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Exhibit 4

NUCLEAR REGULATORY COMMISSION

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In the matter of Duke Catawba

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Exhibit 4

Grandjean, C. *et. al.*, "High Burnup UO2 Fuel LOCA Calculations to Evaluate the Possible Impact of Fuel Relocation After Burst," NEA/CSNI/R(2001)18, Aix-en-Provence, March 2001

HIGH BURNUP UO_2 FUEL LOCA CALCULATIONS TO EVALUATE THE POSSIBLE IMPACT OF FUEL RELOCATION AFTER BURST

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Abstract

A literature review, conducted at IPSN, of available results of past LOCA in-pile experiments with irradiated fuel has revealed that irradiated rods behavior was significantly different from that of unirradiated rods under similar conditions.

Particularly, as suggested from the results from PBF-LOC, FR2 and FLASH5 experiments indicating a general occurrence of the relocation of fragmented fuel within the ballooned cladding, a main concern was raised regarding the possible impact of fuel relocation on peak clad temperature and local oxidation rate.

In view of obtaining some insight into the fuel rod performance following fuel relocation in a PWR high BU UO_2 rod under LOCA, calculations were being performed, using the French CATHARE-2 code with specific modifications in the fuel routines so as to describe a fuel accumulation after burst in the ruptured mesh of the rod cladding.

Main results indicate that the peak clad temperature may increase significantly, but still remains below the ECCS acceptance limit on PCT. On the other hand, the maximum cladding oxidation rate may exceed the 17% acceptance limit when the initial (in service) oxidation rate is cumulated with the transient oxidation rate. However, alternative embrittlement criteria based on residual thickness of ductile metal, such as the Chung and Kassner criteria, indicate a fair remaining margin to the thermal shock embrittlement limit, whereas the handling embrittlement limit may be exceeded.

1 INTRODUCTION

In the following of the studies that were jointly conducted by IPSN and EDF in order to investigate the behavior of high burnup fuel cladding under LOCA conditions, IPSN has been re-examining the problem of Loss-of-Coolant-Accidents with consideration of specific aspects related to fuel and cladding irradiation, so as to identify the remaining needs for further studies and experimental data.

These concerns have led IPSN to initiate new studies in order to provide the answers to pending questions regarding the behavior of irradiated rods and assemblies under LOCA conditions.

In a preliminary step, in view of obtaining some insight into the fuel rod performance following fuel relocation in a PWR high BU UO_2 rod under LOCA, calculations were being performed, using the French CATHARE-2 code with specific modifications in the fuel routines so as to describe a fuel accumulation after burst in the ruptured mesh of the rod cladding.

2 BACKGROUND

2.1 Irradiated fuel rod behavior

2.1.1 Literature review

There exists a few number of available results of such experiments with irradiated fuel rods under LOCA conditions : main issues were found in results from the PBF-LOC tests in the USA[1,2], the FR2 tests in Germany[3], and the FLASH5[4] test in France.

A process of fuel relocation was clearly evidenced from the experimental observations made in these tests series : in all irradiated rods of the PBF-LOC, FR2 and FLASH5 tests, fuel relocation has occurred as a result of slumping of pellets fragments from upper locations into the swollen region of the burst cladding. Fuel relocation phenomena is not restricted to high burnup fuel since fuel fragmentation occurs as soon as low burnup levels (it was thus noticed on LOC5-7B rod, fresh rod pre-conditioned up to 48 MWd/t).

A main question concerns the instant of fuel relocation occurrence in these experiments. It is not easy to make it perfectly clear for most of tests but, in FR2 tests E3 and E4 that were specially instrumented for that purpose, it was demonstrated that the fuel movement initiation occurred at the time of cladding burst, possibly initiated by the pressure difference between rod plenum and coolant channel with assistance of gravity slumping.

The fuel movement was probably favored in PBF-LOC and FR2 experiments where the fuel-cladding gap was not totally closed, due respectively to low burnup or to the inverted rod internal-external pressure difference during initial irradiation at low temperature. A tight bonding between fuel and clad was supposed to counteract the fuel motion inception. However, in FLASH5 experiment with high burnup fuel (50 GWd/t), and in spite of a low clad ballooning (not higher than 16%) post-test examinations have shown that fuel fragments were no more stuck to the cladding : the transient temperature rise combined to clad deformation may be sufficient to suppress fuel-cladding bonding.

2.1.2 Main concern

For irradiated fuel rods, as observed in the PBF-LOC results, the clad deformation is expected to be larger than for fresh rods, as a result of a more uniform temperature distribution associated to pellet-clad gap reduction following clad creepdown during rod irradiation. The increase in clad deformation will leave more space for fuel fragments to relocate. Since the fuel fragmentation is clearly associated to burnup, with finer fragments at higher BU, a pellet stack slumping is likely to occur after burst resulting in more or less compact filling of clad balloons. A major question is then what could be the impact on peak clad temperature and final oxidation ratio of the local increase in lineic and surfacic power and of the associated local decrease in fuel-clad gap ?

It should be emphasized that this question is particularly important for UO_2 fuel at beginning-of-life and for MOX fuel at end-of-life where power generation is not reduced unlike for UO_2 fuel.

2.1.3 Early evaluations

The State-of-the-Art Review performed by P.D. PARSONS et al. for CSNI/PWG-2 and published in 1986[5], thus after PBF-LOC and FR2 tests completion, reports two calculation studies addressing the impact of fuel relocation on peak clad temperature.

2.1.3.1 Calculations in Sweden

The first one was conducted in 1978-79 in Sweden by Bergquist[6], within the frame of the ECCS evaluation for the Ringhals 3 power plant. It consisted of a series of parametric transient calculations, performed with the TOODEE-2 code, so as to evaluate the response on clad temperature with/without fuel relocation in the balloon after rod burst.

The main assumption for fuel relocation was a uniform redistribution of fuel in the deformed meshes of the balloon with a density taken to 50% of the theoretical density in the base case, a fuel thermal conductivity of 0.6 W/m/K and heat exchange between fuel and cladding dealt with an exchange coefficient of 5000 $W/m^2/K$. In the reference case, the hoop strain of the most deformed mesh of the balloon was 42%, and the peak clad temperature (PCT) without fuel relocation did not exceed 2000°F (=1093°C).

Calculations with fuel relocation showed that the evolution of clad temperature in the ruptured mesh is essentially dependent of the power rating in that mesh, in relation with fuel average density :

- at 43 kW/m linear power (Fq = 2.09), the clad temperature evolution remains of classical shape, with a PCT around 2050°F (1121°C) ;
- at 47.87 kW/m linear power (Fq = 2.32) the clad temperature evolution exhibits a significant rate increase around 2000°F with a subsequent temperature escalation after 45 s in the transient ;
- at 43 kW/m linear power, but with a 60% fuel theoretical density in the balloon (instead of 50%), the clad temperature evolution again exhibits a significant rate increase after 45 s, reach of the 2200°F limit around 62 s, followed by subsequent temperature escalation.

Although these early calculations had to be considered with large reservations, it may look surprising that they were not much discussed nor compared to counter-calculations, in consideration of the possible importance of calculated trends with respect to safety analysis.

2.1.3.2 INEL Calculations

The second evaluation was a steady state thermal analysis of a ballooned fuel rod following a fuel redistribution, the amount of which based on PBF-LOC tests results. This analysis was performed by T.R Yackle[7] as a response to a NRC request ; it is also mentioned by Broughton in the PBF-LOC3/LOC5 test report [1].

Fuel redistribution in the ballooned cladding is modeled by a series of up to 7 concentric rings of different width to take account of large particles of original fuel and small particles of additional fuel, neighbor rings being separated by gas gaps. Only radial heat transfer is considered, with a rod power corresponding to ANS decay heat 100 s after scram (~ 3% original power), and a flat radial power profile. A cladding surface heat transfer coefficient of 60 W/m²/K was assumed, a fuel thermal conductivity constant at 2.6 W/m/K and no radiative transfer between fuel particles.

The amount of fuel redistribution has been determined from the results of the PBF LOC-3 and LOC-5 tests. A line fit through the available data of fuel relative increase as function of cladding relative volume increase indicates an average filling ratio closed to 0.65. Three calculations have then been considered, corresponding to clad strain of 0, 44 and 89%. The following table gives the temperatures at fuel centerline and clad outside surface obtained in these three calculations.

Clad strain (%)	T_{clad} (K)	$T_{centUO2}$ (K)
0	1095	1180
44	1120	1620
89	1320	2450

For the worst case, with 89% clad strain allowing the redistribution of 160% additional fuel, the outside clad temperature is 225 K larger than for the reference case (without deformation), while the corresponding increase on maximum fuel temperature is 1270 K.

The conclusion that was drawn at that time appears presently quite surprising, as it was stated that "fuel relocation into a balloon (with conditions such those calculated) will not pose a significant problem during a LOCA since both fuel and clad temperatures remain well below the corresponding melting points"...It may be thought that the relatively close occurrence of the TMI-2 accident is likely to explain such shift of concerns from LOCA to Severe Accident issues.

3 IPSN CALCULATIONS

3.1 Reference code and calculation procedure

The French CATHARE-2 code has been chosen as a base tool due to its capability to provide a best-estimate evaluation of the thermal-hydraulic evolution in hot assembly as well as in mean core subchannels. The code organization allows to run stand-alone calculations of the fuel module (the

CATHACOMB module) in order to provide rapidly information about the behaviour of specific fuel rods subjected to a given set of hydraulic conditions ; these hydraulic conditions will thus not be influenced by the behaviour of such specific rods. The hydraulic conditions may be retrieved from a previous CATHARE whole calculation, or may be that of the current CATHARE computation with which the stand-alone fuel module is carried out in parallel.

