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FAILURE CRITERIA FOR THE PROBABILISTIC FUEL PERFORMANCE CODE FRP

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In nuclear reactors the fuel element cladding yields the first protective barrier against the release of radioactivity. The number of cladding failures must therefore be kept as low as possible. The computer program FRP was developed for probabilistic analysis of the fuel performance. The prediction of failures is an essential part of FRP. In order to improve the failure prediction, failure criteria reflecting different assumptions with regard to the failure mechanisms have been compared to the results from a large number of irradiation experiments.

The failure models are derived from the failure mechanisms observed in out-of-reactor laboratory tests of irradiated and unirradiated zircaloy. The failure mechanisms considered are: stress corrosion, creep rupture, overstress and overstrain, and in addition a correlation between power shocks and the failure probability is considered.

When the failure criteria are applied to ramp experiments the mechanical and thermal behaviour of the fuel is calculated by the fuel performance code FFRS which is part of the FRP program. FFRS calculates the average mechanical and thermal behaviour of a fuel pin, and for the maximum interaction (at ridges) a simple empirical model is included. The influence of the large uncertainties in material and design data is reduced by calibrating the simulation of each individual experiment to closely reproduce the existing PIE data for the average and maximum strain, the fission gas release and the maximum centre temperature.

The analysis shows that the stress corrosion failure criterion, based on out-of-reactor stress corrosion experiments performed on irradiated zircaloy cladding with iodine present, provides reasonable correlations for the included ramp experiments.

If the parameters of the failure criteria are estimated by regression analysis of the ramp experiments, the overstrain and overstress failure criteria also provide reasonable correlations of the data.
Regression analysis was also applied to the parameters of the stress corrosion failure criterion, to investigate whether there is a significant dependency of the stress corrosion failure probability on the amount of released fission gas or on the release rate. A dependency of this form could not be proven significant.

If the parameters of the failure criteria are based on regression analysis of the ramp experiments, several criteria representing different failure mechanisms seem to correlate the data. In these ramp experiments the basis for choosing the stress corrosion failure criterion is the observed time delay between the ramp and the failure detection.

In general the failure criteria can give considerable differences in the failure predictions, this is demonstrated by calculations with FRP. It is therefore very important to use a failure criterion based on the correct physical mechanism, when extrapolating the experience from ramp experiments to more general applications.

1. Introduction

The probabilistic fuel performance code FRP [1] was developed for the stastical prediction of nuclear fuel performance. The prediction of failures is an essential part of FRP. For some applications it is sufficient to have a measure for the damage, which can be used to evaluate the influence of changes in design and irradiation conditions; but for applications like performance evaluations for nuclear power plants, the exact failure probability should be known.

The failure criteria previously used in FRP are based on out-of-reactor tests of irradiated an unirradiated zircaloy. Since stress corrosion seems to be the dominant failure mode in power reactors, the failure criterion considered to be the most important is based on iodine stress corrosion tests. In these tests the environment is different from the in-reactor environment, and the failure limits are therefore expected to be different.

In the present investigation the in-reactor failure limits for a number of failure mechanisms are found by regression analysis, under the assumption that the observed failures in the considered ramp experiments (39 experiments with 20 failed and 19 unfailed pins) all are caused by the same failure mechanism.

The necessary information regarding the thermal and mechanical behaviour of the fuel pins was calculated by the fuel performance code FFRS [2], which is the deterministic fuel code utilized in FRP.

2. Simulation of the Thermal and Mechanical Behaviour of the fuel Rod

The thermal and mechanical performance of the fuel pins were simulated by the deterministic fuel performance code FFRS. FFRS was developed for use in FRP; the code was required to be fast (minimal computer time) and therefore an axisymetrical model of the fuel was utilized in it. Each simulation represents one slice of the fuel rod. In the model the slice is divided into 5 regions: cladding, gap, a rigid fuel zone, a bridge annulus, and a plastic fuel zone.

