Reliability Considerations of NDT by Probability of Detection (POD) Determination Using Ultrasound Phased Array

Jochen H. KURZ[1], Anne JÜNGERT[2], Sandra DUGAN[2], Gerd DOBMANN[1], Christian BOLLER[1]

[1] Fraunhofer Institute for Nondestructive Testing (IZFP), Campus E3 1, 66123 Saarbrücken, Germany, Phone: +49 681 9302 3880, Fax: +49 681 9302 11 3880,
email: jochen.kurz@izfp.fraunhofer.de
[2] Materials Testing Institute University of Stuttgart, Pfaffenwaldring 32, 70569 Stuttgart, Germany,

Abstract
Reliable assessment procedures are an important aspect of maintenance concepts. Non-destructive testing (NDT) methods are an essential part of a variety of maintenance plans. Reliability aspects of NDT methods are of importance if quantitative information is required. Different design concepts e.g. the damage tolerance approach in aerospace already include reliability criteria of NDT methods. NDT is also an essential part during construction and maintenance of nuclear power plants. This paper will show the results of a research project designed for POD determination of ultrasound phased array inspections of real cracks. The continuative objective of this project is to generate quantitative POD results and to integrate these results in a probabilistic damage assessment concept. The distribution of the crack sizes of the specimens and the designed inspection instruction will be discussed, and results of the ultrasound inspections will be presented. Furthermore, additional considerations for POD determination of phased array inspections of real cracks will be discussed. In the context of the results, the remaining uncertainty of the inspections has to be taken into consideration for failure analysis.

Keywords: Probability of detection (POD), ultrasound phased array, Ultrasound sampling phased array, cracks, quantitative NDT, nuclear safety program

1. Introduction

A reliable prognosis of the condition and behavior of a structure or component is an important basis for an effective service life management. Non-destructive testing (NDT) methods are able to retrieve information on the geometry of flaws [1-3], on states of material degradation [4], on material parameters [5] and on stress related material states [6]. This information is required for damage assessment concepts, especially those related to the applied design concepts. The strongest relation to NDT exists in case of damage tolerant (DT) design where non-destructive testing methods are an essential part of the design concept. So far this is primarily applied in the field of transportation vehicles and here especially with regard to aviation and also naval applications [7]. Furthermore, other life cycle assessment concepts exist (e.g. database lifing, retirement for cause) which are in some points different from the classical DT approach (iterative life extension beyond damage tolerant life by shorter service intervals) [8]. In contrast to the damage tolerant approach, the safe life (SL) design approach is applied in a variety of industry sections [9]. NDT is also an essential part during construction and maintenance of nuclear power plants. In Germany, type and extent of inspection are specified by the Nuclear Safety Standards Commission (KTA). Only certified inspections are allowed in the nuclear industry. The qualification of NDT is carried out in form of performance demonstrations of the inspection teams and the equipment, witnessed by an authorized inspector. The results of these tests are mainly statements regarding the detection capabilities of certain artificial flaws. In other countries, e.g. the U.S., additional blind tests on test blocks with hidden and unknown flaws may be required, in which a certain percentage of these flaws has to be detected. The knowledge of the probability of detection (POD) curves of specific flaws in specific testing conditions is often not present.
A quantitative consideration of NDT methods in assessment procedures requires quantitative statements about the reliability of the applied NDT method. The determination of the

probability of detection (POD) is one possibility to quantify the probability to detect a specific flaw with an NDT method. Each NDT measurement is influenced by a variety of factors: the stage of development and the quality of NDT equipment, the quality of written procedures, the skills and attitude of the operators, the geometry and material of the component, the environment in which the inspection takes place, the location, orientation and sizeof flaws, as well as the materialstate. Therefore, reliability information about an NDT method requires defining a probability of detection which can be described as: the proportion of cracks that will be detected in the total number of existing cracks in a component by an NDE technique when applied by qualified operators to a population of components in a defined working environment.

In general, publications dealing with POD applications can be found in different fields (medical sciences, biology, materials science, physics, engineering sciences, telecommunication etc.) [10-15]. From which of these fields the POD concept originated cannot be determined with certainty. However, some of the earliest studies of a variety of aspects concerning POD can be found in the development of radar technology during World War II.

