IRSN

# LOCA Issues Related to Ballooning, Fuel relocation, Flow Blockage and Coolability

## Main Findings from a Review of Past Experimental Programs

*Claude GRANDJEAN, Georges HACHE*

IRSN, CE Cadarache, France

SEGFSM Topical Meeting on LOCA Issues

ANL, May 25-27, 2004

# IRSN State-of-the Art Review on LOCA

***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

CLAD BALLOONING and RUPTURE / FLOW BLOCKAGE

## OUT-OF-PILE TESTS

| *SINGLE ROD* | *MULTI ROD* |
|---|---|
| **EDGAR (CEA)** | |
| **KfK (REBEKA)** | **KfK (REBEKA)** |
| **ORNL** | **ORNL (MRBT)** |
| JAERI | **JAERI** |
| ANL | |
| BCL | |
| KWU | KWU |
| UKAEA | UKAEA |
| Westinghouse | Westinghouse |

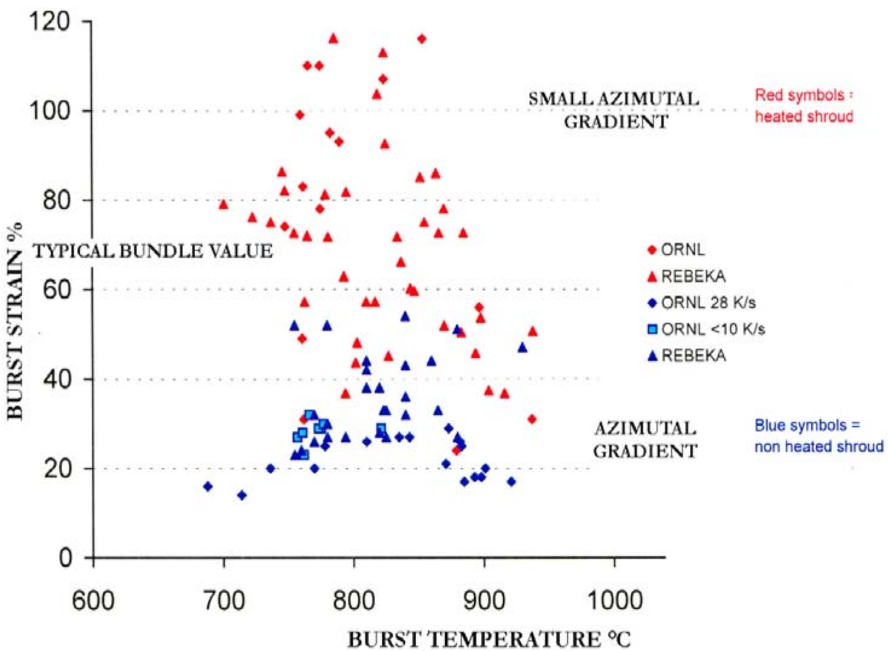
## IN-PILE TESTS

| *SIGLE ROD* | *MULTI ROD* |
|---|---|
| **PBF-LOC (INEL)** | **PHEBUS (IRSN)** |
| **FR2 (KfK)** | **NRU-MT (AECL)** |
| **EOLO-JR (Ispra)** | TREAT FRF (USA) |
| **FLASH (CEA)** | |

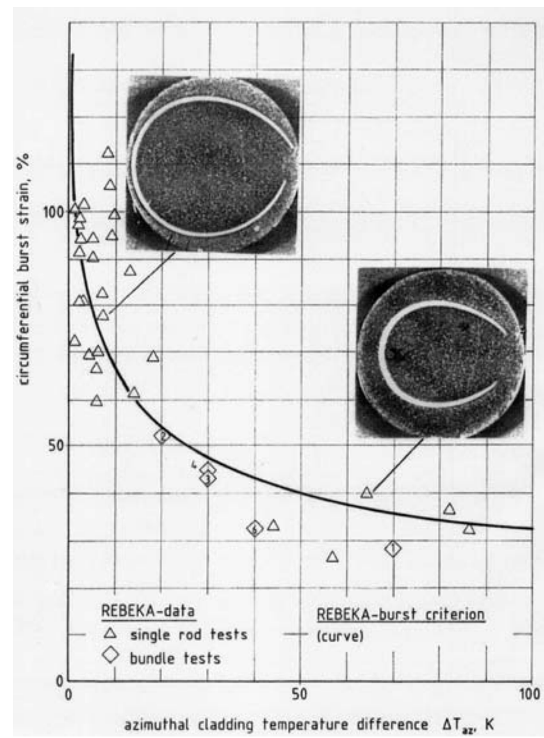
# BALLOONING / BLOCKAGE. Main Findings (1A)

