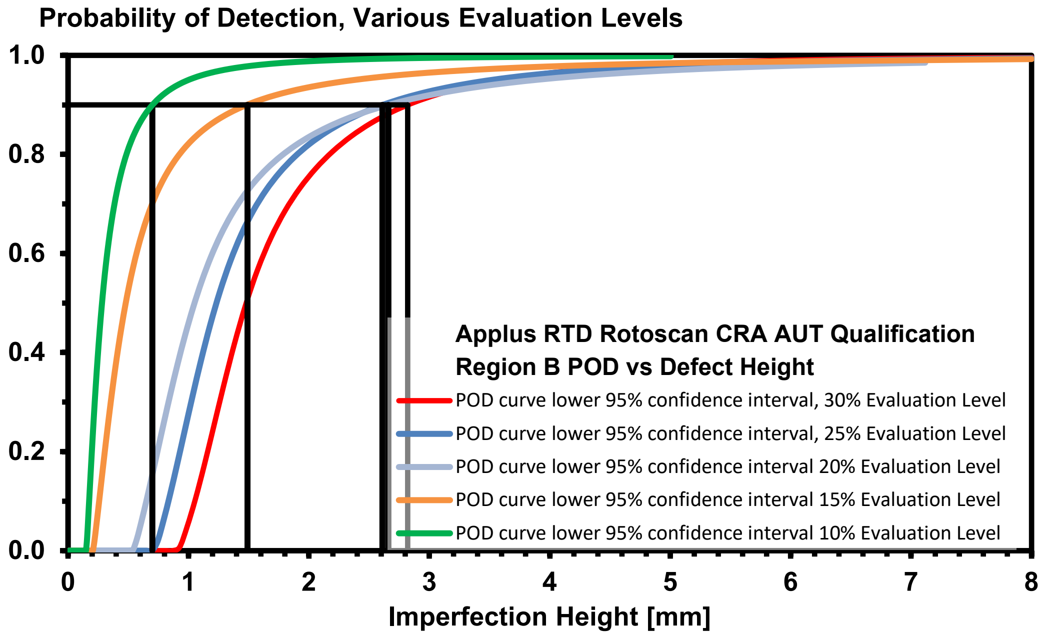

Figure 7-10: POD-curves at 95% confidence, Region B. 90%|95% POD indicated.

7.4.4 Region C Detectability

POD analysis for Region C has been performed at several evaluation levels, the results are summarised in Table 7-2. The calculated 95% confidence bands for evaluation levels of 15%, 20%, 25% and 30% are plotted in Figure 7-11 below.

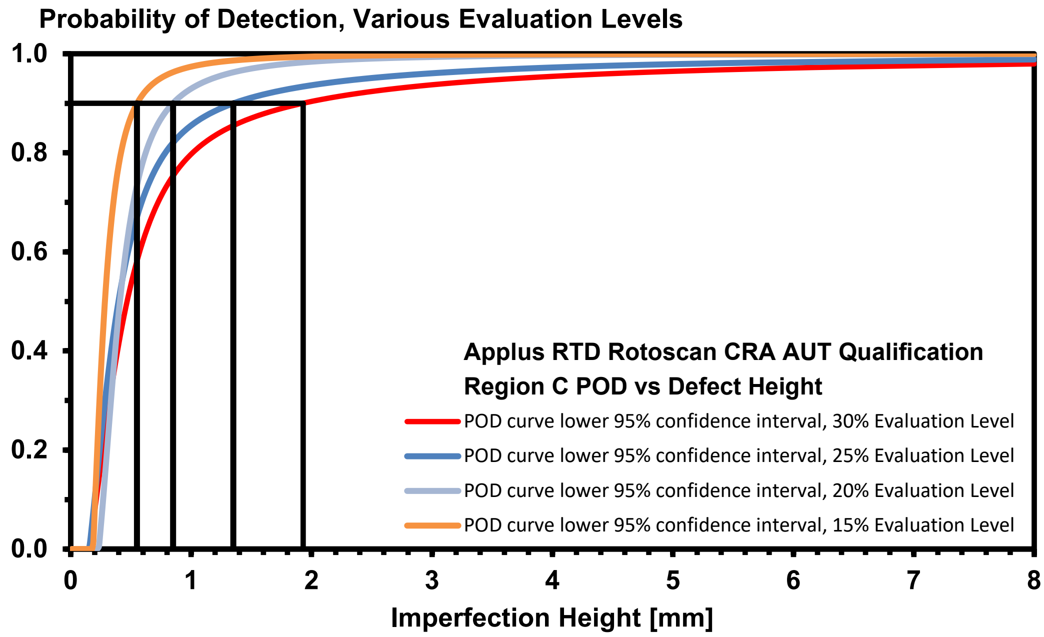

Figure 7-11: POD-curves at 95% confidence, Region C. 90%|95% POD indicated.

7.4.5 Region C* Detectability

POD analysis for Region C* has been performed at several evaluation levels, the results are summarised in Table 7-2. The calculated 95% confidence bands for evaluation levels of 15%, 20%, 25% and 30% are plotted in Figure 7-12 below. It should be noted that there are no indications in this category with amplitude response between 25% FSH and 30% FSH, so the POD curves at these evaluation levels are identical.

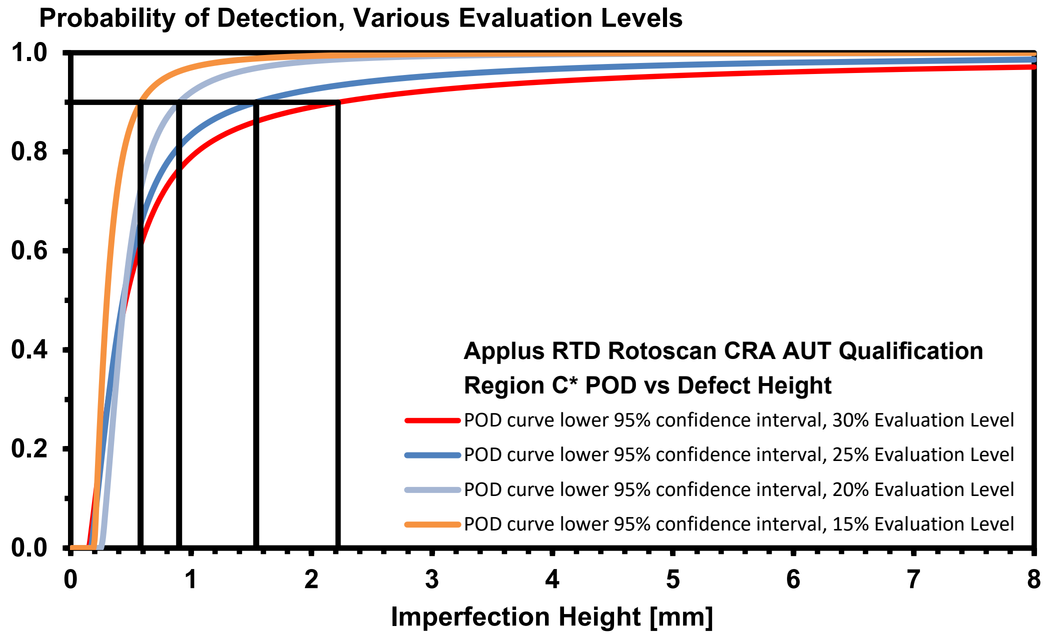

Figure 7-12: POD-curves at 95% confidence, Region C*. 90%|95% POD indicated.