For the purpose of this study, the calculations were performed as follows :

- in a first step a whole CATHARE-2 computation was run, for a large break LOCA transient occurring on a typical French PWR, with an input deck corresponding to a fresh fuel "mean core" rod and a high burnup UO_2 fuel "hot assembly" rod ; this computation provided the hydraulic file used as input in the following calculations ;
- in a second step a series of stand-alone CATHACOMB calculations were run, using the previously created hydraulic file, for a specific hot rod of the hot assembly, and with the inclusion of specific modifications in some fuel routines in order to simulate fuel relocation after burst in the ruptured mesh ; these modifications will be briefly described in the following.

3.2 Code version

The CATHARE-2 V13L code version was used as starting version, according to the known improvements implemented in this version to calculate the reflooding phase of the LOCA transient.

Slight modeling improvements have been added in the fuel routines so as to compute at the end of each time step the oxidation weight gain (using both Cathcart-Pawel and Baker-Just rate laws) as well as the thickness of α-Zr[O] oxidation layer ; the former variable allows a direct calculation of the equivalent oxidation rate ECR, while the latter variable allows to derive the remaining thickness of the central β-Zr layer.

3.3 Basic input options for the initial CATHARE-2 whole calculation

3.3.1 Accident transient conditions

The main assumptions are in agreement with those retained in the Standard Safety Report for 900 MWe French PWRs :

- double ended break on cold leg of the loop bearing the pressurizer,
- core at 102% nominal power at accident initiation,
- residual power = ANS71 + 20%.

3.3.2 Fuel rods description

Basically, three fuel rods may be described for a CATHARE calculation :

- the mean core rod, with a weight of $(N_{as}-1)\times N_{rpa}$
  where N_{as} is the number of assemblies in the core and N_{rpa} the number of active rods per assembly
- the hot assembly mean rod, with a weight of N_{rpa}
- one (or several) hot rod(s) in the hot assembly

Each of these rods is described in terms of geometry, cladding oxide thickness profile, power profile. A typical axial meshing with 40 meshes was chosen.

In agreement with the options retained in sensitivity studies performed at EDF some years ago, the lineic power of the mean core rod was chosen as that of beginning of life (BOL) while only the hot assembly rods were chosen irradiated to 57 GWj/tU ; the ratio F_{dh} of hot rod power to mean core rod power was chosen to 1.28 (as compared to the 1.55 value for BOL case), and the ratio F_{ap} of hot rod power to hot assembly mean rod power was kept to 1.05 identical to BOL case.

Prior to the LOCA initiation, the reactor core is then supposed to be subjected to a transient evolution that brings the three above mentioned rods respectively to : 68.20 kW, 83.25 kW and 87.41 kW, and with a truncated cosine axial power profile.

The irradiated rods bear an external oxide layer on the zircaloy clad, with a thickness profile typical of 4 cycles irradiation, the maximum thickness reaching 106 µm at 2.79 m elevation. The pellet-cladding gap is supposed to be closed in the irradiated rods at transient initiation. The internal pressure in hot conditions in irradiated rods is significantly higher (~15.6 Mpa) than in mean core fresh rods.

Two hydraulic channels are associated to the mean core and hot assembly rods. The thermo-mechanical behaviour of the hot rod(s) is influenced by the hot assembly channel hydraulics during the blowdown and refill phases and by the mean core channel hydraulics during the reflooding phase.

3.4 Reference case behaviour (without fuel relocation)

A reference calculation without fuel relocation was first performed for the hot rod of the hot assembly. It must be pointed out that a best-estimate treatment of the clad ballooning and burst for the irradiated rod was not searched here : the standard clad deformation and burst models for fresh fuel were kept unchanged in CATHARE.

However, in consideration of the results of the TACIR experiments (oxidation and quenching tests) on irradiated cladding [8], having clearly indicated that the initial oxide scale was no more protective for high temperature oxidation, it was chosen to suppress the protective effect of the initial oxide scale towards transient oxidation of the clad, that is normally active in the standard oxidation model of CATHARE.

The rod cladding appeared to rupture at 30.2 seconds on mesh 24 (elevation 2.15 m) with a hoop strain of 56.3%. All the following results, unless explicitly stated, will refer to the ruptured mesh elevation.

Figure 1 displays the evolution of the fuel centerline and clad outside temperatures : the clad outside temperature rises to a maximum of 970°C while the fuel centerline temperature remains below 1100°C during the heatup phase.

Figure 2 displays the equivalent cladding reacted ECR evolution, as calculated with Cathcart-Pawel rate law, for the ruptured mesh and the two neighbor meshes. For the non ruptured meshes, due to unprotected oxidation on the external face only, the oxidation rate ECR is increased by about 1.7% in absolute value, while on the ruptured mesh, due to two-sided oxidation, the ECR rises from an initial value at 9.2% to 12.6% at the end of the transient.

Figure 3 compares the equivalent cladding reacted ECR evolutions, as calculated with Cathcart-Pawel and Baker-Just rate laws, for the ruptured mesh. It can be noticed that both correlations give very close results in the corresponding range of clad temperature. Acceptance criterion on clad maximum oxidation rate (<17%) is clearly well satisfied.

Figure 4 displays the evolution of the remaining thickness of the clad β-Zr layer, showing the sharp drop in thickness (from ~520 to ~330 µm) corresponding to clad ballooning up to rupture, followed by a slow decrease corresponding to high temperature oxidation. The final thickness remains just above 300 µm, indicating a fair remaining resistance to thermal shock embrittlement, with reference to embrittlement criterion proposed by Chung and Kassner[9], while the handling limit proposed by these authors is just reached.

3.5 Fuel relocation case

3.5.1 Basic assumptions and modeling options

With reference to the FR2 experimental results discussed before in section 2.1.1, we assumed that fuel pellets crumbling and relocation occurred immediately after the cladding burst, leading to a partial filling of the inside volume of the ballooned cladding ruptured mesh. This volume was calculated as that of a cylindrical volume with clad inner radius at burst and mesh height. It was then assumed that this ruptured mesh volume was filled homogeneously with fuel fragments up to an user's input filling rate (= ratio of dense fuel volume to new mesh volume). A base calculation was performed with a filling ratio of 61.5% corresponding to a value measured in the FR2 experiment E5. Two other calculations were conducted with values of the filling ratio of 40% and 70% in order to evaluate the sensitivity of the results to this main parameter.

The fuel fragments were assimilated to spherical particles with user's input diameter. These fragments are in contact with the cladding, leading thus to a closed fuel-cladding gap.

The effective thermal conductivity of the fuel fragments was derived from the Imura[10] correlation and taking into account the radiative transfers between particles according to the Yagi theoretical model. The resulting model, so-called "Imura-Yagi" model, had been implemented in the SFD code ICARE2 of IPSN after it had been validated against Sandia DC1 experiment.

According to the results of the TAGCIR experiments mentioned in previous section, the protective effect of initial oxide scale towards LOCA transient oxidation was again suppressed in all the following calculations involving fuel relocation.

3.5.2 Results of the base case (61.5% filling ratio)

A basic calculation was performed with a filling ratio of 61.5% corresponding to a local value measured on a sample taken from the ballooned region (with 67.5% total circumferential elongation) of the the FR2 experiment E5. The particle diameter was taken as the average size determined in FR2 experiments, i.e. 2.7 mm.

Figure 5 displays the evolution of the fuel centerline and clad outside temperatures : the clad outside temperature reaches a maximum level around 1100°C while the fuel centerline temperature remains below 1200°C during the heatup phase.

Figure 6 shows the evolution of the oxidation rate ECR, as calculated with Cathcart-Pawel rate law, for the ruptured mesh and the two neighbor meshes. It appears that the oxidation rate rises from 9.2% to near 18% on the rupture/relocation mesh, while the increase in ECR does not exceed 2% on the neighbor meshes. Figure 7 displays the evolution of ECR values at ruptured mesh, as calculated with Cathcart-Pawel and Baker-Just rate laws ; compared to the corresponding curves for the calculation without fuel relocation (figure 3) a clear distinction can now be made between both evolutions, corresponding to the increase in clad temperature. The maximum value of ECR calculated with Baker-Just rate law is 19.4%, thus exceeding the current acceptance limit.

Figure 8 displays the evolution of the remaining thickness of the clad β-Zr layer, showing the same sharp drop as in reference case corresponding to clad ballooning up to rupture, followed by the decrease corresponding to high temperature oxidation, with a final thickness just below 250 µm. Since the maximum oxygen content at this temperature level remains below 0.9 wt %, it appears that the Chung/Kassner criterion would be satisfied for the thermal shock limit but not for the handling limit.

3.5.3 Sensitivity to the balloon filling ratio

Finally, comparative calculations were performed with filling ratio values of 40% and 70%, the latter value corresponding to the fuel void fraction measured by gamma decay counts in some PBF-LOC experiments. The particle diameter was kept at the same value as in the previous calculation (2.7 mm).

Figure 9 displays the evolution of clad outside temperature with increasing value of the balloon filling ratio : for 40% filling the temperature level is similar to that of reference case without fuel relocation whereas peak clad temperature reaches 1144°C with 70% filling.

Figures 10 and 11 display the evolutions of the oxidation rate ECR, as calculated with Cathcart-Pawel, and of the remaining thickness of the clad β-Zr layer respectively, with increasing filling ratio values. For highest filling value, the total oxidation rate ECR reaches 19.7% (22% with the Baker-Just rate law) while the β-Zr layer remaining thickness remains near 230 µm at the end of LOCA transient.

4 SUMMARY AND CONCLUSIONS

LOCA transient calculations have been performed with an adapted version of the French code CATHARE-2 in order to evaluate the possible impact of crumbling and relocation of irradiated fuel in the ballooned region of a cladding after burst.

