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## SYNTHESIS OF CABRI-RIA TESTS INTERPRETATION

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**ABSTRACT :** The CABRI REP-Na programme performed in the sodium loop of the CABRI reactor by the French "Institut de Radioprotection et de Sûreté Nucléaire", has been devoted to the study of the behaviour of high burn-up  $UO_2$  and MOX fuel submitted to a RIA (8 tests with  $UO_2$  and 4 with MOX fuel). The observed failures of some of the  $UO_2$  and MOX fuel rods at enthalpy levels ranging from 30 to 113 cal/g enthalpy levels have underlined the need of evolution of the present safety criteria. The detailed interpretation of the phenomena together with SCANAIR analysis, led to identify the key parameters during the first phase of the transient, without significant clad temperature increase, which are the deleterious influence of a high clad corrosion level with hydride concentrations on clad failure and the contribution of grain boundary gases on fission gas release and potential clad loading, mainly in case of MOX fuel.

Pending questions still concern the transient fission gas behaviour and the impact on clad loading during the whole transient, the rod behaviour with high clad temperature, the high internal pressure effect and the post-failure phenomena (fuel ejection, fuel-coolant interaction with finely fragmented solid fuel).

The CABRI International Programme (CIP) already launched in 2000 (two first tests performed in 2002), will provide under typical pressurised water conditions, relevant additional knowledge relative to high burn-up  $UO_2$  and MOX advanced fuels.

### 1 INTRODUCTION

Since the start of the 1990s, the optimisation of the French PWR core management has led utilities to consider the use of  $UO_2$  fuel assemblies with higher burn-up and to introduce MOX fuel concept in these reactors. For instance, in 1998, "Electricité de France" (EDF) was authorised to raise its  $UO_2$  assembly average burn-up from 47 to 52 GWd/t and is considering further increase up to 62 GWd/t in the near future. Additionally, applying similar management scheme to both  $UO_2$  and MOX fuel is envisaged so that MOX fuel assembly burn-up could also be increased up to 52 GWd/t.

These long anticipated developments had created the need for new investigation of fuel behaviour under design basis reactivity initiated accident (RIA) such as control rod ejection (due to failure of the control rod drive mechanism) that leads to rapid energy injection (some tens of ms) in the fuel rods neighbouring the ejected control rod assembly.

Within this framework, in 1992, the "Institut de Radioprotection et de Sûreté Nucléaire" (IRSN, formerly IPSN), initiated, in partnership with EDF, the CABRI REP-Na research programme [1], [2], [3]. The  $UO_2$  part of the programme was also supported by the US Nuclear Regulatory Commission (NRC).

The main objectives were to study the behaviour of highly irradiated fuel ( $UO_2$  and MOX) under RIAs, verify the adequacy of the present safety criteria<sup>1</sup> previously defined on the basis of the available experimental data base (from SPERT, PBF and early NSRR experiments) that was restricted to fresh or

<sup>1</sup> These criteria, independent of burn-up level are mainly reflected in an average fuel enthalpy value (200 cal/g for irradiated fuel and 230 cal/g for fresh fuel) that must not be exceeded in the calculated transient and should guarantee the absence of significant mechanical energy release and preserve core cooling capability.

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lightly irradiated  $\text{UO}_2$  fuels (up to about 30 GWd/tM for  $\text{UO}_2$  fuel). Establishing the necessary basis for possible evolution of these criteria and evaluate safety margins were also of concern.

As a first step of investigation in France, the CABRI REP-Na experimental programme has been launched in the sodium loop of the CABRI reactor [4] in which consequences of a fast power transient applied to an irradiated single rod could be studied in a sodium coolant environment. Due to this last point, the investigation was focused on the first phase of the power transient that of strong pellet-clad mechanical interaction (PCMI) with limited clad heat-up and was devoted to the study of rod failure mechanism and onset of fuel dispersal if any.

In parallel to the REP Na experiments, the SCANAIR code [5] was developed in order to interpret the test results, perform sensitivity studies and extrapolate to reactor conditions. The main feature of the SCANAIR code is its ability to process closely coupled phenomena such as rod thermics and thermal hydraulics, fuel and clad mechanics and transient behaviour of fission gases based on an initial rod state derived from base irradiation calculations.

Separate-effects tests were launched for the study of the cladding mechanical properties (PROMETRA, [6]) and the clad to coolant (water) heat transfer under fast transients (PATRICIA, [7]) ; a programme for the study of the transient behaviour of fission gases is also envisaged.

In this paper, we will focus on the present understanding of  $\text{UO}_2$  and MOX fuel behaviour under RIA transients and the main outcomes derived from the detailed interpretation of the first ten tests of the CABRI REP-Na programme (REP-Na1 to REP-Na10) that is based on the analysis of the experimental results (including pre and post-test examinations) and SCANAIR calculations. The objectives and status of the new CABRI International Programme (CIP) launched in 2000, will also be presented.

## **2 THE CABRI REP-NA TEST PROGRAMME**

### **2.1 The main objectives of the test programme**

The most immediate consequence of a fast power transient simulating an RIA is fuel heat-up with thermal expansion which, associated to fission gas induced swelling, generates strong PCMI (particularly during the first phase of the transient, that of fast energy injection) and thus clad straining up to possible rod failure.

Therefore, the objectives of the REP Na test programme were focused on the identification and quantification of the main physical phenomena that can lead to rod failure and fuel ejection during the first phase of the power transient without significant clad heat-up (consistently with the use of sodium as coolant and based on the results of the first Japanese tests in NSRR with irradiated fuel at 20 GWd/tM indicating PCMI failure mode at relatively low clad temperature). The next phase of the transient, in which clad temperature rises, especially if boiling crisis inducing rod dry-out takes place under reactor conditions, was not reproduced and the consequences of fuel dispersal in the fluid after rod failure such as pressure increase in the channel, were not representative.

Some specific aspects of the irradiated  $\text{UO}_2$  and MOX fuels may influence the transient rod behaviour : the high clad corrosion level with hydrogen absorption, possible local hydride concentration (hydride rim or blisters due to the spalling of the oxide layer during in-reactor irradiation) leading to clad embrittlement, the important fission gas retention, the high burn-up fuel micro-structure developed in the pellet periphery (rim zone of  $\text{UO}_2$  fuel) and in the Pu-rich zones of MOX fuel.

