PARTICIPATION IN THE IAEA COORDINATED RESEARCH PROJECT
FUMEX-III: FINAL REPORT OF AREVA NP

ADDITIONAL INFORMATION:

PROJECT
FUMEX-III

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## REVISIONS

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[1] F. Sontheimer, C. Garnier
Participation in the IAEA Coordinated Research Project FUMEX-II: Final report of Framatome ANP
AREVA NP Technical Report FS1-0003974 Rev. 1.0

International Fuel Performance Experience (IFPE) database
NEA/IAEA/OECD

Studsvik Report STIR-53

Studsvik Report STSR-32
1. INTRODUCTION

After the Co-ordinated Research Project (CRP) FUMEX-II [1], participants asked for a new exercise within an IAEA CRP. This CRP started in December 2008 in Vienna with the first Research Coordination Meeting (RCM). The CRP is titled “Improvement of Computer Codes Used for Fuel Behaviour Simulation FUMEX-III”.

The object of FUMEX-III were the improvement of fuel rod performance codes for modeling high burnup phenomena in modern fuel. This includes transient behavior, as well as mechanical interaction between pellet and cladding and, in progression to the FUMEX-II exercise, fission gas release during various conditions (steady state, load follow, transient).

AREVA NP agreed on participating in this exercise under the IAEA research agreement no. 15369 and expressed interest in the modeling of pellet-clad mechanical interactions as well as fission gas release under steady state and transient conditions. In this exercise AREVA NP used its new global fuel rod code GALILEO, which is still under development (formerly known under the project name COPERNIC3).

During a Consultants Meeting potential topics and a proposed selection of cases have been prepared, which were discussed during the 1st Research Coordination Meeting (RCM) in Vienna in December 2008. During the discussions a number of additional cases motivated by the participants have been identified. Finally, a case table has been agreed upon, which included several cases for the different topics. Most of the cases have been based on the International Fuel Performance Experiments (IFPE) database [2], but additional cases have been provided during the exercise (e.g., the AREVA idealized case: see chapter 3.1).
2. **THE FUEL ROD CODE GALILEO**

AREVA NP is currently developing a new global fuel rod code.

The main models in the context of FUMEX-III are the thermal models, the fission gas release model, the gaseous swelling model and the mechanical analysis models.

The GALILEO thermal models consist of the usual sub-models of gap conductance, gap closure, fuel thermal conductivity and radial power profile. The models were benchmarked with over 5000 fuel centerline temperature data.

For the fuel, the main points of development of the thermal models were an improved correlation for the burnup degradation of the conductivity and its high temperature dependence, the influence of the high burnup rim structure and modern radial power density distributions.

In the fission gas release (FGR) model, athermal and thermally activated processes are taken into account. It is a typical two-step diffusion model (Booth model), following the formalism of Turnbull for the diffusion coefficients and which in addition to the steady-state thermal release describes also transient effects. It takes into account grain boundary incubation and saturation and irradiation-induced resolution from the grain boundaries, which counteracts the diffusion flux and delays the onset of release. The transient model regards additional burst effects for relevant rapid power changes. Both FGR models have been calibrated with measurements of several hundred fuel rods from commercial and research reactors.

The gaseous swelling model is complex and includes, among other factors, the generation, coalescence and interconnection of gas bubbles and their impact on creep and deformation.

Gaseous swelling and FGR are closely linked. In the model, there is no gaseous swelling below the temperature threshold for FGR. During transients, gaseous swelling increases with the kinetics that follows the FGR.

For FGR modeling, new phenomena were introduced to describe the high burnup enhancement observed in AREVA's FGR data including the additional FGR from the rim structure (relatively small) and the more relevant additional FGR from the inner parts of the fuel pellet due to effects of exceeding Xe concentration limits in the fuel matrix at high burnups.

