A SIMULATION OF THE TEMPERATURE OVERSHOOT OBSERVED AT HIGH BURNUP IN ANNULAR FUEL PELLETS

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Abstract

Instrumented experiments have been carried out in recent years to calibrate and improve temperature calculations at high burnup in PWR nuclear fuel rods. The introduction of a thermocouple in the fuel stack allows the experimenter to record the centre-line temperature all along the irradiation or re-irradiation. Power history is predefined to obtain a relation between local power levels and centre-line temperatures. The results obtained on fresh fuel have not revealed any abnormal behaviour as have observations done on high burnup rods. In this case, a sudden overshoot has been recorded on the thermocouple temperature above an average power threshold. Several hypotheses have been suggested. Only two seem to be acceptable: one in relation to an effect of grain decohesion, another based on a modification of fuel chemistry. The apparent reversibility of the phenomenon when power decreases led us to prefer the first explanation. Indeed, the introduction of a thermocouple means that annular fuel pellets must be used. These are either initially manufactured with a central hole or drilled after base irradiation, using the "RISOE" technique. One must bear in mind that the use of such annular pellets drastically changes the crack pattern as irradiation proceeds. This is due to a different stress field which, combined with a weakening of the grain binding energy, leads to a partial grain decohesion on the inner face of the annular pellet. Modification of the grain binding energy is related to the presence of an increasing local population of gas bubbles and metallic precipitates at grain boundaries. as swelling creates intergranular local stresses which also could probably enhance the grain decohesion process. This grain decohesion concerns a 250 to 350 μm depth and shows a narrow cracks network through which released fission gas can flow, temporarly pushing the resident helium gas out. The low conductivity of these gaseous fission products and the numerous gas layers created this way could partly explain the unexpected temperatures measured in high burnup fuels. The purpose of this paper is to present a simulation of such a phenomenon and the parametric study conducted to reinforce this hypothesis. This approach is also convenient to explain why the fission gas release level measured after re-irradiation is not in agreement with centerline temperatures recorded. One can also assume a reversibility of the phenomenon as soon as the fission gas release process stabilizes, and suggest a methodology in order to avoid such problems when undertaking similar experiments in the future.

1. INTRODUCTION

Because temperature is the most influential parameter in most of the phenomena induced in a nuclear fuel rod under irradiation, the mastership of the radial temperature gradient must be continuously improved in the thermomechanical behaviour codes. This improvement is particularly needed for the fuel rod simulation at high burnup to insure conservatism in safety calculations. One can only evaluate the margins if uncertainties are well known. For fresh fuel rods, the discrepancy level on the fuel centre-line temperature is never less than several percents. It is due mainly to the power history uncertainties. A better accuracy can however be achieved in experimental irradiations, using in-pool gamma calibrations as is done in the CEA pools [1].

rain growth and fission gas relesase are currently used to evaluate temperature predictions in high burnup fuel rods. However, using grain growth as temperature marker, assumes that growth mechanism is not modified by fuel chemichal and physical modifications. On the other hand, using the fission gas release level does not allow the designer to calibrate thermal and fission gas release models separately. An eventual drift on one model with burnup must be counterbalanced by the others. In this configuration one model cannot be easily changed for another.

To solve such a problem, as has been done for fresh rods, instrumented experiments have been carried out in the framework of the High Burnup Chemistry program (HBC program, managed by the Belgonucleaire Company). The introduction of a thermocouple in the fuel stack (similar to CONTACT experiments [2] [3] [4]) allows the experimenter to record the centre-line temperature all along the re-irradiation. Power history is predefined to obtain a relationship between local power levels and centre-line temperatures.

Indeed, the introduction of a thermocouple means that annular fuel pellets must be used. These are either initially manufactured with a central hole or drilled after base irradiation, using the "RISOE" technique. Central hole diameter is minimum 1.5 mm due to thermocouple size.

