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A Brief Review on the Design Factors of Steam Generator U-Tube Assembly for CANDU Type Nuclear Power Plant

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Abstract

During the plant operation, steam generator U-tube assembly will potentially be subject to adverse environmental conditions which can cause damages to them. This report addresses the major design factors of CANDU type steam generator which are intended to minimize the potential tube damages. Such factors include U-tube material, high circulation ratio, tube-to-tubesheet joint, tube support design. Also a few suggestions are presented for the design and performance improvement of CANDU type steam generators.

1. Introduction

Since the first operation of nuclear steam generator in the early 1960s, the steam generator problems have been a major cause of reducing the operational reliability, plant safety and availability. During the plant operation, steam generator U-tube assembly will potentially be subject to adverse environmental conditions which can cause damages to them. The types of damage depend upon the combined effects of design factors, materials and chemical environment of steam generator. Such damages include pure water stress corrosion cracking, intergranular attack, pitting, wastage, denting, fretting and fatigue, etc. [1]. In this report, a brief review of major design factors of CANDU type steam generators has been performed in respect to the potential tube damages. Tube material, high circulation ratio, tube-to-tubesheet joint, tube support design were selected as major design factors.

2. Major Design Factors

To maintain the integrity of U-tube assembly forming pressure boundary between the primary and secondary systems, it is necessary to remove the cause of tube degradation or to lower the level of the degradation below the allowed limits. This chapter deals with the design factors for U-tube assembly of CANDU type steam generators. The design factors affecting the U-tube integrity can be classified as the followings :

(1) U-Tube Material
(2) High Circulation Ratio
(3) Tube-to-Tubesheet Joint

(4) Tube Support Design
(5) Water Chemistry
(6) Sludge Management

Among these factors, this report focuses on first four items.

2.1. U-Tube Material

Alloy 800 (nominal composition 30-35% Ni, 19-23% Cr, <0.10% C, remainder Fe) was developed by Inco in 1949 as an economic replacement for Alloy 600 for the sheathed elements of electric cookers. Alloy 800 has been used by Kraftework Union in their PWR units, in France for LMFBR heat exchanger tubing, and in Canada for the CANDU PHW reactors.

The designation "Alloy 800L" was adopted for compositions which contained <0.03% C. The technical specification of u-tube material used for Wolsong 2,3&4 is very similar to the Alloy 800's [2]. Table 1 shows the composition of several types of Alloy 800 [3]. Alloy 800 has been studied along with Alloys 600 and 690 in several test programs designed to simulate primary and secondary side nuclear steam generator environments. Laboratory and operating experiences with Alloy 800 tubing show that Alloy 800 is a viable steam generator tubing material for the following reasons : [3]

- Modifications to the standard Alloy 800 composition have been developed which optimize the corrosion behaviour.
- Alloy 800 displays general resistance to stress corrosion cracking in primary water. As with Alloy 690, this characteristics makes Alloy 800 an attractive alternative to Alloy 600.
- The susceptibility of Alloy 800 to other forms of secondary side attack (e.g., intergranular attack, pitting and wastage) is comparable to that displayed by Alloy 690.
- Alloy 800 steam generator tubing has performed well in service. However, this performance has been obtained under conditions of very tight water chemistry control.

2.2. High Circulation Ratio

One of the key factors of steam generator thermal hydraulic design is the circulation ratio. By maximizing the circulation ratio for the steam generator secondary side fluid, concerns regarding heat transfer performance, steam generator sludge management, corrosion product transfer concerns, tube dry-out, etc. can be alleviated.

The circulation ratio is defined as the ratio of fluid mass rising up through the tube bundle to the fluid mass exiting the steam generator at the steam outlet nozzle. CANDU steam generators have high circulation ratios, typically a minimum of 5.0. The Wolsong steam generators are no exception to having a circulation ratio of 6.0 [3] .

2.3. Tube-to-Tubesheet Joint

The tube-to-tubesheet joint must perform the function of securely fastening the tube to the tubesheet in such a manner that not only must the strength of the connection resist the separating forces of the applied pressure, but it must also not impose conditions which would cause the tube to fail through crevice corrosion or stress corrosion mechanisms.

CANDU tube-to-tubesheet joint technique using a fillet weld and hydraulic expansion of the tubes meets these requirements [4]. By this design exclusion of sludge deposits from entering between the tube and the hole and minimum residual stress in the tube can be achieved.

