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FUEL PIN RESPONSE TO AN OVERPOWER TRANSIENT IN AN LMFBR

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Summary

As part of the safety assessment of any nuclear reactor, it is necessary to analyse the reponse of the core to the most severe accidents, even though these may have extremely low probabilities of occurrence. Codes have been developed, termed "whole-core" codes, which model, with varying degrees of sophistication, the events which occur throughout the core during a transient. The most comprehensive whole-core codes model the neutron kinetics, thermo-hydraulics and the mechanical behaviour of representative fuel pins. Pin failure criteria are included and events following pin failure are modelled (e.g. sodium voiding, either by fission gas release or by molten fuel coolant interaction (MFCI)). The reactivity effects of such events are taken into account.

Such a code makes very great demands on computing resources. It is necessary, therefore, that the models should be as simple as possible, yet should not give misleading predictions of core behaviour. This is the crux of the problem surrounding whole-core codes: they are always open to the criticism that the models of the various phenomena can be compared unfavourably with the best "stand alone" models.

This paper describes a method by which the ability of a whole-core code accurately to predict the time and location of the first fuel pin failures may be tested. The method involves the use of a relatively simple whole-core code to "drive" a sophisticated fuel pin code, which is far too complex to be used within a whole-core code but which is potentially capable of modelling reliably the response of an individual fuel pin. The method cannot follow accurately the subsequent course of the transient because the simple whole-core code does not model the reactivity effects of events which may follow pin failure.

The codes used were the simple whole-core code FUTURE and the fuel pin behaviour code FRUMP. The paper describes an application of the method to analyse a hypothetical LMFBR accident in which the control rods were assumed to be driven from the core at maximum speed, with all trip circuits failed. Taking 0.5% clad strain as a clad failure criterion, failure was predicted to occur at the top of the active core at about 10s into the transient. A repeat analysis, using an alternative clad yield criterion which is thought to be more realistic, indicated failure at the same position but 24s into the transient. This is after the onset of sodium boiling.

Pin failures at the top of the core are likely to cause negative reactivity changes. In this hypothetical accident, pin failures are likely, therefore, to have a moderating effect on the course of the transient.

1. Introduction

As part of the safety assessment of any nuclear reactor, it is necessary to analyse the the response of the core to the most severe accidents, even though these may have extremely low probabilities of occurrence. In an earlier paper [1] , the authors described an analysis of the initial response of an unconstrained LMFBR core to an "elastic srpingback" accident. That is a hypothetical accident in which the subassemblies spring back to a more reactive configuration, following an initial perturbation of core geometry, which might be caused, for example, by a localised MFCI. The codes used were FUTURE [2] and FRUMP [3] . FUTURE is a relatively simple whole-core code which models the response of the core to a specified reactivity input, using point kinetics. FRUMP is a highly sophisticated "stand-alone" fuel pin behaviour code, suitable for steady-state or transient analysis. The codes were used in tandem, the fuel pin ratings and surface temperatures predicted by FUTURE being used as input data to FRUMP, which analysed the internal temperature distribution and mechanical response of the fuel pins.

This method does not take account of reactivity changes due to events following pin failure, but the method can given an indication of the time and location of the first fuel pin failures. It is important to know the location of pin failures: events which follow fuel pin failure may be benign or may cause reactivity changes which could be positive or negative depending on the location of the failure. For example, sodium voiding, due either to fission gas release or MFCI, may cause positive or negative reactivity changes depending on whether the voiding occurs at the centre or at the edge of the core.

While some of the more comprehensive whole-core codes do model events following fuel pin failure, the complexity of these events makes such demands on computing resources that the behaviour of individual fuel pins is necessarily modelled relatively simply. The method used in the present work could provide a basis of comparison, against which the ability of the more comprehensive codes to predict the time and location of the first pin failures may be checked.

This paper describes an analysis of another hypothetical LMFBR accident in which all the control rods are assumed to be driven from the core, at maximum speed, the reactor remaining untripped. It is estimated that the rate of reactivity addition would be 17.5 ¢/s (compared with 50 $/s for 50 ms in the springback accident).

2. Future Analysis

For the purpose of the FUTURE analysis, a representative LMFBR core was modelled by five radial zones, each zone being represented by two fuel pins, one located near the centre of a subassembly and the other at the edge of a subassembly. The fuel pin details are given in Table I. Only the centre pins, which have higher clad surface temperatures than the edge pins, were subsequently analysed with FRUMP. Each pin was represented by nine axial stations, including one in each of the axial breeder regions. Because of the high cost of the FRUMP analyses, these were made only for the four axial stations in the upper half of the active core (including the station in the core mid-plane). The total number of FRUMP runs was therefore 5 x 4 = 20. Preliminary FRUMP analyses of all seven axial stations in the active core, for a fuel pin located at the centre of the core, confirmed expectations that clad failure was likely to occur first in the upper half of the active core.

