Assessment of FGR by TRANSURANUS Code in LWR Fuels Subjected to Power Ramps, From the IFPE Database

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ABSTRACT

The fuel matrix and the cladding constitute the first barrier against radioactive fission product release. Therefore, a defense in depth concept requires also the comprehensive understanding of fuel rod behavior and accurate prediction of the lifetime in normal operation and in accident condition as well.

OECD/NEA sets up the “public domain database on nuclear fuel performance experiments for the purpose of code development and validation – International Fuel Performance Experiments database”. This database includes the Super-Ramp Project (BWR and PWR) and the BWR Inter-Ramp Project. The common objective of these projects is to establish the failure-safe operating limits, the failure mechanism and associated phenomena, during power ramp tests. The study of this integral phenomenon requires the understanding of several connected phenomena. One of the most important is the Fission Gas Release (FGR) from the fuel matrix to the pellet-cladding free volume. The prediction of FGR allows to the assessment of the activity released in the primary loop in case of rod failure.

This work is carried out with the aim to compare, investigate and summarize the main results obtained after the simulations by TRANSURANUS code of 64 fuel rods with particular focus on the prediction of the FGR. Emphasis is given to the main variables, which are involved or may influence the FGR. Systematic comparisons of the code results with the experimental data are performed. The importance of the sensitivity analysis as tool to address the relevance of the knowledge of the boundary conditions, as well as the impact of selected parameters and code options on the results is discussed.

1 INTRODUCTION

The present activity is focused on the behavior of the fuel component. The aim is to investigate the Fission Gas Release phenomenon during power ramp tests in LWR fuels.

The relevance of FGR in nuclear technology is connected with the assessment of coolant potential contamination in case of cladding failure as well as the investigation of the rod performances under normal up to transient conditions.

The impact of FGR on rod performances is briefly recalled in the following\cite{1}\cite{2}:

- Xe and Kr (the main released species) degrade the thermal conductivity of the He inside the pin, and thus enhance fuel temperatures. Enhanced fuel temperatures may further increase FGR and may initiate an unstable process called “thermal feedback”.

\cite{1}

\cite{2}
The release of fission gases increases the inner pin pressure limiting the lifetime of a fuel rod since the inner pressure should not exceed the coolant pressure\(^3\).

The swelling due to gaseous fission products may lead to enhanced pellet–cladding mechanical interaction (PCMI), especially in transients conditions.

The release of radioactive gases (and of volatile solids) from the UO\(_2\) matrix to the free volume decreases the safety margin of a nuclear plant.

Various isotopes of gases are directly created inside the grains by fission, nevertheless, they may originate also from the decay processes. Since their solubility in UO\(_2\) matrix is very low, they diffuse inside the grain (intragranular diffusion process) or precipitate into intra-granular bubbles. The metal part of the gas tends to migrate from the grain matrix to the grain boundaries (inter-granular process) where it precipitates to inter-granular bubbles. Finally, they may reach the pin free volume basically by inter-linkage of inter-granular bubbles and subsequent venting of the grain boundary inventory.

The TRANSURANUS code performance in predicting the FGR is hereafter investigated and presented. Two experimental databases based on PWR and BWR rods at burn-up ranging from 10 to 44 MWd/kgU have been modeled for this purpose: the Super-Ramp Project\(^4\) (BWR and PWR) and the BWR Inter-Ramp Project\(^5\). The datasets of these experiments, are part of the International Fuel Performance Experiments (IFPE)\(^6\)\(^7\) and are included in the FUMEX-III project\(^8\).

TRANSURANUS\(^1\)\(^2\)\(^9\) is a computer program for the thermal and mechanical analysis of fuel rods in nuclear reactors. Its mechanical–mathematical concept consists of a superposition of a one-dimensional radial and axial description (the so-called quasi two-dimensional or 1½-D model). The code was specifically designed for the analysis of a whole rod. TRANSURANUS code incorporates physical models for simulating several specific phenomena occurring in nuclear reactor fuels. Besides its flexibility for fuel rod design, the TRANSURANUS code can deal with a wide range of different situations, as given in experiments, under normal, off-normal and accident conditions.

\section{DESCRIPTION OF THE EXPERIMENTS}

The Super-Ramp Project\(^4\) investigates the failure propensity of 16 BWR and 28 PWR test fuel rods when subjected to power ramps in the R2 Reactor (Studsvik), after base irradiation to high burn-ups in power reactors. The PWR test fuel rods had a burn-up in the range of 35 to 45 MWd/kgU and were all tested using a fast ramp rate. The BWR test fuel rods had a burn-up in the range of 28 to 38 MWd/kgU and were tested using either a high or a very low ramp rate. The groups PK1, PK2, PK4, and PK6 are PWR rods from Kraftwerk Union (KWU/CE), and the groups PW3 and PW5 are PWR rods from Westinghouse (W). The group BK7 contains BWR rods from KWU/CE, and the groups BG8 and BG9 are BWR rods from General Electric Company, GE.

