IMPROVEMENTS OF PCMI CRITERION FOR ANTICIPATED OPERATIONAL OCCURENCES

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ABSTRACT

During a Pellet - Clad Mechanical Interaction (PCMI), clad deformation is driven by fuel pellet expansion. In the event of anticipated operational occurrences (AOO), significant power increases can induce cladding failures due to PCMI.

To prevent this phenomenon, design and safety studies have to demonstrate that the clad deformation caused by any AOO remains below a strain criterion. The historical value of this criterion is 1% total hoop strain. This value was obtained from a database of burst tests on irradiated cladding. Considering the mechanical loading and failure mode induced by burst tests and the outdated clad designs on which these tests were carried out, the historical criterion can be relatively conservative.

This paper describes an approach (proposed in 2016 to the French Safety Authority) to assess a strain criterion based on experimental results from tests that more accurately represent cladding failure by PCMI. To this end, specific tests were developed in hot cells by the CEA: fixed-end EDC (Expansion Due to Compression) tests. Experimental results are post-processed to get a penalized assessment of allowable strains induced by PCMI in the event of AOO.

The penalized experimental strains at failure show that a 2% total hoop strain criterion can be considered for irradiated claddings, with hydrogen contents of up to 250 ppm.

1. Introduction

In its standard review plan [1], the U.S. NRC defines a strain criterion to prevent fuel rod failure due to Pellet-Clad Mechanical Interaction (PCMI):

“*The first criterion limits uniform strain of the cladding to no more than 1 percent. In this context, uniform strain (elastic and inelastic) is defined as transient-induced deformation with gauge lengths corresponding to cladding dimensions; steady-state creepdown and irradiation growth are excluded. Mechanical testing must demonstrate that the irradiated cladding ductility at maximum waterside corrosion (hydride embrittlement) is well within the 1-percent strain criterion*”

This 1% strain criterion has been used worldwide since the first PWR and BWR designs, and generally represents the transient-induced total (i.e. elastic + plastic) hoop strain. Its value is derived from strains at failure measured during burst tests on irradiated claddings.

In France, the 1% strain criterion is used as a design limit for Anticipated Operational Occurences. As clad ballooning is precluded for this kind of operating conditions, burst tests can be considered as too penalizing. Furthermore, mechanical performances of the current cladding materials are better than those of the claddings on which the criterion is based. A new method to assess the strain criterion for AOOs is addressed in this paper. The main steps of this method are the following:

- analysis of the thermal-mechanical loading induced by PCMI during AOOs;
- mechanical tests based on strain-driven loadings, in representative thermo-mechanical conditions;
- penalization of the experimental strains at failure, to ensure comprehensive inclusion of in-core AOO power transients.

In the following sections, this method is detailed and applied to irradiated Zircaloy-4 and M5.

2. Thermal-mechanical loading during AOOs

Significant PCMI loadings can be caused by various types of AOOs, such as Rod Drop (RD) ; Excessive Increase of Steam Flow (EISF) ; or Uncontrolled Rod control cluster assembly Bank Withdrawal (URBW) at power or in Hot Stand-by conditions. The following parameters can be derived from simulations of these transients :

- The outer clad surface temperature (which is the lowest one across clad thickness) can rise to the boiling temperature of the coolant (345°C for a PWR operated at 155 bar) ;
- Kinetics of fuel pellet expansion can lead to a clad strain rate up to $10^{-2}s^{-1}$ for URBW in hot stand-by conditions, and $10^{-4}s^{-1}$ for other types of AOOs.

Concerning the loading direction induced by PCMI, test programs carried out in France (CABRI RIA tests) and in Japan (NSRR RIA tests) have indicated that the fuel cladding experiences a biaxial loading in which the strain ratio ($\varepsilon_{zz}/\varepsilon_{\theta\theta}$) falls in the range between 0 and 1 [2]. These values were obtained from measurements of the residual strain components, ε_{zz} and $\varepsilon_{\theta\theta}$, on cladding tubes.