For the HBC program, in order to avoid pellets drilling in high burnup fuel, annular pellets already irradiated at consequent burnup, with a standard initial hole about 2.5 mm diameter, have been proposed. Indeed, one must bear in mind that the use of such annular pellets drastically changes the crack pattern as irradiation proceeds. But no one thought of the effect of an induced grain decohesion at the inner surface. This could be an explanation of the abnormal thermocouple temperatures measured during power transients.

The purpose of this paper is to present a simulation of such a phenomenon and the parametric study conducted to reinforce this hypothesis to explain abnormal temperatures. We will see that this approach is convenient to explain why the fission gas release level measured after re-irradiation is most in agreement with the temperatures expected than with the centre-line temperatures recorded.

2. ASSUMED MECHANISMS

2.1 OBSERVATIONS AND DISCUSSION

All the similar experiments reported on fresh fuel have not revealed any abnormal behaviour as have observations done on the 45000 MWd/tU fuel rod examined. In this case, a sudden overshoot has been recorded on the thermocouple temperature above an average power threshold.

Several hypotheses have been suggested. Only two seem to be acceptable: one in relation to an effect of grain decohesion, another based on a modification of fuel chemistry. The apparent reversibility of the phenomenon when power decreases led us to prefer the first explanation.

Several points should be made:

- the rod power was rised step by step, one step lasted a few hours, enough to reach temperature steady state but not fission gas release stability,
- power level during base irradiation up to 45000 MWd/tU was low enough to avoid any strong fission gas release. For this reason, all the gaseous and volatile fission gas products are retained in the fuel matrix before the experiment (in a fresh rod the amount of retained gas is negligible),
- post irradiation examinations showed a 250 to 350 μm zone at the inner surface where grain decohesion occurs (figure 1),
- when power decreases under the power threshold identified, the thermocouple temperature level is back to expected values.
- cumulative time at maximum power does not exceed 8,5 hours,

