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A Review of APR 1400 Steam Generators Tube Degradation and State-of-The-Art Inspection Techniques

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1. Introduction

The steam generator (SG) of a nuclear power plant plays a crucial role as a large heat exchanger and as a physical barrier that confines radioactive materials within the nuclear steam supply system (NSSS). Since the primary coolant of NSSS has higher pressure than the secondary coolant of plant of balance (BOP) system, any flaw in SG tube may lead to the rupture of tube and the release of radioactive materials to the environment. A schematic of APR 1400 SG is shown in Figure 1.

According to the operating experiences of nuclear power plants in the world, SG tubes of Alloy 600 undergo several degradation mechanisms such as stress corrosion cracking, wall thinning and etc. that may result in the leak or the rupture of tube [1]. Therefore, thermally treated Alloy 690 has been used as tube material of APR 1400 reactor due to its high resistance to degradation mechanism [2].

This paper presents a summary of recent research on the degradation phenomena and relevant state-of-the-art inspection techniques of steam generator tubes to ensure safe and reliable SG operation.

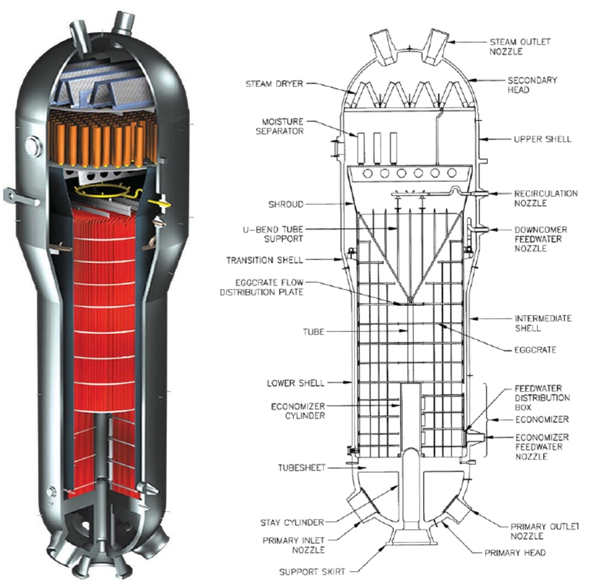


Fig. 1 Typical steam generator of APR-1400

2. Methods

The articles reviewed discuss SG tubes degradation mechanisms in addition to latest detection and inspection technologies. The scientific studies presented here were selected based on the following criteria:

- Scholarly articles published in renowned journals
- Latest literature review of SG tubes and Alloy 690 degradation mechanisms
- Diversity of in-service inspection (ISI) techniques such as state-of-the-art eddy current testing (ECT) technologies and equipment.

Based on the research methodology described above, the results are presented in the next section.

3. Results

3.1 Common Degradation Mechanisms

Steam generator tube degradation mainly depends on the tube materials and operating environment including water chemistry. For example, Phosphate wastage was the major cause of tube failures in PWR steam generators until the mid-1970s [3]. Past 1979, more degradation mechanisms were identified as major causes for SG tube failure such as outside diameter stress corrosion cracking (ODSCC), intergranular attack (IGA), primary water stress corrosion cracking (PWSCC) on the inside surfaces, and fretting wear [3]. Table 1 shows a description of the degradation mechanisms in SG tubes.

3.2 Thermally Treated Alloy 690

Alloy 690 material is widely used for steam generator tubes as it has high resistance against stress corrosion cracking. Furthermore, 30 out of 69 operating PWR plants had thermally treated Alloy 690 as SG tube material in the United States as of 2005 [4]. In comparison to Alloy 600 material, Alloy 690 has a higher weight percentage of Chrome. Thus, higher Chrome content makes Alloy 690 more resistant to stress corrosion cracking [4]. However, some research found the following:

1. Although Alloy 690 was resistant to stress corrosion cracking (SCC) in 0.1 mole NaOH solution whether lead oxide (PbO) is added. However, Alloy 690 resistance to SCC decreased in higher alkaline condition more than 2.5 mole NaOH solution and further rapidly decreased by adding PbO [6]. Also, Alloy 690 susceptibility to SCC increased in pH higher than 10.2 and it accelerated by adding PbO [7].
2. Two types of corrosion fatigue behavior for Alloy 690 SG tubes were observed in borated and lithiated high temperature water [8].

It is noteworthy that these studies were conducted in labs on experimental models. Since there are very few reported cases of Alloy 690 degradation in SG tubes in American power plants [4], it is necessary to collect more field inspection data to build a consolidated library on the degradation behavior of Alloy 690 tubes.

