UPDATED RIA CRITERIA IN FRANCE

C. BERNAUDAT (*), H. BILLAT, J.J. VERMOYAL, N. WAECKEL
Electricité de France, DIPNN/DT, 19 rue Pierre Bourdeix, CS 80323, F-69363 Lyon Cedex 07

A. KECECIOGLU
Electricité de France, R&D/MMC, F-77250 Orvanne

(*) Corresponding Author, Tel: +33 4 7282 7138, e-mail: christian.bernaudat@edf.fr

ABSTRACT

This paper presents the updated safety criteria applicable to REA transients in PWRs, defined on the basis of the full-scale RIA tests for the different rod designs used in the French NPP fleet. These criteria cover all discharge burnups and depend on the fuel and cladding materials. They aim at precluding rod failure by oxidation-embrittlement at low burnup, and by PCMI at high burnups. The starting of the CIP programme in the new pressurized water loop of the Cabri reactor will help assessing rod failure conditions by clad ballooning after DNB onset.

1. Background

1.1 Safety requirements in PCC4 situations

According to the French safety regulation regarding nuclear installations, the safety requirements applicable to PCC-4 situations are the following:

i) To maintain the integrity of the 2nd containment barrier (i. e; the core vessel and its internal structures);
ii) To maintain a coolable geometry of the core, and;
iii) To limit the radiological consequences of the accident.

In order to meet these requirements, some dispositions can be taken in order to:

i) Preclude fuel dispersal in the primary circuit; this allows maintaining both a coolable geometry of the core and the integrity of the 2nd barrier, by avoiding deleterious consequences such as a mechanical loading due to the pressure wave generated by violent fuel-coolant interaction;
ii) Limit the number of rods that undergo DNB onset and, as a consequence, are assumed to be failed.

A more conservative surrogate to these dispositions consists in precluding fuel rod cladding failure; this allows meeting all the safety requirements simultaneously, although it is not, strictly speaking, required in accidental (PCC-4) situations.

1.2 The current RIA criteria

In order to fulfill the safety requirements, the following criteria have been proposed by EDF [1]:

i) At low burnup (Bu < 33 GWd/tM, F/A average), the maximum averaged fuel enthalpy shall be lower than 200 cal/g in order to preclude fuel dispersal in the coolant channel; this limit is based on prototypical full-scale tests performed in SPERT-CDC and PBF and has been confirmed for both UO2 and MOX fuels by the results of Cabri tests REP-Na2 and REP-Na9, respectively.
ii) At high burnups (Bu > 47 GWd/tM, F/A average), a “safety domain” is defined by:
    a. A maximum fuel enthalpy rise (ΔH) lower than 57 cal/g;
    b. A pulse width at mid-height (L1/2) greater than 30 ms;
    c. A clad temperature lower than 700°C.

The limits on ΔH and L1/2 are based on the analysis of full-scale tests performed in Cabri on UO_2/Zircaloy-4 rods with highly oxidized claddings and waterside zirconia layer spallation, namely REP-Na8 and REP-Na10 tests. The limit on clad temperature has been proposed in order to preclude the deleterious effects of DNB onset in PWR conditions, since this situation could not be reproduced in the sodium loop of the Cabri facility.
The ASN (the French Nuclear Safety Authority) has agreed these criteria, but only for clad materials or situations for which no zirconia layer spallation occurs. For Zircaloy-4 cladding, spallation cannot be precluded for zirconia layers thicker than 80 µm. In this situation, specific limits and plant operation specifications had to be defined.

1.3 Drawbacks of the existing criteria

The criteria described hereabove exhibit two major drawbacks:

i) Nothing has been proposed for intermediate burnups, i. e. between 33 and 47 GWd/tM (F/A average).
ii) In the recent years, many full-scale tests have been performed on high-burnup rods with M5™, Zirlo® or M-MDA claddings: REP-Na11, CIP0-1 and CIP0-2 in the Cabri sodium loop in France, RH-1, RH-2, GR-1 and the VA, BZ and OI series in the NSRR in Japan. The results of these tests show that the current criteria seem too restrictive and could be relaxed and/or cancelled.

