Sizewell B

A review by HM Nuclear Installations Inspectorate
Supplement 5: Fuel clad balloning   NII 01 (SUPP 5)

CONTENTS

LIST OF FIGURES

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INTRODUCTION

1 In its review of the Sizewell B pre-construction safety report (PCSR) (ref 1) the Inspectorate listed ballooning of the fuel rod cladding as one of the main unresolved issues. At that time the PCSR did not contain a justification that such ballooning would not invalidate the LOCA safety case. This report presents the Inspectorate's views on the current situation regarding the CEGB's clad ballooning safety case, which was finally received at the end of September 1982.

SAFETY ASSESSMENT OBJECTIVES

2 The clad ballooning safety case has been assessed against the Inspectorate's safety assessment principles (ref 7). The principles relating to fuel and core design which are relevant to clad ballooning are intended to ensure that, at all times, the fuel assemblies are maintained in a condition where coolable geometry is guaranteed, the core safety limits are not exceeded and the assemblies can be removed following the accident. In the assessment of the CEGB case, emphasis has been put on examining the extent to which the information given demonstrates that the blockages which result from ballooning are coolable.

THE CLAD BALLOONING PROBLEM

3 The sequence of events which are postulated to occur in a PWR loss of coolant accident (LOCA) are shown in figure 1. In the LOCA safety case for the PWR made in the USA and elsewhere in the world, the standard approach involves the analysis of the time varying behaviour of the highest rated fuel rods by means of a pessimistic analytical evaluation model (EM). This EM has a procedure for calculating local fuel rod swelling and consequential flow blockage with its effect on the temperature of the peak rated fuel rod. However, swelling of the fuel rod cladding is not a linear function of temperature and, as shown in figure 2, in the case of a large break LOCA the peak rated rod in the core (which follows the upper bound of the shaded area) does not have the chance to deform in the lower

temperature range where the cladding has its maximum ductility. Hence the EM, by concentrating on the peak rod, could be underpredicting the consequences of fuel rod swelling in other parts of the core.

The possibility of more severe swelling in other parts of the core caused the Inspectorate at the time of its generic review (ref 2) to question the emphasis placed upon the peak rated rod behaviour in the LOCA-ECCS evaluation model. This point was raised because experiments (ref 4) showed that the high ductility of Zircaloy made it possible for the fuel rod cladding to exhibit not only high circumferential strain but also an axially extended ballooned region quite unlike that used in the EM calculations.

5 This change from a localised swelling to a balloon shape, as shown in figure 3, gave rise to the possibility of large flow blockages where the balloons overlapped. The Inspectorate's concern was that these blockages could impair the ability of the emergency core cooling system to cool the core and cause more severe temperatures than were being predicted by the EM.

6 Since the Generic Review, the UKAEA has devoted a great deal of research effort to the resolution of the clad ballooning problem and the review by Mann et al (ref 3) gives an indication of the progress that has been made in the UK and other countries, notably the USA, West Germany and Japan. An important development during this period has been the realisation that the "sausage" shaped balloons produced in the initial experiments (see figure 3), are not representative of the deformation which might be expected to occur under the convective cooling conditions of a LOCA. Hindle et al (ref 5) have now shown that convective cooling tends to force the deformation to occur in the downstream end of a grid span with the result that the fuel rod cladding takes up a "carrot" shape, as shown in figure 4. The findings of these relatively simple experiments appear to be confirmed by the results, as shown in figure 5, of the more recent multirod in-reactor experiment (ref 19) sponsored by the UK in the Canadian NRU reactor. These experiments have shown that the Inspectorate's concerns over the possibility of coplanar blockage are still valid in fuel assemblies with more representative two phase cooling conditions.

PRESENTATION OF THE SAFETY CASE

The PCSR

7 In the PCSR, the CEGB's LOCA safety case is based on the Westinghouse EM calculations which show that the temperature and oxidation limits are not exceeded in the Sizewell B core. As mentioned above, this approach does not address the clad ballooning problem, and the CEGB proposed an additional argument aimed at showing that axially extended ballooning would not cause blockages which would invalidate the conclusions drawn from the EM calculations. The LOCA safety case is made up therefore of two parts, the EM analysis and the clad ballooning safety case as given in the NNC report PWR/R662 (ref 6).

