Thermochimica Acta 542 (2012) 80–88

Contents lists available at SciVerse ScienceDirect

Thermochimica Acta

journal homepage: www.elsevier.com/locate/tca

Experimental evaluation of primary water chemistry for prevention of axial offset anomaly

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ARTICLE INFO

Article history:
Available online 5 January 2012

Keywords:
Axial offset anomaly
CRUD
Sub-cooled nucleated boiling
Boron
Lithium

ABSTRACT

A test loop was designed to simulate the operating conditions affecting the axial offset anomaly on the fuel cladding in nuclear power plants. In this study, accelerated simulation tests for deposit formation on the Zirlo cladding surface were performed in a solution containing varying amounts of Li and B with different concentrations of Ni and Fe. The amounts of formed deposit were relatively low in the non-boiling condition, while the amounts of formed deposit were increased in the zone in which the boiling occurred. The external surface showed numerous pores, and the thickness of deposits on the cut surface was approximately 20 μm. In addition, the commercial code, FLUENT 6, was applied to calculate the thermal-hydraulic analysis of nucleated boiling on the simulated AOA water chemistry. SEM, EDX and SIMS were used for surface analysis of the deposit, and the separated deposits were analyzed by ICP-AES and AAS. In conclusion, the water chemistry with operation conditions of 5.0 ppm Li and pH 7.4 was found to produce the least deposit formation on the fuel cladding surface. The current simulated tests may be applied for developing methods for preventing AOA in nuclear power plants.

1. Introduction

Axial offset anomaly (AOA) is caused by the deposition of CRUD on the fuel cladding in the top half of the core as a result of increased nucleate boiling in this region. CRUD is very porous and the pores in CRUD can become enriched in boron, which is known to be a neutron poison inducing AOA or lithium, which is the species that enhances corrosion in Zircaloy if boiling occurs [1]. Boron can accumulate in the pores of CRUD as a concentrated solution or a solid phase when the levels of CRUD have built up on the cladding. When significant levels of boron are accumulated on the fuel cladding, the axial distribution of neutrons can be changed. Therefore, the safety tolerance of fuel operation is decreased and the output of power is diminished [2]. This also could lead to economic losses [3–5].

Cases of AOA have been reported throughout the world, and especially in plants which employ longer term cycles of operation or higher burn-up [3]. AOA was first observed in plants where CRUD deposits had built up to 25 μm. The bonaccordite (Ni_2FeBO_5) containing boron had been identified in the CRUD when the thickness of the CRUD deposits were exceeded 80 μm [2,5,6]. Examinations of fuel CRUD scrapes have indicated a Ni-rich deposit compared to CRUD scrapes from non-AOA plants [2,5]. The CRUD deposition that causes AOA has been reported to be prevalent in the whisker surfaces of needle-like structures consisted of nickel oxide (NiO) [7]. Temperature distribution has been calculated across a thickness of the CRUD and the CRUD temperature is higher than 673.15 K when the thickness of CRUD is exceeded 59 μm [2]. It has been reported that the Ni_2FeBO_5 in needles is formed in the aqueous slurry of $NiO–Fe_2O_3–H_3BO_3–LiOH$ at a temperature exceeded 673.15 K [6]. The CRUD analysis from a plant which experienced AOA showed blocky CRUDs composed of nickel ferrite, nickel oxide, bonaccordite and zirconium oxide, and they are composed of numerous crystals with a highly porous structure [8,9].

It is now reported that conditions of elevated and constant pH are important for reducing susceptibility to AOA. For the power plant which experienced AOA, the plant was advised to use 3.5 ppm Li at the beginning of a cycle and to operate at pH 7.1 [10]. These pH_T guidelines have been recently revised and advised using higher levels of Li for constantly elevated pH_T regimes, e.g., constant pH_T of 7.1–7.3. These revised regimes have resulted in little or no penalty in the characteristic time to needed to develop primary water stress corrosion cracking (PWSCC), and no significant PWSCC effects of using higher pH regimes have been observed at French, Swedish, and U.S. plants [11]. In this study, tests for simulating AOA were provided to assess the potential effects of operation parameters under the proposed elevated pH/Li environment, and finally develop the operating method to minimize AOA by controlling the water chemistry variables.