2. Bases for RIA criteria definition and assessment

2.1 General review of the safety criteria

In June 2017, the Permanent Experts' Group held a meeting devoted to a general review of all the safety limits applicable to all situations: normal operation (PCC-1), off-normal transients (PCC-2) and accident transients, except for LOCA (PCC-3 and PCC-4). Within this review, the limits applicable to RIA transients had to be reviewed and documented prior to the meeting. The main conclusions of this review regarding RIA transients are described in the following sections.

2.2 Basic principles

The reviewed RIA criteria are devoted to cover all burnups and, beyond 33 GWd/tM, to preclude clad failure by PCMI (clad failure by ballooning after DNB onset is not considered). With such a loading, the mechanical parameter that governs clad failure is the material total elongation. This parameter is strongly dependent on clad hydriding (both the H content and hydride morphology). As a consequence:

i) Tests triggered at low temperature enhance hydrogen precipitation and tend to exacerbate the cladding embrittlement;
ii) Fully RXA cladding materials enhance the build-up of radially oriented hydride platelets, which also exacerbate the cladding embrittlement.

So the assessment of RIA criteria is highly related to the OPEX regarding cladding waterside oxidation and subsequent hydriding during base irradiation.
Moreover, in order to define and assess new RIA criteria, the choice has been made to analyse the RIA full-scale test database.

2.3 The RIA full-scale test database

Since 1999, a significant number of full-scale tests have been performed in France and Japan. In France, the last tests performed in the Cabri sodium loop (between 2000 and 2002) are described in Table 1 below.

Test	Fuel	Clad	Rod Bu (GWd/tM)	ZrO2 layer thickness (µm)	[H] (ppm)	ΔH (cal/g)	L1/2 (ms)	F/NF
REP-Na11	UO2	M5	63	15	- (a)	77.1	30.7	NF
CIP0-1	UO2	Zirlo	75	100-110	1000 (b)	78.6	32	NF
CIP0-2	UO2	M5	77	20	- (a)	67.7	28	NF

Table 1: main features of the last tests performed in Cabri (2000-2002)

N.B.: (a) Value not reported but certainly below 100 ppm
(b) With local values up to 3000 ppm at pellet-pellet interface locations

In Japan, many tests have been performed within the framework of the ALPS programme in order to explore high burnups (up to 85 GWd/tM) and advanced cladding materials (M5, Zirlo, MDA, M-MDA, NDA). These tests include the VA series (8 tests), the OI series (3 tests), the BZ series (4 tests on MOX fuel rods) and RH-1, RH-2 and GR-1 tests (all on UO2/M5 rods). Table 2 recalls the main features of these tests.

Test	Fuel	Clad	Rod Bu (GWd/tM)	ZrO2 layer thickness (µm)	[H] (ppm)	ΔH (cal/g)(c)	L1/2 (ms)	F/NF
VA-1	UO2	Zirlo	71	73	660	64	4.4	F
VA-2	UO2	MDA	77	70	760	55	4.4	F
VA-3 (a)	UO2	Zirlo	71	82	670	82	4.4	F
VA-4 (a)	UO2	MDA	77	80	760	108	4.4	NF
VA-5	UO2	MMDA-SR	81	30	(236) (b)	71	4.4	F
VA-6	UO2	MMDA-RX	78	60	(440) (b)	34	4.4	F
VA-7 (a)	UO2	MMDA-SR	81	30	(236) (b)	115	4.4	NF
VA-8	UO2	MMDA-RX	78	60	(440) (b)	42	4.4	F
BZ-1	MOX	Zy-4	48	30	340	76	4.4	F
BZ-2	MOX	Zy-4	59	20	160	130	4.4	F
BZ-3 (a)	MOX	Zy-4	59	20	160	126	4.4	NF
BZ-4	MOX	Zy-4	59	20	140	108	4.4	NF
RH-1	UO2	M5	67	6	70	110	4.4	NF
RH-2 (a)	UO2	M5	67	6	70	89	4.4	NF
GR-1	UO2	M5	85	15	-	110	4.4	NF
OI-10	UO2	MDA	60	27	(216) (b)	107	5.6	NF
OI-11	UO2	Zirlo	58	28	400	124	4.4	F
OI-12	UO2	NDA	61	41	(311) (b)	149	4.4	NF

Table 2: main features of the recent NSRR tests
N.B.: (a) Test performed in the HTHP capsule (stagnant water at 68 bars, 280°C)
(b) Estimation on the basis of the ZrO2 layer thickness
(c) If failure occurs, the enthalpy rise at failure is reported

2.4 French NPP fleet operation

Table 3 below gathers valuable information on the French NPP fleet operation. It is interesting to notice that fuel rods with Zirlo or M5 claddings are now widely used. Rods with Zircaloy-4 claddings are progressively disappearing from the reactors (the last UO2/Zy-4 fuel assembly reload has been delivered in 2016).