The cladding is modelled as an axisymetrical, hollow, thin cylinder with a given pressure on the inside. The boundary between fuel and cladding is the gap which provides heat transfer, inner pressure, and contact pressure. The outer part of the fuel, the rigid zone, is assumed to be cracked, and the thermal expansion is calculated as for a rigid bar. Only swelling and densification strains are assumed to exist in this zone. In the inner part of the fuel, the so-called plastic zone, the fuel is assumed to be stress-free, apart from hydrostatic pressure. A rigid annulus, the bridge, forms the boundary between the rigid and plastic fuel zones. The thermal expansion of the fuel is determined by the temperature distribution and the bridge position. The movement of the rigid annulus is accountable to the creep at the bridge and the crack volume during steady power conditions. During large power ramps the position is fixed by a balance between the ramp rate and the creep rate at the bridge. The model has been verified by simulation of a large number of irradiation experiments [2] and the results are in good agreement with the experimental results.

Only the average mechanical and thermal behaviours are calculated in the model. In order to predict the failure probability the maximum stress and strain must be estimated. The peak stress in the cladding is assumed to be the average stress plus a constant multiplied by the contact pressure. This simple approach seems to yield a reasonable prediction of the maximum expected deformation relative to the observed ridges.

3. Fuel Failure Criteria

The failures observed in nuclear fuel pins today are normally characterised as pellet-cladding interaction, PCI failure. They are caused by high tensile stresses in the cladding resulting from a power increase.

The strain observed at the fuel failures is normally below the out-of-reactor fracture strain for irradiated cladding and the fracture surfaces resembles those seen in out-of-reactor stress corrosion tests; therefore the failure mechanism is generally described as stress corrosion. Other failure mechanisms which characterize fuel failures are overstrain, overstress, and creep rupture. Common to these failure mechanisms is the knowledge required of the mechanical and thermal conditions of the fuel pin. Finally a failure criteria based on the power history and the initial cold gap alone is considered.

3.1 Stress Corrosion

The stress corrosion failure criterion used in the fuel models FRP and FFRS is derived from out-of-reactor stress corrosion experiments performed with unirradiated and irradiated zircaloy exposed to iodine vapour.

The time-to-failure, t_{FSC} for stress corrosion in reference [1+3] was found as

$$t_{FSC}=f_1(\text{environment})*f_2(\text{stress, material condition})* \\ *f_3(\text{temperature}) \qquad (1)$$

where

$$f_3(\theta)=\text{const.}*10^{\frac{220-\theta}{\theta_{FC}}} \quad 220^{\circ}C<\theta<400^{\circ}C$$

$$\theta_{FC}=40^{\circ}C$$

$$f_2(\text{stress, material condition})=f_2(\sigma_N)$$

$\sigma_N=\sigma/\sigma_u$; $\sigma_u=400$ MPa for irradiated zircaloy

$f_2(\sigma_N)$ is shown in Figure 1 for irradiated cladding

$$f_1(\text{environment}) = \text{const.}/(\min(P_o, P))$$

$$P_o = 0.1\text{MPa}$$

For continuously changing conditions the stress corrosion damage, SCD is defined [3] as

$$SCD(t_n) = \int_{t_o}^{t_n} \frac{dt}{t_{FSC}(t)} \qquad (2)$$

and failure is assumed if SCD $(t_n) \geq 1$.

This damage function was found to be very sensitive to difference in design and material data; therefore the stress corrosion damage is transformed to a stress corrosion damage stress, σ_{sc}, defined as the stress for which the time-to-failure calculated by Equation (1) is equal to 1/SCD under specified conditions such as irradiated cladding, 360°C, and saturation pressure.