Output from FUTURE includes fuel ratings, average fuel and clad temperatures and the sodium mixed mean temperatures. FRUMP requires, as input, the fuel rating and the clad surface temperature. This was taken to be the average of the clad mean and sodium mixed mean temperatures calculated by FUTURE.

In the FUTURE analysis, the peak burnup at the start of the transient was assumed to be 4.5%, corresponding to a dwell time of 204.5 days. The dwell time was assumed to be the same for all fuel pins, corresponding to single batch refuelling. The condition of each fuel pin at the start of the transient was defined by running FRUMP for a single load cycle consisting of an up-ramp lasting one day, followed by operation at constant power for 204 days, giving the required burnup (4.5% at the centre of the core).

Whereas in the analysis of the springback accident the most significant cause of clad strain was a strong pellet-clad interaction, it was anticipated that in this slower transient the fission gas pressure would be the dominant cause of clad strain. The version of FRUMP used for the analyses does not yet contain a physically-based model for fission gas release, although such a model has been developed and implemented at AERE Harwell [4,5]. For the present analyses, the total fission gas generation was estimated on the basis of the formula fission gas generated = $6 \times 10^{21} \times$ (fuel rating in w/g) atoms per day per m^3 of fuel. It was assumed that during the pre-transient irradiation at constant power, fission gas was totally released by fuel at 1500K and above. The resulting plenum pressure was estimated on the basis of the known plenum volume and the assumption that the gas temperature equalled the sodium inlet temperature (658K) (i.e. the plenum is located at the inlet side of the core). The resulting plenum pressures for the five radial zones are given in Table II. The tabulated pressures include the initial helium pressure which was assumed to be 0.272 MPa. The plenum pressures were assumed to increase linearly from the helium pressure to the tabulated pressures during the pre-transient period. The retained fission gas was assumed to be released during the first two seconds of the transient. The plenum pressures were assumed to increase linearly, during this period, to the higher values given in Table II. These values were calculated in the same way, but assume total release of the fission gas. The assumption that gas release will be complete two seconds into the transient is thought to be conservative, but not excessively so.

3. FRUMP Analyses

Fig.1 shows representative results from the FRUMP analyses. The figure shows the pellet-clad contact pressure at axial stations 5 (core mid-plane) and 7 (near the top of the active core) for radial zone 1 (the axis of the core). The figure also shows the circumferential plastic strain, at the outer surface of the clad at the same axial stations. At each station the contact pressure passes through a peak at about 4s into the transient, thereafter reducing as the fuel pellet becomes too hot to sustain the contact pressure: the pellet collapses by creep into the central hole and finally melts. Most of the plastic strain in the clad occurs after the peak of contact pressure has relaxed. The plastic strain is caused primarily by yielding due to the increased plenum pressure, coupled with the high clad temperatures which occur late in the transient (e.g. at station 7, the clad outer temperature increases from 873.8K at the start of the transient to 1124K at 12s into the transient). Note that the plastic strain (γ_θ) is the sum of yield and creep strains, but is primarily due to yielding.

Figs.2 and 3 show contours of plastic strain at the outer surface of the clad, at 10s and 12s into the transient. The contours were plotted automatically, using an off-line contouring package. Some of the irregularities are undoubtedly due to the small number of computed values. Nevertheless the figures show clearly that the highest strains develop on the axis of the core, near the core-upper breeder interface. In the absence of an accepted failure criterion, we may reasonably assume 0.5% plastic strain as a failure criterion for the irradiated 316 20% CW material [6]. On this basis, we see from Fig.2 that clad failure may be expected to occur first on the axis of the core, at the core-upper breeder interface, at about 10s into the transient. By 12s (see Figure 3), the clad failures were predicted to have spread outwards to include radial zone 2 and downwards to a point midway between axial stations 6 and 7.

This is a significant result. If fuel pins fail in this region, and if pin failures cause sodium voiding, the effect is likely to be a negative reactivity change. This contrasts with the result of the springback analysis, which indicated that clad failures would occur first at the centre of the core. Sodium voiding at the centre of the core is likely to cause a positive reactivity change.