7.5 Imperfection Height Sizing Accuracy

Imperfection height sizing is performed with all available information in the AUT scans, and is mainly performed through evaluation of amplitude responses. TOFR can also be used for sizing. However TOFR is regarded most suitable to provide supplemental information to the direct beam inspection channels, and should not be the preferred sizing method.

The results are summarised in the Table 7-3 below.

Table 7-3: Summary of height sizing accuracy analysis results

	General	Region A	Region B	Region C	Region C*
5% Probability Under Sizing	-0.9 mm	-0.9 mm	-0.7 mm	-1.0 mm	-1.0 mm

The overall distribution of imperfection sizes within the data is showed in Figure 7-13 below.

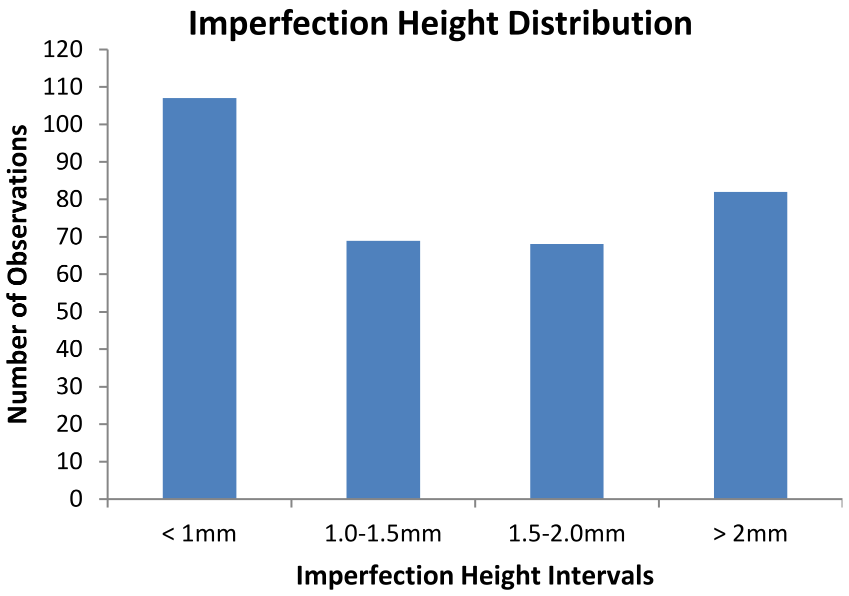

Figure 7-13: Imperfection height distribution in general for the imperfections included in the analysis.

7.5.1 General Height Sizing Accuracy

The general height sizing accuracy (the 95% limit against under-sizing) is estimated to -0.9 mm, Figure 7-14. The mean height sizing error is estimated to 0.4 mm over sizing, with a standard deviation of 0.79 mm. The same sample of imperfections as used in the POD analysis is included in the height sizing accuracy evaluation.

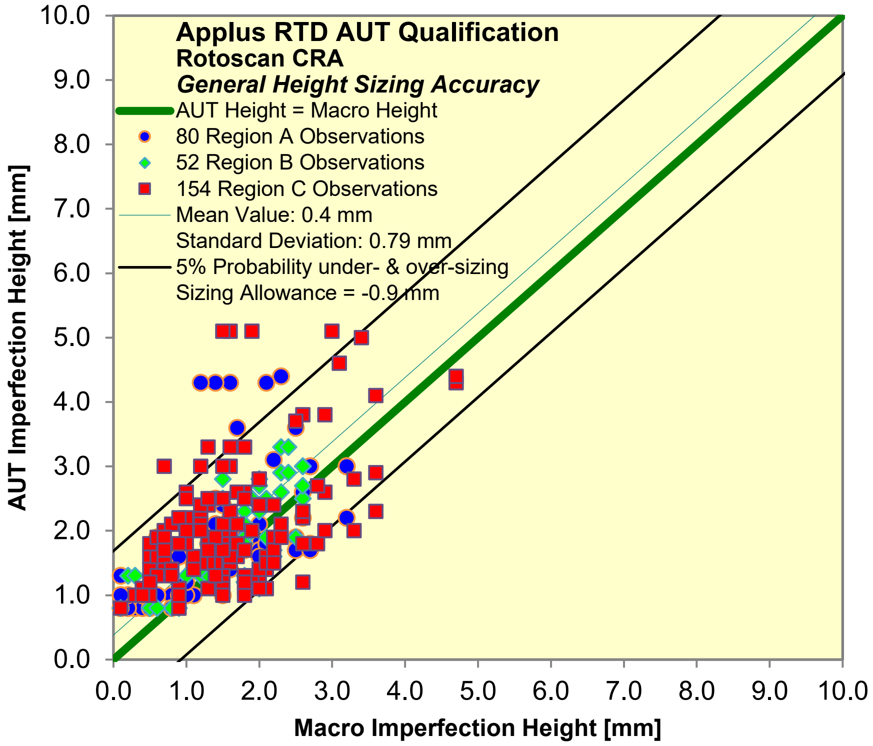

Figure 7-14: General height sizing accuracy plot.

7.5.2 Region A Height Sizing Accuracy

In total 80 independent imperfection observations have been included in the analysis for sizing accuracy in the OD surface area. For the OD surface imperfections investigated, there is a mean height sizing error of 0.4 mm over sizing, with a standard deviation of 0.78 mm. The 95% limit against under sizing is estimated to -0.9 mm, Figure 7-15.

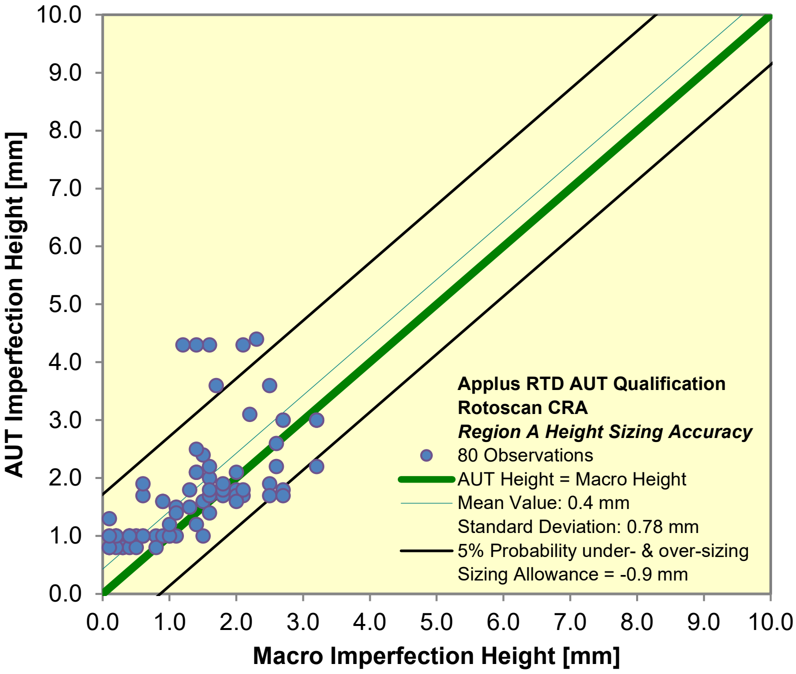

Figure 7-15: Height sizing accuracy for Region A.