The failure criterion with respect to stress corrosion is then

$$P(\text{stress corrosion failure}) = P(\sigma_{sc} \geq \sigma_{sc,L}) \qquad (3)$$

3.2 Creep Rupture

If the creep strain at rupture is constant within the considered operation conditions, the failure probability with respect to creep rupture is then

$$P(\text{creep rupture failure}) = P(\varepsilon_c \geq \varepsilon_{cR}) \qquad (4)$$

where ε_c is the accumulated primary and secondary creep. The rupture strain is large even for irradiated zircaloy. If the onset of accelerated creep is used as the failure limit a value of approximately 2.5% with standard deviation 0.5% can be taken based on the data of Watkins and Wood [4]

3.3 Overstrain

Irradiated zircaloy is brittle and the fracture strain can be very small. In tests on irradiated zircaloy Scott [5] found fractures at less than 2% for some of the tests. If failure is defined as the point where the uniform limit is exceeded the probability of overstrain failure is

$$P(\text{overstrain failure}) = P(\varepsilon_{pl} + \varepsilon_{pr} \geq \varepsilon_u) \qquad (5)$$

where ε_{pl} is the time-independent plastic deformation and ε_{pr} is the primary creep during a short ramp. The data from Scott gives ε_u=normally distributed with a mean value of 0.21% and a standard deviation of 0.04%.

3.4. Overstress

In out-of-reactor tests overstress and overstrain failures are equivalent, and the stress limit is the burst strength which is very close to the yield strength for irradiated cladding. Then

$$P(\text{overstress failure}) = P(\sigma \geq \sigma_u) \qquad (6)$$

where σ is the tangential stress and σ_u the corresponding burst strength. A typical value for the burst strength of irradiated zircaloy around $300^{o}C$ is 500 MPa.

3.5 Overpower

When defining a failure criterion which does not require simulation of the fuel, it is necessary to know the dominant mechanisms in fuel behaviour. Two of the most important are the closing of the gap during long irradiations at steady power, and the relaxation occuring during a slow ramp.

The overpower, δ, is defined as the difference between the actual power, η, and the onset power, η_o, which should represent the power at which the fuel-cladding gap is just closed. At begin-of-life η_o is defined in terms of the cold gap, $\eta_o = A_3 * g$; η_o is reduced with burnup until the present power level is reached with a rate A_1. If the present power level is greater than η_o, η_o is raised towards the present power level at a rate $A_2 * (\eta - \eta_o)$ where η is the present power.

The values for A_1, A_2, and A_3 are based on the following:

A_1: 3 months at 300 w/cm will reduce η_o with 100 w/cm, $A_1 = 5.37 \times 10^6$ w/m/FIMA

A_2: η_o is raised at a rate of 400 w/cm per week for a power increase of 400 w/cm ($\eta - \eta_o = 400$ w/cm) $A_2 = 5.18 \times 10^3$ FIMA^{-1}

A_3: from simulations with FFRS it is found that A_3 should be around 730×10^6 w/m^2

The model is illustrated in Figure 2.

The probability of failure is

$$P(\text{overpower failure}) = P(\delta \geqslant \delta_L) \qquad (7)$$

4. Choice of Ramp Experiments

Only ramp experiments are included in this investigation in which detailed information regarding design, irradiation and post-irradiation examination are available to the author. The information has been utilized to check the predictions of FFRS and confirms that the calculated deformations are in agreement with the observed deformations. In order to assure the best possible agreement between the predicted and observed deformations a few modifications were made in the material equations relative to the equations used in reference [1+2]. The material property for which the modelling was changed was hot-swelling. Furthermore the initial gap was reduced by 30 µm for the 8 SGHWR pins. After these adjustments were made the end-of-life strain as well as the strain during the final ramp were found to be in good agreement with the experimental observations.

The fuel experiments included in the investigation were the 20 interramp pins [6], 8 of the pins from the ramped SGHWR element C [7], 8 Danish fuel tests [8+9] and 3 of the experiments from the EPRI fuel-rod modelling code evaluation [10].

These pins extend over a diversity in design data and irradiation conditions. Twenty of the 39 pins failed during the final ramp test.

5. In-reactor Failure Limits

The failure limits for stress corrosion, creep rupture, overstrain, and overstress have all been estimated from out-of-reactor experiments and the following estimates are given

$$\sigma_{sc,L}=(225,18)\text{MPa};\ \varepsilon_{cR}=(2.5,0.5)\%$$

$$\varepsilon_u=(0.21,0.04)\%\ ;\quad \sigma_u=(500,25)\text{MPa}$$

Where (a,b) is (mean value, standard deviation). A limit for the overpower, δ_L, can be based only on in-reactor experiments.