Core management	NPP type	Number of reactors	Number of FAs in the core	Cycles (number x duration (months))	Rod designs
CYCLADES	CP0 (900MW)	6	157	3 x 18	UO2/Zy-4, UO2/M5
GARANCE	CPY (900MW)	6	157	4 x 12	UO2/Zy-4, UO2/Zirlo
MOX-Parity	CPY (900MW)	22	157	4 x 12	UO2/Zirlo, MOX/M5
GEMMES	PQY (1300MW)	20	193	3 x 18	UO2/Zirlo, UO2/M5
ALCADE	N4 (1450MW)	4	205	3 x 17	UO2/M5
EPR	EPR (1600MW)	1	241	4 x 18	UO2/M5

Table 3: main features of the core managements applied on the French NPP fleet

3. Definition of the updated criteria

3.1 Criteria applicable at any burnup

As was already the case before the review, two safety limits have been kept unchanged:

i) The number of rods that undergo DNB onset (and are considered as failed) shall be limited to 10% of the whole core. This decoupling limit has been established to limit the radiological consequences of the accident. It must be kept since the non-failure criteria described hereunder do not address clad failure by ballooning after DNB onset.
ii) The clad temperature shall remain below 1482°C. This limit was originally established to preclude clad failure by high-temperature oxidation and embrittlement. For long transients, it has been replaced by a limit expressed in ECR, which takes into account the clad temperature history. For short transients, according to the Baker-Just correlation [2], the 1482°C limit is consistent with a transient duration shorter than 20 seconds, which is always the case for RIA transients where the DNB duration is less than 10 seconds.

3.2 Criteria applicable at low burnups

For low burnups (i. e. below 33 GWd/tM F/A average), the criteria have been kept unchanged since no new tests have been performed on low-burnup rods. The maximum averaged fuel enthalpy is limited to 200 cal/g. This limit has been defined, on the basis of the SPERT and PBF test series, to preclude fuel dispersal in the coolant channel. It has been confirmed for both UO2 and MOX fuel rods, by the results of the Cabri REP-Na2 and REP-Na9 tests, respectively. It is worth noticing that these tests have been performed in conservative conditions compared to PWR ones, since no DNB was possible in the Cabri sodium loop.

The fuel enthalpy limit is applicable whatever the core management and the related fuel rod designs.

3.3 Criteria applicable at intermediate and high burnups

For burnups beyond 33 GWd/tM, the safety limits have been reviewed on the basis of the results of all the tests described in Tables 1 and 2. These limits are expressed in fuel average enthalpy rise and depend on both the fuel and cladding materials.

3.3.1 For Zircaloy-4 cladding

The safety limit is based on CIP0-1 test (see Table 1). Since it is applicable only for oxidation levels below 80 µm, where zirconia spallation is not supposed to occur, the CIP0-1 test is bounding in terms of waterside oxidation and subsequent cladding hydriding. Although the cladding material was not Zircaloy-4, it had a similar microstructure (CWSR) and thus a similar hydride morphology. By taking into account the uncertainty on the injected energy, the safety limit is defined by:

i) $\Delta H \leq 75$ cal/g

ii) $L1/2 \geq 30$ ms.

For oxidation levels above 80 µm, specific limits, based on a detailed analysis of the REP-Na1 test [3] and expressed in fuel enthalpy variations, have been established to preclude fuel dispersal in the coolant, since the cladding failure cannot be avoided. These limits are coupled with reactor operation limitations.

3.3.2 For Zirlo cladding

Since no spallation has been observed so far on irradiated and oxidized Zirlo claddings, the safety limit is identical to the one applied to Zircaloy-4 claddings, whatever the level of oxidation and hydriding. Figure 1 below illustrates the OPEX in terms of oxidation and hydriding of Zirlo claddings in the French reactors. This OPEX is limited to ca. 60 µm and 600 ppm, respectively, and is thus well bound by the features of the rodlet tested in CIP0-1.

