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NUCLEAR REGULATORY COMMISSION

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In the matter of Duke Catawba
Staff IDENTIFIED 7/14/04
Applicant RECEIVED 7/14/04
Intervenor ✓ REJECTED
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LOCA Issues Related to Ballooning, Fuel relocation, Flow Blockage and Coolability

Main Findings from a Review of Past Experimental Programs

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SEGFSM Topical Meeting on LOCA Issues
ANL, May 25-27, 2004

INSTITUT DE RADIOPROTECTION ET DE SÛRETE NUCLEAIRE

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

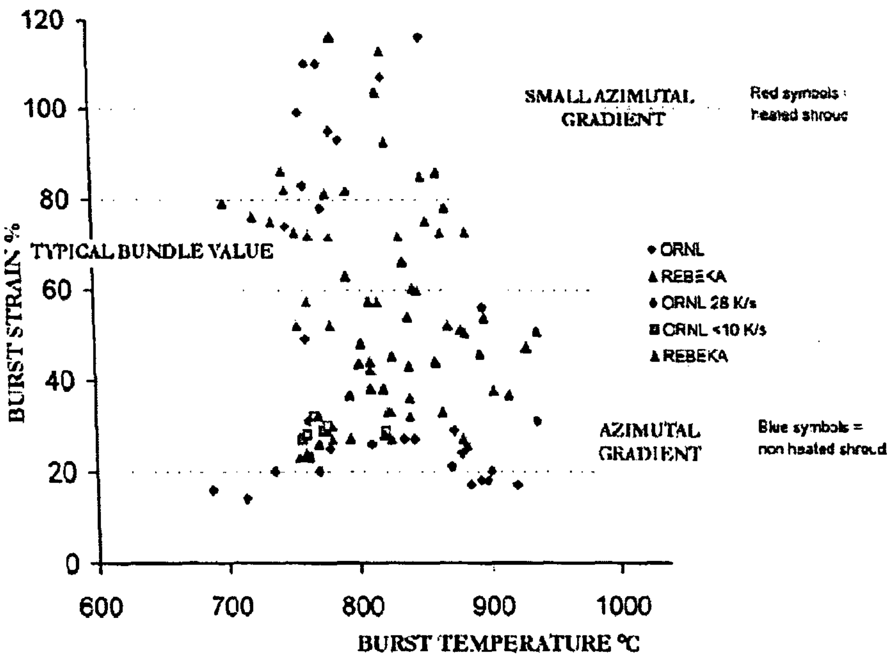
SIGLE ROD	MULTI ROD
PBF-LOC (INEL)	**PHEBUS (IRSN)**
FR2 (KfK)	**NRU-MT (AECL)**
EOLO-JR (Ispra)	TREAT FRF (USA)
FLASH (CEA)	

BALLOONING / BLOCKAGE. Main Findings (1A)

Out of Pile Single Rod Tests ⌧ *leading influence of azimuthal ΔT*

- 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 ")



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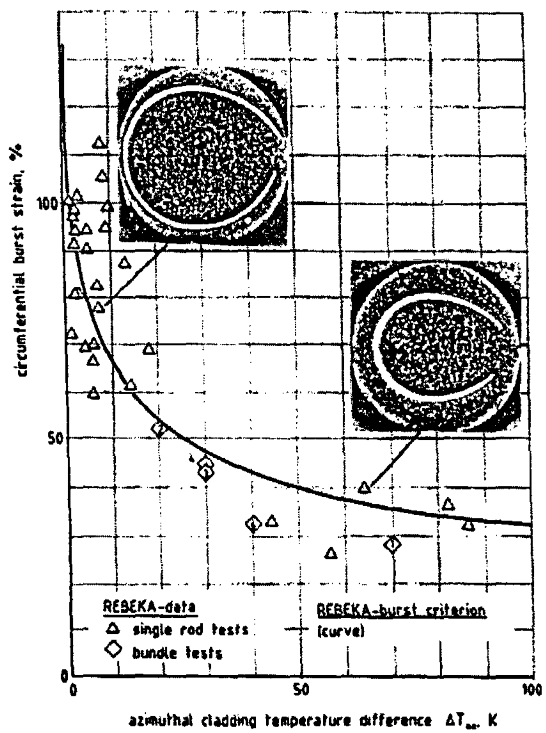


