ANALYSIS OF CABRI DRIVER CORE NEW SAFETY DEMONSTRATION FOR FUEL RODS INTEGRITY DURING FAST POWER TRANSIENTS

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ABSTRACT

As the technical support of the French Nuclear Safety Authority, IRSN examined the new methodology proposed by the operator of the CABRI experimental reactor to insure the cladding integrity of the driver core fuel rods during fast reactivity insertion tests. This new methodology associates new criteria based on temperature and hoop strain limits with the use of thermal mechanical simulations predicting behavior of rods during transients. This methodology is based on physical analysis of foreseen failure modes of stainless steel cladding during fast reactivity transients. IRSN approach consists first in an analysis of the results of past experiments realised in SPERT (USA) and NSRR (Japan) facilities on fuel rods similar to CABRI ones. These integral experiments consist in submitting a single fuel rod to very short period power transients with various levels of injected energy. In the past, it led to identify a failure limit in terms of maximum injected energy. After analysing these experiments, thermal mechanical simulations performed with SCANAIR code on future CABRI experiments have been realised. SCANAIR code is devoted to thermal mechanical behavior simulations of fuel rods during reactivity injection accident (RIA). Those simulations allowed IRSN to compare precisely the failure limit resulting from past integral experiments with the failure limits issued from the new methodology proposed by the operator of CABRI.

Keywords: RIA, safety criteria, cladding integrity, clad failure limit, injected energy, SCANAIR, CABRI.

1. Introduction

The CABRI reactor is an experimental facility located on the French Commissariat à l'Energie Atomique (CEA) site at Cadarache (FRANCE), devoted to the study of core fuel rods behavior under simulated reactivity initiated accident condition. The reactor includes:

- A driver core with a nominal power of 25MW cooled with water in forced convection. This driver core includes slightly enriched fuel rods (6% in U_{235}) and a stainless steel cladding material,
- An experimental loop, with its own cooling system. A part of this loop is located at the centre of the driver core and contains the instrumented test device with the experimental fuel pin.

The fast power transients are simulated by nuclear pulses generated thanks to "transient rods", which consist of gaseous absorber rods (Helium 3 gas). The mean increasing reactivity is 3 \$ with a 50 \$/s ramp.

Since 1978, experiments were carried out on fast breeder reactor (FBR) and pressurized water reactor (PWR) fuel pins cooled by sodium in the experimental loop. Then, it was decided at the beginning of the years 2000 to replace the experimental sodium-cooled loop by a pressurized water loop able to recreate the thermal-hydraulic conditions of a PWR. The replacement of the experimental loop leads to a global review of the safety assessment of the reactor. This paper deals with one specific point of the safety assessment: the new safety criteria defined to warrant driver core cladding integrity during the future tests.

2. CABRI driver core new safety criteria

2.1 CEA criteria

The operator of CABRI facility, CEA, considered two possible failure modes of the clad fuel rod [1] during power transients in the reactor: clad melting and ductile rupture.

Therefore, CEA proposed two new criteria [1] to warrant the cladding integrity of the driver core during the future tests:

- The first criterion is the maximum clad temperature allowed. In order to prevent the clad from melting, it must be lower than 1300°C. The operator applies a margin of 150°C to the melting temperature of the stainless steel cladding material (1450°C).
- The second criterion concerns the maximum clad hoop strain, which must be lower than 3.65% to prevent from ductile rupture. This figure is 50% of the lowest value of the rupture elongation measured on samples representatives of the clad.

Furthermore, as it was the case in the former safety demonstration, fuel melting is prohibited. Maximum fuel temperature should remain below 2800°C.

These criteria are verified thanks to thermal mechanical simulations to predict behavior of rods during transients, using the SCANAIR computer code (see § 4).