3. Mechanical tests on irradiated cladding

3.1. Free-ends EDC test

Many different types of tests have been developed in an effort to reproduce, in the laboratory, the stresses and strains produced in the fuel cladding during PCMI. One of the most representative tests involves placing a pellet-shaped cylindrical device inside a sample of fuel cladding. The device is compressed axially, causing it to expand in diameter, and thereby creating a hoop strain in the cladding sample. Mishima [3] developed a test in which a ductile, pellet-shaped lead cylinder was compressed by two pistons to measure the failure hoop strain of beryllium cladding tubes. Researchers have also used a segmented expanding mandrel with an axial core of ductile material, in order to simulate PCMI for stress corrosion cracking tests on fuel cladding [4]. Compression of the ductile core causes the segmented mandrel to expand in diameter, thereby imposing a hoop strain on the sample. These types of Expansion Due to Compression (EDC) tests have been widely used to test the failure conditions of fuel cladding, including tests on irradiated fuel cladding ([5]-[7]).

In the original version of the test, the ends of the tubular sample were free and unconstrained. During this type of free-end EDC test, the sample shrinks axially as it expands in diameter. Therefore, the strain biaxiality in the sample, $\varepsilon_{zz}/\varepsilon_{\theta\theta}$, is not representative of that experienced by fuel cladding during PCMI. In order to produce a more representative biaxial strain state in the sample, a fixture was introduced to restrain the tube from axial shrinkage [8]. The end restraining fixture prevents any change in length of the sample, so the strain biaxiality is much more representative than that of a free-end test.

3.2. Fixed-ends EDC test

Fixed-end EDC tests have been implemented in the hot labs at CEA Saclay in order to perform tests on samples of irradiated fuel cladding. In these tests, the tubular sample of irradiated fuel cladding has an outer diameter of approximately 9.5 mm and a length of 27 mm. The wall thickness is approximately 0.57 mm. A cylindrical aluminum media of height 14 mm is inserted into the sample. Stainless steel disks are inserted on either side of the media. A plug is then welded to each end of the sample. Each plug contains a central axial hole so that a piston can pass through it in order to compress the aluminum media. The outer end of the plug is threaded so that it can be connected to an end restraining fixture, as shown in Figure 1.

The sample and the end restraining fixture are mounted in a compression cage inside a furnace on a tensile testing machine. The device is then heated to the test temperature, and the aluminum media is compressed at the desired rate and expands in diameter in the process. The media imposes a hoop strain on the sample, but the sample length remains constant due to the end restraining fixture, whereas the sample length usually decreases during a free-ends EDC test. As a result, the strain biaxiality in the sample is close to that produced in fuel cladding during PCMI.

During the test, the outer diameter of the sample is measured using an image analysis method. The hoop strain is then calculated as a function of time. The rupture of the sample is accompanied by a sudden drop in the force measured by the tensile testing machine. The hoop strain measured at this moment represents the failure strain of the sample.

