

**LOCA Issues Related to
Ballooning, Fuel relocation,
Flow Blockage and Coolability**
Main Findings from a Review of Past Experimental Programs

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The S.o.A. review has been divided in 3 parts :

- ❑ **1st Part : Clad Ballooning and Rupture. Flow Blockage. Fuel relocation.**

- ❑ **2nd Part : Coolability of Partially Blocked Regions in Rod Bundles after Ballooning.**

- ❑ **3rd Part : Cladding Oxidation. Resistance to Quench and post Quench Loads. Safety Criteria.**

Clad Ballooning and Rupture

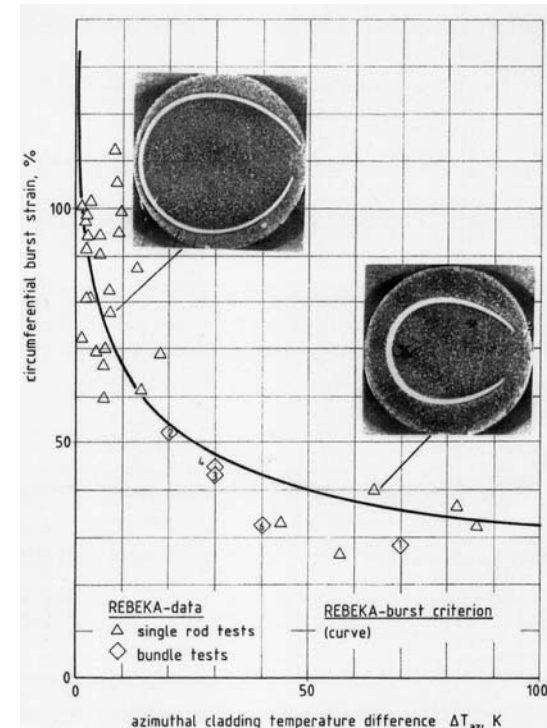
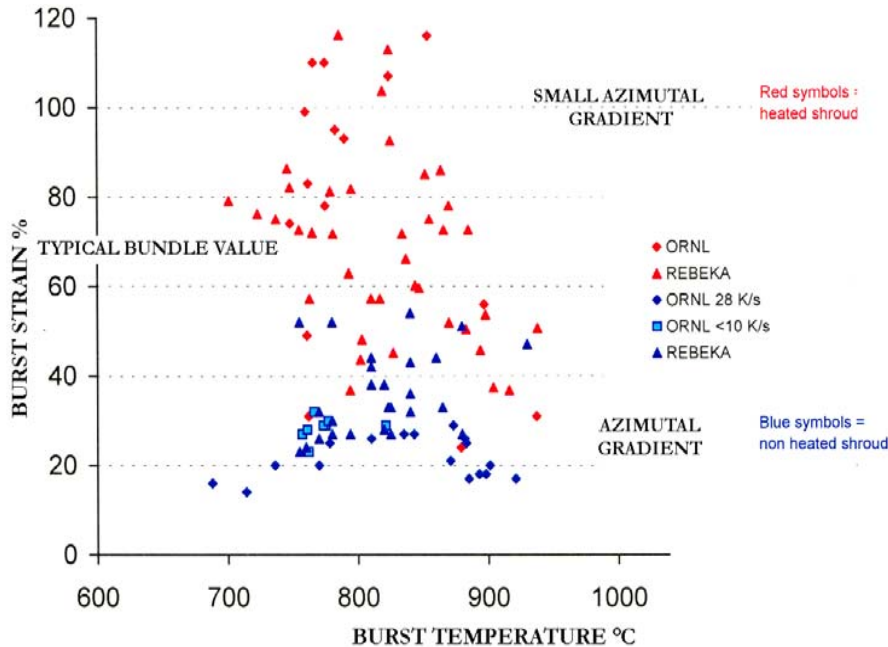
Flow Blockage

Fuel relocation

OUT-OF-PILE TESTS*SINGLE ROD***EDGAR (CEA)****KfK (REBEKA)****ORNL****JAERI****ANL****BCL****KWU****UKAEA****Westinghouse***MULTI ROD***KfK (REBEKA)****ORNL (MRBT)****JAERI****KWU****UKAEA****Westinghouse****IN-PILE TESTS***SIGLE ROD***PBF-LOC (INEL)****FR2 (KfK)****EOLO-JR (Ispra)****FLASH (CEA)***MULTI ROD***PHEBUS (IRSN)****NRU-MT (AECL)****TREAT FRF (USA)**

Out of Pile Single Rod Tests \boxtimes leading influence of azimuthal ΔT

- ◆ Direct heating (EDGAR) or internal heating and heated shroud (KfK, ORNL...)
 - \curvearrowright azimuthally uniform temperature \rightarrow large circumferential burst strains (up to $> 100\%$)
- ◆ Internal heating with unheated shroud
 - \curvearrowright non uniform temperature \rightarrow low average burst strains
 - process linked to the anisotropy of α -Zircaloy (" hot side straight effect ")*