8 The EM accounts for local fuel rod swelling and flow blockage in its peak rated rod calculation and paragraphs 11 to 23 of this report discuss this treatment and its ultimate effect on fuel rod temperature.

PWR/R662

9 The clad ballooning part of the LOCA safety case is given in R662. There are two main features of the clad ballooning evaluation presented there: the overview or "perspective" of the problem, and the calculational analysis of the response of the fuel in the most severe loss of coolant accident (limiting design basis accident). The perspective attempts to show that the potential for clad ballooning is limited to only a few of the postulated loss of coolant accidents and that in these accidents the inherent characteristics of the core prevent core wide ballooning and blockage. The arguments used to support the above claims are discussed below in paragraphs 24 to 29 of this report.

10 The calculational analysis in R662 attempts to show, by using computer codes to model the fuel rod response to the thermal hydraulic conditions which exist in the core as a result of a LOCA, that the blockage produced by clad ballooning is coolable; ie the temperatures

in the core as a result of the [illegible] are below the current secondary limit of 1200°C. The codes used to perform the Sizewell B calculations and their results are discussed in paragraphs 34 to 44 of this report.

CLAD DEFORMATION AND BLOCKAGE IN THE [illegible]

11 As stated in paragraph 7 above, the LOCA safety case in the PCSR is based upon the EM. This assessment examines only the clad deformation aspects of the EM since the assessment of the LOCA case as a whole is covered elsewhere (ref 1). The intention here, therefore, is to examine the models used to predict fuel rod swelling and the consequences of that swelling on heat transfer degradation to see whether they are conservative and consistent with those used in relation to clad ballooning in R662. Four main features of the code have been assessed, clad strain, clad rupture, flow blockage and heat transfer degradation. These are reviewed in the following four sections. It will be seen that the Inspectorate has reservations about the models and general philosophy used. These reservations result from inconsistencies between the EM and R662.

Clad Strain

12 Clad strain is treated in the LOCTA code, which is part of the Westinghouse 1981 EM. There are a number of aspects of that treatment where more information is required before a judgement can be made about the overall conservatism of the strain calculation.

13 The first of these relates to the description of the creep of the cladding material. The EM uses a different approach from that in R662, which uses data derived by CEGB (refs 8 and 9) for Westinghouse Zircaloy 4 tubing. Since this latter data is directly relevant to the material to be used for Sizewell B, the Inspectorate has asked for confirmation that the two approaches are consistent. It is possible that the difference between the two approaches reflects the different temperature range over which the equations apply, but this needs to be clarified.

14 The second aspect of the strain calculation where further justification is required is in relation to the [illegible] limit imposed on rod strain before clad rupture. This apparently arbitrary limit is difficult to justify given the experimental evidence reported in R662 which shows significantly greater strains. This could influence the internal rod pressure calculation and hence affect the rupture calculation.

15 The third reservation, which is related to that above, concerns the calculated strain just outside the rupture zone. The current EM has applied a "correction" to the creep equation in order to obtain a better fit between the calculated strain and that which is observed experimentally. This correction makes it difficult to assess the extent to which the current equations are physically based and hence the conditions over which the equations are valid.

Clad Rupture

16 The calculation of clad rupture is an important aspect of the Westinghouse EM for two reasons. First, blockage in the hot assembly is only assumed to occur if the average rod in this assembly is calculated to rupture. Secondly, the size of the blockage depends upon the strain which is calculated to occur at clad rupture.

17 The Inspectorate has reviewed the models used to predict the conditions which result in clad rupture. It is felt that more information is required to justify the correlations used, especially in relation to the uncertainties associated with these correlations and the effects they have on the Sizewell B calculation.

Flow Blockage

18 The Inspectorate has two main concerns about the flow blockage modelling in the Westinghouse EM. These relate to the two points raised in paragraph 16 above. It will be seen that for each of these points there are inconsistencies between the EM approach and that given in R662.

[illegible] In the case of the first point the Inspectorate can find no justification for the criterion of [illegible] for blockage. Its shortcomings are apparent when the EM calculation given in the PCSR is compared with the [illegible]. The EM calculation assumes that the average rod [illegible] has a power of [illegible]% of the peak rated rod [illegible] calculation for Sizewell B the average rod in the hot assembly is not calculated to burst and hence no flow blockage is assumed to occur. As a result, the peak clad temperature is calculated to be [illegible]°C ie [illegible]°C below the limit.