7.5.3 Region B Height Sizing Accuracy

The buried category comprises of 52 independent imperfection observations detected at the buried parts of the weld. For the buried imperfections investigated, there is observed a mean height sizing error of 0.2 mm, with a standard deviation of 0.54 mm. The 95% limit against under-sizing is estimated at -0.7 mm, Figure 7-16.

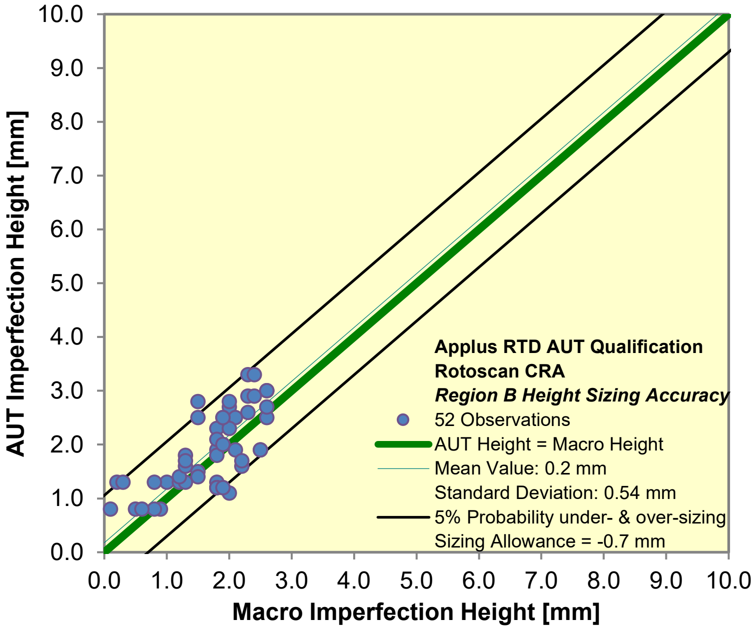

Figure 7-16: Height sizing accuracy for Region B.

7.5.4 Region C Height Sizing Accuracy

The Region C category includes 154 independent imperfection observations, both surface breaking and buried in the CRA layer area. A mean height sizing error of 0.4 mm was observed, the standard deviation was 0.86 mm. The 95% limit against under-sizing is estimated to -1.0 mm under-sizing, Figure 7-17.

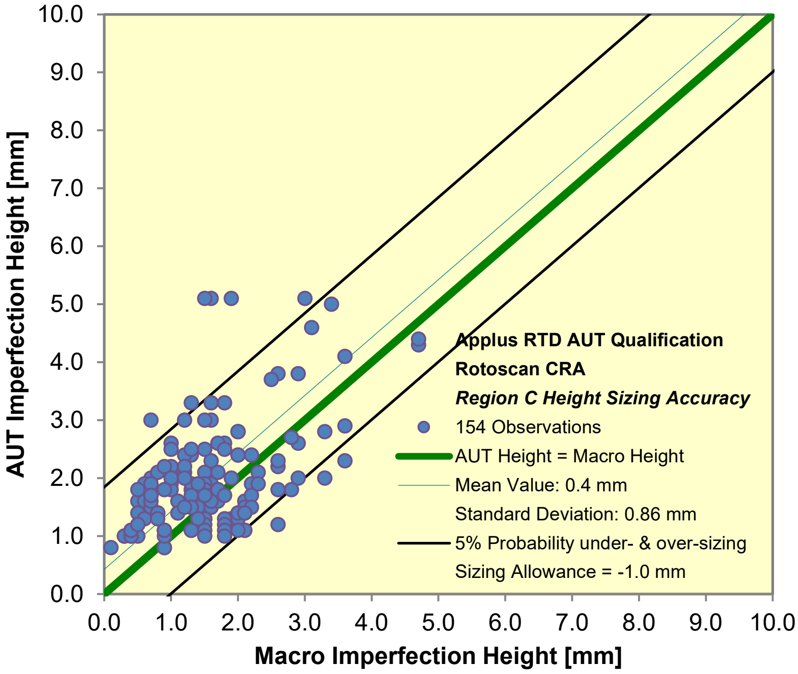

Figure 7-17: Height sizing accuracy plot for Region C.

7.5.5 Region C* Height Sizing Accuracy

The Region C* category includes 131 independent imperfection observations, both surface breaking and buried in the CRA layer area. A mean height sizing error of 0.5 mm was observed, the standard deviation was 0.87 mm. The 95% limit against under-sizing is estimated to -1.0 mm under-sizing, Figure 7-18.

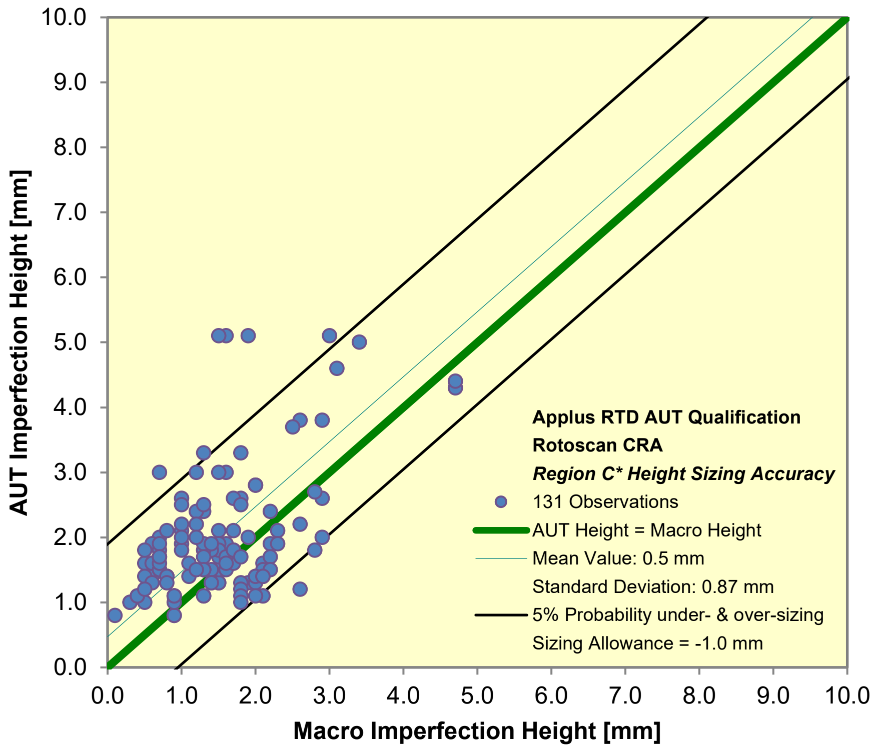

Figure 7-18: Height sizing accuracy plot for Region C*.

