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Guidelines for the Design of Test Pieces and Conduct of Test Piece Trials

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FOREWORD – BRIEF REVISION HISTORY OF RP5

The first issue of ENIQ Recommended Practice 5 (RP5) was produced by the former ENIQ Task Group 2.2 and was approved by the ENIQ Steering Committee for publication in 1999. The second issue of RP5 was prepared by the former ENIQ Task Group Qualification (TGQ) and was approved by the Steering Committee for publication in 2011. As part of the revision of all ENIQ RPs in 2017 / 2018 RP5 was revised once again. The content of the Issue 2 of RP5 is to a large extent still valid. However, a number of sections (e.g. on modelling) were added for Issue 3 of RP5.

EXECUTIVE SUMMARY

ENIQ Recommended Practice 5 (Issue 3) identifies issues to be considered when designing test pieces for use in experimental inspection qualification trials and provides recommendations for conducting these trials. This document will help plant owners, qualification bodies and inspection vendors in the execution of their respective roles in the qualification process. It is also intended to help the user in understanding the influence of essential input for the design of test pieces. Practical trials of inspection systems play an important role in the qualification of both inspection procedures and inspection personnel. RP5 addresses consecutively the design of practical trials, test piece design and test piece fabrication.

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1. Scope

Recommended Practice 5 (RP5) identifies issues to be considered when designing test pieces for use in experimental inspection qualification trials and provides recommendations for conducting these trials. The document will help plant owners, qualification bodies (QBs), and inspection vendors in the execution of their respective roles in the qualification process. The document also helps in understanding the influence of key input for the design of test pieces. Examples of key input data are:

- List of defect parameters;
- Inspection requirements;
- Sizing tolerances, etc.

The ENIQ Methodology [1] [2] is a framework that combines technical justification (TJ) and results from practical trials to provide evidence that the inspection system is capable of meeting the inspection objectives. The TJ and the practical trials are intimately linked in that:

- TJ identifies the essential parameters for the inspection (see [3]);
- TJ performs physical reasoning and other analyses to identify the worst case defects (those defects that are most challenging for the inspection of the relevant component). This process plays an important role in reducing the number of test pieces;
- TJ is supposed to document the design of test pieces.

This document is relevant to any inspection configuration.

The ENIQ approach has been deliberately developed to allow the role and design of test pieces and practical trials to meet the requirements for each specific case. This document discusses how this “case-based” approach can be applied to the design of test pieces and practical trials. Additionally, this RP discusses the application of quality management to the test piece fabrication process, which should be considered along with the quality requirements of the entire qualification process.

Relevance of practical trials

The ENIQ Methodology can be used to qualify both inspection procedures and inspection personnel (where required). The aim of qualifications is to gather and assess evidence to demonstrate that the inspection system and the instructions contained in the inspection procedure are capable of meeting the inspection objectives.

Personnel qualification, where required, is normally performed following a satisfactory procedure qualification. This phased approach tests the ability of the key inspection personnel to perform roles necessary for the inspection to deliver its objectives. The task for which personnel qualification is most often used, is data analysis and interpretation. In some areas it is common practice to make a further division between the tasks of defect detection and defect sizing (and characterisation if required).

Practical trials of the inspection system play an important role in both procedure and personnel qualification and are most commonly used to:

- Provide experimental evidence for the inspection capability to be included in the TJ;
- Demonstrate the statements in the TJ about the performance of the procedure;
- Demonstrate the statements in the TJ about the performance of the equipment and manipulator;
- Qualify inspection personnel.

2. Design of Practical Trials

Before designing practical trials, it is assumed that all the input information is available including:

- Component geometry;
- Component materials;
- Manufacturing processes (welding procedures, forging specifications);
- Defect details;
- Inspection objectives;
- Environmental variables (temperature, hygrometry, radiation level, fluid level in the circuit).

The above data, called input parameters, comprises of basic information such as the characteristics of the defects to be detected and sized, as well as a series of object-specific and working environment related details, which together make up the object description. The generation of this data requires co-operation of a wide range of technical disciplines (see [4]).

