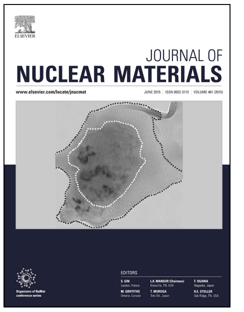

Stress corrosion crack initiation of Zircaloy-4 cladding tubes in an iodine vapor environment during creep, relaxation, and constant strain rate tests

T. Jezequel, Q. Auzoux, D. Le Boulch, M. Bono, E. Andrieu, C. Blanc, V. Chabretou, N. Mozzani, M. Rautenberg

PII: S0022-3115(17)30146-0

DOI: 10.1016/j.jnucmat.2017.07.014

Reference: NUMA 50386

To appear in: *Journal of Nuclear Materials*

Received Date: 31 January 2017

Revised Date: 6 June 2017

Accepted Date: 6 July 2017

Please cite this article as: T. Jezequel, Q. Auzoux, D. Le Boulch, M. Bono, E. Andrieu, C. Blanc, V. Chabretou, N. Mozzani, M. Rautenberg, Stress corrosion crack initiation of Zircaloy-4 cladding tubes in an iodine vapor environment during creep, relaxation, and constant strain rate tests, *Journal of Nuclear Materials* (2017), doi: 10.1016/j.jnucmat.2017.07.014.

Stress corrosion crack initiation of Zircaloy-4 cladding tubes in an iodine vapor environment during creep, relaxation, and constant strain rate tests

T. Jezequel [a,b,] *, Q. Auzoux [a], D. Le Boulch [a], M. Bono [a], E. Andrieu [b], C. Blanc [b], V. Chabretou [c]; N. Mozzani [d], M. Rautenberg[e]

[a] *Den-Service d'Etude des Matériaux Irradiés (SEMI), CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France*
[b] *CIRIMAT, Université de Toulouse, CNRS, INPT, UPS, ENSIACET, 4 allée Emile Monso, CS 44362, 31030 Toulouse, France*
[c] *AREVA NP 10 rue Juliette Récamier, 69456 Lyon, France*
[d] *EDF R&D, Site des Renardières, 77818 Moret-sur-Loing, France*
[e] *EDF Septen, Avenue Antoine Dutrievoz, 69100 Villeurbanne, France*

Abstract
During accidental power transient conditions with Pellet Cladding Interaction (PCI), the synergistic effect of the stress and strain imposed on the cladding by thermal expansion of the fuel, and corrosion by iodine released as a fission product, may lead to cladding failure by Stress Corrosion Cracking (SCC). In this study, internal pressure tests were conducted on unirradiated cold-worked stress-relieved Zircaloy-4 cladding tubes in an iodine vapor environment. The goal was to investigate the influence of loading type (constant pressure tests, constant circumferential strain rate tests, or constant circumferential strain tests) and test temperature (320, 350, or 380°C) on iodine-induced stress corrosion cracking (I-SCC). The experimental results obtained with different loading types were consistent with each other. The apparent threshold hoop stress for I-SCC was found to be independent of the test temperature. SEM micrographs of the tested samples showed many pits distributed over the inner surface, which tended to coalesce into large pits in which a microcrack could initiate. A model for the time-to-failure of a cladding tube was developed using finite element simulations of the viscoplastic mechanical behavior of the material and a modified Kachanov's damage growth model. The times-to-failure predicted by this model are consistent with the experimental data.

1. Introduction

The fuel rods of a pressurized water nuclear reactor consist of fuel pellets stacked inside cladding tubes, which act as the first of several barriers that contain the fuel and prevent the dissemination of fission products. During the fabrication of the rods, there is initially a small radial gap between the pellet and the cladding. In the reactor, the gap closes as the result of cladding diameter decrease due to irradiation creep and pellet diameter increase due to swelling. This phenomenon leads to the Pellet-Cladding Interaction (PCI). Once this occurs, the synergistic effect of the tensile hoop stress and strain imposed on the cladding by the thermal expansion of the fuel during accidental power transient conditions and corrosion by released fission products may lead to cladding failure by Stress Corrosion Cracking (SCC) [1], [2], [3] and [4]. Iodine, one of the fission products, is known to be a causative agent of SCC, referred to as I-SCC [2], [5] and [6]. A number of researchers have investigated I-SCC of zirconium-alloy cladding, notably with creep tests in an iodine vapor environment [7], [8], [9], [10], [11], [12], [13] and [14].

During a power transient, the loading path on the cladding is quite complex and consists of two phases. As the pellet expands due to its temperature increase, the stress and strain in the cladding increase rapidly, and once the temperature and pellet diameter have stabilized, the stress in the cladding relaxes as its total strain remains constant [5], [15] and [16]. In that context, the primary goal of the present work was to study the response of the cladding in an iodine vapor environment with several different loading modes, including constant internal pressure tests (creep), constant hoop strain rate tests, and constant hoop strain tests (relaxation). Tests were performed with an experimental device that monitored and measured the strain and stress in the sample. After the tests, specimens were examined by SEM to study the inner surface of the tube, and to characterize the fracture mode on the crack faces. A model for cladding failure via I-SCC was computed based on the results of the creep and relaxation tests using a viscoplastic material behavior law and a progressive damage law.

2. Material and experimental procedure

The material used in this study was cold-worked stress-relieved (CWSR) Zircaloy-4 cladding. It was commercially produced and supplied by AREVA NP. The tubes had an outer diameter of 9.52 mm and an inner diameter of 8.36 mm. The chemical composition is given in Table 1.