NDT in aerospace is the field where the modern concepts of POD determination were developed and where POD determination is most widespread for the qualification of NDT procedures. Therefore, the basic POD concepts are documented in detail in [11] and [16]. Brown [17] gives also an overview about the POD principle and the underlying philosophy. The DT design approach in aerospace requires a quantification of the reliability of inspection procedures. Furthermore, the compound of NDT and damage assessment by considering the POD information shows an increasing amount of concept developments and applications in fields where safety and reliability issues are concerned. Since the POD determination has to be performed for every entity of flaws and each NDT method which is applied, there are many different studies, also recent ones, especially for materials of practical relevance. Lee et al. [18] describe the POD determination of eddy current testing for steam generator tubes. Spies and Rieder [19] show results from ultrasound measurements at ship propellers and discuss the influence of signal enhancing technologies in form of POD calculations. The POD analysis of fatigue cracks in railway axles inspected by ultrasound is discussed in [20]. POD curves for well defined specimens of aerospace materials like aluminum or titanium alloys and different NDT methods were cataloged in [21]. Palanisamy [22] performed a comparative experimental evaluation to quantify the detection capabilities of flux leakage, eddy current, electromagnetic acoustic transducer and conventional ultrasonic methods.

Experimental POD determination requires a sufficient number of specimens containing the required entity of flaws to be considered. Furthermore, at least one team of inspectors is required to perform the investigations. Therefore, to reduce the time consuming experimental procedures, the model assisted POD approach (MAPOD) was developed. Several studies exist, describing the approach, describing the concept and showing case studies [20, 23]. However, neglecting experimental POD determinations completely especially for complex materials is currently not possible.

The work presented in this paper deals with the experimental POD determination from inspections of test blocks with real cracks, done within the framework of a German nuclear safety research project.

In this paper, the detection of real and artificial flaws of different sizes and different types using ultrasound is considered. The POD provides the probability for the detection of a certain flaw size. This does not exclude the occurrence of an isolated event that a larger crack is not detected. The POD delivers the realistic, statistical assessment of the reliability for an NDT method. The knowledge of a POD does not increase or decrease the occurrence of such an exception. However, a realistic safety oriented design and assessment is possible since risks can be evaluated. The knowledge of the probability of detection of a certain flaw allows assessing the consequences of this flaw in a probabilistic manner. With the objective of POD determination, ultrasonic phased array [24], sampling phased array [25] inspections were carried out. Due to the increasing number of applications of the phased array technique in ultrasonic testing, the focus was put on the inspection using phased array transducers.

2. Specimens, procedure and tests

Within the scope of the investigations, the Material Testing Institute (MPA) at the University of Stuttgart is responsible for manufacturing and supplying suitable test specimens for the ultrasonic investigations which are the basis for the calculation of the POD curves. The MPA holds a wide variety of test specimens and has broad experience with the creation of test specimen with realistic flaws. The selection of suitable test specimens is essential, because the flaws should be as realistic as possible and not limited to artificial flaws. Therefore mainly test specimens with realistic flaws were chosen. The test specimens are listed in table 1.

Table 1. Test specimens for the ultrasonic investigations

	Number of test specimen	Total number of flaws	Realistic flaws	artificial flaws
Austenitic test specimen	29	43	24	19
Ferritic test specimen	2	5	5	-
Dissimilar metal welds	1	15	2	13
Cladded specimen	4	> 65	> 59	6
Total	36	> 128	> 90	38

Different materials were chosen to cover different materials commonly used in nuclear facilities.

A picture of three austenitic stainless steel test specimens is shown in figure 1. The test specimens are bar-shaped with a “wall thickness” of 32 mm, and contain different types of welds (different weld geometry). Some of the specimens are only base metal without weld. Most of the flaws are realistic flaws induced by inter-granular stress corrosion cracking or fatigue cracking [26].

Figure 1. Austenitic test specimens with and without weld.

Some of the test specimens contain EDM notches and some of them are completely intact. The flaws were documented using different reference tests like surface crack testing, radiography and creation of microsections.

The ferritic test specimens are made from ferritic pipe sections with an outer diameter of 275 mm and a wall thickness of 14.5 mm, and contain different welding irregularities such as porosity and lack of fusion. The flaws were documented using radiography. To determine the through-wall extension of the flaws, an additional X-ray computer tomography (CT) will be necessary.

The test specimen with a dissimilar metal weld consists of a circumferential pipe weld connecting an austenitic stainless steel pipe with a ferritic low alloy steel pipe, with austenitic cladding on the inner surface of the ferritic pipe section [27]. The test block has an outerdiameter of 327 mm, a wall thickness of 29.5 mm, and a total length of 435 mm. A cross section of the weld is shown in figure 2. The test block contains several EDM notches in the weld and in the base metal, as well as one axial and one circumferential crack.

