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PELLET CLAD INTERACTION IN PWR FUEL: ANALYTICAL IRRADIATION EXPERIMENT AND FINITE ELEMENT MODELLING

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1. Abstract :

In order to describe accurately the thermomechanical behaviour of the fuel elements during power transients, a specific module has been developed based on a finite elements advanced code. In connection with the precise data obtained during analytical experiments performed on specific fuel rodlets, this module allows a broad analysis of the different parameters controlling the fuel strain and stress state during PCI.

2. Introduction :

The Pellet Cladding Interaction (PCI) is a potential cause of damage of water reactor fuel during severe transients. In order to understand this PCI mechanism, several aspects have to be studied in detail. The two main topics to be covered are connected to the stress corrosion cracking induced by iodine, and to the loading induced by pellet expansion. CEA has been working in both fields in co-operation with the French fuel designer and vendor Framatome and the utility EDF [1]. The aim of this paper is to present recent progress related to the improved knowledge of the stresses and strains induced by PCI during fuel rod power transients.

In order to have access to the cladding strains specific analytical experiments have been performed in which the PCI induced deformations were measured either after irradiation and power transients or directly in-situ using specific irradiation devices. The complexity and the cost of such experiments limits them to calibration and acquisition of reference data, the specific effect of a given parameter being evaluated using advanced thermomechanical computation. In the framework of a general fuel behaviour code developed by CEA, named METEOR, this aspect of the fuel behaviour is developed as the TOUTATIS module.

3. Analytical PCI related irradiations

3.1. Technological procedures

The simplest irradiation technique used to record the effect of PCI on cladding strain was to prepare fuel rodlets with pellets of larger than normal diameters in order to reduce the gap to the minimum necessary for assembly (20 and 40 µm). Under such conditions, the solid contact between fuel and cladding is obtained at a linear heat generation rate (LHGR) smaller than 20 kW.m^{-1}, and thus PCI is obtained on fresh fuel. The fuel rodlets were much larger than the SILOE pool reactor core, and therefore, during the same power transient, the axial power profile allowed us to analyse the behaviour of the fuel over a large power range (typically from 3 to 50 kW.m^{-1}). This procedure was used in the FLOG program [2] in which various pellets types were studied. In each case two identical rodlets were tested, one maintained at high power 2 min. and the other 2 hours. Rod diameter profiles were performed on the same device in hot cell before and after irradiation, with an accuracy of ± 2 µm. Using those experiments, we had access only to the remaining plastic cladding strain induced by PCI, elastic and thermal deformation being recovered during cooling of the rodlet. The contribution of relaxation to this deformation was obtained analysing the difference between the 2 min. and the 2 h. irradiations, the second one allowing time for some limited creep of the fuel and/or of the Zry cladding.

In order to have access to the actual cladding strain during irradiation, rod measurements have to be performed inside the irradiation loop. Early experiments were performed using strain gages welded on the cladding [3], but then the cladding strain is only known at the location of the gages. In the DECOR irradiation device [4], a contact diameter measurement tool is moved up and down along the fuel rod during irradiation, within the PWR type environment simulated by a loop running in the nucleate boiling regime at 1.3 MPa. This device has been tested for the begining of the program using a fresh fuel rodlet (250 mm length) and a series of power transients up to 40 kW.m^{-1}. The duration for a complete length measurement is about 45 min.. In order to acquire kinetics data during the transients, the measuring device is displaced back and forth over a very limited number of pellets at the centre of the rodlet. At both ends of the pellet stack, a low enrichment pellet is introduced in order to depress power peaking due to reduced self-screening at the ends. In addition two Inconel calibration steps end the rod in order to allow in-situ calibration of the gages. Detailed corrections for gages drift, thermal expansion and standard calibrations were undertaken to reach an in-situ absolute accuracy of ± 2 µm.