2.2 IRSN approach

As the technical support of the French Nuclear Safety Authority (ASN), IRSN has examined the new criteria submitted by CEA. For that purpose, IRSN considered the results of past experiments realised in SPERT and NSRR facilities on fuel rods similar to CABRI ones. These integral experiments, very close to CABRI ones, described in the next section (§ 3), consisted in submitting a single fuel rod to very short power transients. It aimed at identifying the failure threshold as a maximum injected energy.
IRSN objective is then to compare the new criteria defined by CEA with this failure threshold. To do so, IRSN computed by means of the SCANAIR code, clad and fuel temperatures, hoop clad strains and injected energies of the hottest rod of the driver core for transients that are representative of future CABRI experiments.

3. Overview of SPERT and NSRR experiments results

The analysis of past experiments results realised in SPERT and NSRR facilities on fuel rods, similar to CABRI ones, is here presented.

3.1 SPERT experiments results

The SPERT experiments were conducted in the United States in the 1960's and 1970's. Unirradiated UO_2 fuel rods with different cladding materials [2] were subjected to a single power burst in order to determine the approximate injected energy in the fuel rods required to cause clad failure, and to obtain information on the consequences associated with tests where failure occurred. The injected energy is given at the axial flux peak [3].

SPX and F-type fuel rods clad with Type-304 annealed stainless steel were tested in the Capsule Driver Core (CDC); their main characteristics are detailed in Table 1, compared with CABRI core fuel rods. The SPX rods contained 3% and 10% of enriched pelletized UO_2 cladded with ¼-inch OD annealed stainless steel [4] whereas the F-type fuel rods contained 4.8% enriched pelletized UO_2 fuel cladded with 0.466-inch OD annealed stainless steel [3].

Characteristics	Fuel rod type F-type	Fuel rod type SPX	CABRI driver fuel rod
UO2 pellet			
Diameter (mm)	10.67	5.59	9.19
Length (mm)	15.2	11.4	11.5
Density (%T.D.)	92	95	94
Enrichment (%)	4.8	3 / 10	6
End shape	flat	flat	Chamfered
Cladding			
Material	304-SS	304-SS	Al Si 304-SS
Outer diameter (mm)	11.84	6.35	10.0
Wall thickness (mm)	0.508	0.356	0.4
Fuel rod			
Pellet-cladding gap (mm)	0.076	0.025	0.05
Fuel length (mm)	910	460	800
Plenum gas	He	He	He
Overall length (mm)	1060	530	800

Table 1 : Characteristics of the SPERT-CDC test fuel rods

A series of 7 and 47 fuel performance tests has been respectively conducted on SPX and F-type fuel rods. Single rods encapsulated in stagnant water at ambient temperature and atmospheric pressure were subjected to injected energies ranging from about 200 to 570 cal/g (type SPX) and about 50 to 300 cal/g (F-type). The instrumentation of all tests is described in [3, 4].

The initial failure threshold for stainless steel clad SPX rods was determined to be in range of 244 to 276 cal/g (Table 2). Initial cladding failure was apparently by cladding melting, and subsequent cladding failure was by cracking, probably occurring during the quenching or cooldown cycle. Finally, a total of 4 tests involved failure by cladding melting.
Cladding failure in the form of melting was first observed by the authors at 276 cal/g, with a 3.05ms reactor period test (test 329). The maximum measured cladding surface temperature rise of 1330°C occurred about 1.5s after peak power at the 10-inch elevation. The melted cladding had slumped onto the intermediate space wires. The cladding surface oxidation was advanced. Similar results have been obtained with the test 323 by considering a 10%-enriched rod with 6.4ms reactor period test and 277 cal/g.
For injected energies greater than 400 cal/g, failure occurred prior to melting, indicating that internal pressure contributed to the failure.

The initial failure threshold for stainless steel clad F-type rods was in the range of 263 to 278 cal/g (Table 2). The documentation of the test results [2] showed that one test (test 203) conducted to failure by cladding melting and two tests (tests 188 and 193) to failure by cracking. Among these two cases of rupture by cracking, the post-rupture analyses of the first one (single test n°193) showed small patches of melted cladding and a longitudinal cladding crack ~1.3cm long, and the second one was a sequential test (test 182-188). The rod had seen 7 sequential tests, at reactor periods from 25 to 3.5ms with injected energies ranging from 57 to 257 cal/g, resulted in progressive bowing, cladding growth and cladding discoloration. The cladding showed significant deterioration, with air activity measurements indicating a loss of cladding integrity following the final test (seventh test n°188). In fact, the sharp bow in the region of the lower intermediate spacer caused one of the spacer set screws to significantly indent the clad [4].