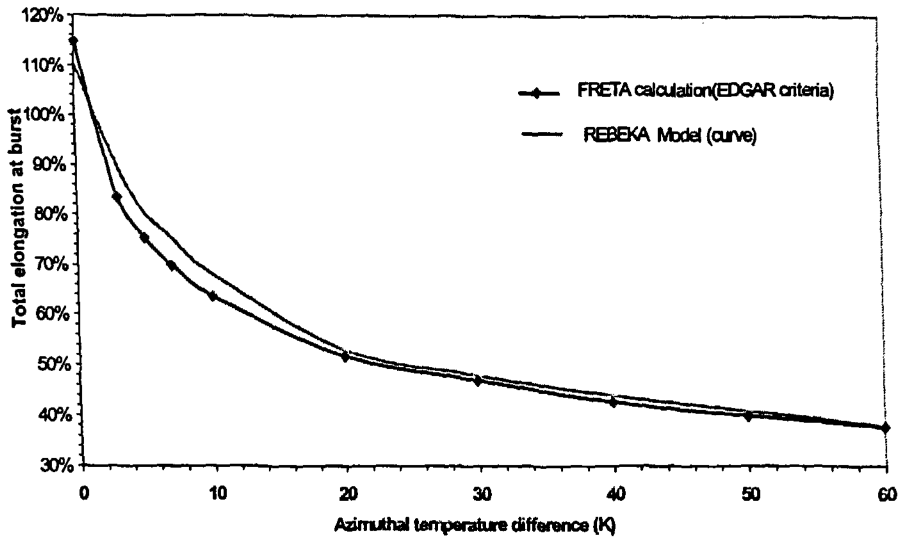
BALLOONING / BLOCKAGE. Main Findings (1B)

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,...**)



BALLOONING / BLOCKAGE. Main Findings (2)

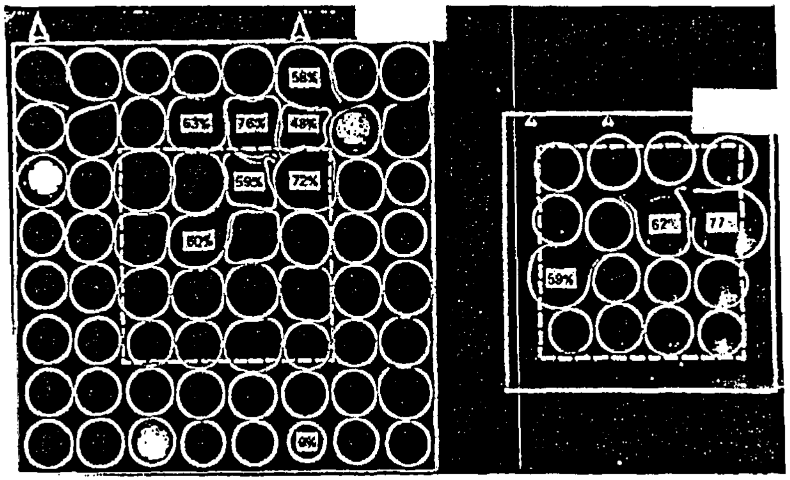
Multi Rod Tests

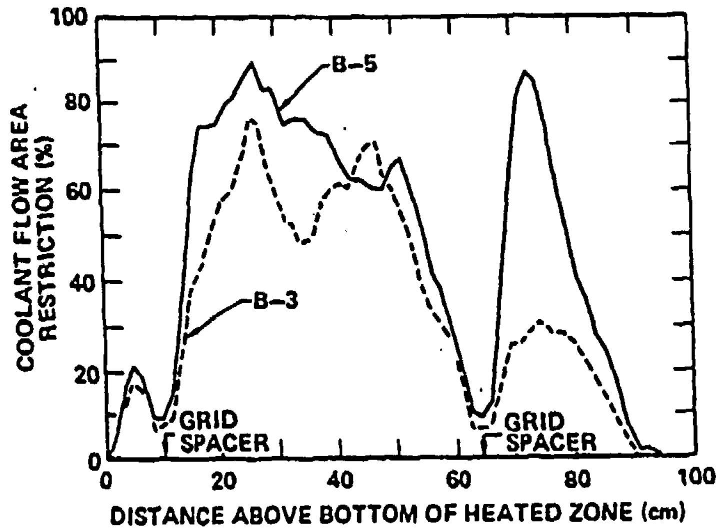
influence of thermal and mechanical interactions between rods