Based on these considerations, the whole experimental programme aimed at investigating the impact of the following parameters on the rod failure risk or mechanism :

- the  $\text{UO}_2$  fuel burn-up (maximum pellet value of the test rod) : low value (33 GWd/tM) providing a link with the available RIA data base, medium value (52 GWd/tM) corresponding to the maximum assembly average burn-up of 47 GWd/t authorised in the early 90s, and high values (60-64 GWd/tM) corresponding to the target burn-up after four 18 months cycles in PWR with fourth core reload,

- the clad corrosion : oxide thickness from 4  $\mu\text{m}$  in REP-Na2 up to 130  $\mu\text{m}$  in REP-Na8, with more or less initial spalling of the oxide layer (REP-Na1, REP-Na 8, REP-Na 10),
- the fuel pellet type :  $\text{UO}_2$  and MOX fuels, the later being of MIMAS type,
- the energy deposit, from about 100 cal/g in most experiments to more than 200 cal/g in case of low burn-up tests (REP-Na2, REP-Na9),
- the power pulse width : from 9.5 ms to larger values (30 to 75 ms) resulting in different energy injection rates.

## 2.2 The test conditions and main experimental results

From 1993 to 1998, seven REP-Na tests were performed on  $\text{UO}_2$  fuel and three others on MOX fuel. Additionally, in the year 2000, two other REP-Na tests were conducted : one relative to high burn-up  $\text{UO}_2$  fuel with M5 cladding, the second one with MOX fuel irradiated during five cycles ; the results and outcomes of these latter tests are not included in the present paper.

Test specimens of about 560mm fissile length consisted of commercially manufactured reconditioned rodlets from EDF rods (except for REP-Na2 which was a full length rod from BR3 reactor and REP-Na3 which was an EDF segmented rod). The test rods were filled with helium at low pressure (0.3 MPa, 0.1 MPa in REP-Na1 at 20°C) in order to simulate the fuel rod internal pressure balance with the coolant at the end of in-reactor irradiation. Fluid flow velocity and temperature conditions (4 m/s and 280°C respectively) were those corresponding to reactor hot shutdown. The test rod was inserted into a test section located in the sodium loop in the center of the CABRI driver core (80cm height). The power pulse is generated and controlled by depressurisation of  $^3\text{He}$  circuit.

The CABRI REP-Na test matrix is reported in the table 1 gathering the main characteristics and results of the different tests.

**TABLE 1 : CHARACTERISTICS AND RESULTS OF CABRI REP-NA TESTS (FLOWING SODIUM AT 0.5 MPa AND 280 °C).**

Test (date)	REPNa1 (11/93)	REPNa2 (6/94)	REPNa3 (10/94)	REPNa4 (7/95)	REPNa5 (5/95)	REPNa6 (3/96)	REPNa7 (2/97)	REPNa8 (7/97)	REPNa9 (4/97)	REPNa10 (7/98)
Fuel type	$\text{UO}_2$	$\text{UO}_2$	$\text{UO}_2$	$\text{UO}_2$	$\text{UO}_2$	MOX	MOX	$\text{UO}_2$	MOX	$\text{UO}_2$
Initial enrichment ***(%)	4.5	6.85	4.5	4.5	4.5	5.925	5.948	4.5	6.559	4.5
Internal pressure (Mpa,20°C)	0.1	0.101	0.31	0.301	0.302	0.302	0.3	0.3	0.304	0.301
Active length (mm)	569.4	1004.9	440.8	567.6	563.5	553.5	554.2	559	561.2	559
Max. burnup (GWd/t)	64	33	53.8	62.	64.	47	55	60	28.1	63
Corrosion thickness( $\mu\text{m}$ )**	80-100 (spalling)	10	35-60	60-80	15-25	35	50	84-126 (spalling)	10	60-100 (spalling)
Energy deposit* (J/g ) (cal/g)	463 110.7	865 207	511 122.2	397 95	435 104	652 156	710 170	430 102.9	974 233	453 108.3
Pulse width (ms)	9.5	9.6	9.5	76.4	8.8	32	40	75	33	31
Peak fuel enthalpy (J/g) (cal/g)	475 <sup>(2)</sup> 113.7 <sup>(2)</sup>	832 199	516 123.5	355 85	451 108	556 133	577 <sup>(2)</sup> 138 <sup>(2)</sup>	410 <sup>(2)</sup> 98 <sup>(2)</sup>	824 197	410 <sup>(2)</sup> 98 <sup>(2)</sup>
Max. mean hoop strain (%)	brittle failure H=28-36 cal/g	3.5	2.2 oxide transient spalling	0.4 oxide transient spalling	1.1	2.6 oxide transient spalling	failure H=113 cal/g	failure <sup>(1)</sup> H=44 cal/g crack initiation H=78 cal/g loss of tightness	7.2	failure H=81 cal/g
Fission gas release (%)	Gas and Fuel ejection (6g or 2%)	5.54	13.7	8.3	15.1	21.3	strong gas ejection —	-Gas escape at H=78 cal/g	-33.4	No fuel dispersal
Helium release (mm <sup>3</sup> /g)		9.53	35.7	38.2	43.1	34.45	Pressure peaks		-66	Slow gas ejection
He released/(Xe + Kr) formed (%)	Sodium pressure peaks	1.28	2.48	2.27	2.46	3.	Fuel dispersal	H=78 cal/g -No fuel dispersal	-10	

\* for fast ramps at 0.4 s, for slow ramps at 1.2 s

\*\* Maximum value

\*\*\*  $\text{U}_{235}/\text{U}$  for  $\text{UO}_2$ , Pu / (U + Pu) for MOX

Standard Zr4 cladding except BR3 clad in REP Na2 and low tin Zr4 in REPNa3 and REP-Na 9.