7.6 Depth Sizing Accuracy

In AUT reports, the reported imperfection depth is the vertical distance from the OD surface to the lowest indication of the imperfection. Depth sizing accuracy is in principle relevant for non-surface breaking imperfections, as the depth of surface breaking imperfections is known to the operator. For imperfections at the inner surface (ID surface), the reported depth is fixed as the wall thickness. The analysis includes therefore the same set of data from all parts of the weld as used for the height sizing accuracy evaluation reported in paragraph 7.5.1, except from all surface breaking observations in Region C (in total 65 observations).

It is estimated a depth inaccuracy of 0.9 mm average, with a standard deviation of 1.27 mm, Figure 7-19. The positive value indicates that imperfections tend to be estimated deeper in the weld by AUT than they appears on the macro sections.

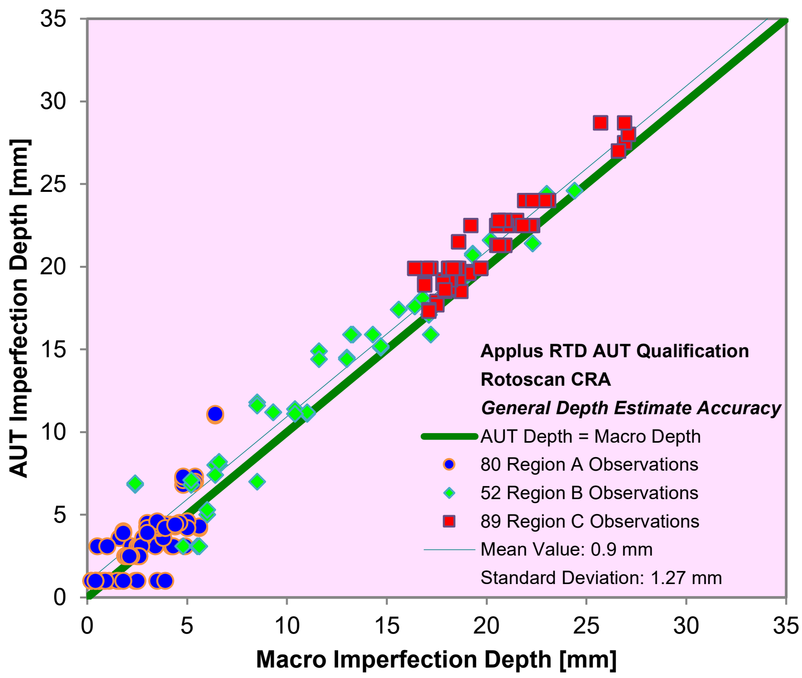

Figure 7-19: Depth sizing inaccuracy for non-surface breaking imperfections.

Depth sizing accuracy has been evaluated for Region C separately. The analysis includes only non-surface breaking imperfections with a ligament to ID surface not more than 4.5 mm. A mean depth inaccuracy of +1.3 mm is estimated, with a standard deviation of 0.87 mm, Figure 7-20. The positive value indicates that imperfections tend to be estimated deeper in the weld by AUT than they appear on the macro sections. This is on the conservative side for Region C.

Similarly, ligament estimate accuracy has been evaluated for Region C and Region A. The analysis includes only non-surface breaking imperfections with a ligament to ID surface and OD surface not more than 5 mm. At ID surface, this corresponds to the Region C dataset, while 11 surface breaking imperfections have been excluded for the analysis in Region A.

For Region C, a mean inaccuracy in ligament estimate of -1.3 mm is calculated, with a standard deviation of 0.87 mm, Figure 7-21. The negative sign indicates that imperfections tend to be estimated with smaller surface ligament by AUT than they appear on the macro sections. This is on the conservative side for Region C.

For Region A, a mean inaccuracy in ligament estimate of 0.1 mm is calculated, with a standard deviation of 1.63 mm, Figure 7-21. The positive sign indicates that imperfections tend to be estimated with some more surface ligament by AUT than they appear on the macro sections.

Depth sizing can be adjusted within the AUT procedure by the mean value upon depth sizing, provided that this approach is accepted by all parties. In such case, the approach shall be taken into account during the project specific AUT validation.

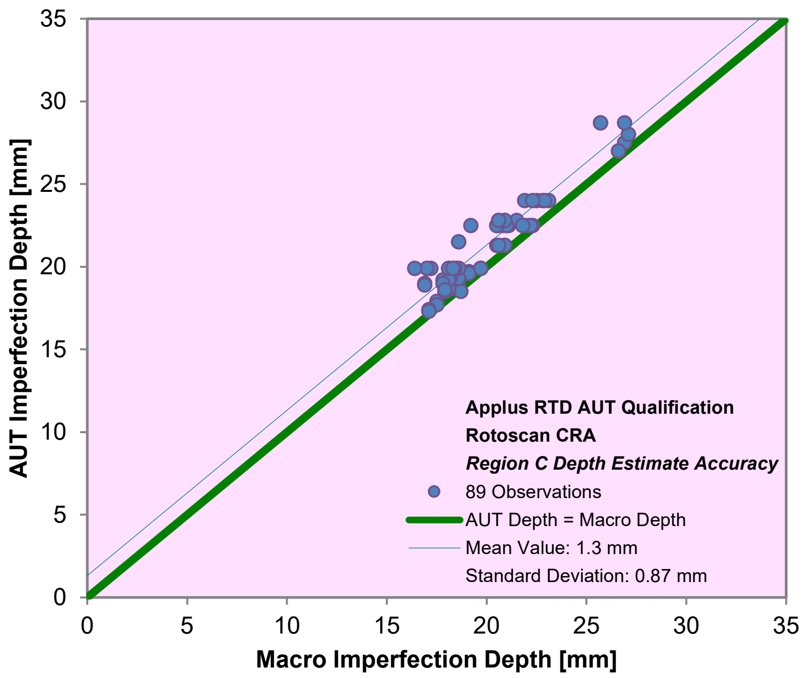

Figure 7-20: Depth sizing inaccuracy for Region C non-surface breaking imperfections.

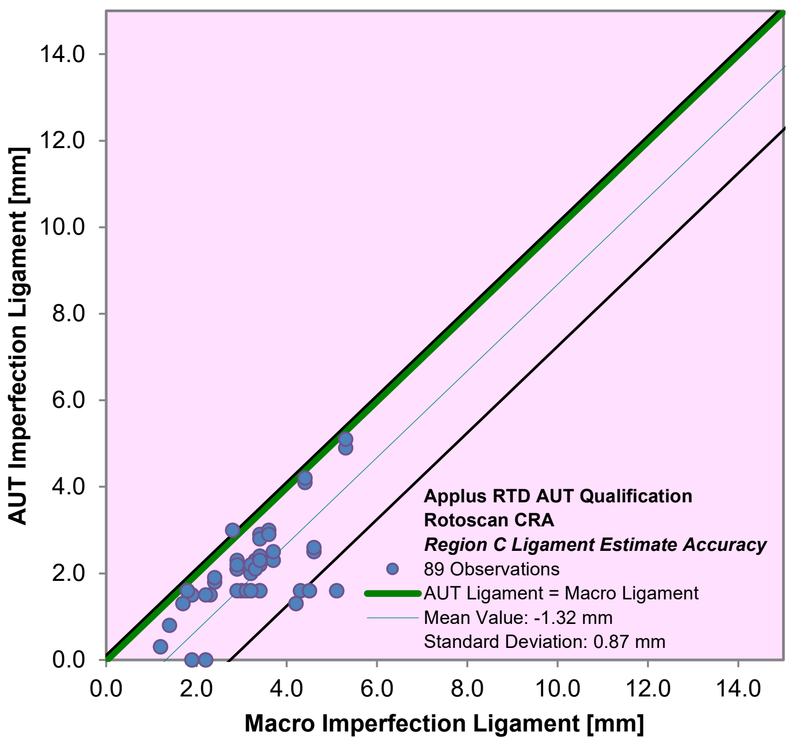

Figure 7-21: Ligament estimate inaccuracy for Region C non-surface breaking imperfections

