The Clad Rupture in the CABRI-TOP LMFBR Safety Experiments

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ABSTRACT

During a severe transient-over-power in a LMFBR, the starting point of all phenomena influencing the further evolution of the reactivity is the failure of the fuel cladding.

Therefore, special attention is devoted to this problem in the development of accident analysis codes.

The aim of this presentation is to describe the modelling and the criteria used to predict clad failure in the PHYSURA code. Some examples of the validation of this modelling using CABRI-TOP experiments leading to clad failure is also given.
I. Introduction

During a severe transient-over-power in a LMFB BR, the starting point of all phenomena influencing the further evolution of the accident is the failure of the fuel cladding.

Although this failure has no direct influence on the core reactivity, a good knowledge of its timing and location is absolutely necessary.

- The timing of the rupture influences the fuel enthalpy, the fuel melt fraction, the proportion of fission gases released and then the molten fuel motion which has a direct influence on the core reactivity.
- The location of the rupture determines the direction of the first fuel motion and influences the reactivity.

For these reasons, an important effort has been made to model the rupture phenomena. In addition, the validation of this modelling can be made using the CABRI in-pile experiments.

Two kinds of clad rupture can be envisaged:

- failure due to overloading of the cladding (mechanical failure)
- failure due to overheating of the cladding leading to melting (thermal rupture).

This presentation will deal only with mechanical failure.

II. Problems to solve

Two different problems are to be solved:

- The calculation of the clad strains and stresses by means of codes
- The choice of a rupture criterion.

The calculation of the clad strains and stresses is made using the PHYSUR A code in a manner described in [1].

Concerning the failure criterion, two different ways can be followed:

- Comparison of the calculated stresses or strains with ultimate values given by out-of-pile experimentation. This method assumes that the mechanical history of the cladding has no influence on rupture.
- The life fraction equal unity. This life fraction is linked to a time of rupture experimentally correlated to the stress or strain via respectively the Larson-Miller and Dorn parameters.

Our philosophy in this domain can be summarized in three points:

- choice of a criterion
- out-of-pile calibration of the criterion
- verification on in-pile experiments.

For evident reasons, the problem of fresh claddings has been separated from the case of irradiated ones.

III. Fresh fuel pins

III.1. Choice of the type of criterion for clad failure

The main characteristic of a fresh fuel is its low gas content in the case of fuels with a high sintering density (as in the CABRI fuel). After
fuel melting, the molten fuel-porosity gas mixture can be considered as incompressible.
So that, when the fuel-clad gap closes, the main part of the fuel thermal expansion is converted into clad plastic deformation. Thus, the clad straining can easily be deduced from the fuel thermal expansion.
That is the reason why we have chosen, in the case of fresh fuel, a criterion based on the clad strain (ε).

III.2. Out-of-pile calibration
The calibration of the rupture criterion has been made by mechanical testing of the material.
The stainless steel used for CABRI claddings is a 316 SS 15% cold worked.
A series of tensile tests have been performed at SACLAY. The strain rate was constant and representative of CABRI tests (some tens per second). The temperature (T) and the temperature rate (dT) were varied in a way representative of CABRI (500 to 1000 °C for T and 10 °C/sec to 1600 °C/sec for dT).
Figure 1 presents the evolution of the uniform elongation (UE) and total elongation (TE) as a function of T anddT. Some conclusions are:

. In the case of transient-over-power, the clad temperature (about 600 °C) at the expected time of failure (peak of the TOP) is sufficiently low due to the ramp rate to avoid any recovering of the cold-working. The uniform elongation is about 2.5% and the total elongation is about 10%.
. In the case of CABRI loss-of-flow-driven-TOPs, the rate of clad temperature rise is about 15 °C/sec during the LOF and the temperature reaches 900 to 1000 °C at the peak of the TOP. Due to the non-negligible recovery of the cold-working in this case, the uniform elongation is about 15% and the total elongation reaches 20%.

III.3. In-pile experiments
III.3.a. A2, A3, A4, A5, A6

A2, A3 and A4 were experiments starting from a steady-state at 480 W/cm (peak power node) followed by a TOP with an energy injected of respectively 1.0, 1.4 and 1.8 KJ/g. These tests have already been described in /2/, /3/, and /4/.

Figures 2 and 3 present the evolution of fuel enthalpy at peak power node and clad plastic deformation as calculated by PHYSURA. The time of clad rupture is quoted for A3 and A4. No failure was predicted and observed in A2. The main data concerning A3 and A4 at the time of clad rupture are summarized in table 1. Some key observations are:

. The fuel enthalpy, the clad plastic strain at the time of failure and the location of the rupture are exactly the same in the two tests (A3 and A4). Thus, we can conclude that these tests are perfectly consistent. The fuel enthalpy at rupture (1.61 KJ/g) must be considered as specific to CABRI tests. Thus, a code is necessary to extrapolate to the reactor case.
The clad failure is located at the clad hot point (2/3 of the fissile column) confirming the out-of-pile observation that the fresh clad mechanical properties are a function of temperature. This is due to the uniformity of the internal pressure linked to the uniform axial shape of melting in CABRI ramps.