2.1 General Issues to Consider in Designing Trials

The fabrication of test pieces is often time-consuming and sometimes costly. Where test pieces are required it is recommended to make full use of the TJ to minimise the number of test pieces.

The balance between test piece trials and TJ will vary greatly depending upon the inspection situation being qualified. Important considerations are:

- Complexity of the inspection situation;
- Degree to which theoretical modelling can be used to predict inspection performance;
- Availability of prior experimental data and inspection experience;
- Previous qualifications;
- Qualification level, if applicable.

As mentioned in the list above, modelling has the potential to provide complementary information to experimental work. Modelling issues are addressed in RP6 [5]. With respect to experiments and test pieces, modelling may be helpful as follows, provided that adequate modelling is performed, and model validity is justified:

- It may significantly reduce the number of defects in test pieces.
- It may expand the validity of the parametric study by means of additional parametric studies performed by modelling.
- It may be used to investigate worst case defects: By modelling, location and orientation of defects can be identified which are the most difficult to detect and/or size.
- It may allow justifying the use of defects with simplified morphology in cases where it is difficult to manufacture realistic defects representative of the actual damage mechanism. This can be done by comparing model responses on defects with various morphologies.
- It may allow justifying the use of test pieces with simplified geometry. This can be done by comparing simulations of inspections on different geometries.

The extent of experimental demonstration needed and the design of the trials is ultimately dependent on the QB's judgement based on the amount of necessary evidence in the TJ[1] and the complexity of the inspection, and in most cases, is based upon the above factors.

The ideal qualification test piece would be fully representative of the plant component. It would contain a set of defect conditions which themselves are fully representative of those sought by the inspection and whose parameters were known to high precision. In many situations it is not practical to achieve this ideal test piece and thus a balanced case-based choice of specimen geometry, material composition and defects must be made.

It is important to maximise the cost effectiveness of test pieces by considering the objective of the practical trials, some examples being:

- Practical trials may be needed to confirm that the inspection techniques are capable of detecting and/or sizing complex defects. Here it may be necessary to concentrate on fabricating a large number of representative defects (for example to generate some statistical information) in small components of simple geometry.
- Trials may focus on different parts of the inspection, such as procedure, NDT system, personnel etc.
- Test pieces representing the full geometry of the component may be needed to test the application of a manipulator to a complex component and to demonstrate the coverage over the inspection volume.
- Type of defect response required: Realistic (yielding a signal response like real defects) or artificial (e.g. notches produced by electric discharge machining (EDM)). Depending on the goal of the qualification, either may be suitable.

2.2 Generic Types of Practical Trials

The previous section discussed the need to maximise the effectiveness of practical trials. This section discusses some of the different types of trials that can be conducted. In all cases the scope of the practical trials should be agreed upon by the plant owner, inspection vendor and QB.

2.2.1 Fully Representative Mock-up Performance Demonstration

In this case, the qualification exercise is performed using test pieces which are representative of the component to be inspected and contain intentional defects with a signal response for the NDT system that is representative of those sought in practice. Such trials may require the use of the full inspection system that has to be deployed on site.

Whilst the application of the full inspection system gives the opportunity to assess the overall capability of the inspection, it has some disadvantages:

- It can be very difficult (and in many cases not practically possible) to manufacture controlled, representative defects, particularly in large and complex geometries.
- Large test pieces can be difficult and time-consuming to make and hence expensive. Often the high cost of test pieces restricts the number that can be manufactured and consequently (for blind trials) it can be difficult to preserve the confidential nature of the defect distributions.
- Some fully representative test pieces can be very large and require large storage and handling facilities.

[1] Occasionally, conditions may be imposed by the plant owner or regulator regarding the minimum number of defects to be included in the exercise.

However, in any case, there is no need for test pieces larger than the material volume requested by the inspection method.