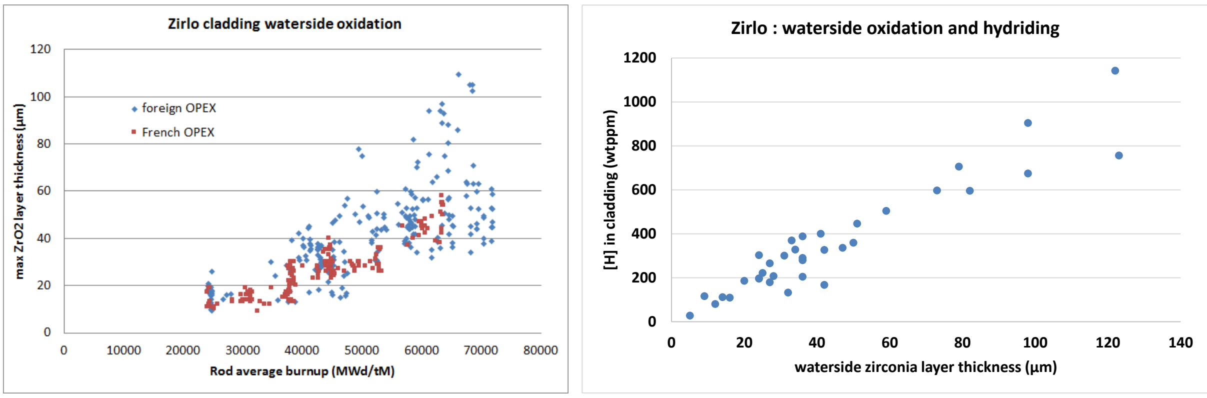

Figure 1: French OPEX in terms of oxidation and hydriding of Zirlo claddings

3.3.3 For UO2 fuel with M5 cladding

First, the irradiation OPEX in French reactors shows that the zirconia layer thickness and H content in the cladding are limited to ca. 20 µm and 100 ppm, respectively (Figure 2). Then, the full-scale test database (Tables 1 and 2) shows that no failure occurs on rodlets with M5 claddings with an enthalpy variation up to 110 cal/g (RH-1 and GR-1 tests in NSRR). A more careful examination of the database (Figure 3) reveals that seven tests on rodlets with Zircaloy-4 claddings and a low level of oxidation and hydriding ended in rod survival with enthalpy variations greater than 150 cal/g and H content up to 170 ppm. The only tests that ended in rod failure are:

i) Some tests of the FK series with RXA Zircaloy-2 cladding and [H] ~ 180 ppm;

ii) Tests TK-2 and HBO-1 with CWSR Zircaloy-4 cladding and [H] ~ 200 ppm.

iii) Test TK-7 with CWSR Zircaloy-4 cladding and [H] ~ 223 ppm.

With such results, it is possible to conclude that clad failure is unlikely for rods with M5 claddings submitted to an enthalpy variation up to 150 cal/g (or 140 cal/g by taking into account the 7% uncertainty on the injected energy in NSRR tests). Moreover, no limitation is required on the pulse width since most of the tests (the TK series) have been performed with very narrow pulses (L1/2 = 4.4 ms). It is worth recalling that these test conditions are very conservative, since the tests are triggered at room temperature and the narrow pulses induce a cladding PCMI over-deformation due to the barrel-shaped deformation of the fuel pellets (Figure 4).