The mechanical analysis models include the radial discretization of the cladding and fuel, fuel-cladding axial interaction and accurate pellet and cladding material relationships. Pellet fragmentation is modeled with an empirical relocation model. Also, the thermal expansion of a fragment is modeled with a bulge of the fragment proportional to the pellet temperature gradient.

The clad creep model includes low and high stress relationships for Zy-4 cladding. Low stress creep is a function of both irradiation and temperature, while high stress creep is primarily a function of temperature. For Zy-2 a viscoplastic thermal and in parallel an irradiation creep law is applied for all stress regions.

The mechanical interaction between pellet and cladding is calculated in two planes: mid-pellet and at the pellet-pellet interface. This modeling accounts for the hourglass shape of the hot pellet and additional effects at the pellet-pellet interface (e.g. dish filling).

The code mechanical predictions were validated with several types of post-irradiation examination data, including fuel rod and fuel column growth, fuel density, cold fuel-clad gap measurements and fuel rod profilometries that were obtained after irradiation in power reactors and ramp tests.

For mechanical modeling, the main new points developed were fuel creep, dish filling and pellet cracking and improved correlations for cladding creep.

A special feature of the code is its restart capability, which is very useful for the analysis of the re-fabricated FUMEX-III cases. It allows the transition from a commercial reactor (pre-irradiation phase) to a research reactor with a change in fuel geometry (length, plena, thermocouple hole), fill gas and pressure, radial power profiles and also the coolant and neutron flux conditions.
3. RESULTS OF THE FUMEX-III CASES

3.1. AREVA IDEALIZED CASE FOR FUMEX-III

AREVA has been asked to provide an idealized case for normal operation FGR. This has been done for FUMEX-II, too, but participants asked for a less demanding power history. The new idealized case is (as the case presented to FUMEX-II) based on real measurements of rods irradiated in a PWR. Manufacturing details are adapted to nominal values as well as stress-relieved Zr4 cladding (with high corrosion resistance). Details are given in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Details for the FUMEX-III AREVA idealized case</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel rod</strong></td>
</tr>
<tr>
<td>Length of active zone mm</td>
</tr>
<tr>
<td>Plenum volume cm³</td>
</tr>
<tr>
<td>Fill gas</td>
</tr>
<tr>
<td>Fill gas pressure MPa (absolute)</td>
</tr>
<tr>
<td>Flow area of rod mm²</td>
</tr>
<tr>
<td><strong>Cladding</strong></td>
</tr>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Inner diameter mm</td>
</tr>
<tr>
<td>Outer diameter mm</td>
</tr>
<tr>
<td><strong>Pellet</strong></td>
</tr>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Enrichment % U-235</td>
</tr>
<tr>
<td>Density % theoretical density</td>
</tr>
<tr>
<td>Grain size μm (mean linear intercept)</td>
</tr>
<tr>
<td>Diameter mm</td>
</tr>
<tr>
<td>Length mm</td>
</tr>
<tr>
<td>Chamfer height mm</td>
</tr>
<tr>
<td>Chamfer width mm</td>
</tr>
<tr>
<td>Dishing radius mm</td>
</tr>
<tr>
<td>Dishing depth mm</td>
</tr>
<tr>
<td>Dishing volume mm³ (both pellet sides)</td>
</tr>
</tbody>
</table>

The fuel rod averaged power history of the case is shown in Figure 1. Zero power indicates cycle changes (about one per year each) of the fuel rod. Despite reduced power in the second insertion cycle, the power history is decreasing with each insertion cycle from around 200 W/cm fuel rod average linear heat generation rate down to a little more than 150 W/cm.
Figure 1: Power history of the FUMEX-III AREVA idealized case

Figure 2 shows the calculated fission gas release from GALILEO and the expected fission gas release. The results show a very good agreement between calculated and expected values. The values are summarized in Table 2.