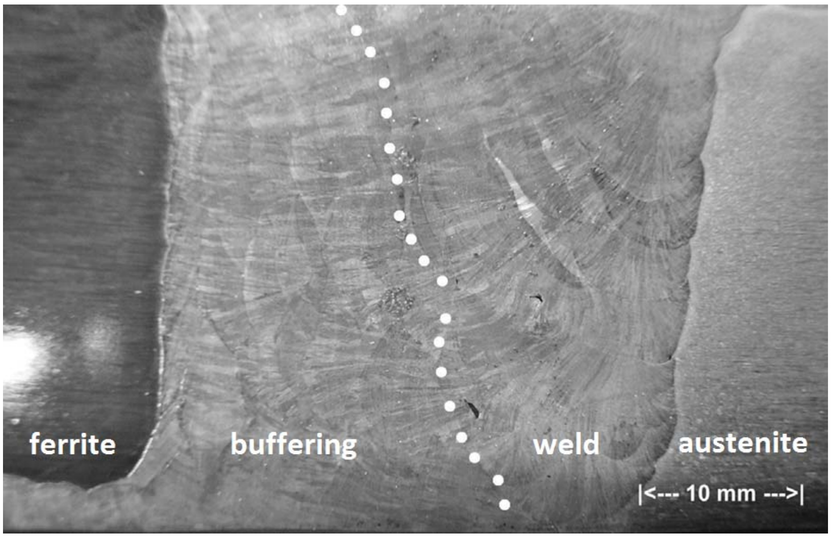

Figure 2. Micrograph cross section of the dissimilar weld. On the left side there is the ferrite which is cladded at the underside. The white dots mark the transition between buffering and weld zone. On the right side there is the austenite

The cladded test specimens consist of thick ferritic plates with an austenitic cladding, originally made to serve as pressure vessel test specimens, with wall thicknesses between 95 and 146 mm. The test specimens contain flaws that were created before, after and during the welding process [28]. A great number of flaws are natural unterclad cracks, which were created by applying a wrong heat treatment after the welding process. This type of crack forms as inter-granular in the heat affected zone. The reference tests to determine the distribution of flaw sizes for the cladded test specimens are still going on. Due to the great wall thicknesses, the detection capability of radiography is limited.
Altogether there are more than 128 flaws in the test specimens; more than 90 are realistic flaws. The number of flaws therefore is sufficient for the POD estimation. The distribution of flaw sizes is shown in figure 3.
It can be seen that the distribution is asymmetrical with the maximum at a flaw size of 3 mm. It is expected that smaller flaws are harder to detect so this distribution is suitable for the POD-estimation.
Three teams of ultrasonic inspectors using two different types of measurement equipment examined the test specimens, using ultrasonic phased array and ultrasonic sampling phased array techniques. The details for the inspection are specified in a test procedure. The recording limits specified were based on the Safety Standards of the German Nuclear Safety Standards Commission (KTA). The results of each team were compared to the actual flaws within the test specimens, known from reference tests. These results were then used as input for the POD determination. More details about the inspection procedure can be found in [29].