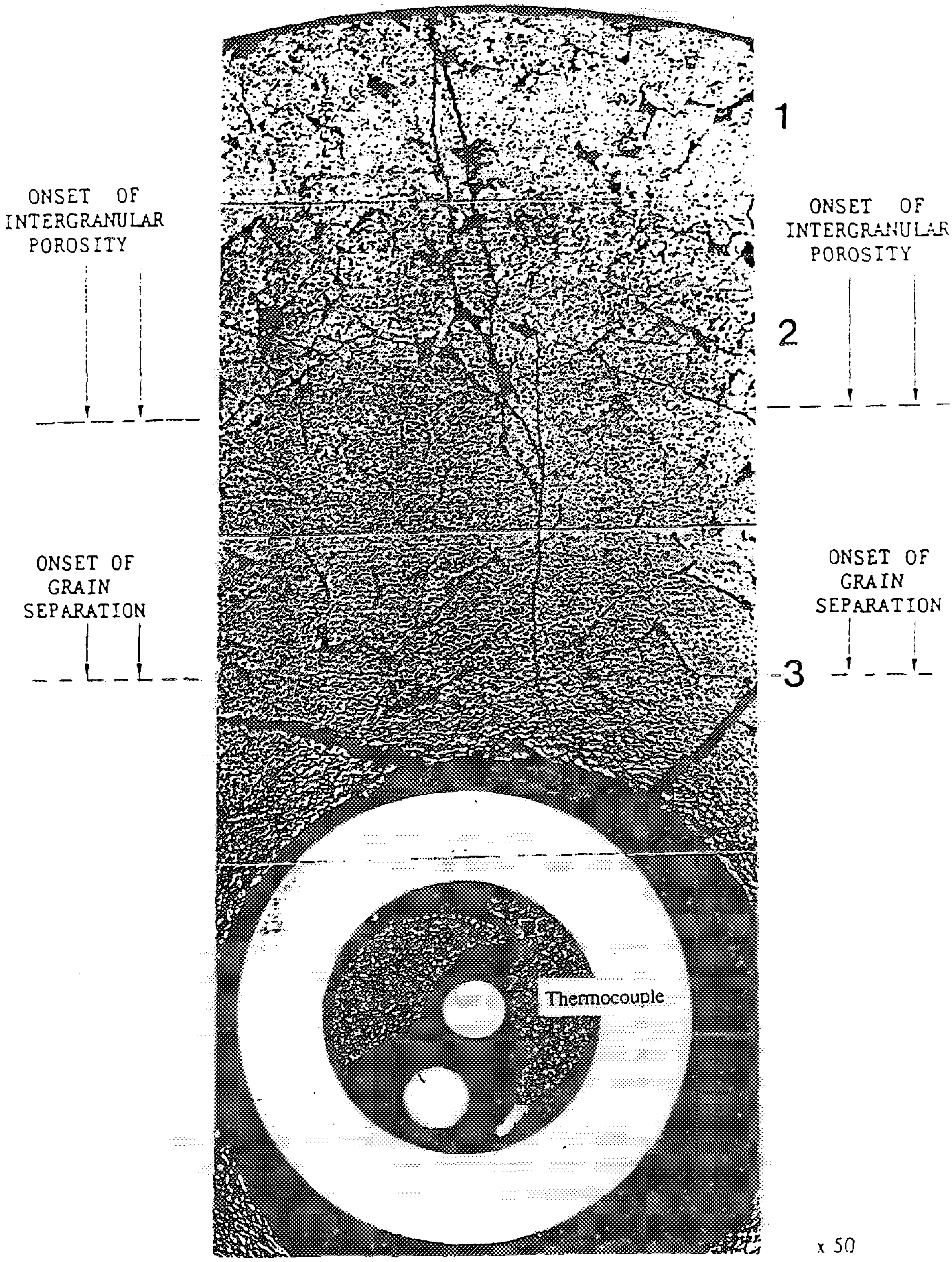


FIG. 1. Post-Irradiation Fuel Ceramography

- the end of life fission gas release fraction measured is consistent with code evaluation but not consistent with the thermocouple temperatures,
- the temperature drift kinetic seems to be consistent with fission gas migration kinetic,
- the maximum Gamma power deposit in the thermocouple components is evaluated to a level of 1.6 W/cm.

Thermal fission gas release is a threshold phenomenon. The release temperature threshold is related to saturations effects allowing progressive gas percolation in grain boundaries. It must not be confused with the diffusion temperature threshold within the grains representative of an activation energy level.

Simplifying, the release temperature threshold is a parameter decreasing with the local average fuel burnup. This means that, at high burnup, when the power level is high enough for more than 40 hours - time for which fission gas release steady state is reached (High Burnup Effect Program [5]) - , fission gas release fraction can be roughly evaluated by the ratio between the fuel volume above the temperature threshold and the total fuel volume. This is due to the fact that the remaining amount of gas trapped in the matrix is negligible in comparison to the amount of gas created.

For that reason, if the fission gas release level is roughly as expected by the codes, it means that the radial temperature gradient is properly evaluated from the pellet surface to the fission gas release transition zone or that the position of the transition zone is certainly properly simulated. That leads us to conclude that if something abnormal occurs, it must be between the transition zone and the thermocouple.

2.2 SCENARIO PROPOSED

Power is increased step by step. As long as the thermal fission gas release is not activated by the fuel local temperature, the thermocouple temperature is as expected. When the fission gas release temperature threshold is reached and passed over in the pellet central zone, bubble gas diffusion starts. Most of the gas migrates towards the grain boundaries, building a bubble chain all along the grain boundaries, paticularly in triple intergranular sites.

A minimum of time is required to accumulate enough gases to allow percolation along grain boundaries and gas to flow outside the fuel. During this period, pressure rises in intergranular bubbles inducing stresses between grains.

This situation, combined with a weakening of the grain binding energy, can lead to a partial grain decohesion on the inner face of the annular pellet. Modification of the grain binding energy is related to the presence of an increasing local population of gas bubbles and metallic precipitates at grain boundaries. In a plain pellet, because of different limit conditions in the center of the pellet, compressive stresses probably enable such a grain decohesion or limit this decohesion to a fine network of microcracks as observed in the HATAC experiment rods [6] [7].

