WAFER-3. AN EXTENDED VERSION FOR HIGH-SPEED ANALYSIS OF RODS WITH AN AXIAL POWER PROFILE

N. KJAER-PEDERSEN

Risø National Laboratory, Department Metallurgy, DK-4000 Roskilde, Denmark

Summary

WAFER-3 is the latest reference version of the Danish LWR fuel performance code WAFER which has previously been described in the literature. Relative to previous versions, WAFER-3 features the following new capabilities:
(i) Axial power shape. The axial heat-load variation along the rod may be specified in up to 20 nodes, relative to the heat load at a selected reference node. A complete thermo-mechanical calculation is carried out at the reference node throughout the specified power history. At each of the other axial nodes a revised temperature profile is derived from that of the reference node, on the assumption that the center-to-surface temperature drop of the rod is proportional to the local heat-load. This revised temperature profile is used in a detailed fission-gas release calculation for each individual node. The total gas release from all the nodes is assumed to be evenly mixed in the fuel-cladding gap volume, and from there, with a user-defined time-delay, released to the end plenum. The gas composition in the gap feeds back iteratively into the gap conductance calculation at the reference node.

The fuel cladding gap, if present, varies with the local heat-load. On the assumption that the contribution to gap closure from pellet expansion is proportional to the local heat-rating, the code defines the axial node(s) at which the fuel stack goes into locking contact with the cladding tube, so as to initiate axial force interaction.
(ii) Interaction threshold. WAFER-3 defines, by an iterative approach, the exact heat load (at the reference node) that causes incipient axial interaction due to gap closure anywhere in the system.
(iii) Improved pellet cracking model. The pellet cracking model has been augmented to implicitly reflect the number of cracks, radial as well as transversal, formed throughout the pellet. In previous versions, the stress normal to a crack face (equal to minus the plenum pressure) was taken as the typical principal stress in the one-dimensional stress-strain analysis, whereever cracks were encountered. Thus, infinitely many cracks were essentially simulated. In WAFER-3, the user may specify the typical principal stress normal to cracks to lie anywhere in between minus the plenum pressure and the fracture stress. This feature recognizes stress build-up between cracks, and thus the fact that the number of cracks is finite. When properly used, it provides more realistic mechanical response (stiffness) of the multicracket pellet.
(iv) Ridge model accuracy. Through improved numerics, the energy-principle based ridge model now performs more accurately than before.
(v) Computing speed. The computing speed has been much increased through optimization of the coding. A typical case of a detailed, whole-life rod irradiation history may now be analyzed in about five minutes on a UNIVAC 1110 system, or equivalent.

With WAFER-3, the goal of providing an optimally designed, simplistic yet realistic, deterministic fuel performance code, capable of meeting the needs of the nuclear industry from a view-point of fuel operational efficiency has been further pursued, and largely accomplished.

*) Work performed under contract with Risoe National Laboratory, DK-4000 Roskilde, Denmark.

1. Introduction

WAFER-3 is a deterministic LWR fuel performance code. Like WAFER-1 and WAFER-2 [1,2,3], it is characterized by emphasizing localized clad strains at pellet-pellet interfaces for the purpose of predicting fuel failures.

WAFER-3 investigates an entire, full-size rod with a time-varying axial flux-distribution, throughout its life-time. This capability is especially useful in cases of a high axial form-factor under such operating conditions when fission-gas release from the fuel dominates the performance.

Previous versions offered a selection of temperature-dependent gas release models from the literature, with a time-delay for parametric study of transient gas release. WAFER-3 offers a new, first-principles release model,which inherently accounts for the influence of local temperature, local burn-up, columnar and equiaxed grain-growth, time-dependent diffusion, and resolution effects.

The fuel temperature calculation has been improved by introducing an empirical flux depression factor as a function of pellet radius and enrichment.

The point of onset of axial mechanical interaction is more accurately defined in WAFER-3 than in previous versions, through the application of a special iteration loop.