## *Out of Pile Single Rod Tests* ✉ ***leading influence of azimuthal $\Delta T$***

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




*SEGFSM Top. Meet. on LOCA Issues, ANL May 25-27, 2004*



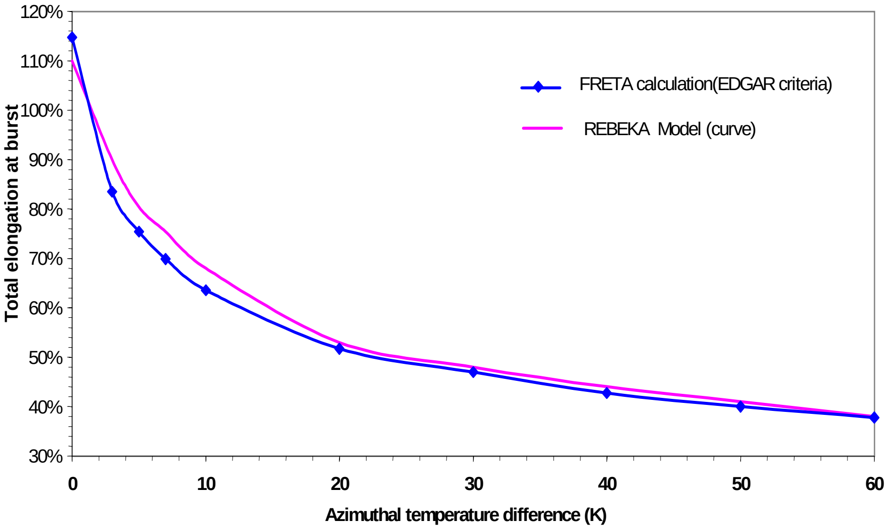
# BALLOONING / BLOCKAGE. Main Findings (1B)

***Out of Pile Single Rod Tests*** ✉ ***leading influence of azimuthal $\Delta T$***

## ***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 $\Delta T_{az}$
burst criteria : maximum local strain
**(→ FRETA,…)**