3.2. Results

3.2.1. Cladding strains

A typical result of the diameter measurement obtained in-situ in the case of the reference fresh fuel rod is presented in Fig. 1. An increase of the cladding strain is obtained as soon as the power rises, due to the thermal expansion of the cladding. This effect is important due to the thermohydraulic behaviour of the irradiation device used. At low power, the nucleate boiling condition is not reached and the loop operates in single phase conditions. The outer surface temperature is then a linear function of the LHGR, until the saturation occurs near 23 kW.m^{-1}.

As the power is increased, the cladding expands, but its expansion rate changes as the pellets contact the cladding, allowing a precise determination of the contact occurrence. After contact, any further power increase leads to diameter changes induced by the fuel thermal expansion. The pellet shape is then clearly visible and the height of the ridges was found to increase with power, reaching 21 μm at 40 kW.m^{-1}.

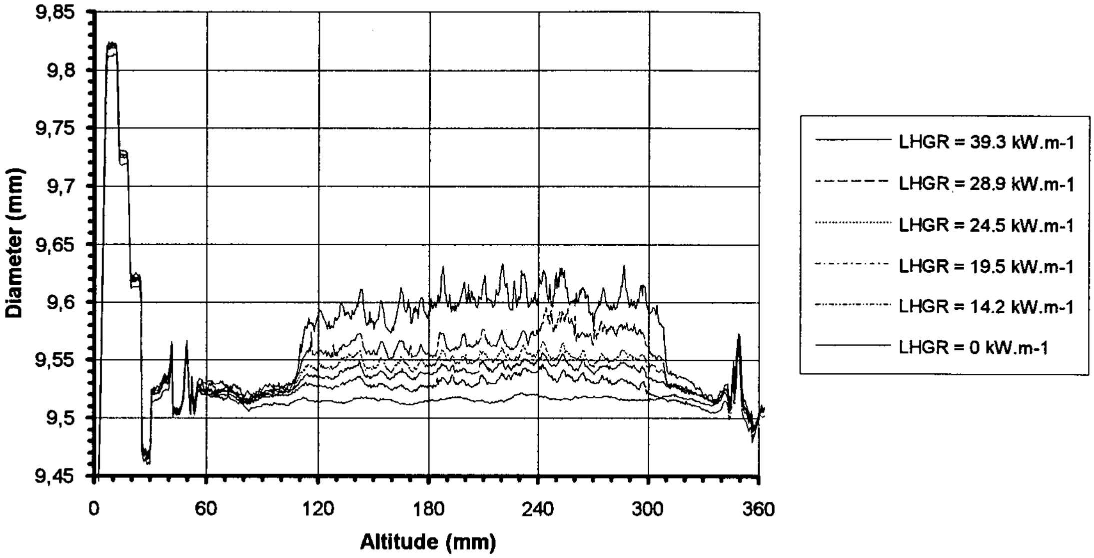

Fig. 1 : DECOR device, fuel diameter measurement of a small gap fresh fuel at different power levels

The cladding expansion versus local power is better expressed when focusing on only one pellet during a power change. In Fig. 2, the diameter of rod is plotted for only two locations corresponding to a pellet-pellet interface and to a pellet mid-plane. In the same figure, results of the 2D and 3D computations, to be described in paragraph 4, are plotted for comparison purposes.