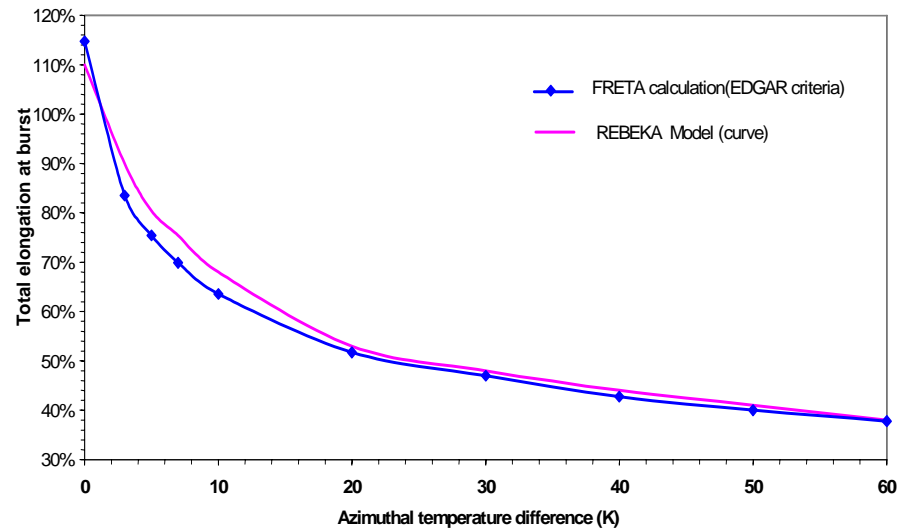
Out of Pile Single Rod Tests

✉ leading influence of azimuthal ΔT

Modeling of strain and burst

- 1D : mean strain, deduced from an "average" of experimental results (ex : **NUREG-630**)
burst criteria : average stress = f(T) (→ **CATHARE** versions up to V1.4,...)

- 2D : strain azimuthal profile
→ allows to take account of ΔT_{az}
burst criteria : maximum local strain
(→ **FRETA**,...)



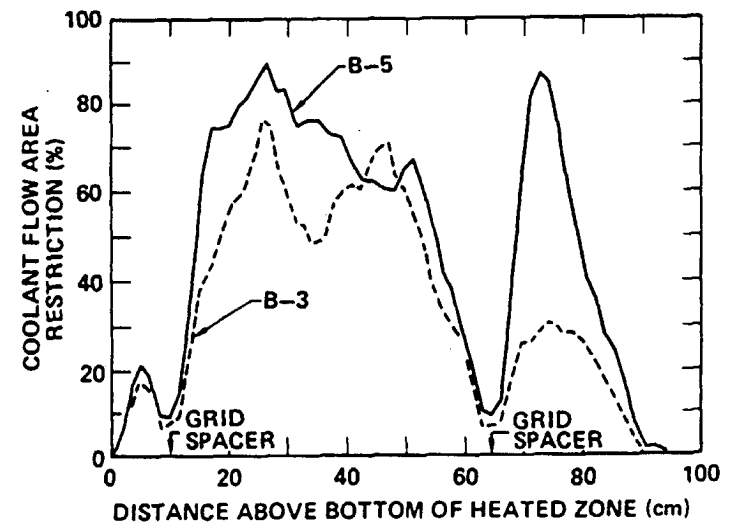
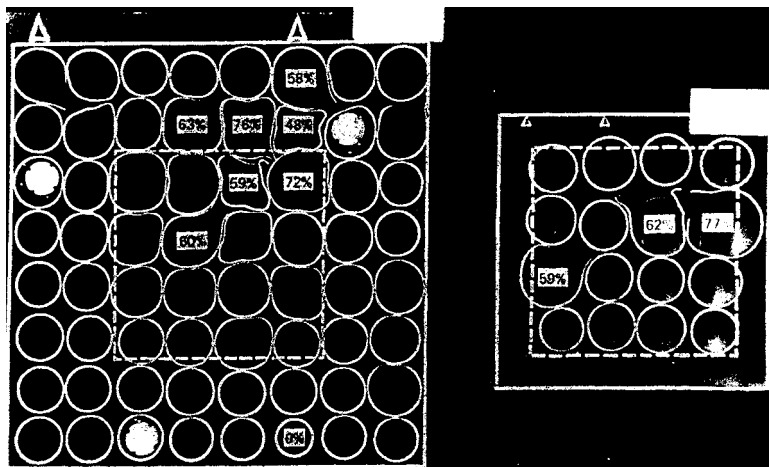
Multi Rod Tests

✉ *influence of thermal and mechanical interactions between rods*

Tests : ORNL MRBT (4x4, 8x8) and JAERI (7x7)

↪ large deformations of inner rods → contact on peripheral rods before clad burst

↪ axial extension of straining and blockage



ORNL Recommendation (Chapman, 1982) : bundle tests : at least 2 rings of guard rods are required to reproduce representative conditions of the inner rods in a reactor assembly