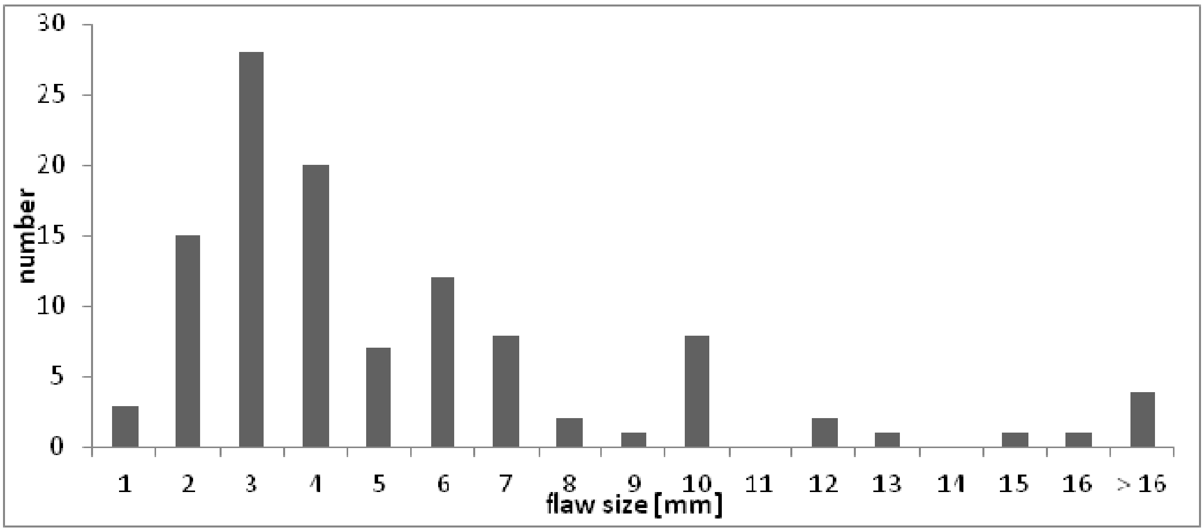

Figure 3. Distribution of flaw sizes.

3. POD determination

For an NDT inspection, a variety of factors can influence the inspection result, i.e. whether or not a flaw will be detected. The POD allows quantifying the reliability of NDT methods. The results can therefore have a direct influence on component design, maintenance and assessments. In principle, two related approaches to a probabilistic framework for the inspection of reliability data can be used [30]. One is based on the analysis of binary data, i.e. whether or not a flaw was found (hit/miss) and the other one is based on the correlation of signal response and flaw size (â vs. a). Analyzing binary data requires maximum likelihood regression to get the cumulative distribution function representing the chosen POD model.

However, as [30] points out, different results will be obtained when the two POD analysis methods are applied to the same data set.

The crucial decision in a hit/miss analysis is to define a hit/miss criterion. If a threshold value for the signal response is sufficient to characterize a hit or a miss event, the criterion can be easily defined. In our case, flaw size and location based on the evaluation of the registration length is the relevant information. Therefore, accuracy in the determination of size and location are the parameters which should be considered for POD determination in this case. Finding a criterion transfering the accuracy information into a hit/miss decision would allow applying a hit/miss POD analysis. A fracture mechanics based approach could be successful here, however, this was not yet part of the investigations presented here. Furthermore, the used maximum likelihood regression requires more data to achieve stable results [11, 30]. The main focus of the investigations presented here is laid on the â vs. a POD analysis.

POD determinations based on signal response data (â vs. a) have already been carried out for a variety of NDT methods. Therefore, the applicability of ultrasound data was already proved. However, using ultrasound Phased Array or SPA data no direct correlation between signal response and flaw size is existing any more since the registering length is analyzed to get the flaw size, Nevertheless, the POD concepts can be applied to quantify the accuracy of the inspection in terms of a POD. The mathematical concept behind a POD analysis is of general sense. That means also other data than direct signal response data can be applied to the POD concept. If other than direct signal response data is used it has to be shown that this data is in accordance with the underlying POD models. In general, four conditions have to be fulfilled when measurement data is to be used for an “â vs. a” POD determination: a) linearity of the parameters, b) uniform variance, c) uncorrelated responses, and d) normal distribution of test flaw sizes. In our case, the determined flaw size represents the signal response data. Regarding an “â vs. a” POD analysis the four conditions have to be valid for the data used. Otherwise the underlying POD model assumptions are invalid and uncorrect results would be gained. The detailed proof that the ultrasound phased array data from the described inspections fullfils the four conditions for an “â vs. a” POD analysis is given in [29]. There it is shown that the collected data which is based on the analysis of the registration length could be used for an “â vs. a” POD analysis. Here, the influence of the decision threshold on the POD values and the resulting POD curves from the different inspections are shown and discussed.

Fig. 4 shows exemplarily the linearity of the parameters of the austenitic and one cladded specimen. The data is from one of the teams which were carrying out phased array measurements. With the fulfilled conditions for an “â vs. a” POD analysis the first step consists of a linear regression. The resulting parameters according to the underlying lognormal distribution model define the shape of the POD curve [30].