Figure 2: Fission gas release of the FUMEX-III AREVA idealized case
### Table 2: Fission gas release of the FUMEX-III AREVA idealized case

<table>
<thead>
<tr>
<th>End of cycle</th>
<th>Insertion time</th>
<th>Burnup</th>
<th>FGR expected</th>
<th>FGR calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>d</td>
<td>MWd/kg(HM)</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>3</td>
<td>916.4</td>
<td>36.6</td>
<td>0.5 $^{+0.5}_{-0.2}$</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>1239.1</td>
<td>49.7</td>
<td>1.9 $^{+1.0}_{-0.7}$</td>
<td>1.8</td>
</tr>
<tr>
<td>7</td>
<td>2141.9</td>
<td>81.5</td>
<td>9.0 $^{+2.5}_{-2.0}$</td>
<td>8.9</td>
</tr>
</tbody>
</table>
3.2. **US 16X16 PWR LEAD TEST ASSEMBLIES TSQ002 AND TSQ022**

From the US 16x16 PWR Lead Test Assembly program, the cases TSQ002 and TSQ022 have been chosen for FUMEX-III. These cases are full length fuel rods irradiated in a commercial 2 loop US PWR. Both cases have standard Zy4 cladding, but different pellet designs: TSQ002 were loaded with standard chamfered and dished pellets, while TSQ022 had a chamfered annular pellet design.

<table>
<thead>
<tr>
<th>Table 3: Details for US 16x16 PWR LTA cases TSQ002 and TSQ022</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel rod</strong></td>
</tr>
<tr>
<td>Length of active zone</td>
</tr>
<tr>
<td>Fill gas</td>
</tr>
<tr>
<td>Fill gas pressure</td>
</tr>
<tr>
<td>Fill gas volume</td>
</tr>
<tr>
<td>Initial free volume</td>
</tr>
<tr>
<td><strong>Cladding</strong></td>
</tr>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Inner diameter</td>
</tr>
<tr>
<td>Outer diameter</td>
</tr>
<tr>
<td><strong>Pellet</strong></td>
</tr>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Enrichment</td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Grain size</td>
</tr>
<tr>
<td>Outer diameter</td>
</tr>
<tr>
<td>Inner diameter</td>
</tr>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Dishing</td>
</tr>
</tbody>
</table>

Figure 3 shows the power history for the two cases. At the end of the insertion, zero power steps with PIE conditions (20°C and 0.1 MPa atmospheric pressure) had been applied for comparison of the fuel rod free volume.
Figure 3: Power histories of US 16x16 PWR LTA cases TSQ002 and TSQ022

Figure 4 shows the calculated free volume of both cases in comparison to the measured values. The calculated free volume of the fuel rods and the measured values matches quite well at PIE conditions. Please note, that the measured values during PIE are at cold conditions. The hot condition free volume is typically a little lower than the one at cold conditions. GALILEO is able to calculate the values at PIE conditions as well, so the sudden increase in free volume at beginning and end of irradiation is attributed to this conditional change.

Figure 4: Free volume of US 16x16 PWR LTA cases TSQ002 and TSQ022
The measured gas inventory of the rods shows a good agreement between measured and calculated values for both cases (see Figure 5 and Table 4) with a slight overestimation in the case of TSQ022. Both cases show a rather low fission gas release, which is mainly driven by athermal release.

![Graph showing free gas inventory over time for TSQ002 and TSQ022](image)