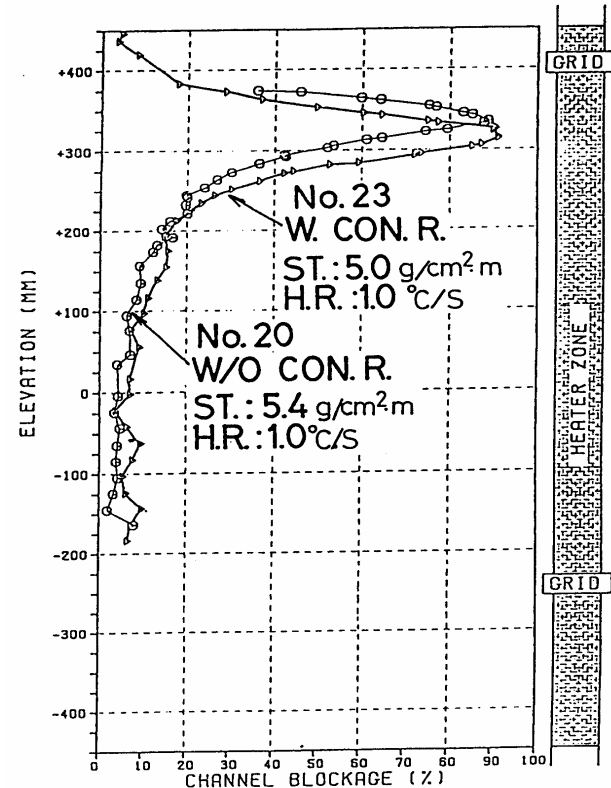
Multi Rod Tests

influence of guide tubes

- Test REBEKA-4 (5x5 bundle with unpressurized rods in outer ring)
 - Test R-4 : $\epsilon_{\max} = 79\%$ on a rod neighbor of G.T.
- JAERI Tests 21 to 24 (7x7 bundle) with 4 G.T.
 - ↳ presence of G.T. does not reduce, and even increases strain on neighbor rods, despite large ΔT_{az} (57°C in REBEKA-4, 71°C in JAERI-24)

KfK explanation : stop of "hot side straight effect" due to contact of deforming rod with GT (for $\epsilon < 20\%$), then gap re-opening on hot size

→ ΔT_{az} reduction → increase of burst strain



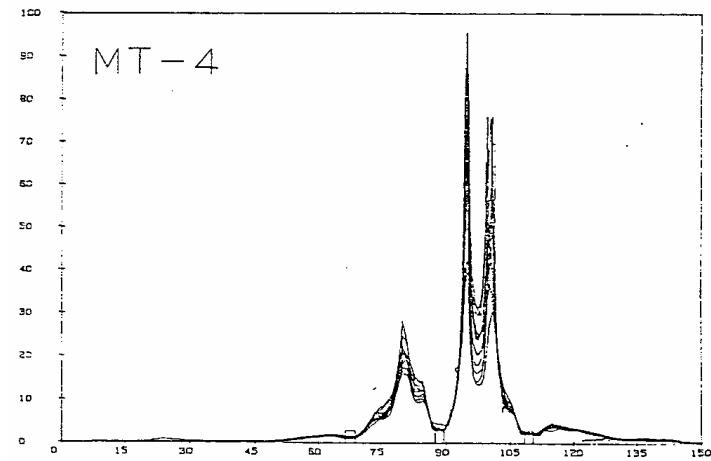
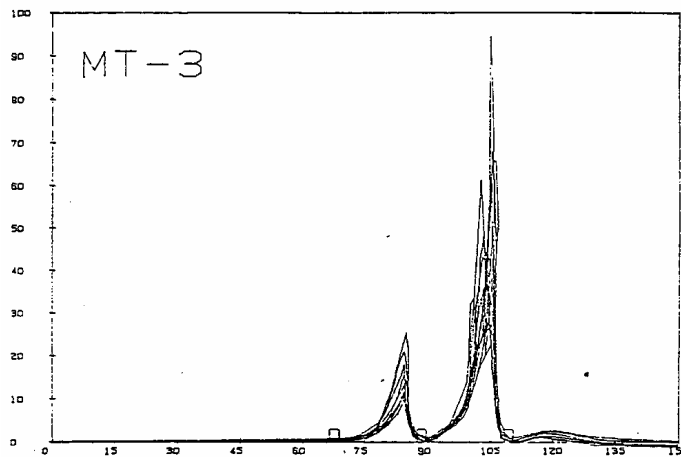
- *Modeling* : importance to describe thermal (radiative) and mechanical (contact) interactions between rods and rods and structures

Multi Rod Tests

influence of thermal-hydraulic conditions

partially illustrated by NRU MT-4 vs. MT3 tests (32 full length rods, 12 inner rods pressurized)

MT-3 : early reflood, clad rupture under 2 ϕ cond. / MT-4 : late reflood, rupture during heat-up under steam