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***

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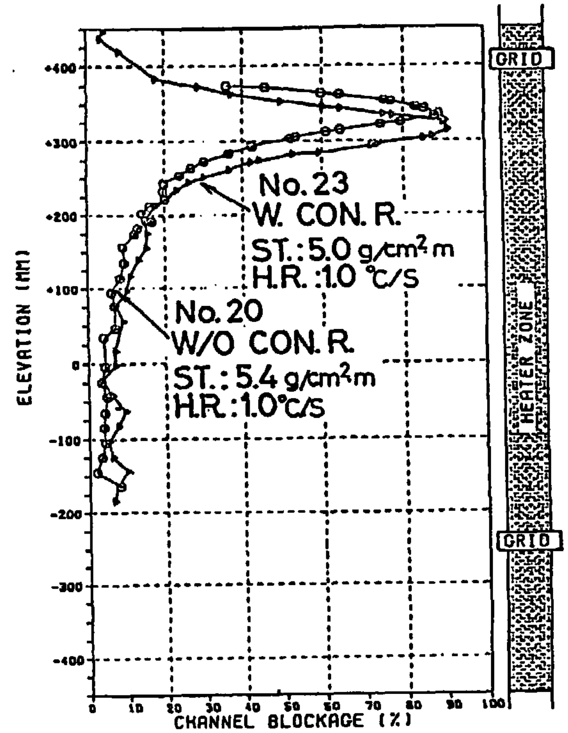
BALLOONING / BLOCKAGE. Main Findings (3)

Multi Rod Tests

influence of guide tubes

- Test REBEKA-4 (5x5 bundle with unpressurized rods in outer ring)
  - Test R-4 : ε_{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 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***

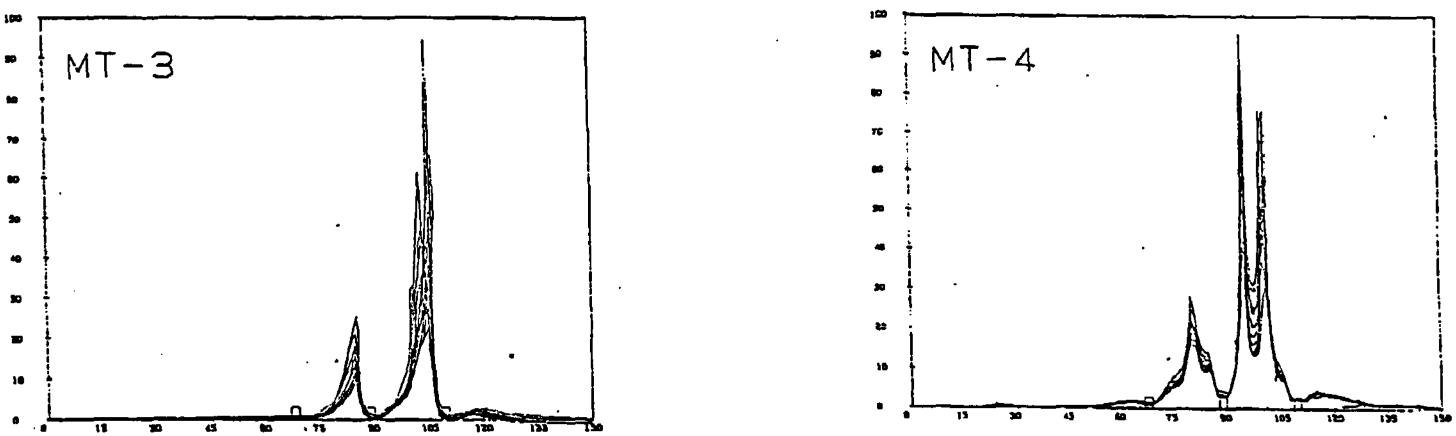
BALLOONING / BLOCKAGE. Main Findings (4)