The BWR Inter Ramp\(^5\) investigates the performance of specially manufactured BWR test fuel rods when subjected to fast power ramps, after base irradiation in the Studsvik R2 test reactor to a burn-up in the range of 10 to 20 MWd/kgU.

The main technical objectives of the considered experiments were the following:

- Establish the PCI failure threshold of standard design BWR/PWR test fuel rods by mean of fast power ramping at burn-up levels in the range from 10 to 45 MWd/kgU.
- Investigate the influence of design parameters on fuel performance such as: clad heat treatment and fuel density (BWR-IR), pellet/clad diametric gap size (all databases), remedy cladding, Gd doped pellets and large grain size rods (PWR-SR).
- Establish safe reduced ramp rates for passing through the failure threshold using high burn-up rods (very slow ramps), (BWR-SR).
The ramp test consisted of three main phases:
1. Conditioning at a selected power level for a given time.
2. Ramping at fast or very slow rate up to the ramp terminal level RTL.
3. Keeping constant the RTL for few hours or until the occurrence of cladding failure.

In Figure 1 and Figure 2 are reported the base irradiation of a sample rod and the power ramp scheme adopted in the PWR-SR. Non-destructive and selectively destructive examinations were made to determine the rod changes under irradiation. The FGR was measured after the power ramping for the intact rods by mean of the puncturing technique.

The detailed design and test parameters are given in Refs. [4] and [5]. The parameters that affect the FGR are listed in Table 2.

3 ASSESSMENT OF FGR BY MEAN OF TRANSURANUS CODE

The reference simulations have been developed based on standard models and correlations (i.e. according with the code manual) and nominal design values. The code version is TUv1m1j09.

Only the active part of the fuel is accounted for the simulation, it has been divided into appropriate axial slices, according to the experimental data available. The boundary conditions implemented for the analysis are:
1) Linear heat rate (LHR) at the axial positions according to the ASCII files (histogram);
2) Cladding temperature histories at the same positions of the LHR (histogram format);
3) Fast neutron flux (average value over the irradiation or histogram format at the same positions of the LHR);
4) Pressure (constant value).

3.1 Analysis of the FGR models

The simulation of FGR requires the selection of two models: the first one deals with intra-granular gas behavior the second one refers to grain boundary behavior (inter-granular processes). Each case has been labeled according to the TU code manual[2] in order to connects the results with the use of the code (see Table 1). The intra-granular processes can be modeled with the following options:
- The thermal diffusion coefficient is that of Matzke[10], the athermal diffusion coefficient has been obtained according to White and Tucker[11]. Identified as FGRMOD 4.
- The thermal diffusion coefficient is that of Matzke and for the athermal part of the diffusion coefficient a constant is assumed[2]. Identified as FGRMOD 6.
The single gas atom diffusion coefficient is given by T. Turnbull\textsuperscript{[12]}, the athermal diffusion coefficient is that of White and Tucker. Identified as FGRMOD 9.

The inter-granular processes can be modeled with the following options\textsuperscript{[2]}:

- No gas on the grain boundary. Identified as IGRBDM 0.
- The grain boundary saturation concentration is a constant. Identified as IGRBDM 1.
- The grain boundary saturation concentration depends on the fuel temperature. Identified as IGRBDM 2.

The model newly implemented in TRANSURANUS code to consider the additional release that can be observed in the event of rapid power variations. This model consists of two contributions: micro-cracking in case of power increase or reduction, and gas transport from the grain to the grain boundaries. The entire fission gas inventory stored at the grain boundaries is instantaneously released if transient conditions are met. This model should be invoked in case of power ramps. Identified as IGRBDM 3.

Finally, the FGR equations can be solved with two different models\textsuperscript{[2]}: the URGAS algorithm and the FORMAS algorithm. The reference calculation assumes FGRMOD 6, IGRBDM 3 and the URGAS algorithm. The exploited models are indicated in Table 1.
The results are presented from Figure 3 to Figure 8. The reference simulations are in good agreement with the experimental results in the cases of PWR-SR (with exception of rods PK4-S and PK6-S), and BWR-SR. The reference simulation of BWR-IR results over-predicted\[13\].