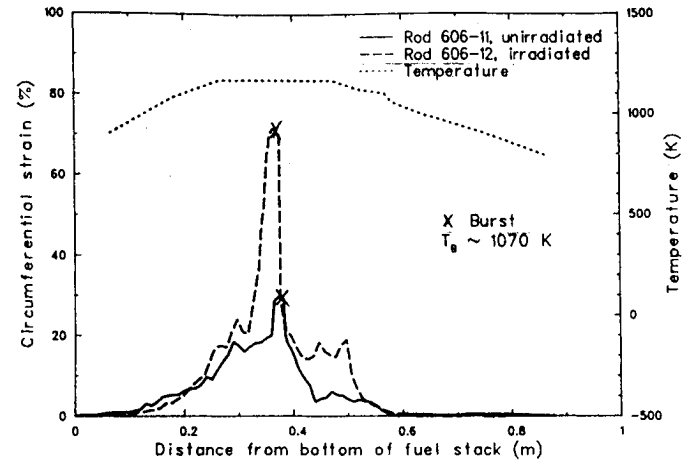
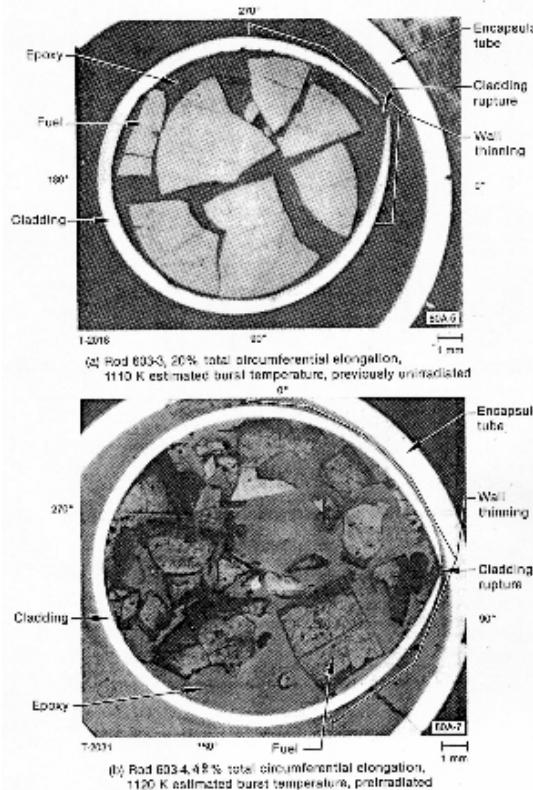
Axial distribution of strain in NRU MT-3 and MT-4 tests (x unit= inch)

Deformations appear significantly coplanar, due to the homogenizing effect of grids and not much different (maximum value, axial spread) in MT-3 / MT-4 (...as opposed to REBEKA 6 / 5 results)

Two-phase TH influences on blockage are complex and difficult to foresee and transpose at \neq scales

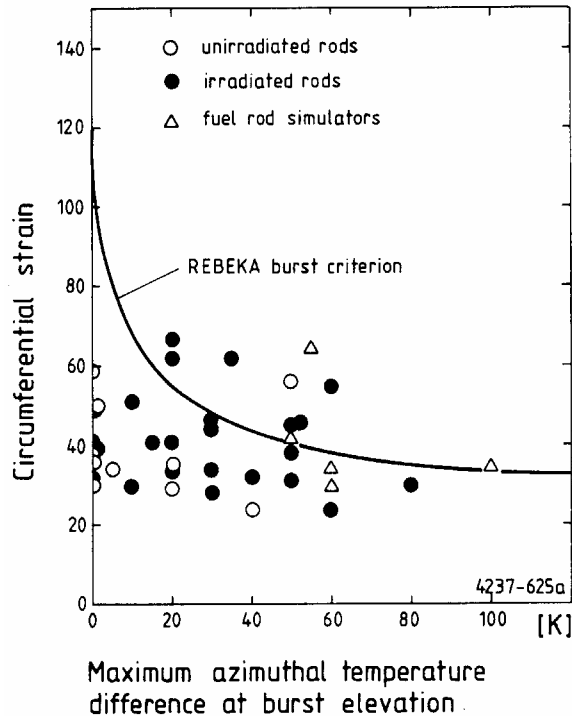
In pile tests with irradiated fuel rods

- ✉ influence of pellet/clad gap reduction or closure during prior irradiation (\searrow azimuthal ΔT)
- ☐ PBF-LOC Tests: \rightarrow increase of circumferential burst strain on irradiated rods (< 16 GWj/t) /unirrad. ($\sim \times 2$), larger axial extension and clad thinning over whole circumference



In pile tests with irradiated fuel rods (cont.)

- **FR2 Tests: → no apparent effect of irradiation on clad deformation nor apparent sensitivity to azimuthal ΔT**



may result from particular irradiation conditions in FR2
 (low T and P → no clad creepdown)
 with additional effects of axial constraint due to spring, limiting hoop strain, and of the closeness of shroud to test rod, limiting rod bowing

In pile tests with irradiated fuel rods (cont.)

□ No bundle test with irradiated rods carried out up to now

what could be the cumulative effects of irradiation and bundle size on blockage ratio?