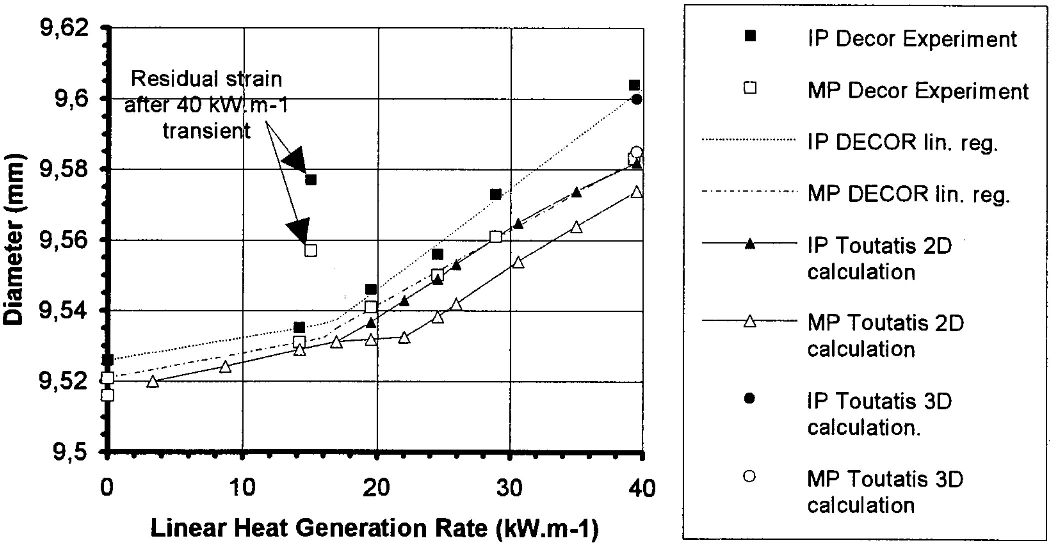

Fig. 2 : Clad strain = f(LHGR), comparison of DECOR diameter measurements with TOUTATIS computation results (IP : pellet-pellet interface, MP pellet mid-plane)

3.2.2. Pellet fracture

Although not measured during the power transients, an important parameter for the thermal expansion of the pellets during PCI, is their cracking behaviour. During post-irradiation examination of the FLOG, fuel ceramography was used to analyse this parameter. Indeed in the same fuel rod, sections at different elevations allowed us to examine the fracture pattern at various power levels. It was found that in addition to the standard macroscopic fracture network of about 5 main cracks per pellet, a series of fine radial cracks were open in the outer part of each pellet, the number of which increasing with the local LHGR. At 25 kW.m^{-1} they are 15 in number, while more than 30 are present at 50 kW.m^{-1}.

4. Thermomechanical modelling

4.1. Mainframe of Toutatis computer code

The Toutatis fuel thermomechanical module is based on the CASTEM 2000 finite element computer code. This code, about 500 000 instructions in size, is designed to handle various types of complex thermal and mechanical situations of structures, like contact conditions, non-linear behaviour due to the materials or to the structure itself [5] ...

The use of such a code to the specific case of the fuel rod, requires particular procedures :

- The geometric description of the pellet and cladding is straightforward, 2- or 3 D if non revolution condition are chosen, like fragmented pellet.
- The thermal field is first computed as it is the main driving parameter and then the dimensional changes on the different parts induced by this thermal field. A loop procedure is run until convergence is obtained.
- For a given irradiation history, this computation procedure is performed for each time step in order to allow changes in thermomechanical behaviour of the material as the irradiation proceeds.

The specific aspect of the pellet cladding contact is resolved using a single side, discrete or continuous contact with variable friction coefficient. It allowed us to compute stress enhancement at pellet ridges by a factor of 4. Pellet fragmentation is analysed using a 3D configuration of the code. Any type of fracture pattern can be performed, but the radial type of cracks being the most common was the only tested for this experiment. In Fig. 2, a direct comparison between results and computation shows the necessity of taking into account the fragmentation to compute strains as large as those measured. Fig. 3 gives an example, on a perspective view, of the strain distribution of a fragmented pellet in the clad.

4.2. Impact of fuel parameters

The interest of fuel computer code is to analyse the effect of various parameters and material properties on the behaviour of the fuel rod with the aim of reducing the number of expensive and time consuming irradiation experiments.