(1) microphone signal at H = 44 cal/g

(2) enthalpy evaluation without rod failure consideration

The most striking results evidenced from the on-line diagnoses and post-test examinations are the following :

- the failure of the 5 cycles  $\text{UO}_2$  rods with heavily corroded and initially spalled Zr4 cladding (REP-Na 1, REP-Na 8, REP-Na 10), that occurred at enthalpy level (maximum radial average) ranging from about 30 to 81 cal/g,

- the failure of the REP-Na7 rod with a 4 cycles MOX fuel and an a priori sound cladding, at an average pellet maximum enthalpy of 113 cal/g,
- the significant residual clad straining in the un-failed rods (from maximum mean values of 0.4% in REP-Na4 to 7.2% in REP-Na9), increasing with fuel enthalpy level,
- the fission gas release increasing with burn-up and fuel enthalpy, together with significant Helium release,
- an important fuel fragmentation (mainly in the peripheral zones for UO<sub>2</sub> fuel), with grain boundary opening, enhanced with energy deposit and clad deformation,
- the transient clad spalling of the Zr<sub>4</sub> oxide layer when initial oxide thickness is above 30-40 μm,
- depending on the rod failure conditions, gas and fuel ejection observed after rod failure.

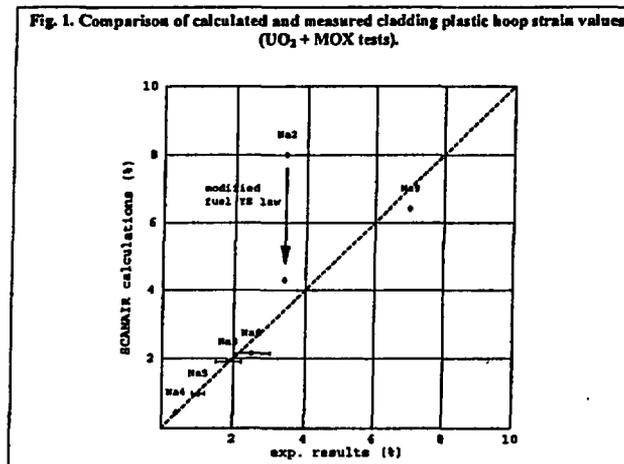
As a first outcome, the failure of the REP-Na1 and REP-Na7 rods followed by gas and fuel ejection clearly confirmed that the current safety criteria were no longer adapted to high burn-up fuel (UO<sub>2</sub> and MOX fuel). A similar conclusion was drawn from the Japanese NSRR tests which likewise led to failure of UO<sub>2</sub> rods at 50 GWd/tM and at low fuel enthalpy (60 cal/g), although under different thermal-hydraulic conditions (stagnant water at ambient conditions).

### 3 PRESENT UNDERSTANDING OF THE IRRADIATED FUEL BEHAVIOUR UNDER RIA

The detailed interpretation of the test taking into account pre-and post-test examinations, transient data and studies performed with the SCANAIR code led to the present understanding of the main physical phenomena.

#### 3.1 Clad straining

The clad straining obtained in the un-failed rods is due to strong PCMI loading caused by fuel thermal expansion and fission gas induced swelling (mainly intra-granular if sufficient energy injection) and is increasing with fuel enthalpy (fig.1)



Under high energy injection leading to fuel temperature above 1800°C (corresponding to maximum radial average enthalpy of 110 cal/g), intra-granular swelling is activated by vacancy diffusion mechanism linked to bubble over-pressurisation (temperature increase and coalescence). For instance in the REP-Na2 or REP-Na9 tests, the calculated contribution of intra-granular swelling to the clad deformation is about 70% ; it is more limited in REP-Na3 and REP-Na6 due to lower injected energy. Inelastic fuel behaviour is also evidenced at high energy injection by the filling of the pellet dishings in REP-Na2 or REP-Na9 tests (confirmed by scoping calculations, see figure 1).

Cladding ovalizing has been observed in several tests in association with clad oxide transient spalling, when the initial Zr<sub>4</sub> oxide thickness is above 30-40 μm (REP-Na3) ; this effect has been attributed to an azimuthal heterogeneity of the zirconia build-up during base irradiation leading to temperature differences within the cladding and ultimately to clad yield strength variations as illustrated on the following scheme (fig. 2).

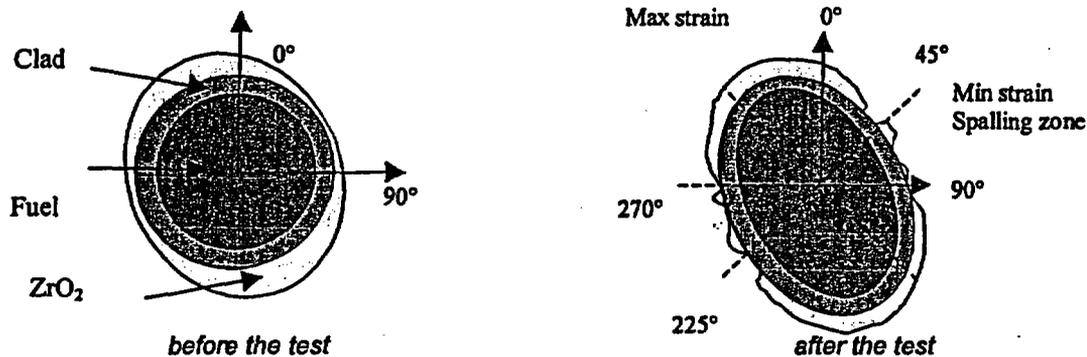


Fig 2 : rod ovalisation in the REP Na 3 and REP-Na6 rods.

Rod ovalizing is also obtained with highly irradiated fuel under rapid transient even without oxide spalling (REP-Na5) : in such a case, a non uniform azimuthal distribution of Pu build-up may lead to azimuthal variations of energy deposit (whose effect is enhanced by quasi-adiabatic heat-up in fast transients) resulting in non uniform clad straining.

However, using average values of oxide layer and radial power profile leads to a good agreement between calculations and average measured cladding deformation (fig 1).

### 3.2 Rod failure mechanism for UO<sub>2</sub> fuel

The failure of the REP-Na UO<sub>2</sub> rods occurred with PWR rod segments that evidenced high corrosion level (spans 5) and in-service oxide spalling (REP-Na1 and REP-Na10 were twin rods with mean corrosion thickness of 80μm and axially spread spalling, REP-Na8 had 84-126 μm mean corrosion thickness and localised spalling).