In the mechanical treatment of the cladding and the multi-cracked pellet, two improvements have been made. Firstly, the number of transversal and radial fuel cracks is no longer assumed to be infinite. The finite size of the fuel fragments is reflected in generalized assumptions on the average axial and hoop stresses across a fragment. Secondly, the calculational technique of the ridge model has been refined to suppress numerical scatter in the ridge heights. The basic mechanical sub-model has been optimized for maximum calculational speed.

Previous versions have provided a basis for predicting fuel failure, whereas the prediction per se was left to the user. WAFER-3 offers a set of fuel failure integrals, which are direct measured of the accumulated clad damage.

WAFER-3 has been excercised extensively on experiments from the Danish test reactor DR3, the OECD Halden Reactor Project, and on the entire Interramp Project [4]. It has demonstrated its capability to predict fuel central temperatures, fission gas release up to 40,000 MWd/tUO_2, clad creep-down and ridge formation with very good accuracy.

2. Recent Improvements

2.1. Axial Power Shape

In WAFER-3, the fuel pin may be divided in up to 20 axial segments of equal length. One of these segments is the reference segment, where the complete thermo-mechanical analysis is carried out. The power history is given by pairs of linear heat-rating and time-step length at the reference segment. Along with this, an axial shape-function may be specified at each time-step by defining the nodal heat-rating relative to that of the reference node.

The shape-function is used in two contexts:

(i) Thermally, for calculating nodal fission gas release, and

(ii) Mechanically, for defining the type of axial mechanical interaction at the reference node.

ad (i): The fission gas release model, to be described in section 2.2, is based on the radial temperature profile of the fuel and on grain-growth. Since temperature and grain-growth are calculated in detail only at the reference node, a temperature profile and a zone of "active columnar grains" (section 2.2) are determined for each axial node from the conditions at the reference node. The assumptions are that the total temperature drop over the fuel is proportional to heat-rating, and that the radius of the active columnar grains' zone follows the same isotherm in all nodes.

ad (ii): The axial interaction model assumes that the fuel goes into locking contact with the cladding when the local hot gap drops below an input limit. If locking contact occurs above and below the reference node, that node is in axial interaction, even if the gap is larger than the limit value at the reference node itself. Also, if the reference node is located between a point of locking contact and the rod bottom, it is in axial interaction. Further, if the reference node itself has a closed gap, it is in axial interaction. Fig. 1 A, B, C illustrates these concepts. The cross-hatched node is the reference node, L1 denotes lower contact node, L2 upper contact node. In all cases, the interactive axial force is calculated on the principle that the incremental average expansion of the locked pellet stack must equal that of the corresponding clad segment, after locking. The average expansion of the segments involved is determined from the shape-function. The local gap closure is determined from the hot gap at the reference node by assuming inverse proportionality between hot gap and heat rating. The approximations explained above are most efficient if the reference node is chosen within the hotter part of the rod.

2.2. The New Fission-Gas Release Model

Purely temperature-dependent fission-gas release models fail to predict the true gas release under realistic operating conditions. Time and burn-up are important parameters. The USNRC has published an empirical correction term [5] for use with any temperature-dependent model whenever the burn-up exceeds 20,000 MWd/tU. Experience with this correction term, however, indicates the necessity of using a more refined model, if realistic predictions are desired.

The following principles are used in the present model:

(i) When the fission gas concentration in a fuel grain exceeds the "barrier concentration" in a certain "surface layer" of the grain, as well as the gas concentration in the plenum (corrected for the temperature difference), diffusional release may occur.

(ii) The "barrier concentration" is due to the resolution effect induced by fission fragments traversing the grain boundaries and, hence, depends on fission density as well as temperature (through the diffusion coefficient). It

has been evaluated by Speight [6].