Parameter	Fuel rod type SPX			Fuel rod type F-type			
	Test 322	Test 329	Test 323	Test 187	Test 188	Test 192	Test 193
Injected energy	244 cal/g	276 cal/g	277 cal/g	200 cal/g	257 cal/g	263 cal/g	278 cal/g
Reactor period	3.5ms	3.05ms	6.4ms	4.1ms	3.5ms	3.4ms	3.2ms
Maximum cladding temperature	1210°C	1330°C	1380°C	-	-	1195°C	1255°C
Cladding elongation	1.44%	-	-	-	-	0.88%	0.84%
Cladding surface oxidation	Full oxidation	Full oxidation	Full oxidation	Full oxidation	Full oxidation	Full oxidation	Full oxidation
Failure mode	No failure + bowing	No failure + bowing	Failure by cladding melting	No failure + bowing	Formation of crack split	No failure + bowing	Formation of crack split

Table 2 : Failure limit in terms of maximum injected energy for some tests with SPX and F-type fuel rods

In conclusion, 7 fuel rod tests out of 54 have failed. The failure mechanism was mainly the cladding melting. The extent of the cladding oxidation was important. The initial failure threshold for stainless steel clad rods was in the range of 244 to 278 cal/g, with a reactor period between 3 and 6ms.

3.2 NSRR experiments results

The NSRR experiments were performed in Japan, in the 1970's, to study the failure behavior of unirradiated stainless steel clad fuel rods, under a simulated reactivity initiated accident (RIA) condition in water environment [5]. The authors have compared the obtained fuel rod failure behavior to that of Zircaloy fuel rods, examined previously in the NSRR facility.

The test fuel rod was installed in a capsule filled with stagnant water at atmospheric pressure and room temperature, and subjected to injected energies ranging from 114 to 457 cal/g.

The main characteristics of stainless steel and Zircaloy cladded fuel rod clad are detailed in Table 3 and compared with CABRI core fuel rod characteristics.

A total of 10 tests with stainless steel cladding rods were then conducted in the NSRR facility [5] by increasing the injected energy. No visual change was observed at an injected energy of 114 cal/g. The various tests showed that the extent of the oxidation and the deformation became greater with increasing injected energy. Indeed, the cladding was oxidized and deformed at 157 cal/g. The last non failed fuel rod occurred at 221 cal/g with an important cladding oxidation. The fuel rod failure occurred at an injected energy of 258 cal/g, due to local melting of the cladding.

Characteristics	NSRR stainless steel clad	NSRR Zircaloy clad	CABRI driver fuel rod
UO2 pellet			
Diameter (mm)	9.54	9.29	9.19
Length (mm)	10.	10.	11.5
Density (%T.D.)	94.4	95.	94.
Enrichment (%)	10.	10.	6.
Shape	Chamfered	Chamfered	Chamfered
Cladding			
Material	Stainless steel (type 304)	Zircaloy-4	Al Si 304-SS
Outer diameter (mm)	10.53	10.72	10.
Wall thickness (mm)	0.40	0.62	0.4
Fuel rod			
Pellet-cladding gap (mm)	0.095	0.095	0.05
Fuel length (mm)	135.	135.	800.
Plenum gas (MPa)	He 0.1	He 0.1	He 0.5
Overall length (mm)	279.	265.	800.

Table 3 : Characteristics of the NSRR test fuel rods

The results of the study allowed the authors to conclude the following:

- The failure threshold energy of the stainless steel clad fuel rod was determined to be between 221 and 258 cal/g, almost 240 cal/g. This value was about 20 cal/g lower than that of the Zircaloy clad fuel rod.
- The failure mechanism of the stainless steel clad fuel rod is the cladding melting whereas the oxygen-induced embrittlement was observed in the Zircaloy clad fuel rod in the same test condition.
- The radial expansion of the fuel rod depends on the thermal expansion of the fuel and the initial gap width between the fuel and the cladding, regardless of cladding material.