In REP-Na1, the detailed analysis of the micro-phones, pressure sensors and flow-meters allowed to conclude that the rod failure occurred when the maximum fuel enthalpy was in the range of 28-36 cal/g, with loss of tightness at 36 cal/g at the latest.

In REP-Na8 test, several micro-phone events were detected before evidence of the loss of rod tightness that occurred at a maximum fuel enthalpy of 78 cal/g ; however, the correlation between the micro-phone event located at 30cm bfc (bfc : bottom of fissile column) and a limited axial crack extension inside an hydride blister suggests a possible failure initiation (without gas or fuel ejection) at this level corresponding to a maximum fuel enthalpy of 44 cal/g, before the loss of rod tightness at 78 cal/g (located in the upper part of the rod).

On the other hand, in REP-Na10 test, rod failure and loss of rod tightness clearly occurred when the maximum fuel enthalpy reached 81 cal/g.

The metallographies performed on the three rods underlined that these failures occurred with no or limited plastic deformation (multiple brittle failure in REP-Na1, figure 3, brittle failure in REP-Na10, residual strains in REP-Na8 lower than 1% with 0.5 % at 31.5cm bfc, see radial cut RC1 in figure 4). In REP-Na8, the larger pulse width may explain the limited plastic deformation linked to the clad temperature evolution in comparison to the brittle failure of the two other rods. Those results are fully consistent with the results of the PROMETRA programme performed on cladding samples from the test rods or father rods [6] that evidenced the brittle behaviour of the spalled claddings.

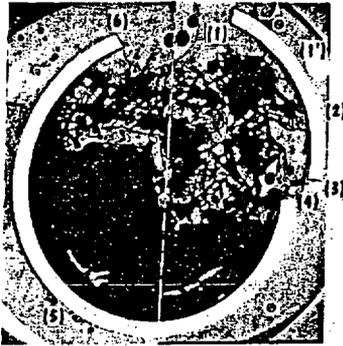


Fig. 3 CABRI REP-Na1 RC8 at 215mm/bfc.

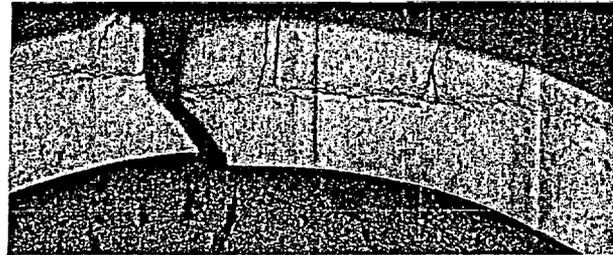


Fig. 4 : CABRI REP-Na8 macrography at 315mm/bfc.

On the basis of these results, the  $\text{UO}_2$  fuel rod failures are explained by the drastic loss of apparent ductility of the  $\text{Zr}_4$  cladding linked to the high corrosion level with hydrogen absorption into the metal and in reactor oxide spalling which lead to formation of large hydride concentrations or hydride blisters (blisters are formed by hydrogen migration towards cold points as a result of oxide removal).

Nevertheless, the very early failure of the REP-Na1 rod led to deep investigations in order to clarify whether other parameters could have affected the rod behaviour.

The impact of a fast power pulse has been analysed with the SCANAIR code through the comparison of the thermo-mechanical conditions of the failed  $\text{UO}_2$  tests when the fuel enthalpy reaches the REP-Na1 failure value : the differences on the strain rates ( $0.1 \text{ s}^{-1}$  in REP-Na8 and REP-Na10,  $0.5 \text{ s}^{-1}$  in REP-Na1) and on the clad temperatures ( $30^\circ\text{C}$  difference on outer clad temperature) were not sufficient to explain the early failure of REP-Na1 by the low pulse width itself.

During the pre-conditioning phase of the REP-Na1 test (isothermal state at  $380^\circ\text{C}$  during 14h followed by slow cooling down to  $280^\circ\text{C}$ ), the possible generation of stresses on the cladding leading to precipitation of deleterious radial hydrides has been suggested, but it was demonstrated that the probability of clad failure resulting from that mechanism is very low.

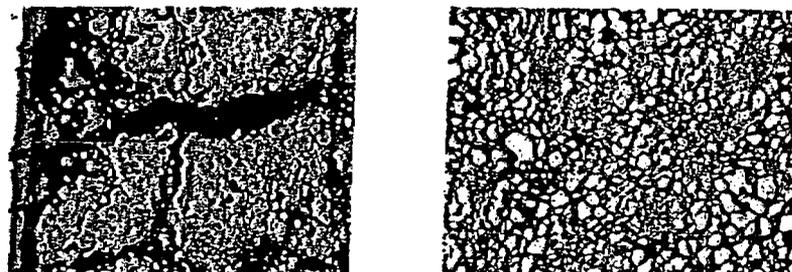
In consistency with REP-Na8, REP-Na10 and PROMETRA results, the most likely cause of the REP-Na1 failure is attributed to the presence of a deep initial hydride damage (blister or rim) in the zone around peak power level, however not precisely localised mainly because of the lack of neutron-radiography examination before test ; moreover, due to the small axial extent of an hydride damage, the detection of such a damage could have been missed in spite of the numerous destructive examinations performed on this rod.

The above results showing  $\text{UO}_2$  rod failures at different level of maximum fuel enthalpy (radially average) underlined that failure prediction of spalled rods, even apparently similar, is difficult.

### 3.3 Fuel microstructure evolution and fission gas behaviour

The evolution of the fuel micro-structure under RIA transients is highly influenced by the characteristics of the high burn-up fuel, that are closed gap, bonding between-fuel and internal zirconia layer and high fission gas retention which increases quasi-linearly with burn-up (due to the low gas release in operating conditions). Furthermore, there is a strong increase of the fraction of the fission gases stored at grain boundaries mainly due to the formation of the typical High Burn-up Structure (HBS) in the rim zone and in the MOX agglomerates. This leads to a high gas content in over-pressurised micrometer inter-granular pores (for  $\text{UO}_2$  fuel at 60-65  $\text{GWd/t}$ , pore gas content in the rim zone amounts to 8 to 10% of the pellet total gas retention) which may contribute to transient fuel swelling and gas release under fast transients.