On the basis that :

- *Burst strain for PBF-LOC fresh rods \approx ORNL Single Rod, unheated shroud*
- *Burst strain for ORNL Multi-Rod \gg ORNL Single Rod, unheated shroud*
- *Burst strain for PBF-LOC irradiated rods \gg PBF-LOC fresh rods* |

☞ *INEL recommended to perform bundle tests of sufficient bundle size with irradiated rods (J.M. Broughton, Sun Valley, 1981)*

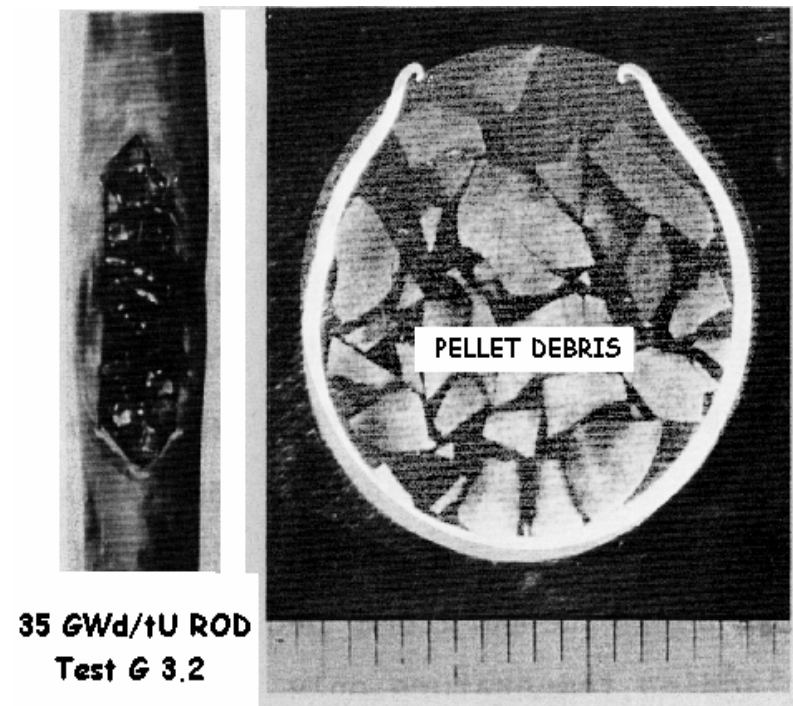
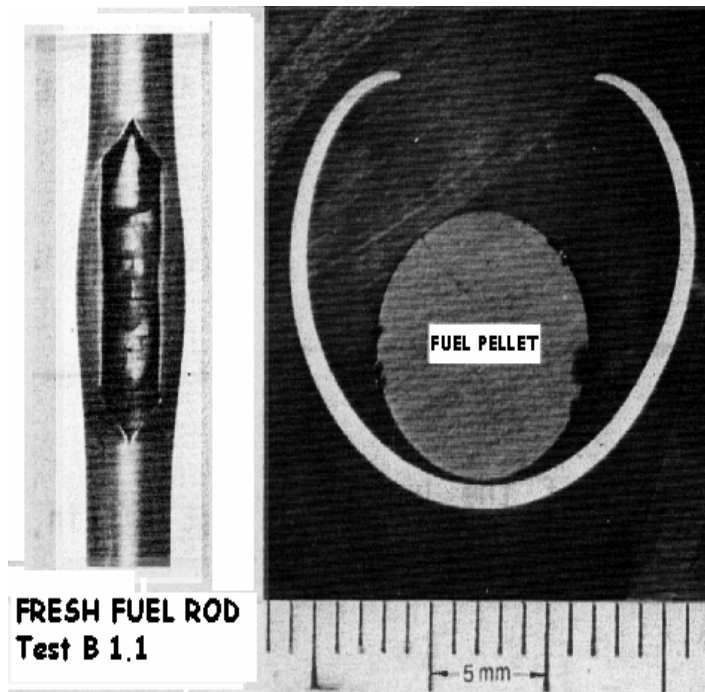
According to the known effect of H charged during irradiation on clad mechanical properties (*shift of transus temperature $T_{\alpha/\alpha+\beta}$ \rightarrow significant reduction of burst strain for high BU irradiated Zircaloy (~ 600 ppm H), see EDGAR results on pre-hydrided Zy)*

