Comparison of Integral and Local Gas Release Results with the Predictions of the Uranus Code

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ABSTRACT

Base irradiation of the assembly IFA-148 and transient tests carried out by the 'Risoe Fission Gas Project' on single pins from this assembly are analysed using the URANUS code. The predicted gas release under normal operating conditions (base irradiation) and after an increase in power at the end of life (bump test) is compared with the experimental data obtained by puncturing the fuel pin or by non-destructive plenum spectrometry and by electron probe microanalysis which gives local gas retention data from which release levels may be deduced. Fair agreement exists between the experimental data and the theoretical results.

1. INTRODUCTION

Current interest in raising the burn-up at which LWR fuel is discharged from the reactor is motivated by a desire to improve fuel utilization and a need to decrease the quantity of spent fuel stored and reprocessed. One of the most important factors influencing the performance of a water reactor fuel is fission gas release which increases the gas pressure in the fuel rods and the temperature of the fuel. The present work compares predictions of the URANUS code /1/ with experimental data.

2. TEST ASSEMBLY AND IRRADIATION HISTORY

The test assembly IFA-148 which consisted of 12 pins was irradiated in the OECD Halden reactor in Norway. The assembly was discharged at an average burn-up of 31500 MWD/tU. After the base irradiation the International Risoe Fission Gas Project /2/ carried out transient tests on single pins in the Danish test reactor DR3 at Risoe and provided experimental data on integral fission gas release; local gas retention data were produced by the European Institute for Transuranium Elements, Karlsruhe. Pin design data are given in Ref. 2, the pellets were 5 % enriched and double-dished, the Zircaloy cladding was cold-worked and stress relieved. All fuel stacks included a 13 mm long pellet of natural uranium at each end. The internal void volume was approximately 10 cm**3 and the fill gas was helium at approximately 0.1 MPa.

The comprehensive power history of one rod which even takes control rod movements into account is shown in Fig. 11. An uncertainty of the power of approximately ±5 % is assumed which is of importance since the low helium inventory leads to a sensitive thermal feedback of gas release on fuel temperatures (see below). Two pins from the upper (F9–3 and M1–3), and two pins from the lower cluster of the assembly (F14–6 and G3–2) were selected for detailed theoretical analyses. Pin M1–3 was a reference pin and was not bump tested. The integral fuel rods were analysed by dividing them into 10 axial sections.

1 The detailed power histories have been evaluated by I. Misfeldt at the Risoe National Laboratory
3. THEORETICAL DESCRIPTION

3.1 The Temperature Calculation

Accounting for pellet fragment relocation and its influence on gap conductance is the most crucial part of the fuel temperature calculation. The solution of the nonlinear heat conductance equation itself can be obtained by standard techniques using measures to accelerate convergence. Three different relocation models are optional in the URANUS code:

1. the model of Brzoska et al. /3/,
2. the operational-relocation model of Eberle and Stackmann /4/ and
3. the simplified URANUS model, which has been developed from LFMBR applications using the more complicated URANUS crack model.

All three models have been compared by predicting measured centreline temperatures from several Halden experiments. Fair agreement between the experimental data and the predictions of all three models was found (see Fig.2). In the present investigation the model of Brzoska et al. was used in its original form:

\[
\Delta R = 0.45 \times \Delta s
\]

with

\[
\Delta R = \text{increase of pellet radius due to pellet relocation}
\]

\[
\Delta s = \text{gap width}
\]

The URANUS gap conductance model has been extensively verified and needs no further explanation here. Standard values were taken for the thermal conductivity.

3.2 Gas Release

An earlier investigation /5/ showed that the standard empirical models such as the Beyer-Hann model significantly underpredict gas release during a power transient. Consequently, URGAS /6/ was developed which can accommodate transient conditions much better. The basic equation assumes that all complicated physical processes leading to gas release can be described by a diffusion algorithm using an effective burn-up dependent diffusion coefficient. This approach is also used in the ANS-5.4 model but in URGAS the mathematical treatment differs significantly with the result that storage requirements and computational costs are greatly reduced.

3.3 Radial Burn-up Profile

Recently, the RADAR model of Palmer et al. /7/ which calculates the radial power profile in a fuel pin has been incorporated into the URANUS code² . Fig. 3 shows that there is good agreement between the prediction and the measured data. The relative burn-up profile was derived from the radial distribution of fission product neodymium which was determined with the electron microprobe. The profile exhibits a sharp fall in the region between the fuel surface and \( r/r_0 = 0.9 \) due to resonance absorption of neutrons creating plutonium, but then remains reasonably flat.

4. ELECTRON PROBE MICROANALYSIS

Electron probe microanalyses were performed on the following sections:

² The kind assistance of I. D. Palmer, British Nuclear Fuels plc is gratefully acknowledged.
pin M1-3 (unbumped) : section 11
pin F9-3 (bumped) : sections 44, 48, 82
pin G3-2 (bumped) : section 10
pin F14-6 (bumped) : sections 44, 56

The concentration of xenon dissolved in the fuel lattice and contained in intragranular gas bubbles smaller than 0.4 μm was measured by electron probe microanalysis /8/. Little, if any, of the gas contained in intergranular bubbles contributed to the measured X-ray intensity.

In the region of the fuel between r/r₀ = 0.6 and the fuel centre an appreciable fraction of the retained xenon is contained in bubbles and the intensity of X-ray emission is highly dependent on their size and distribution. Generally, the larger and more dispersed the bubbles the lower is the emitted X-ray intensity.