20 The mechanistic calculation of flow blockage in R662 on the other hand shows that for an 85% power rod there is extensive clad ballooning, with the result that the coolant flow area is reduced by 80% in the blocked region. This reduced flow area is calculated to cause a degradation in heat transfer which R662 suggests would increase the peak fuel rod temperature by somewhere between 113°C and 128°C. If this increase in temperature is scaled up for the 100% power rod the increase could be in the region of 150°C. It is clear from this that there is a significant inconsistency between the modelling of the fuel rod swelling and blockage in the EM as compared with the modelling of ballooning in R662, and it would appear that the average rod burst criterion for blockage assessment is inadequate.

21 The other aspect which requires further justification is the size of the blockage once it is calculated to occur. The EM uses the methods given by Powers and Meyer (ref 10) to derive the flow blockage from the burst strain. When these methods were being formulated the Inspectorate expressed reservations (ref 11) about the use of non-prototypic experiments for relating single rod strain to multirod flow blockage. The EM has been used to study the sensitivity of peak fuel temperature to flow blockage for Sizewell B (ref 13) and when the power of the average rod was increased so that rupture occurred the flow blockage was calculated to be 53%. However, this is significantly less than the 80% flow blockage calculated using the mechanistic methods in R662 for rods of similar power. Even allowing for the fact that the EM is calculating an average blockage across the hot assembly, the power variations across the assembly are not large

[illegible] into account [illegible] In the light of these results it would appear that the EM calculation may be underestimating the degree of flow area reduction in the [illegible].

Heat Transfer Degradation

22 Once a blockage is calculated to occur in the hot assembly the EM goes on to calculate the degradation in the cooling of the hot rod which results from the combination of flow diversion around the blockage and the change in heat transfer associated with the lower flow through the blockage. The sensitivity studies reported in the PCSR and in reference 13 indicate that, for the cold leg double ended guillotine break LOCA, the peak clad temperature is increased from 1039°C to 1199°C when flow blockage occurs. Although this increase of 160°C is consistent with the 150°C derived from the 80% flow blockage calculation in R662, the extent to which these results can be used to justify the conservative nature of the EM calculation is unclear, since there are aspects of both calculations which require clarification. Those associated with R662 are discussed below. In relation to the EM, the aspects which require further justification are the validation of the THINC code (ref 12), which calculates the flow diversion, the blockage geometry used in the THINC code, and the heat transfer calculation in and downstream of the blockage.

23 It is possible that the apparent agreement between the EM and the mechanistic calculation results from the fortuitous combination in the EM of non-conservative blockage modelling and over-conservative assumptions relating to flow and heat transfer. This latter point is supported by the Inspectorate's extra mural research at Manchester University in which a flow blockage model has been used to predict the effects of various sized blockages on peak clad temperature under conditions similar to those predicted by the EM. These studies indicate that the EM heat transfer degration for a 53% blockage is overly conservative.

CORE WIDE BALLOONING PERSPECTIVE IN R662

24 As explained earlier, the main problem associated with clad ballooning results not from the peak rated rod but from the behaviour

of the fuel rods operating at lower rating than the peak rated rod, ie rods for which the cladding exhibits the high ductility associated with the α phase Zircaloy. The safety case perspective, as outlined in R662, attempts to show that clad ballooning potential is limited to only a few loss of coolant accidents and for these only small areas of the core are affected. The Inspectorate has assessed the arguments put forward in this perspective because they are considered to be important, especially in the case of core-wide ballooning. Such ballooning could cause the overall level of temperature in the core to rise and increase the total clad oxidation above the allowable 1% limit. However, the main part of the safety argument is the case presented to demonstrate coolability in the event of ballooning occurring.

LOCA Transients at Risk

25 The safety case in R662 (ref 6) uses the EM fuel rod code LOCTA to identify the accidents in which ballooning is likely to occur. As discussed in paragraphs 12-15, the Inspectorate has doubts about the clad strain calculation in LOCTA and this, in combination with other factors, has caused the Inspectorate to question the suitability of the approach used to determine ballooning potential. As a result of its assessment, the Inspectorate believes that there is insufficient justification for restricting the LOCAs where ballooning is a risk to those given in R662.