This grain decohesion concerns a 250 to 350 μm depth and shows a narrow cracks network through which released fission gas can flow, temporarily pushing the resident helium gas out. Interlayer gas mixture during this period can be assumed to be constituted of nearly 100 % of fission gases (Xenon and Krypton isotopes).

The low conductivity of these gaseous fission products, combined with the grat number of gas layers degrade in this region the fuel average apparent thermal conductivity. We propose to evaluate such an effect in the next chapter.

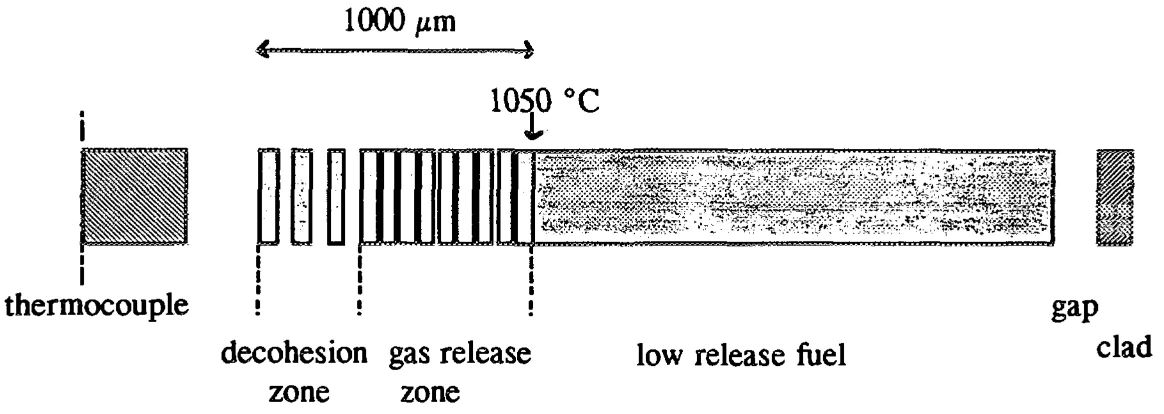
The reversibility of the phenomenon can be explained by a gas re-mixing during the power decrease. This re-mixing can be activated by a natural convection flow monitored by temperature gradients. If that occurs, the gas mixture thermal conductivity is strongly improved by Helium which represents more than 95 % of the mixture.

When power is back to the highest level, gas flow starts again and fuel thermal conductivity is degraded again. However because fuel gas content is decreasing, interlayer gas flow will also decrease progressively until total possible fission gas release is achieved. The consequence would certainly have been a decrease of the thermocouple temperature if the highest power could have been maintained long enough.

3. SIMULATION

3.1 MODELLING

Fuel decohesion has been simulated in an unidimensional thermal calculation by an alternation of fuel zones and gas layers where gas mixture can be modified (figure 2). Fuel zones thickness is representative of grain diameters. Effect of Gas composition, gas layers thickness and decohesion zone thickness were studied.



Because an assumption was made on a non-modification of the transition zone position, calculation is made from this isothermal line towards the center with a specific code using the thermal standard subroutine of the EDF fuel rod thermomechanical code. Temperature threshold at the transition zone was assumed at 1050°C, which is consistent with the lowest bound evaluated for a 45000 MWd/tU burnup [5].

Power sources are distributed in the fuel and take into account the radial depression due to plutonium build up in the pellet "rim". Average power level is assumed as 340 W/cm. A maximum value of 1.6 W/cm for the gamma power deposit in the thermocouple components is assumed.

