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Long-term corrosion kinetics in pressurized water loop of an accident tolerant fuel cladding candidate: AISI 348 stainless steel

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1. Introduction

Worldwide there is an increased interest in improving operational reliability, economical performance and safety of nuclear power plants, especially after the events at Fukushima Daiichi, and due to necessity of reducing greenhouse gas emissions, studies have been taken in different directions for service life extension, waste reduction, increased efficiency, and safety. In addition, the progress on the development of advanced materials, motivate a search for different candidates to be used as an accident tolerant fuel (ATF), which are materials for nuclear reactor fuel cladding that offer better performance under normal operation, transient and accident conditions [1].

One of the most discussed topic in the study of alloys for nuclear application is the oxidation fuel cladding behavior [1], because in addition to being the first fission product barrier, the design limits have been established to ensure that the fuel system is not damaged, fulfilling its safety objective which is to protect people and the environment from harmful effects of ionizing radiation [2], it should also fulfill Standard Review Plan requirements, on the performance and the oxidation levels exhibited by the fuel rod material [3].

Furthermore, to validate computer codes that simulate nuclear fuel behavior it is necessary with an extensive collection of reliable data based on experimental results. This work presents a long-term corrosion kinetics study of type 348 stainless steel (AISI 348 SS) in pressurized water (20 MPa) and high temperature (360 °C) during approximately 85 days through a recirculating loop system with autoclaves connected online. This alloy was chosen since it was one of the ATF claddings candidates tested during a round robin proposed in the ACTOF framework [1] and because it was included in a modified fuel performance code to model the thermal-mechanical behavior of PWR (Pressurized Water Reactor) fuel rods by IPEN-CNEN/SP researchers [4].

2. Methodology

Four sets of triplicate specimens were submitted to long-term corrosion in ultrapure deoxygenated water ($DO_2 < 0.1$ ppm / $DH_2 < 5$ ppb) at 360 °C and 20 MPa in autoclaves connected to a water recirculating loop during 21, 63.5 and 84.5 days. The tested specimens were cut from a 22 mm diameter bar of AISI 348 SS with approximately 2 mm thickness and had one face ground up to 400 grit SiC paper.

The prepared circular coupons were cleaned, dried, weighed and had their dimensions measured before the test started to obtain mass gain data with 0.01 mg analytical balance after each interval of exposure studied. The samples were put inside two autoclaves connected to a recirculating loop system fabricated by Cormet Oy, with online sensors monitoring temperature, pressure, conductivity, dissolved oxygen (DO_2) and hydrogen (DH_2).

Autoclave 1 (AC1) was maintained closed during the whole test (84.5 days) with one set of triplicate coupons. Autoclave 2 (AC2), which started with 2 sets of coupons, was opened after 21 days to have one set replaced by a new one of unoxidized specimens. After that, the system ran for more 63.5 days, when the test was ended and the last 3 sets of coupons (1 from AC1 and 2 from AC2) were removed, as shown schematically in Figure 1.

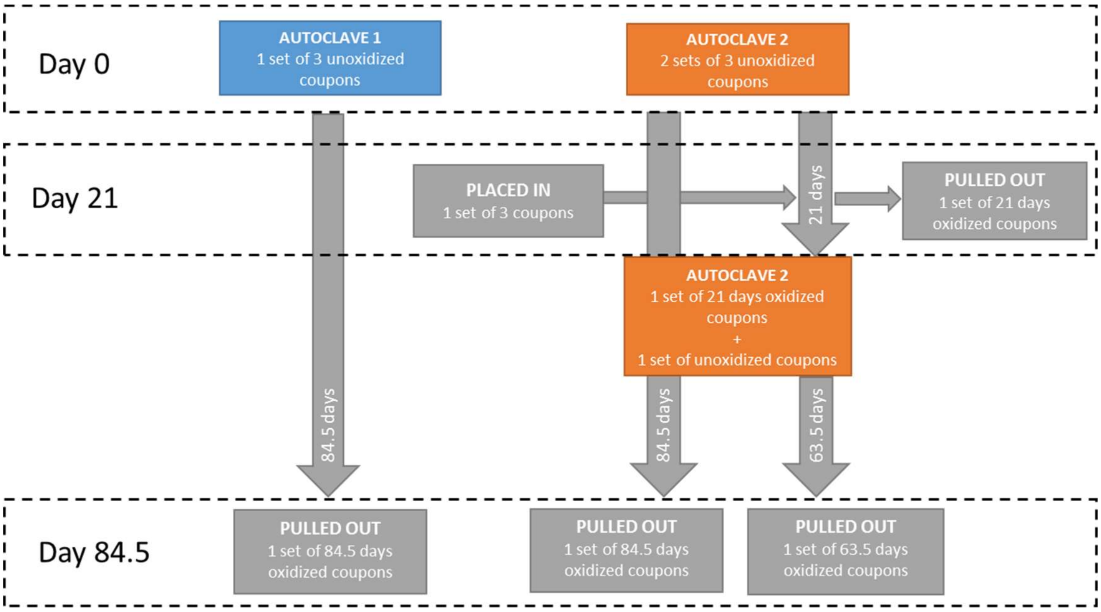

Figure 1: Schematic experimental methodology used in long-term corrosion test.

After the visual inspection, the coupons were dried and weighed again to determine the weight gain. Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) were also used to characterize the oxide scales formed during corrosion test.

3. Results and Discussion

The oxide layer formed onto the surface of AISI 348 SS was adherent, and seems to neither delaminate nor dissolve in pressurized water conditions. The colors vary from a goldish to bluish and gray, this color variation could be related to the increase in weight gain observed, as shown in Figure 2.