(iii) Diffusional release is described in sufficient detail by assuming an exponential approach to equilibrium with a time-constant that varies inversely with the diffusion coefficient. The diffusion coefficient may, according to Collins, et al. [7], be expressed as a function of temperature by a dual exponential.

(iv) Gas release may also result from grain boundary sweeping. All gas in the fuel matrix is swept up (i.e. released), as a grain boundary moves across it. Hence, equiaxed grain-growth results in the instantaneous release fraction of $(V-V_o)/V$, where V is grain volume after growth, V_o before growth.

(v) Instantaneous gas release results from columnar grain-growth. The radius of the columnar grains zone is a function of temperature and time. If the heat-rating is reduced after the formation of columnar grains, the "cool" columnar grains are no longer active, i.e. they may resume accumulation of fission-gas. Thus, the radius of the active columnar grains zone, within which no fission-gas may be retained, is important, and is calculated throughout.

Fig. 2 illustrates the "burn-up threshold", at which the concentration in the grain equals that of the surface layer, as a function of temperature for various fission densities. For instance, at 10 W/g and 1200°C, it takes 5000 MWd/tUO_2 to saturate the grains. After that burn-up, all extra gas generated is released by diffusion. Fig. 3 shows the diffusional release time-constant as a function of temperature, relative to the value at 1000°C, T_{1000}. At 1200°C the release time is one fifth of T_{1000}. If T_{1000} is a thousand hours, the potential release at 1200°C will require 200 hours to materialize, and a transient temperature peak may be passed without release.

The new release model accounts for the release from each of a number of concentric fuel rings in each axial node. The total release, therefore, strongly reflects local burn-up as well as transient variation of heat-rating.

The release barrier due to the resolution effect is very sensitive to a number of experimental constants [6,7]. A tuning factor is therefore made available through the input for the adjustment of this critical function to experiment. Further, T_{1000} is adjustable through the input.

2.3. Interaction Threshold

Incipient axial interaction is governed by the local hot gap becoming lower than a limit value (section 2.1). Since the power history of the rod is input by discrete time-steps, WAFER-3 uses a special subdivision of the time-step in addition to the subdivision based on creep criteria, for the purpose of accurate determination of the interaction threshold.

Thus, a more accurate axial force determination and, hence, a more accurate ridge calculation is achieved.

2.4. The Pellet Cracking Pattern

In WAFER-3, the pellet is conceived as a pile of disc elements, all treated identically by means of a one-dimensional model. Since the fuel can-

not support stresses beyond the fracture stress, cracks are introduced where necessary. The stress perpendicular to a crack surface equals minus the plenum pressure. For infinitely thin fragments, this stress is valid also between cracks. However, for finite fragments, the stress may build up as high as the fracture stress. WAFER-3 allows the user to specify the mid-fragment stress to reach a weighted average of minus the plenum pressure and the fracture stress, the weight factors being specified independently for radial and transversal cracks.

2.5. The Ridge Model

The principles of the ridge model have previously been published [2]. Some improvements, however, have been achieved by refining the numerical techniques. Hence, the ridge model now performs considerably more smoothly and accurately than before.

2.6. Computing Speed

The basic mechanical models of the fuel and of the clad are now so well established that it has been considered worth-while to invest a major effort in optimizing the coding. Thus, a factor of two has been gained in computing speed.

2.7. Failure Integrals

The mechanism of fuel rod failure, i.e. loss of integrity of the cladding, is not quantitatively understood. However, a stress corrosion mechanism is probably responsible for most failures in present-day fuel.

Stress-corrosion cracking comes about only if sufficient stress, strain, time and fission product concentration are available. WAFER-3 does not deal with details of the failure mechanism. It provides, however, a number of "failure integrals" as guidelines for determining whether or not the analytical predictions of stresses, strains and gas release versus time indicate failure.