# BALLOONING / BLOCKAGE. Main Findings (2)

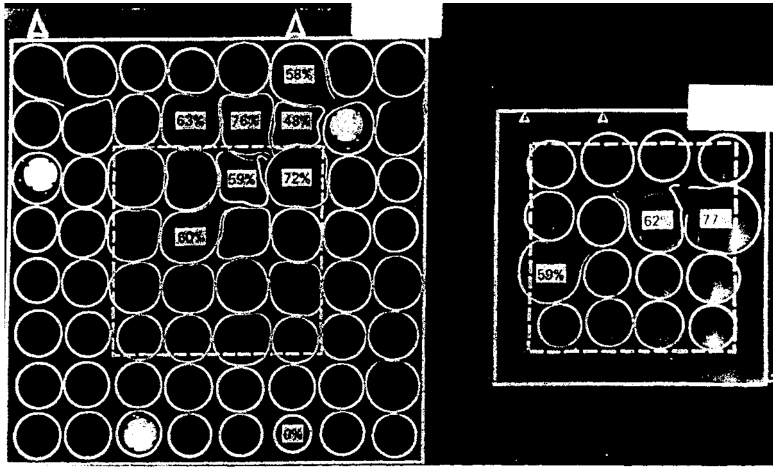
## ***Multi Rod Tests***

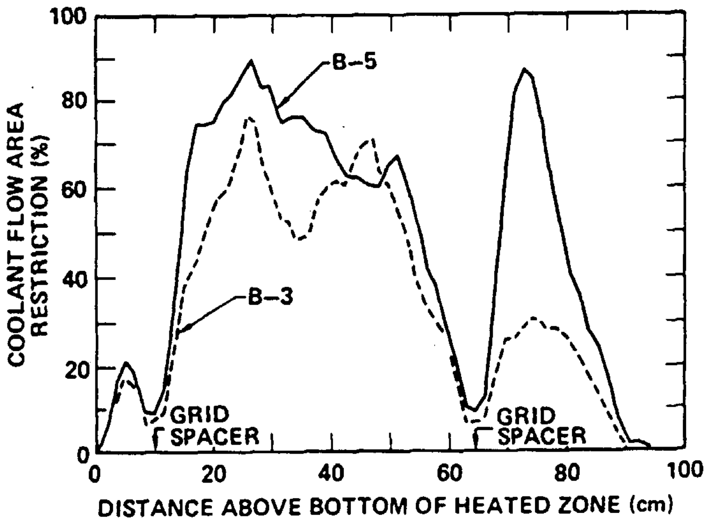
***influence of thermal and mechanical interactions between rods***

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 Recommandation (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***

# BALLOONING / BLOCKAGE. Main Findings (3)

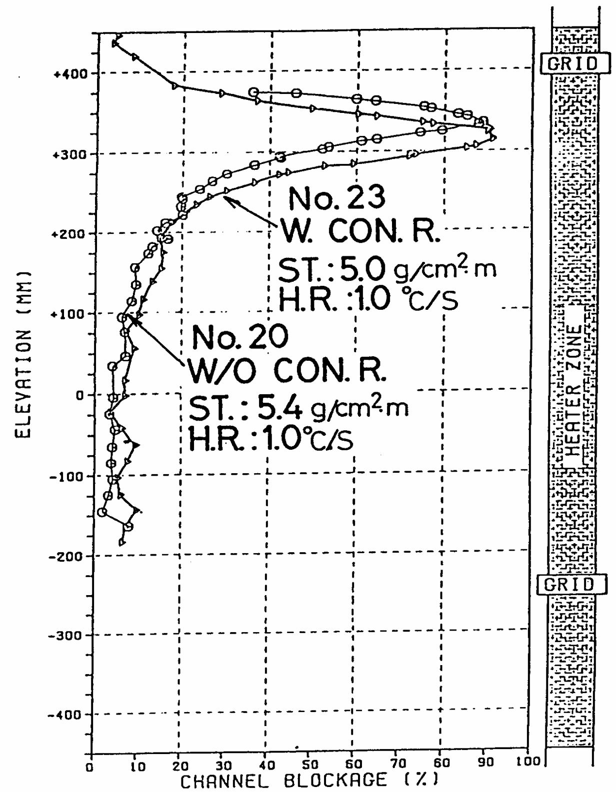
## Multi Rod Tests

### *influence of guide tubes*

- Test REBEKA-4 (5x5 bundle with unpressurized rods in outer ring)
  - Test R-4 : $\varepsilon_{max}$= 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 $\Delta T_{az}$ (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 ε<20%), then gap re-opening on hot size
→ ΔTaz reduction → increase of burst strain




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

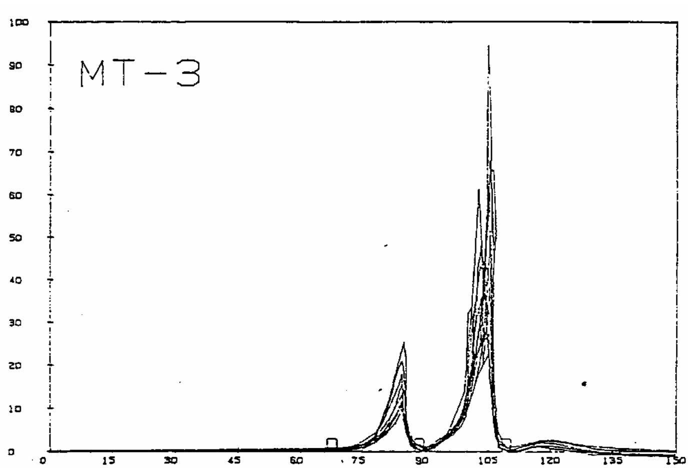
# BALLOONING / BLOCKAGE. Main Findings (4)