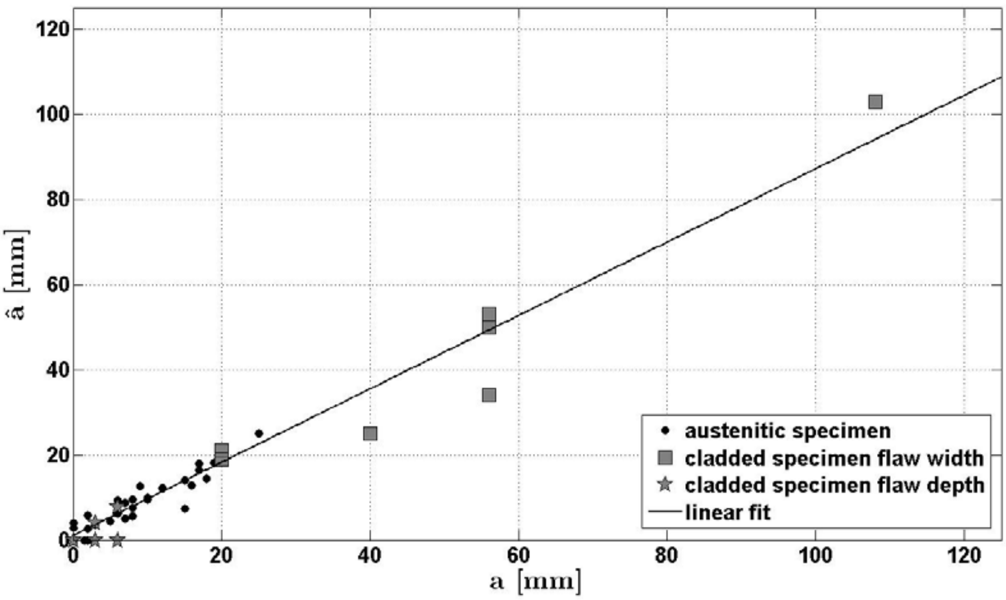

Figure 4. linearity of the parameters.

A critical point in the POD analysis of signal response data is the definition of the decision threshold [11, 31]. This is the second major step in an “â vs. a” POD analysis. With the decision threshold the lateral position of the POD curve relative to the flaw size axis is defined. In an analysis where the amplitude value of the signal is directly used, the noise level can be also directly considered for selecting the decision threshold. In general, the decision threshold influences both the minimum size detected and the probability of false positive detections [11]. In our case, when the flaw size is the parameter used for a signal response based POD analysis, a criterion is required for the selection of a decision threshold based on the accuracy of the inspections. According to the approach of [31], a criterion was chosen which considers noise and false positive detections in an indirect manner. The difference between true flaw size and determined flaw size was taken and the standard deviation was calculated. The accuracy of the measurements is considered and also the false positive indications which are an indication of the signal to noise ratio. Fig. 5 shows the difference between true flaw size and determined flaw size taken from the measurements at the austenitic specimens (including artificial flaws). The calculated standard deviations for the two distributions shown in Fig. 5 are 3.0 mm and 2.7 mm. It becomes clear that the decision value also depends on the chosen entity of data.

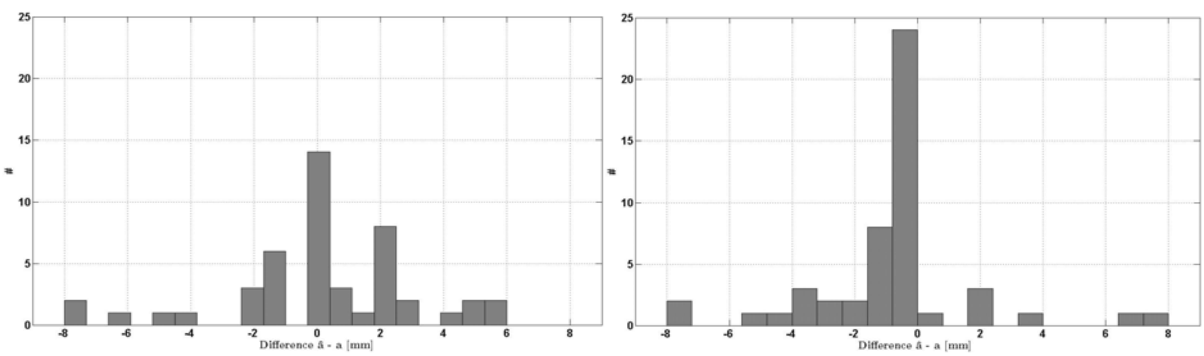

Figure 5. Differences between true flaw sizes and determined flaw sizes obtained from the measurements on the austenitic specimens including specimens with artificial flaws. Left: phased array probe. Right: sampling phased array technique.

The influence of the decision value on the resulting POD values was investigated in a sensitivity study. Therefore, for one phased array data set the decision value was varied and for each decision value the resulting POD curve was determined. Fig. 6 shows how the value of the flaw size with 50 % POD (a_{50}) and how the values of the flaw size with 90 % POD within a confidence interval of 95 % ($a_{90/95}$) increase with increasing decision value. The change of the decision threshold leads to a linear shift of the resulting POD values. It is obvious from Fig. 6 that the decision value has a severe influence on the position of the final POD curve and therefore the decision value should be chosen with care.