Focus has been put on the sensitivity of peak clad temperature and final oxidation rate on the filling ratio of the ballooned cladding with fuel crumble.

The calculations do not intend to give a best-estimate view of the detail behaviour of high burnup fuel rod under LOCA transient. In particular, the thermo-mechanical properties of irradiated zircaloy were not available for the calculation of cladding deformation and burst with irradiated material.

The results indicate that for fuel relocation in the ballooned region with a filling ratio up to the values obtained in FR2 or PBF-LOC experiments, the peak clad temperature may increase significantly, but still remains below the ECCS acceptance limit (1200°C) on PCT.

On the other hand, the maximum cladding oxidation rate exceeds the 17% acceptance limit when the initial (in service) oxidation rate is cumulated with the transient oxidation rate and when the initial oxide layer is assumed no more protective for transient oxide growth. However, alternative embrittlement criteria based on residual thickness of ductile metal, such as the Chung and Kassner criteria, indicate a fair remaining margin to the thermal shock embrittlement limit, whereas the handling embrittlement limit appears exceeded.

The results of the present study give some insight into the possible impact of the crumbling and relocation of high burnup UO_2 fuel in a LOCA transient, a phenomena that was observed previously in in-pile experiments and which might significantly affect the late evolution of accident transient and associated safety issues. It must be pointed out that results of corresponding calculations with low burnup UO_2 or high burnup MOX fuels would have been more severe with regard to acceptance limits.

The results of the present calculation study give some support to the need for further experimental data, to be provided by irradiated fuel LOCA experiments involving fuel relocation. A best representativity should be obtained with in-pile experiments, so as to maintain heat generation in fuel fragments whatever their displacement may be during the relocation process. Such experiments are currently under planning by Halden Reactor Project and by IPSN.

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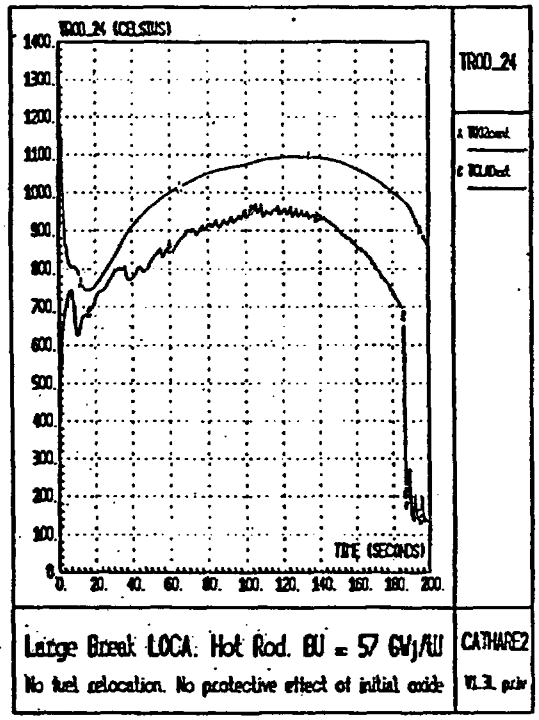

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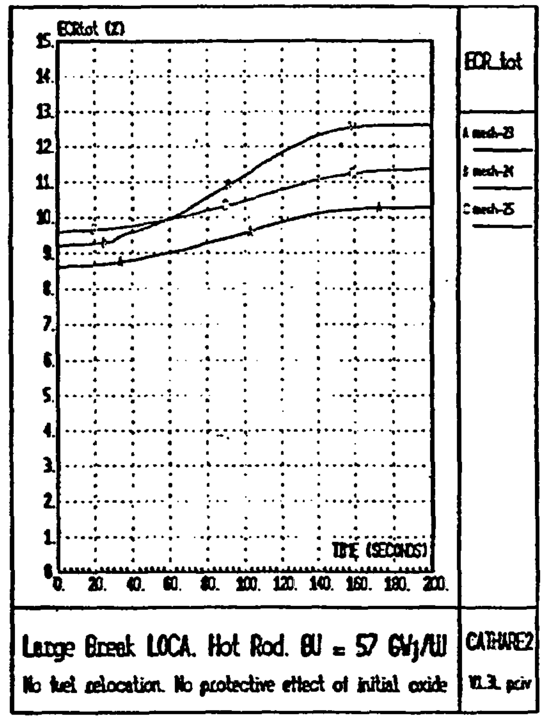

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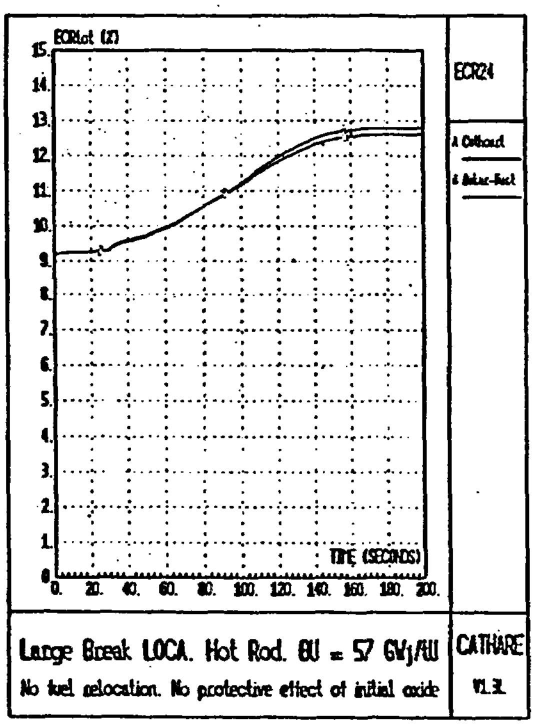

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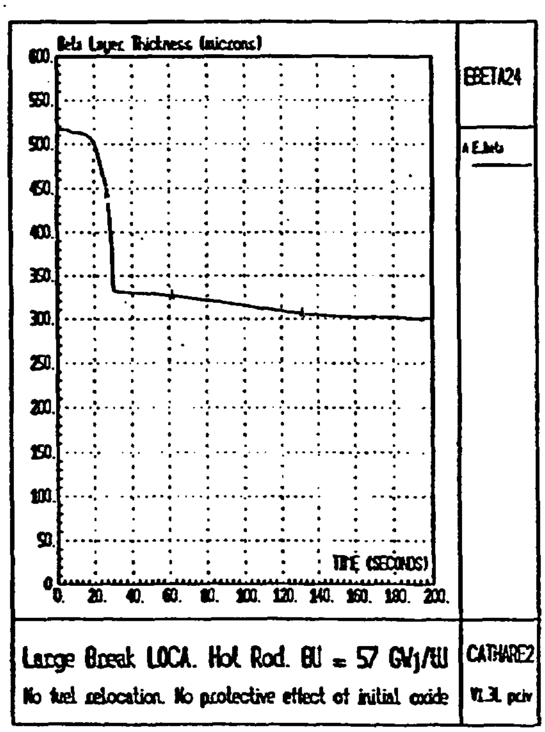

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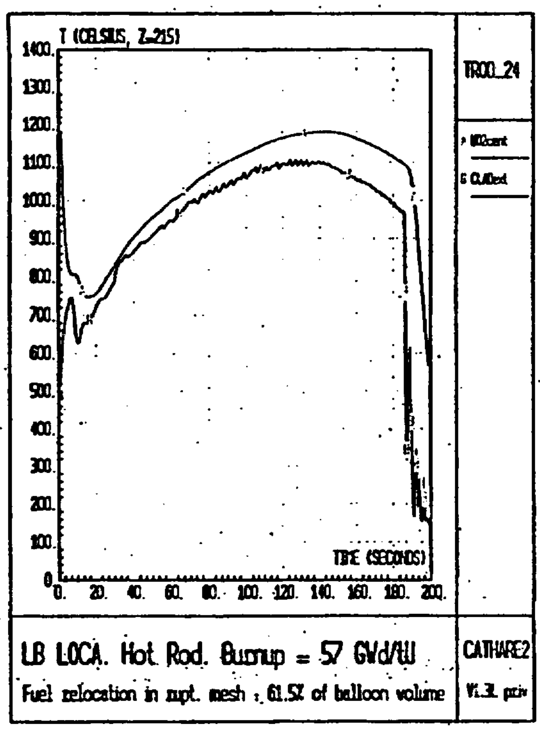

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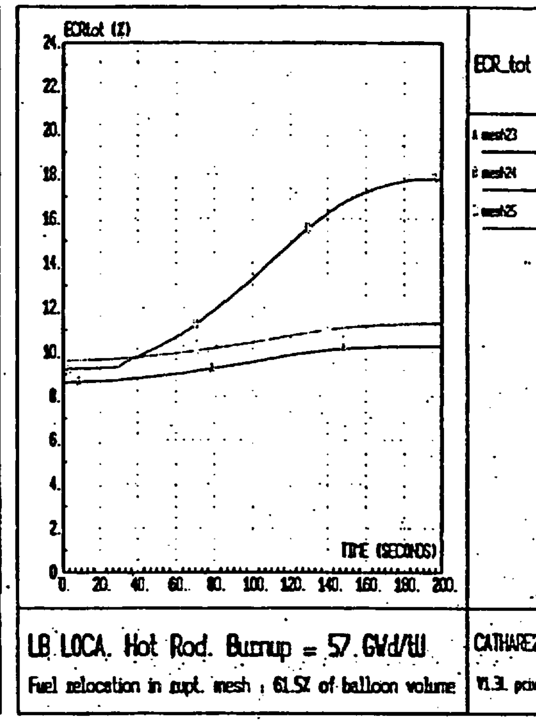