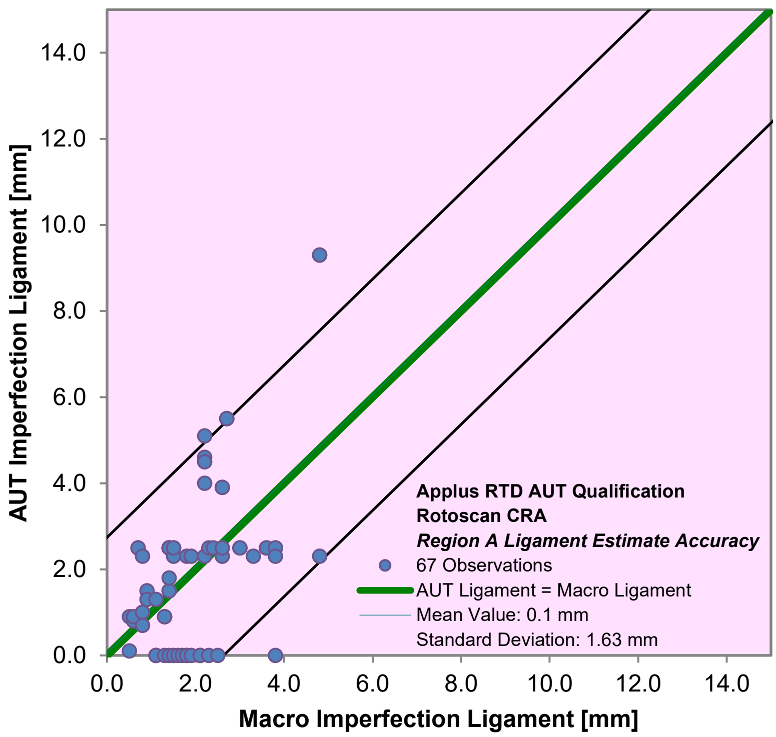

Figure 7-22: Ligament estimate inaccuracy for Region A non-surface breaking imperfections

7.7 Length Sizing Accuracy

Length sizing accuracy has been briefly evaluated. According to the AUT procedure [1], indication length is assessed at a 20% FSH threshold. In addition, beam spread is subtracted from the measured indication lengths. The beam spread is estimated from the measured length of each reference reflectors on the calibration scans. Based on all observations the mean value beam spread is evaluated to give the representative number, as described in paragraph 6.8.5. The length of the reference reflectors was briefly evaluated in some random calibration scans, and typical beam spread for the 3 mm FBHs for the fill channel was seen to be around 3.4 mm on each end of the reflector. For the 10 mm ID surface notch, a beam spread was evaluated to be 7.3 mm at each ends.

7.8 Reported Imperfection Type

The imperfection types reported by AUT correspond well with the actual imperfections observed by macro sectioning. ID surface imperfection types (lack of penetration and lack of root fusion) are consistently reported, with a note for the surface interacting buried imperfections. For buried lack of fusion imperfections in the weld overlay or CRA layer, the main response is in the root channels. It was observed that these can be reported as surface breaking in cases where there is no response available in the other channels. Lack of fusion type of imperfections is in general consistently reported. OD surface imperfections are observed to be consistently reported.

8 APPLUS+RTD ROTOSCAN PARTIAL WELD CRA AUT RESULTS

8.1 Height sizing accuracy

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

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

	No	5% under-sizing [mm]	Mean [mm]	Std.Dev [mm]
Partial Weld Region C	70	-0.9	0.3	0.76
Partial Weld Region C*	58	-0.8	0.4	0.69
Full weld Region C[1]	84	-1.0	0.5	0.93
Full weld Region C*[1]	73	-1.0	0.6	0.98

[1] Including only observations from full weld inspection

The height sizing accuracy results from the partial weld are confirmed to be similar to the results with full weld derived from the same Regions C and C*. Only minor differences are observed in the results for mean value and standard deviation. A direct comparison between scatter plots from the qualification and the qualification confirms the similar performance characteristics. It is therefore concluded that the Rotoscan CRA AUT procedure can be applied on partial welds as a stand-alone method with no impact on the height sizing performance. The slight differences observed in the results between the full weld and partial weld datasets are considered to be insignificant and due to the inherent uncertainties in AUT qualification design introduced by varying conditions with trial welds. The consistent results leave no indication of different AUT performance between full weld and partial weld setups.

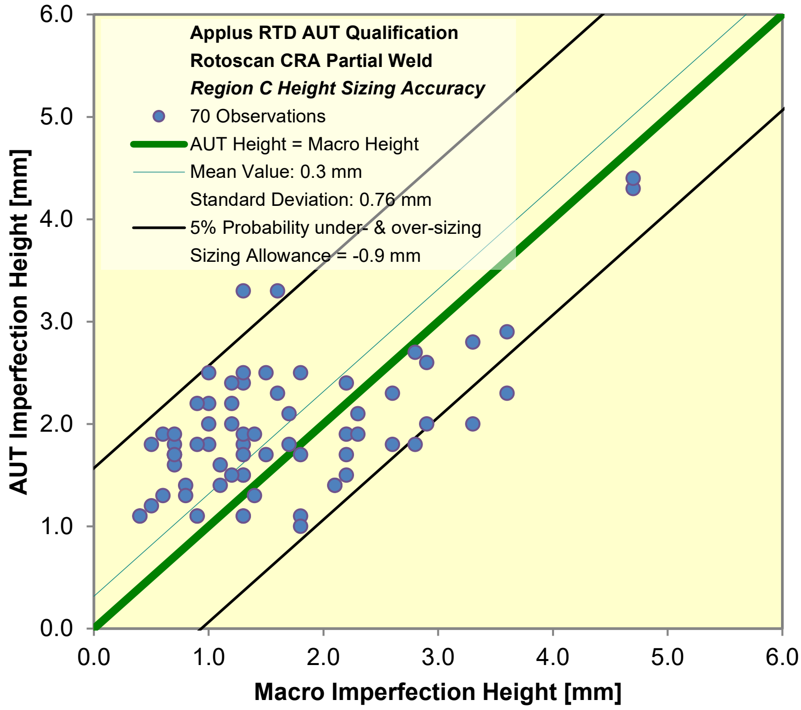

Figure 8-1: Partial weld AUT qualification data height sizing accuracy results, Region C*.

