DYNAMIC RELIABILITY MODEL FOR THE PICKERING CLADDING STRESS CORROSION CRACKING FAILURES

NT LETTER

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A dynamic reliability model is used to describe test data on stress corrosion cracking failures of cladding rings cut of the Pickering post-reactor fuel. This model provides an expression that fits the data points very well. The main goal of the model is to take into account the in-reactor reliability drop prior to the test. An equivalent test time parameter responsible for the fuel burning is used to move the time axis origin to the left for the beginning of the test. The nonzero failure fraction at the real test beginning is supposed to exist appearing as a very large fraction of the specimens failed at the very first moments of the test.

Penn et al.[1] have reported the test data for the stress corrosion cracking (SCC) failures of stressed slotted rings cut of irradiated Pickering cladding while exposed to iodine at 573 K. Their data are shown in Fig. 1 by circles. These data were fitted with the following expression[1]:

$$F(t) \triangleq \frac{N_F}{N_T} = A[1 - \exp(-\lambda t)] \ , \qquad (1)$$

where F is a fraction of rings failed, $A = \frac{56}{63}$ is a fraction of rings failed after the end of the test (t = 10 h), and λ = 0.9 1/h and λ = 1.8 1/h are two failure rate parameters, chosen to bound experimental points. It can be seen from Fig. 1 that no λ would let the curve go along with the points.

We use here a dynamic failure model based on failure under cycling load conditions.[2] This model enables to fit experimental points as shown in the figure by the curve, according to the following expression:

$$F = 1 - R(t) \ ; \quad R(t) = R_0 + (1 - R_0)\exp[-\lambda(t + \tau)] \ , \qquad (2)$$

where $R(t)$ is the time-dependent system reliability under cycling loads,

$$R_0 = \lim_{t \to \infty} R(t) \ ,$$

where

λ = rate of load cycles

τ = beginning of cycling load applications

$\tau \neq 0$ means that equivalent cycling load conditions existed before the beginning of the test.

To derive Eq. (2), we assume the following.

1. There exists in the test conditions a main damaging factor, which appears at random times, leading to cycling loads on the cladding.
2. The number of cycles for time t is distributed according to the Poisson law:

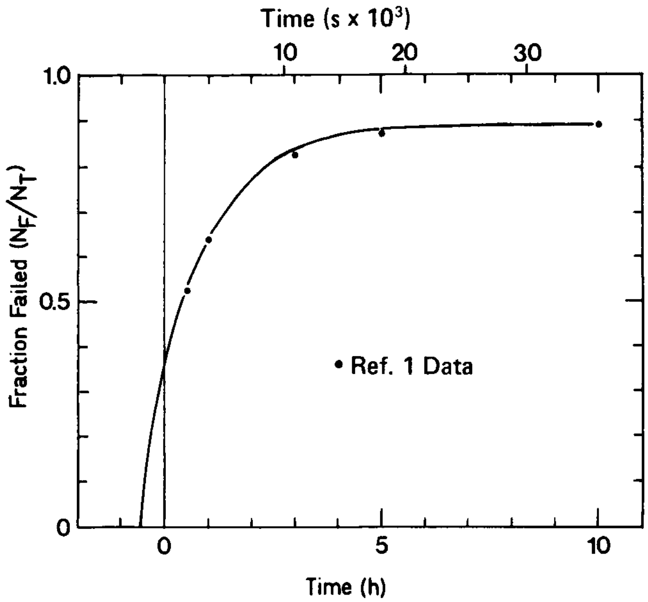

Fig. 1. Results of stress corrosion cracking tests of Ref. 1 fitted with dynamic reliability model curve of the following form:

$$F = (1 - R_0)\{1 - \exp[-\lambda(t + \tau)]\} \ ,$$

where

$R_0 = 0.11$

$\lambda = 0.8$ 1/h

$\tau = 0.6$ h.

$$P(N_t = k) = \frac{\exp(-\lambda t)(\lambda t)^k}{k!} \quad , \tag{3}$$

which brings the λ parameter to Eq. (2).