3.3 Discussion

The integral experiments realised in SPERT reactor and NSRR reactor were used to define failure criteria based on injected energy in rod during the transient. The rods used during these tests had mechanical characteristics close to those of the rods of the CABRI reactor (UO_2 fuel and stainless steel clad). Thermal hydraulic conditions were also similar in terms of stagnant water at ambient temperature and of atmospheric pressure.

One of the main differences between those experiments and the foreseen transients in CABRI concerns the pulse width. The narrowest pulses of the future CABRI transients have a full with at half maximum of 10 ms. Reference [6] presents a synthesis of past RIA experiments and precise that the natural pulse width of SPERT CDC core is about 20 ms and NSRR about 5 ms. Thus these values constitute an interval in which is included CABRI value of 10 ms.

The obtained results are consistent between the two studies. Indeed, the identified failure mechanism is the melting cladding. The tested fuel rods have also undergone a significant oxidation without lowering the clad strength as much as to induce failure.

In both cases, injected energy values leading to rod failure are close: it is estimated at 240 cal/g in the NSRR experiments and in the interval of [244, 278] cal/g in the SPERT experiments. Moreover the lower NSRR value is consistent with the fact that this reactor produces very narrow pulses. From now on, we consider a failure threshold of 240 cal/g.

4. Comparison of the new CABRI criteria to integral experiments

The operator of CABRI performed thermal mechanical simulations, by means of the SCANAIR code, in order to demonstrate that the new criteria will be respected during foreseen experiments. IRSN, then, used the SCANAIR code to check the coherence between the results of the integral experiments and the new criteria proposed by the CEA.

4.1 The SCANAIR Code

The SCANAIR computer code [7], developed by IRSN, is devoted to the modelling of the complex physical phenomena occurring during fast power transients. Three modules are closely coupled:

- The thermal module calculates the radial conduction in the fuel and the clad, as well as clad-to-coolant heat transfer in sodium or water conditions. The coolant flow is computed thanks to a one-dimension single-phase fluid model.
- The fission gas behavior module calculates the swelling of fission gas bubbles, the grain boundary failure within the fuel and the gas flow into free volumes.
- The mechanical module calculates the strain contributions to the fuel and clad deformation (thermal expansion, elastic, plastic, strain simulating the fuel expansion induced by the presence of cracks and fuel swelling due to gaseous fission product).

The code has been qualified using integral tests performed in CABRI reactor, NSSR reactor and PATRICIA CEA facility [8].

4.2 The reference calculations

According to the future tests conditions in CABRI, the power transients will be performed at a 100kW power with full width at half maximum in the range of 10 to 75ms. CEA, thus, considered three power transients that are representative of the whole tests range. The full widths at half maximum of the pulses are 10, 30 and 75ms.

Three kinds of calculations have been performed:

- Conservative calculation for clad temperature,
- Conservative calculation for clad strain,
- Best-estimate calculation.

In this study, we focus on the most penalizing power transient (10ms). These three calculations were then labelled “reference calculations”. For each calculation, the simulated pin is the C5 pin, identified as the hottest one in the driver core. At first, IRSN checked that the results of the “reference calculations” were consistent with those obtained by CEA [9]. The Figure 1 shows the results of the conservative calculation for clad temperature: the straight lines represent the levels of criteria.

