IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

IRSN Views on the Revision of LOCA Acceptance Criteria

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Role and missions

Système de management
de la qualité IRSN certifié

New Basis for a Revision of the Acceptance Criteria ?

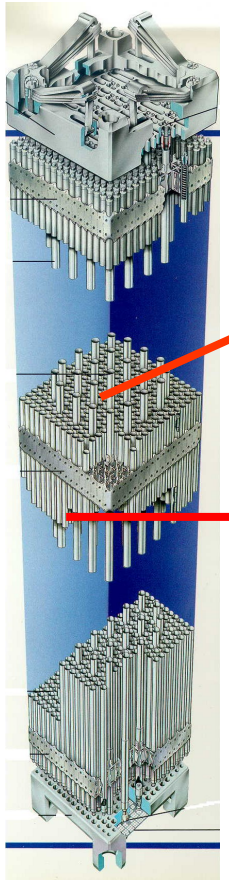
In view of the fundamental and historical importance of maintaining core coolability, this original objective is kept by IRSN as the main basis within current considerations for a future revision of the LOCA acceptance criteria

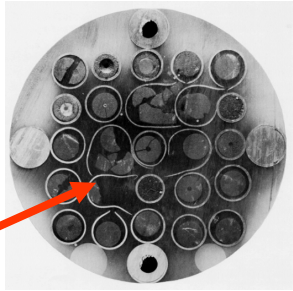
Even if it will need to be complemented by additional concerns :

- *Limit dispersal of fuel particles in the reactor primary circuit,*
- *Maintain structural material integrity,*
- *Limit radiological release.*

Maintaining the Core Coolability

In LOCAs there are two modes that may affect the core geometry and impair the core coolability:





PHEBUS LOCA TEST

1. Ductile mode

Clad ballooning leading to partial blockage of the FA channels

2. Brittle mode

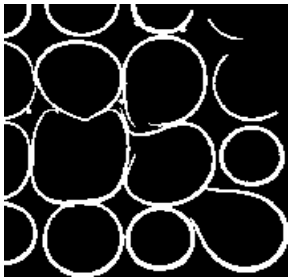
Loss of cladding integrity upon quench and post-quench loads

Maintaining the Core Coolability - LOCA acceptance Criteria

1. Ductile mode : Clad ballooning leading to partial blockage of the FA channels

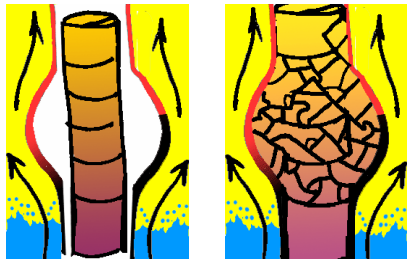
☞ ***addressed** in 10CFR50.46(b) by:*

(b)(4) Coolable geometry



PHEBUS LOCA TEST

"Calculated changes in core geometry shall be such that the core remains amenable to cooling."



Maintaining the Core Coolability - LOCA acceptance Criteria

2. Brittle mode : **Loss of cladding integrity upon quench and post-quench loads**

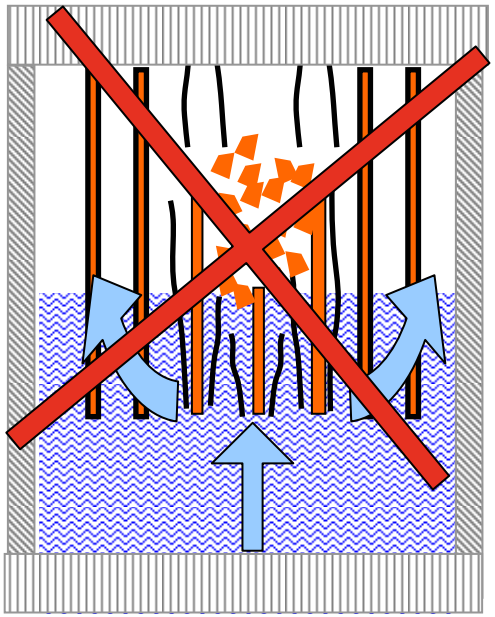
☞ ***addressed in 10CFR50.46(b) by the well-known non-embrittlement limits:***

(b)(1) Peak cladding temperature :

PCT < 2200°F (1204°C)