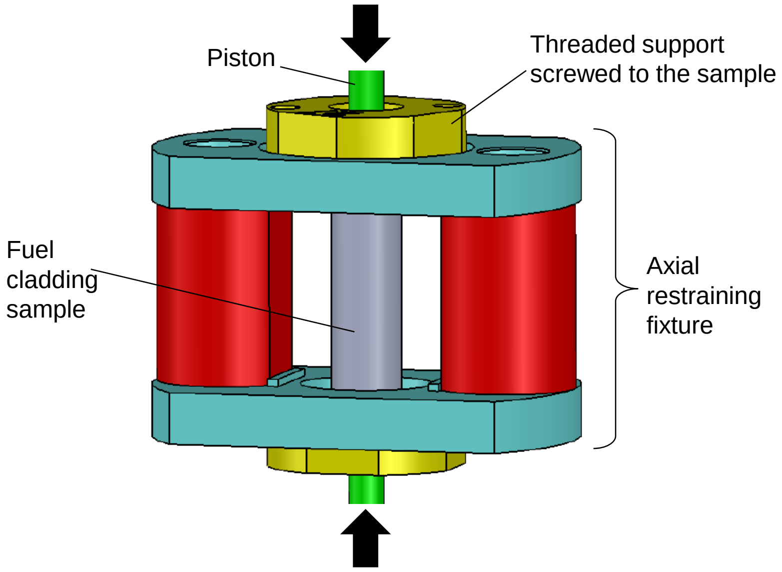

Figure 1. Fixed-end EDC test

3.3. Test matrix

The test matrix is given in

Table 1. The objective is to study the effect of strain biaxiality (free-end EDC and fixed-end EDC, for which biaxiality ratios are discussed in §4.1), temperature (from 330°C to 400°C) and strain rate (from around 10^{-6} s^{-1} to 10^{-4} s^{-1}) on irradiated Zircaloy-4 and M5 cladding. The tested irradiated samples contain less than 250 ppm of hydrogen.

Table 1. Test matrix

Cladding	Test	Burnup (GWj/tU)	Clad oxide (µm)	Test temperature (°C)	$\frac{d\varepsilon_{\theta\theta}}{dt}$ (10^{-5} s^{-1})	$\varepsilon_{\theta\theta}$ max (%)	Failed ?
M5	Free-ends EDC	48	14	350	0.7	68	Yes
				350	8	80	Yes
				380	0.08	46	No
				380	0.9	65	No
				380	9	75	No
				400	0.7	68	No
	Fixed-ends EDC	48	15	350	20	20	Yes
				351	15	15	Yes
				380	1.2	31	Yes
				380	20	22	Yes
				400	20	25	Yes
Zircaloy-4	Free-ends EDC	44	20	350	0.8	62	Yes
				350	10	85	Yes
				380	0.08	60	No
				380	1.1	68	No
				380	10	70	No
				400	0.8	77	No
	Fixed-ends EDC	29	14	350	20	19	Yes
				381	1.6	26	Yes
		44	11	330	20	10	Yes
				349	16	13	Yes
				395	21	21	Yes

3.4. Results

Figure 2 shows the evolution of circumferential fracture strain ($\varepsilon_{\theta\theta}$) as a function of test temperature for free-end and fixed-end EDC tests. For all of the test conditions, the circumferential fracture strain is greater than 10%. Increasing the test temperature from 330°C to 400°C increases the fracture strain. The greater strain biaxiality of fixed-end EDC tests leads to drastically reduced fracture strains, compared to free-end EDC tests. For M5 cladding tested at 350°C, the average fracture strain is around 74% for a free-end EDC test and around 17% for a fixed-end EDC test.

Figure 3 shows the evolution of circumferential fracture strain ($\varepsilon_{\theta\theta}$) as a function of temperature and strain rate for Zircaloy-4 and M5 fixed-end EDC tests. For Zircaloy-4 tested at around 10^{-4} s^{-1} in the temperature range 330°C to 400°C, the circumferential fracture strains are between 10% and 26%.

For the conditions tested, Zircaloy-4 fracture strains are similar to those of M5. For M5 cladding tested at 380°C, increasing the strain rate from 10^{-5} s^{-1} to 10^{-4} s^{-1} reduces the fracture strain from 31% to 21.5%.