3. Both the value of cycling load and the ability to resist it are fixed random values (i.e., both were random on their first appearance and behave due to a certain time dependence from cycle to cycle.)

4. The post-reactor specimens were used in the above test. This fact is treated by us by introducing effective time τ, representing real in-reactor time t_r or burnup b in terms of test conditions.

The attack of the fixed number of iodine molecules on the main crack might serve as a cycling load, which time of appearance obeys Poisson law.

We suppose that the dynamic failure mechanism leading to Eq. (2) for the test conditions was also in action at in-reactor conditions before the test.

This would suggest the dynamic failure model to work, with burnup b as more appropriate variable as follows:

$$R(b) = R_0 + (1 - R_0)\exp(-\alpha b) \quad , \tag{4}$$

where α is the attack-on-cladding rate parameter.

From Ref. 1 we learn that the cladding tested was cut from the fuel that had burnups in the range from 30 to 150 MWh/kgU. Let us suppose the $f(b)$ being a distribution function of tested rings over the burnup b. By averaging R over all rings tested we obtain

$$\langle R\rangle = \int_0^\infty R(b)f(b)db = R_0 + (1 - R_0)\int_0^\infty \exp(-\alpha b)f(b)db$$
$$= R_0 + (1 - R_0)\langle\exp(-\alpha b)\rangle = R_0 + (1 - R_0)\langle B(b)\rangle \quad , \tag{5}$$

where $\langle B(b)\rangle = \langle\exp(-\alpha b)\rangle$ is a kind of "SCC buildup coefficient," which is responsible for the cladding reliability drop with burnup in respect of the above mechanism.

We can rewrite Eq. (5) in the form of Eq. (2), where $t = 0$ and

$$\tau = -\frac{1}{\lambda}\ln\langle\exp(-\alpha b)\rangle \quad . \tag{6}$$

If $\langle\alpha b\rangle \ll 1$, then

$$\langle\exp(-\alpha b)\rangle \simeq \exp(-\langle\alpha b\rangle)$$

and

$$\tau \simeq \frac{\alpha}{\lambda}\langle b\rangle \quad , \tag{7}$$

where the independence of α on b was suggested. On arriving at Eq. (2), we can fill the τ value by the physical sense of a measure of the "readiness to fail" for the cladding being put to the test conditions, according to the following failure fraction:

$$F(0) = 1 - R(0) = (1 - R_0)\,[1 - \exp(-\lambda\tau)] \quad . \tag{8}$$

In other words, in spite of all the specimens being intact before the test, the SCC defects were accumulated and ready to make specimens fail at the very first minutes during the test. Such accumulated information on the fuel pre-history defects can be treated as fuel aging.

We also can introduce the in-reactor λ_r parameter as follows:

$$\langle\lambda_r t_r\rangle = \lambda\tau \quad , \tag{9}$$

where $t_r \approx 100$ to 300 day according the above burnup range. By fitting Eq. (2) to the data points, we obtain

$$\lambda = 0.8\ 1/\text{h} \quad , \quad \tau = 0.6\ \text{h} \quad ,$$

arriving at

$$\langle\lambda_r\rangle = \lambda\frac{\tau}{\langle t_r\rangle} \approx 10^{-4}\ 1/\text{h} \quad .$$

The authors of Ref. 1 use λ obtained by fitting Eq. (1) to test data points to approve the $\lambda = 2.3$ 1/h value for their generalized defect criteria with time dependence. In obeying Eq. (9), care must be taken of just picking up test data for in-reactor criteria without appropriate scaling.

Note that the same following expression for the failure rate $h(t)$:

$$h(t) \triangleq -\frac{d[\ln R(t)]}{dt} = \lambda\left[1 - \frac{R_0}{R(t)}\right] \tag{10}$$

can be obtained from both the original Eq. (1) and actual Eq. (2) failure models. By taking into account an in-reactor SCC defects accumulation, we can fit experimental data with this model.

REFERENCES

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