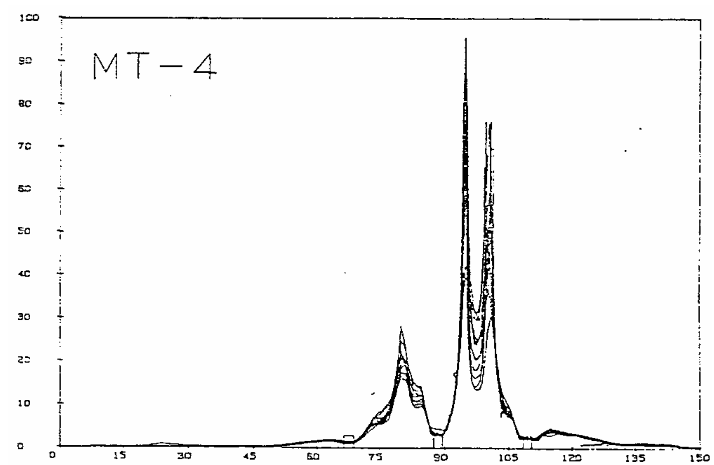
## ***Multi Rod Tests***

### ✉ *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 2φ 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)

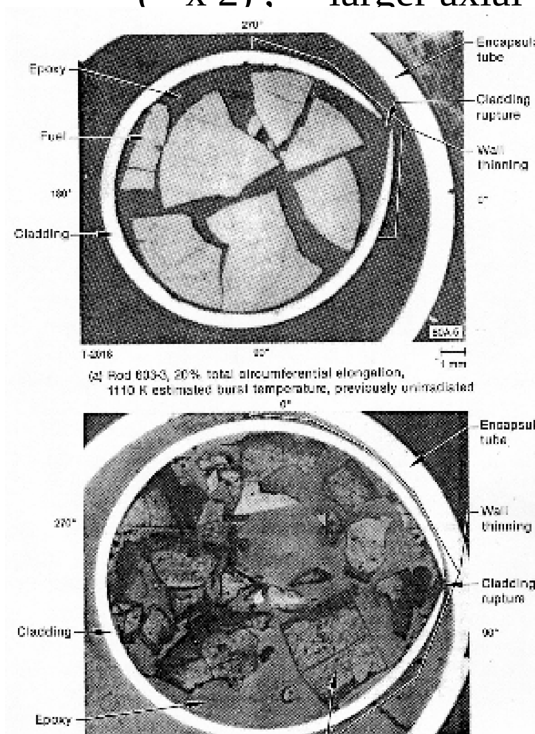
Deformations appear significantly coplanar, due to the homogenizing effect of grids and not much different (maximum value, axial spread) in MT-3 / MT-4 (….as opposed to REBEKA 6 / 5 results)

☞ **Two-phase TH influences on blockage are complex and difficult to foresee and transpose at ≠ scales**

# BALLOONING / BLOCKAGE. Main Findings (5A)

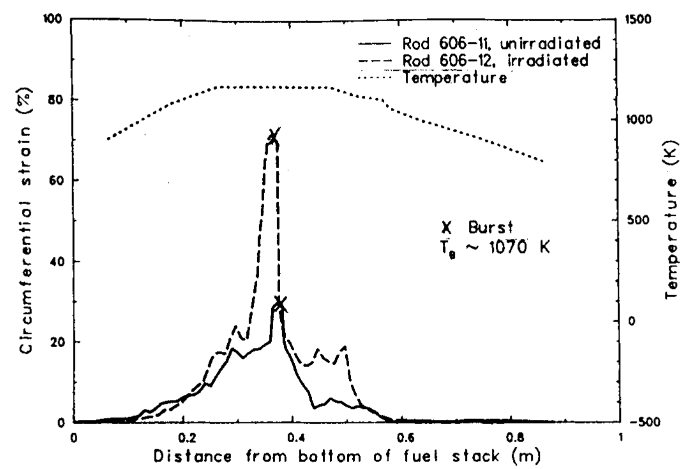
## ***In pile tests with irradiated fuel rods***

- ***influence of pellet/clad gap reduction or closure during prior irradiation*** ***(*** ↘ azimuthal ΔT)
- PBF-LOC Tests:➔ increase of circumferential burst strain on irradiated rods (<16 GWj/t) /unirrad. (~ x 2) , larger axial extension and clad thinning over whole circumference




(a) Rod 603-3, 20% total circumferential elongation, 1110 K estimated burst temperature, previously unirradiated