Regression analyses have been utilized for the estimation of these failure limits under the assumption that the observed failuers in the 39 experiments can all be explained by the corresponding failure mechanism.

The failure limit should be chosen as to minimize the sum-of-squared deviations between the experimental observations and the calculated failure criteria. Unfortunately the experimental information regarding the failure process is limited to pin failure alone, that is, no information is available regarding how close an unfailed pin was to failure or how much the failure limit was exceeded for a failed pin. The problem is illustrated in Figure 3, where we have a number of paired observations (x_i, y_i), where x_i is the experimental failure index. For y_i, for example, it is known only whether it lays in the interval from zero to L or is greater than L.

As the exact size of the deviations, d_i, can not be defined, ordinary linear regression for estimation of the line l and thereby the failure limit is not possible. A lower bound for the deviations d_i can be defined as shown in the figure. All y_i values in area I and III are assumed to fall on l, and in area II and IV the y_i values are assumed to be equal to y_L.

For this definition of the deviations it is possible to minimize the sum of the squares, $\Sigma(di)^2$. The problem has the trivial solution $y_i=y_L$ for all x. If l is assumed to go through the origin the problem has a non-trivial solution. The sum of the squares must be minimized numerically. When the value of x_L that minimizes the sum of squares is found, a measure of the degree of linear correlation between y" and x can be expressed by the coefficient of correlation between them, where y" is defined as $y_i''=x_i+d_i$. This correlation coefficient expresses an upper limit for the correlation between the calculated and the experimental failure indices.

In table 1 the values of x_L are shown as well as the lower bound for the standard deviation of x_L, and the correlation coefficient based on the experiments descreibed in Chap. 3. These results clearly indicate that neither creep rupture, overstrain, or overstress can explain the failures unless a stronger stress concentration than used in FFRS were present, or the in-reactor failure limits are below the out-of-reactor limits. If the estimated failure limit is used, all parameters except creep rupture seem to correlate the failures satisfactorily.

6. Parameter Estimation

The failure probabilies for creep rupture, overstrain, and overstress are calculated directly from the mechanical behaviour of the fuel pins and do not involve any parameters apart from the failure limit. The failure criterion for stress corrosion, on the other hand, involves a number of parameters which, for a given mechanical and thermal time history, can influence the failure probability. Also the overpower failure criterion depends on its own set of parameters. The optimal sets of these parameters for the considered ramp experiments are found by regression analysis.

6.1 Stress Corrosion

The time-to-failure for stress corrosion, Eq. (1), contains the three independent parameters, P_o, θ_{Fc} and σ_N.

The optimal parameter set is that which minimizes the sum-of-squared deviations as defined in Chap. 5. The lack of knowledge of the y_i values can again lead to a trivial solution; if the damage, x_i, approaches zero for all x_is, the sum-of-squares also approaches zero. This undesired minimum can be avoided if the failure limit were defined to be a fixed value, for example, $x_L=y_L=1.0$. The parameter set minimizing the sum-of-squared deviations is then found iteratively from the set $(\sigma_N, \theta_{FC}, P_o) = (400 MP_a, 40^{\circ}C, 0.1 MPa)$. The result is shown in Table 2.

In order to investigate whether or not all the parameters in the expression for stress corrosion are significant for this set of experiments, the minima were also sought. The time-to-failure equation modified by exclusion of respectively f_1 and f_2 yields results which are listed in Table 2.

The model for fission gas release in FFRS is a steady-state model with no time delay in the release. The influence of a delay in the release was investigated assuming that the release was exponential in time with a half release period of 24 hours. The influence of this change is also shown in Table 2. This change did improve the prediction of fission gas significant, but the influence on the failure prediction is small.

The results in Table 2 show that the dominating factor in Eq. 1 is f_2 (σ_N). Both f_1 and f_3 can be excluded without significant influence for these ramp experiments. This is not surprising since Table 1 shows that the stress alone yields an excellent correlation for the failures in these ramp experiments.

