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DISCO—A Code for Analysis of Irradiation Induced Distortions and Thermal-Hydraulics in LMFBR Fuel Elements

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Abstract

The achievement of the current economic goal of high burn-up for fast reactor fuel requires an understanding of the way in which irradiation-induced distortion influences the thermal hydraulic performance. There is an interaction between the distortion-influenced temperature field and the temperature-influenced rate of distortion, requiring the two phenomena to be computed simultaneously as a function of neutron dose. The DISCO code is designed to provide such a computation for gridded bundles. The paper describes the salient features of the code and presents a selection of results for a typical fuel element.

1. Introduction

A current economic goal for LMFBRs is the achievement of high burn-up, to reduce fuel cycle costs. The realisation of this aim requires an understanding of the behaviour of the fuel element under irradiation, and of the conditions likely to lead to fuel pin failure. A probable mode of clad failure is the exhaustion of ductility due to thermal creep, driven by fission gas pressure. Since the creep rate is strongly temperature dependent, quite modest increases of temperature late in life could lead to failure in advance of the target burn-up, for fuel designed on the start of life peak temperature . Because of the consumption of fissile material, the power output of the fuel tends to diminish with time, hence for a fixed level of coolant flow the peak clad temperature might correspondingly be expected to reduce. However, all structural materials currently in use in fast reactors are subject to irradiation induced distortion, which may so change the geometry of the pin bundle and its wrapper as to cause local increases in temperature tending to outweigh the 'burn-down' effect.

The establishment of sensible design criteria therefore requires an investigation of the combined effect of the irradiation-induced distortions on the thermal hydraulic performance. Since the rate of distortion, for many structural materials, is sensitive to temperature, account must be taken of the feed-back between the distortion-influenced temperature field and the temperature influenced distortions. The DISCO code is designed to study this interaction for grid-supported bundles having 331 or 325 pins.

The computations in DISCO proceed through successive increments of neutron dose, calculating changes in geometry due to swelling and irradiation on the basis of temperatures evaluated using the geometry at the start of the step. The calculation ceases when a prescribed peak neutron dose is reached or when pin bowing becomes so severe that the geometrical model breaks down.

This paper presents a brief description of the code and some results of its application to a typical LMBFR (Liquid Metal Fast Breeder Reactor) gridded fuel element, for alternative combinations of irradiation-induced swelling and creep characteristics. These results can point the way towards an optimum spacing of the honeycomb grids, with potential advantages for cost savings, reduction of circuit pressure loss, and avoidance of bowing-induced hot-spots which could be life-limiting.

2. Description of the DISCO code

2.1 General Features

DISCO is essentially a pin bundle thermal hydraulics code of the subchannel type, the subchannels being defined, except at the edge of the bundle, by triangles having vertices at the centre of adjacent pins. Within a subchannel the coolant pressure, axial velocity and temperature are assumed to be uniform at any axial position. Hydraulic and thermal communication exist between subchannels, through pin-to-pin to pin-to-wrapper gaps. The almost universal use of oxide fuel in LMFBRs permits internal thermal conduction to be neglected, and an azimuthally uniform heat flux is assumed for each pin. The code is currently designed for 325 or 331 pins, to conform with current UK practice, but its adaptation for smaller bundles is straightforward. Its unique features consist of calculations of irradiation-induced geometrical changes for the wrapper, the pins and the honeycomb grids.

At the start of life, all dimensions are nominal. The first pass through DISCO calculates the temperature field for all components, and establishes the elastic deflection of the wrapper due to internal pressure, and calculates thermal bowing of the fuel pins. The second pass, still at zero dose, calculates the modified temperature field, and this set of temperatures is used to determine the rates of swelling and irradiation creep for all components.

The wrapper swells due to neutron voidage growth, and its walls deflect due to irradiation creep induced by the hydraulic pressure differences across them. The magnitudes may differ between the six faces of the wrapper, if transverse gradients of neutron flux and/or temperature exist. The honeycomb grids swell according to the local dose and mean coolant temperature. If the free swelling of any grid exceeds that of the wrapper at any axial position, it is assumed that the grid is restrained completely at the corners, but will distort to conform, at least partially, to the curved profile of the dilated wrapper. In so doing it expands the pin bundle, the expansion being least in the across-corners direction, causing the matrix of grid cells, and hence of pin pitches, to become irregular. If in the across flats direction the grid swelling is substantially less than the wrapper deflection due to both swelling and creep dilation, a corresponding gap will develop between the grid (and hence the pin bundle) and the wrapper, causing a coolant by-pass flow.