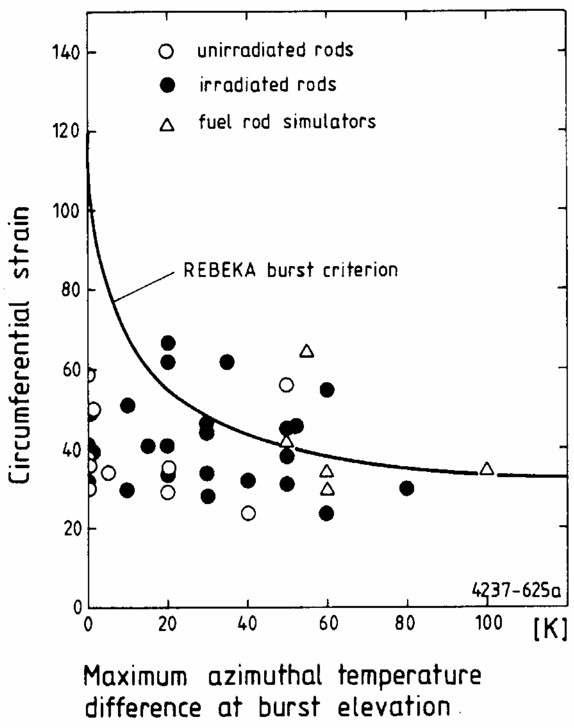
(b) Rod 603-4, 48% total circumferential elongation, 1120 K estimated burst temperature, preirradiated



# BALLOONING / BLOCKAGE. Main Findings (5B)

## ***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

IRSN

# BALLOONING / BLOCKAGE. Remaining Needs.

## ***<u>In pile tests with irradiated fuel rods</u>*** ***(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 ≈ ORNL Single Rod, unheated shroud*
- *Burst strain for ORNL Multi-Rod >> ORNL Single Rod, unheated shroud*
- *Burst strain for PBF-LOC irradiated rods >> PBF-LOC fresh rods*

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

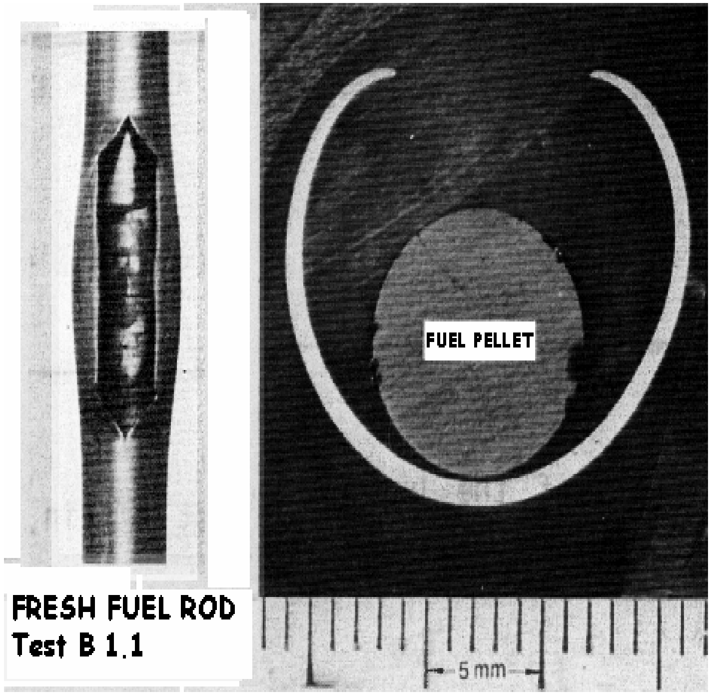
**According to the known effect of H charged during irradiation on clad mechanical properties** (*shift of transus temperature $T_{\alpha/\alpha+\beta}$ → significant reduction of burst strain for high BU irradiated Zircaloy (~600 ppm H), see EDGAR results on pre-hydrided Zy )*