Three zones are to be considered:

a) fuel part without grain decohesion

Even if grain decohesion doesn't occur within this zone, fission gas diffusion is activated by the local temperature. Gas bubbles are then present in the grain boundaries, filled by Xenon. This bubble decoration is assumed to create thermal bridges at each grain boundary because of the fission gas low

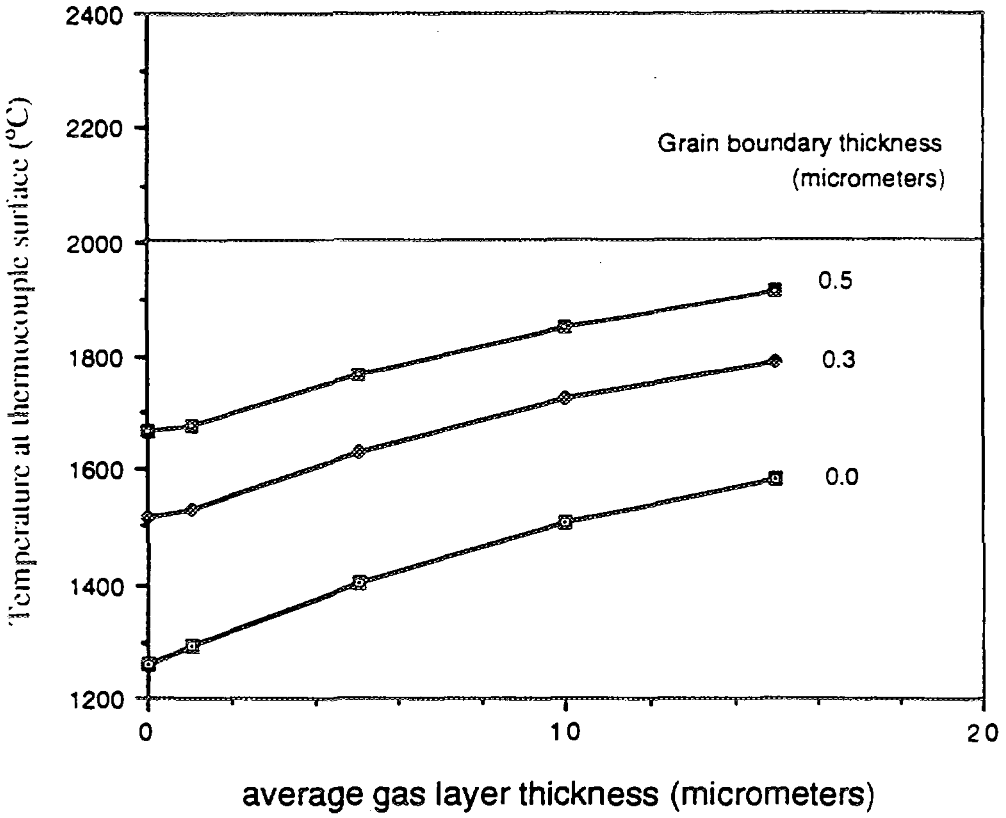


FIG. 2a. Decohesion Zone width = 190 micrometers

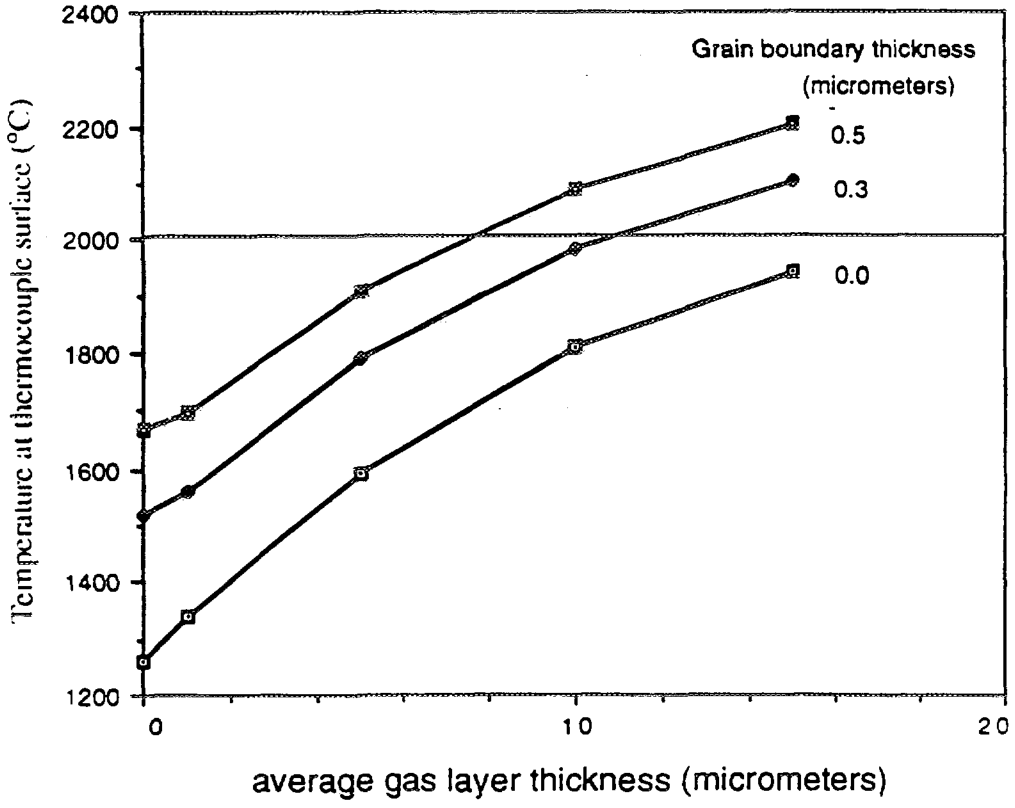


FIG. 2b. Decohesion Zone width = 290 micrometers

conductivity. The average fuel thermal conductivity degradation is indeed certainly stronger in comparison with the same amount of porosities spread within the fuel matrix. Average bubble size in the grain boundaries is 2 μm. Because bubbles are distributed discontinuously along the grain boundaries the simulation takes into account an equivalent maximum grain boundary thickness of 0,5 μm which is the quarter of the bubble average diameter.

b) fuel part concerned by grain decohesion

The thickness of each fuel zone in the decohesion area is assumed equivalent to the average grain size: 12 μm. Measurements on post-irradiation ceramographies show a grain decohesion zone width evaluated from 250 to 350 μm and an average inner radius decreased of 60 μm. The fuel zone concerned by grain decohesion is then between 190 to 290 μm.

c) gap between the fuel and the thermocouple envelope

The gap between the inner fuel surface and the thermocouple envelope is assumed to be filled by fission gases. Thermal transfer proceeds by convection through the gas but also by a radiative transfer which limits strongly the temperature drop through the gap. In spite of what is observable on the fuel ceramography, the thermocouple has been assumed to be centred in the pellet hole.