Fuel Rods at Risk

26 Having attempted to establish that only a small number of LOCA's have ballooning potential, the safety case goes on to claim that because of certain inherent core characteristics ballooning will not cause a core-wide blockage. The arguments have been reviewed and it will be seen below that the Inspectorate has reservations about some of the claimed blockage inhibiting effects.

27 The safety case argues that blockages are only of significance if they involve the ballooning of fuel rods in an array greater than 3x3. It further argues that there are only limited areas in the core where

[illegible] greater than [illegible] features of the PWR core: the distribution of control rod guide tubes and the distribution of fuel rod power resulting from the fuel management scheme.

28 The arguments made in relation to the effect of control rod guide tubes and other non-fuelled locations, such as instrument or burnable poison thimbles, have been reviewed. It is felt that insufficient information is presented to justify the claim made that these "cold" tubes will inhibit ballooning and hence blockage. Experiments carried out in West Germany (ref 14) have shown that, in electrically heated multirod bundle experiments, cold tubes do not restrict the deformation of neighbouring fuel rods to the extent that was originally postulated. The relevance of these and other experiments to Sizewell B will need to be assessed before it can be accepted that ballooning will be limited to the outer corners of the fuel assembly.

29 In the areas of the core where there are no cold tube effects the safety case argues that a further criterion restricts the possibility of blockage, namely, that significant blockage can only occur if the power variations within the array are less than 4%. This 4% figure is claimed to be conservative because calculations show that a 1% difference in power between adjacent rods is sufficient to cause a change in the ballooning behaviour such that the rods will balloon at different times and that this difference is sufficient to cause ballooning to occur at different axial locations with the result that coplanar blockage will be inhibited. The Inspectorate has reservations about the claimed effects of these small power differences since they are based on idealised TAPSWEL calculations which are not supported by the behaviour seen in the MT3 multirod in-reactor experiment at Chalk River, Canada (ref 19). From the information available on this test the Inspectorate has been unable to identify a clear relationship between burst time and rod power. This suggests that for multirod arrays there may be other factors, possibly for example pellet eccentricity or thermal hydraulics, which invalidate the simple assumptions used in the TAPSWEL calculation.

[illegible] SAFETY ARGUMENT [illegible]

[illegible] Since the 'perspective' in [illegible] shows that clad ballooning will occur in the limiting large break LOCA, the main safety argument rests on the ability of computer codes to calculate the response of fuel rods in this accident. The case relies [illegible] on the two Westinghouse computer codes TAPSWEL and BART to determine how the fuel rod cladding deforms, restricts the coolant flow and suffers an increase in temperature. A third code, ASTRA, has been used to support the validation of TAPSWEL. However, as no information has been submitted on the ASTRA code, the Inspectorate has only been able to assess the two Westinghouse codes.

31 These two codes provide the means to study fuel rod ballooning by modelling the physical processes which take place. The major code is BART and it calculates the axial variation of rod strain during the LOCA transient. Having calculated the strain, it also calculates the flow diversion and heat transfer associated with the blockage so that the fuel rod temperatures in the core as a result of the blockage can be calculated. BART has the restriction of being an axisymmetric code and, as a result, it cannot calculate rupture of the cladding arising from eccentric pellet effects. This aspect of the calculation is performed by TAPSWEL and the two codes are used to determine what is essentially a physically integrated process.

32 The Inspectorate has reviewed the two codes and the way in which they are combined to perform the Sizewell B ballooning calculations. This treatment represents an improvement in the modelling of clad ballooning and its consequences. Nevertheless, several reservations have been identified and these are discussed in paragraphs 34 to 45 below.

33 An important part of the clad ballooning safety case is the reliance placed upon clad strain being restricted by the eccentricity of the fuel pellet within the fuel rod cladding. There are several questionable aspects of the eccentricity calculation and these are discussed in paragraphs 46 to 52.

Calculational Models

The TAPSWEL Code

34 The TAPSWEL code is used to calculate the rupture strain of the cladding. The calculation is done for the axial position and the pressure differential across the cladding, the location of the fuel pellet and the heat transfer conditions throughout the transient must be supplied from other codes. The TAPSWEL code is based on a two dimensional heat conduction code with an additional module to calculate strain and this structure makes it inflexible for calculating the behaviour of the dynamically deforming cladding.