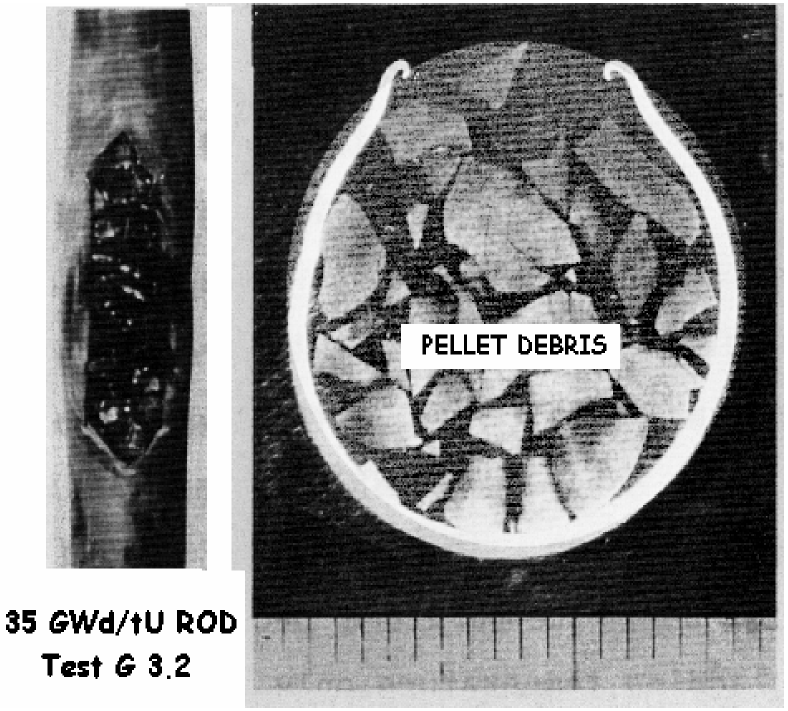
↳ ***we expected the issue to concern more specifically irradiated fuel rod claddings with low H uptake under irradiation (low burnup Zy4, BWR alloys or advanced PWR alloys at high BU)***

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

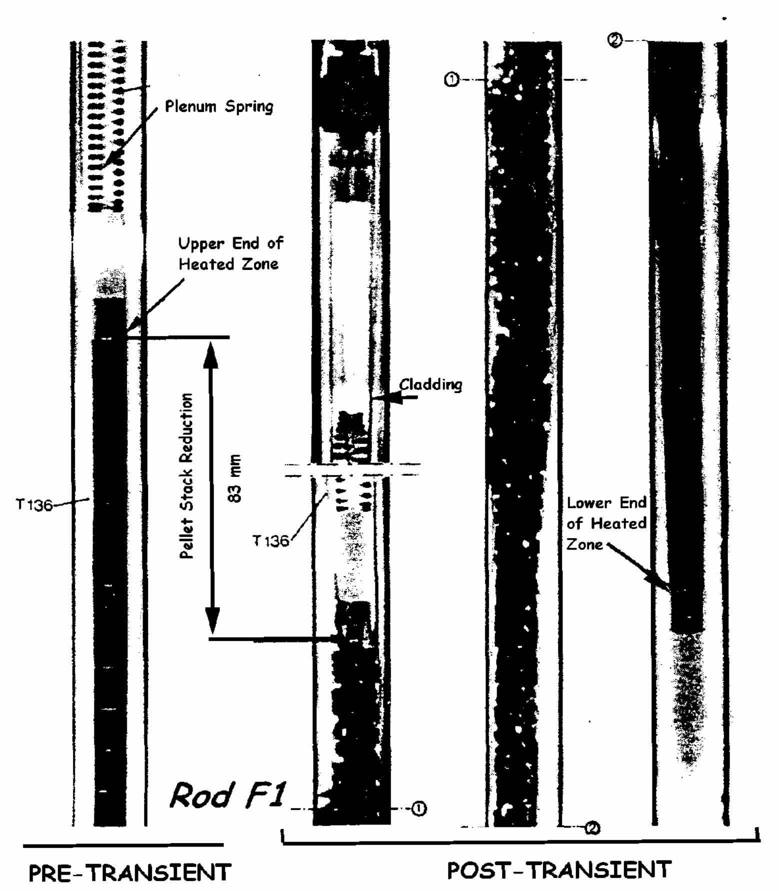
## ***In pile tests with irradiated fuel rods*** *(cont.)*

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



# FUEL RELOCATION. Main Findings (2)




FR2 rod F1 (20 GWj/t)