Table 1. Description of SG tubes degradation mechanisms [5]

Type of Degradation	Definition
Denting	The physical deformation of the Inconel Alloy 600 tubes as they pass through the support plate. Caused by a buildup of corrosive material in the space between the tube and the plate.
Fatigue cracking	Caused by tube vibration.
Fretting	The wearing of tubes in their supports due to flow induced vibration.
Intergranular attack/stress-corrosion cracking (outside diameter)	Caused when tube material is attacked by chemical impurities from the secondary-loop water. It occurs primarily within tube sheet crevices and other areas where impurities concentrate.
Pitting	The result of local breakdown in the protective film on the tube. Active corrosion occurs at the site of breakdown.
Stress-corrosion cracking (inside diameter)	Cracking of steam generator tubes occurring at the tangent point and apex of U-bend tubes, at the tube sheet roll transition, and in tube dents. It occurs when Inconel Alloy 600 tubing is exposed to primary-loop water.
Tube wear	A thinning of tubes caused by contact with support structures either as the tubes vibrate or as feedwater entering the vessel impinges on the tube bundle at that location.
Wastage	A general corrosion caused by chemical attack from acid phosphate residues in areas of low water flow.

3.3 State-of-The-Art Inspection Techniques

Early and timely flaw detection of SG tubes is essential for ensuring SG safe operation. Eddy current testing (ECT) has been commonly used for detecting volumetric degradation of SG tubes since the early days of nuclear power plants operations [9]. Overtime as more degradation mechanisms were identified, more advanced in-service inspection techniques were needed. Traditional inspection equipment was composed of a number of parts which made them heavy, complex, and required many people to carry them [9] as shown in Figure 2.

To effectively carry out in-service inspections, in addition to ECT, Ultrasonic Testing (UT) is also used. UT is a non-destructive examination (NDE) method that uses sound wave to detect crack or defect in materials [10]. Due to the limited scope of this paper, we only focus here on eddy current testing latest technologies used by the nuclear industry.

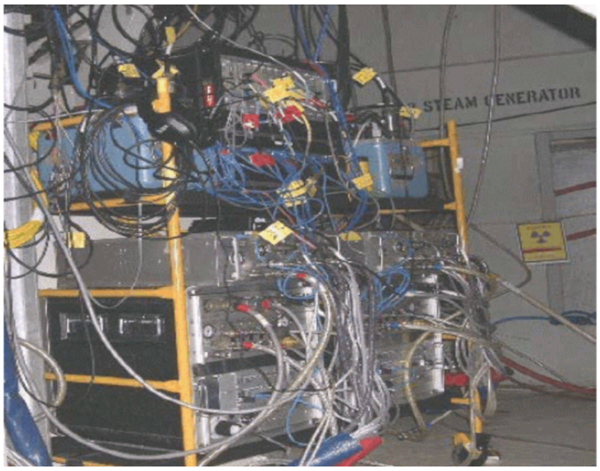


Fig. 2. Illustration of cable complexity with legacy ECT systems.

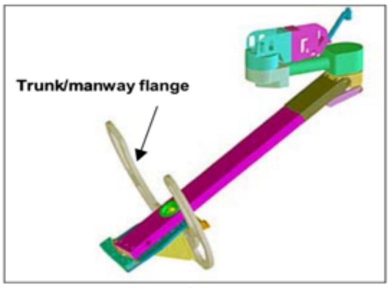
3.3.1 ECT Equipment

Modern ECT equipment has greatly assisted in conducting effective inspections of thin wall tubes. The two main components of ECT equipment are the probe manipulators (communication tools) and probe technologies (degradation mechanisms detectors). Ease of use, ease of transport, fast assembly into a single-box and other components make them unique [9]. The system communicates with the computers via standard ethernet connection. Additionally, these systems require the following: plant air supply for cooling in addition to assistance in probe push operations, and electric power. Systems such as Zetec MIZ-80iD, Tecnatom TEDDY+SP, and CoreStar OMNI-200-TP are considered state-of-the-art ECT equipment used in nuclear industry as shown in Figure 3 [9].