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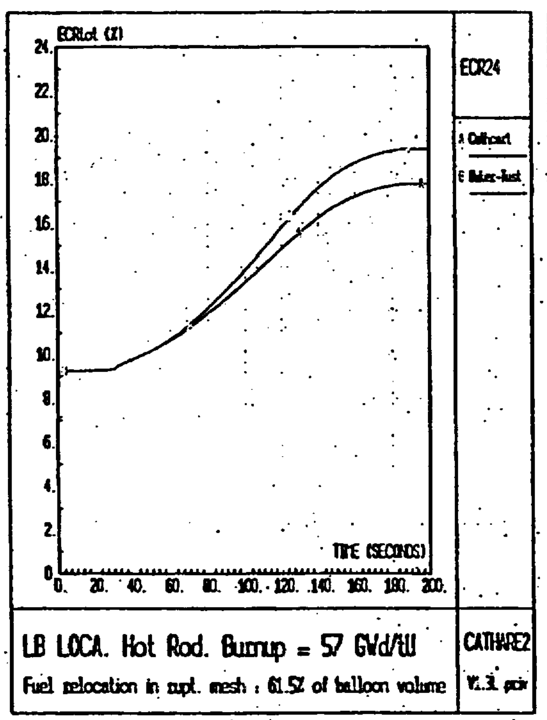

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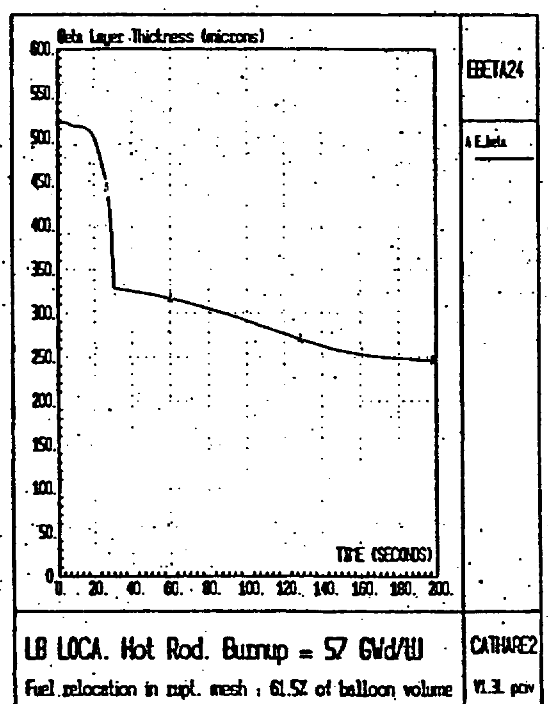

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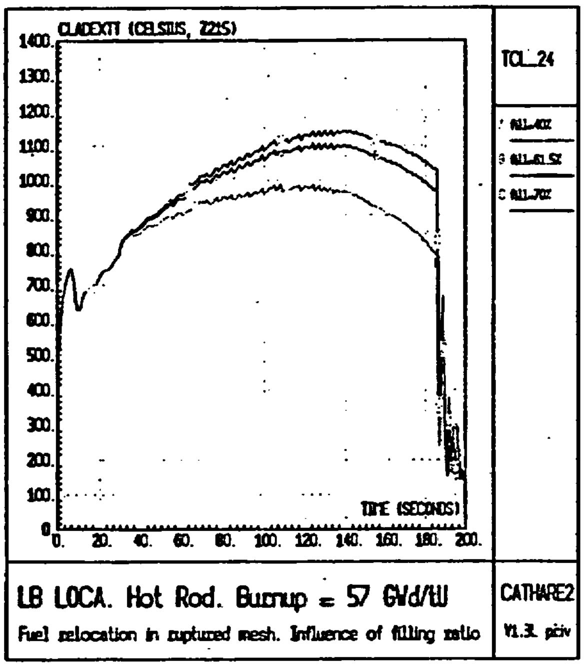

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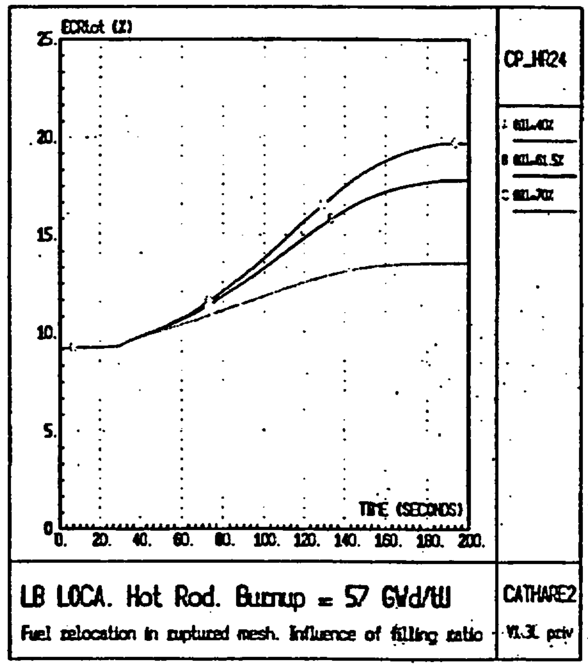

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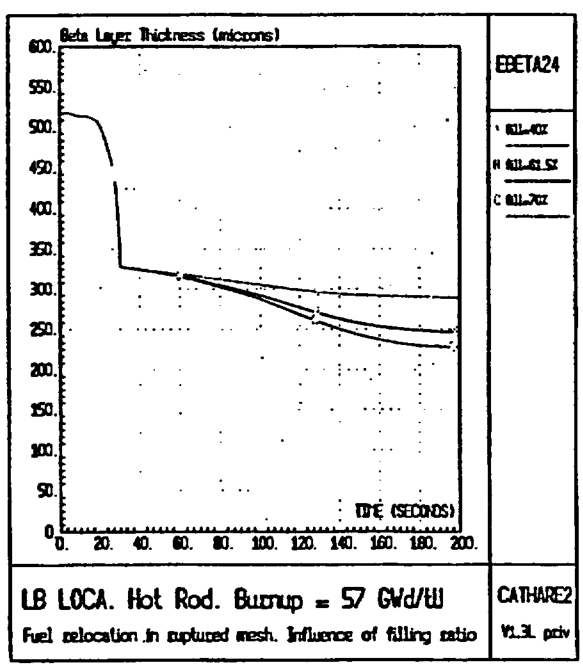

figure 11.

High Burnup UO_2 Fuel LOCA Calculations to Evaluate the Possible Impact of Fuel Relocation After Burst

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OECD Topical Meeting on LOCA Fuel Safety Criteria,
Aix-en-Provence, March 22-23, 2001

BACKGROUND (1)

EXPERIMENTAL OBSERVATIONS

Main findings were provided by the results of : PBF-LOC, FR2, FLASH5 experiments :

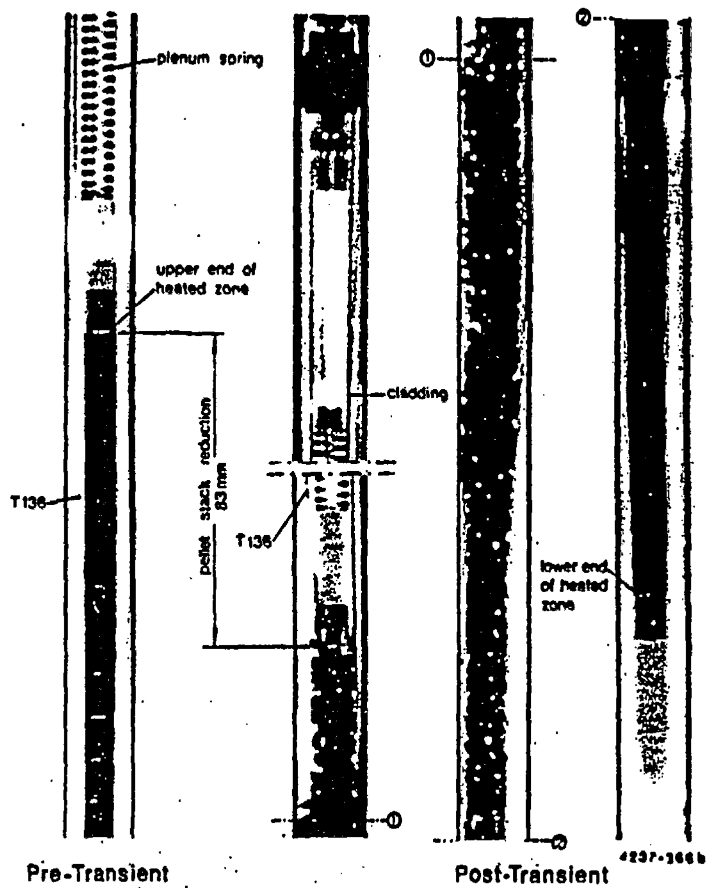
- fuel relocation was observed in all irradiated rods as a slumping of fuel fragments from upper locations into the swollen region
- fuel movement initiation occurred at burst in E3 and E4 FR2 tests
- fuel motion, (favored in FR2 due to non closure of gap) is supposed to be counteracted by a tight fuel-clad bonding
  - ➔ *bonding was not observed on FLASH5 (50 GWd/t) despite low clad ballooning (16%)*

<u>Important issue :</u>

Fuel relocation ⇨ increases local power and reduces drastically pellet-clad gap

↳ *impact on Peak Clad Temperature and Oxidation Rate ?*

importance : UO_2 at BOL, MOX at EOL



Neutron radiographs of rod F1 (burnup 20 000 MWd/t_U).
Comparison between status pre-transient and post-transient

BACKGROUND (2)

EARLY ANALYTICAL EVALUATIONS

✱ BERGQUIST (Sweden, 1978-79) : Parametric transient calculations with TOODEE-2 code

- impact of fuel relocation after clad ballooning and burst / reference case without relocation
- main sensitivity to peaking factor (F_q) and density of relocated fuel (ρ_{reloc})

