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Integrity Evaluation of Alloy 600 RV Head Penetration Tubes in Korean PWR Plants

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Abstract

The structural integrity assessment of Alloy 600 RV head penetration tubes has been an important issue for the economical and reliable operation of power plants. In this paper, an overview of the integrity evaluation program for the RV head penetration tubes in Korean nuclear power plants is presented. Since the crack growth mechanism of the penetration tube is due to the primary water stress corrosion cracking(PWSCC) which is mainly related to the stress at the tube, the present paper consists of three primary activities : the stress evaluation, the flaw evaluation, and data generation through material and mechanical tests.

1. Introduction

Since the leaking crack was discovered on BUGEY 3 reactor vessel head penetration tube during 10 years hydrotest (September, 1991), many work has been done both in US and in Europe to develop the analytical approaches and the maintenance strategies on this issue. Based on their work, it was demonstrated that the cracking of reactor vessel head penetration tube was not an immediate safety issue. However the results of their works indicated that the tube cracking has to be managed as a long term project in order to develop optimal maintenance strategy.

The nuclear industries in Korea have given great attention to the structural integrity of RV head penetration tubes since the first indication of cracking was reported at Bugey-3 unit. The present work starting from August, 1994 to August, 1996 is to provide a quantitative measure of the integrity of the RV head penetration tubes of Korean nuclear power plants for the continuation of safe operation.

Stress evaluations, flaw evaluations, and material tests for selected plants are carried out in this evaluation program in order to evaluate the structural integrity of the RVH penetration tubes.

Stress evaluation focuses on the analysis procedure and the simulation methodology of the input loads such as thermal effect due to welding, hydrotest pressure, and operating pressure and temperature. For flaw evaluation some assumptions are established and related literatures for the PWSCC crack growth assessment are surveyed. And tests for obtaining the material properties are being done. Inspection program of the head penetration tubes of Korean PWR power plants is briefly presented.

2. Stress Evaluation

The stress analysis is required to evaluate the structural integrity for the RVH penetration tubes. The stress analysis for the RVH penetration tubes is very complicate, because all tubes are geometrically non-symmetry except center one. Thus 3D finite element analysis should be employed for the stress analysis. Also, the residual stress resulted from non-symmetric weld procedure at the RVH area should be determined, because that is one of the key stress components at the RVH penetration tubes. The magnitude and distribution of residual stress resulted from welding can be determined analytically by simulating welding procedure. The weld pass, weld volume and weld heat input may be the main parameters for the determination of stress values. However, the plant specific weld procedures which can give above informations are not available. Thus the parametric study with 2D finite element model is carried out to develop the conservative and simplified analysis procedure, which is directly applied to the 3D finite element stress analysis.

Followings are the our basic approaches and procedures to calculate the stress at the RVH penetration tubes.

The loads included for stress analysis are thermal effect due to welding, hydrotest pressure, and operating load. The reliability of the stress analysis results is entirely dependent on the simulation method of the loads. The simulation methodology used in this work is described at the following sections.

Finite Element Modeling

For stress evaluation, 2D and 3D finite element models for three kinds of penetration tubes at center, medium, and outermost location are constructed. The elastic-plastic stress analysis for those models is performed by using ANSYS code. Since the central penetration tube and surrounding vessel head is axisymmetric through the tube centerline, two-dimensional model is enough. This 2D axisymmetric model of central penetration tube is used to determine the detailed analysis procedures such as the number of load steps for transient heat transfer analysis and elastic-plastic stress analysis by lots of trial and error. Also, the main parameters for load simulation are determined by various sensitivity studies with the 2D model. Since most of cracks are known to be detected at outermost tubes, more precise modeling and analysis for an outermost tube are required. Half the outermost tube is modeled by taking advantage of symmetry through the vessel and tube centerline.

The reactor head, cladding, and tube are modeled as carbon steel, stainless steel, and Inconel, respectively. The materials of weld and weld buttering are also Inconel.

