STEAM GENERATOR HEAT TRANSFER TUBE INTEGRITY BASED ON LEAK RATE DETECTING

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ABSTRACT

In nuclear industry, mainly two kinds of steam generator are used, that is U-tube steam generator and helical coil tube steam generator. The former is used in PWR with loop-type layout reactor coolant system, such as AP1000 and EPR, while the later finds its application in PWR with integral reactor coolant system, such as SMART and IRIS, and HTR. Whatever which kind tube structure is used, if it is too long or its bending radius is too small, application of the volumetric in-service inspection to the helical coil tube is difficult.

This paper presents the state-of-the-art of study on the method to guarantee the integrity of the structure without using volumetric in-service inspection. The method uses tests and finite element analyses to determine the leak rate of a heat transfer tube with a crack of specific shape and dimension. Then the functional relation between leak rate and the crack size of a specific shape, such as an axial crack, can be found. Thus, after measuring the leak rate in an in-service inspection, the crack size of a specific shape can be deduced according to the functional relation above, and whether it is equal to the critical crack size can be judged. If not, the fatigue crack analysis software can be used to determine whether the crack propagates under the fluctuating stress cycles during the next in-service inspection interval, and the extended amount is obtained if the crack propagates. Then whether the structure is safe can be judged by comparing it to the critical crack size.

INTRODUCTION

Steam generator (SG) tubes act as the barrier coupling and isolating the primary circuit and secondary loop. The integrity of SG tubes plays an important role in preventing the coolant with radioactive substances from primary circuit entering into the secondary loop in control. So it is significant to study the integrity of flawed tubes, then to find a set of integrity assessment methods and procedure of SG tubes.

When the bending radius of the steam generator tube is too small, using volumetric in-service inspection to detect the flaw of tubes is difficult. Leak-Before-Break (LBB) [1,2] analysis technology provides a new idea to conduct the integrity assessment of such tubes. But unlike LBB when comparing the crack size detected directly and the critical crack size to determine tubes integrity, this paper presents a new integrity assessment procedure of SG tubes based on leak rate, which can be detected by a leakage detection system for such tubes. The main idea is, computing the crack size by detecting the leak rate based on the relationship between crack size and leak rate, then comparing it to the critical crack size, and integrity assessment and life prediction of SG tubes can be achieved.

In order to demonstrate the feasibility of this procedure further, 10WM high temperature gas cooled reactor (HTR-10) SG tubes are taken as an example. Finite Element (FE) Analysis Method and Experimental Research Method are used, and the FE models, including failure and leak rate models of SG tubes, can be modified after the comparison of tests results and numerical computation results. A system of feasible integrity assessment and life prediction procedure of SG tubes based on the leak rate detection is summarized at the end of this paper.

The research result of this paper provides an available approach to conduct the integrity assessment of SG tubes, which are not suitable to use volumetric in-service inspection. And it is significant to ensure the integrity and to achieve life prediction of SG tubes.

FE models of SG tubes

Stress Analysis Models

In the operation course of SG, the locations of flaws in tubes are closely related to the stress distribution. Meanwhile, one of the most important steps of LBB is to establish the stress distribution of SG tubes under normal operation condition and safety shutdown earthquake condition. So, establishing the effective mechanic models, to obtain the stress distribution of SG tubes, is very important for the flaw assessment.

HTR-10 uses helical coil tubes as the heat transfer tubes for SG, and the geometry dimensions must be obtained to build the three-dimensional solid model. The first three helical tube sections are warm-up section and phase-change section with diameter of 18 mm and thickness of 3mm, respectively. The final helical tube section is superheated section with a diameter of 18mm and a thickness 2mm. The bending radius of the tube is 56mm. Each helical tube section has 23 turns with a distance between the turns of 22.5mm. [3] Then CATIA is used to build the 3-D model, and ABAQUS is used to build the FE model and to do the stress analysis.

Since the 3-D model is a simplified model, it needs to be verified. Helical coil tubes of different cycles are built, and the analysis results verify the accuracy of the simplified models.

Fracture Analysis Models

In the safety evaluation of SG tubes, the most important two factors are the crack behaviour, including the initiation and propagation of the crack, and the leakage caused by the crack, which mainly refers to the leak rate. And most safety assessment methods are carried out specific to these two factors.