Assessment of the information provided on this code has revealed only limited validation against experiment. Additional information is necessary to show that the code accurately calculates rupture strain. Areas where validation of TAPSWEL needs special attention are the effect of azimuthal noding and time steps used in the numerical solution and the creep data used in the strain calculation.

The BART Code

35 The BART code couples the core thermal hydraulics models to the clad deformation models so that the axial extent of the clad deformation, the associated flow area reduction and the increase in clad temperature resulting from the blockage can be calculated. The main safety case argument that ballooning does not present a problem depends to a large extent on the predictions of this code. Hence, acceptance of the case by the Inspectorate will depend upon the extent to which the BART code has been validated.

36 In the BART calculation there are four aspects which are crucial to the safety arguments:

(i) two phase reflooding characteristics,

(ii) clad deformation,

(ii) coolant flow diversion around the blockage

(iii) heat transfer within the blockage.

37 Satisfaction on the first of these essentially depends upon the validation of the codes used in the EM since the BART thermal hydraulics are derived by the same codes used in the EM. The EM codes are currently being studied as part of the LOCA assessment. However, the detailed thermal hydraulics in BART itself have not been assessed because the proprietory reports were not available to the Inspectorate.

38 With regard to the second aspect (clad deformation), the Inspectorate has some reservations regarding the calculation of clad strain and of blockage. In the case of the strain calculation, BART currently uses the same methods and data as are employed in the EM code LOCTA. The Inspectorate's concerns about this code were expressed earlier and it is felt that, before this aspect of the BART modelling can be accepted, the CEGB will have to demonstrate that the strain calculation gives results which are consistent with the information derived by them for Westinghouse tubing in references 8 and 9. Another aspect of the strain calculation is the assumed internal fuel rod pressure. During the deformation transient this is influenced by the temperature of the gas plenum at the top of the fuel rods. The Inspectorate has reservations about the assumptions used to calculate this temperature. It is felt that the current calculation may be under-predicting temperature and hence internal rod pressure. More information is needed to clarify this point.

39 In the BART calculation of blockage there are two important features, the axial shape of the balloons that cause the blockage and the maximum flow area reduction. The Inspectorate has reservations about the way BART and TAPSWEL are currently used to derive the maximum flow area reduction and this will be discussed more fully in the commentary on the calculations given in paragraphs 45 to 61 of this report. With regard to the axial extent of the blockage, BART appears to simulate the deformation seen in the NRU multirod ballooning experiments. This comparison shows that in the maximum

[illegible] the BART calculation conservatively predicts the axial extent of the deformation. It is likely, therefore, that BART is conservative in this respect. However, whilst recent UKAEA work (ref [illegible]) using the MABEL code appears to support the conservative nature of the axial blockage calculation in BART, further validation of BART against multirod ballooning experiments is considered to be necessary to confirm this conservatism.

40 The third aspect of the BART calculation which has been assessed involves the flow diversion around the blockage, and again the Inspectorate has reservations about the modelling. The two channel model used in BART is a very simple way of representing blocked and unblocked regions of the core. The safety case does not make clear the exact size of the blocked array which the blockage channel is modelling or how the flow resistance coefficients are related to blocked and unblocked dimensions. The Inspectorate, therefore, requires more information to demonstrate that the approach used in BART conservatively models the flow diversion effects associated with the largest blockage that is calculated to occur in Sizewell B.

41 The fourth aspect of importance to the BART calculation concerns the heat transfer between the fuel rod cladding and the coolant which remains within the blocked region. The Inspectorate has reservations about this calculation for a number of reasons. The first results from the lack of detailed information relating to the equations used; this information is in the proprietory document which, because of its late submission, has not yet been assessed.

42 The second reservation arises because the heat transfer coefficient correlation used in the blockage throat is based upon data derived from flow in circular channels. The research work carried out for the Inspectorate at Manchester University has shown that, for single phase cooling in non-circular ducts of similar shape to those which could be expected from interacting ballooned fuel rods, heat transfer is less than that predicted by correlations derived for circular ducts. It is possible that for two phase cooling this difference is unimportant, but the Inspectorate will require

information to show that BART is not underpredicting the clad temperatures in the blockage as a result of this effect.