In most of the CABRI tests (and also in the NSRR tests) fuel fragmentation with grain boundary separation and structure changes are evidenced in the external zones of  $\text{UO}_2$  fuel or in the matrix of MOX fuel, as shown in figure 5). This effect is understood as the result of the high overpressure that is developed in the small inter-granular bubbles under fast heating rates and which induces high stress fields between the grains ; depending on gas pressure and fuel constraint, grain boundary cracking and grain boundary separation may occur and lead to fission gases availability (inter-granular bubbles and large pores) for internal solid fuel pressurisation and swelling [8].



left :  $\sim 0.98R$  right :  $\sim 0.9R$   
 scale=216  $\mu\text{m}$   
 Fig. 5 : REP-Na6 radial cut at peak power location.

The contribution of the fuel fragmentation mechanism to the failure of the REP-Na  $\text{UO}_2$  rods cannot be settled with certainty because of the dominant effect of the low clad ductility in the failed  $\text{UO}_2$  rods ; indeed, an evaluation of the contribution of this phenomenon on the clad straining has been performed based on one option of the present SCANAIR modelling which simulates equilibrium of the pores and inter-granular gas pressure with the hydrostatic fuel pressure after grain boundary cracking : the effect on clad straining was found small in comparison to the final clad deformation.

On the other hand, with sodium cooling in the REP-Na tests, the grain boundary gas expansion is limited during the PCMI phase, with low temperature increase and high clad strength ; this is not the case in the NSRR tests [9] where the high clad temperature after dry-out and the low channel pressure allowed significant gas driven fuel expansion as evidenced by the high clad straining in the TK1 test result (10% in average and up to 25% locally). Under pressurised water conditions, the possibility and amplitude of grain boundary gas expansion are not yet known ; nevertheless, sensitivity studies with SCANAIR calculations are foreseen as a first approach.

In case of high energy injection, when fuel enthalpy (maximum radial average) overpasses 110 cal/g (REP-Na2, REP-Na9 and most likely REP-Na3 and REP-Na6), the contribution of the intra-granular fission gas induced swelling to clad loading and deformation is underlined, in addition to the fuel thermal expansion ; such a contribution is confirmed in REP-Na2 and REP-Na9 by the observation of the intra-granular bubbles precipitation and in REP-Na9 by the measured reduction of the fuel hydrostatic density. High energy injection also leads to fuel creep behaviour as underlined by the filling of the pellet dishings in the REP-Na2 and REP-Na9 tests.

Significant fission gas release (FGR) is obtained due to RIA transients, consistently with the fuel fragmentation and grain boundary separation mechanisms which modify the fuel permeability.

The different FGR results in REP-Na4 and REP-Na5 (difference not reproduced by SCANAIR, fig.6) clearly show a correlation between FGR, clad residual strain and free volume evolution ; this indicates that if the cladding permanent strain offers an additional free volume sufficient to induce a significant grain boundary opening, an important interconnected porosity network (including the initially closed porosity) is created and leads to a significant increase of the free volume available for FGR of grain boundary gases. In case of low clad deformation as in the REP-Na4 test, there is no significant opening of the closed porosities and only partial release of grain boundary gases occurred, probably from the rim zone since there is no significant evolution of the free volume. On the contrary, in case of significant clad deformation as in the REP-Na5 test, most of the closed porosities are opened and the corresponding part of GB gas was released. The results of the ADAGIO<sup>2</sup> measurements performed on REP-Na4, REP-

<sup>2</sup> ADAGIO examinations allow to measure the grain boundary gas inventory based on measured fission gases retained inside the fuel after oxidation at low temperature followed by thermal annealing of the samples

Na5 and father rod samples confirmed this understanding with no contribution of the grain boundary gases in the inner zone in REP-Na4 while gases from the whole pellet are involved in REP-Na5.

These results underline that in case of low energy injection in UO<sub>2</sub> fuel, with maximum fuel enthalpy lower than 110 cal/g (without contribution of intra-granular gas migration, as confirmed by micro-probe measurements), the FGR is mainly due to the contribution of the grain boundary gases, with participation of the rim zone under slow and fast pulses.

In addition, the whole set of REP-Na tests shows that FGR increases with burn-up level in relation with grain boundary gas content (REP-Na2, REP-Na3, REP-Na5 and MOX fuel compared to UO<sub>2</sub> fuel) and is correlated to clad deformation and to free volume evolution.

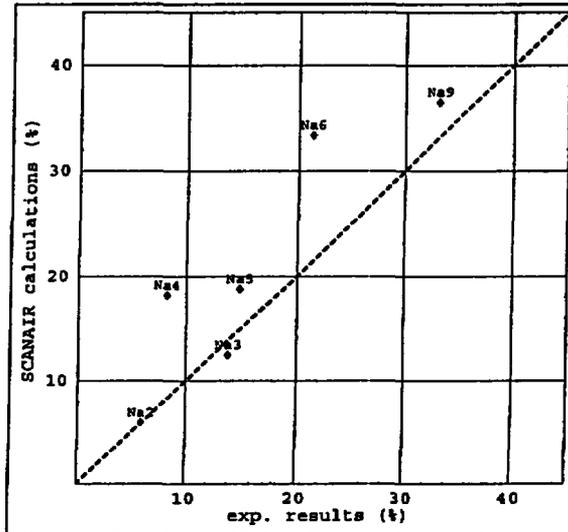


Fig. 6 : Fission gas release (REP-Na UO<sub>2</sub> + MOX tests).

The FGR results also evidenced a significant amount of released Helium gas (up to 27% of the Xe, Kr release) and its potential role on the RIA phenomenology should be considered in the future due to its possible contribution to the internal pressure increase, especially after clad heat-up.

### 3.4 Transient oxide spalling

The transient spalling of the cladding oxide layer has been observed in several REP-Na tests with rods having a moderate (30-40 μm) or large corrosion thickness as a result of the power pulse and subsequent clad straining. As already discussed in 3.1, azimuthal heterogeneity of the initial oxide layer leading to deformation with rod ovalization, can activate oxide spalling on the azimuths with less corrosion thickness (see fig.2).