When volumetric in-service inspection is applicable for the SG tubes, the crack and the leak rate can be detected directly to determine whether the tubes are safe. However, there also exist SG tubes for which volumetric in-service inspection is not applicable and SG tubes having no corresponding models in stress intensity factor manual, and finite element analysis becomes a very suitable method under this circumstance.

In order to analyse the crack behaviour qualitatively and quantitatively, ABAQUS is chosen. And Extended Finite Element Method (XFEM) and Contour Integral Method provided in ABAQUS are used. The detailed steps are,

①   Modeling tubes with a crack by XFEM to determine the crack propagation direction, and then

②   Using the crack propagation direction determined in the first step to model tubes with a crack by Contour Integral Method, and the J integral and stress intensity factor K can be obtained.

For through wall cracks, another important parameter can be obtained from the fracture analysis models is the crack opening distance, and it is related to the leak rate through the crack opening area.

Since cyclic load or sustaining load can also make the crack propagate, and pressure oscillation happens to SG tubes time to time, it is significant to do the fatigue crack propagation analysis for SG tubes. NASGRO is chosen, including the geometry model database and the "Data Table" module.

After analysis of the FE models of SG tubes with axial or circumferential cracks, the laws that rupture pressure changes with crack shape and size, the laws that leak rate changes with pressure and crack shape and size, and the crack propagation law under low cycle fatigue loads can be obtained.

INTRODUCTION OF CRACK PROPAGATION TEST

Although the accuracy and feasibility of the FE models can be verified initially by stress intensity factor manual and theoretical calculation models, being verified by tests is more accurate.

Excimer laser is chosen for machining of cracks on tubes specimen made of 2.25Cr1Mo, and this processing technology can precast microcrack of tens of micrometers on tubes to simulate the cracks on SG tubes well. A serial of cracks of different shapes and sizes are precasted, such as axial through wall and part through wall cracks, and circumferential through wall cracks. Cracks of the former shape is of *4mm*, *8mm* and *12mm*, respectively. And cracks of the latter shape are of *60°*, *90°* and *120°*.

The original static burst pressure test bench is used to study the effect of flaws on the strength of SG tubes and the plugging criteria. The test bench is mainly used for measuring plastic limited load and bursting pressure of small diameter tubes. Test schematic is shown in Fig.1. High pressure pump is used to apply pressure on tubes inside. Pressure gauge and pressure sensor are installed in the oil circuit. Pressure signals are captured by the sensor, and passed into the computer through data acquisition card. A special tool is used to improve the static burst pressure test bench, so that it can be appropriate for crack propagation test. And the pressure is applied on the inside of tube specimens by the tool, then the crack size changes with the pressure can be measured by high-resolution camera.
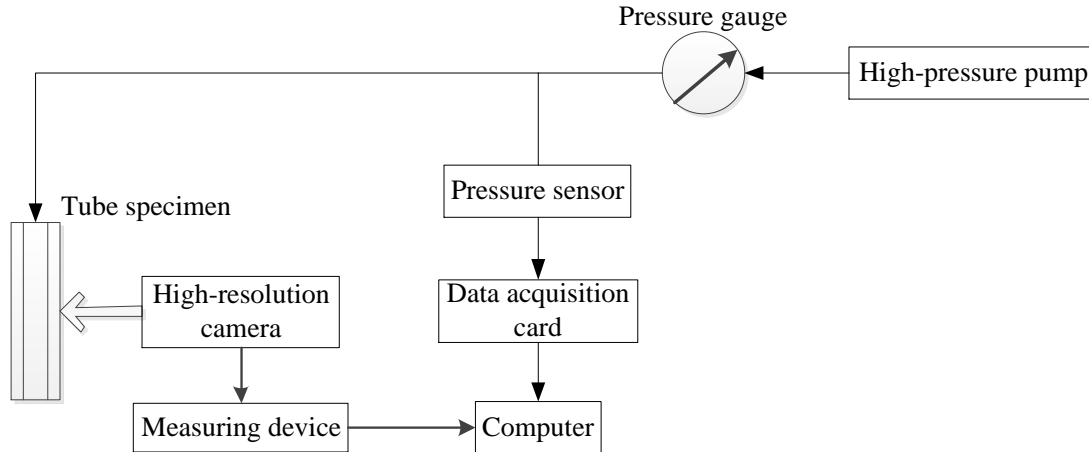
Fig.1 Test schematic

After the crack propagation tests, the laws that failure pressure changes with crack shape and size, the laws that crack open distance changes with pressure and crack shape and size can be obtained. Then the fracture analysis FE models can be modified by the comparison between the tests results and the FEA results.