4. Sensitivity of Results to Changes of Clad Yield Stress

The results shown in Figs.1,2,3 were obtained using the following expressions for the clad yield stress: $T < 1173$; $\sigma_y = 1497 - 1.257T$; $1173 \leqslant T \leqslant 1700$; $\sigma_y = 22.54 \left[1 - \frac{T-1173}{1700-1173}\right]$ where T = temperature (K) ; σ_y = yield stress (MPa). These expressions are now thought to underestimate the yield stress over the entire range of temperature. They overestimate the effects of annealing and take no account of strain hardening. The computations were therefore repeated using the following expression for the yield stress [7]:

$$\sigma_y = 115 \exp (140/T) + A \left[\frac{\bar{\varepsilon} + \varepsilon_{CW}}{4.4 \times 10^{-7}}\right]^{\frac{1}{2}} \frac{1}{1 + 100 \exp (- 4500/T)}$$

where $\bar{\varepsilon}$ = equivalent plastic strain, ε_{CW} = cold-work strain and $T < 1173$; $A = 1$; $1173 \leqslant T \leqslant 1273$; $A = (1273 - T)/100$; $1273 < T$; $A = 0$.

The effects on the computed clad strains are illustrated by Figs.4 and 5, which show contours of clad strain at 20s and 24s into the transient. Comparing these figures with Figs. 2 and 3 there are two obvious conclusions to be drawn: (i) clad failure will still occur first at the top of the core; (ii) clad failure will occur much later into the transient; about 24s compared with about 10s.

The computed clad strains are predominantly creep strains, whereas in the previous calculations, using the original yield function, the computed plastic strains were due predominantly to yielding. At the time at which clad failure is indicated (24s into the transient), sodium boiling has started at the top of the active core. (FUTURE predicts the onset of sodium boiling at 22s into the transient, at axial stations 7 and 8 in the central zone.) Fuel failure is therefore less likely to cause voiding.

5. Conclusions

The use of a simple whole-core code to "drive" a sophisticated fuel pin behaviour code provides a method of predicting the time and location of the first fuel pin failures in a reactor transient. The method cannot model the subsequent course of the transient, because the reactivity effects of events which might follow fuel pin failures are not modelled in the simple whole-core code. The method can be used, however, as a basis of comparison against which to check the ability of the more comprehensive whole-core codes to predict initial pin failures. These comprehensive whole-core codes necessarily model the behaviour of individual pins in a simplified manner and are therefore open to criticism.

The technique has been used to analyse the initial response of a representative LMFBR core to a hypothetical accident in which all control rods are assumed to be driven from the core at maximum speed and all trip circuits fail. The rate of reactivity addition has been taken to be 17.5 ¢/s. The first analysis of this hypothetical accident indicated that fuel pins in the central zone fail at the core-upper breeder interface at about 10s into the transient. Any resulting sodium voiding in this region is likely to cause a negative reactivity change. The analysis was repeated, using what is thought to be a more representative clad yield function. The repeat analysis indicated that pin failures could be expected in the same region of the core, but not until about 24s into the transient, after the onset of sodium boiling has caused partial voiding. Reactivity changes due to events following fuel failure are likely to be smaller, but still negative. For a full account of this work see [7]

Table I: Fuel Pin Details

Fuel	Mixed Oxide Pellet	Clad inner dia.	5.18 mm
Clad	SS type 316, 20% CW	Clad outer dia.	5.94 mm
Pellet inner dia.	2.27 mm	Plenum volume	$11.0 \times 10^{-6} m^3$
Pellet outer dia.	5.08 mm		

Table II: Plenum Pressures

Radial Zone	1	2	3	4	5
Plenum Pressure at Start of Transient (MPa)	1.227	1.083	0.708	0.464	0.272
Plenum Pressure at 2s into Transient (MPa)	3.473	3.313	3.008	2.973	2.141