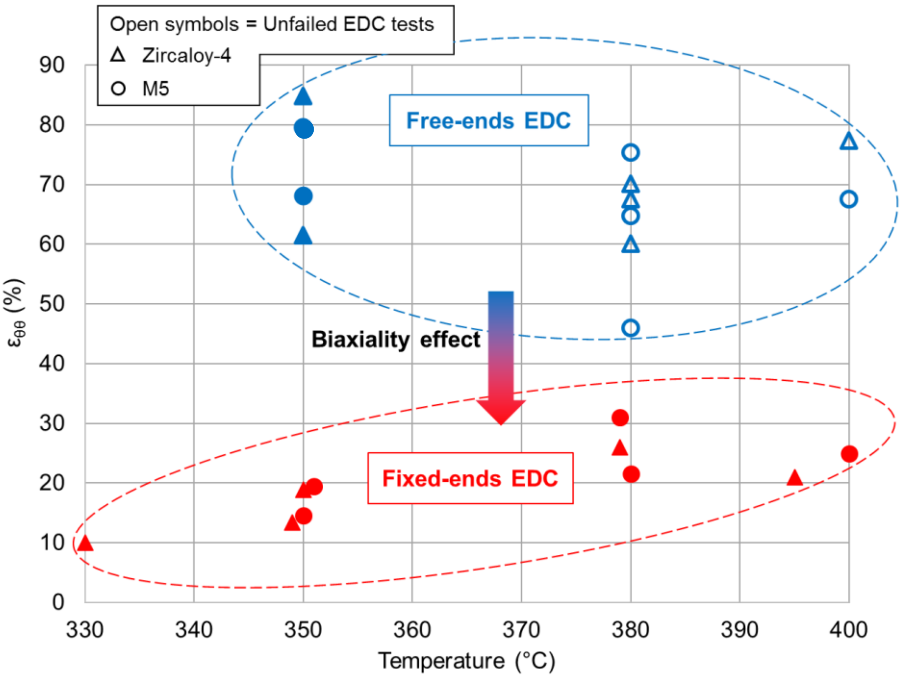

Figure 2. Biaxiality effect on circumferential fracture strain

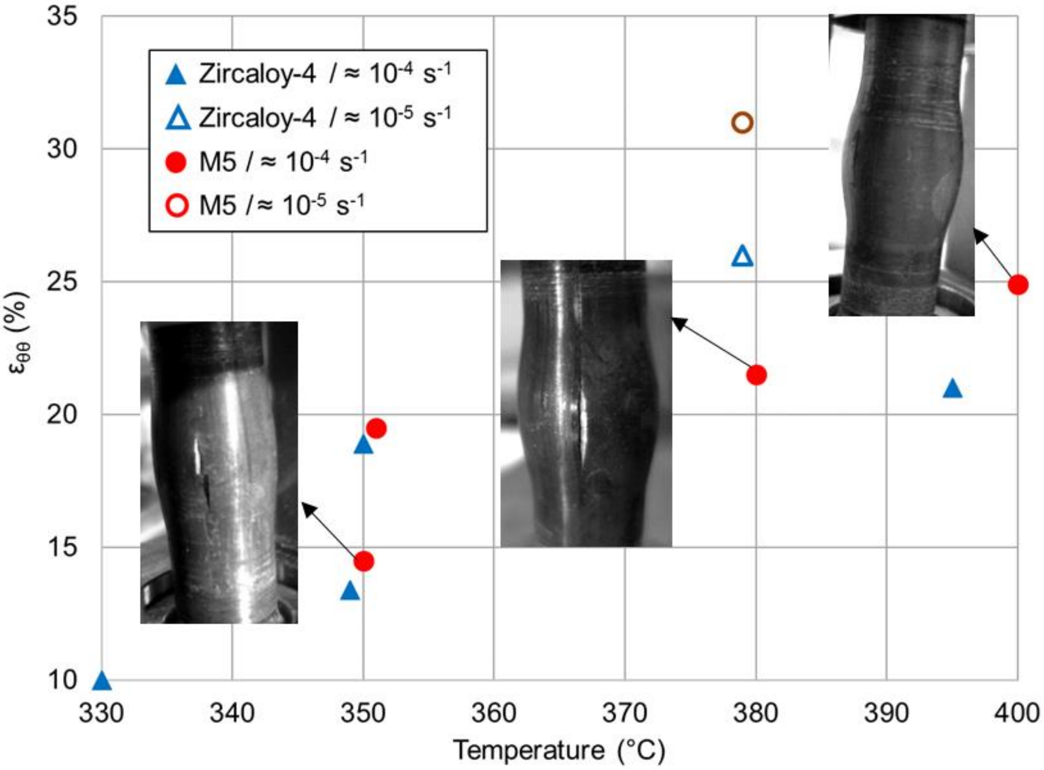

Figure 3. Temperature and strain rate effects on circumferential fracture strain during fixed-end EDC tests