Results : ref case (F_q =2.32) w/o relocation → PCT ~ 2000°F = 1093°C
relocation, F_q =2.09, ρ_{reloc} = 50% ρ_{theor} → PCT ~ 2050°F = 1121°C
relocation, F_q =2.09, ρ_{reloc} = 60% ρ_{theor} → T_{clad} ↗ above 2150°F and subsequent escalation

✱ YACKLE (INEL, 1980) : Steady state thermal analysis of a fuel rubble in clad balloon

- fuel relocation ratio extrapolated from PBF-LOC experiments
- relocated fuel modeled as a series of 7 concentric nodes with stagnant steam gaps
- power : ANS decay heat at 100 s ; flat radial power profile ;

Results : worst case : 89% cladding strain → 160% fuel redistribution
↳ T_{clad} = 1320 K (+ 225 K) and $T_{cent\text{-}fuel}$ = 2450 K (+1270 K)

Conclusion : *fuel relocation = not a problem since both T are well below melting points !!*

IPSN Calculations : Large Break LOCA calculations with irradiated fuel rods

Code version

CATHARE2 V1.3L with specific modifications to :

- ➢ simulate fuel accumulation in the ruptured mesh after burst
- ➢ calculate oxidation rate ECR and β-Zr remaining thickness

Calculation Procedure

- 1st step : whole CATHARE2 LOCA computation run <u>without fuel relocation</u>
  - ↳ provides the hydraulic conditions for following calculations
- 2nd step : stand-alone fuel module (CATHACOMB) calculations
  - ➢ under imposed hydraulic conditions retrieved from previous step
  - ➢ without fuel relocation (reference case)
  - ➢ with simulation of fuel relocation after burst, according to user's input characteristics for the filling of the clad balloon

CHARACTERISTICS OF CALCULATIONS (1)

Whole CATHARE2 standard calculation :

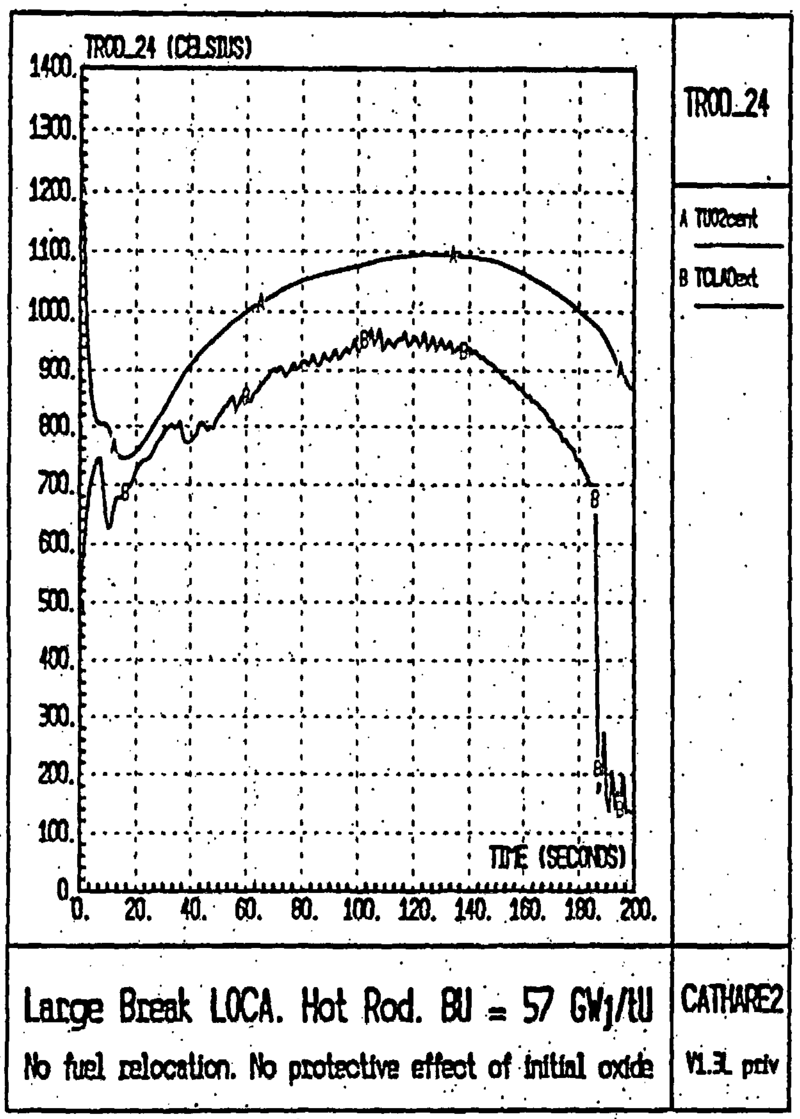
- large break LOCA (double ended break on cold leg)
- mean core rod : fresh fuel
- hot assembly rods : irradiated fuel 57 GWd/t

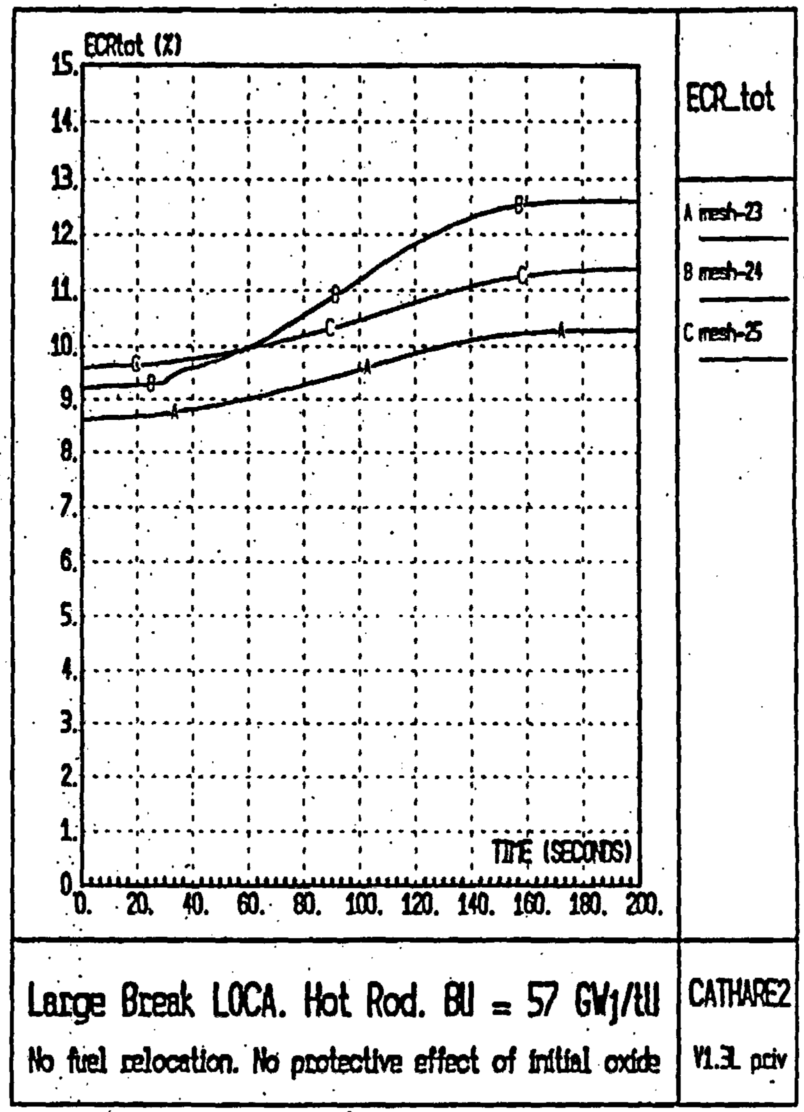
  $P_{hot\ rod}/P_{mean\ core\ rod} = 1.28$ (1.55 at BOL) ; Fq = 1.94 (2.35 at BOL)
- at accident initiation :
  - core at 102% of nominal power,
  - cosine axial power profile,
  - pellet-clad gap closed in irradiated rods,
  - rod internal pressure P_{int}= 15.6 Mpa

CHARACTERISTICS OF CALCULATIONS (2)

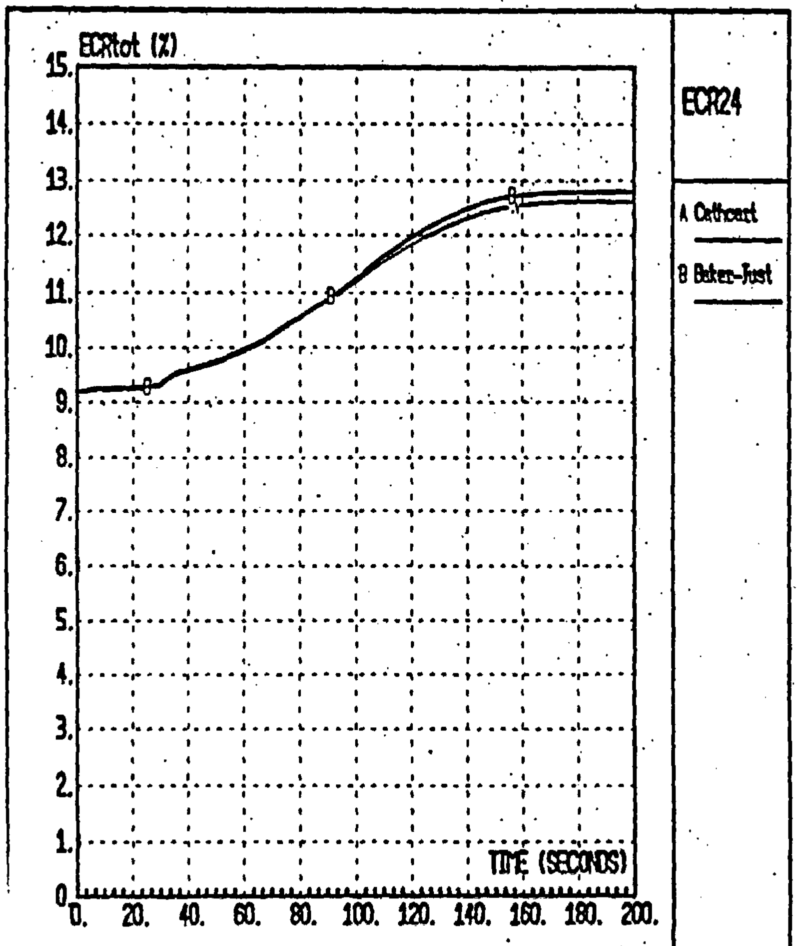
Stand-alone CATHACOMB calculations :