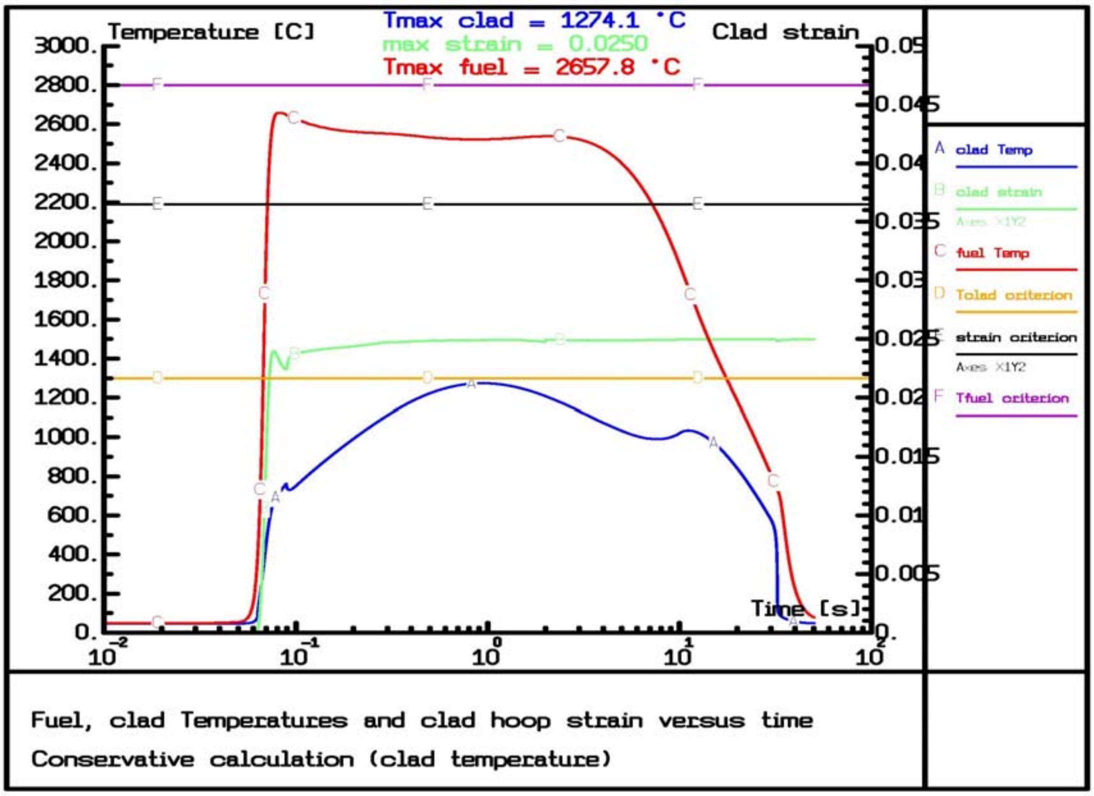

Figure 1: Conservative calculation for clad temperature

Then, IRSN calculated the injected energy for these "reference calculations". The injected energy, denoted E_{inj}, is the integral of the power generated at the maximum flux plan during the transient. The unity is cal/g (1 cal = 4,184 J).

The Figure 2 presents a pulse for the conservative calculation.

The power transient unfolding is:

- t = 0s: helium gas depressurization and start of the pulse,
- t = 0.1s: end of the pulse,
- t = 1s: automatic control rod shutdown,
- t= 50s: end of the transient.