4. Post-processing of experimental data

4.1. Finite Element simulations

For free-end EDC tests, the biaxiality ratio is estimated at $\varepsilon_{zz}/\varepsilon_{\theta\theta}$=-0.5 [2], which is not representative of PCMI conditions. As explained in Section 3.1, the fixed-end EDC test was designed to produce a state of nearly plane strain conditions in the sample by limiting the negative axial deformation of the cladding. In order to determine the level of stress and strain biaxiality present in such a test, a finite element mechanical model was developed with ANSYS Mechanical 15.0 [9]. Taking into account cylindrical symmetry, the model represents one quarter of the cladding surrounding the media, with potential contact between the two structures (Figure 4). In the results presented here, all of the interfaces are assumed to be frictionless. The objective of this model is to analyze the mechanical stress and strain biaxiality that can be expected in this kind of fixed-end EDC test: $\varepsilon_{zz}/\varepsilon_{\theta\theta} \sim 0$; $s_{zz}/s_{\theta\theta} \sim 0.5$. The mechanical behavior laws for the cladding are chosen to be as representative but as simple as possible to analyze the problem. The media is modeled by an isotropic elastoplastic behavior with nonlinear isotropic strain hardening (Ramberg-Osgood model) derived from [10]. The cladding has been modeled with an elasto-viscoplastic law using a Lemaître formalism:

$$\frac{d\varepsilon}{dt} = \left(\frac{\sigma}{a \cdot \varepsilon^m}\right)^n \cdot e^{-\frac{Q}{T}} \text{ with}$$

ε: equivalent Von Mises creep strain (-)
t: time (s)
σ: equivalent Von Mises stress (MPa)
a: activation temperature parameter (-)
m: strain exponent (-)
n: stress exponent (-)
T: temperature (K)
Q : activation energy (K)

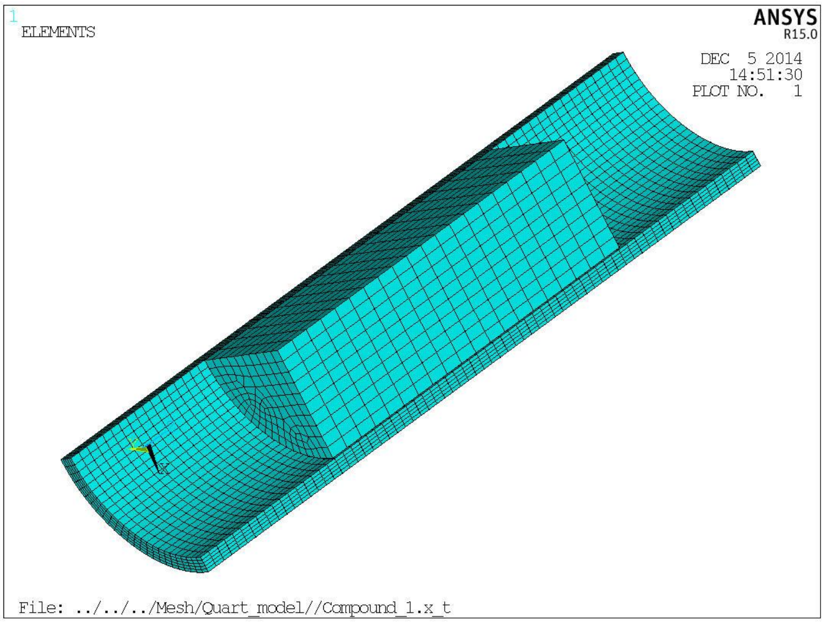

Figure 4. Mesh used for Finite Elements simulations

This law is integrated over time and then combined with an elastic strain to get the complete elasto-viscoplastic response of the material. The law is calibrated using different kinds of mechanical data (Hardening – relaxation tests, tensile tests, burst tests). The same set of parameters is used for both M5 and zircaloy-4 alloys.