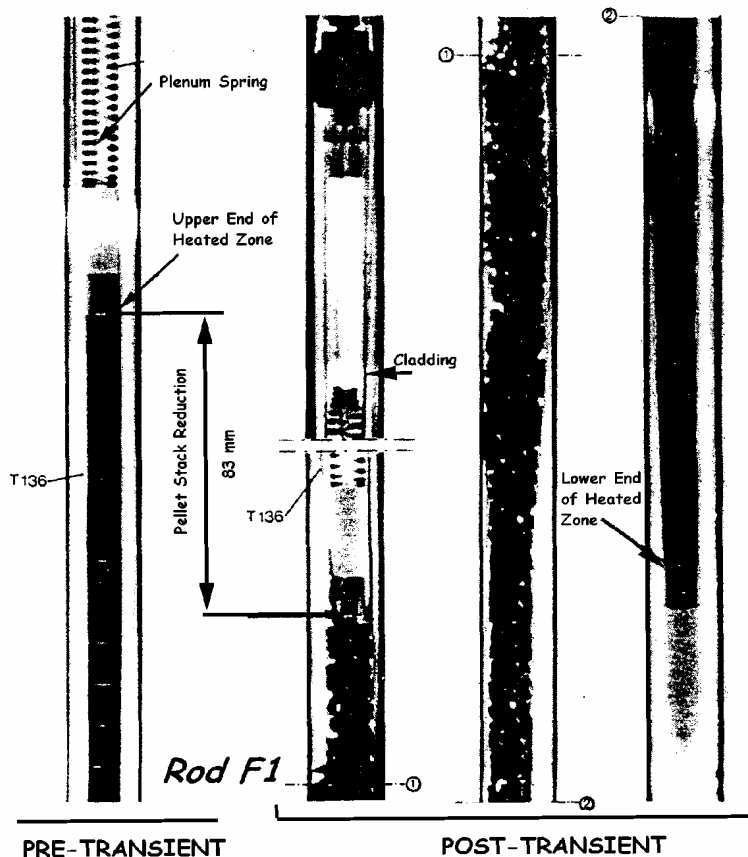
☞ *we expected the issue to concern more specifically irradiated fuel rod claddings with low H uptake under irradiation (low burnup Zy4, BWR alloys or advanced PWR alloys at high BU)*

But recent results (see presentation by N. Waeckel) indicate this may also concern high BU Zy4

In pile tests with irradiated fuel rods (cont.)

✉ *fuel relocation observed in PBF-LOC, FR2, FLASH-5, ANL-Limerick tests with irradiated fuel rods ($2.5 < BU < 56 \text{ GWj/tU}$)*





FR2 rod F1 (20 GWj/t)

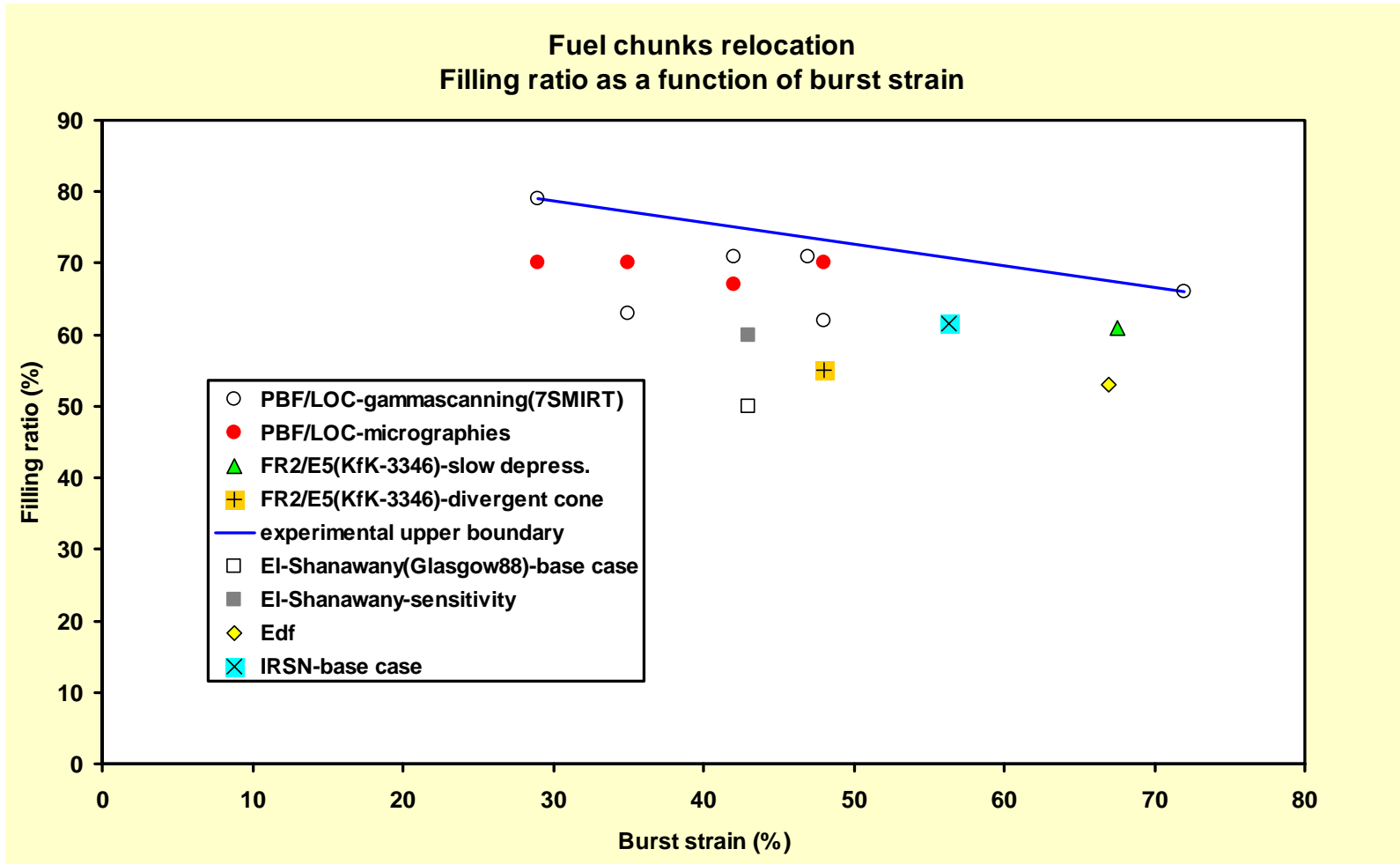
Main parameters :