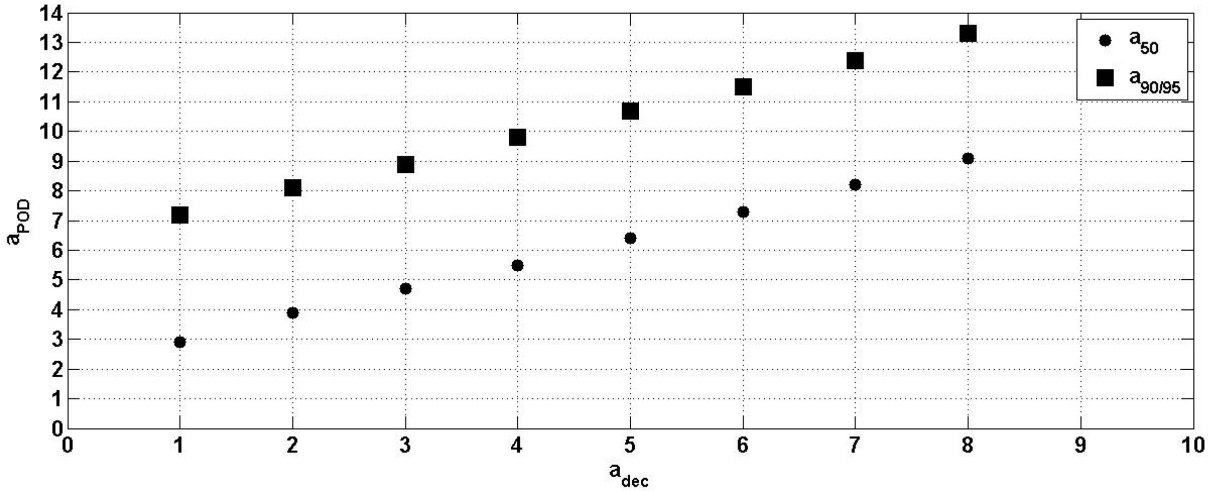

Figure 6. Influence of the decision value on the POD result.

Applying a linear regression and using the calculated decision threshold values POD curves in form of cumulative density functions can be calculated. Due to the scattering of the signal response values confidence bounds can be defined. This was performed for 4 data sets from measurements at the austenitic specimens. Figs. 7 and 8 show the results. All teams used ultrasound phased array probes. One team used a phased array transmitter – receiver probe allowing a better focussing in depth. Two teams used the pure phased array approach and one team used the sampling phased array (full matrix capture) technique which also leads to a better spatial resolution due to the constructive summation (high-frequency averaging by the SAFT-algorithm) of the signals.

The data used for the POD calculations shown in Figs. 7 and 8 was taken from the inspections of the austenitic specimens. These 27 flaws are realistic flaws. The corresponding decision threshold value was calculated according to the described concept: 2.5 mm (Fig. 7, left), 3.2 mm (Fig. 7, right), 3.6 mm (Fig. 8).