The simulation reproduces a test lasting 3000 s, during which a global axial force (order of magnitude of 10 kN) is applied to the media, resulting in a total hoop strain in the cladding of around 20% (predominantly plastic strain at the end of the simulation). The total hoop cladding strain increases monotonically with time. figure 5 shows the evolution of the strain biaxiality ratio $\varepsilon_{zz}/\varepsilon_{\theta\theta}$ as a function of the total hoop strain of the external surface at the mid-plane of the sample. The simulation indicates that the strain ratio initially decreases and reaches a minimum value of about -0.2 at around 2% hoop strain. During this initial period, the end restraining fixture is unable to prevent a small negative axial strain in the mid-plance of the sample. The strain ratio increases thereafter and reaches -0.08 at 5% hoop strain. At 20% hoop strain, the strain ratio is about 0.05. Thus, the loading of the sample is close to a plane strain condition.

Figure 5 Evolution of the inelastic strain biaxiality ratio as a function of total (elastic + plastic) hoop cladding strain (external skin of the cladding)

4.2. Penalization of measured strains at failure

Results of fixed-end EDC tests cover a temperature range of 330°C to 400°C, and a strain rate up to $10^{-4}s^{-1}$. These test conditions are consistent with the temperatures and strain rates induced by AOOs (except URBW in hot stand-by conditions), as described in §2. However, fixed-end EDC tests do not represent the entire range of interest for the strain biaxiality, as they are limited to nearly plane strain conditions, as shown in §4.1.

Strain ratios between 0 and 1 can be covered assuming that, at a given temperature and strain rate, the failure during a fixed-ends EDC test and the failure at higher strain ratios occur at the same equivalent strain. There is not clear theoretical background to support such a choice but cladding is a thin shell and as such triaxiality is low. Therefore cavity growth should be limited and most of the deformation to rupture would be due to plastic deformation. As a consequence, equivalent plastic deformation strain should not be a bad indicator of rupture.

This is illustrated in Figure 6, where it can be seen that, for a given equivalent strain at failure, the corresponding hoop strain is higher in plane strain situations ($\varepsilon_{zz}/\varepsilon_{\theta\theta}=0$) than in an equiaxial situation ($\varepsilon_{zz}/\varepsilon_{\theta\theta}=1$). For a PCMI loading at a given equivalent strain at failure, the equiaxial direction is therefore the most penalizing regarding the accumulated hoop strain. To derive a strain criterion, usually expressed in the hoop direction, from fixed-ends EDC results, a penalization factor is then applied on experimental fracture hoop strains. This factor is calculated as the ratio between the hoop strains at $\varepsilon_{zz}/\varepsilon_{\theta\theta}=0$ and $\varepsilon_{zz}/\varepsilon_{\theta\theta}=1$, obtained at a constant equivalent strain.