In general, the intra-granular models FGRMOD 4 (Matzke and Tucker), and FGRMOD 9 (Turnbull) predict larger values of FGR with respect to the reference case (Figure 3, Figure 5 and Figure 7). The Turnbull model largely overestimates the FGR as stated in the TU handbook\[2\].

The assessment of the inter-granular models highlights two different trends (Figure 4, Figure 6 and Figure 8). The IGRBDM0 model predicts the largest values; this is due to the hypothesis of release of the gas inventory without considering the recovery capabilities of the grain boundaries. The remaining models highlight similar results generally lower than the reference case. They are more representative of the experimental measures of BWR-IR.

In conclusion the FGR models largely affect the predictions causing a considerable spreading of the results. The reference model agrees with the experimental results in the case of the Super-Ramp.

Table 1: Summary of the investigations on FGR.

<table>
<thead>
<tr>
<th>Case</th>
<th>Run</th>
<th>DESCRIPTION</th>
<th>ADDITIONAL NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>0</td>
<td>FGRMOD 6</td>
<td>Thermal diffusion coefficient of Matzke and the athermal part of the diffusion coefficient constant.</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>IGRBDM 3</td>
<td>Transient FGR model</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>Idifsolv 0</td>
<td>URGAS algorithm</td>
</tr>
<tr>
<td>Fission gas</td>
<td>M1.1</td>
<td>As Reference</td>
<td></td>
</tr>
<tr>
<td>inter-granular</td>
<td></td>
<td>• Igrbdm 0</td>
<td>No gas on the grain boundary</td>
</tr>
<tr>
<td>behavior</td>
<td>M1.2</td>
<td>As Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Igrbdm 1</td>
<td>The grain boundary saturation concentration is a constant</td>
</tr>
<tr>
<td></td>
<td>M1.3</td>
<td>As Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Igrbdm 2</td>
<td>Grain boundary saturation concentration depends on fuel temperature</td>
</tr>
<tr>
<td>Fission gas</td>
<td>M2.1</td>
<td>As Reference</td>
<td></td>
</tr>
<tr>
<td>intra-granular</td>
<td></td>
<td>• Fgrmod 4</td>
<td>Thermal diffusion coefficient of Matzke, athermal diffusion coefficient according to White and Tucker</td>
</tr>
<tr>
<td>behavior</td>
<td>M2.2</td>
<td>As Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Fgrmod 9</td>
<td>The single gas atom diffusion coefficient is given by T. Turnbull, the athermal diffusion coefficient is that of White and Tucker</td>
</tr>
<tr>
<td>Gap dimension</td>
<td>B1.1</td>
<td>As Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Max gap</td>
<td>Minimization of gap conductance</td>
</tr>
<tr>
<td></td>
<td>B1.2</td>
<td>As Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Min gap</td>
<td>Maximization of gap conductance</td>
</tr>
<tr>
<td>Density</td>
<td>B2.1</td>
<td>As Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Max density</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>B2.2</td>
<td>As Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Min density</td>
<td>--</td>
</tr>
<tr>
<td>Grain size</td>
<td>B3.1</td>
<td>As Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 0.5 initial grain size</td>
<td>Minimization of the intra-granular gas bubbles precipitation</td>
</tr>
<tr>
<td></td>
<td>B3.2</td>
<td>As Reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 1.5 initial grain size</td>
<td>Maximization of the intra-granular gas bubbles precipitation</td>
</tr>
</tbody>
</table>

M: sensitivity concerning a model available in TU B: sensitivity concerning a boundary condition imposed in TU.

3.2 Impact of the design tolerances on the simulations

The FGR is affected by a large variety of design parameters. The gap initial size and the pellet density are here considered. In this section is investigated the effect of the design tolerances. The summary of the analyses is reported in Table 1 and Table 2.
In the case of PWR-SR, Figure 9, the effect of the uncertainty of the gap dimension as well as the pellet density due to tolerances results negligible.

The simulation of the BWR-SR, Figure 10, highlights a slight dependence of the results from the gap uncertainty.

In the case of BWR-IR, Figure 11, both the gap and the pellet density affect the simulations. In particular a noticeable enhancement of the predictions is observed maximizing the pellet density.

3.3 Impact of the uncertain parameters on the simulations

The FGR is affected by several local parameters as the grain size of the fuel matrix and the pellet open porosity. This type of parameter is usually well known only by the fuel fabricant. In the case of grain size, the data are provided as average value within the pellets. This means that the data are representative of the ideal situation in which the grain size is uniform in the pellet volume and do not account for local deviations. The investigations assume that the average grain size is obtained from the contribution due to grains of dimension within +/- 50% the average value (Table 2). The impact of this range is analyzed in order to assess if the effective grain contribution to FGR is or not symmetric with respect to its average value.