It is assumed that the fuel pins are a close fit in the honeycomb grid cells, but they sustain diametral growth due to clad swelling, and, as burn-up increases, due to irradiation creep driven by the developing fission gas pressure. Transverse temperature gradients, caused by over-cooling in the peripheral subchannels and modified by the initial thermal bowing, induce differential swelling of the cladding, which enhances the bowing. The bowing restraint loads relax due to irradiation creep, which leads to a further modification of the bowed shaped. A more detailed descripton of the mathematics of this approach was given in Reference 1.

The basic method of calculating the thermal hydraulics of the distorted pin bundle was also described in detail in Reference 1. A further development is the inclusion of a routine which traces the redistribution of the coolant flow between subchannels as it passes through each honeycomb grid. This routine takes account of the inclination of bowed pins to the grid cell axis, and of the additional 'sub-channels' which develop between the outer edge of the grid and the dilating wrapper. It has not been employed for the cases reported in this paper.

DISCO also calculates the rate of heat transfer across the wrapper wall to the external by-pass flow, and if appropriate, to its neighbouring subassemblies. The change of power output due to the burn-up of heavy atoms can be automatically included, and more generally, a complicated power/burn-up history can be accommodated. Rotation of a subassembly in the same reactor location is also allowed for. In the applications reported here the total coolant flow through the fuel element was assumed to be fixed, but work is in hand to allow the flow to change with burn-up in response to any changes in hydraulic resistance caused by distortion.

2.2 Calculation Procedure

Spatially, DISCO calculates distortions and thermal hydraulics at 12 axial intervals between successive honeycomb grids. This frequency is chosen to ensure that the configuration of pin bow is properly represented, but may be inadequate locally if pin bowing becomes severe. In this event, stability problems can arise due to excessive outflow of coolant from subchannels whose area is reducing. DISCO surmounts this problem by reducing the axial integration step locally to a satisfactory value. The number and location of such subdivisions are indicated in the output. A further indication is given if bowing becomes severe enough to reduce a subchannel cross-sectional area to less than the value corresponding to three pins in contact. The computer run can be terminated at this point.

The size of the neutron dose step is also limited by a stability criterion, related to the irradiation creep constant for the cladding. A dose step of about 2 displacements per atom (dpa) on the 'half-nelson' scale (N/2) is found to be adequate for the creep rules normally in use.

3. Application of DISCO

Preliminary work suggested that the pin bundle thermal hydraulics would be sensitive to the relative swelling of the honeycomb grids and the wrapper. Hence two cases have been selected for illustration. The first assumed that the grids swell faster than the wrapper, for the same temperature and dose. In the second case the same swelling and creep data was used for the wrapper, but the grids were assumed to swell at a much smaller rate. In addition the swelling and irradiation creep rates for the pins was lower than in the first case. The spacing of the 10 honeycomb grids is shown in Fig 1. The pin and subchannel designation is shown in Fig 2.

4. Results

A post-processor code has been written to facilitate graphical display of the formidable quantity of data generated by DISCO. For the purposes of the present paper it is possible to show only a very limited selection of the more interesting results.

4.1 High Grid Swelling

Fig 3 is a composite diagram, made up from computer produced cross-sections of the pin bundle drawn at six successive grid positions over the core region, for a peak neutron dose of 100 dpa (N/2). At grid 4 the grid can be seen to have taken up the initial clearance gap at the corners, and to have distorted slightly at its outer edge, leaving a significant bundle/wrapper gap due to the creep dilation of the wrapper wall. At the next three grid positions the dilation is reducing because of diminishing internal presssure, but the grids are swelling more, due to the combined effects of increasing neutron flux and increasing temperature. The grid/wrapper gap becomes completely closed, eliminating the bundle by-pass flow, but raising the question of possible local straining of the wrapper. Towards the top of the bundle the wall dilation becomes very small, and a small gap reappears between the last grid and the wrapper.

The bulk of the pin bundle is scarcely affected by the grid and wrapper distortions. Pin distortion is largely confined to the outer row of pins, and particularly to those furthest from the corners. Even here pin bowing is slight at the final dose. Fig 4 shows the bowed configuration of two pins, the central one in the outer row and an adjacent one in the next row. By plotting the components of pin displacement in the direction of their centres, and adding in their respective diametral increases, the effective change in the pin-to-pin gap with axial position can be clearly seen.