In all the following results gas mixtures in grain boundaries bubbles, in gas layers and in the fuel to thermocouple gap, are assumed to be 100 % Xenon. However, other calculations have also been done to evaluate the mixture influence but are not reported here.

3.2 RESULTS AND DISCUSSIONS

The simulation results are reported in Table 1 and Table 2 for two respective width (190 and 290 μm) for the decohesion zone. For each case, temperatures are given for the pellet inner surface and the thermocouple outer surface.

In the decohesion zone, the calculation is done for different values of the average gas layer thickness: 1, 5, 10 and 15 μm.

In the high fission gas release zone, the effect of an equivalent gas film at grain boundaries is given for several average values of the thickness: 0, 0.1, 0.2, 0.3, 0.4 and 0.5 μm.

Figures 2A and 2B give a graphic representation of the influence of the parameters upon the maximum temperatures at thermocouple outer diameter. They show that a 2000 °C can be easily reached in spite of the quite low fuel power (340 W/cm). This is consistent with the results obtained for the instrumented rod. The temperature drop between the fuel and the thermocouple is always within 10 to 60 °C.

Figure 3 gives a good idea of the thermal gradient to which such a simulation leads. This gradient is not parabolic any more and only a few fuel volume, corresponding to the decohesion zone, achieve really more than 1400 °C. Because decohesion occurs probably during the first minutes at power or during the transient, grain growth is unlikely. Indeed, no evidence of grain growth was observable on post irradiation fuel ceramographies.