A third aspect of the BART [illegible] which requires further justification is the extent to which two phase effects are being conservatively modelled. This aspect of the modelling is crucial to the determination of blockage coolability since some other work at Manchester University has shown that, for the blockage size calculated by BART for Sizewell B, cooling by single phase steam would result in much higher temperatures in the blockage than is currently calculated by BART.

44 It follows from the above that more work is necessary to validate BART. The Inspectorate expects to see a clearly defined validation programme for BART involving blind predictions of tests such as those proposed for the UKAEA facilities, MERLIN and THETIS. MERLIN is a two phase cooled multirod dynamically ballooning experiment and this could be used to test the balloon and blockage shape models in BART. The current THETIS programme comprises some very sophisticated blockage experiments. However, they do have limitations and, because blockage coolability is crucial to the understanding of the safety implications of ballooning, the Inspectorate supports the UKAEA proposals to build a new rig (ACHILLES) to study the Sizewell B fuel assembly geometry with a representative flow blockage. Since this facility will not be operational before 1984, it is unlikely that full confirmation of BART modelling will be available before then.

Safety Case Calculations

45 As discussed above, the clad ballooning safety case depends upon the ability of BART and TAPSWEL to demonstrate that clad ballooning in LOCA will not result in a loss of fuel rod coolability. However, in addition to the code uncertainties discussed above, there are several aspects of the assumptions made in the calculations which need to be reviewed, namely, fuel pellet eccentricity within the cladding, fuel and internal pressure, the influence of fuel rod power and the predicted blockage consequences.

Fuel Pellet Eccentricity

46 In the BART safety case calculations the flow blockage has been limited to 60% a value which arises from the clad burst strain calculated by the TAPSWEL code. This burst strain results from the combination of the transient temperature conditions and the eccentricity of the fuel pellet within the cladding. If the fuel pellet were assumed to be concentric, the BART code would calculate blockages in excess of that given in the safety case.

47 The dependence of blockage size on pellet eccentricity results from the azimuthal variations in temperature which are caused by the eccentric pellet and these produce non-symmetric straining of the clad. This in turn produces rupture at a lower average strain than would be the case without azimuthal temperature variations. The Inspectorate accepts the general argument in relation to azimuthal temperature effects, but the important issue is the extent to which the pellet eccentricity can be quantified for the fuel in Sizewell B.

48 The safety case in R662 suggests that fuel pellets are randomly distributed within the available gap between the pellet and the cladding. This may be the case for new unirradiated fuel rods, but it is not clear from the evidence presented that the random distribution of eccentricity still applies when the fuel has been irradiated or when it starts to deform. However, the Inspectorate is satisfied that pellet eccentricity exists in ballooned fuel rods. Experiments (ref 15) have been carried out by the UKAEA in its Windscale laboratories in which irradiated fuel rods were "ballooned" to various strain levels and the contents subsequently fixed in a resin which enabled the undisturbed fuel pellet structure to be examined. These tests showed that pellet eccentricity is present at all strains measured but, in addition, the fuel pellet fragments were observed to relocate; this could have an opposing effect to the eccentricity with the result that azimuthal temperature differences would be reduced.

49 For the Sizewell B calculations, R662 uses the Westinghouse pellet eccentricity probability distribution to determine a mean value of pellet eccentricity. However, there are uncertainties associated

with the applicability of this to [illegible] ballooning rods. The CEGB [illegible] proposed [illegible] defining a representative pellet eccentricity for Sizewell B. Essentially the CEGB has assumed that the [illegible] can be represented by the use of an effective pellet eccentricity which characterises the behaviour of an average rod in an array. The value used is derived from the UK sponsored multirod ballooning test (MT-3) in the Canadian NRU reactor. Making the assumption that eccentricity remains constant during deformation, the TAPSWEL code has been used to determine the range of eccentricities which corresponds to the range of burst strains measured for the [illegible] rods in MT3. The average eccentricity derived from the MT3 fuel rods is used in the Sizewell B calculations.

50 This approach has yet to be written into the formal safety case, but it seems reasonable given the current uncertainly over the physical processes which affect ballooning in multirod bundles. The use of an effective constant eccentricity seems a convenient way of sweeping up both the pellet eccentricity distribution and other effects such as fuel fragment relocation. However, the information on which the mean value of 0.35 is based is very limited due to both the small number of rods in the MT3 test and the lack of detailed information on the exact temperature and pressure conditions pertaining to each rod during the test. This latter point means that the TAPSWEL calculations are only approximate and this could affect the predicted eccentricity.