Four types of failure integral are considered:

$$\text{(i)}\ \int_o^t \sigma_\theta\, d\varepsilon_{p\theta},\quad \text{(ii)}\ \int_o^t \sigma_\theta\, F\, d\varepsilon_{p\theta},\quad \text{(iii)}\ \int_o^t \sigma_\theta\, \Delta F_r d\varepsilon_{p\theta},\quad \text{(iv)}\ \int_o^t \sigma_\theta\, \Delta F_f d\varepsilon_{p\theta}$$

where σ_θ is the cladding hoop stress, $\varepsilon_{p\theta}$ the cladding permanent hoop strain, F the total concentration of released gas in the plenum, ΔF_r the concentration of gas released within the last 300 hours, and ΔF_f the concentration of released gas generated within the last 300 hours.

The time enters these integrals implicity through the strain-rate. Creep strain and yield strain are considered on an equal basis. The integrals are monotonous functions, since they are updated only when all the composing factors are positive. Thus, the failure integrals are measures (in arbitrary units) of the accumulated strain-hardening work deposited locally in the clad under tensile conditions, weighted with the various categories of gas concentration.

Indications as to which failure integral is the most relevant and what

the failure threshold would be, are to be derived from experience with the code.

The code calculates the value of each of the four failure integrals at the mid-pellet and at the pellet-pellet interface positions at each individual time-step.

3. Verification

3.1. General

The WAFER code, in various versions, has been excercised on the many experiments mentioned in chapter 1.

The present version, WAFER-3, has been used to analyse the entire Inter-ramp program, a dozen Halden experiments and a similar number of DR3 experiments. The experience with the code may be described with respect to several categories of comparison:

(i) First approach to power temperature predictions: Excellent agreement.

(ii) Long-term, high-rating irradiation fission gas release and grain-growth predictions: Excellent agreement.

(iii) Long-term, lower rating irradiation fission-gas release and grain-growth predictions: Generally good agreement. For the Inter-ramp program the calculated volume of released gas matches experiment generally within 20%.

(iv) Short-term in-pile ridge strain predictions: Normally, ridge heights are predicted about 50% too high.

(v) Permanent ridge strain after long term irradiation: The results of the comparisons are much varying, since the predictions depend critically on permanent local strains received over a long period, involving many sources of uncertainty.

(vi) Interaction threshold: This quantity has been studied especially in the Inter-ramp program. Very good consistency between power shocks relative to the calculated interaction threshold and measured times to failure was obtained.

(vii) Failure integrals: From the Inter-ramp program it seems that a failure integral of type (iii) or (iv) (section 2.7) is most adequate for failure prediction, and can indeed correlate the analytical predictions with the major part of the failures observed.

3.2. Sample Case

A sample case from the Inter-ramp program (case LR4 [8]) has been selected to illustrate the performance of WAFER-3.

This short test fuel pin of BWR design was irradiated through alternate periods of high and low heat rating and with a fairly flat axial profile up to about 10,000 MWd/tUO_2. The rod was then removed from the reactor for pre-ramp inspection. Then, the rod was reconditioned in the reactor for 24 hours at 353 W/cm and ramped at a rate of 40 W/cm/min. to the terminal level of 654 W/cm. After 0.008 hours at ramp terminal level the rod failed. After another 0.075 hours it was removed from the rig. Post-ramp profilometry revealed a permanent ridge-height of 27 microns (± 5 microns), radial measure.

The entire power history was simulated in detail by means of WAFER-3.

After the pre-ramp irradiation the calculated hot gap had vanished. The major results from the simulation of the conditioning and ramp irradiations are presented in fig. 4.