6. Acknowledgements

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7. References

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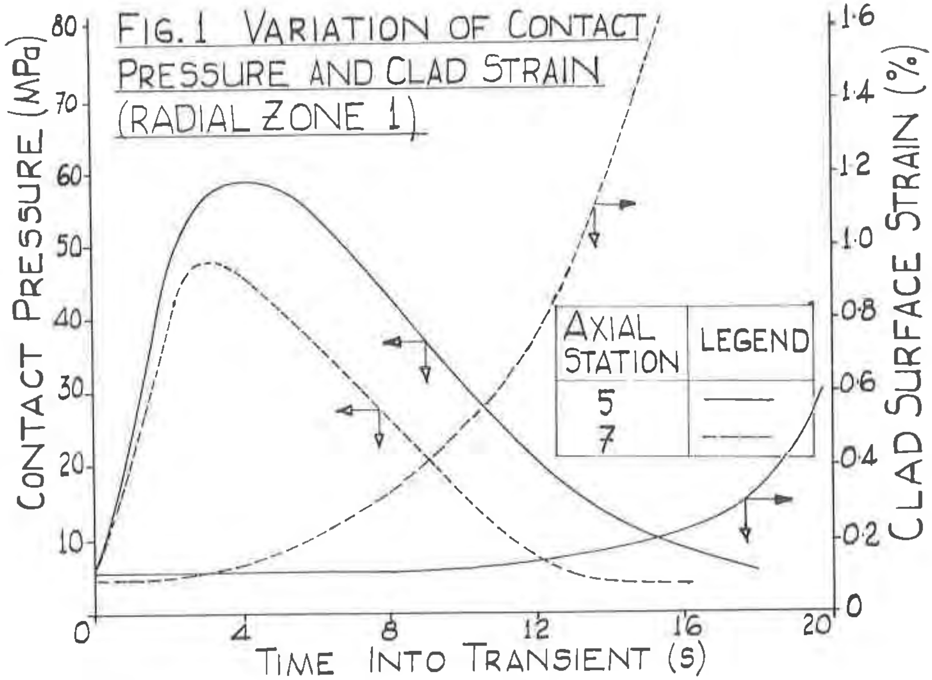

FIG. 1 VARIATION OF CONTACT PRESSURE AND CLAD STRAIN (RADIAL ZONE 1)

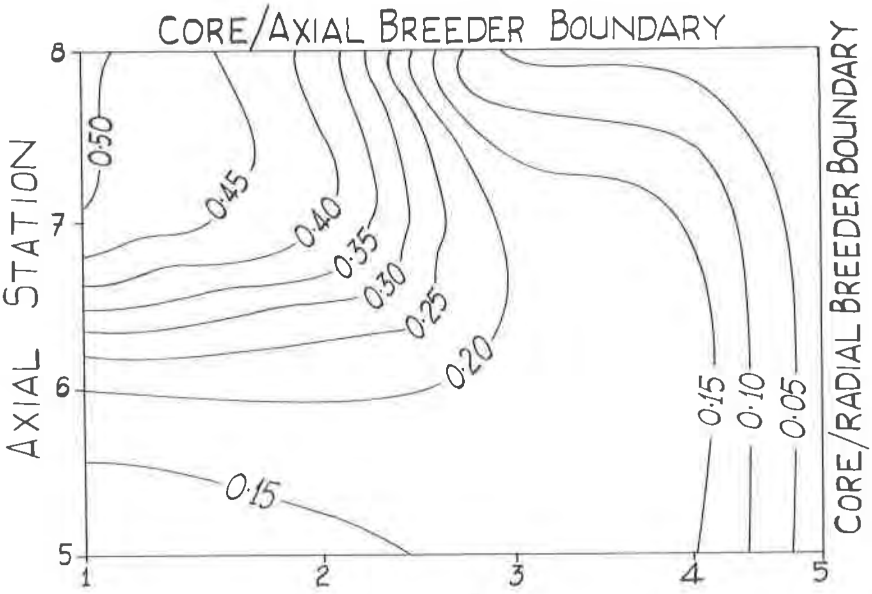

FIG.2. CLAD STRAIN (%) AFTER 10 S.