51 Independent work by the UKAEA (ref 17) using different calculational tools shows that an effective eccentricity of 0.35 can represent the average conditions seen in MT3. However, the UKAEA conclude that there is no unique relationship between burst strain and eccentricity since there are many interacting effects.

52 It can be seen from the above discussion that the information given in the safety case does not provide sufficient justification for the constant eccentricity concept. The Inspectorate regards the eccentricity value of 0.35 as representative of the NRU-MT3 experiment, but it is concluded that further information is necessary

to confirm that such a value is suitable for the Sizewell B calculations.

Fuel Rod Internal Pressure

53 The rupture strain derived from TAPSWEL which is an input to BART relies on internal rod pressure as well as pellet eccentricity. The Inspectorate has reservations regarding the way in which the two codes are used to derive pressure for the Sizewell B calculation.

54 The TAPSWEL code cannot determine the change in internal rod pressure due to the changing circumstances in the transient. The Inspectorate believes that the method used for the Sizewell B calculations may induce an error in the strain calculation which could lead to an underprediction of the blockage. This concern arises from the fact that the two codes are not run interactively.

Fuel Rod Power

55 In its safety case the CEGB argues that for Sizewell B the degree of flow blockage increases with increasing rod power and hence the most conservative results will be produced for the array of fuel rods which have maximum power. It is stated that the highest average rod power in an array of fuel rods large enough to cause a blockage is 92% of the peak rated rod in the core. The Inspectorate has taken the view that this is a reasonable value to select for this purpose.

56 The Inspectorate has had difficulty relating the clad temperatures calculated by BART for the lower power rods reported in R662 to those published in the PCSR for the 100% power case. A preliminary comparison suggests that the R662 calculation may be giving lower temperatures and, if this is the case, then the conclusion relating to the power levels at which significant blockage is avoided may be optimistic. Hence further information to clarify the BART and EM calculations is necessary.

Blockage Prediction

57 The final arguments supporting the [illegible] safety case rest on the BART calculation of flow blockage and its effect on clad temperatures, and on the fact that none of the temperatures exceed the 1200°C secondary limit. Assessment of the reported calculations has revealed some anomalies which support the reservations expressed above relating to computer code modelling.

58 The first of these anomalies arises in the calculation of fuel rod strain and is best illustrated in the case of the 70% power calculations. These results show a flat topped temperature transient in the Zircaloy high α temperature region with the TAPSWEL code indicating no rupture and a maximum strain of about 10%. However, for the same transient BART calculates an average strain of around 38%. Similar transient conditions in the idealised UKAEA ballooning experiments (ref 4) resulted in strains in the region of 80 to 90%. The difference between TAPSWEL and BART is probably due to pellet eccentricity effects and the specification of internal rod pressure, as discussed above. However, given that BART and the UKAEA experiments have no azimuthal temperature variations around the clad, the difference in strain needs explaining since the rod strain determines the flow blockage.

59 The second apparent anomaly results from the difference in time calculated to reach rupture strain in the BART and TAPSWEL codes. In the case of the 85% and 92% rod power calculations, TAPSWEL calculates a shorter time for clad rupture than that calculated to reach maximum blockage in BART. As discussed earlier, the claim is made that burst strain does not depend upon time and hence the inconsistency is not important. However, it is felt that the safety case does not provide sufficient information to justify this statement, especially for situations where the clad temperature is rising during the formation of a blockage.

60 The third anomaly results from the difference in the location of the peak clad temperature. Sensitivity calculations have been performed but in the main these have not addressed the areas with the

between [illegible] and heat transfer degradation. However, [illegible] sensitivity calculations have been done and [illegible] in both cases [illegible] the peak clad temperature is different [illegible] base case calculations. In the [illegible] the peak clad temperature occurs in the blocked [illegible] downstream as in the base case calculations for the 80% blockage. The safety case does not adequately explain the reasons for the difference in peak temperature location. Furthermore, the temperatures calculated to exist in the 90% blockage are much higher than those in the 80% case, despite the fact that the 90% blockage has a shorter axial length.