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**

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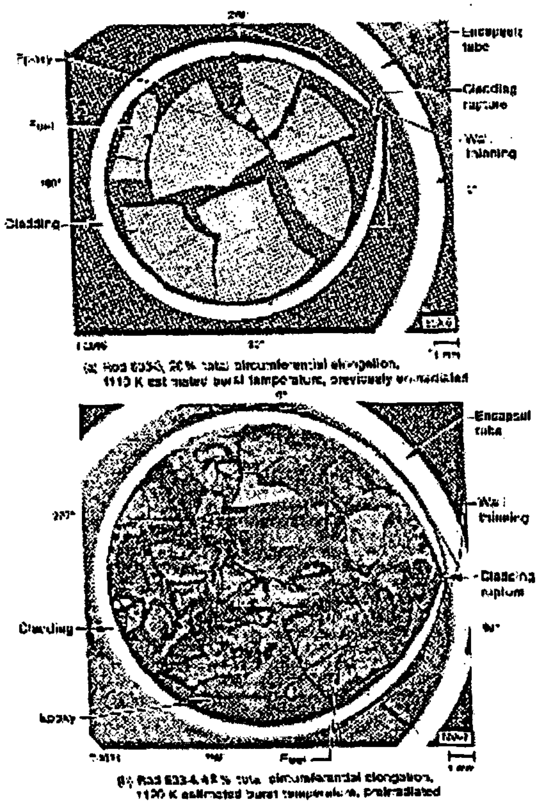
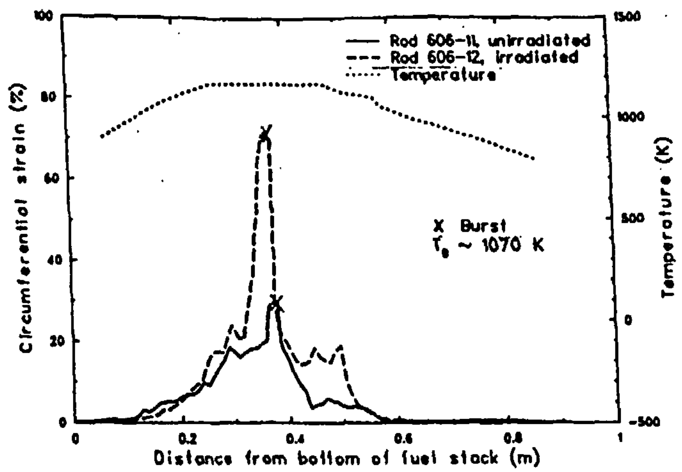
BALLOONING / BLOCKAGE. Main Findings (5A)

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

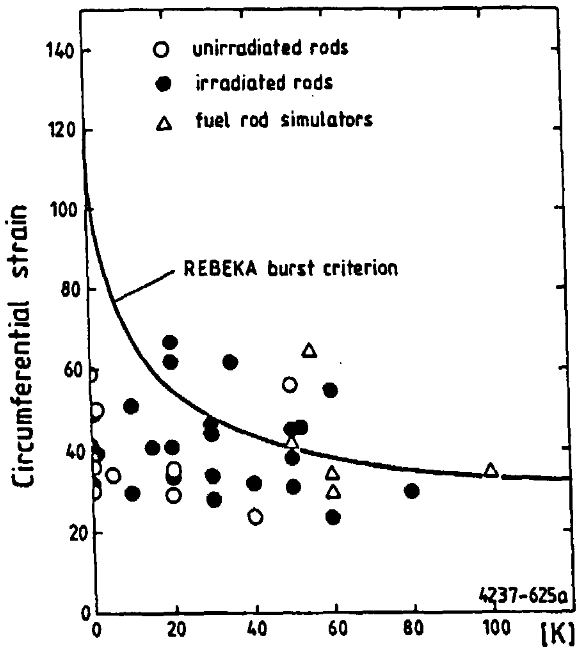




BALLOONING / BLOCKAGE. Main Findings (5B)

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

BALLOONING / BLOCKAGE. Remaining Needs.