On raising the power from zero to the conditioning level, axial interaction started at 240 W/cm, resulting in some elastic ridge formation. During conditioning, the total ridge height decreased, while the permanent ridge height increased, and the ridge-top over-stress (hoop stress at ridge-top minus hoop stress at mid-pellet) vanished. The reason for this is creep relaxation. On entering the ramp, a steep increase in elastic ridge height and ridge-top over-stress with heat-rating occurs, gradually followed by an increase in permanent ridge height, and a corresponding stagnation of ridge-top over-stress. At a certain point the permanent ridge starts to increase very fast without a similar increase in total ridge-height, while the ridge-top over-stress is drastically reduced and quickly vanishes. This development is due to the generalized stress in the cladding approaching the yield point, which also leads to a saturation contact pressure. After onset of yielding the ridge remains entirely permanent. However, the continuing expansion of the cladding due to the continuing power increase leads to a gradual elimination of the permanent ridge ("ironing effect"). Shortly before the power peak, this decrease is halted. At the same time significant plastic flow of the fuel central region (which reaches temperatures in excess of 2000°C) occurs. Obviously, the fuel softness relieves the push on the cladding, so that the contact pressure (still near saturation) moves the fuel inwards rather than the clad outwards. After the ramp terminal level has been reached, the contact pressure relaxes and the permanent ridge height remains constant through the hold-time, giving a post-experiment, calculated, permanent ridge height of 29 microns, as compared with the measured value of 27 microns.

Rod LR4 is the Inter-ramp rod that received the highest ramp, and, as indicated, it failed almost promptly. Because of this severe ramping the case is well suited for illustrating some typical phases of mechanical behaviour, and their simulation by WAFER-3.

4. Conclusion

WAFER-3 enables the simulation of full-length LWR rods through their entire life-time, taking account of a wide range of thermal and mechanical phenomena in the fuel-clad structure under typical in-pile load conditions.

The detailed, first-principles gas release model, which takes account of a varying axial power shape, provides a solid basis for the thermo-mechanical analysis of the reference node. The calculated peak local strains in the cladding, combined with the transient gas release analysis, enable the calculation of failure integrals that are true, though arbitrary, measures of the accumulated stress corrosion impact.

By virtue of the above features, WAFER-3 provides an economic tool for detailed and realistic thermo-mechanical fuel pin performance studies, aiming directly at the design of long-life, fail-safe fuel.

5. References

1. N. Kjaer-Pedersen: "Mathematical Description of WAFER-1, A Three-Dimensional Code for LWR Fuel Performance Analysis", Nuc. Eng. and Des. 35 (1975), 387-398.
2. N. Kjaer-Pedersen: "A New Version of the LWR Fuel Performance Model WAFER", 4th International Conference on Structural Mechanics in Reactor Technology, San Francisco, USA, 15-19 August 1977. Paper no. D 1/3 .
3. N. Kjaer-Pedersen: "WAFER-2. A Code for Thermal and Mechanical LWR Fuel Performance Modelling", Paper to the IAEA Specialists Meeting on Fuel Element Performance Computer Modelling, Blackpool, UK, 13-17 March 1978.
4. G. Thomas: "The Studsvik Inter-ramp Project, An International Power Ramp Experimental Program". Meeting on Ramping and Load Follow Behaviour of Reactor Fuel, Petten, Netherlands, Nov. 30-Dec. 1, 1978.
5. R.O. Meyer, et al.: "Fission Gas Release from Fuel at High Burn-up", NUREG-0418.
6. M.W. Speight: "A Calculation on the Migration of Fission Gas in Materials Exhibiting Precipitation and Re-solution of Gas Atoms under Irradiation", Nuc.Sci. and Eng. 37 (1969), No. 2, 180-185.
7. D.A. Collins, et al.: "A Quantitative Model for Fission Gas Release and Swelling in Irradiated Uranium Dioxide", J. of Br. Nucl. En.Soc. 15 (1976), No. 4, 311-318.
8. The Inter-ramp Project Committee. With Permission.