With large oxide thickness (80 μm, REP-Na4), extensive transient oxide spalling has been evidenced even with low clad straining (0.4% in REP-Na4, figure 7), which tends to indicate that in case of higher residual strains and high corrosion level, the spalling phenomenon occurs early in the transient (confirmed by SCANAIR results).

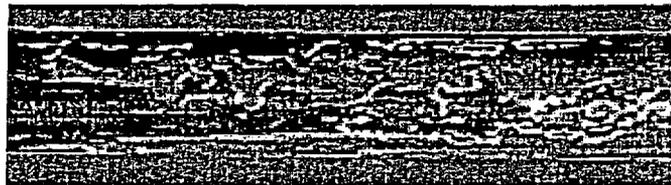


Fig.7 : REP-Na4 oxide spalling due to transient.

The SCANAIR calculations of the REP-Na tests, showing a satisfying description of the sodium temperature evolution (fig.8) with the assumption of oxide spalling at the beginning of the transient, confirms that this phenomenon affects the clad-fluid transient heat transfer.

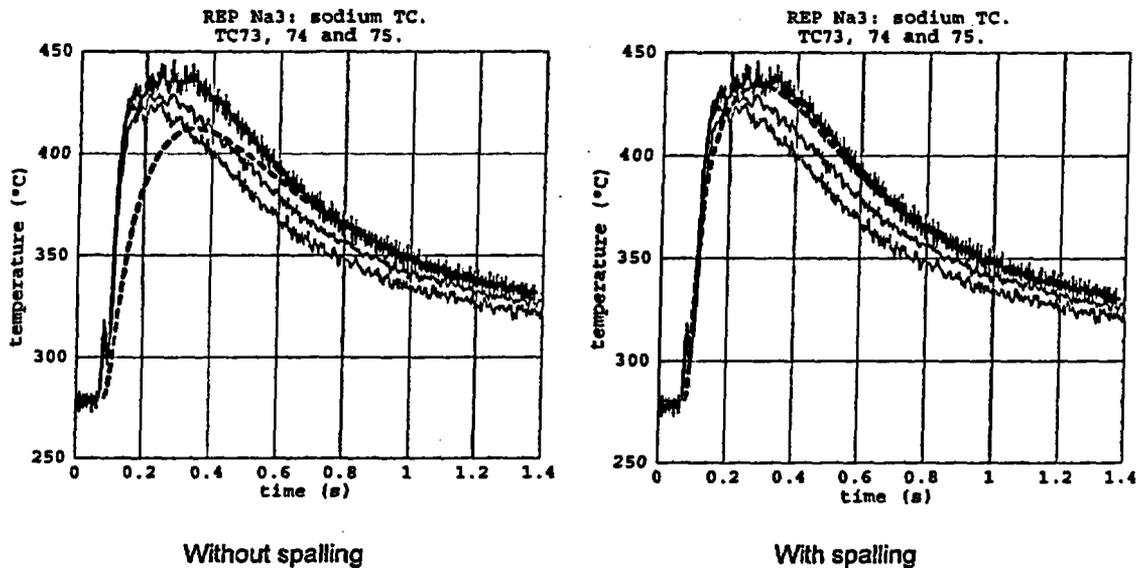


Figure 8 : REP-Na3 transient sodium temperatures at top of fissile column.

This underlines that under pressurised water conditions, transient oxide spalling might influence the clad to coolant heat transfer and hence the onset of boiling crisis.

### 3.5 Gas and fuel ejection after rod failure

Gas and fuel ejection that occurred in the failed tests REP-Na1 and REP-Na7 (see table 1) is understood as a consequence of fuel fragmentation and grain boundary separation with important driving force due to the gas pressure depending on the energy injection rate.

With  $UO_2$  fuel, the combined effects of a fast power pulse and cladding brittleness as in REP-Na1, favour gas and fuel ejection ; as a matter of fact, the multiple failures occurring early in the transient at low enthalpy level allowed additional amount of energy to be injected on a fragmented fuel with HBS zones under low clad constraint which enhanced fuel ejection into the coolant channel (6g of ejected fuel corresponding to 2% of the fissile mass). On the other hand, the lack of fuel dispersal in the REP-Na10 experiment can be understood as the result of the late rod failure with loss of rod tightness leading to small amount of energy injected after failure. However, if the REP-Na8 rod failure was initiated earlier in the zone of the hydride blister at maximum power level (as suggested by the microphone events and the radial cut RC1), the limited axial extension and the brittle-ductile shape of the crack could have prevented an early gas and/or fuel ejection.

With MOX fuel, the REP-Na7 post-failure results based on the pressure sensors, flow-meters and hodoscope (the later measuring the amount of fuel ejected into the sodium channel), indicated that a strong pressure peak (up to 200bar) occurred before the detection of fuel ejection (total ejected fuel mass of 17.5g, corresponding to 6% of the fissile mass). This underlined that a strong gas ejection contributed to the channel pressure increase, fuel-sodium interaction being a minor effect : it is however, to be noticed that a different conclusion is expected in pressurised water conditions where fuel-water thermodynamic interaction might be the dominant mechanism.

## 4 SPECIFIC ASPECTS OF MOX FUEL BEHAVIOUR

The MOX fuel is characterized by its heterogeneous structure as the result of its fabrication process (MIMAS, *Micronisation Master Blend*) which blends Pu-rich particles into a  $UO_2$  matrix (mixture of  $UO_2$  and  $PuO_2$  powders with average particle size ranging from several to several tens of micro-meters). The presence of these  $PuO_2$ -rich zones, in which fissile material is initially concentrated and local burn-up values exceed the pellet-averaged value, results in generalization of a "rim-type" structure locally distributed over the entire pellet. This effect starts at an average pellet burn-up of 30 GWd/tM and raises

the question of a possible specific behaviour under RIA transients. Grain boundary gas is in major part contained in the porosities of these PuO<sub>2</sub>-rich zones ; however, only the agglomerates of a significant size (higher than the recoil distance of fission gas atoms : 7-9 μm) are concerned, the others contributing to the increase of gas retention in the MOX fuel matrix and probably to some accumulation of fission gases at inter-granular sites. The figure 9 illustrates the estimation of the grain boundary gas fraction done on the basis of the few microprobe results presently available and shows an increase of grain boundary gas inventory in comparison to UO<sub>2</sub> fuel at similar pellet burn-up.