INTEGRITY ASSESSMENT AND LIFE PREDICTION METHOD AND STEPS OF SG TUBES

When the crack shape and dimensions can be detected directly, LBB is used to do the safety assessment analysis. And when the volumetric in-service inspection is hard to carry out for SG tubes, the integrity assessment can be done as follows,

① To obtain the stress distribution of SG tubes

With the establishment of the FE simplified model for SG tubes, the stress distribution under current operation condition can be determined, and the dangerous section can be found. Then it can be key section monitored in the next step.

② To monitor the leak rate of flawed SG tubes

For pressurized water reactors, the leak rate of the crack can be real-time monitored by the leakage monitoring system, which is set in the secondary circuit. And for HTR, the leak rate of the crack can be real-time monitored by the three leakage monitoring systems, which are set in the primary coolant circuit.

③ To compute the crack size, d_e, corresponding to the leak rate

Based on the congruent relationship between cracks of different shapes and sizes and leak rate, the equivalent crack size correspond to the leak rate can be computed.

④ To compute the critical crack size, d_c

Based on the congruent relationship between cracks of different shapes and sizes and failure pressure, the critical crack size under current operation condition can be determined. And then d_e and d_c are compared,

If $d_e \geq d_c$, the crack will propagate unsteadily at any time, and depressurization, sleeving or plugging can be used to prevent more serious accidents.

If $d_e < d_c$, the crack has not propagated yet, or propagates steadily. Although the integrity of SG tubes has not been threatened yet, it should be analyzed in the next step.

⑤ To obtain the load of SG tubes during the previous in-service inspection cycle

During the operation of SG tubes, there exists pressure oscillation. And in order to analyse fatigue crack propagation, the load changes of SG tubes during an in-service inspection cycle, which can be set as the input conditions of fatigue crack propagation and life prediction, should be obtained.

⑥ To compute the crack propagation length in the next in-service inspection cycle

Load changes of SG tubes during an in-service inspection cycle obtained in the previous step, are put into NASGRO as the input conditions. Then the fatigue propagation of this crack is analyzed to compute the propagation length of this crack in the next in-service inspection cycle.

⑦ To determine the integrity of SG tubes, and take proper safety measures

If the crack will propagate to critical crack size before the next in-service inspection, appropriate measures should be taken to deal with it in advance.

Problems and Prospects

US NRC SRP 3.6.3 [4] requires that if the temperature is above 371℃, creep effect must be considered. And the average normal operation temperature of HTR-10 SG tubes is 540℃, so whether creep rupture happens to SG tubes must be determined.

The excimer laser processing technology can be amended, or more advanced processing technology (such as Femtosecond Laser) can be used to improve the machining precision, to machining cracks more similar to the real cracks. What is better, taking samples from the real SG tubes, and the real crack can be used for the experiments.

Among all the current problems, the most crucial one is that the integrity assessment and life prediction method presented in this paper, is based on the correspondence between the leak rate and the crack size. However, the leakage detection system cannot detect the part through wall and surface cracks timely until the cracks propagate to penetrate the tubes wall. Thus, it is very possible that there is no enough time to deal with the unstable cracks, and serious accident may occur. So, how to monitor the part through wall and surface cracks must be solved in the future.

CONCLUSION

In HTR, helical heat transfer tube is used, and in PWR, U type heat transfer tube is used. These kinds of tube structure make it very difficult to conduct in-service inspection by volumetric defect examination technology. Referring to LBB analysis technology, this paper present a performance-based integrity assessment and life prediction method for SG tubes by monitoring the leakage of the flawed tubes without using volumetric defect examination technology. Although this method can evaluate the tubes with through wall cracks well, it is not applicable for part through wall and surface cracks at present. And there are still many challenging problems to be solved for this method.

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