- ★ **instant of fuel collapse**
likely near t_{burst} at least for low BU (FR2 : E3 & E4)
- ★ **fragments granulometry**
heterogeneous at high BU (see ANL test ICL2)
↳ will enhance filling ratio
- ★ **filling ratio**
may be altered during post test handling
(PBF-LOC)

Impact

- ◆ **local heat generation and transfer to clad**
↳ raises T and ECR (for observed fill. ratios)
- ◆ **may affect secondary hydriding conditions**

↳ 1st objective of Halden LOCA tests



**Coolability of Flow Blockages
Due to Clad Ballooning
under LOCA Transient Conditions**

✚ investigations on cooling under LOCA reflood conditions of a rod bundle containing a pre-established partial blockage region

□ Common Experimental Characteristics

Bundle of electrically heated full length rod simulators, with a group of rods bearing a pre-shaped deformation over a given axial length (→ pre-determined blockage ratio)

- establishment of steady state initial conditions in steam ($T_g \sim 600$ to 800°C)

- heating power \sim residual power

NB : *no power increase in the ballooned region of heated rods, and large gap*

- run of a liquid reflood transient under forced or gravity reflood conditions

✚ *impact of flow blockage on coolability evaluated upon comparison of clad temperatures in the blockage and by-pass regions*

Specific Experimental Programs

◆ FEBA (KfK, Germany)

- 5x5 rod bundle; $L_{\text{heat}}=3.9$ m ; "conventional" simulators ; forced reflood
- Blockage over 3x3 or 5x5 rods ; $\tau=62\%$ or 90% ; thick sleeves ; $LB_{\text{max}} = 65$ mm (90%)

◆ SEFLEX (KfK, Germany)

- 5x5 rod bundle; $L_{\text{heat}}=3.9$ m ; REBEKA simulators ; forced reflood
- Blockage over 3x3 rods ; $\tau= 90\%$; thinned cladding ($e \sim 0.5$ mm) ; $LB_{\text{max}} = 65$ mm (90%)

◆ THETIS (AEA Winfrith, UK)

- 7x7 rod bundle; $L_{\text{heat}}=3.6$ m ; "conventional" simulators ; forced or gravity reflood
- Blockage over 4x4 rods ; $\tau=80\%$ or 90% ; thin sleeves ($e \sim 0.3$ mm); $LB_{\text{max}} = 200$ mm

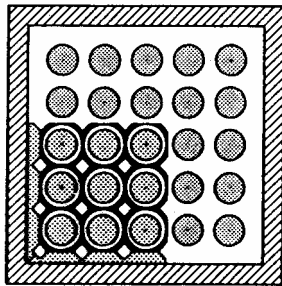
◆ CEGB (Berkeley, UK)

- 44 rod bundle ; $L_{\text{heat}}= 1$ m ; blockage over 4x4 rods ; $\tau= 90\%$; $LB_{\text{max}} = 147$ mm ; forced reflood

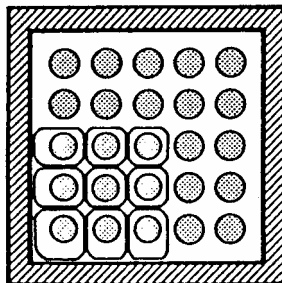
◆ FLECHT – SEASET (W, USA)

- 21 and 163 rod bundles ; $L_{\text{heat}}= 3.66$ m ; forced or gravity reflood
- Short concentric sleeves, coplanar or not ; long non-concentric sleeves, non-coplanar

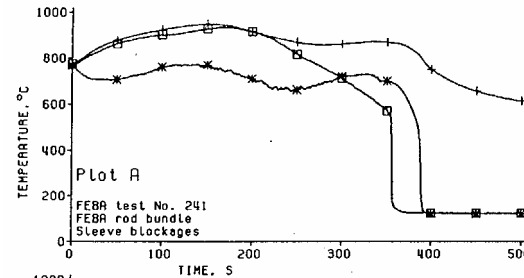
FEBA and SEFLEX Main Results



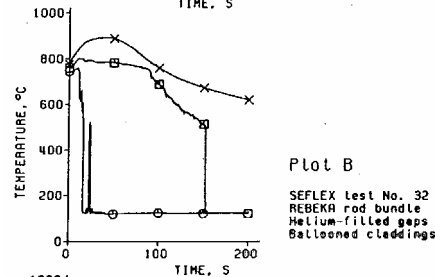
FEBA Test section ; Blockage 90% on 3x3 rods