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 ≈ 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

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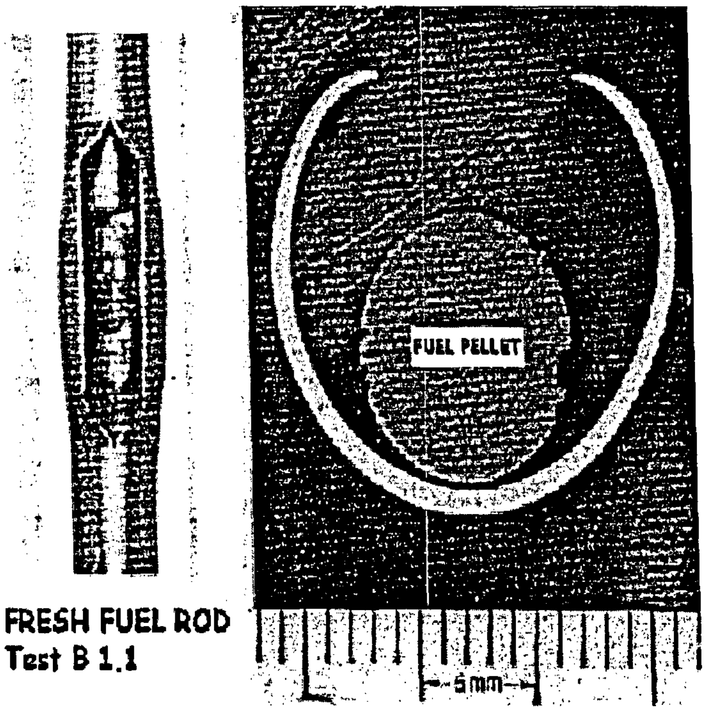
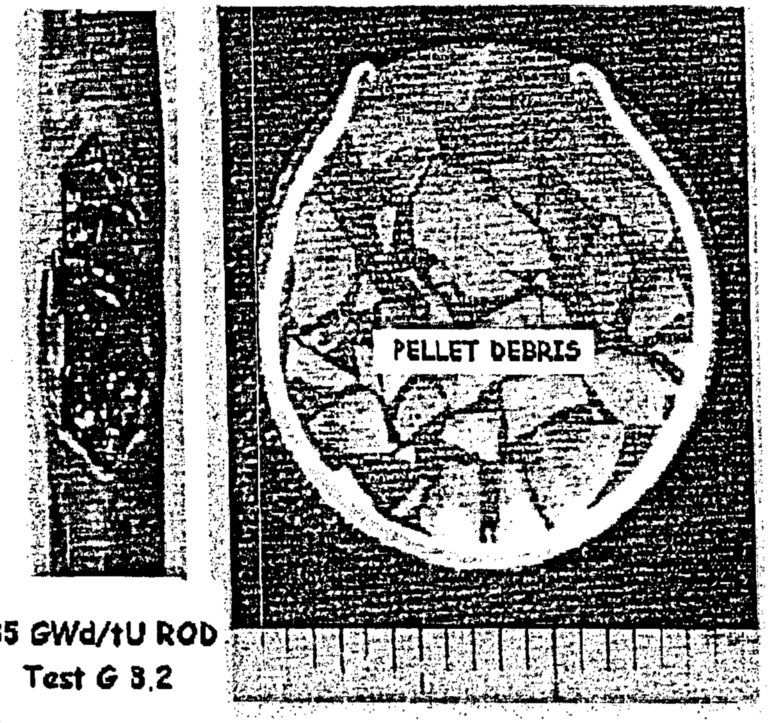
FUEL RELOCATION. Main Findings (1)