To calculate this ratio, the hoop strain rate is expressed as a function of an equivalent stress and strain rate with a Hill formalism taking into account clad anisotropy, through two H_r and H_z coefficients:

$$\frac{d\varepsilon_{\theta\theta}^{p}}{dt} = [H_r(\sigma_{\theta\theta} - \sigma_{zz}) + H_z(\sigma_{\theta\theta} - \sigma_{rr})]\frac{d\varepsilon_{eq}^{p}/dt}{\sigma_{eq}}$$

This equation can be applied to both plane strain and equiaxial situations, using H_r and H_z coefficients obtained from creep and hardening – relaxation tests on irradiated M5 or Zircaloy-4 claddings. The resulting ratio $\varepsilon_{\theta\theta}(\varepsilon_{zz}/\varepsilon_{\theta\theta}=0)$ / $\varepsilon_{\theta\theta}(\varepsilon_{zz}/\varepsilon_{\theta\theta}=1)$ is lower than 1.8. Thus, regarding the loading directions that can occur in PCMI, the fracture hoop strains obtained from fixed-ends EDC tests can be considered conservative if they are divided by 1.8.

Another parameter that can have an influence on the fracture strain is the hydrogen content. Indeed, hydrogen-induced decrease of ductility is a well-known phenomenon for irradiated zirconium alloys [11]. As a consequence, in a conservative approach, the fracture strains obtained from fixed-ends EDC tests are not considered to cover hydrogen contents above the highest tested value (250 ppm in the present case).

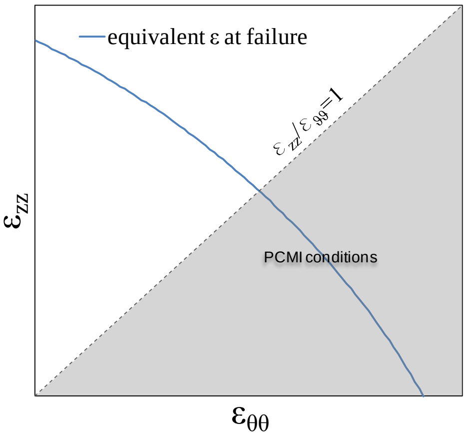

Figure 6. Illustration of the equivalent strain (blue curve) at failure on a theoretical (ε_{zz} ; $\varepsilon_{\theta\theta}$) plot based on the Von Mises theory.

5. Conclusion

A strain criterion can be used to prevent fuel rod damage due to PCMI in the event of AOO. This paper describes an approach, which was proposed to the French Safety Authority in 2016, to assess a hoop strain criterion based on experimental results from tests that accurately represent cladding failure by PCMI. To this end, fixed-end EDC (Expansion Due to Compression) tests were performed in hot cells by the CEA. These tests show that the parameter having the greatest influence on the hoop strain at fracture is the strain biaxiality, $\varepsilon_{zz}/\varepsilon_{\theta\theta}$. The measured fracture hoop strains are significantly lower for fixed-end EDC tests than for free-end EDC tests.

To assess quantitatively the strain biaxiality induced by fixed-ends EDC tests, finite element simulations are presented. The simulations show that the fixed-end EDC tests limit the negative axial deformation of the cladding, as designed, and provide nearly plane-strain loading above a given deformation. Nevertheless, as simulations show that a part of the strain biaxiality range that can be encountered in PCMI is not covered by this test, a penalization factor is calculated and applied to the measured fracture strains.

The proposed method for determining a hoop strain criterion is as follows:

- Temperature of 350°C, which is the lowest temperature for AOO conditions;
- Hoop strain rate of $1.10^{-4}s^{-1}$, which is the highest value for AOO conditions (excluding URBW in hot stand-by conditions);
- The fracture hoop strain measured from a fixed-end EDC test is penalized by dividing it by 1.8, to account for the difference in strain biaxiality ratio.

Table 1 indicates that the lowest measured fracture hoop strain in the conditions of interest was 13.4% for a fixed-end EDC test on irradiated Zircaloy-4. Dividing this measured hoop strain by 1.8 leads to a value of 7.4%. In order to maintain a significant margin, a 2% total hoop strain criterion was proposed for irradiated claddings having hydrogen contents of up to 250 ppm. As this criterion does not cover hoop strain rates above $10^{-4}s^{-1}$, it does not applies to URBW in hot stand-by conditions.

M5 is a trademark or a registered trademark of Framatome or its affiliates in the USA or other countries.

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