The clad failure occurs when the calculated plastic deformation reaches 2.5 %, which is the uniform elongation measured out-of-pile. This can be easily explained by the fact that internal molten fuel motion leads to a concentration of strain at the location where the uniform elongation (beginning of clad necking) is first reached.

III.3.b. B3 and B3 Tests

These experiments have been described in /2/, /3/ and /4/. They were TOP tests with energy injection of respectively 1.2 and 1.4 KJ/g. The TOP was triggered after a loss-of-flow (LOF) sufficient to increase the clad temperature up to 900 - 1000 °C within 20 seconds.

Our present analysis of these tests is that early sodium boiling (detected by flowmeters) occurred during the TOP, producing a clad burn-out followed by a later clad melting. So, no mechanical rupture was observed in B3 although the energy input was the same as in A3.

Due to the higher clad temperatures and thus greater clad thermal expansion compared to A3, the maximum plastic strains calculated are of the same order of magnitude as in A3 (about 5 %) although the fuel temperatures are higher due to the LOF.

If we apply the results of figure 1 to a rate of increase of temperature of 15 °C/sec and a clad temperature of 1000 °C, we find the uniform elongation in this case to be 15 % much greater than the calculated 5 %.

Thus, this is not in contradiction with the criterion calibrated on out-of-pile tests. An overall picture of the CABRI fresh fuel tests compared to the failure threshold is given in figure 4.

It is worthwhile to notice that to have a complete picture, a test with clad temperature between 600 °C and 900 °C should have been performed.

III.4. Final definition of a criterion for pin failure

The criterion can be formulated as follows.

Clad rupture is reached when the clad plastic strain reaches uniform elongation.

This uniform elongation can be measured out-of-pile by tensile tests and is a function of the temperature and the rate of increase of temperature. More precisely, the material ductility is strongly enhanced by low temperature rates (some tens of °C per second) so that mechanical rupture of fresh hot cladding becomes doubtful during rapid ramps of reactivity.

IV. Irradiated fuel pins (1 at E burn up)

The situation for irradiated claddings is less clear for the two following reasons.

The out-of-pile testing of the material is not yet completed.
The interpretation phase of the first CABRI experiments related to irradiated fuel pins is in progress. Nevertheless, the experimental work is sufficiently advanced to allow for some preliminary conclusions.

IV.1. First experimental results

Three CABRI tests are of interest:

- AI 2 : TOP with 0.9 KJ/g energy injection starting from a steady-state at 600 W/cm (peak power position)
- AI 3 : TOP with 1.3 KJ/g energy injected starting from a steady-state at 600 W/cm.
- BI 2 : same test as AI 3 but a LOF is generated before the TOP to increase the outlet sodium temperatures up to 850 °C.

All the pins used were pre-irradiated in the PHENIX reactor up to 1 atom percent burn-up.

Clad rupture in AI 3 and BI 2 was observed some milliseconds after the peak of the transient. In AI 2, the failure was obtained after the reactor scram, but due to the low clad temperatures at that time, the failure can only be mechanical.

The main data concerning AI 2, AI 3 and BI 2 at the time of clad failure are summarized in table II. The main observations arising are the following:

- The fuel enthalpy at the time of rupture is quite the same in the three cases although the clad temperature is somewhat different (680 to 920 °C). One can also notice (figure 5) that the AI 2 test was just at the rupture threshold.
- The clad failure is located between the clad hot point (56 cm) and the midplane (37.5 cm). This is just lower than predicted by the PHYSURA code which foresaw the rupture at the hot point. This is directly linked to the assumption of homogeneity of the molten fuel cavity pressure which leads to maximum strains and fraction of life at the clad hot point. A modification of this assumption is presently in progress in order to homogenize the pressure only in a region with a melt fraction large enough (~ 50 %) to allow for molten fuel movements leading to uniformisation. The consequence of this new assumption will be to lower the location of the calculated rupture and lead to a better agreement with experimental results.

Concerning the time of rupture, the predicted values were somewhat late compared to experimental ones (5 to 10 milliseconds). But it was demonstrated that the fuel thermal behaviour (directly linked to the fuel thermal conductivity of the irradiated mixed oxide) plays an important role in the determination of the time of failure and explains the major part of the discrepancy.

This problem was not present in fresh fuel tests because the thermal conductivity of the UO₂ was measured out-of-pile and used in the calculations. Presently, the rupture criterion used, is the fraction of life based on Larson-Miller correlations for irradiated claddings given in /5/. The problem of comparison of this criterion to the in-pile CABRI experiments will be solved only...
after adjustment of the fuel thermal behaviour.