Nevertheless, back to the temperatures obtained, the simulation assumes the worst conditions corresponding to the first hours at power: all grain decohesion is achieved, fission gas release is underway with a high release rate (gas mixture being essentially fission gases). After this period, grains are providing with less and less fission gases and so, fission gas release rate decreases; the gas mixture in the gas interlayers improve their conductance by an homogeneisation with Helium. This means that, if the power level is maintained more than 30 to 40 hours, the temperature as measured by the thermocouple will drop down to a value more consistent with the codes evaluations.

TABLE I

CALCULATION FOR A DECOHESION ZONE WIDTH OF 190 μm

	Average gas layer thickness in the decohesion zone			
grain boundary thickness (μm)	1	5	10	15
0	1236 (1293)	1356 (1404)	1468 (1509)	1551 (1585)
0,1	1326 (1377)	1440 (1483)	1546 (1583)	1625 (1656)
0,2	1412 (1457)	1520 (1559)	1621 (1655)	1695 (1725)
0,3	1492 (1533)	1595 (1631)	1692 (1723)	1763 (1790)
0,4	1568 (1605)	1667 (1700)	1760 (1789)	1827 (1853)
0,5	1642 (1676)	1738 (1768)	1826 (1853)	1891 (1915)

T1 (T2):
T1 temperature at pellet inner surface (°C)
T2 temperature at thermocouple outer surface (°C)
pellet average power: 340 W/cm
reference from standard calculations: 1202 (1263)

TABLE II

CALCULATION FOR A DECOHESION ZONE WIDTH OF 290 μm

	Average gas layer thickness in the decohesion zone			
grain boundary thickness(μm)	1	5	10	15
0	1286 (1340)	1556 (1593)	1782 (1808)	1930 (1941)
0,11370 (1418)	1628 (1661)	1844 (1868)	1986 (1996)	
0,2	1449 (1492)	1696 (1727)	1904 (1927)	2040 (2050)
0,3	1524 (1563)	1762 (1791)	1962 (1984)	2093 (2103)
0,4	1594 (1631)	1824 (1851)	2018 (2039)	2144 (2153)
0,5	1662 (1696)	1884 (1910)	2072 (2091)	2193 (2202)

