The Study for Technology Application Status and Problems of Thimble Tube Eddy Current Testing

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Abstract. The technology application status of eddy current testing are expatiated based on the analysis of failure and the accident examples of NPP in-core flux thimble tube, as well as the regular inspection requirements for thimble tube both in China and abroad. In addition, according to the experience of thimble tube in-service inspection in China's nuclear power plant, the existing problems in the practical application of this technology are analyzed and studied, and feasible suggestions are put forward.

1. Introduction

Nuclear power plant in-core flux thimble tube (hereinafter referred to as the thimble tube) is the channel of reactor core neutron flux measurement probe for 300 MW test reactor and M310 type NPP reactor, etc. It is an important part of NPP in-core neutron flux measurement system. Since the 1980s, the cases of thimble tube damage have appeared successively in several countries with developed nuclear technology such as the United States and France, many countries have successively carried out related research and established the in-service inspection method of thimble tube. Eddy current testing is one of the main methods used to perform in-service inspection of thimble tube. It has features of high detection speed, high detection sensitivity to defects on the thimble tube surface and near-surface defects, especially crack type defects [1, 2]. At present, China has established a relatively mature technology system for thimble tube eddy current testing based on the experience of international and domestic nuclear power plant operation and maintenance.

2. Examples of thimble tube accident in nuclear power plant

The thimble tube provides a guide and channel for neutron flux measurement probe of NPP reactor core. The probe moves in thimble tube to achieve point-by-point measurement over the entire height of the core. The total length of thimble tube is about 14 m to 17 m. The major part of thimble tube is located in guide tube, and part of it is exposed in the fluid of RCS, understand the pressure of RCS, it is the barrier between the high-pressure water of primary circuit and the outside atmosphere. Its leakage will cause the leakage of RCS coolant and the spread of pollution, the importance of it is same as the heat transfer tube of steam generator. The shape of thimble tube in the reactor is shown in Figure 1, the area of thimble tube prone to wear are shown in Figure 2.

The thimble tube leaks have occurred in Salem and Trojan nuclear power plant of United States, and Paluel nuclear power plant of France, etc, causing reactor accidental shutdowns and radioactive contamination. In 1981, three thimble tube leaks occurred in Salem Unit 1 nuclear power plant in the
United States, caused the plant to replace all 58 thimble tubes in February 1982. In March 1985, thimble tube leaks occurred in Paluel Unit 1 nuclear power plant in France, caused reactor accidental shutdown. In 1991, thimble tube leaks occurred in Trojan nuclear power plant in the United States, these thimble tubes only be used for about three years, led to leakage in the instrument room, and consequently the plant isolated 32 thimble tubes. Thimble tube thinning were found in the North Anna Unit 1 nuclear power plant, the Millstone Unit 3 nuclear power plant, the Beaver Valley Unit 1 nuclear power plant, and the Diablo Canyon Unit 1 nuclear power plant of the United States, the worst is over 60% thimble tube thickness.

In order to minimize the possibility of potential leakage of reactor coolant, the US Nuclear Regulatory Commission (NRC) issued the bulletin 88-09 on July 26, 1988 [3], requesting the US nuclear power plant operating organization to adopt the following control measures:

1) Develop an inspection plan to supervise the in-service performance of thimble tubes, such as acceptance criteria of thimble tube wear, frequency of periodic inspection, and inspection methods.

2) Execute inspection plan and take appropriate corrective action. For the nuclear power plant under construction, inspections shall be carried out during the first refueling overhaul. For the nuclear power plant in operation, inspections shall be carried out within the current fuel cycle. If there is any tube thinning caused by wear that beyond the acceptance criteria, corrective action shall be taken; Schedule the detection time of thimble tube in shutdown plan.

3) Submit a written report on the results of implementing the corrective action plan to the NRC.
Since then, owners of nuclear power plants around the world have begun to pay attention to and implement the in-service inspection program. In South Korea, for example, at the end of 1995, 40 in-service inspections of thimble tubes were performed on eight PWR nuclear power plants. According to the inspection results, 38 were replaced, 7 were isolated, and 39 thimble tubes were repositioned. The thimble tube inspection results of the US COOK nuclear power plant and the Belgium Doel nuclear power plant are shown in Table 1 and Table 2 respectively.