Simulation of Weld Residual Stress

One of the governing stress components at head penetration tube is the residual stress which results from thermal effect due to welding. To simulate the weld procedure by finite element analysis, the transient heat transfer analysis and the elastic-plastic thermal stress analysis are carried out. The weld residual stress is affected by the number of weld passes and the combination of heat-input rate and time. Those parameters are examined by various sensitivity studies applied to 2D central penetration tube model. The stress analyses are performed independently for 1, 2, and 4 weld pass models to determine the number of simulated weld passes to conservatively predict the stress. Heat input rate and time as a heat source of the weld elements are determined based on the diameter of filler metal and weld speed. In the welding the peak temperature is used about 3500° F for the weld elements and about 2000° F for the adjacent base metal elements.

Simulation of Hydrotest Load and Operating Load

The manufacturing and the installation hydrotest pressure are applied through a series of loading and unloading procedure. The operating load is also applied by full loading and unloading step to check the variation in the stress distribution between at final unloading state and before applying the operating load. In this case the effects of temperature as well as pressure are considered. Both the hydrotest pressure and the operating load are applied incrementally for elastic-plastic stress analysis.

Stress Evaluation for Crack Growth

Since most of detected cracks at penetration tube are in axial direction, the critical stress component is the circumferential stress at outermost tube wall during operation. This stress distribution is approximated by cubic polynomial function for the flaw evaluation. Therefore, the mesh density at tube wall thickness becomes another important parameter. If the stress results vary seriously at tube wall, the more fine mesh will be adopted.

Even though fatigue is known to have minor influence on the crack growth of penetration tube, stress analyses for assessing the effect of the fatigue crack growth are carried out by applying transient load due to plant heatup and cooldown.

Present Status

The elastic-plastic stress analysis procedure established in this paper is shown on Figure 1 assuming two weld passes. Sensitivity studies on the main parameters for simulating input loads with 2D model are almost completed. The number of weld passes is determined as 2 in view of conservatism. Heat input to the weld element is as follows ;

1) Linear increase of heat input rate from 0 to 100 BTU/sec/in^2/rad during 0.7 sec.
2) Maintain the maximum heat input rate uniformly for 1.1 sec.
3) Linear decrease of heat input rate to 0 during 0.5 sec.

These parameters will be used for stress analysis of outermost penetration tube.

3. Flaw Evaluation

There are two objectives of the penetration tube flaw evaluation to predict the time required for a crack to propagate to the acceptance criteria. The first objective is to perform the parametric evaluation for a postulated crack. The second objective is to develop the flaw evaluation program for the cracks detected during the inspection.

Assumptions

Since it has been reported that most of the cracks in the RV head penetration tubes resulted from PWSCC in the Alloy 600 base metal, there is high probability for a crack to be initiated from the surface in contact with primary water. One of geometric assumptions is the location and orientation of the postulated cracks. Experience with European plants has shown that the cracks are located above and below the tube J-weld, and primarily in axial direction. In addition, cracks have occured predominantly in outermost tubes.

For the parametric evaluation, it is assumed that an ID-initiated axial crack propagates through the penetration tube above and below the tube J-weld. Although not expected, it is further assumed that a circumferential crack exist potentially. The effect of the fatigue crack growth rate obtained from experimental results is also evaluated.

Methodology

The crack growth evaluation for the part-through surface crack is based on the stress distribution through the tube wall thickness at the highest stress locations along the inner surface of the tube. The stress profile along the tube thickness is approximated by a cubic polynomial to calculate the stress intensity factor. For the throughwall crack, it is assumed that the crack is subjected to the average stress through the tube wall thickness.

To perform the parametric study for a postulated crack and develop the flaw evaluation program for the cracks detected during the inspection, the stress intensity factor expression for a wide range of the surface crack configuration is required. The stress intensity factor expression presented by Raju & Newman[1] is used for the axial surface crack, while the expression by Poette and Albaladejo[2] is used for the circumferencial surface crack. These expressions include a relatively wide range of the surface crack configuration. The stress intensity factor for crack growth prediction of a throughwall crack is calculated using the standard expression for a throughwall crack in a plate. The crack propagation rates are calculated by integrating a stress intensity factor verse crack growth curve. The formula for the crack growth rate is to be obtained from a survey of the available literature, considering the temperature effect on the growth rate based on a collection of crack growth information from both laboratory and field data [3,4].