6.2 Overpower

The overpower depends on the three parameters A_1, A_2 and A_3. The parameters are based only on the judgement of the author and therefore are in no way optimized. The optimal set of the parameters was sought as the set which minimizes the sum-of-squared deviations given $x_L=y_L=1.0$. This result is shown in Table 3.

Although the overpower failure criterion seems to yield an excellent correlation with the experiments, care should be shown when applying the criteria to power histories and designs different from those included in this investigation.

7. Examples Calculated by FFP

From the results of chapters 5 and 6 the expression is obtained that the stress corrosion, the overstrain, the overstress, and the overpower failure criteria are almost equivalent. This is valid only for conditions like those in the ramp experiments. If the results from the ramp experiments are extrapolated it is very important that the failure criteria be based on the correct physical mechanism. That there can be large differences among the predictions based on the different failure criteria as is illustrated by a few examples.

The failure probability is evaluated for the power history shown in Figure 5 with Δt = 1 hour, 1 day, and 1 week. The ramp rate for the 3 ramps is 50 w/cm/min. The design is chosen as the interramp rod nr. 1 [6].

The second example is a short overpower after a long steady power period. The power history is shown in Figure 5. The failure probability is evaluated for the time at the overpower equal to 1 min, 1 hour, and 1 day. The ramp rate in the overpower is 400 w/cm/min.

The failure index, as calculated by FRP, and the failure probability using the limits of Chapter 5 are shown i Table 4.

8. Conclusion

The "best estimate" failure limits for a number of failure criteria have been calculated by regression analysis of a large number of ramp experiments. Only for the stress corrosion failure criteria the estimated failure limit was close to the limit found in out-of-reactor tests. All the failure criteria, except creep rupture, provide reasonable correlation of the experiments if the "best estimate" failure limits are used. In general the failure criteria can give considerable differences in the failure predictions, this is demonstrated by examples.

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Table 1. Results of the regression analysis of 39 ramp experiments

	X_L out-of-reactor	X_L in-reactor	ρ coefficient of Correlation	ρ^2
Stress corrosion	(225,18)MPa	(220,38)MPa	0.86	.76
Creep rupture	(2.5,0.5)%	(0.32,0.08)%	0.65	.42
Overstrain	(0.21,0.04)%	(0.1,0.02)%	0.94	.88
Overstress	(500,25)MPa	(234,20)MPa	0.95	.90
Overpower	-	(161,27)w/cm	0.89	.79

Tabel 2. Minimum parameter sets of the stress corrosion failure criterion.

	σ_H MPa	θ_{FC} °C	P_o MPa	limit $\sigma_{SC,L}$ Mpa	ρ
Initial set	400	40	0.1	220	.86
minimum set	583	65	122	145	.97
minimum set excluding f_1	1400	125	-	213	.97
minimum set excluding f_3	850	-	15	193	.96
dealyed release	522	37	26	132	.97

Tabel 3. Minimum parameter set for the overpower failure criterion.

	Parameter set			limit		
	f_1	f_2	f_3	P_L w/cm	$\Sigma\left(\frac{d_i}{\gamma_L}\right)^2$	coefficient of correlation
initial value	5.37×10^6	5.18×10^3	7.3×10^8	161	281×10^6	0.894
minimum set	7.92×10^6	88.2	10.8×10^8	174	206×10^6	0.924

Table 4. Failure index and failure probability for the examples.