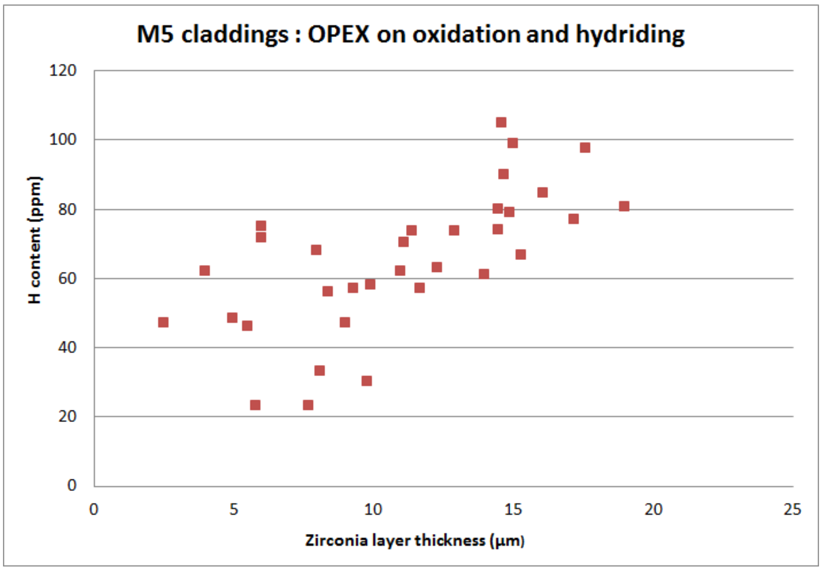

Figure 2: OPEX on oxidation and hydriding of M5 claddings in French reactors

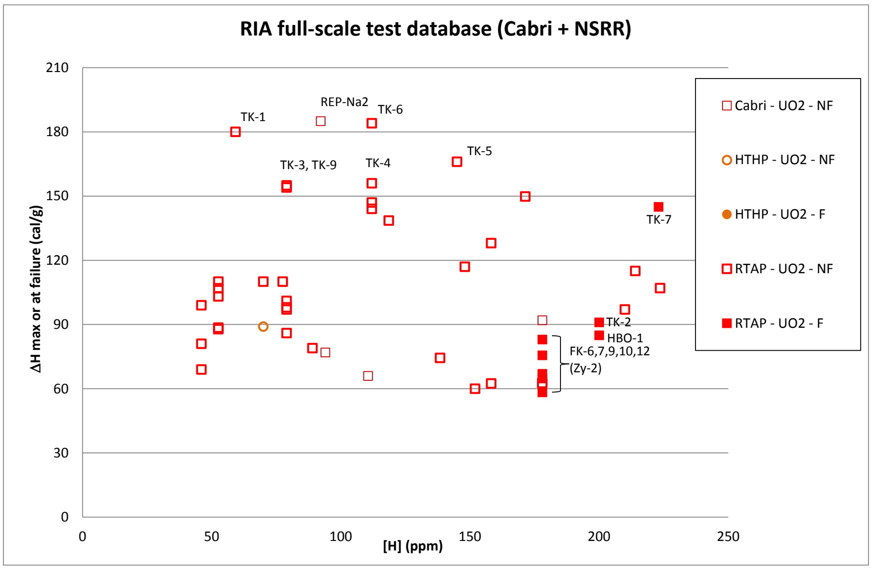

Figure 3: the RIA full-scale test database on UO2 rodlets with low levels of cladding oxidation and hydriding

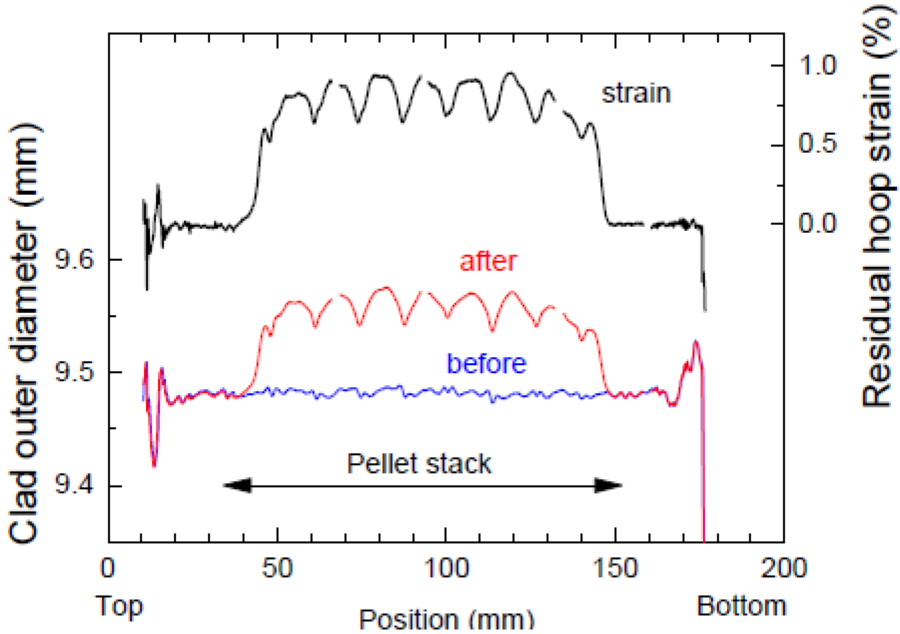

Figure 4: rod diameter profilometry after RH-1 test showing the local effects of PCMI due to the narrow power pulse