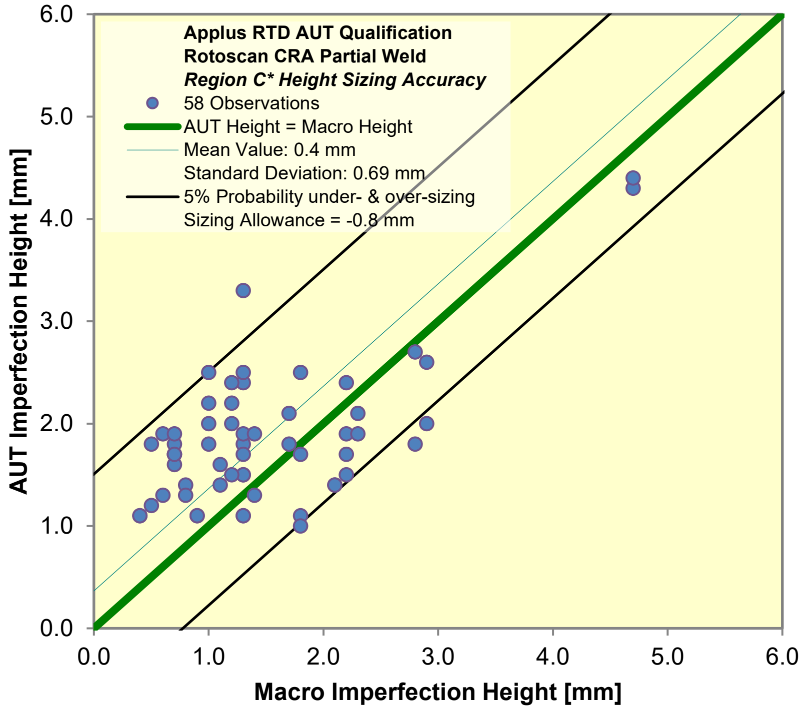

Figure 8-2: Partial weld AUT qualification data height sizing accuracy results, Region C*.

8.2 Depth and Ligament Estimate Accuracy

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

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

	No	Mean [mm]	Std.Dev [mm]
Partial Weld Region C	70	1.1	1.00
Partial Weld Region C*	58	0.9	0.83
Full weld Region C[1]	84	1.4	0.89

[1] Including only observations from full weld inspection

The depth estimate accuracy results from the partial weld are confirmed to be similar to the results with full weld derived from the same Regions C and C*. The scatter plot including the results for Region C is provided in Figure 8-3. The observed tendency that imperfections are AUT estimated lower in the weld than the actual imperfection depth is regarded to be on the conservative side at the ID surface. The same observation is also made for accuracy in remaining ligament estimate by AUT at the ID surface, Figure 8-4.

A direct comparison between scatter plots from the qualification and the qualification confirms the similar performance characteristics. It is therefore concluded that the Rotoscan CRA AUT procedure can be applied on partial welds as a stand-alone method with no impact on the depth estimate performance. The slight differences observed in the results between the full weld and partial weld datasets are considered to be insignificant and due to the inherent uncertainties in AUT qualification design introduced by varying conditions with trial welds. The consistent results leave no indication of different AUT performance between full weld and partial weld setups.

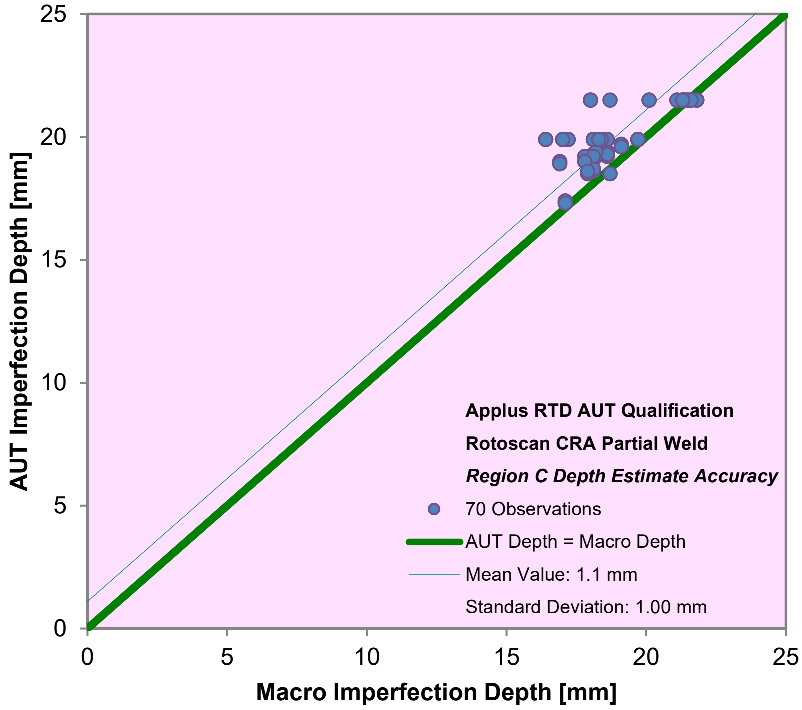

Figure 8-3: Partial weld AUT qualification data depth estimate accuracy results, Region C.

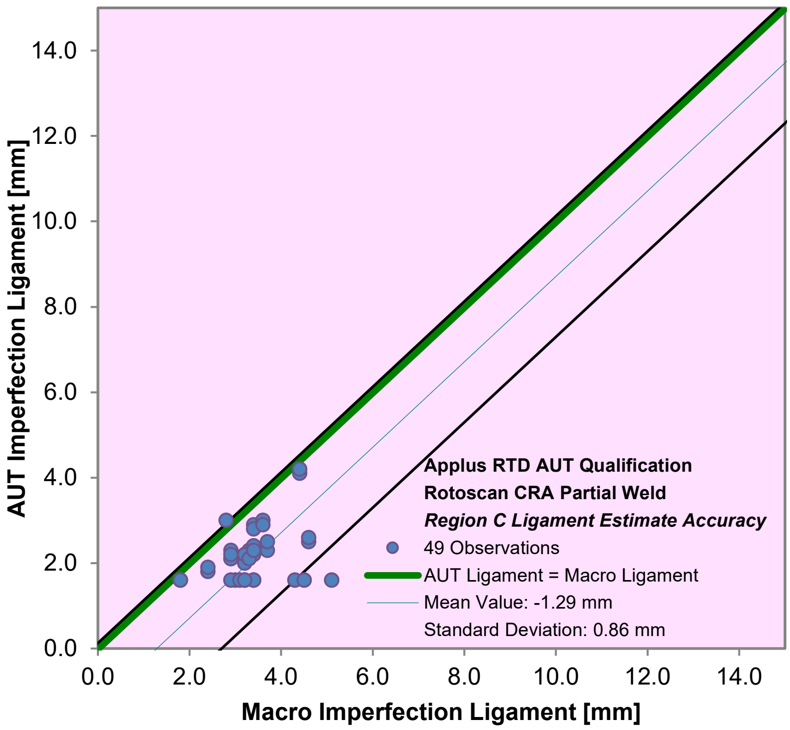

Figure 8-4: Partial weld AUT qualification data ligament estimate accuracy results, Region C.

