NDE within VVER Steam Generator Structural Integrity Assessment

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ABSTRACT

A steam generator, a component which in case of defects may cause release of radioactive material into the environment, is one of the most important components of nuclear power plants. Therefore, it is required to monitor its condition from fuel cycle to fuel cycle, documenting the type, size, orientation, location, growth of its flaws as well as indicate the tubes that do not meet the performance criteria. These tubes must not remain in service because they may impair the structural stability during normal and accidental conditions in the following cycle. Indicated tubes shall be eliminated from the service by applying corrective action-plugging.

Structural integrity assessment is performed during a reactor refuelling outage. Acquired data on steam generator condition through inspection applying NDE, is the basis for the structural integrity assessment. We may observe the structural integrity assessment as a period that takes place before and after the outage: looking back being before the outage-condition monitoring, and looking forward after the outage-operational assessment. Condition monitoring implies the end of the previous cycle. The inspection results are compared against defined performance criteria and they also provide an analysis of previous operational assessment predictions. On the other hand, operational assessment predicts component condition at the end of the following cycle. Forced shutdowns caused by structural integrity impairment and leakage must be avoided during the following cycle.

This article will focus on NDE system performance related to inspection of VVER steam generators. Degradation detection as well as degradation sizing aspects of performance will be considered; detection quantified by probability of detection and degradation sizing quantified by measurement uncertainty. Probability of detection and NDE measurement uncertainty are one of the key elements of the steam generator structural integrity assessment.

1 INTRODUCTION

As the steam generator condition may change during operation, it is necessary to monitor its condition from fuel cycle to fuel cycle and based on the acquired results make a decision to run or remove the tube from service. The run/remove decision is based on the structural integrity assessment. The fundamental objective of the structural integrity assessment is the evaluation of the current tube integrity capacity by performing an inspection as well as evaluating their integrity capacity at the end of the next operating interval. The tube integrity capacity shall meet the structural integrity performance criteria. If the tube integrity is impaired, radioactivity penetrates from the primary to secondary side.
The structural integrity performance criteria is defined as: “All in-service steam generator tubes shall retain structural integrity over the full range of normal operating conditions (including startup, operation in the power range, hot standby, and cool down and all anticipated transients included in the design specification) and design basis accidents. This includes retaining a safety factor of 3.0 against burst under normal steady state full power operation primary-to-secondary pressure differential, and a safety factor of 1.4 against burst applied to the design basis accident primary-to-secondary pressure differentials. Apart from the above requirements, additional loading conditions associated with the design basis accidents, or combination of accidents in accordance with the design and licensing basis, shall also be evaluated to determine if the associated loads contribute significantly to burst collapse. In the assessment of tube integrity, those loads that do significantly affect burst or collapse shall be determined and assessed in combination with the loads due to pressure with the safety factor of 1.2 on the combined primary loads and 1 on axial secondary loads.” [1].

Currently, there is no unique approach to the run/remove strategy in countries owning the VVER nuclear power plants. Moreover, a standard steam generator structural assessment strategy does not exist. The run/remove strategy is based upon the plugging criteria which vary from 40% through-wall depth to 90% through-wall depth.

The results obtained by the non-destructive examination are used as input for the structural integrity assessment. The steam generator tube examination approach differs within VVER nuclear power plants, whereas this diversity arises from non-uniform standards and regulations applied, different financial resources, education, personnel training, readiness for newly developed and improved technologies. Notwithstanding these differences, the acquired data shall be reliable and correct as any decision regarding the steam generator tube is based on them. Otherwise, our conclusions would be incorrect and the consequences would be unimaginable.

2 INTEGRITY ASSESSMENT

Steam generator structural integrity assessment implies identification and characterization of degradation forms within steam generator, application of appropriate non-destructive technology, and application of appropriate integrity assessment methodology to evaluate the current tube integrity capacity as well as their integrity capacity at the end of the next fuel cycle. Structural integrity assessment consists of three elements (Figure 1): degradation assessment, condition monitoring and operational assessment. [2]

Degradation assessment is the planning process that identifies and documents information about present degradation mechanisms. Its purpose is to prepare for an upcoming outage, to ensure the appropriate inspection scope and technique in order to obtain necessary information.

Condition monitoring is the assessment of the current state of steam generator tubing. Monitoring is performed by NDE techniques at the end of the steam generator inspection and provides the information on type, size and presence of flaws. It is necessary that detected flaws do not exceed the condition monitoring limit for each degradation mechanism. Condition monitoring results are to be evaluated with respect to the previous operational assessment.
Operational assessment is a forward looking prediction of the steam generator condition at the next inspection. The determination of the operational assessment limit considers factors such as probability of detection, measurement uncertainty and growth rate. The data acquired by non-destructive examination presents the input for determinating the beginning of a cycle as well as the end of a cycle condition.

2.1 Degradation Mechanisms

Various degradation mechanisms may occur on the VVER steam generator tubes such as pitting, intergranular attack/stress corrosion cracking as well as their combination.

Pitting

Pitting is a form of corrosion in which degradation is driven by local galvanic differences in the tube. Pitting occurs by surface material dissolution with no preferential grain boundary attack. As pitting is driven by small and localized galvanic differences, a pit does not tend to grow large in volume. Pits are filled with oxide and metallic deposits which often have a layered structure. The pitting is diagnosed on the secondary side of the VVER steam generator tubes, mostly on the free span and under the tube support plate.

Intergranular attack/Stress corrosion cracking (IGA/SCC)

Intergranular corrosion is degradation occurring due to the combination of susceptible material, corrosive environment and stress. Intergranular attack is a term used to describe uniform or relatively uniform attack of grain boundaries over the surface. On the other hand, stress corrosion cracking consists of single or multiple cracks. Cracks propagate intergranularly, along the grain boundaries, or transgranularly. IGA/SCC appears on the outer diameter of steam generator tubes specially on the free span and under the tube support plate.