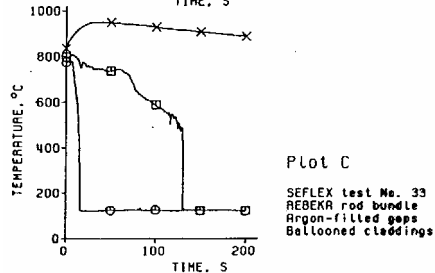
SEFLEX Test section ; Blockage 90% on 3x3 rods



FEBA



SEFLEX
He gap



SEFLEX
Ar gap

Flooding rate 3.8 cm/s
System pressure 2.1 bar

Axial level 2025

FEBA rod bundle
□ Bypass, rod cladding
* Blockage, sleeve
+ Blockage, rod cladding underneath sleeve

REBEKA rod bundle
□ Bypass, rod cladding
○ Blockage, rod cladding
x Blockage, heater sheath

Temperatures at the blockage midplane

The evolution of temperatures within and downstream of a blockage region results from the combined effects of :

- **the by-passing of fluid flow towards the unblocked flow channels**

- ↳ **significant reduction of flow, then of cooling capacity**
(under similar lineic heat flux)

- **penetration of liquid droplets inside the blockage** (due to inertia)

impact of droplets on balloon walls, fragmentation, re-entrainment in finer droplets, increase in turbulence

- ↳ ↗ liquid / vapor heat transfer (vapor de-superheating)

- ↳ **→ enhanced cooling of walls** (at least for short blockages)

- **possible fall of droplets at the blockage outlet** (widening section)

- ↳ dispersion and evaporation in steam jets

- ↳ **→ enhanced cooling** (at least for short blockages)

① Blockage representativity (thin vs. thick sleeves)

observed from SEFLEX / FEBA tests results

SEFLEX : lower heat capacity of the balloon walls and low coupling with heater

↳ early rewetting of the balloon , propagation of secondary quench fronts up- & downstream

➤ *FEBA results conservative / reactor rod balloon with fresh fuel (not for irradi. fuel)*

② Influence of flow restriction and blockage length

FEBA (90% / 62% ; $L_{\text{Block}} = 65/125$ mm), THETIS (90% / 80% ; $L_{\text{Block}} = 200$ mm)

- FEBA 62% : blockage always better cooled than by-pass region
- FEBA 90% : low penalty (+40°C on T_{max} at blockage outlet) for $V_{\text{flood_min}} = 3.8$ cm/s
- THETIS 90% : coolability limit for $V_{\text{reflood}} < 2$ to 3 cm/s
- 80% blockage ratio : better cooled than 90% for high V_{reflood} , opposite for low V_{reflood} (2 cm/s)

Influence of blockage length → linked to penetration and length of influence of droplets

↳ highly dependent on flow blockage ratio and T.H conditions : flooding velocity and lineic power

③ Influence of the blockage configuration : coplanar / non coplanar

➤ FLECHT SEASET 21 rods, short balloons (low axial overlapping)

under non coplanar configuration :

- the flow redistribution around one balloon increases local turbulence, then cooling of neighbor rods,
- but the isolated influence on droplets fragmentation in the adjacent channel is lower than in coplanar configuration

④ Influence of the nature of reflood (forced / gravity)

➤ THETIS tests, 80% blockage ratio, forced / gravity reflood

- rapid oscillations of inlet flow and liquid level under gravity reflood, vanishing after 90 s
- temperature evolution, in blockage and by-pass, very similar to those in comparable forced flow

⑤ Influence of the presence of a by-pass region or not

➤ FEBA tests, blockage 3x3/5x5 ; FLECHT SEASET 21 rods (config B/ config C)

tests without by-pass non representative : no flow redistribution \Rightarrow velocity increase in the blockage, thus enhanced cooling / configuration with by-pass

□ Impact of fuel accumulation in the balloon (fuel relocation)

- EXISTING : analytical tests on bundles of electrically heated fuel rod simulators with partially blocked regions bearing pre-shaped balloons, large heater/clad gap
 - ☞ heaters are fixed and heating axially uniform (inside / outside balloons)
- significant differences between results of comparable tests FEBA and SEFLEX
 - underlines the large impact of thermal coupling between the heat source and the ballooned cladding

☞ ***The impact of fuel relocation in fuel rod balloons, as was observed in all in-reactor tests with irradiated fuel, leading to an increase in local power (lineic and surfacic) as well as a very reduced fuel-clad gap, on the coolability of the blocked region, is still fully questionable and should be addressed by specific analytical tests with a simulation of fuel relocation.***

❑ Flow Blockage in a Bundle of Irradiated Rods

- ◆ No multi-rod burst test with irradiated fuel available up to now

↳ *Such tests (with low H uptake clad material ?) would be of main interest*

❑ Fuel Relocation

- ◆ Instant of fuel collapse, granulometry and filling ratio at high BU

↳ *Halden single rod tests (IFA-650)*

❑ Coolability of Blocked Bundles with Fuel Relocation

- ◆ Open question, particularly for long balloons and low reflood rate, for which the blockage ratio still coolable might be less than the widely accepted value of 90% derived from FEBA/SEFLEX tests results.

↳ *Need of specific analytical tests with a simulation of fuel relocation (representative lineic power and gap)*