The radial concentration profiles for the pin sections F9-3-44, F9-3-48 and G3-2-10 were corrected for the effect of bubble size and bubble distribution using the model of Ronchi and Walker /9/. This model considers the probability of an electron-gas bubble interaction, the depth distribution of X-ray production and the effects of gas density on X-ray production. For the purpose of carrying out the correction, the local size distribution of the gas bubbles was established at intervals along the fuel radius using replica and transmission electron microscopy.

Gas bubbles larger than 300Å were not observed in the fuel of the unbumped pin section M1-3-11, consequently it was not necessary to correct the measured concentration profile for this specimen. The xenon concentration profiles for the remaining sections have also not been corrected. For these sections, it is expected that after correction the averaged experimental release values will be smaller by about 10% relative.

At a significance level of 99% , the confidence interval on the measured xenon concentrations varies from about 5% relative near the fuel periphery to about 20% relative in the vicinity of the fuel centre.

5. RESULTS

As mentioned earlier, 4 of the 12 pins irradiated in the test assembly IFA-148 were selected for the present investigation. The analyses of the base irradiation (all 4 pins) and the analysis of the subsequent bump tests (pins F9-3, G3-2 and F14-6) give numerous results which cannot all be presented here. Fig. 4 shows, as an example, the temperature history of the unbumped pin section M1-3-11. At the beginning of irradiation the centreline temperature follows the power history, whereas from the middle of the irradiation the feedback of gas release on temperature leads to a higher temperature than would be expected from the power. The other pins investigated have similar temperature histories.

The integral gas release after the base irradiation of all 12 pins of the test assembly IFA-148 are shown in Fig. 5. It is difficult to judge whether minor differences in design or other differences between the pins account for the spread in the data. A statistical analysis gives a rather low correlation coefficient of 0.6 and a large standard deviation of 3.2% absolute. This spread in the data should be kept in mind when theoretical and experimental results are compared (Table 1).
Table 1: Comparison between predicted and measured integral gas release after the base irradiation

<table>
<thead>
<tr>
<th>Pin</th>
<th>URANUS-URGAS prediction</th>
<th>Experimental value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 -3</td>
<td>11.</td>
<td>8.8</td>
</tr>
<tr>
<td>F9 -3</td>
<td>5.6</td>
<td>7.3</td>
</tr>
<tr>
<td>G3 -2</td>
<td>2.0</td>
<td>3.8</td>
</tr>
<tr>
<td>F14-6</td>
<td>1.4</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Similar results were obtained in an earlier work /10/ in which the fuel performance code FRP was compared with an older URANUS version. However, both codes showed some shortcomings in predicting the results after the bump tests. Table 2 demonstrates that the predictions made with the URGAS model compare reasonably well with the experimental values.

Table 2: Characteristic data of the bump tests and integral gas release after the bump test.

<table>
<thead>
<tr>
<th>Pin</th>
<th>Bump terminal level (peak/average)</th>
<th>Hold time</th>
<th>Gas release after bump test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W/cm</td>
<td>h</td>
<td>URANUS-URGAS prediction</td>
</tr>
<tr>
<td>F9 -3</td>
<td>424 / 279</td>
<td>24</td>
<td>15.2</td>
</tr>
<tr>
<td>G3 -2</td>
<td>385 / 273</td>
<td>24</td>
<td>13.6</td>
</tr>
<tr>
<td>F14-6</td>
<td>415 / 30</td>
<td>72</td>
<td>27.3</td>
</tr>
</tbody>
</table>

Extensive gas release measurements have been performed along the axis of pin F9-3. Table 2 shows that the URANUS-URGAS predictions are lower than the experimental value by 13% relative. The same trend is found in the axial distribution (Fig. 6). Radial gas retention profiles are compared in Fig. 7 a-d. The experimental data have been normalized to the uncorrected averaged gas retention in the section, the URANUS results have been normalized to the calculated average. At the outer pellet surface gas release is low, consequently, the retention profile is proportional to the burn-up profile. The corresponding radial temperature profiles for the bumped sections at the end of the bump test are given in Fig. 8.

6. DISCUSSION

Three factors contribute to the difficulty in evaluating these experiments: an unsteady power during irradiation, an uncertainty in the rating and above all the low helium inventory which causes a sensitive thermal feedback of gas release on fuel temperature. In addition, the transient experiments were performed deliberately in a power range where gas release is very sensitive to bump terminal level and hold time. This sensitivity of gas release during a very similar bump test was demonstrated in Ref. /10/ by a statistical analysis. A variation of the bump terminal level of ±10% resulted in a scatter of 6 to 28% in gas release.

Taking these uncertainties into account the agreement between predicted and measured gas release is considered to be reasonably fair. In all cases where the integral release data agree, good agreement is also found for the local data. This indicates that the temperature dependence of the URGAS model is correct.
REFERENCES


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Fig. 2: Comparison between measured and predicted fuel centreline temperatures: Data are from helium filled rods in the same assembly during the first rise to power (1: relocation model of Brzoska et al. /3/; 2: model of Eberle and Stackmann /4/; 3: URANUS model)

Fig. 3: Relative burn-up profile for pfn section F9-3-44: Comparison between URANUS predictions and experimental data derived from the radial distribution of neodymium measured with the electron microprobe
**IFA 148 - M1-3**

**ALL SECTIONS**

![Graph of Linear Power vs. Time](image)

**Fig. 1:** Linear power as a function of time for fuel rod M1-3 from IFA-148

![Graph of Temperature vs. Time](image)

**Fig. 4:** URANUS prediction of the fuel centerline temperature for section M1-3-11
Fig. 5: Integral gas release of all 12 IFA-148 pins after the base irradiation.

Fig. 6: Comparison between measured and predicted local gas release in pin F9-3 as a function of the relative axial height.

Fig. 7: Comparison between the predicted local gas retention and experimental values.

Fig. 8: Radial temperature profiles at the end of bump.