Fig 5 shows the calculated clad temperatures for the central pin and for the indicated segment of the central pin of the outer row, at zero dose (at power) and at 100 dpa. The central pin temperature has increased slightly at 100 dpa because of the small bundle by-pass flow below the high power section of the bundle. The temperature profile of the edge pin changes noticeably between 0 and 100 dpa, becoming ~ 20°C lower over much of the fissile section.

4.2 Low Grid Swelling

When the grids swell at a much lower rate than the combined swelling and creep dilation of the wrapper, large gaps will develop, due to creep, between the wrapper and the pin bundle. This can be clearly seen in fig 6. The effect on coolant flow redistribution is considerable, because the area of a peripheral channel doubles for an additional gap equal to about one-third of a pin diameter (for $p/d = 1.26$). The initial overcooling of the edge subchannels thus increases with burn-up, enhancing cross-pin temperature gradients for peripheral pins. This leads to severe bowing because of the temperature dependence of clad swelling. Fig 7 shows the bowed shapes of the same two pins as in fig 4, at 100 dpa (N/2). It is seen that the pin-to-pin gap is almost closed between the sixth and seventh grids.

The corresponding effect on clad temperatures is much greater than for higher grid swelling. Fig 8 shows that the central pin clad temperature increases some 15°C between 0 and 100 dpa (N/2). This increase, however, would be counteracted by 'burn-down'. The edge pin, pin 6, is seen to develop a complex pattern of peaks and troughs in clad temperature along its length, because of bowing. Despite this, the peak temperature is less than the undistorted value because wall dilation produces a general reduction in temperature around the outer rows of pins.

5. Discussions and Conclusions

The results presented show that distortion due to voidage swelling and irradiation creep can have a considerable effect on the thermal hydraulics of LMFBR sub-assemblies. The magnitude of the effects is strongly influenced by the relative swelling of the honeycomb grids and the wrapper. In the cases considered it appears that no serious overheating would occur up to a peak neutron dose of 100dpa (N/2) even with low swelling grids. Beyond that dose it seems likely that pin-to-pin contact would become increasingly apparent. If it should occur near the top of the fissile length then serious local hot spots may develop. However, DISCO will readily point the way towards controlling these events by judicious positioning of the grids.

In general the grid support style seems to provide a particularly stable pin bundle. The effects of distortion are largely confined to the peripheral rows of pins, and they provide a general lowering of coolant temperatures in this region. The wire-wrap support style, by contrast, has been shown to develop severe pin bowing and corkscrewing accompanied by ovalisation and indentation of the cladding at high burn-up. It is anticipated that the DISCO code will provide a satisfactory means of designing fuel subassemblies so as to ensure that distortion due to swelling and irradiation creep will not lead to excessive hot-spots in advance of the target burn-up.

6. References

/ 1 / McAreavey, G. "Thermal Hydraulic Bowing Stability Analysis of Grid-supported Multi-pin Bundles", Proceedings 4th Intl. Conf. on Structural Mechanics in Reactor Technology, San Fransisco, USA, August 15-19, 1977, Paper D2/1*.

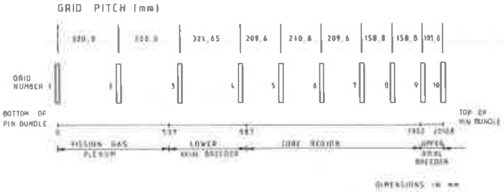

Fig 1 Honeycomb grid positions in subassembly.

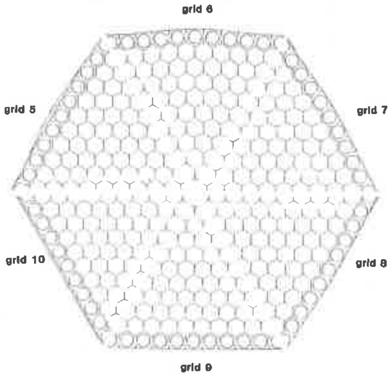

Fig 3 Variation of wrapper deflection and grid-wrapper interaction with axial position at 100 dpa. High grid swelling.