<u>In pile tests with irradiated fuel rods</u> *(cont.)*

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



FRESH FUEL ROD
Test B 1.1



35 GWd/tU ROD
Test G 3.2

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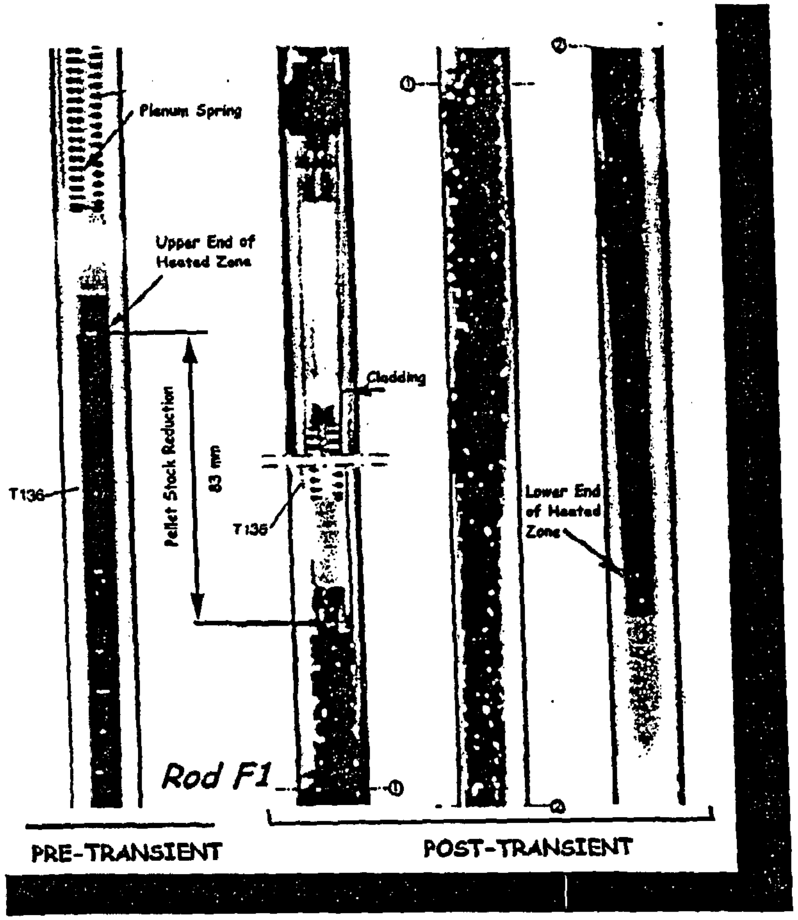
FUEL RELOCATION. Main Findings (2)



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**

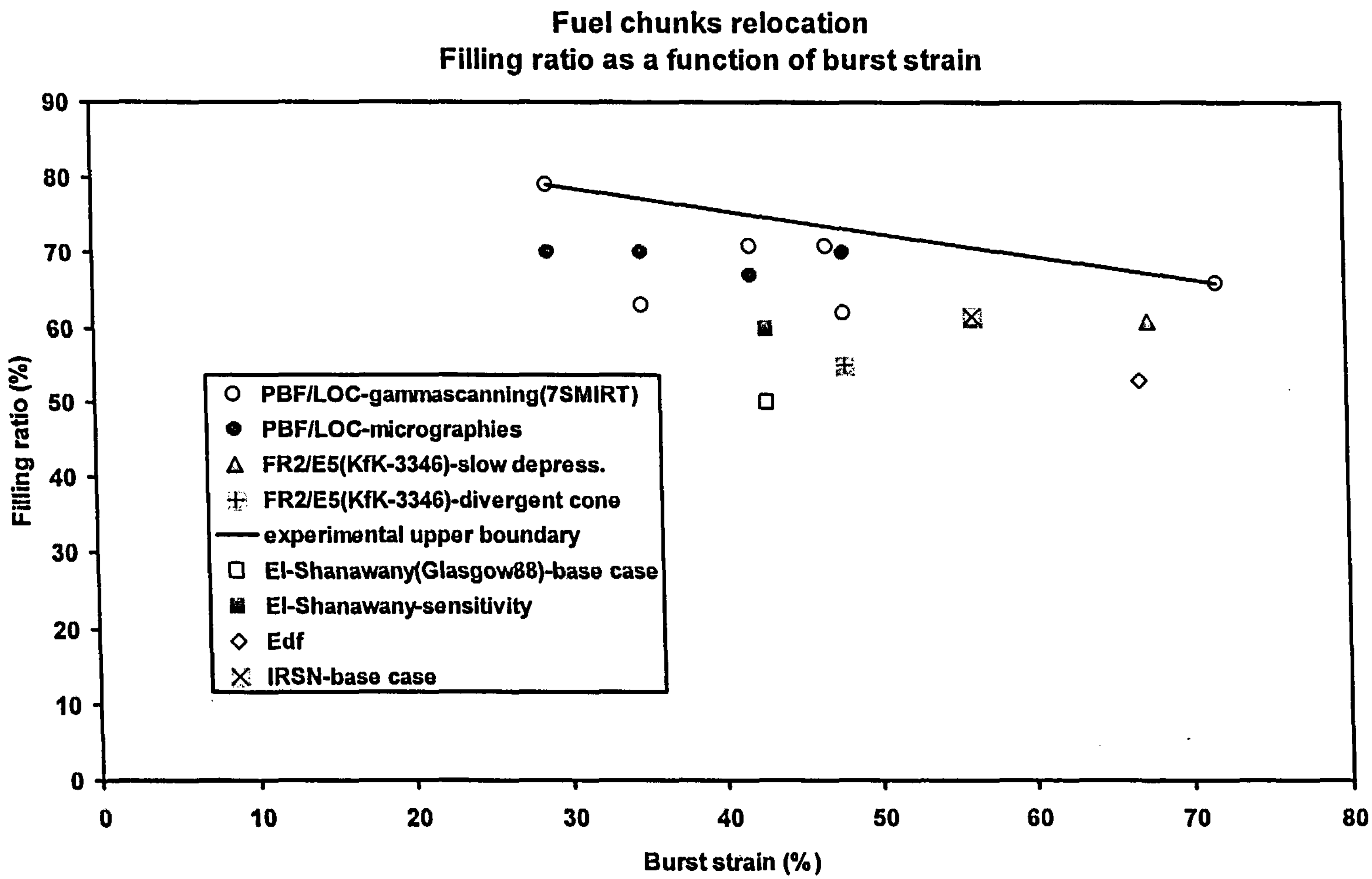
may be altered during post test handling (PBF-LOC)