2.4 Tube Support Design

2.4.1 Flow Calculations

The first step in understanding flow-induced vibrations is to asses the flow conditions. Because the geometry of components is complex, computer-based multi-dimensional calculation techniques are required to model the thermal-hydraulic behaviour of steam generator to provide detailed flow information in complicated geometries. Thermal-hydraulic analyses using THIRST can give an overall representation of the flow conditions in steam generators [6]. These results are used as input to the analysis of flow-induced vibration analyses.

2.4.2 Vibration Excitation Mechanisms

Dynamic forces are generated by fluid flow in nuclear components causing them to vibrate. Generally, four flow-induced vibration excitation mechanisms are relevant in nuclear components, namely : a) fluidelastic instability, b) periodic shedding, c) turbulence-induced excitation, and d) acoustic resonance [5,8]. The relative importance of these mechanisms for different flow situations is outlined in Table 2 [6]. PIPEAU code has been used to predict the vibration response to both turbulence and periodic forces, and critical velocities for fluidelastic instabilities [6,7,8].

2.4.3 Tube Support Design

Worldwide operational experience of nuclear steam generators has shown corrosion problems at tube supports to be the major cause of tube failure. It is generally agreed that tube support design is one of the key elements in reducing tube degradation and maintaining equipment availability.

A lattice grid support system incorporating the best materials and design factors offers exceptional thermal-hydraulic characteristics and outstanding corrosion-resistance properties without sacrificing mechanical performance.

The design requirements for the tube supports can be summarized as follows : [3]

(a) Preclude excessive Flow Induced Vibration (FIV) response.

(b) Provide a minimum pressure loss to promote high circulation ratios which result in sweeping flows.

(c) Provide line support contact to reduce the potential for deposition of corrosion-causing impurities.
(d) Provide sufficient tube contact length to lower contact stress, and hence, minimize fretting wear of tubes.
(e) Provide a strong tube support design to withstand lateral seismic loads, loads caused by burst pipe events and handling and shipping loads.

CANDU design meets above design requirements for the tube supports.

3. Conclusions

Through a brief review of the design factors of U-tube assembly for CANDU type steam generator , some comments and conclusions can be suggested as follows :

(1) Because all processes from design phase to manufacture phase can give various effects on the U-tube integrity, system and component(S/G) designers should support and help actively each other to certify the required reliability and performance during the design lifetime. Especially, it is required for the system designer to monitor carefully the major design factors which are important to the tube integrity [9] .

(2) It is very important to reflect the results of experiments or studies related to the operational problems performed throughout the world to improve the tube integrity in the steam generator design.

(3) According to the worldwide tube plugging statistics to April of 1990, it can be noted that the average plugging ratio of CANDU steam generators is very much lower than that of PWR S/Gs . CANDU specific design features of the U-tube assembly is considered to be a significant contributor to such a good record.

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Table 1. Types of Alloy 800 - Composition

Composition(%)	Alloy 800	Modified Alloy 800	CANDU Spec.	800H
C	0.10 max.	0.03-0.06%	<0.03	0.05-0.10
Si	1.0 max.	1.0 max.	0.75 max.	1.0 max.
Mn	1.5 max.	1.5 max.	1.00 max.	1.5 max.
S	0.015 max.	0.015 max.	0.015	0.015 max.
Cr	19-23	19-23	21-23	19-23
Ni	30-35	30-35	32.5-35.0	30-35
Fe	bal.	bal.	bal.	bal.
Cu	0.75	0.75	0.75 max.	0.75
Al	0.15-0.60	0.15-0.60	0.15-0.45	0.15-0.60
Ti	0.15-0.60	0.15-0.60	.35-.60	0.15-0.60
Ti:C			12 min.	
Ti:C+N			8 min.	
other			P=.015 max Co=.014 max N=.03 max N+P=.07 max Grain Size ASTM 5 to 10	Grain Size ASTM 5 or coarser
heat treatment	mill annealed 1600-1800F		mill annealed 1760-1830F	solution annealed 2050F

Table 2. Vibration Excitation Mechanism

FLOW SITUATION	FLUIDELASTIC INSTABILITY	PERIODIC SHEDDING	TURBULENCE EXCITATION	ACOUSTIC RESONANCE
AXIAL-FLOW				
<u>Internal</u>				
Liquid	o	o	*	V
Gas	o	o	V	*
Two-Phase	o	o	*	o
<u>External</u>				
Liquid	o	o	*	o
Gas	o	o	V	V
Two-Phase	o	o	*	o
CROSS-FLOW				
<u>Single Cylinder</u>				
Liquid	o	*	*	o
Gas	o	V	V	o
Two-Phase	o	o	*	o
<u>Tube Bundle</u>				
Liquid	*	V	V	o
Gas	*	o	V	*
Two-Phase	*	o	*	o

o Unlikely V Possible * Most important