However, pitting and stress corrosion cracking usually occur in combination. The flaw is initiated by pitting and its progression continues by stress corrosion cracking as illustrated by Figure 2.

Figure 1: Elements of Structural Integrity Assessment
2.2 NDE Technique

In order to obtain quality picture of tube condition implying existing degradation, its type, location and size, it is necessary to apply the appropriate NDE technique. Proper characterization of the tube condition helps establish precise condition monitoring as well as operational assessment. Application of appropriate NDE technique providing more correct and more reliable information concerning flaw detection and its sizing, leads to better steam generator structural integrity assessment. This results in increased safety level and decreased risk of the unexpected tube burst or leakage. However, it may generate an increase in power plant expenses.

Eddy current method is a non destructive testing method applied by different industries to find defects and to make measurement. It is also used for steam generator tube inspection being subject of our interest. As the eddy currents concentrate on the surface of the material, they can only be used to detect surface and near surface defects.

Nowadays, several eddy current probes are applied during the steam generator inspection such as a bobbin probe, a rotating probe and an array probe. There are also several types of rotating and array probe. Each type of the abovementioned probes has its advantages and disadvantages, but it may be considered as an improvement in the field of probe design.

The bobbin probe is widely used for steam generator tube inspection. Some of the advantages are fast data collection, sensitivity to axial oriented defects and the flaw depth can be precisely determined. However, length and width cannot be determined, nor can circumferential defects be recognized. Rotating probe can recognize axial and circumferential flaws, the information about depth and width can be obtained but the acquisition is slow. Therefore, combining the mentioned techniques can provide valuable information. The latest technology achievement is array probe with rotating magnetic field (Figure 3). INETEC-Institute for Nuclear Technology has developed such a probe, and first applications are soon expected to take place. The probe is characterized by excellent visual presentation of the flaw, its orientation and sizing measures such as depth, length and width are precisely determined, data analysis is very simple and the data collection is fast.
2.3 NDE Performance

The NDE performance is considered as flaw detection and sizing; sizing is quantified by the NDE measurement uncertainty, and detection is quantified by the probability of detection. The NDE performance parameters hinge on NDE techniques, degradation mechanisms, their location, and steam generator tube condition.

NDE measurement uncertainty

The NDE system uncertainty is a combination of NDE technique uncertainty and the analyst uncertainty. The NDE sizing uncertainty is based on assessing the deviation of the measured NDE value from the true flaw size value determined by destructive examination. No destructive examinations error is considered and the examination is performed on the pulled steam generator tubes. This comparison is done over the desired range of the values, where the measured NDE values are paired with true flaw size values, and the NDE sizing uncertainty is determined by linear regression analysis. The example is illustrated by Figure 4.
Probability of detection (POD)

The probability of detection (POD) is the ability of an inspection system to detect a degradation mechanism. Inspection system implies equipment, personnel and procedures. The POD is expressed as a function of a flaw size (i.e. depth), although in reality it is a function of many other physical and operational parameters, such as the material, geometry, degradation mechanism, tube condition, and personnel for example their education, certification, and experience. Repeated inspections of the same indication will not necessarily lead to the same result. [4] A POD model is conducted applying a binary system; the hit and miss philosophy. The found indication is indicated as “1” where the report corresponds to the real situation. The “0” occurs in two cases: if the indication exists but is not called, or if the indication does not exist but is called. The ideal POD curve is presented by a step function, POD is zero for flaws not being of our interest, and POD is 1 for flaws being of our interest. It means that all the flaws that interest us are always detected. However, the realistic POD curve is not presented by step function, but by logistic or log logistic curve (Figure 5). [2]
Growth rate

The flaw growth rate is one of the key elements of operational assessment. It helps project degradation flaw size to the end of the upcoming cycle. Growth rates can be calculated provided that degradation is identified in two successive inspections.

If the active degradation mechanisms within steam generator exists, the analysis of steam generator tubes report from the previous outages is required in order to develop the flaw growth rate. They should be performed for each active degradation mechanism. The growth rate is obtained by dividing the change of NDE measurement parameter with the length of the operating interval between inspections.

As growth rates are being calculated based on data obtained by non-destructive examination, they may result in being negative. In reality this case is not possible, but as NDE data includes NDE measurement uncertainty such cases can occur.

If the operating conditions such as chemistry, temperature, cycle length or repair limit have changed, the growth rate needs to be adjusted. Sometimes it is acceptable to use data from other power plants, provided that the plant data is scarce and units are similar.

CONCLUSION

Information on steam generator tube condition acquired by performing the non-destructive examination is the key component for steam generator structural integrity assessment. Each of structural integrity elements: degradation assessment, condition monitoring and operational assessment is based upon results obtained by non-destructive examination. Experience has shown that pitting, intergranular attack/stress corrosion cracking and their combination appear on the VVER steam generator tubes. For each of the abovementioned degradation mechanism, the appropriate NDE performance measures shall be defined, otherwise undesired consequences may occur. NDE performance includes both technique and personnel. NDE is described by the capability to precisely measure the size and detect flaws: sizing is quantified by NDE measurement uncertainty, and detection is quantified by probability of detection. The selection of techniques shall be based on degradation assessment. Applying the appropriate technique will result in quality picture of tube condition, present degradation mechanisms, their location, size and orientation and above all detection of degradation. As afore-mentioned, personnel has also an impact on the NDE performance. Therefore, their education, training and experience are essential for the structural integrity assessment.

REFERENCES