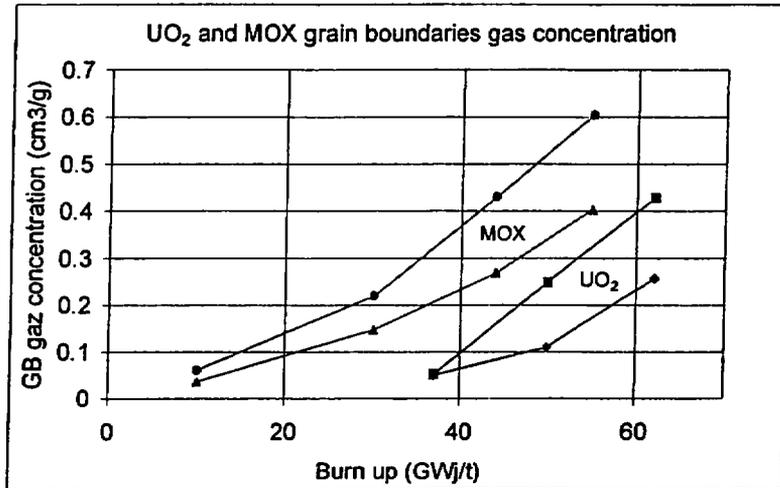


Fig. 9 : estimation of the grain boundary gas fraction versus burn-up for UO<sub>2</sub> and MOX fuel.

Consistently with this estimation, the REP-Na MOX tests evidenced higher transient FGR than in UO<sub>2</sub> fuel (fig 6) at similar pellet burn-up and under close conditions (ie REP-Na2, REP-Na9).

From the detailed analysis of the three tests performed at different burn-up levels (28, 47, 55 GWd/t), it first came out that no specific thermal effects resulting from the presence of the UPuO<sub>2</sub> agglomerates have been highlighted under RIA transients (no local fuel melting in spite of the high energy deposit in REP-Na9, no clad melt-through).

On the other hand, the tendency of the MOX fuel to have important creep rates possibly increasing with burn-up, is underlined by SCANAIR studies showing that, although the experimental clad hoop strain is well reproduced (fig.1) for the un-failed tests, the clad elongation is largely overestimated (better agreement is reached when fuel creep is simulated).

Besides, the comparison of the sodium displaced volume (representing the rod volume change) and of the clad elongation in both REP-Na6 and REP-Na7 with similar power pulses and a priori sound claddings (fig.10), showed in REP-Na7, a significant increase of the mean clad deformation above a fuel enthalpy of 60 cal/g and a decrease of the clad elongation above 85 cal/g : such results and the higher gas content in the REP-Na7 rod due to higher burn-up, suggest an enhanced contribution of the fission gases to the clad loading together with a visco-plastic MOX fuel behaviour.

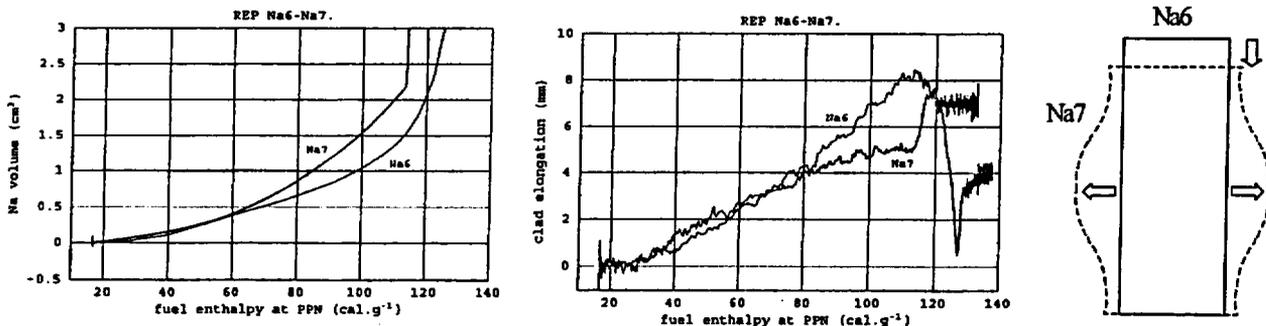


Fig.10 : Compared evolution of sodium displaced volume (left) and clad elongation (right) in REP-Na6 and REP-Na7.

However the failure mechanism of the REP-Na7 is not fully clarified. Indeed the rod failed close to the peak power level (at an enthalpy level of about 113 cal/g) with a low clad straining and an "a priori" sound cladding (low corrosion level, oxide thickness of 50  $\mu\text{m}$ ).

On the post-test examinations, the crack propagation with a "zig-zag" shape suggests the possible presence of a local brittle site near failure level, which is to be investigated by complementary post-test examinations.

## 5 MAIN OUTCOMES FOR THE MODELLING AND CODE DEVELOPMENT

The detailed interpretation of the tests led to major improvements of the physical understanding, to an improved qualification of the SCANAIR code and to new outlines for future developments.

Concerning thermal aspects, the correct description of the global thermal rod behaviour with the SCANAIR code is confirmed through the good agreement with experimental results on the sodium temperature evolution and the absence of fuel melting in the highly energetic tests (REP-Na2, REP-Na9). The heat transfer to the coolant is satisfactorily reproduced provided that one assumes a perfect fuel-clad contact in case of closed gap conditions and an early onset of the transient oxide spalling, when the latter is to occur, that is for oxide layer above 30-40  $\mu\text{m}$  with standard Zr4. However, fuel-clad heat transfer during the late phase of a RIA transient in water conditions (after significant clad heat-up, gap re-opening and under lower fuel-clad contact pressure conditions), might be different and should be determined. The effect of clad oxide spalling on the onset of boiling crisis, if any, should also be checked and evaluated under pressurised water conditions.