Design data for stress analysis and flaw evaluation were reviewed and the mechanical property data were provided by a series of experiments on the alloy 600 specimens which had been similarly heat-treated to the penetration material of specific power plants.

4. Charcterization of Material Properties of Alloy 600

Data for integrity evaluation of penetration tubes will be provided by combination of experimental tests with literature survey of available laboratory and field data. Tensile tests were performed to specify the stress-strain relationship and fatigue crack growth tests were performed to estimate the extent of crack growth during transient loads. The materials used in these tests were similarly heat treated to the actual PWR penetration tubes of Ulchin unit in Korea. The microstructure will be reviewed to compare with the metallographic characteristics of Alloy 600 of foreign power plant's penetration materials. And data for PWSCC crack growth were surveyed and accumulated in database of Alloy 600 material properties. The purpose of these study is to provide data which are similarly represent the properties of PWR power plants in Korea. The data will be used to analyse the stress distribution around penetration tubes. And the PWSCC data will be used for intergrity evaluation of crack growth rate for the penetration tubes.

Materials Tests

Alloy 600 materials which satisfy the specification of ASME-SB-168 were used in this tests. The Alloy 600 materials were heat treated to simulate and investigate the carbide distribution of the actual materials used in head penetration tube in Ulchin units.
Solution treatments of the as-received Alloy 600 for tensile and fatigue crack growth test were performed at 1150 ℃ for 30 min. Then the alloys were water quenched. After water quenching the specimens were annealed to simulate the condition of heat treatments of head penetration materials of Ulchin Units.

Tensile tests were performed on the as-received and heat treated materials at room temperature and 300 ℃ in air to investigate the stress-strain characteristics of the materials. Tensile strength decrease as the test temperature increase. And the tensile strengths of similarly heat treated to Ulchin units' head penetration tubes were relatively lower than those of as received materials. One of the reasons of the decrease in tensile properties of heat treated Alloy 600 is grain growth during heat treatments.

So the effects of grain size should be accounted for determininig the stress-strain characteristics.

Fatigue crack growth tests were carried out on the as-received and heat treated materials in air to assess it's effects to crack growth during transient loads. The specimens for these tests were prepared according to ASTM E 647. The width of specimens is 50mm and the thickness is 6mm. The fatigue crack growth test were carried out at frequency (10Hz) at a load ratio, R=0.2. The test results show that the total cycles number of the heat treated specimens for the crack to grow from the length of 13mm to the length of 23mm is larger than that of the as-received materials. The crack growth rate data which are shown in Figure 2 have similar tendancy to the data of other researcher[5].

The PWSCC data for Alloy 600 will be collected from open literature and field data. The accumulated data will be arranged in materials property database of Alloy 600. We will rearrange the collected data into a database system according to material properties, stress intensity factor, and environmental conditions. Finally a formula for crack growth rate for PWSCC of Alloy 600 which accounts for various environments, materials properties and stress intensity factors will be obtained by the analysis of the database system.

The microstructures of similarly heat treated Alloy 600 to materials of Ulchin penetration tubes will be reviewed to compare with the metallographic properties of foreign unit's penetration materials. The carbide distribution of the materials will be carefully studied to estimate the susceptibility of the materials of Ulchin units penetration tubes to PWSCC.

5. Inspection Plan

The inspection program starting from December, 1995 and to April, 1996 shown in Table 1 was planned to determine the existence, shape and size of crack in head penetration tubes of PWR in Korea. The target reactors of inspection were Ulchin unit 1, 2 which were supplied by Framatom and the oldest one in Korea, Kori unit 1, supplied by Westinghouse. The number of head penetration tubes is 57 for Ulchin units and 40 for Kori unit 1. This first inspection program will cover all penetrations at the Kori and Ulchin units.

ECT inspection will be used to investigate the existance of crack in penetration tubes. UT reinspection for crack sizing will be applied if any cracks exist in the tubes. The information about the shape and size of crack in penetration tubes from UT inspection will be provided as an input data to the final integrity evaluation program.