Among the parameters that have been tested, the following have been shown to have important effects :

- The pellet fracture behaviour controls drastically the deformation mode during power increase. For the same initial geometry, a pellet fractured in 6 segments exhibits an expansion almost twice as large as a solid one.
- The mechanical strength of the cladding affects the ridge height, a harder alloy reducing them; but it does not affect significantly the mean fuel expansion.
- Oxide mechanical behaviour (creep) controls the mechanisms of dish filling. At high power the internal hydrostatic compression stresses drive the creep strain of the fuel, leading to the filling of the dishes.
  Otherwise this strain is found, on fuel ceramographies, to be linked to grain growth. The locus of observed same grain size areas, close to the pellet ends, allows then to adjust the creep laws (stress exponent) in calculations and thus to describe more precisely the fuel deformation behaviour.

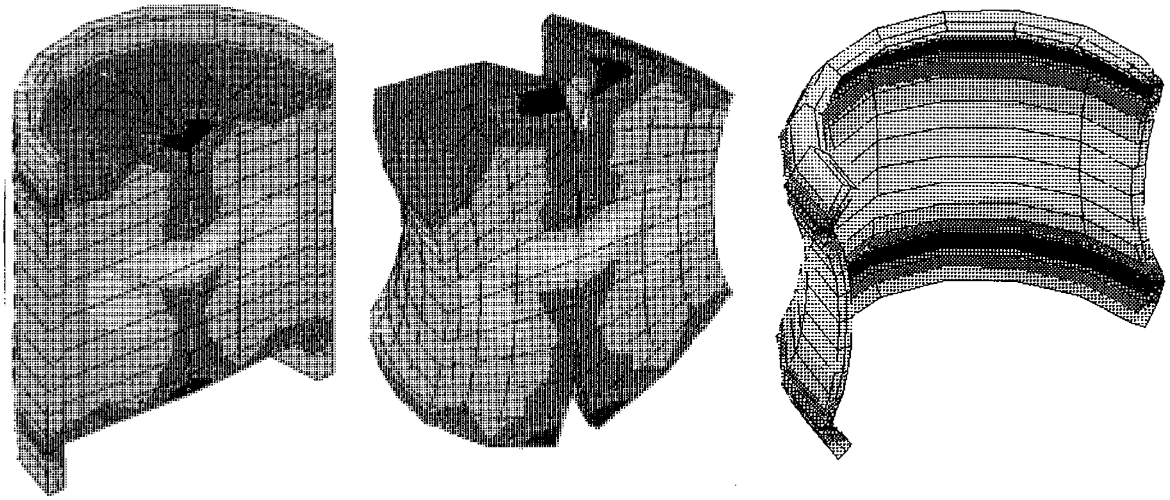

Fig. 3 : Deformation of a fragmented pellet in the clad, result of a TOUTATIS 3D computation

5. Discussion and prospects

A difficulty encountered when comparing computer code results and experimental results is the fact that the cladding strain is measured on a series of pellets and that for each of them various random physical characteristics affect the local strain. That is why it was found useful to compare the computed results with the average value of the diameter measured over a set of 3 - 5 contiguous pellets.

The number of fractures, as stated earlier, is a controlling parameter of the cladding strain. As observed in different programs, this quantity is dependant of the local power, during the first power change. After a long irradiation, this number may change as some pellet cracks develop during power decrease, while other heal at the centre during irradiation at high power. This behaviour, as well as pellet relocation, now considered as initial boundary conditions, will be incorporated in future development of the code.

6. Conclusions

A better understanding of the fuel behaviour can be achieved using a close interaction between in pile analytical experiments, in which very precise data can be acquired on a limited number of fuel rodlets, and advanced computer code achieved by a critical adaptation of standard finite element thermomechanical code to the specific case of nuclear fuel. Although more complex to model than large structural components common in industry, due to the strong interactions of all the physical phenomena involved (neutron physics, thermal and mechanical behaviour, thermodynamics of fission products...), the fuel thermomechanical behaviour can be described accurately enough to test the effect of different fuel parameter changes.

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7. References

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