IV.2. Preliminary conclusions

Due to the fact that the interpretation of this series of tests is in progress, the conclusions are only preliminary. They are as follows:

- The three tests considered are consistent. It will be of great help for the definition of a criterion for failure.

- Although the clad temperature at the time of rupture is different, the fuel enthalpy is the same. This tends to demonstrate the small effect of the temperature on the rupture threshold. This is the most important difference compared to fresh pins.

- The effect of the temperature rate (BI 2) is not visible and this is also an important difference compared to fresh pins (B3).

- The influence of the strain rate cannot be studied because of the unique ramp rate used in CABRI. A programme with slower ramps should give the answer to this remaining problem.

Nevertheless, the problem of the choice of a criterion for rupture remains open.

V. Preliminary conclusions on the influence of burn-up

At the present stage of the CABRI programme, two different burn-ups have been studied (0 and 1 atom per cent). The tests concerning pins at high burn-up (5 at %) will begin late in 1984.

If we draw the curve representing the clad rupture energy threshold as a function of burn-up (figure 7), we can notice a decrease of about 400 J/g between fresh and low burn-up pin. This decrease is mainly due to the decrease of the clad ductility with irradiation, the effect of fission gases at 1 at % being limited.

At 5 at % burn-up, the clad mechanical properties will be identical to those at 1 at % (saturation effect), but the effect of fission gases will be more important. Two scenarios are then possible:

- Curve 1, dashed line of figure 7: due to the high smeared density of the CABRI pins (87 %), the effect of fission gases will be smoothed by the effect of fuel thermal expansion.

- Curve 2, dashed line of figure 7: the fission gases play a major role due to an important fission gas induced fuel swelling.

Our present understanding of the phenomena leads us to foresee the curve 1 to be more probable.

VI. Conclusions

The first important remark we can make concerns the very impressive consistency of all the tests. This is certainly due to the good quality of the experimental work performed but also to the use of a pin with well defined characteristics, as opposed to a common reactor pin.

As far as fresh fuel pins are concerned, a failure criterion has been obtained by comparing the clad strain calculated to the uniform elongation of the material measured out-of-pile. This uniform elongation is a function of
temperature and temperature rate.

Concerning the irradiated fuel, the situation is not yet clarified due to the state of experimental and analytical work. But, as a preliminary observation, it seems that the influence of temperature and temperature rate is negligible compared to fresh pins. Nevertheless, as soon as out-of-pile results are available, an as complete as for fresh fuel study will become possible.

Two important subjects of study are also still remaining:

- Study of the rupture criterion for rapid ramps on high burn-up fuel pins (5 at %). This will be done with the current progress of the CABRI programme.

- Study of the influence of the ramps rate on the threshold. This will be done using the CAPT programme and a possible CABRI follow-on programme with slower ramp rates.

References

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/2/ D. STRUWE et al - Fuel pin behaviour in power burst experiments performed in CABRI - Topical meeting on reactor safety aspects of fuel behaviour - SUN VALLEY - Idaho (U.S.A.) 1981.

/3/ J. DADILLOU et al - CABRI project: recent progress and present status - International topical meeting on liquid metal fast breeder reactor safety and related design and operational aspects - July 19-23, 1982 LYON (FRANCE)

/4/ J.C. MELIS et al - Analysis of the in-pile CABRI experiments - International topical meeting on liquid metal fast breeder reactor safety and related design and operational aspects - July 19-23, 1982 LYON (FRANCE)

### TABLE I
Clad rupture in CABRI fresh fuel tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Time of rupture (ms)</th>
<th>Location of rupture (cm)</th>
<th>Fuel enthalpy (KJ/g)</th>
<th>Clad strain (%)</th>
<th>Clad midwall temperature (° C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3</td>
<td>58.2</td>
<td>49 ± 2</td>
<td>1.61</td>
<td>2.5</td>
<td>645</td>
</tr>
<tr>
<td>A4</td>
<td>54.0</td>
<td>48.5 ± 2</td>
<td>1.61</td>
<td>2.5</td>
<td>620</td>
</tr>
</tbody>
</table>

### TABLE II
Clad rupture in CABRI low-burn-up fuel pins (1 at %)

<table>
<thead>
<tr>
<th>Test</th>
<th>Time of rupture (ms)</th>
<th>Location of rupture (cm)</th>
<th>Fuel enthalpy (KJ/g)</th>
<th>Clad midwall temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>AI 2</td>
<td>230 - 231*</td>
<td>43 - 47*</td>
<td>1.20</td>
<td>860</td>
</tr>
<tr>
<td>AI 3</td>
<td>82 - 83*</td>
<td>38 - 47</td>
<td>1.20</td>
<td>680</td>
</tr>
<tr>
<td>BI 2</td>
<td>80 - 81*</td>
<td>50*</td>
<td>1.18</td>
<td>920</td>
</tr>
</tbody>
</table>

*Preliminary results

N.B. Length of the fissile column is 75 cm