***Main parameters*** :

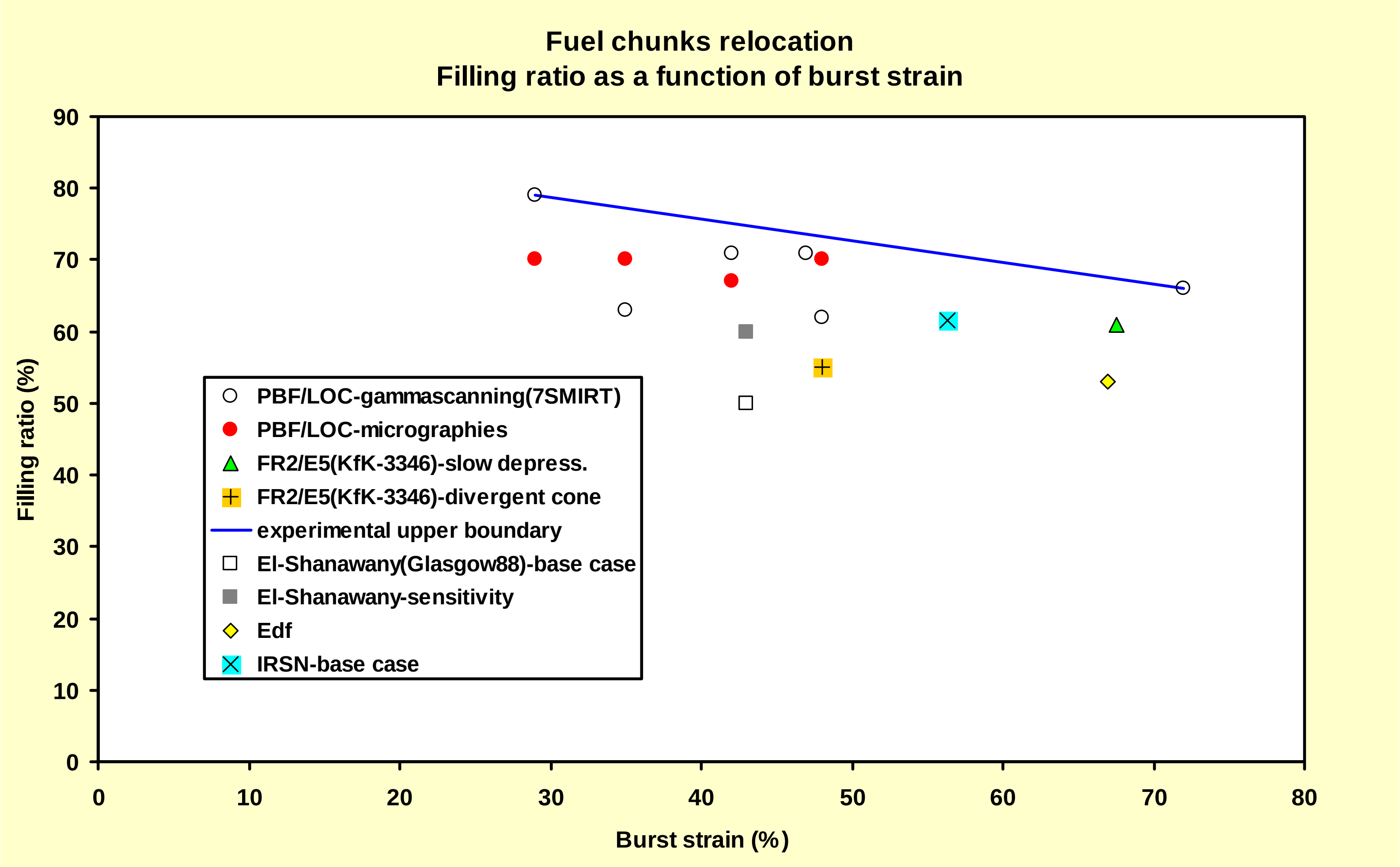
- **instant of fuel collapse**
  likely near $t_{burst}$ at least for low BU (FR2 : E3 & E4)
- **fragments granulometry**
  heterogeneous at high BU (see ANL test ICL2)
  ⇘ will enhance filling ratio
- **filling ratio**
  may be altered during post test handling (PBF-LOC)