**Figure 5: Free gas inventory of the US 16x16 PWR LTA cases TSQ002 and TSQ022**

**Table 4: Free volume and fission gas release of US 16x16 PWR LTA cases TSQ002 and TSQ022**

<table>
<thead>
<tr>
<th>Time</th>
<th>Exp.</th>
<th>Free volume measured</th>
<th>Free volume calculated</th>
<th>Gas inventory measured (cm³ at STP)</th>
<th>Gas inventory calculated (cm³ at STP)</th>
<th>FGR measured (%)</th>
<th>FGR calculated (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>TSQ002</td>
<td>25.4</td>
<td>25.4</td>
<td>609.9</td>
<td>610.6</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>TSQ022</td>
<td>37.2</td>
<td>37.2</td>
<td>892.9</td>
<td>896.5</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>1641</td>
<td>TSQ002</td>
<td>17.8</td>
<td>18.3</td>
<td>644.4</td>
<td>640.6</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>TSQ022</td>
<td>31.0</td>
<td>30.3</td>
<td>915.9</td>
<td>932.1</td>
<td>0.8</td>
<td>1.2</td>
</tr>
</tbody>
</table>

*) Calculated from differences in gas inventory, produced fission gas (burnup) and estimated fuel mass.
3.3. IFA 409 AND IFA 535.5 ROD 809

In the frame of FUMEX-III the Halden experiment IFA 535.5 rod 809 has been chosen for transient fission gas release calculations. The original purpose of this experiment was to investigate the performance of high burnup fuel.

The experiment was irradiated in two phases. A rodlet of 466 mm active length has been base irradiated in the Halden HBWR in IFA 409. After this base irradiation, an additional end cap has been mounted on the rodlet and a magnetic driven drill used to puncture the rod. A pressure transducer has been installed in the new end cap for online monitoring of the pressure in the rod. With the new end cap, the free volume of the rodlet increased, while the end cap has been evacuated before mounting, i.e. the gas composition of the rodlet has been maintained. After the instrumentation of the rodlet, a ramp and subsequent high power has been applied in IFA 535.5.

Details for fuel rod design are summarized in Table 5. This case has been modeled with a refabrication step to include the additional plenum volume (end plug volume) from the instrumentation. The upper plenum volume of the rod is calculated by the difference of the measured total free volume and the free volume in the active zone. The additional volume due to instrumentation is added in the refabrication step to the upper plenum volume by matching the calculated total free volume at the end of the base irradiation plus the additional end plug volume and keeping the total amount and composition of gas in the fuel rod constant.

Table 5: Details for IFA 409 and IFA 535.5 rod 809

<table>
<thead>
<tr>
<th>Fuel rod</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of active zone</td>
<td>mm</td>
<td>466.0</td>
</tr>
<tr>
<td>Rod free volume (IFA 409)</td>
<td>cm³</td>
<td>9.8</td>
</tr>
<tr>
<td>Additional volume instrumentation (IFA 535.5)</td>
<td>cm³</td>
<td>8.9</td>
</tr>
<tr>
<td>Fill gas</td>
<td></td>
<td>He</td>
</tr>
<tr>
<td>Initial fill gas pressure (IFA 409)</td>
<td>MPa (absolute)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cladding</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>ZY2</td>
<td></td>
</tr>
<tr>
<td>Inner liner (Nb foil)</td>
<td>µm</td>
<td>13</td>
</tr>
<tr>
<td>Inner diameter (incl. Nb foil)</td>
<td>mm</td>
<td>10.81</td>
</tr>
<tr>
<td>Thickness</td>
<td>mm</td>
<td>0.86 (nominal)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pellet</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td></td>
<td>UO₂</td>
</tr>
<tr>
<td>Type</td>
<td>solid, flat end</td>
<td></td>
</tr>
<tr>
<td>Enrichment</td>
<td>% U-235</td>
<td>9.88</td>
</tr>
<tr>
<td>Density</td>
<td>% theoretical density</td>
<td>94.7</td>
</tr>
<tr>
<td>Diameter</td>
<td>mm</td>
<td>10.54</td>
</tr>
<tr>
<td>Length</td>
<td>mm</td>
<td>10.4</td>
</tr>
</tbody>
</table>
The operational and thermal-hydraulic data of the base irradiation corresponds to the normal HBWR conditions (IFA 409). During the ramp irradiation, BWR conditions had been applied (IFA 535.5).