A variation to this approach is to simulate the full geometry of the inspection situation by using models manufactured as a mock-up (e.g. in wood, plastic or thin sheet steel) into which test pieces representing a relatively small section of the component can be inserted. This approach can have several advantages:

- Several smaller test pieces can be inserted into the mock-up, thereby easing the problem relating to confidentiality.
- Overall cost and the handling issues can be reduced significantly.
- Further smaller section test pieces can be fabricated at later dates to allow changes in the inspection requirements or inspection techniques (for example if ultrasonic inspection is changed to eddy-current). This could also be done if the confidentiality of the existing inserts was felt to be compromised (for blind trials).

For blind trials, test piece security (control of access to information on defect location, character and dimensions) needs to be maintained or the significant investment associated with the test piece or test pieces can be lost and/or the validity of the output may be degraded.

2.2.2 Parametric Studies

Parametric studies are often used to provide information for the TJ, but can equally be applied by the QB as part of either open or blind trial activities. Parametric studies might be part of the holistic demonstration, although this can further add to the time and cost of the qualification process.

An alternative to holistic demonstration is to use test pieces which replicate only part of the inspection situation. For example, a weld in a thin plate might be an adequate representative of a reactor pressure vessel weld for surface inspection techniques or to assess the capabilities of the manipulator. The advantages of using this approach are numerous, although it must be recognized that such test pieces can only be used to assess the capability of a part of the inspection system. The TJ explains this.

The design of parametric study specimens and the assurance that they replicate the inspection situation sufficiently in the vicinity of the defect is an area in which inspection modelling may be applied to give greater confidence.

3. Test Piece Design

One of the strengths of the ENIQ Methodology is its flexibility. However, this flexibility means that there is little prescription which can direct activities such as the design or use of test pieces. This document aims to identify issues of importance which may need to be considered when making critical decisions on the design and use of test pieces.

The extent to which experimental demonstration is required is defined by the qualification procedure, which must provide sufficient information to allow test piece requirements to be specified. Test piece requirements may also be influenced by existing information:

- Valid previous evidence of inspection capability can justify a reduction in the experimental demonstration requirement.
- Existing test pieces may be used to provide the necessary inspection capability assessment.
- Pre-recorded data from similar applications can supplement or negate the need for a new experimental programme, provided essential parameters can be reconciled between both configurations.

In many cases, especially first-of-a-kind qualifications, the QB is likely to require new test pieces to execute the qualification procedure. This will require some design process to be followed to decide upon the geometry of the test piece(s) and upon the defect parameters such as type, location etc.

The extent of the demonstration is proposed by the QB based on the extent of any existing evidence and qualifications, the safety consequences of the inspection, and the novelty and complexity of the inspection. Even when the inspection is simple, a number of defects will be used in the test pieces since multiple results are needed to establish inspection capability and reliability trends. In complex cases where there may be many different defect definitions, capability demonstration for one element of the potential defect population does not imply performance for other elements of the potential defect population, which place different, possibly more demanding requirements upon the inspection. Therefore, in such complex cases, the population of defects used to assess and assure the inspection capabilities must be chosen with regards to the range of possible defects contained in the inspection scope. These variations and requirements and the number of defects shall be decided upon for each qualification by the plant owner, vendor and QB.

3.1 Use of Worst Case Defect Assessment

The different stakeholders (inspection vendor, QB, …) must agree on what type of defects are to be implanted and where. In particular it is important that all parties have a common understanding of worst case defect characteristics such that the adequate technique is developed, and adequate qualification performed. The defect description generally includes a range of different parameters such as:

- Location (circumferential, through-wall and longitudinal);
- Orientation (tilt and skew);
- Roughness;
- Size.

To simulate all combinations of these parameters within a realistic number of test pieces is often not practical. Consequently, the concept of worst case defects is used. Here, those combinations of parameters that pose the greatest challenge to the inspection are identified and then included in the test pieces.

The rationale of using worst case defect assessment can be explained as follows: If inspection capability can be demonstrated for this most challenging set of defects, then it follows that inspection capability can be inferred for the rest of the defect set specified in the inspection scope. This rationale may also be used to assess the capability of similar inspections applied to a group of similar components and from this assessment, to identify the worst case component, thus reducing the number of test pieces from one per component type in a group to one or two to describe the entire group.