Futher inspection plan will be determined based on the inspection results of the three power plants in Korea.

6. Future Work

The final integrity evaluation of penetration tubes will be carried out in parallel with the inspection plan of penetration tubes for power plants in Korea starting from December, 1995 to April, 1996. A further R & D program is going to be followed by the present study.

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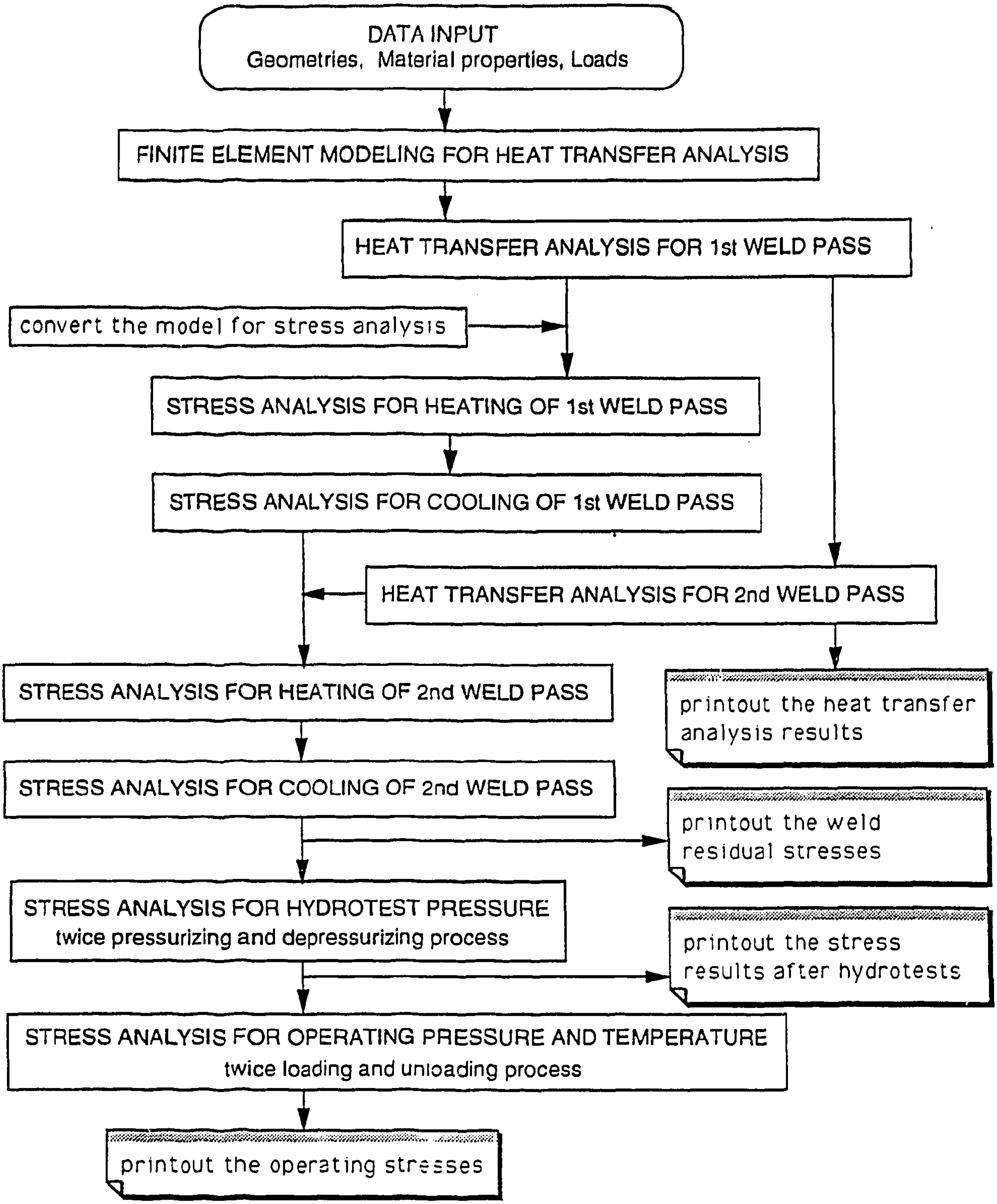