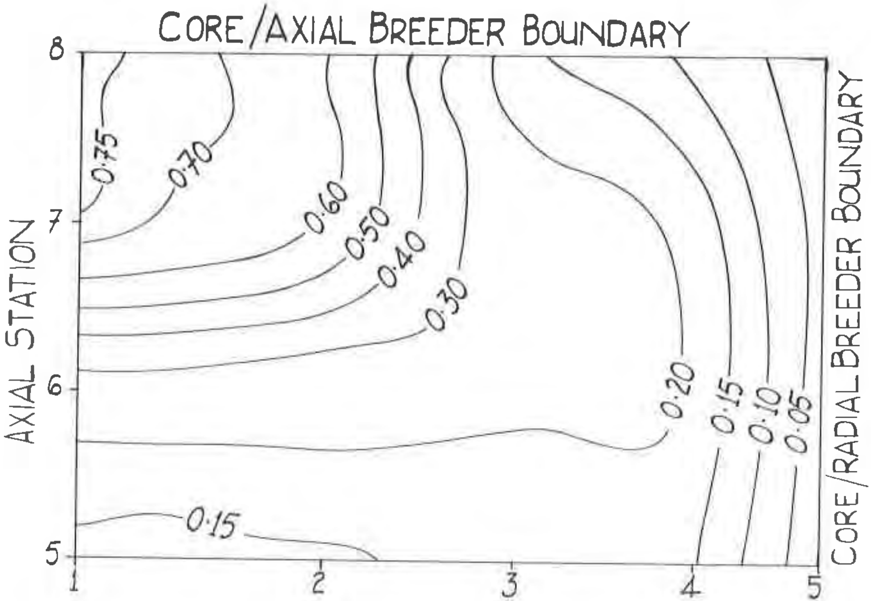

FIG.3. CLAD STRAIN (%) AFTER 12 S.

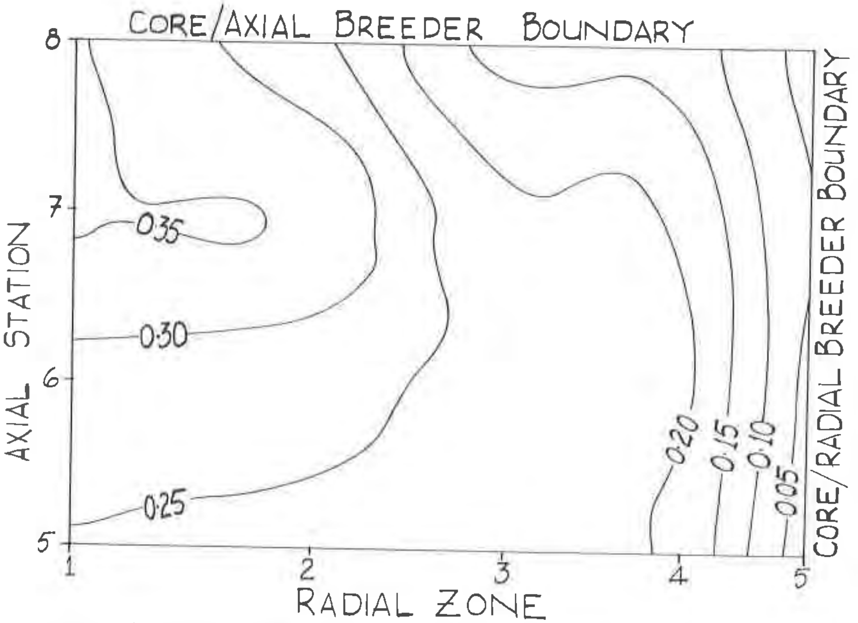

FIG 4 CLAD STRAIN (%) AFTER 20 S (NEW σ_Y)

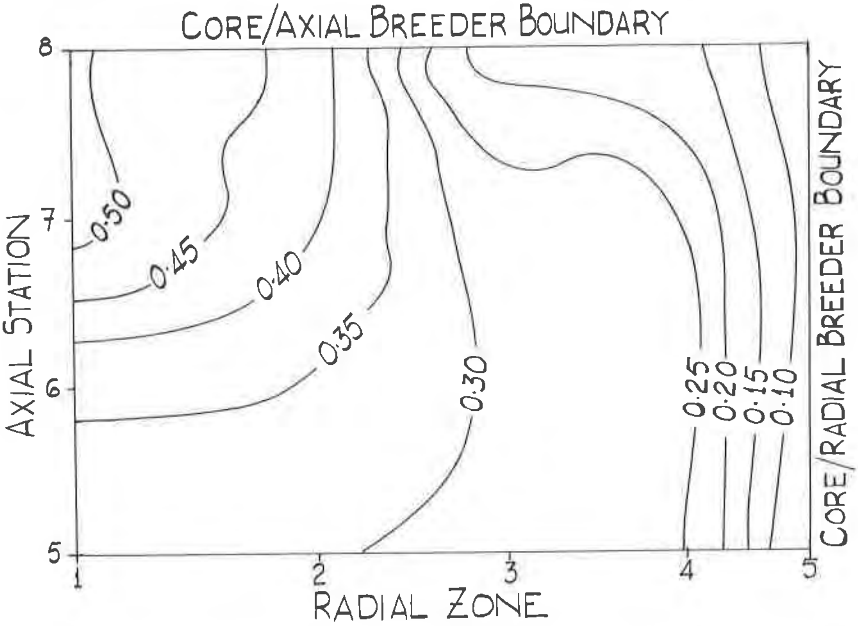

FIG. 5. CLAD STRAIN (%) AFTER 24 S. (NEW σ_Y)