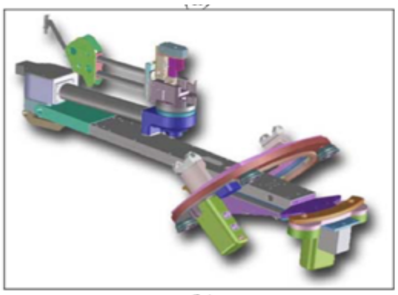
Fig. 3. Typical ECT systems: (a) Zetec MIZ-80iD, (b) Tecnatom TEDDY+SP, (c) CoreStar OMNI-200-TP

3.3.2. Probe Manipulators

Old versions of probe manipulators required human involvement to access SG channel head and manually place them to cover areas that the manipulators can't reach. This made the inspectors susceptible to radiation exposure [9]. Thus, latest probe manipulator technologies eliminated such risk as they require minimum or no-entry of inspectors into the SG channel head. As shown in Figure 4, probe manipulators such as Zetec SM 23 are most advanced probes in nuclear industry.

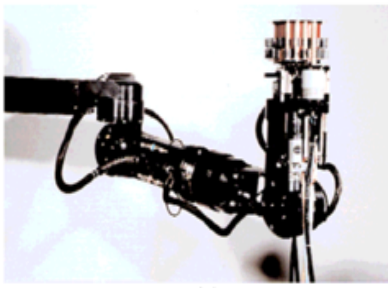


(a)

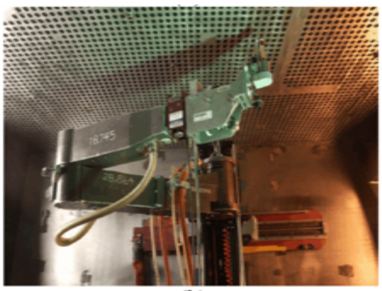


(b)

Fig. 4. Examples of man-way-mounted manipulators: (a) Zetec SM 23 and (b) Zetec SM 23A



(a)



(b)

Fig. 5. Examples of non-entry manipulators: (a) Westinghouse ROSA III and (b) AREVA Non-Exclusion zone ROGER

3.3.3 Probe Technology

The common and typical probe of ECT used for SG tube inspection is bobbin probe. Although bobbin probes are good at detecting volumetric degradation, the probes have a limitation for detecting circumferential cracks [9]. As a result, Motorized Rotating Pancake Coil (MRPC) and Plus Point probes are known as the best probes as they detect, in addition to providing flaws morphology, both axial and circumferential cracks in SG tubes [9]. The typical rotating Plus Point probe is shown in Figure 6.

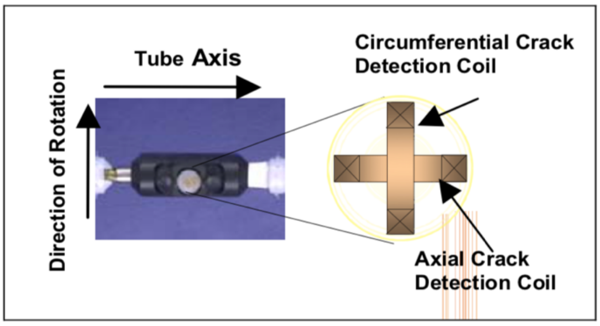


Fig. 6. View of a rotating Plus Point probe for axial and circumferential crack detection

X-probe is another advanced probe which can detect axial and circumferential cracks in addition to volumetric flaws [9]. However, unlike MRPC and Plus Point probes, it can accurately detect loose parts in SG due to its unique components [11]. Moreover, another excellent probe is Mitsubishi intelligent probe which compared to other probes, has higher inspection speed, performance, degradation and flaws detection in one single pass [9] as shown in Figure 7.

(a)

(b)

Fig. 7. Examples of advanced probes: (a) X-probe, (b) Mitsubishi Intelligent probe

The diversity of ECT probes provide excellent, efficient, and more accurate results for detecting defects in SG tubes. Although widely used bobbin probes have some limitations for sizing the crack and detecting circumferential crack, different probe technologies such as MRPC, Plus Point, X-probe, and Mitsubishi Intelligent probe can solve this issue.

3. Conclusions

The integrity of steam generators tube is a critical for ensuring the safety of the people and the environment. In this paper, a summary of recent research on the degradation phenomena and relevant state-of-the-art inspection techniques of steam generator tubes is presented.

Although proven to be highly resistant to stress corrosion cracking, based on published research, Alloy 690 materials are found to have susceptibilities to degradation in high alkaline solution containing lead oxide and in higher pH conditions. Furthermore, ECT techniques are widely used for detecting flaws in SG tubes. In order to overcome the limitations of bobbin probe, state-of-the-art probes such as MRPC are used for more accurate detection.

This paper will be available to serve as a reference for nuclear regulatory authorities and nuclear power plant operators on recent published papers on SG tubes degradation and detection methods.

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