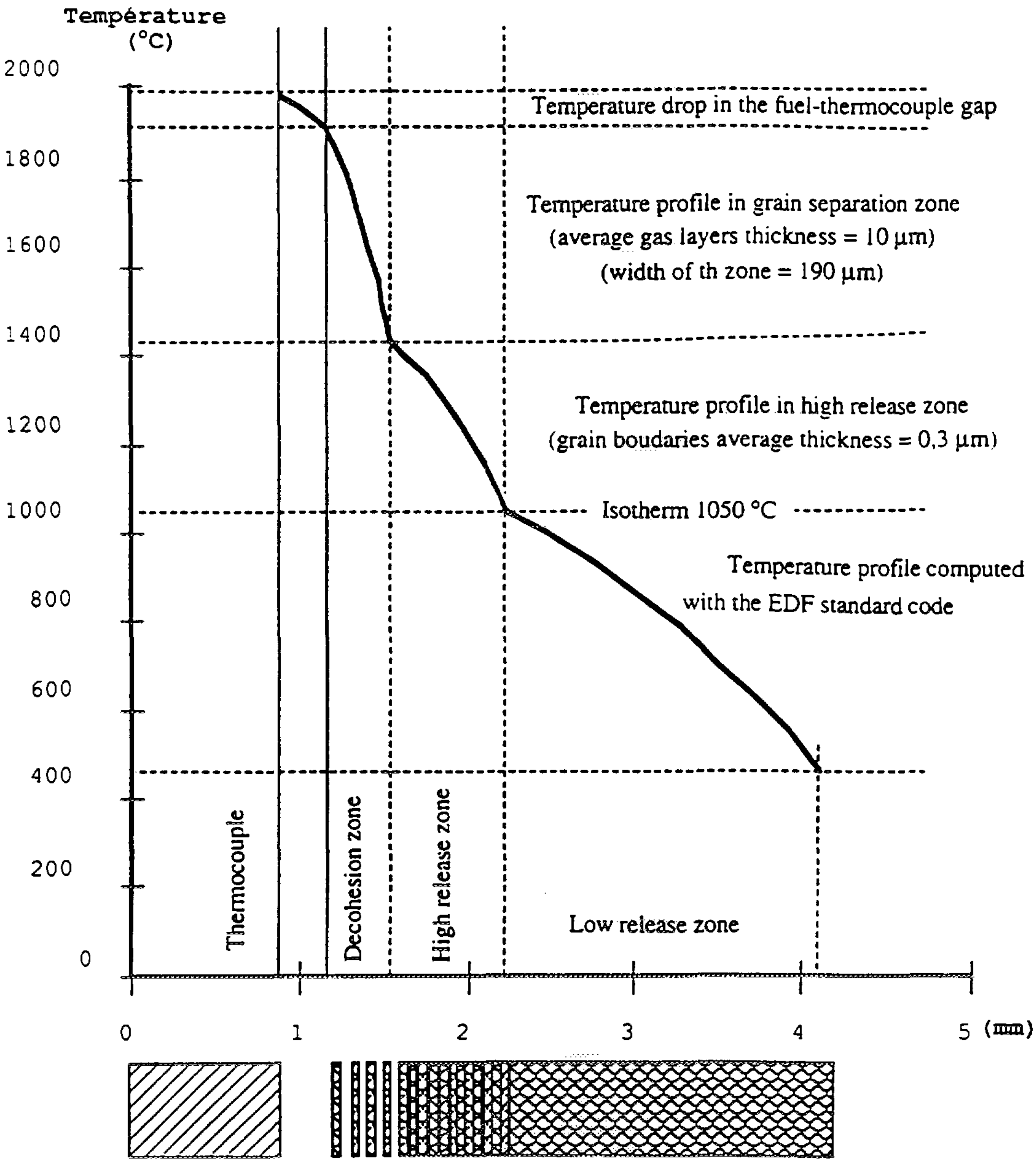


FIG. 3. Radial Profile in the Fuel Pellet

However, in the zone not concerned by grain decohesion, the effect of the bubbles, still remaining in the grain boundaries, should certainly degrade slightly more than expected the fuel central temperature just because the modellings used in our codes assume the porosities to be always spread homogeneously in the fuel matrix. This effect cumulated with the residual effect of the decohesion zone with a majority of Helium in the interlayers leads to a non-total but partial reversibility of the phenomenon as described.

If this scenario is to be retained, that leads to conclude that such a phenomenon could be avoided when undertaking a similar experiment just using smaller power steps and longer holding times at each step. Surely, one can expect that even operating in such a manner, fuel grain decohesion will still occur. However, these operating conditions will give time for gases to be released progressively, zone by zone, and so limit the effect on the average thermal transfer. Such an experiment could also confirm the scenario proposed.

4. CONCLUSION

Instrumented experiments have been carried out in recent years to calibrate and improve temperature calculations at high burnup in PWR nuclear fuel rods. The introduction of a thermocouple in the fuel stack allows the experimenter to record the centre-line temperature all along the irradiation or re-irradiation but impose the use of annular pellets.

The results obtained on fresh fuel have not revealed any abnormal behaviour as have observations done on high burnup rods. In this case, a sudden overshoot has been recorded on the thermocouple temperature above an average power threshold.

The scenario proposed in this communication shows that an overshoot on the fuel central temperature in an annular pellet can be explained by the effect of a fuel grain decohesion and the possibility for the fission gases to flow through the cracking network so generated. The fuel thermal behaviour is then strongly correlated with the fission gas release kinetic. However, it has also been shown that, in this simulation, the temperature overshoot has almost no influence on the total fission gas release level within the fuel rod.

This scenario is very consistent with all the observations done during post irradiation exams on the concerned experimental fuel rod. It assumes a partial reversibility of the phenomenon as soon as the fission gas release process stabilizes. A methodology has been suggested in order to avoid such problems when undertaking similar experiments in the future.

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