3.3.4 For MOX fuel with M5 cladding

Up to now, no tests have been performed on rodlets with MOX fuel and M5 cladding. The only reliable tests on MOX fuel have been performed on Zircaloy-4-cladded rods. They are the following:

Test	Fuel	Clad	Rod Bu (GWd/tM)	ZrO2 layer thickness	[H] (ppm) (b)	ΔH (cal/g)(c)	L1/2 (ms)	F/NF

				(µm)				
REP-Na6	MOX-AUC	Zy-4	47	44	(303)	116	32	NF
REP-Na7	MOX-AUC	Zy-4	55	48	(330)	96.2	40	F
REP-Na9	MOX-AUC	Zy-4	28	18	(132)	183	33	NF
REP-Na12	MOX-AUC	Zy-4	65	72	(488)	87	62.5	NF
BZ-1	MOX-SBR	Zy-4	48	30	340	76	4.4	F
BZ-2	MOX-AUC	Zy-4	59	20	160	130	4.4	F
BZ-3 (a)	MOX-AUC	Zy-4	59	20	160	126	4.4	NF
BZ-4	MOX-AUC	Zy-4	59	20	140	108	4.4	NF

Table 4: RIA tests performed in Cabri and NSRR on MOX fuel irradiated in PWR

NB: (a) test performed in the HTHP capsule of NSRR
(b) values in brackets are estimations based on the ZrO2 layer thickness measurement
(c) maximum or at-failure value.

On the basis of these results, it is possible to conclude that failure of MOX/M5 rods (with H content below 100 ppm) is unlikely for enthalpy variations up to 108 cal/g, or 100 cal/g if we consider the uncertainty on the injected energy. This value is based on BZ-4 test, for which the clad profilometry clearly shows the effects of PCMI loading (Figure 5). The BZ-3 test has not been used since the cladding underwent significant deformation by ballooning. Nevertheless, this test allows applying the ΔH limit of 108 cal/g for hydrogen contents up to 160 ppm. Moreover, as a conservatism, a lower bound of 30 ms is applied on the pulse width.

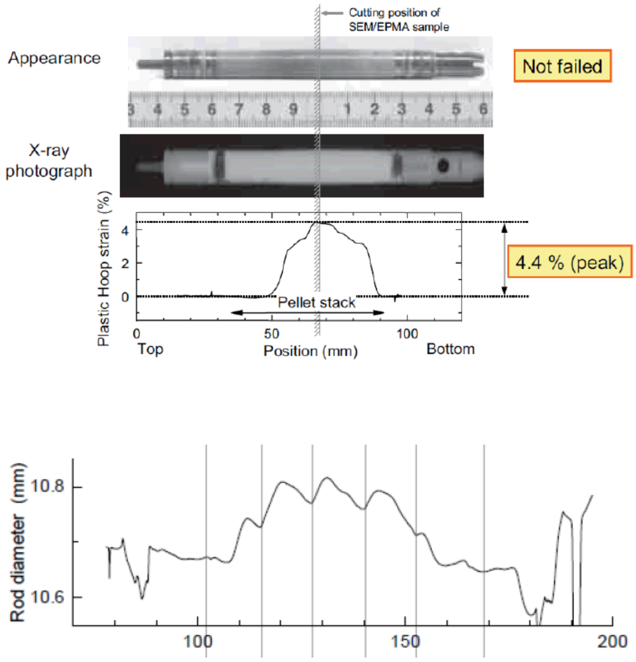

Figure 5: rod diametrical profilometries after BZ-3 (top) and BZ-4 (bottom) tests, showing ballooning for BZ-3 and PCMI loading for BZ-4

3.4 Synthesis

Table 5 below summarizes the safety limits applicable to RIA transients, according to the phenomena to preclude, the burnup range and the nature of fuel and clad materials.