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doi:10.1016/j.tca.2011.12.011

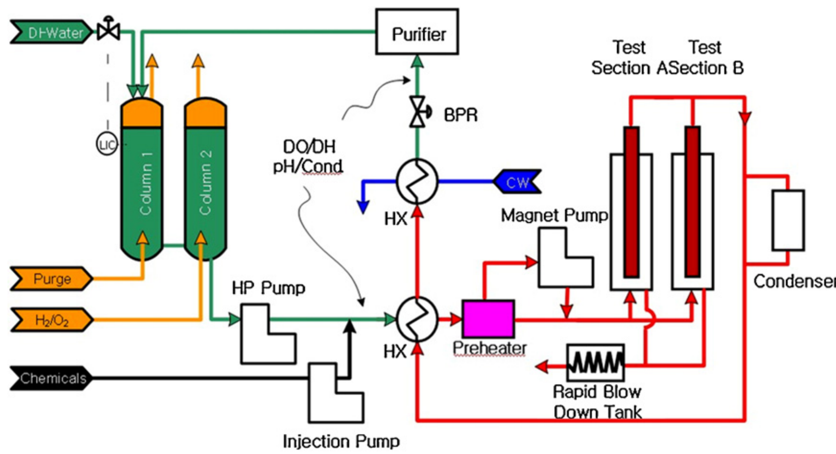

Fig. 1. Schematic drawing of AOA simulation test loop. A test loop was designed and used to simulate the conditions of AOA on the cladding surface. The test loop has a test section A with a low flow rate at a low temperature, and a test section B with a higher flow rate at a higher temperature, respectively. BPR = back pressure regulator; CW = cooling water; HP = high pressure; HX = heat exchanger; LIC = liquid injection controller.

2. Experimental

2.1. Test loop design

A test loop was used to simulate the conditions of AOA on the cladding surface (Fig. 1). The test loop had a test section with a low flow rate at a lower temperature (580.15 K). A rapid blow-down tank was installed to prevent partial dissolution of the compounds deposited on the specimen surface following each specimen analysis. The high pressure valve under the test section was opened and the test solution was passed through the spiral condensing tube in the water bath with ice. The dissolution of the compounds on the specimen surface was minimized by driving out the test solution from the test section in a few seconds during the cooling process.

2.2. Specifications for test section and cladding tube preparation

Table 1 shows specifications for the test section and a schematic drawing for this test section is shown in Fig. 2. The cladding tube was heated with an internal rod-type heater, and the gap between the cladding tube and the heater was filled with MgO paste. The heated length of the heater was 160 mm. The pressure of the loop system was maintained at 96.5 kg/cm^2, and reached equilibrium pressure at 580.15 K. The temperature at a thermocouple in Fig. 3 was set to 582.15 K during the test to maintain continuous sub-cooled nucleated boiling (SNB) on the outside surface of the top portion of the heated length. Then the formation of deposits was measured in the boiling portion and the non-boiling portion, respectively.

Table 1
Specification for test section A.

Thermal hydraulic parameter	Test condition
Dimension and material of tube	25.4 mm OD × 2.77 mm thickness, 316 L stainless steel
Dimension and material of heater	8.0 mm OD × 600 mm length, 316 L stainless steel
Dimension and material of test specimen	8.3 mm ID (9.5 mm OD) × 600 mm length, Zirlo
Electric capacity of heater	1 kW
Heated length	160 mm
Heat flux of specimen surface	0–24 W/cm^2
Bulk water temperature (inlet) and overpressure	580.15 K, 96.5 kg/cm^2
Inlet flow rate and fluid velocity on the test specimen	200 cc/min, 1.4 cm/s

2.3. Chemical composition of a Zirlo

Zirlo is commonly used as a fuel cladding material. The chemical composition and mechanical properties of the Zirlo cladding material used for a test in this study are shown in Table 2. This tubing material was degreased in acetone and washed with distilled water before testing. A test Zirlo rod was heated by a rod-type heater at 0–80 W/cm^2.

2.4. Thermal-hydraulic analysis of AOA water chemistry loop on the CRUD deposition

The commercial code, FLUENT 6, which is applied to analyze various single phase heat transfer and fluid flow parameters, was used to calculate the thermal-hydraulic conditions of nucleate boiling on simulated AOA water chemistry. Contrary to the conventional single phase heat transfer and fluid flow, thermal-hydraulic conditions of nucleate boiling on the AOA water chemistry loop were determined using the User defined function in FLUENT, in addition to the necessary modeling to simulate the phase changes. EAGLE code, which was developed to analyze the SNB two-phase flows, was applied to compare the calculated results by FLUENT code [12,13]. Finally, these calculated results were applied to evaluate the correlations of the CRUD occurrences in simulated AOA tests.

2.5. Preparation of specimen and surface analyses

Three pieces of a specimen (20 mm in length) were cut after each test by a diamond saw in a decane solution, as shown in Fig. 3. The specimen AX-3 was cut near the top of the heated length, whereas the specimen AX-1 was cut near the bottom. To analyze the composition and degree of the specimen surface, the insides of tube specimens (15 mm in length) were filled with a resin. Then, the deposit on the outside of the specimens were removed by ultrasonification and measured by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) and atomic absorption spectrometry (AAS). Additionally, the remaining specimen in the

Table 2
Chemical composition and mechanical properties of Zirlo.

Material	Composition (%)					Mechanical properties at RT		
	Sn	Fe	O	Nb	Zr	YS (MPa)	UTS (MPa)	Elong. (%)
Zirlo	1.0	0.1	0.12	1.0	Balance	448	820	24.6