(b)(2) Maximum cladding oxidation :

ECR < 17%



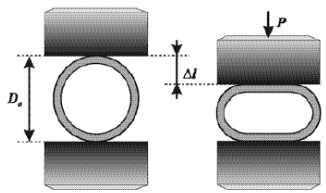
➪ *so as to keep the fuel rod structure in place and essentially intact*

Rationale for *embrittlement* criteria in 10 CRF50.46

Maintain coolable geometry

- Keep fuel pellets inside the cladding
  - Preclude the cladding fragmentation or break in **several** pieces
    - Retain some **ductility** in the cladding
      - **Limit cladding oxidation and temperature**

☞ Basic current requirement was to preclude the clad fragmentation upon **quench and post-quench** loads at any location, **including the ballooned and burst region**



☞ 10CFR50.46: **Cladding oxidation (ECR 17%) and temperature (PCT 220°F) limits** derived mainly from ring compression tests on oxidized and quenched samples of **unirradiated Zr cladding**

No effects of BU and of secondary hydriding were originally considered

Summary of Main Results of LOCA Research with respect to retention of post-quench ductility

- Ductile-brittle transition ECR-CP threshold > **17%** for unirradiated un-ballooned cladding (ANL test results)
- **Low ECR** threshold for high BU Zircaloy undeformed cladding due to hydrogen influence (ECR threshold ~ **5%** for the HBR quenched sample),
- Very low ECR threshold for irradiated cladding after oxidation at T<1000°C due to O diffusion from initial oxide layer into metal sub-layer (to be confirmed by tests under progress at IRSN),
- **Very large H content** upon absorption on clad inner side (secondary hydriding) of the balloons ➲ **No practical limit** can be derived to ensure **ductility retention** in balloons

Towards a revision of LOCA acceptance criteria

Pending question

How to handle the **no ductility retention** in the ballooned region of the cladding ?

Might the original requirement to preclude **cladding fragmentation** upon quench and post quench loads at any location be relaxed to **allow an exemption over a limited part** of the fuel rod cladding ?

- **<u>If yes</u>**, departure from the original **Opinion of the Commission (Dec. 73)**, this will require :
  - strong requirements defining the extent of an "acceptable" fragmentation
    Might a "clean break" concept be clearly defined and acceptable ?
  - to evaluate its possible impact on the core coolability and on radiological release
  - experimental data to validate the approach, in particular for high BU fuel

☞ ***on account of high uncertainties remaining for a possible evolution towards an non-coolable situation, IRSN is not currently supporting such a position***

Towards a revision of LOCA acceptance criteria

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- If not,
  - Which requirement to be applied to ballooned regions ? *(e.g. response to impact testing ?)* Can the requirements be different in ballooned and un-ballooned parts of the cladding ?

☞ A **strength-based** approach could provide an acceptable alternative addressing the **structural response of the whole cladding**

e.g.: **quench under controlled axial restraint** (~JAEA)

- need to reach a technical consensus on defining the **loading conditions** being best representative of fuel rod loading conditions and on methods to demonstrate compliance

Towards a revision of LOCA acceptance criteria

Cladding integrity upon quench and post-quench loads

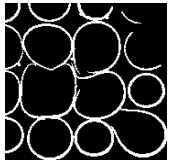
Selection of an adequate parameter to quantify an embrittlement limit

- The **ECR** (any combination of transient and initial oxidation) does not appear as the most appropriate since its relates essentially to the amount of brittle phases and to a low extent to the hardening properties of the remaining ductile phase

☞ An **embrittlement limit based** on the **thickness of the remaining Zr β layer** and its **oxygen content** (as proposed by Chung & Kassner), with account taken of the hydrogen content, appears more appropriate

- **Modeling progress** makes it possible to correctly evaluate the thickness of the β layer and the oxygen distribution in this layer, following a realistic LOCA temperature transient
  - **IRSN advanced code DIFFOX**, with the support of experimental determination of the **O radial profile** in the metal layers by EPMA

Towards a revision of LOCA acceptance criteria



Coolability of Partially Blocked Assemblies under LOCA Conditions

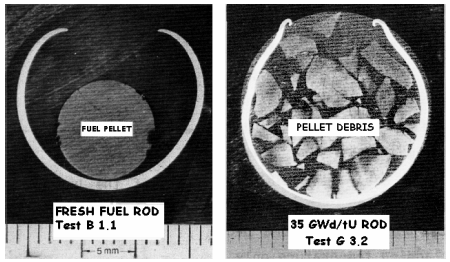
☞ **In the 80s, this requirement was considered as met, in consideration of :**