***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

# FUEL RELOCATION. Main Findings (3)



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

# Effect of Clad Swelling Upon Assembly Cooling

↳ **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 (Tg ~ 600 to 800°C )
- heating power ~ 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; $L_{heat}$=3.9 m ; "conventional" simulators ; forced reflood
- Blockage over 3x3 or 5x5 rods ; $\tau$=62% or 90% ; thick sleeves ; $LB_{max}$ = 65 mm (90%)

♦ **SEFLEX** (KfK, Germany)

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

♦ **THETIS** (AEA Winfrith, UK)

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

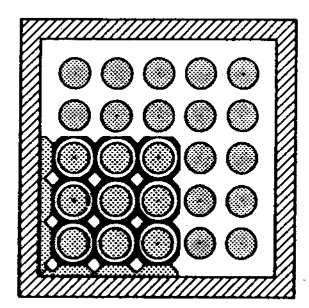
♦ **CEGB** (Berkeley, UK)

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

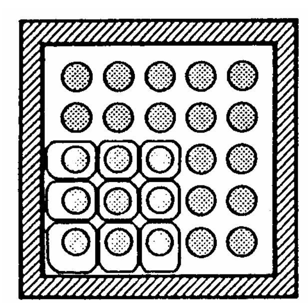
♦ **FLECHT – SEASET** (W, USA)

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

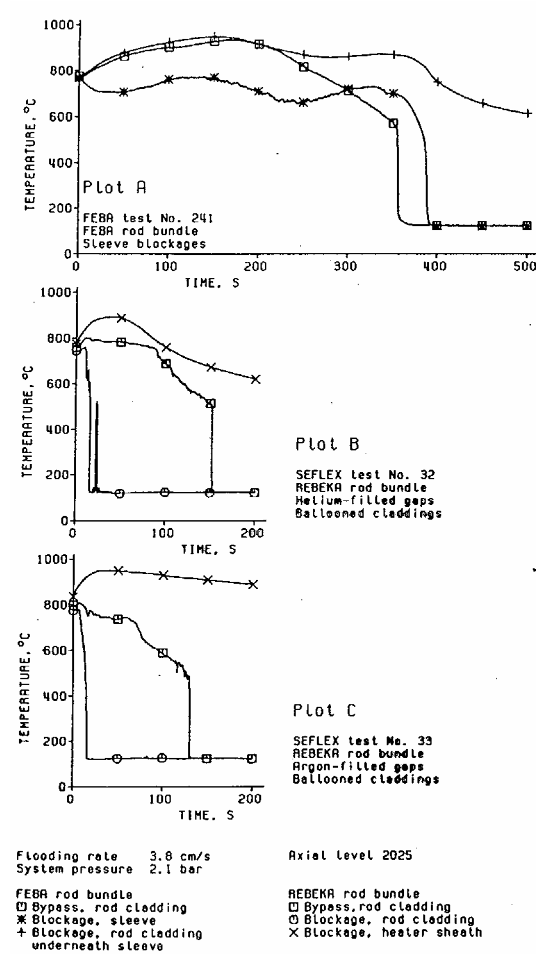
# FEBA and SEFLEX Main Results



FEBA Test section ; Blockage 90% on 3x3 rods



SEFLEX Test section ; Blockage 90% on 3x3 rods




FEBA

SEFLEX He gap

SEFLEX Ar gap

Temperatures at the blockage midplane

# COOLABILITY OF BLOCKED REGIONS
## Main Findings (1)

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)

# COOLABILITY OF BLOCKED REGIONS
## Main Findings (2)

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 irrad. fuel)***

② **Influence of flow restriction and blockage length**

FEBA (90% / 62% ; $L_{Block}$= 65/125 mm), THETIS (90% / 80% ; $L_{Block}$= 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 $V_{flood\_min}$ = 3.8 cm/s

- THETIS 90% : coolability limit for $V_{reflood}$ < 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

# COOLABILITY OF BLOCKED REGIONS
## Main Findings (3)

### 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% blocage 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 ⇒ velocity increase in the blockage, thus enhanced cooling / configuration with by-pass

# COOLABILITY OF BLOCKED REGIONS
## Pending Questions

- **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.*

# CONCLUSIONS. Pending Issues

## 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)***