	Δt	σ_{SC} MPa	$P(\sigma_{SC}\geq\sigma_{SC,L})$	ε_C %	$P(\varepsilon_C\geq\varepsilon_{CR})$	$\varepsilon_{pl}+\varepsilon_{pr}$ %	$P(\varepsilon_{pl}+\varepsilon_{pr}\geq\varepsilon_a)$	σ MPa	$P(\sigma\geq\sigma_u)$	δ w/cm	$P(\delta\geq\delta_L)$
Eksempel 1	1 hour	273	.92	0.52	.993	0.11	.69	242	0.66	197	0.91
	1 day	254	.81	0.50	.988	0.09	0.31	226	0.34	145	.28
	1 week	154	0.04	0.45	.95	0.03	0.001	143	>>0.001	58	>>0.001
Eksempel 2	1 min	122	0.004	0.42	.89	0.08	.16	250	0.79	200	.93
	1 hour	211	0.41	0.44	.93	0.10	.50	243	.67	200	.93
	1 day	272	.91	0.45	.95	0.11	.69	243	.67	200	.93

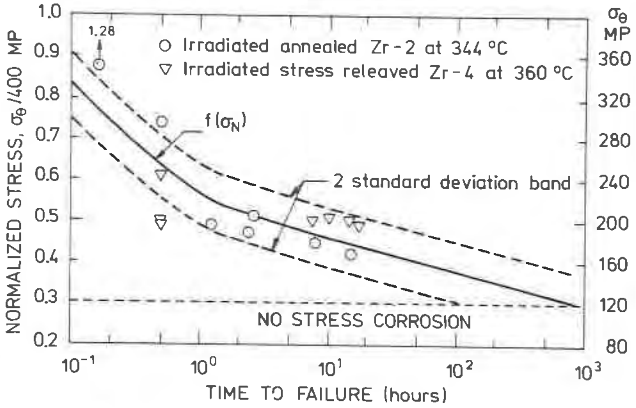

Figure 1. Time-to-failure for irradiated zircaloy in iodine vapour.

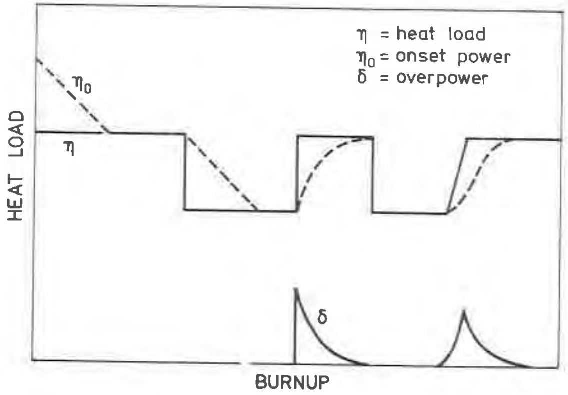

Figure 2. Illustration of the overpower model

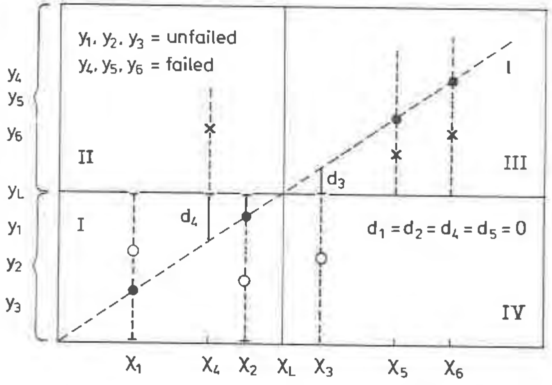

Figure 3. Definition of the minimum deviations from the regression line, l.

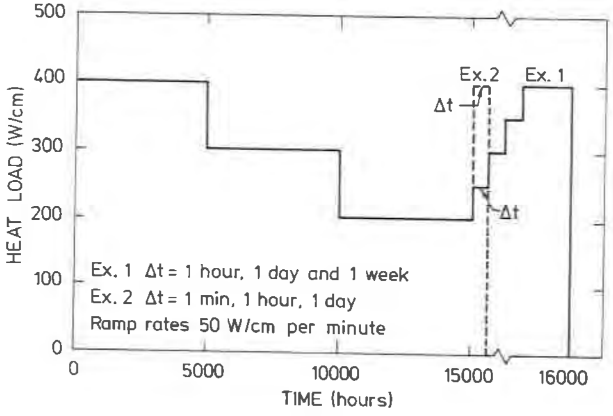

Figure 4. Power history for the examples.