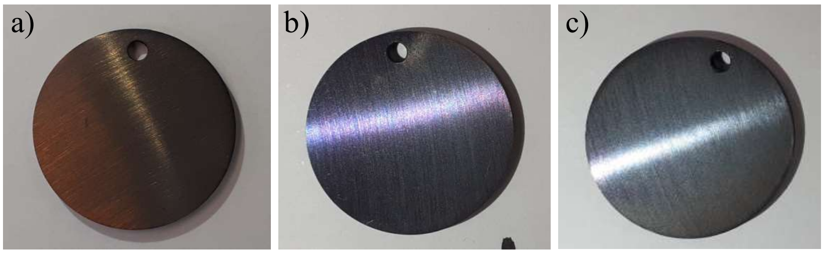

Figure 2: Examples of corroded AISI 348 SS specimens with a) 1,3 ± 0,9 mg/dm² (goldish), b) 3,4 ± 0,8 mg/dm² (bluish) and c) 4,4 ± 0,9 mg/dm² (gray) weight gain.

Considering parabolic kinetic, based on solid state diffusion model [5], for the early corrosion stage studied it was possible to estimate the kinetic parameter (k_p) associated with AISI 348 SS corrosion in deoxygenated water (DO_2 < 0.1 ppm / DH_2 < 5 ppb) at 360 ºC and 20 MPa. As shown in Figure 3, the kinetic parameter for weight gain found using least squares method was $k_p = 0.135 \pm 0.014$ $(mg/dm^2)^2d^{-1}$. Despite the reduced number of data points, the quality of linear fit was good ($R^2 = 0.867$), validating the hypothesis that the corrosion kinetic of AISI 348 SS is almost parabolic. The XRD and SEM results corroborate this model, and an oxide spinel type, such as magnetite, was found in the formed corrosion layers.

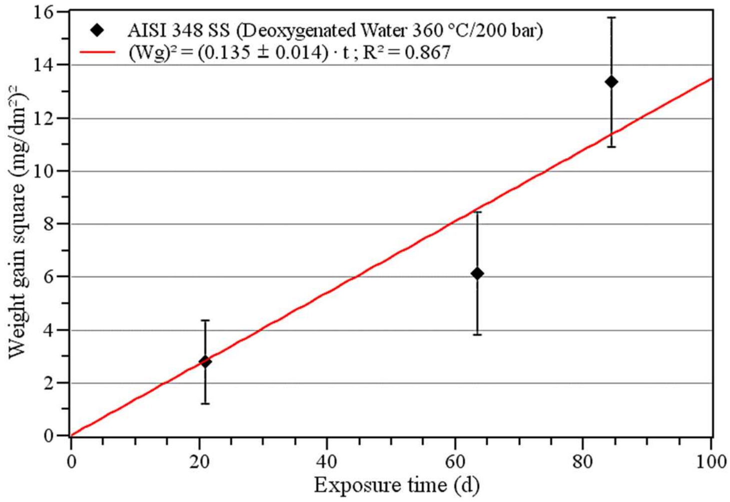

Figure 3: Parabolic fitting for estimation of kinetic parameter associated with AISI 348 SS weight gain.

When AISI 348 SS is compared with the performance of zirconium based alloys in similar test conditions, the corrosion behavior shows a clear enhanced resistance as can be observed in Figure 4, an adaptation from P. Lai *et al.* [6], that compiles data for M5 alloy tested in 360 ºC/20 MPa deoxygenated water [7, 8]. Although preliminary, the data supports AISI 348 SS as a potential ATF cladding, at least under normal operating conditions.

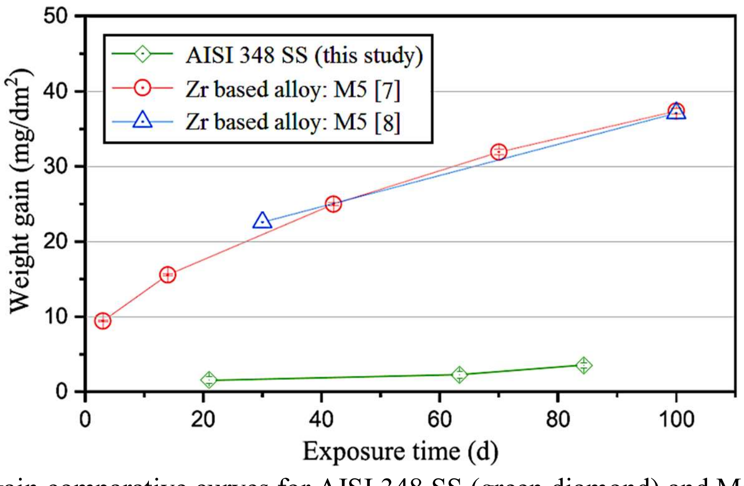

Figure 4: Weight gain comparative curves for AISI 348 SS (green diamond) and M5 (red circle [7] and blue triangle [8]) in deoxygenated water at 360 °C and 20 MPa. Adapted from P. Lai *et al.* [6].

4. Conclusions

The corrosion behavior of AISI 348 SS shows an enhanced resistance to corrosion, when compared to zirconium based alloys, in deoxygenated pressurized water at 360 °C and 20 MPa.
Based on the solid state diffusion model, the kinetic parabolic parameter for weight gain found was $k_p = 0.135 \pm 0.014$ $(mg/dm^2)^2d^{-1}$ and the oxide observed was composed basically of spinel structures, such as magnetite.
Since, for licensing purposes, NUREG 0800 [3] requires collecting reliable empirical data related to corrosion performance of all materials which will be used inside a primary water reactor, and the available updated data on corrosion of stainless steel type 348 in these conditions is still incipient, future work must be carried out to verify if it meets the requirements of an ATF cladding material under normal operation, transient and accident conditions.

Acknowledgements

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