- suppression of the protective effect of initial oxide scale
  (according to the results of TAGCIR experiments on irradiated cladding)
- homogeneous filling of the balloon
  Filling ratio (= 1- void ratio) :
  - base case : 61.5% (value measured in FR2 experiment E5)
  - sensitivity study : 40% and 70%
- fuel fragments assimilated to spherical particles in contact with the cladding wall (res. gap = 1 μm)
  particle diameter : 2.7 mm (= average value in FR2 experiments)
- thermal conductivity derived from a debris bed model, including convective and radiative heat transfer between fuel particles :
  IMURA/YAGI model, validated against the DC1 experiment (SNL)



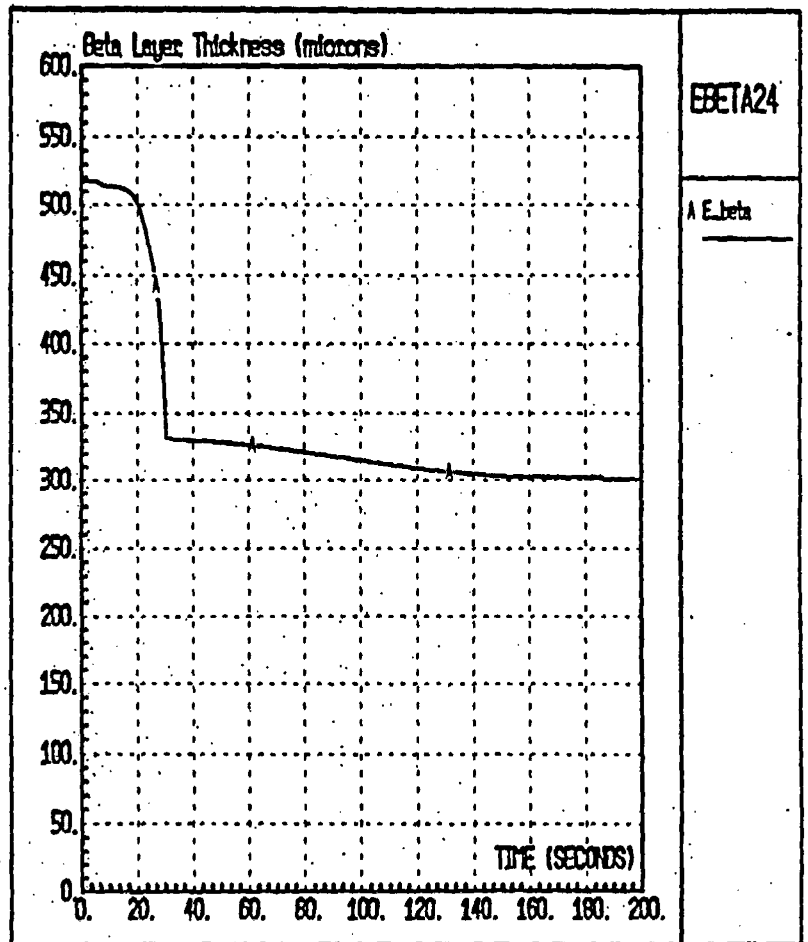


Rod burst at 30.2 s on mesh 24 (z = 2.15 m) with ε_B = 56.3%



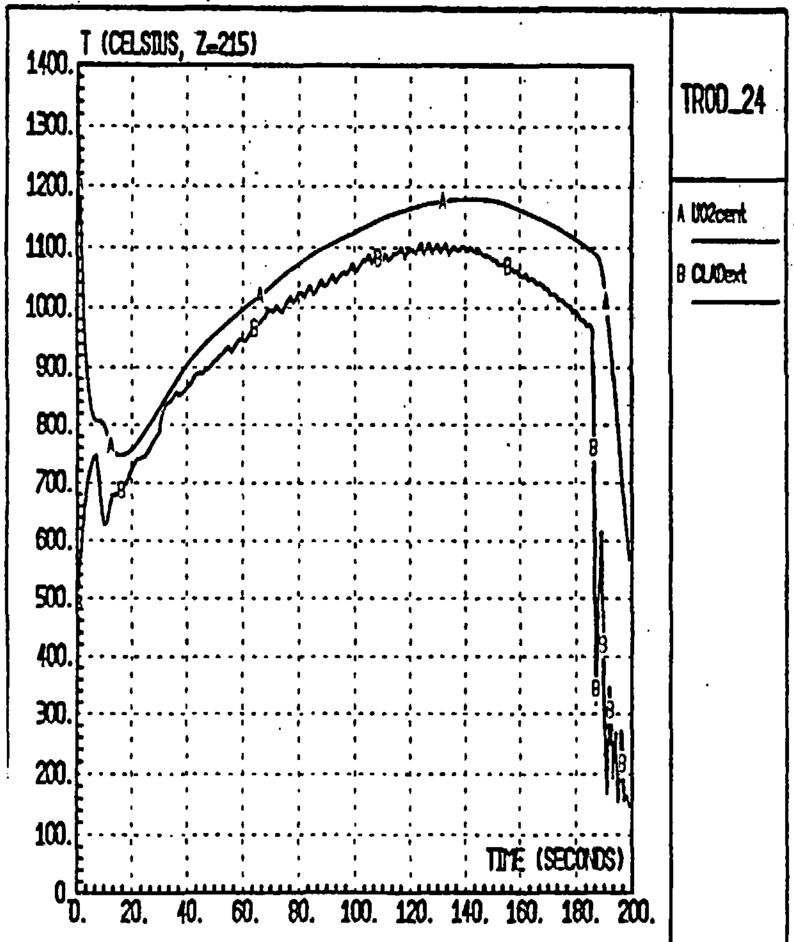
Large Break LOCA. Hot Rod. BU = 57 GWj/tU | CATHARE