-the maximum flow blockage ratio, inferred from NUREG-630 review (~71%)

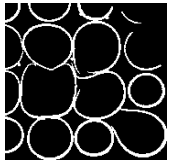
- *Was recognized later as non conservative and should also be reconsidered for advanced alloys and irradiated fuels*

- the results of FEBA/SEFLEX experiments (coolability of blocked arrays) showing that a 90% blockage keeps coolable, *within the favourable configuration of clad balloons thermally decoupled from heater rods*

- *Did not take into account experimental evidence of relocation of fuel in the ballooned cladding*



Towards a revision of LOCA acceptance criteria



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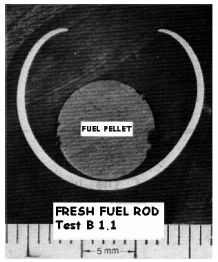
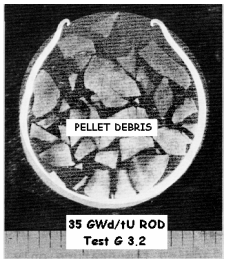
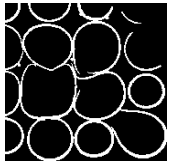




The coolability of blocked bundles **with fuel relocated in clad balloons** remains an open question, particularly **for long balloons and low reflood rate**

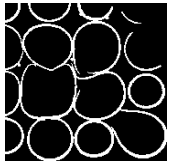


Coolability of Partially Blocked Assemblies under LOCA Conditions

Requirement to be considered

The **maximum flow blockage** that can be obtained in an assembly of (irradiated or unirradiated) fuel rods shall not impair the **cooling of the assembly** taking into account of the possible **relocation of fragmented fuel in the ballooned cladding**

Towards a revision of LOCA acceptance criteria



Coolability of Partially Blocked Assemblies under LOCA Conditions

Main pending question

Could this coolability issue be addressed only by calculations with respect to limits on temperature and time, e.g. the current PCT and ECR embrittlement limits ?

- **Yes**, if **advanced** calculation tools are available and **embrittlement limits do not exclude balloons**
- **If not**, need for an **interim quantified criteria** for the coolability of a partially blocked assembly

☞ In any case, need for complementary research to inform :

- the upper bound characteristics (blockage ratio and length) of a blockage in an assembly of irradiated rods,
- the coolability limit for a flow blockage with taking account of fuel relocation

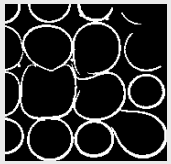
SUMMARY of IRSN VIEWS

1. The very low ductility observed in ballooned region raises the question of the requirement of a post-quench ductility retention at any location
   - ☞ Within current state of knowledge, **IRSN would not support an embrittlement criteria that leaves under question the fragmentation of the cladding in the balloon region**

2. An alternative approach (**strength-based** or impact testing) **should be considered** and **validated** with the appropriate R&D work

3. The thickness of the remaining **Zr β layer** and its **oxygen and hydrogen contents,** appears to be a sound basis to elaborate embrittlement limits

4. The coolability of partially blocked regions should be addressed by a specific **quantified criterion** or **might be addressed by calculations** with respect to embrittlement limits **not excluding the ballooned region**. The **criterion** or **advanced calculation tools** should have been validated upon complementary research for:
   - flow blockage characteristics in irradiated FA,
   - coolability limit with taking account of fuel relocation



For additional information, see :

A State-of-the-Art Review of past programs devoted to fuel behavior under LOCA conditions

Part One. Clad swelling and rupture – Assembly flow blockage.
Technical report IRSN SEMCA 2005/313, December 2005.

Part Two. Impact of clad swelling upon assembly cooling.
Technical report IRSN SEMCA 2006/183, June 2006.

Part Three. Cladding Oxidation. Resistance to Quench and Post-Quench Loads.
Technical report IRSN SEMCA 2008/093, June 2008.

All three reports have been made available through the NRC ADAMS Public system and the IRSN-scientific public web site (http://net-science.irsn.org).

Thank You for Your Attention !