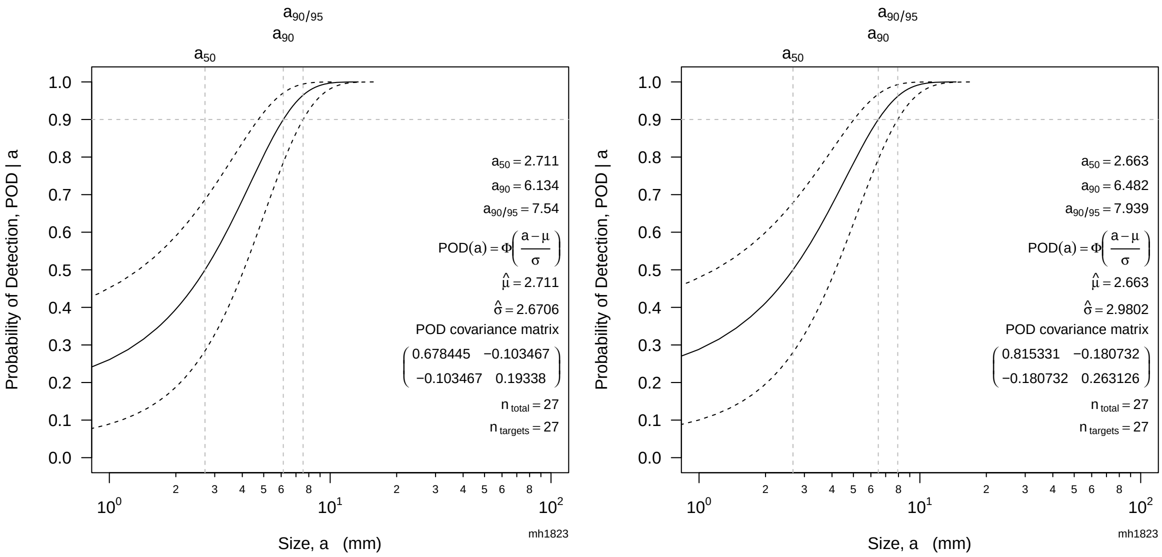

Figure 7. POD curves calculated from measurements at the austenitic specimens. Left: POD curve from RT probe phased array data. Right: POD curve from SPA data. The POD calculation was carried out with the mh1823 software [32].

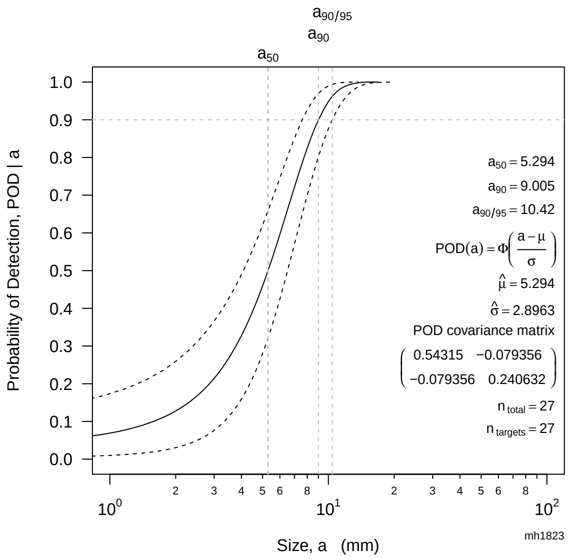

Figure 8. POD curve calculated from measurements at the austenitic specimens. POD curve from phased array data from team one. The POD calculation was carried out with the mh1823 software [32].

The resulting POD curves show that the $a_{90/95}$ values from the phased array RT data and the SPA data do not differ much (7.5 mm and 7.9 mm). The accuracy in flaw sizing of the SPA technique is better compared to the results gained with the RT probe, however, due to the higher decision threshold resulting from false positive detections the POD curves of the SPA results is shifted to higher values. The phased array measurements lead to narrower confidence bounds, however, the $a_{90/95}$ value is with a value of 10.4 mm significantly higher. The a_{50} value indicates the 50 % POD. This value represents the 50 % chance to detect a flaw. The values are: 2.7 mm (Fig. 7, left), 2.7 mm (Fig. 7, right), 5.3 mm (Fig. 8). These values correspond well with expert opinion regarding the detectability of cracks in anisotropic metals.

The selected set of flaws has a severe influence on the POD curve. This is shown in Fig. 9. Here, additional measurements at austenitic specimens containing artificial flaws in form of tilted notches were added to the dataset. These artificial flaws can be detected with a higher accuracy than the realistic cracks. Therefore, the decision threshold values change to the values corresponding to Fig. 5. The confidence bound get narrower and the $a_{90/95}$ value change to 8.9 mm (Phased Array, Fig. 9, left) and 6.0 mm (SPA, Fig. 9, right). The use of artificial flaws leads to a distortion of the POD results since the POD values are better than for realistic cracks only. The SPA results tend to be more sensitive regarding the influence of artificial flaws.