**Table 1.** Eddy Current Test Results of Unit 2 of COOK Nuclear Power Plant in the United States.

| Wear depth (% tube thickness) | Number of thimble tube |
|------------------------------|------------------------|
| < 10                         | 12                     |
| 40- 50                       | 4                      |
| 50- 60                       | 8                      |
| 60- 80                       | 11                     |
| > 90                         | 8                      |

**Table 2.** Visual inspection and measurement results for Unit 3 and Unit 4 of the Doel Nuclear Power Plant in Belgium.

| Nuclear power plant | Doel 3 | Doel 4 |
|---------------------|--------|--------|
| Number of thimble tube | 5      | 1      |
| Depth (mm)          | 0.1 – 0.5 | 0.1 – 0.2 |
| Length (mm)         | 10 – 110 | 10 – 80  |
| Shape               | Triangle | Triangle |

3. **Eddy current testing technology for thimble tube in China**

At present, eddy current testing equipment of thimble tube used in China generally includes eddy current instruments, eddy current probes, data acquisition systems, data analysis systems, and special comparison sample tubes, and usually has the following functions:

1. The eddy current instrument can generate multiple frequencies simultaneously or time-divisionally, and can combine multi-parameter signals. The output can provide phase and amplitude information. The eddy current instrument has the ability to perform eddy current testing under differential mode, absolute mode, or under both conditions.

2. The eddy current probe can induce eddy currents in the inspected material, can measure changes in the impedance of the detection coil caused by eddy currents, can indirectly understand the presence of defects in the inspected material and whether the electromagnetic properties of the material have changed.

3. The data acquisition system can collect the analog signal output by sensor and convert it into digital signal that can be recognized by computer, and then send it to computer. According to different needs, computer can perform corresponding calculations and processing to obtain the required data.

4. The data analysis system can be used to suppress various external disturbances and noise in the detection process, determine data accurately, preprocess the eddy current response signal, eliminate the meaningless dead pixels in data, and smooth the data. Noise removal processing is performed to increase the signal-to-noise ratio of signal and to extract characteristic quantities that characterize the defect.

5. Some special sample tubes for contrast detection are made by selecting a low-noise pipe material, with the same material, specification, processing technology, and surface condition as the pipe material to be inspected. The corresponding relationship between the wear and the signal amplitude can be obtained by using artificial defects similar to the actual wear on contrast tube.
The eddy current testing process for thimble tube is mainly divided into data acquisition and data analysis. The data acquisition process is: 1) Setting a probe pusher, set the appropriate height of pusher bracket; 2) The probe pusher pushes a probe through a guide tube into the heat transfer tube and reach the end of thimble tube; 3) The probe pusher pulls back the probe at a constant speed and simultaneously uses a eddy current instrument to collect eddy current signals; 4) The eddy current signal is transmitted through a network to a data acquisition and analysis workstation for display, storage, and data analysis. Analysts process and analyze the test data, including: 1) Reviewing the data for completeness and validity; 2) Graphically displaying data; 3) Identifying various types of displayed defect and measuring various types of displayed characteristic data; 4) Comparing with displayed feature data of typical defect, the results were analyzed and judged; 5) Recording the analysis results.

According to China's nuclear safety regulations, in terms of the nuclear safety level of thimble tube, it is necessary to conduct in-service inspections and supervise the integrity of its materials [4, 5]. Eddy current testing is the most effective nondestructive testing method for in-service inspection. The eddy current testing for thimble tube is to scan and record eddy current data from the inside of thimble tube. It is used to detect and evaluate defects that may endanger the tightness of thimble tube in tested area, to identify and locate the thimble tube thinning due to mechanical damage or other reasons. The thimble tube thinning is also evaluated by comparing phase-depth curves obtained from sample tube.

At present, China has implemented eddy current testing of thimble tube for Dayawan nuclear power plant, Qinshan Phase I nuclear power plant, Qinshan Phase II nuclear power plant and Lingao nuclear power plant. Through the analysis of operating conditions and testing results of thimble tubes of each nuclear power plant during the in-service period, it was found that there are different degrees of wear of thimble tubes in the domestic nuclear power plant, and the related nuclear power plant has carried out displacement or replacement treatment of thimble tubes with serious wear [6]. For example, in the beginning of 1996 and in the middle of the year, the Dayawan nuclear power plant conducted eddy current testing on thimble tube wear of unit 2 and unit 1 respectively. The eddy current test result of thimble tubes of one nuclear power plant in China is shown in Table 3.

| Table 3. The eddy current test result of thimble tubes of one nuclear power plant in China. |
|---|---|---|---|
| Thimble tube No | Depth of wear (% tubethickness) | Length measurement(mm) | Position |
| Tube a | 11 | 17.6 | Near the fixed plate of instrument catheter |
| Tube b | 18 | 14.65 | Near the bottom grid plate |
| Tube b | 38 | 20.5 | Near the bottom grid plate |
| Tube b | 14 | 16.2 | Near the core support plate |
| Tube c | 18 | 18.0 | Near the fixed plate of instrument catheter |