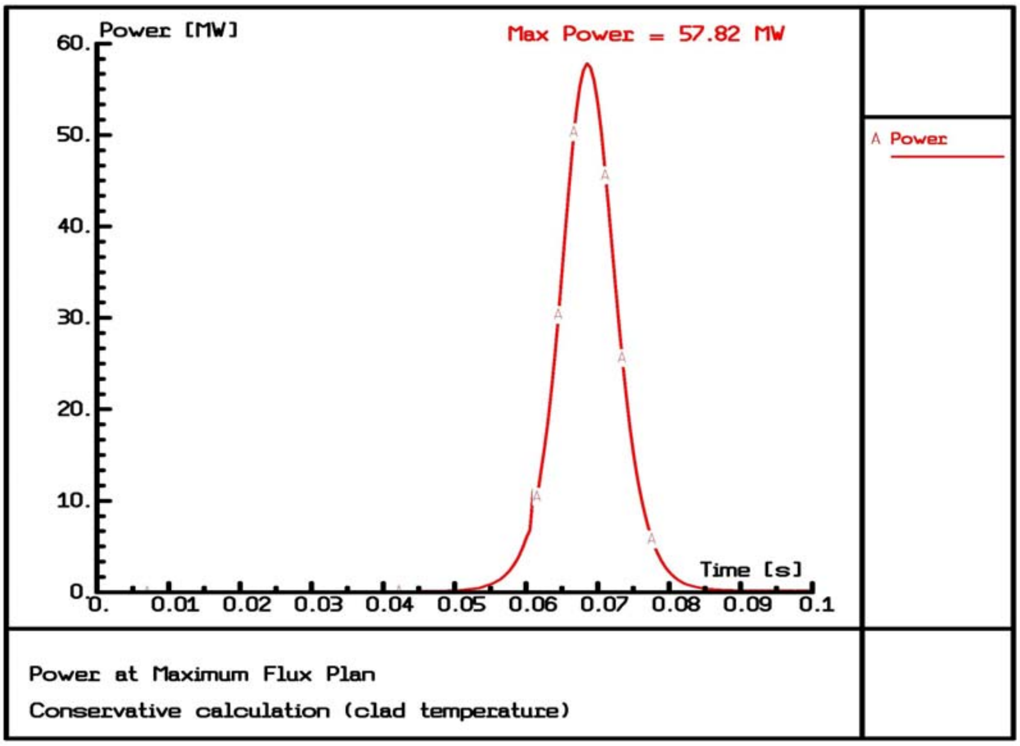

Figure 2 : 10 ms pulse for conservative calculation (clad temperature)

The maximum value of the injected energy is dependent on time interval. After shutdown, the reactor is not completely stopped by the Doppler Effect and a weak power is produced until the end of the transient. However, only the power generated during and shortly after the pulse is really significant for fuel rod behavior. Therefore, IRSN considered that the useful length of transient for calculation of the injected energy is between t0 = 0 and t1 = 1.2 s. The injected energies for the reference calculations are [9]:

10 ms pulse	Injected energy
Conservative calculation (clad temperature)	231 cal/g
Conservative calculation (clad strain)	231 cal/g
Best-estimate calculation	195 cal/g

Table 4: Injected energies for the reference calculations

A difference of 36 cal/g is obtained between the conservative and best-estimate calculations, due to the uncertainties on fuel rod power and axial profile of power taken into account only in conservative calculation.

4.3 Calculations corresponding to the criteria reach

In the second part of the study, the injected energy, during a power insertion transient leading to reach the criteria proposed by CEA, has been computed. The conservative hypotheses were consequently used [9]. The Table 5 presents the obtained injected energies.

10 ms pulse	Injected energy
Clad temperature = 1300°C	236 cal/g
Fuel temperature = 2800°C	246 cal/g
Clad hoop strain = 3.65%	287 cal/g

Table 5 : Injected energies for the reach of the criteria

4.4 Discussion

The injected energies obtained for the “reference calculations” (Table 4) are lower than the failure threshold energy of 240 cal/g (see §3.3). The cladding integrity is therefore maintained.

For the calculations corresponding to the criteria reach (Table 5), the clad temperature limit (1300°C) is reached for 236 cal/g and the strain limit for 287 cal/g. These results are consistent with the experiment conclusions which stressed that the failure mode is cladding melting. Also, the safety criteria proposed by CEA are in the same range as the limit found in the past, based on integral experiments.

5. Conclusion

CEA proposed an innovative analytical approach to insure the cladding integrity of the CABRI driver core by setting limits to physical values that are representative of the fuel rod failure mode. On the contrary, IRSN used an integral approach based on past experiments performed in NSRR and SPERT facilities, that led to identify a failure threshold energy for stainless steel clad fuel rods similar to CABRI ones. The study shows that new criteria were consistent with the failure limit of past integral experiments. This conclusion constitutes one of the important items which lead French Nuclear Safety Authority to accept the safety demonstration of the driver core fuel rods during the new experimental program in CABRI facility.

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