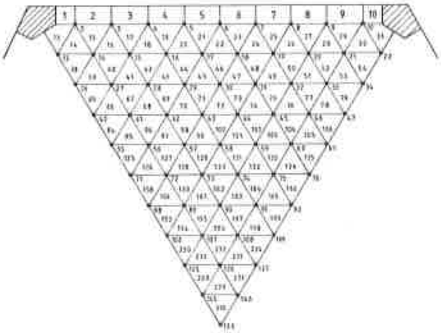

Fig 2 Pin and channel numbering system in DISCO.

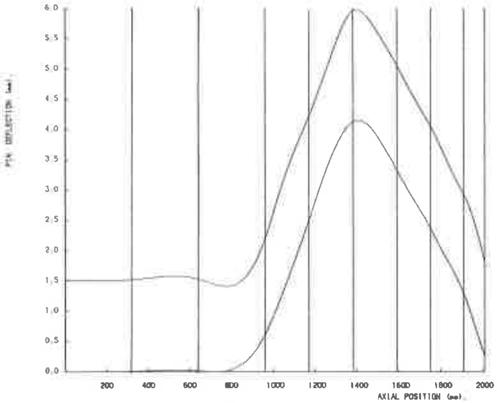

Fig 4 Pin 6, Pin 17 deflection relative to nominal centre of Pin 17 along line of centres. High grid swelling.

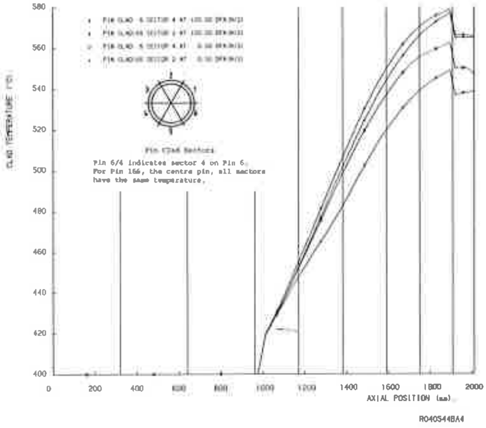

Fig 5 Clad sector temperature for pins 6 and 166, at 100 dpa. High grid swelling.

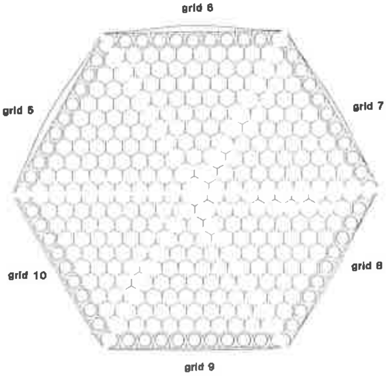

Fig 6 Variation of wrapper deflection and grid wrapper interaction with axial position, at 100 dpa. Low grid swelling.

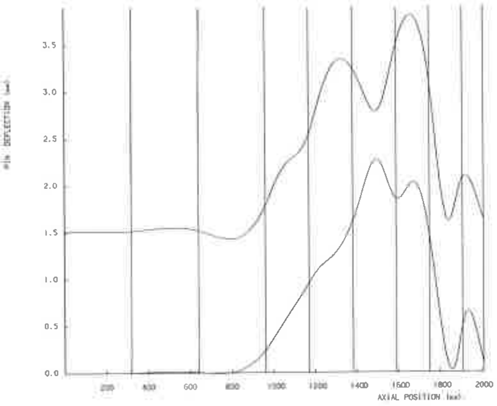

Fig 7 Pin 6, Pin 17 deflection relative to nominal centre of Pin 17 along line of centres. Low grid swelling.

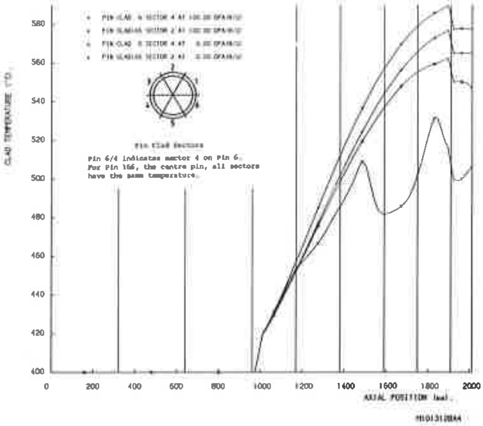

Fig 8 Clad sector temperatures for pins 6 and 166, at 100 dpa. Low grid swelling.