There are however some potential problems with the worst case analysis which need to be understood if it is to be used successfully:

- There must be high confidence in the worst case analysis performed, as it strongly influences the test piece design and hence the outcome of the demonstrations.
- The worst case population may vary with changes in inspection parameters or with the NDT method considered (for instance UT in lieu of RT). So, if the inspection parameters change, so may the worst case defects. This means that if test specimens are designed and built before the inspection parameters are fully determined, there is a risk that the test piece defect population may not represent a valid worst case set for the inspection when it is finally qualified.

All possible permutations of those parameters do not necessarily cover the most likely defects or those with the highest safety consequences. For this reason, it is normal to include in test pieces, in addition to the defects that are most difficult to detect or to characterise, also defects that are representative of the most likely and most safety significant defects.

Worst case design schemes can be used to define defect populations for both open and blind test pieces.

3.2 Number of Defects in Test Pieces

The type and number of defects in test pieces is decided between the parties, based on the type and complexity of the inspection situation. The number of defects also depends on the plant owner's requirements and the vendor's choice of physical phenomena. For instance, for UT techniques one may consider:

- Corner effect;
- Tip diffraction;
- Mirror effect;
- Mask effect.

Experience has shown that maximizing the number of test pieces and defects can lead to technical issues in demonstrations for defect detection, because the density of defects is unrealistic. Sparse defect populations with irregularly distributed defects will provide a more challenging and realistic inspection situation for assessment.

This guidance is relatively easy to apply if the range of defect parameters is small and the concept of worst case defect assessment is applied. In this case the assessment of the practical trials, combined with the assessment of the TJ, will lead to a qualitative judgement on the performance of the inspections. On the other hand, if statistical information is required from the test piece trials then the number of defects will need to be considerably larger. Furthermore, the optimal number of defects may depend on the type of trials (open or blind) and on the qualification scope (procedure and/or personnel).

3.3 Test Pieces for Model Validation

There are some specific issues which must be considered in the design of test pieces for validation of modelling. The following parameters must be well known and defined in order to enter precise input data into the model:

- Test piece geometry, material and surface;
- Defects shape, morphology, size, orientation and position, defect tip sharpness.

Allowable ranges of value of parameters (such as surface quality), which are not considered in validation of modelling (see also [5]), must be smaller than those defined in the inspection data sheet, in order to minimise their influence on experimental and validation results.

4. Test Piece Fabrication

4.1 Quality Management for Test Piece Fabrication

It is vital that appropriate quality control is applied during the specification, fabrication and use of test pieces. This quality control covers as a minimum:

- Test piece geometry;
- Suitability of test piece materials;
- Material condition including heat treatment history;
- Welding processes;
- Surface form & finish and cladding;

- Defect specification (see Section 3);
- Requirements for test piece manufacturer's confirmatory inspections;
- Retention of test piece manufacturer's records;
- Tolerable unintended defects;
- Acceptable repair processes;
- Documentation of the fabrication process;
- Receipt inspections to confirm the acceptability of the as-built test pieces including the structural form of the test pieces, presence of unintended defects, acceptability of stipulated defects, material properties, etc.;
- Supplementary confirmatory inspections (see Section 4.4);
- Test piece security during fabrication, storage and use.

The extent of this material and the identification of essential parameters need to be decided.

4.2 Fabrication Specification

As part of the quality management system, a documented fabrication specification is provided which specifies all requirements for the fabrication process including those listed above in Section 4.1. The fabrication specification is preferably agreed on in advance with the test piece manufacturer. It is recommended to include in the fabrication specification an activity list, which identifies critical activities in the fabrication plan that can be independently witnessed or verified to complete the control of the fabrication process. The significance of any departures from design intent is assessed against the design intent and either formally accepted or rejected. In the latter case, remedial action is required.

4.3 Test Piece Defect Tolerance

The inspection scope generally requires measuring certain defect parameters within certain tolerances. Parameters which are commonly required to be measured are:

- Location;
- Size;
- Ligament.