With regards to mechanical aspects, in case of moderate energy injection with  $\text{UO}_2$  fuel, the clad plastic hoop strain and the fuel and clad elongations resulting from PCMI loading are well described by the SCANAIR code. In case of high energy injection with  $\text{UO}_2$  fuel, the overestimation of the clad plastic hoop strain and axial elongations confirmed the need of a fuel creep modelling together with the simulation of the dishings filling. In case of MOX fuel, the modelling of an apparent macroscopic fuel creep is also needed, taking into account the influence and evolution of the large porosities of the Pu-rich zones and a possible additional contribution due to the swelling of over-pressurised porosities.

Concerning clad failure mechanism, the major influence of hydride concentration on the rod failure risk has been pointed-out. A first approach based on fracture mechanics is underway for PCMI loading and should be extended to imposed pressure loading. In parallel, an evaluation of the failure risk in case of ductile-brittle cladding has been developed on the basis of PROMETRA results. A detailed modelling of the crack initiation and propagation is needed in order to derive a robust failure criterion, taking into account the non-homogeneous structure of the cladding material.

The present understanding of the phenomena has underlined the important role of the grain boundary gases under RIA transients with its contribution on fuel micro-structure changes, fuel swelling, FGR, gas and fuel ejection after failure. The importance of a precise knowledge of the initial rod state and spatial distribution of fission gases at the end of in-reactor irradiation has been confirmed. This is particularly underlined in case of MOX fuel in which fuel micro-structure seems to play a significant role on fission gas behaviour and mechanical loading of the clad. The difficulty of the present SCANAIR modelling to reproduce the FGR results of REP-Na4 and REP-Na5 confirms the need of an improvement of the modelling taking into account the onset and extension of grain boundary cracking and the evolution of the fuel permeability for short and long term phases.

A support experimental programme devoted to the study of fission gas transient behaviour has been defined with the objectives of quantification of the phenomena for loading mechanisms and kinetics of FGR. In addition, the potential contribution of Helium has to be evaluated.

## 6 THE NEW CABRI INTERNATIONAL PROGRAMME

Despite the major findings obtained from the CABRI REP-Na programme, some aspects of the high burn-up fuel behaviour under RIA require additional investigations. Pending questions still concern the transient fission gas behaviour and the impact on clad loading during the whole transient, the rod behaviour with high clad temperature, the high internal pressure effect and the post-failure phenomena (fuel ejection, fuel-coolant interaction with finely fragmented solid fuel).

Moreover, the further burn-up increase for UO<sub>2</sub> and MOX fuel as foreseen by the utilities, led IRSN to initiate the CABRI International Programme (CIP) under OECD auspices with a broad international cooperation and partnership of EDF.

The objectives of the CIP are to provide, under typical pressurised water reactor conditions, the necessary knowledge for assessment of new RIA related criteria for advanced high burn-up UO<sub>2</sub> and MOX fuels, and evaluation of safety margins.

The CIP will consist of twelve tests as a whole, gathered in six series with the following objectives :

- CIP0 : two reference tests in the existing sodium loop with UO<sub>2</sub> fuel at 75 GWd/t and advanced claddings (Zirlo ENUSA rod, M5 EDF rod) ; both tests were realised in 2002 [11]
- CIPQ : qualification test of the water loop (checking of the absence of artefacts)
- CIP1 : tests in the water loop for comparison with CIP0 tests, using CIP0 twin rods
- CIP2 : study of very high burn-up rods behaviour (80-100 GWd/t)
- CIP3 : understanding of the physical phenomena : effect of pulse width, initial power level, post-failure phenomena, irradiation history
- CIP4 : study of high burn-up MOX fuel
- CIP5 : open tests (VVER, BWR fuels ?)

These integral tests will be coupled with mechanical characterisation of the advanced claddings for determination of the constitutive laws and failure conditions.

The first test in the water loop (CIPQ) will be performed in 2006, after renovation of the facility and installation of the water loop in the CABRI reactor.

## 7 CONCLUSION

The CABRI REP-Na programme and associated studies have provided major improvements to the understanding of the high burn-up fuel behaviour under RIA transients.

The observed failures of the UO<sub>2</sub> and MOX fuel rods ranging from 30 to 113 cal/g enthalpy levels have underlined the need of evolution of the present safety criteria.

The present understanding of the phenomena during the first phase of the transient, without significant clad temperature increase, underlined the deleterious influence on clad failure, of a high clad corrosion level with hydride concentrations ; it also revealed the difficulty of prediction of such rod failures.

However, for UO<sub>2</sub> fuel with moderate or high corrosion level, up to 80 µm thickness, the Zr4 cladding shows sufficient ductility to withstand strong PCMI caused by fuel thermal expansion and fission gas induced swelling (if fuel enthalpy higher than 110 cal/g) in the conditions of the REP-Na tests.

Significant changes of the fuel micro-structure such as fuel fragmentation, grain boundary gas expansion together with the contribution of grain boundary gases to high fission gas release increasing with burn-up level, have been understood as the result of high overpressure in the inter-granular and porosity bubbles under fast heating rates. Together with the evidence of a significant Helium release, this underlines the possible additional contribution of fission gases on clad loading, especially in case of MOX fuel due to the higher grain boundary gas inventory as compared to UO<sub>2</sub> at similar pellet burn-up. In addition, high burn-up MOX fuel has exhibited a tendency for significant creep rates.

Important clad oxide spalling during the transient has also been shown with its influence on the clad to coolant heat transfer.

Although a satisfying description of the experiments is obtained with the SCANAIR code, important knowledge has been derived for its future development and qualification.

Pending questions still concern the transient fission gas behaviour and the impact on clad loading during the whole transient, the rod behaviour with high clad temperature, the high internal pressure effect and the post-failure phenomena (fuel ejection, fuel-coolant interaction with finely fragmented solid fuel). The CABRI International Programme (CIP) already launched in 2000 (first two tests performed in 2002), will provide under typical pressurised water conditions, relevant additional knowledge relative to high burn-up UO<sub>2</sub> and MOX advanced fuels.

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In the matter of Duke Catawba

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Intervenor  \_\_\_\_\_ REJECTED \_\_\_\_\_

Cont'g Off'r \_\_\_\_\_

Contractor \_\_\_\_\_

Other \_\_\_\_\_

Reporter Rita Huber \_\_\_\_\_