No fuel relocation. No protective effect of initial oxide | V1.3L



Large Break LOCA. Hot Rod. BU = 57 GWj/tU | CATHARE2

No fuel relocation. No protective effect of initial oxide | V1.3L priv

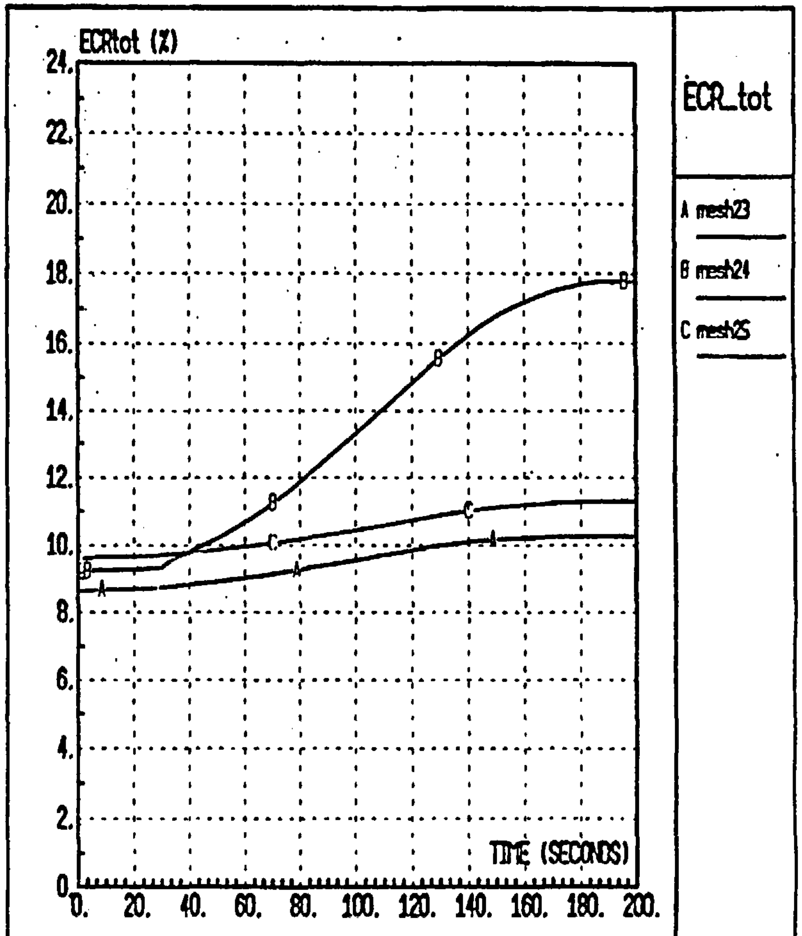


LB LOCA. Hot Rod. Burnup = 57 GWd/tU

Fuel relocation in rupt. mesh : 61.5% of balloon volume

CATHARE2

V1.3L priv

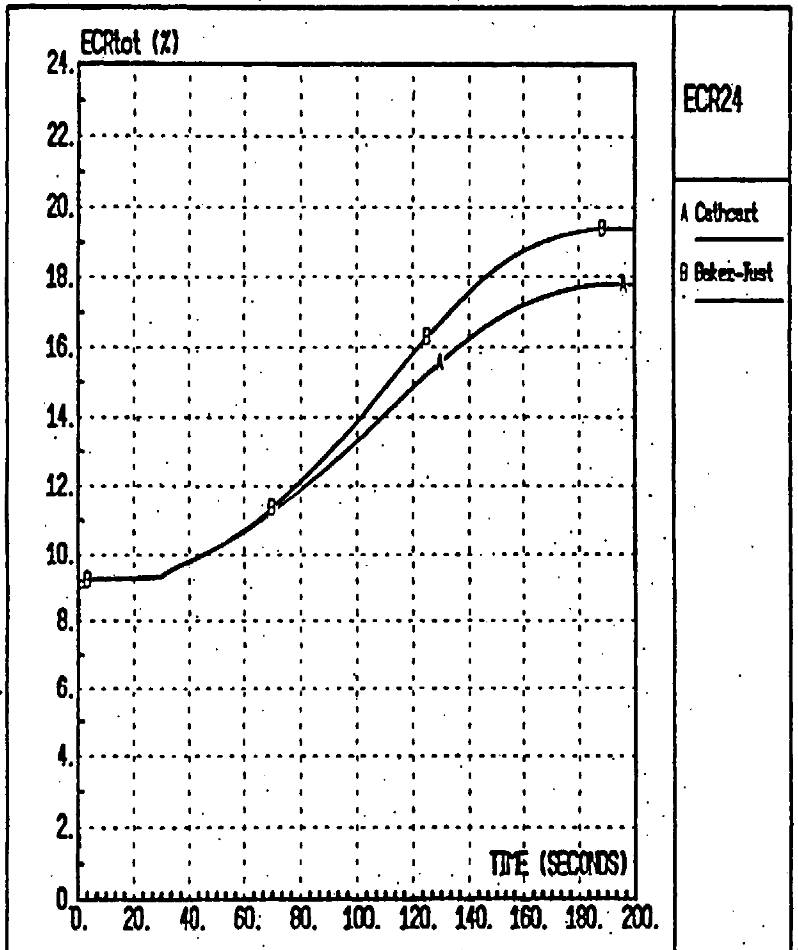


LB LOCA. Hot Rod. Burnup = 57 GWd/tU

Fuel relocation in rupt. mesh : 61.5% of balloon volume

CATHARE2

V1.3L priv



LB LOCA. Hot Rod. Burnup = 57 GWd/tU | CATHARE2

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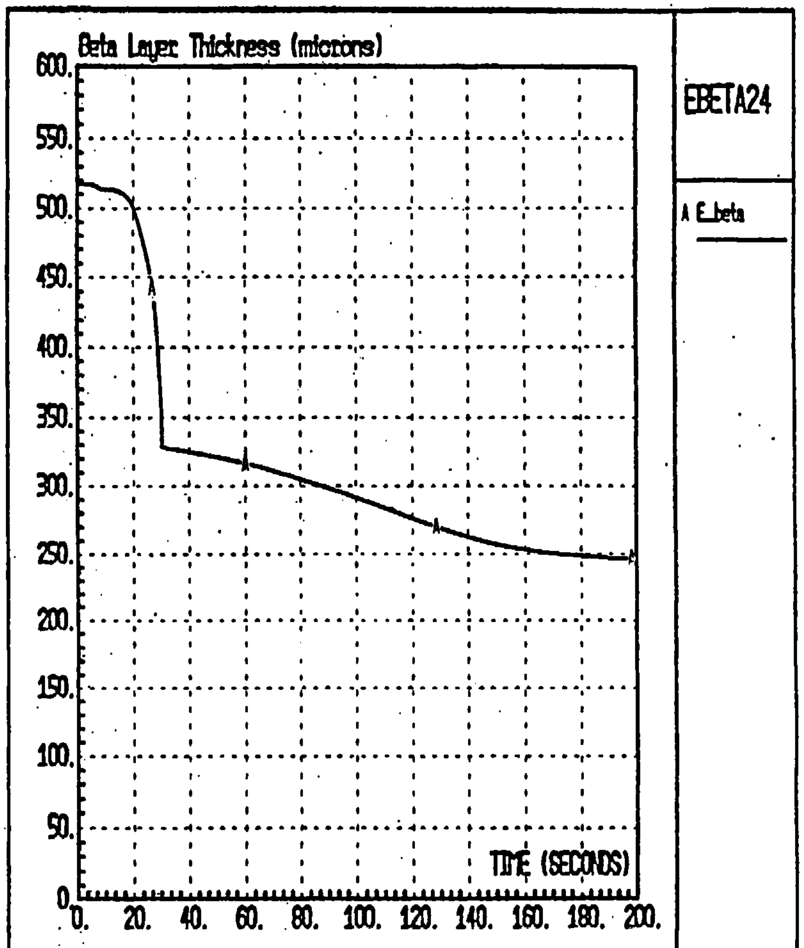
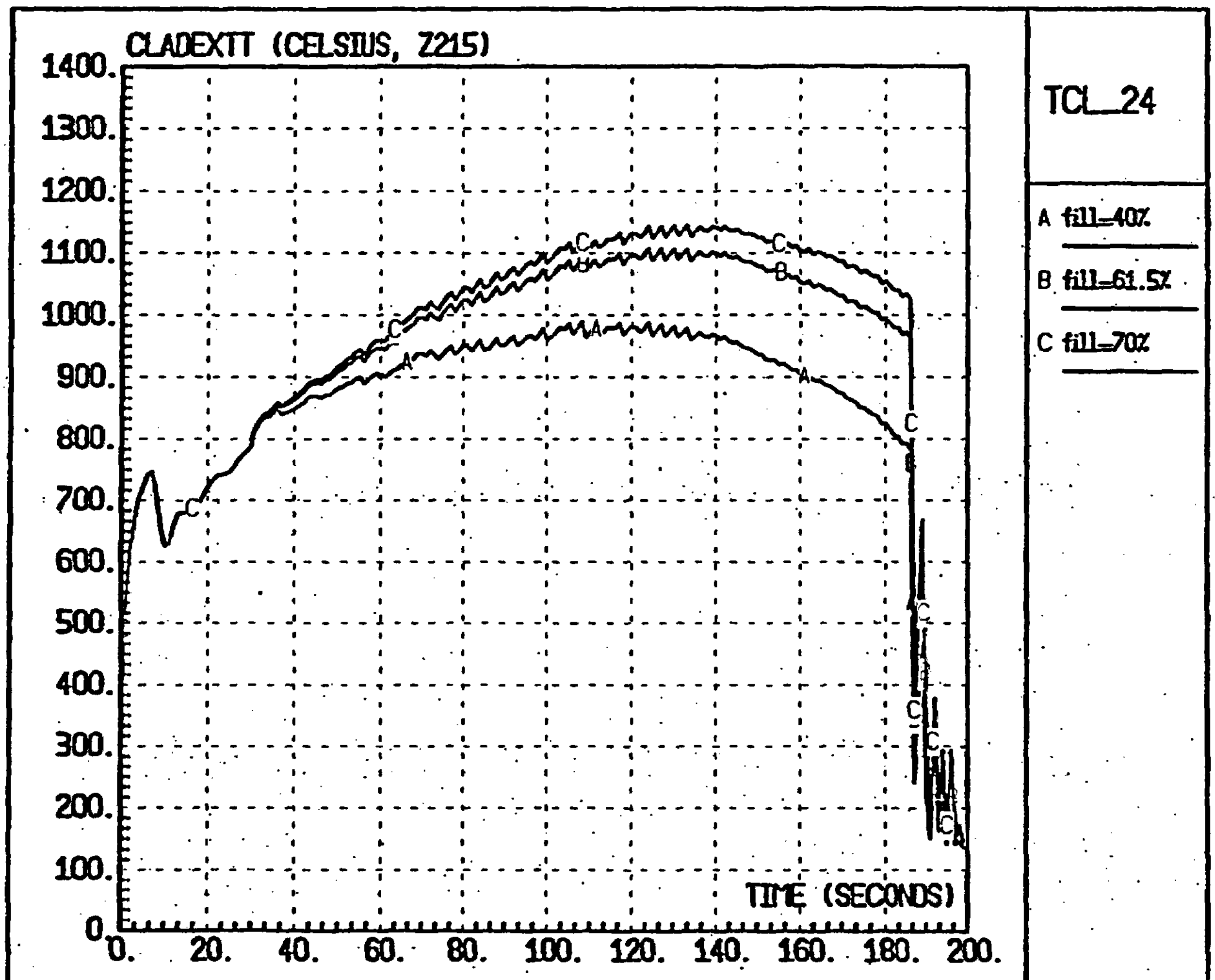