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

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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***

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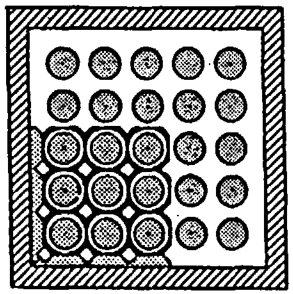
FLOODING EXPERIMENTS WITH BLOCKED ARRAYS

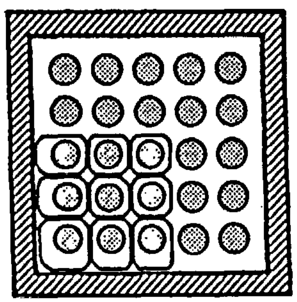
Specific Experimental Programs

- **FEBA** (KfK, Germany)
  - 5x5 rod bundle; L_{heat}=3.9 m ; "conventional" simulators ; forced reflood
  - Blockage over 3x3 or 5x5 rods ; τ=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 ; τ= 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 ; τ=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 ; τ= 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

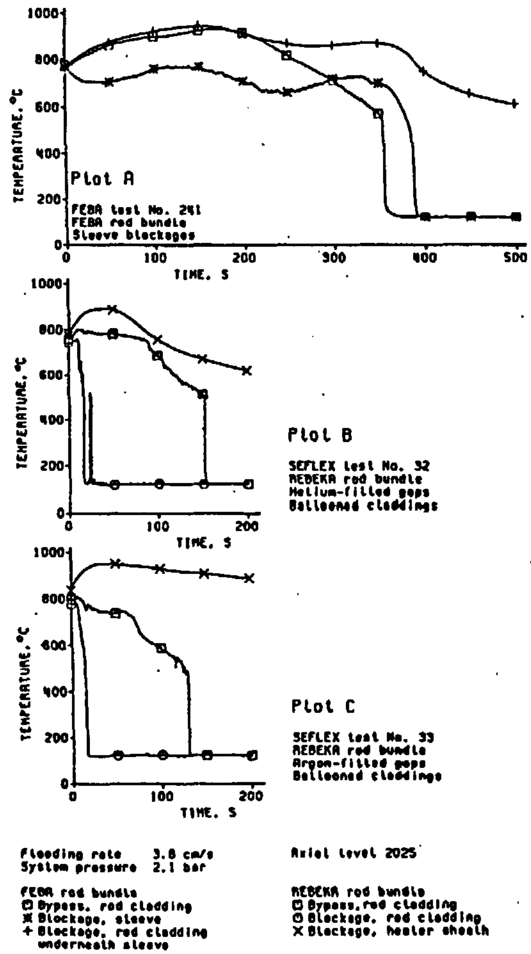
FEBA and SEFLEX Main Results



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

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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)

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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

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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.

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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)*