8.3 Detectability

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

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

	No	Evaluation Threshold [%FSH]	90%|95% POD Height [mm]
Partial Weld Region C	70	20	0.6
Partial Weld Region C*	58	20	0.7
Full weld Region C[1]	84	20	1.1
Full weld Region C*[1]	73	20	1.2

[1] Including only observations from full weld inspection

The POD evaluation results with the partial weld are considered to be similar to the results with full weld derived from the same Regions C and C*. Similar detection performance has been confirmed upon data review. The slight differences observed in the results between the full weld and partial weld datasets is considered to be due to a low number of disregarded observations in both analysis, and not due to varying AUT procedure performance. This makes the results a bit dependent on single observations, and some variations can be observed between datasets.

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

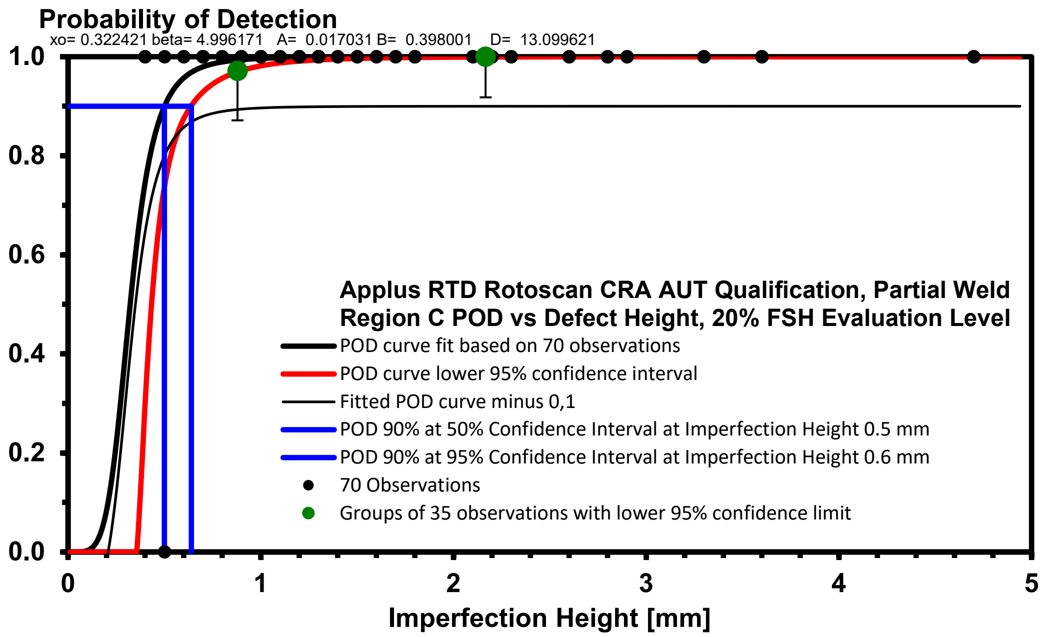

Figure 8-5: POD curve partial welds, Region C, 20% FSH evaluation level

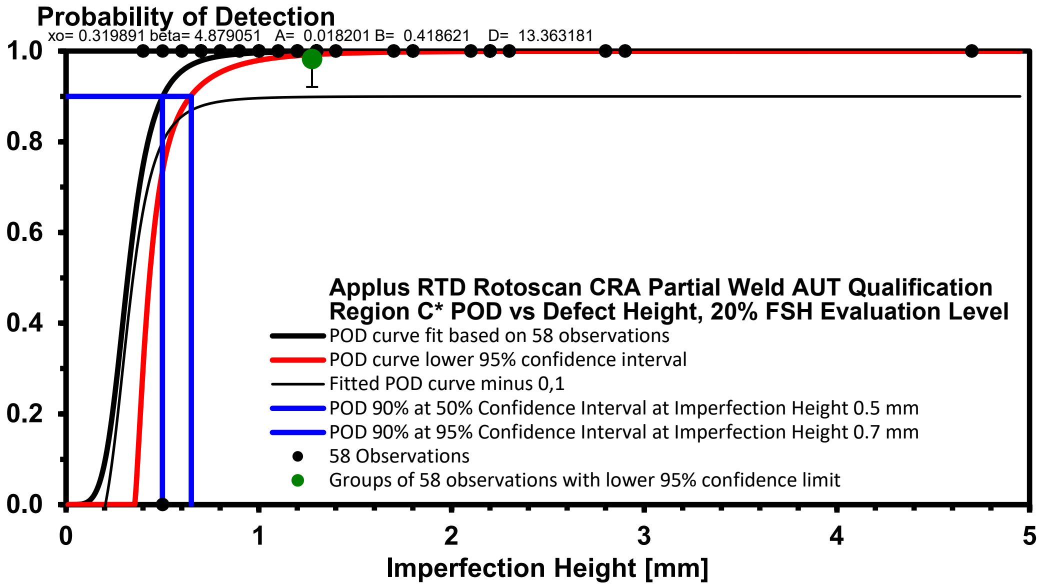

Figure 8-6: POD curve partial welds, Region C*, 20% FSH evaluation level

9 CONCLUSIONS

9.1 Introduction

The Applus+RTD Rotoscan CRA AUT system has been subject to qualification trials with respect to examination in general of girth welds in CRA cladded or weld overlay pipeline according to DNVGL-ST-F101[2]. The qualification work has been done under agreement between Applus+RTD and DNV GL AS, and follows the requirements of DNVGL-RP-F118 [3]. The qualification trials have covered in total 4 welds of 12.75″ OD, 25.4 mm WT + 3 mm clad, 4 welds of 12.75″ OD, 19.8 mm WT + 3 mm weld overlay, 5 partial welds (with a minimum ID ligament of 6 mm) of 9.6″ OD, 18.5 mm WT + 3 mm clad. The analysis includes historical data from 7 welds of 10.75″ OD, 19.2 mm WT + 3 mm clad. The pipe material was DNV MWP 450 PDC grade steel, the weld and overlay weld was UNS S31603. The defective welds and corresponding reference blocks have been subjected to trials for reliability, repeatability and heat influence. In total 288 observations were included for reliability analysis through macro sectioning. DNV GL witnessed scanning, and DNV GL performed the analysis of this report based on AUT reporting by Applus+RTD and macro section reports. DNV GL has also witnessed trial activities to document function and performance of AFLS.

The qualification applies to use of the Rotoscan CRA AUT procedure on both full weld and partial weld applications. The qualification program was designed in order to document consistent inspection performance for use on both types of welds, and the results and conclusions presented in this report applies the same for both the partial weld and the full weld Rotoscan CRA AUT procedures.

9.2 Performance data

Below are the results of the qualification, which is the documented performance of the Applus+RTD Rotoscan CRA AUT system with the set up and calibration for girth weld inspection of the welds with configuration used for the trials. The results are valid provided that the prerequisites of paragraph 9.4 are fulfilled.

9.2.1 Repeatability

Repeatability trials and temperature sensitivity trials have been performed according to DNVGL-RP-F118[3]. Reference block trials were performed with the reference block in vertical position (2G), tilted position (6G) and horizontal position (5G) with 12 o'clock and 6 o'clock start positions, all with series of 10 scans. These trials showed deviations in amplitude within ±2 dB. Elevated temperature trials with defective weld heated to 70°C gave amplitude variations within ±2 dB for maximum response of 6 imperfections.