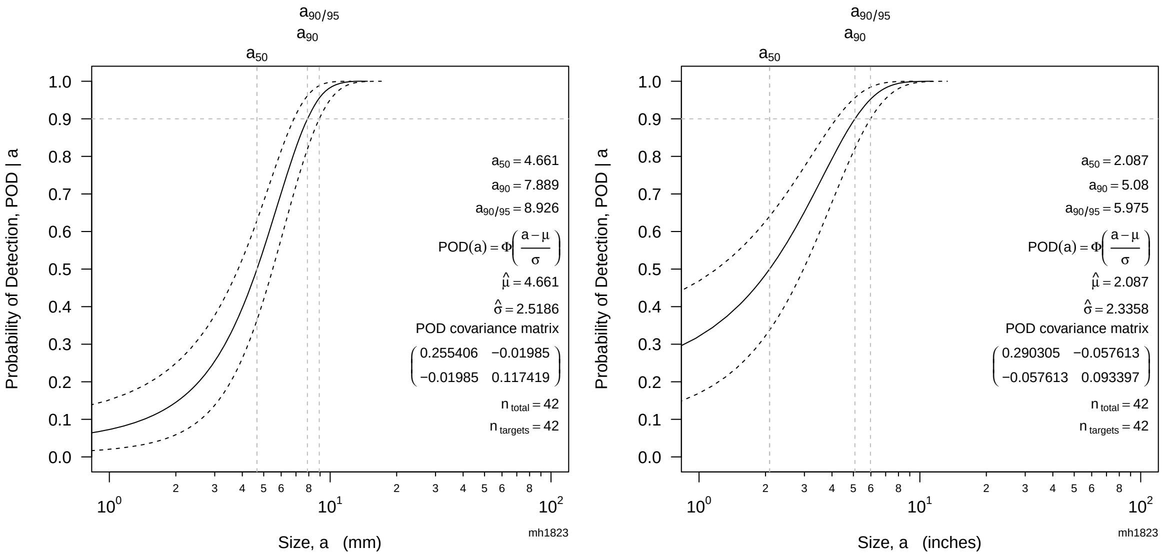

Figure 9. POD curves calculated from measurements at the austenitic specimens additionally including artificial flaws in form of tilted notches. Left: POD curve from phased array data from team one. Right: POD curve from SPA data. The POD calculation was carried out with the mh1823 software [32].

4. Discussion

The determination of the probability of detection (POD) curves is one possibility to quantify the probability to detect a specific flaw with an NDT method from a statistical distribution. The results can therefore have a direct influence on component design, maintenance and assessments. Therefore, it is also possible to quantify the usefulness of a NDT inspection for maintenance procedures. Due to the probabilistic manner of the POD information a consideration requires a probabilistic assessment. Furthermore, requirements on NDT methods can also be defined in form of a POD. This is the case when a certain probability of failure (POF) is required for a defined flaw size distribution considering maintenance inspections. Then, the required POD for a given POF can be determined and inspection procedure and NDT method have to be adapted to meet the requirements.

For the described work on POD determination, test blocks with a large number of real flaws and artificial flaws were inspected by different teams with ultrasonic phased array probes and with the sampling phased array technique. Since no German standard is currently available for phased array inspections, the specifications for the tests were outlined in a detailed inspection procedure.

The inspection results from the austenitic specimens were analyzed in form of a “â vs. a” POD analysis. A direct use of the amplitude of the signals as a measure of flaw size is not possible when using focusing probes and reconstructed data. This has also to be considered

for other NDT devices in the future when more and more inspection results will be based on the analysis of images instead of using amplitude values. The results of the phased array and sampling phased array inspections provide flaw sizes and locations. The chosen approach, which uses the standard deviation of the difference between true flaw size and determined flaw size, also allows considering false positive detections.
The accuracy in flaw sizing of the SPA technique is better compared to the results gained with the RT probe however, due to the higher decision threshold resulting from false positive detections the POD curves of the SPA results is shifted to higher values. The phased array measurements lead to narrower confidence bounds, however, the $a_{90/95}$ value is with a value of 10.4 mm significantly higher. The resulting POD values for austenitic specimens containing realistic cracks correspond to expert opinion about inspection accuracy for these materials. Experienced inspectors verified a level of detectability by chance which corresponds to the a_{50} POD of around 5 mm for Phased Array inspection. It becomes also clear that the use of artificial flaws leads to a distortion of the POD results since the POD values are better than for realistic cracks only. The SPA results tend to be more sensitive regarding the influence of artificial flaws.

5. Conclusions

The experimental results presented in this paper were carried out in the frame of the German nuclear safety research program. The main conclusions can be summarized as follows:

- NDT is an essential part during construction and maintenance of nuclear power plants. However, knowledge of the probability of detection (POD) curves of specific flaws in specific testing conditions using defined inspection methods is often not present.
- Quantifying NDT reliability with an experimental procedure needs appropriate specimens representing the required and realistic set of flaws.
- In the near future ultrasound phased array will be the state of the art ultrasound inspection technique. Then, e.g. flaw size has to be used as an equivalent parameter of the signal response for application of the “â vs. a” POD analysis principle.
- The resulting POD values are in accordance with expert opinion. The accuracy in flaw sizing of the SPA technique is better compared to Phased Array results also when RT probes are used. However, a higher false alarm rate finally leads to a lower POD values for SPA.

6. Acknowledgements

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