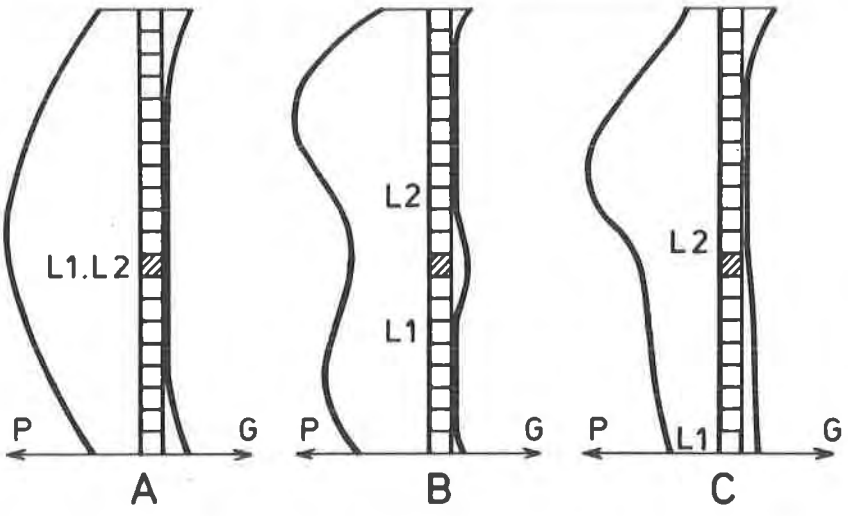

Fig. 1. Axial Mechanical Interaction.
Three Cases of Pellet Stack Locking.

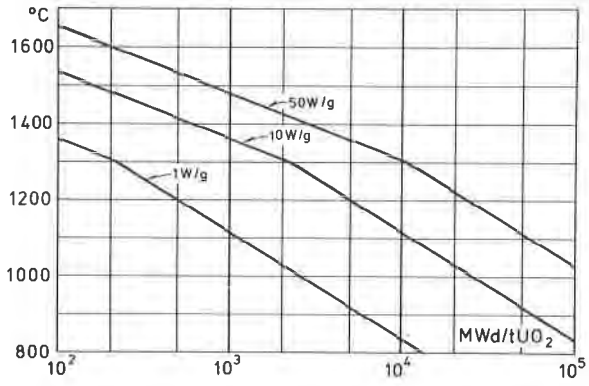

Fig. 2. Burn-up Threshold for Fission Gas Release at Three Power Densities.

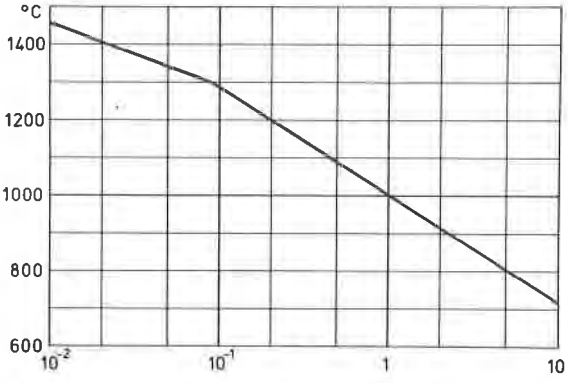

Fig. 3. Fission Gas Release Time relative to Time at 1000°C.

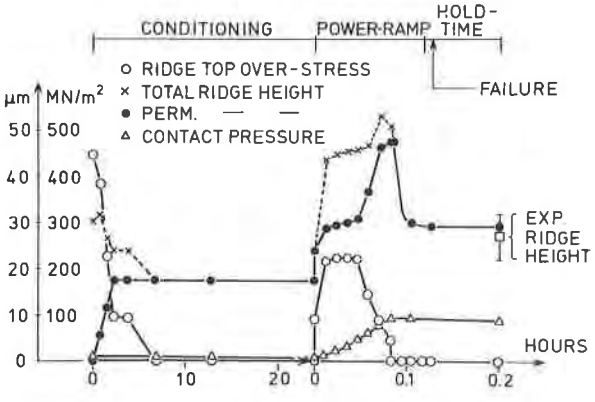

Fig. 4. WAFER-3 Analysis of Inter-ramp Case LR4.