If the means of assessing the inspection's capability to deliver measurements of these parameters is to be established exclusively from the experimental demonstration on test pieces containing defects, it is essential that the as-built values of these sought parameters for the test piece defects are known more accurately than the tolerance requirements given in the inspection scope. This may not be easily achieved, especially in the case of "difficult" inspections. The QB must give attention to finding ways of measuring the defect parameters that are better than those that will be tested in the demonstration.

The test piece fabrication specification should place tolerances on test piece defect parameters. Test piece vendors typically quote tolerances on test piece defect parameter values. These values alone may be insufficient and it is recommended to consult the QB prior to fabrication to agree upon tolerances, especially when the accuracy claimed is at the limit of capability for the measurement techniques used. The extents of fabricated defects should be checked as far as possible.

If tight tolerances are put on defect parameters, this can influence the overall choice of acceptable test piece defect types. In general terms it is difficult to establish the parameter values of complex defects to high accuracy. In some cases, it may be possible to do destructive examination to accurately size complex defects, at the expense of course of future use of the test piece. In other cases, in order to establish defect parameters to a tight tolerance, it is necessary to make use of simple test piece defects

such as EDM slots. However, in making this choice, there is an element of compromise in the extent to which the inspection responses, which are encountered on the test piece match those which would be expected in plant.

4.4 Supplementary Inspections

In some cases, it may be judged necessary to apply additional inspections beyond those which the test piece manufacturer performs to confirm compliance with the fabrication specification. These inspections can be applied as the defects are being introduced into the test piece and/or when the specimen fabrication is complete. These supplementary inspections can be used for a number of purposes including:

- Confirming that the defects are typical of real defects in the plant;
- Checking that there are no significant unintentional defects generated by the fabrication process;
- Generating an “expert” data set, which can be compared to the known defect parameters and/or the data generated by candidate inspections applied during the qualification exercise or as a basis for pre-recorded datasets.

In any case these supplementary inspections are of key importance and should be controlled using formal inspection procedures and adequate quality management (see Section 4.1 above).

When selecting supplementary inspection methods consideration must be given as to how the information will be used. As an example, X-ray tomography can extend the information which can be obtained from supplementary inspection. However, to be able to distinguish real indications from implanted defects it is recommended to use the same inspection technique as the vendor will use during the inspection so the same inspection parameter such as technique, inspection access sensitivity and other parameters that can be inspection specific.

The combination of analysis of supplementary inspections coupled with the fabrication record of as-built defect parameters can be used to produce a best estimate of critical defect parameters, referred to as “the definite defect dimension record”.

Another possibility is that some portion of the fabricated defect set could be destructively examined to determine or confirm generic parameters. This option is particularly attractive when the data from specimens are to be used in trials using pre-recorded inspection data (see above).

ENIQ Report no. 44 [6] provides practical examples for the design and manufacturing of test pieces for inspection qualification.

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ABOUT NUGENIA AND ENIQ

NUGENIA is an international non-profit association under Belgian law established in 2011. Dedicated to the research and development of nuclear fission technologies, with a focus on Generation II & III nuclear plants, it provides scientific and technical basis to the community by initiating and supporting international R&D projects and programmes. The Association gathers member organisations from industry, research, safety organisations and academia.

The activities of NUGENIA cover plant safety & risk assessment, severe accidents, reactor operation, integrity assessment and ageing of systems, structures & components, development of fuel, waste & spent fuel management & reactor decommissioning, innovative light water reactor design & technologies, harmonisation and in-service inspection & their qualification.

The European Network for Inspection and Qualification (ENIQ) is a utility driven network working mainly in the areas of qualification of non-destructive testing (NDT) systems and risk-informed in-service inspection for nuclear power plants. Since its establishment in 1992 ENIQ has issued over 50 documents. Among them are the “European Methodology for Qualification of Non-Destructive Testing” and the “European Framework Document for Risk-Informed In-Service Inspection”. ENIQ is recognised as one of the main contributors to today’s global qualification guidelines for in-service inspection. ENIQ became Technical Area 8 of NUGENIA in 2012.

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