Figure 1 Flow Chart for Stress Analysis Procedure

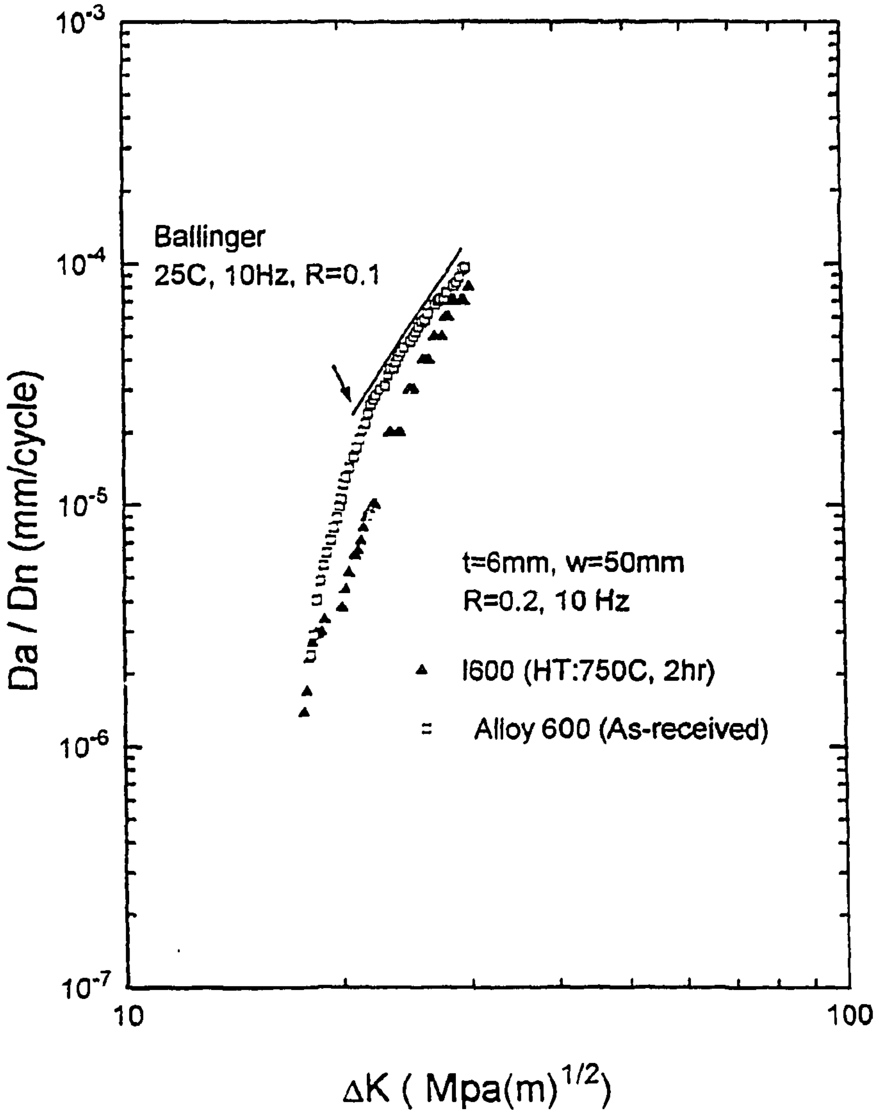

Fig.2 Fatigue Cracking Properties of Inconel 600 Alloys

Table 1. RVHP Inspection Program

Plant	Type & Capacity (MWe)	Commercial Operation Date	Head Temperature (° F)	Total No. of Penetrations	Material of Penetrations	Expected Inspection Date
Kori-1	PWR 587	Apr. 29, 1978	554 ~ 607	40	Inconel 600	Jan., 1996
Ulchin-1	PWR 950	Sep. 10, 1988	548 ~ 613	57	*	Apr., 1996
Ulchin-2	PWR 950	Sep. 30, 1989	548 ~ 613	57	*	Dec., 1995

* KFPCO's Activities Coordination Not Fixed.