LB LOCA. Hot Rod. Burnup = 57 GWd/tU | CATHARE2

Fuel relocation in rupt. mesh : 61.5% of balloon volume | V1.3L priv

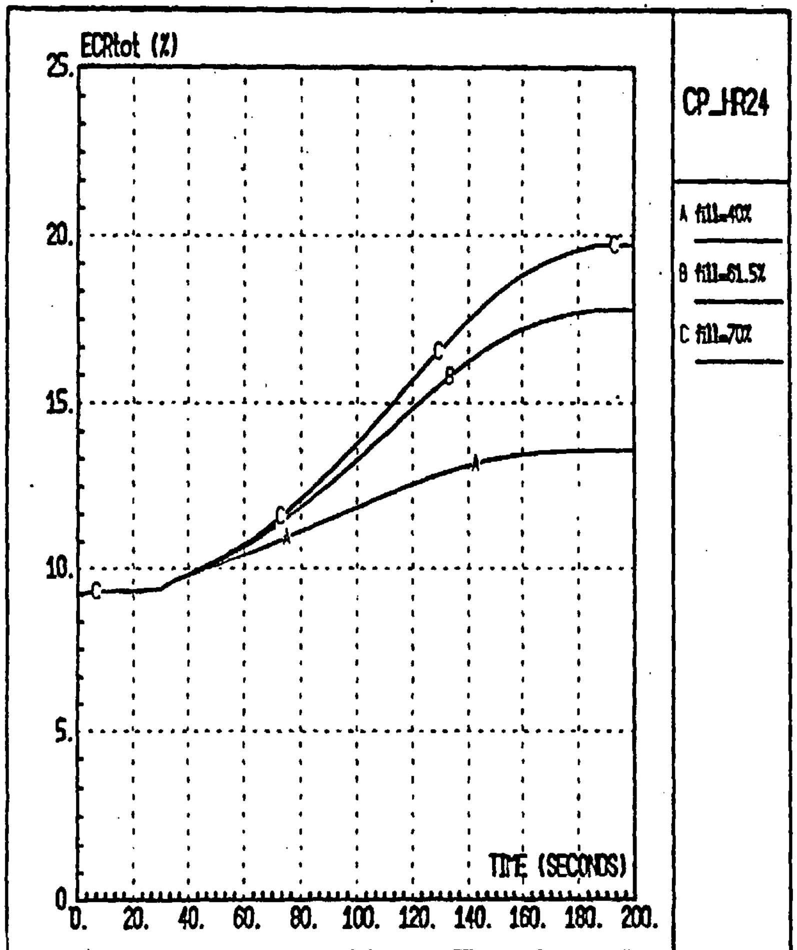


LB LOCA. Hot Rod. Burnup = 57 GWd/tU

Fuel relocation in ruptured mesh. Influence of filling ratio

CATHARE2

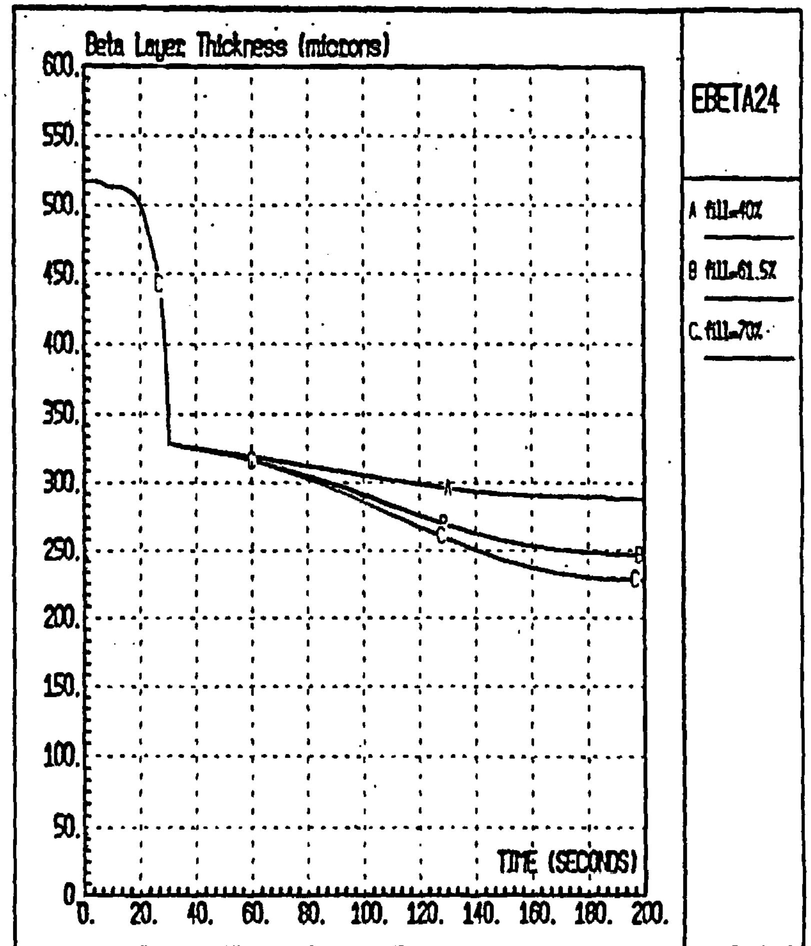
V1.3L priv



LB LOCA. Hot Rod. Burnup = 57 GWd/tU

Fuel relocation in ruptured mesh. Influence of filling ratio

CATHARE2 V1.3L priv



LB LOCA. Hot Rod. Burnup = 57 GWd/tU

Fuel relocation in ruptured mesh. Influence of filling ratio

CATHARE2 V1.3L priv

SUMMARY

- LOCA transient calculations have been performed with an adapted version of the French code CATHARE2 in order to evaluate the possible impact of crumbling and relocation of irradiated UO_2 fuel in the ballooned region of a cladding after burst.
- Focus has been put on the sensitivity of PCT and final oxidation rate on the filling ratio of the ballooned cladding with fuel crumble.
- Results indicate that with a filling ratio up to values obtained in FR2 or PBF-LOC experiments :
  - *the PCT increases significantly but still remains below the 1200°C limit ;*
  - *the oxidation rate ECR may exceed the 17% acceptance limit when initial and transient oxidation are cumulated and when initial oxide is considered no more protective for transient oxidation ;*
  - *alternative embrittlement criteria based on residual thickness of ductile metal, such as the Chung and Kassner criteria, indicate a fair remaining margin to the thermal shock embrittlement limit, whereas the handling embrittlement limit appears exceeded ;*

CONCLUSIONS

* The results of the present study give some insight into the possible impact of the crumbling and relocation of high burnup UO_2 fuel in a LOCA transient, a phenomena that was observed previously in in-pile experiments and which might significantly affect the late evolution of accident transient and associated safety issues.

* Results of corresponding calculations with low burnup UO_2 or high burnup MOX fuels would have been more severe with regard to acceptance limits.

* These results bring some support to the need for further experimental data, provided by irradiated fuel LOCA experiments involving fuel relocation. A best representativity should be obtained with in-pile experiments so as to maintain the heat generation in fuel fragments whatever their displacement may be during the relocation process.

Discussion:

Comment byM.El-Shanawany: *The UK carried out similar analysis (1988) using the computer code BART which included a number of models such as the grid rewetting effect that were not taken into account in your paper.*

The UK analysis used information from a number of experiments such as KfK, PBF, UKAEA, HALDEN and URN. The analysis indicated that the peak clad temperature may increase but the temperature did not exceed the 1204 C limit.

Hence, it is not clear what is new in IPSN's analysis, and how your analysis is adding value to our understanding of fuel pellet fragment axial relocation.

(REF. : Calculations of the effect of pellet fragment axial relocation on the peak clad temperature during a loss of coolant accident in a pressurised water reactor. K. T. Routledge, M. El-Shanawany & D. Utton, Second UK National Heat Transfer Conference, 14-16 September 1988, University of Strathclyde, Glasgow)

Question from the audience: *Was a rupture induced improving of cooling taken into account?*

Answer by C. Grandjean: *The improving of cooling associated to clad ballooning and rupture is not taken into account in the standard version of CATHARE, nor in the version modified for the calculations presented here. Such influence may however have been taken into account in some calculations performed by vendors with their own evaluation models.*

Question by R. Meyer: *What assumptions made a 10-times difference in peak cladding temperature between your calculations and the previous paper's?*

Answer by C. Grandjean: *IPSN calculations differ from EdF calculations on some options in modelling, particularly heat transfer in post-DNB conditions, resulting in different burst time and burst strain, and on options for fuel relocation in ballooned area, mainly filling ratio and residual gap (or not) between fuel fragments and clad.*

G. Hache added: *There was too much azimuthal temperature variation in the EdF model.*

Question by H.M. Chung: *Tight pellet-cladding bonding, commonly observed in high-burnup cladding, is likely to strongly influence the degree of azimuthal temperature variation at burst, and hence, burst size, wall thinning, susceptibility to thermal-shock fragmentation, and fuel relocation. Would* *the degree of azimuthal temperature variation at high burnup be larger or smaller than at low burnup, and why?**

Answer by C. Grandjean:

The azimuthal temperature gradient is reduced for irradiated fuel as a result of fuel fragmentation and relocation associated to cladding creepdown during reactor normal operation. Fuel relocation is supposed to be a bit more compact at high BU with possibly fine fragments interspersed among larger ones. However, fuel rearrangement has been observed to start with early fuel conditioning and the resulting effect on azimuthal temperature variation might not be much larger at high burnup than at low burnup.

Comments by J. R. Jones:

The assessments of heat transfer in the blockage region of the ballooned fuel assembly is sensitive to the dynamics of entrained droplets and in the UK we have found it necessary to depart from the mean-diameter approach in favour of a multi-group representation of the droplet spectrum.

In the early 1980s work was reported by Garlick et al. on the observation of relocation of fractured fuel pellets in simulated LOCA conditions. The degree of pellet relocation around the time of burst was modest, and certainly less that the reported simulations assumed.

I question whether the relocation observed post test in PIE had occurred later than the time of interest.

Let me pointed out that pellets can be conditioned by rampling to high reactor power, prior to atest and relocation can be examined without the need to achieve high fuel burnups. This was confirmed by Dr. Wolfgang WIESENACK of Halden who did this for the IFA 54x test sceries.

Answer by C. Grandjean:

In the FR2 experiments, only two tests (E3 and E4) have been instrumented in such a way to allow to trace the inception of fuel relocation. These two tests have clearly demonstrated that the fuel stack collapse starts at the time of cladding burst.

Comments by C. Vitanza

Halden LOCA tests with internal and external thermocouples showed that it was difficult to have a completely uniform azimutal temperature distribution. Even if one tries to get very uniform boundary conditions at the circumference, there are always small azimutal temperature differences which tend to reduce the effect of balloning.