The overall power history of this experiment is shown in Figure 6. The ramp irradiation of IFA 535.5 is shown in Figure 7 in detail. The high power increase from the base irradiation to the ramp terminal level can be seen. PIE results have been compared at cold conditions (20°C, 0.1 MPa atmospheric pressure) at the beginning and end of the ramp irradiation.
Figure 8: Fuel rod free volume of IFA 409 and IFA 535.5 rod 809

Figure 9: Fuel rod free volume of IFA 535.5 rod 809

The calculated total free volume of the rod is shown in Figure 8 and IFA 535.5 ramp irradiation in Figure 9. A very good accordance between measured and calculated end of life value has been observed (see Table 6).
Figure 10 shows the fuel rod inner pressure development as it is calculated during base and ramp irradiation (IFA 409 and IFA 535.5). Two pressure increases during the base irradiation at around 33500 and 36500 h of insertion can be identified. Both are related to an increase in fission gas release as can be seen in Figure 12. Here, the fission gas release is correlated with an increase in the fuel temperature leading to thermal fission gas release paths.

In Figure 11 the online measurement of the inner pressure together with the GALILEO calculations for IFA535.5 is shown. The calculated values closely follows the measurements, although a deviation is seen, which nearly vanishes towards the end of the insertion time. This can be explained by a delayed gas flow between the fuel rod active zone and the free volume directly connected to the pressure transducer (upper plenum + end cap). This delayed gas flow is emphasized by a sharp increase in the pressure measurements after short power decreases (e.g. see orange circle in Figure 11). In those cases, one can assume an increase in the gas flow by reduced contact between pellet and cladding. In summary, the calculated inner pressures during the ramp irradiation matches the measured values quite well.

In the evaluation of the fission gas release two measurements are given: At the end of the base irradiation (IFA 409) and the end of life (IFA 535.5). The calculation shows a very good prediction for both measured values (see Figure 13 and Table 6).

From these data and the online measurement with the pressure transducer, a correlation of the fission gas release had been established. This correlation can be used as an estimation of the fission gas release based on the pressure measurements. The comparison between the fission gas release calculations and this correlation is shown in Figure 13, indicating a very good accordance between both values. This shows the good prediction capability of GALILEO for fission gas release in stationary and transient conditions during power ramping.

![Figure 10: Fuel rod inner pressure in IFA 409 and IFA 535.5 rod 809](image-url)
*) Example of pressure increase after short power decrease: see text.

**Figure 11: Fuel rod inner pressure in IFA 535.5 rod 809**

**Figure 12: Fission gas release in IFA 409 and IFA 535.5 rod 809**
Figure 13: Fission gas release in IFA 535.5 rod 809

Table 6: Free volume and fission gas release of IFA 409 and IFA 535.5 rod 809

<table>
<thead>
<tr>
<th>Time</th>
<th>Experiment</th>
<th>Free volume measured</th>
<th>Free volume GALILEO</th>
<th>FGR measured</th>
<th>FGR GALILEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td></td>
<td>cm³</td>
<td>cm³</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>0</td>
<td>IFA 409</td>
<td>9.8</td>
<td>9.8</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>62915</td>
<td>IFA 409</td>
<td>N/A</td>
<td>8.5</td>
<td>20.9</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>IFA 535.5</td>
<td></td>
<td>17.4 *)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>64766</td>
<td>IFA 535.5</td>
<td>17.2</td>
<td>17.9</td>
<td>51.0</td>
<td>48.0</td>
</tr>
</tbody>
</table>

*) Increase of plenum volume 8.9 cm³ after refabrication with end plug.
3.4. INTERRAMP AND SUPERRAMP CASES

3.4.1. PELLET CLADDING INTERACTION

A subtask of FUMEX-III is attributed to mechanical interactions between cladding and pellet. This is related to PCMI (Pellet Cladding Mechanical Interaction) and PCI (Pellet Cladding Interaction, a possible failure mode, which is related to fission product assisted stress corrosion cracking) during power ramps. The mechanical interaction of pellet and cladding during power ramps involves complex interactions of different mechanisms and parameters. Some of these are:

- thermal expansion of pellet and cladding
- mechanical gap between pellet and cladding
- cladding creep
- pellet creep
- gaseous swelling of the pellet
- pellet cracking

The interplay of these mechanisms defines the stresses in the cladding during power ramps. Depending on the stress level and the stress distribution, the cladding will experience a permanent plastic strain from stress relaxation. Measurements are only available as residual strains from PIE, but they are depending on the time evolution of pellet and clad deformation during the ramp, which result in the permanent plastic strain of the cladding. These strains can be measured after the ramp, compared to calculated values and used for a validation of the mechanical models.

From the available international ramp test series, the Interramp [3] BWR cases and the Superramp [4] PWR cases from the sub-series PK6 and PW3 have been chosen for analysis with regard to PCI within the FUMEX-III project. The correct prediction of the strains occurring during power ramps are a prerequisite for the calculation of the loads on the cladding during the ramp. As a consequence, the measured residual strains may be used for the validation of the mechanical models for PCI modeling purposes.

In the Superramp series several fuel rod diameter measurements before and after ramp are available at different positions of the rods. For calculations with GALILEO, the ramps PK1-1, PK2-3, PK4-1, PK4-2, PK6-2, PW3-2 and PW3-4 have been selected. Here, the axial distribution of the residual strain measurements has been used and there are several values for each rod used. The basic data of the ramp series are summarized in Table 7. Details of the ramp data can be found in [4].

From the Interramp series, there are several rod averaged residual strain measurements available, which have been calculated with GALILEO. The basic data for the Interramp cases are summarized in Table 8. Details of the ramp data can be found in [3].

Figure 14 shows the results of the calculated diameter change before and after the ramp versus the measured value (residual strain). The results are well centered around the bisecting line showing a rather good agreement between measured and calculated values.

These result shows the capability of GALILEO to predict cladding diameter changes during power ramps with a good accuracy for BWR and PWR conditions.
**Table 7: Basic data for Superramp cases**

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<th>PK2</th>
<th>PK4</th>
<th>PK6</th>
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<th>BK7</th>
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<th>BG9</th>
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Figure 14: Diametral change due to power ramp for Interramp and Superramp cases
3.4.2. TRANSIENT FISSION GAS RELEASE

Further measurements are available from the Interramp and Superramp test series with regard to fission gas release. This data has been used to extend the fission gas release calculations for transient conditions.

Figure 15 shows the calculated fission gas release versus the measured values indicating a good accordance with reasonable scattering. This underlines the good prediction capability of GALILEO with regard to fission gas release in transient BWR and PWR conditions.

![Graph showing transient fission gas release in Interramp and Superramp](image)

**Figure 15: Transient fission gas release in Interramp and Superramp**
3.5. SUMMARY

During the FUMEX-III exercise the following cases for fission gas release prediction have been analyzed:

- Steady state (normal operation) fission gas release
  - AREVA idealized case for FUMEX-III
  - US 16x16 PWR Lead Test Assemblies TSQ002 and TSQ022
  - IFA 409 rod 809

- Transient fission gas release
  - IFA 535.5 rod 809 (after base irradiation in IFA 409)
  - Interramp and Superramp BWR cases
  - Superramp PWR cases

For all analyzed cases, the prediction of fission gas release is very good compared to the measured/expected values, showing an excellent prediction behavior of GALILEO for steady state as well as transient fission gas release conditions. This is valid for low up to very high burnups as well as low to high duty conditions in BWR and PWR.

With regard to PCI, several Interramp and Superramp cases have been calculated with respect to the dimensional change of the cladding due to the ramp. The results show a good balance of calculated and measured values showing the future applicability of GALILEO for PCI calculations.
DISTRIBUTION

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