The effects of the grain size is depicted in Figure 12, Figure 13 and Figure 14. This parameter largely affects all the simulations. An increase of the grain size enhances the recovering capabilities of the gas bubbles in the grain matrix and thus it reduces the FGR. Opposite considerations apply to grain size decrease. In particular, the effect is not symmetric since the impact of grain reduction is larger than those of grain increase. The summary of the analyses is reported in Table 1 and Table 2.

The pellet open porosity provides direct linkage between the fuel matrix and the rod free volume, therefore it influences the FGR. As reported in Table 2, this value (expressed as average % open porosity to total porosity) can range from few percent to more than 50%. It is
not specified in the BWR-IR database. Must be mentioned that this parameter is not considered in the FGR models implemented in TU code, therefore it is not assessed.

Table 2: Summary of the investigations on boundary conditions.

<table>
<thead>
<tr>
<th>Database</th>
<th>Rod group</th>
<th>Number of rods</th>
<th>Grain size [µm]</th>
<th>Open porosity [%]</th>
<th>Gap [µm]</th>
<th>Pellet density [g/cm³]</th>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Design</td>
<td>Max</td>
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<tr>
<td>PWR-SR</td>
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<td>5</td>
<td>6.0</td>
<td>50.0</td>
<td>100</td>
<td>106</td>
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<tr>
<td></td>
<td>PK2</td>
<td>5</td>
<td>5.5</td>
<td>55.8</td>
<td>71</td>
<td>76</td>
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<tr>
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<td>PK4</td>
<td>4</td>
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<td>83</td>
<td>87</td>
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<tr>
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<td>PK6</td>
<td>5</td>
<td>22.0</td>
<td>42.8</td>
<td>73</td>
<td>84</td>
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<tr>
<td></td>
<td>PW3</td>
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<td>10.5</td>
<td>5.3</td>
<td>80</td>
<td>88</td>
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<tr>
<td></td>
<td>PW5</td>
<td>4</td>
<td>16.9</td>
<td>4.6</td>
<td>80</td>
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<td>BWR-SR</td>
<td>BK7</td>
<td>8</td>
<td>7.6</td>
<td>2.5</td>
<td>100</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>BG8</td>
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<td>18.0</td>
<td>6.9</td>
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<td>--</td>
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<td>17</td>
<td>8.3</td>
<td>--</td>
<td>75</td>
<td>102</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS

The FGR phenomenon has been assessed against two experimental databases: the BWR and PWR Super-Ramp and the BWR Inter-Ramp. The burn-up ranges between 10 and 44 MWd/kgU. The fuel rods have been subjected to power ramps before FGR measurement. The results achieved from the simulations bring to the conclusions hereafter summarized.
The selection of the models available in TU code has a large impact on the results. Nevertheless, the recommended options for power ramp conditions seem to sufficiently agree with the experimental measures for the Super-Ramp rods. On the contrary, they over-predict FGR results in the case of BWR-IR.

The gap size and pellet density design tolerances affect the BWR-IR FGR. In particular, the density maximization largely enhances the simulations.

The grain size strongly impacts on the simulation of all the databases. The contribution of small grains is larger than those of large grains. In particular, it will be useful to know the local deviation of grain size with respect to its average value.

The open porosity influences the FGR. The effect of this parameter is not accounted in the FGR models implemented in TU code.

REFERENCES


ABBREVIATIONS

BWR Boiling Water Reactor
BWR-IR BWR Inter-Ramp project
BWR-SR BWR Super-Ramp project
CRP Coordinate Research Project
DIMNP Dipartimento di Ingegneria Meccanica Nucleare e della Produzione
ENEA Agenzia nazionale per le nuove tecnologie, l’energia, e lo sviluppo economico sostenibile
FGR Fission Gas Release
FUMEX FUEL Modeling at EXTended burn-up
GE General Electric company
GRNSPG Gruppo di Ricerca Nucleare di San Piero a Grado
IAEA International Atomic Energy Agency
IFPE International Fuel Performance Experiment database
ITU Institute for Trans-Uranium elements
KWU/CE Kraft-Werk Union/Combustion Energy
LHR Linear Heat Rate
LWR Light Water Reactor
NEA Nuclear Energy Agency
OECD Organization for Economic Cooperation and Development
PCMI Pellet Cladding Mechanical Interaction
PWR Pressurized Water Reactor
PWR-SR PWR Super-Ramp project
RTL Ramp Terminal Level
TU Trans-Uranus code
UNIPI University of Pisa
W Westinghouse