Phenomenon to	Burnup range	Fuel/clad materials	Safety limits

preclude	(GWd/tM, F/A average)		
DNB (and postulated rod failure)	Any	Any	NCE ≤ 10%
Clad failure by oxidation and embrittlement	Any	Any	Tclad ≤ 1482°C
Fuel dispersal	≤ 33	Any	Hmax ≤ 200 cal/g
Clad failure by PCMI	> 33	UO2/Zy-4, eZrO2 ≤ 80 µm	ΔH ≤ 75 cal/g L1/2 ≥ 30 ms
		UO2/Zy-4, eZrO2 > 80 µm	Specific limits to preclude fuel dispersal
		UO2/Zirlo	ΔH ≤ 75 cal/g L1/2 ≥ 30 ms
		UO2/M5	ΔH ≤ 140 cal/g
		MOX/M5	ΔH ≤ 100 cal/g L1/2 ≥ 30 ms

Table 5: summary of safety limits applicable to RIA transients

All these criteria are applicable for transients initiated in HZP conditions. For transients initiated at power, the verification is made as follows:

i) The clad diametrical anelastic strain is calculated for the RIA transient initiated at zero power;

ii) For all the transients initiated at power, the clad strain is calculated and compared to the one obtained at zero power.

4. Conclusions and perspectives

In 1999, EDF proposed safety limits applicable to RIA transients at high burnups, on the basis of the full-scale tests performed so far. These safety limits were agreed by the French Nuclear Safety Authority, but only for fuel rods without zirconia layer spallation and subsequent cladding embrittlement by hydride lenses. Since this date, a lot of tests has been performed in France and Japan, to explore high burnups and advanced cladding materials. The results of these tests revealed that the safety limits previously defined were too restrictive. Moreover, they did not address intermediate burnups.

In June 2017, the Permanent Experts' Group held a meeting during which updated safety limits had to be examined for normal, off-normal and accident situations. Among these limits, updated RIA criteria have been defined for all burnups and all fuel rod designs, on the basis of the full-scale test results obtained between 2000 and 2014. These limits are intended to preclude fuel dispersal in the coolant for burnups up to 33 GWd/tM, and clad failure by PCMI beyond this value.

A better understanding of the fuel rod behavior during RIA transients will be achieved with the completion of the CIP test matrix, which is to be performed in the new pressurized-water loop of the Cabri reactor. The tests are scheduled on various rod designs including UO2/M5, UO2/Zirlo, UO2/Optimized-Zirlo, MOX/M5 with different initial pressure levels, and others. The most interesting phenomena that are to be explored through these tests are clad ballooning after DNB onset in PWR conditions and post-failure events.

Glossary: abbreviations, acronyms and notations

ASN	Autorité de Sûreté Nucléaire (French Nuclear Safety Authority)
CIP	Cabri International Programme
CWSR	Cold-Worked, Stress-Relieved (cladding material)
DNB	Departure from Nucleate Boiling
ΔH	enthalpy variation
ECR	Equivalent Cladding Reacted
EDF	Electricité de France
eZrO2	Zirconia layer thickness
F/A	Fuel Assembly
HTHP	High Temperature, High Pressure
L1/2	pulse width at mid-height
LOCA	Loss Of Coolant Accident
MOX	Mixed Oxide (U-PuO2)
NSRR	Nuclear Safety Research reactor (Japan)
OPEX	OPerationg EXperience
PBF	Power Burst Facility (USA)
PCC	Plant Condition Category
PCMI	Pellet-Cladding Mechanical Interaction
PWR	Pressurized Water Reactor
RIA	Reactivity-Initiated Accident
RXA	Recrystallized (cladding material)
SPERT-CDC	Special Power Excursion Reactor – Capsule Driver Core (USA)

References:

[1] B. Salles, N. Waeckel, C. Bernaudat: “EdF Proposed Safety Domain for Rod Ejection Accident in a PWR”, *ANS Topical meeting on Light Water Reactor Fuel, April 10-13, 2000 Park City, Utah, USA.*

[2] L. Baker, L.C. Just: “Studies of metal-water reactions at high temperatures – III. Experimental and theoretical studies of the zirconium-water reaction”, *ANL 6548, May 1962.*

[3] R. L. Yang, “Resolving our Understanding of REP-Na1 - Microstructural Analysis”, *Proceedings of the 2004 International Meeting on LWR Fuel Performance, Orlando, FL, September 2004, pp. 565-575.*