4. Analysis of existing problems in thimble tube eddy current testing

4.1. Insufficient basic research and development of equipment

In recent years, although China has developed a number of eddy current testing equipment of thimble tube, commercial inspection equipment are mainly imported from abroad. The ability of basic research is also obviously inadequate. Especially, the detection ability of the eddy current probe, the defect imaging technology and the detection speed of the equipment need to be improved.
4.2. Imperfect relevant standard documents

So far, there are no mandatory regulations and standards for eddy current testing of thimble tube in all nuclear power countries including China. Different manufacturing time, different manufacturers and different logic function design will make great differences in function and operation of the eddy current testing equipment, which will bring great difficulty to the management of thimble tube eddy current testing, and it is urgently need to speed up the development of standards to facilitate standardized management.

4.3. Operators' awareness and professional level of nuclear and radiation safety need to be strengthened

The risk of radiation is everywhere from the preparation to the end of thimble tube eddy current testing. Therefore, each operator must have a high level of nuclear and radiation safety awareness and professionalism. However, in China's several large non-destructive testing units for civil nuclear safety equipment that have acquired qualifications, there are still some difference in the configuration of testing equipment and experience in project implementation, and the level of inspection personnel needs to be further improved.

The radiation risk of thimble tube eddy current testing is mainly external radiation and surface radioactivity contamination, and serious internal pollution can be caused, which is manifested in the following aspects:

1) The working place for thimble tube eddy current testing is an instrument room, and there are radiant hot spots near the entrance of the instrument. Therefore, the test personnel should be fast to reduce the external radiation dose.

2) Before the test, the floor of instrument room is cleaned. However, the surface of instrument room may be contaminated by radioactive substances during the test. These substances mainly from the activation products brought by the eddy current probe from thimble tube. Therefore, it is necessary to pre-arrange the temporary control area to avoid pollution diffusion and ground pollution. If these substances accidentally contact with the body surface of workers, surface radioactivity contamination will occur, in serious cases, if radioactive substances enter the body internal pollution will cause. Therefore, staff should be equipped with necessary radiation protection items such as gas masks.

3) After completing the test, all testing equipment should be carefully measured and decontamination should be performed for equipment that has detected loose contamination.

5. Suggestions

5.1. Accelerate formulation of related standards for thimble tube eddy current testing

The standardization of the technology of thimble tube eddy current testing is of great significance for improving the level of testing technology, improving the reliability and standardization of device, and convenient for daily operation, maintenance, review and supervision. Therefore, there is an urgent need for the national energy industry authorities and the national nuclear safety supervision and management departments to coordinate and integrate all sectors of the industry to speed up the formulation of related standards for thimble tube eddy current testing, on the basis of summarizing the years of experience in the operation and maintenance of nuclear power plants in China, propose a set of technical standards and management requirements for thimble tube eddy current testing, regularize the performance indicators of inspection equipment for thimble tube, and clear operation procedures and management measures.

5.2. Strengthen professional training and qualification management

The thimble tube eddy current test belongs to the category of nuclear safety equipment non-destructive testing. The testing unit should follow the regulations of HAF601 and HAF602 to ensure that inspectors participate in the national unified assessment and obtain qualification certificates before they can engage in eddy current testing activities of thimble tube. At the same time, the testing unit
should strengthen investment, strengthen the professional skills training of the testing personnel, and improve the personnel's operational proficiency level. Train a group of professionals to improve the technical level and improve overall quality of all technicians and reviewers involved in eddy current testing activities.

5.3. *Raise the basic research and development capabilities of equipment*
Accelerate the development of basic technology research on design, test and manufacture of eddy current testing equipment for thimble tube. Further study the theory of probe design, optimize the design of instrumentation, improve the scanning speed and detection efficiency. Promote the application of advanced numerical calculation methods and signal processing methods to efficiently complete signal processing and feature extraction. Constantly improve the imaging software design and improve defect recognition capabilities to expand the measurement range.

5.4. *Strengthen the quality supervision during thimble tube manufacturing process*
The artificial defect on the special comparative sample tube of thimble tube eddy current testing is similar to the actual wear. Therefore, the current eddy current detection technology has a high detection sensitivity and accuracy for the wear generated during the service life of thimble tube. If the thimble tube is installed with problems such as size exceeding standard, corrosion, and local noise exceeding the standard, it is difficult to accurately identify and determine other types of thimble tube defects except outer wall wear. Therefore, the quality supervision of thimble tube manufacturing should be strengthened as always, to ensure that each of thimble tube to be installed is a qualified product, thus contributing to the safe operation of the nuclear power plant in China.

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