9.2.2 Detectability

Reliable detection at 90% POD with 95% confidence is in general estimated at 0.30 mm imperfection height. The results are detailed in the Table 9-1 below, and depend on use of all data in the AUT scans upon interpretation. This is the value relevant for the requirements of DNVGL-ST-F101, Appendix E [2].

Table 9-1: Vertical Imperfection Heights of 90% POD at 95% confidence result summary

Evaluation Level	General	Region A	Region B	Region C	Region C*
10% FSH	0.3 mm	-	0.7 mm	-	-
15% FSH	0.6 mm	0.7 mm	1.5 mm	0.6 mm	0.6 mm
20% FSH	1.0 mm	0.8 mm	2.6 mm	0.9 mm	0.9 mm
25% FSH	1.5 mm	1.1 mm	2.6 mm	1.4 mm	1.5 mm
30% FSH	2.0 mm	1.4 mm	2.8 mm	1.9 mm	2.2 mm

* Only includes 3 mm CRA layer

Since detection can be based on different techniques and sometimes a combination of information in several channels, it is relevant to evaluate the probability of rejection (POR). POR has been evaluated in particular for rejection criteria of 1.0 mm imperfections height, which comes out with a 0.6 mm height at 85% POR at a 95% confidence level.

9.2.3 Height Sizing Accuracy

The height sizing accuracy is in general found to be at 0.38 mm mean value over sizing, with -0.9 mm estimated as the margin of 5% probability of under sizing.

A break down on height sizing accuracy for ID surface and buried imperfections separately shows similar figures, as summarized in the table below.

Table 9-2: Vertical Imperfection Height sizing accuracy result summary

Category	# Observations	5% Probability Under Sizing	Mean	Standard Dev.
General	286	-0.9 mm	0.4 mm	0.79 mm
Region A	80	-0.9 mm	0.4 mm	0.78 mm
Region B	52	-0.7 mm	0.2 mm	0.54 mm
Region C	154	-1.0 mm	0.4 mm	0.86 mm
Region C*	131	-1.0 mm	0.5 mm	0.87 mm

9.2.4 Length Sizing Accuracy

Length sizing was briefly evaluated as beam spread on calibration block reflectors. Oversizing in length (beam spread) of reference block reflectors was found to be at around 3.4 mm for the 3 mm FBHs. The imperfection length is evaluated at a 20% FSH evaluation level.

9.2.5 Imperfection Depth Sizing and Surface Ligament Estimate

The observed tendency with the data is that AUT positions imperfections lower in the weld than the actual position as confirmed by macro sectioning. The overall mean value of depth positioning inaccuracy is 0.9 mm depth positioning by AUT below actual position. Imperfection depth is measured from the OD surface.

Surface ligament estimate accuracy mean value is -1.32 mm at Region C and 0.1 mm at Region A. A negative sign means that the AUT tend to position the imperfections closer to the surface than the acutal position confirmed by macro sectioning.

9.2.6 Adaptive Focal Law Setting (AFLS)

The adaptive focal law setting functionality has been demonstrated on defective weld and reference block scans. The functionality is confirmed to function well and according to the intention.

9.3 Partial Weld AUT Performance Results

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

9.4 Prerequisites

The performance documented in this report for the Applus+RTD Rotoscan CRA AUT system girth weld set up is regarded relevant for general use on pipelines with CRA girth welds and an internal CRA layer either as a metallurgical bonded cladding to the backing pipe or as weld overlay. The AUT system shall be operated according to the qualified CRA AUT procedure [1]. These results can be used as a basis for project specific validation trials. This is valid provided the prerequisites regarding the CRA AUT procedure [1] below are met.

Provided that a sufficient signal-to-noise level is demonstrated for all channels, the qualified range for total wall thickness (pipe + cladding/overlay weld) is above 10 mm. The qualified range for outer pipe diameters is ≥6”. Use on pipe diameters below 6” shall require project specific validation.

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.

Detailed inspection technique documents, similar to the ones used during the qualification [1], shall be used for relevant welds in question taking material thickness and variations, bevel preparation details and other relevant items into consideration.

The validity of the results shown in this report is mainly dependent on AUT scanner set-up for the different channels (pulse echo direct beam, TRL probes for ID surface detection, creeping wave) and on calibration. The same type of reference reflectors (up to 3 mm FBHs buried, 1 mm surface notch at ID and OD surface) as during the qualification trials shall be used. Reflector sizes may be reduced (but not increased), provided that necessary area focus, resolution and noise level is maintained. The qualification is valid for setups using both PA and TRL probes, either fully PA probes, fully TRL probes or a combination of PA and TRL probes. A valid setup shall be confirmed by detection of all relevant reference reflectors with regards to sensitivity and coverage (i.e. over trace and coincidence reflectors), and documentation of a sufficient and consistent signal-to-noise ratio. Sectorial scans can be included as supplemental inspection, and are covered within this qualification.

For use on projects when accurate sizing of imperfections with height larger than one weld pass height (ie >3.0 mm) is a requirement, project specific validation is required to establish vertical height sizing accuracy.

The qualification is valid for use with all types of CRA materials. However, it is emphasized that due to the unpredictable conditions for sound propagation and attenuation in CRA materials, project specific validation trials are required for use on specific projects as described in section 9 of DNVGL-RP-F118[3]. The inspection approach shall be considered as valid when a consistent and sufficient signal to noise ratio is demonstrated for all channels, in accordance with the AUT procedure [1]. Provided this, 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 ranges specified above. Variations in bevel angle and bevel preparation are not considered major, as long as the probe set-up and calibration/sensitivity of the AUT remains as qualified.

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.

Applicable to partial weld inspection: The partial weld shall be filled minimum 6 mm from ID, to ensure minimum 3.0 mm weld material above the nominal (design) CRA layer thickness.

Qualified personnel as according to DNVGL-ST-F101 [2] requirements shall be used.

9.5 Validity

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

It can also be noted that compliance according to DNVGL-ST-F101 ensures compliance with all previous revisions of DNV-OS-F101 which includes requirements to AUT, i.e. the 2000, 2007, 2010, 2012 and 2013 editions.

10 REFERENCES

/1/ General Procedure for Automated Ultrasonic Testing of Corrosion Resistant Alloy (CRA) welds, Doc. No. PIPL-06.02.0001

/2/ DNVGL Standard DNVGL-ST-F101: Submarine Pipeline Systems, edition October 2017

/3/ DNVGL Recommended Practice DNVGL-RP-F118: Pipe girth weld automated ultrasonic testing system qualification and project specific procedure validation, May 2017

/4/ Guidelines for NDE Reliability Determination and Description, Nordtest TechReport 394, Nordtest, Espoo, Finland, Approved 1998-04

/5/ Norne Satellite Flowline POR Summary for AUT Qualification Work, Doc No. C093-TECP-F-RE-9031

/6/ Guideline Procedure CRA Weld Coupons for AUT Reference Blocks, Doc No. PIPL-03.01.0014