61 A fourth anomaly is the difference in the prediction of strain and hence blockage between the TAPSWEL/BART approach and the independent calculations done by the UKAEA (ref 17) which use the TRAC/MABEL calculational route. The UKAEA calculation, using the same average eccentricity of 0.35, calculates a larger strain and hence a higher flow area reduction than that given in the safety case. The differences in blockage probably results from the thermal hydraulic modelling in TRAC, but this needs to be explained in order to demonstrate that the BART/TAPSWEL calculation is conservative.

CONCLUSIONS

62 Since the PWR Generic Review, where the Inspectorate expressed concern about clad ballooning and its effect on the LOCA safety case, significant progress has been made. Substantial amounts of research have been carried out into the deformation behaviour of Zircaloy cladding, the ballooning of rods in multirod arrays such as the UKMT3 experiment, the study of blockage coolability in THETIS and the development of advanced computer codes such as MABEL 2. This and other similar work in USA, Germany and Japan, has greatly increased the nuclear industry's understanding of the ballooning behaviour of PWR fuel rods.

63 The Inspectorate has reviewed the safety case both in relation to the clad deformation and blockage models used in the EM and the clad

supporting calculations given in [illegible] the [illegible] claim that the safety case demonstrates that clad ballooning will not inhibit the effectiveness of the ECCS [illegible]. The Inspectorate regards the case [illegible] supporting reports as being the most thorough [illegible] of the [illegible] implications of clad ballooning done so far. The [illegible] are encouraging. Nevertheless, a number of areas have been identified where further information is required to support the [illegible] claim.

64 The modelling of clad strain, clad rupture, flow blockage and heat transfer degradation aspects of the EM part of the safety case have been examined. The main concern is related to the definition of flow blockage and its effect on the peak rated fuel rod temperatures. In this context there is a discrepancy between the EM, which assumes no flow blockage in the PCSR calculations, and R662 which calculates an 80% flow blockage for similar conditions. Since the temperature calculated by the EM for the average rod in the Sizewell B hot assembly is within a few degrees C of the blockage criterion, the Inspectorate would expect blockage effects to be incorporated into the PCSR calculation. This would reduce the margin between the limit and the calculated peak clad temperature from 161°C to 1°C. Given this small margin the Inspectorate requires further information to demonstrate that the flow blockage model used in the EM and its associated heat transfer penalty are conservative.

65 From its study of the clad ballooning safety case given in PWR/R662, the Inspectorate has raised a number of reservations regarding both the techniques used to assess ballooning potential and the modelling used in the computer codes.

66 Regarding the range of LOCAs at risk from ballooning, the Inspectorate believes that insufficient justification has been presented to support the claim made that only the few accidents described in R662 will result in conditions which are conducive to clad ballooning. Therefore improvements to the methods used in R662 will be necessary to provide adequate justification for this claim. This is not regarded by the Inspectorate as being of overriding

importance because the objective of the safety case has been to demonstrate coolability in the presence of clad ballooning.

67 More information is required to justify the claims made that control rod guide tubes and rod to rod power variations will limit the extent of ballooning and blockage. This is regarded by the Inspectorate as a matter of concern because, if the ballooning and blockage across the core were extensive, this would cause the general level of temperature across the core to rise with the result that the total clad oxidation in the core would increase and possibly exceed the 1% oxidation limit. The Inspectorate will require information to demonstrate that this will not happen.

68 The Inspectorate wishes to see better validation of both the TAPSWEL and BART codes, and more justification for the approach currently used to combine them. Since the clad ballooning safety case depends upon the predictions of these codes the Inspectorate expects to see a clearly defined validation programme which includes both ballooning and blockage experiments; those being conducted by the UKAEA would seem appropriate for this task.

69 Finally, the Inspectorate believes that further justification is needed for the assumptions used to define fuel pellet eccentricity in the Sizewell B calculations.

70 In summary the Inspectorate has a number of reservations concerning the CEGB's clad ballooning safety case. These reservations result, in the main, from there being insufficient evidence at present to support the claims made about the limited extent of clad ballooning and its consequences. At this stage, the above reservations mean that the Inspectorate is not yet satisfied with the CEGB's case. However, if the additional work which is proposed in R662 achieves its objectives and the detailed criticisms made in this report are satisfied, then the Inspectorate can see no reasons why an acceptable case could not then be made.

HM NII, Janaury 1983

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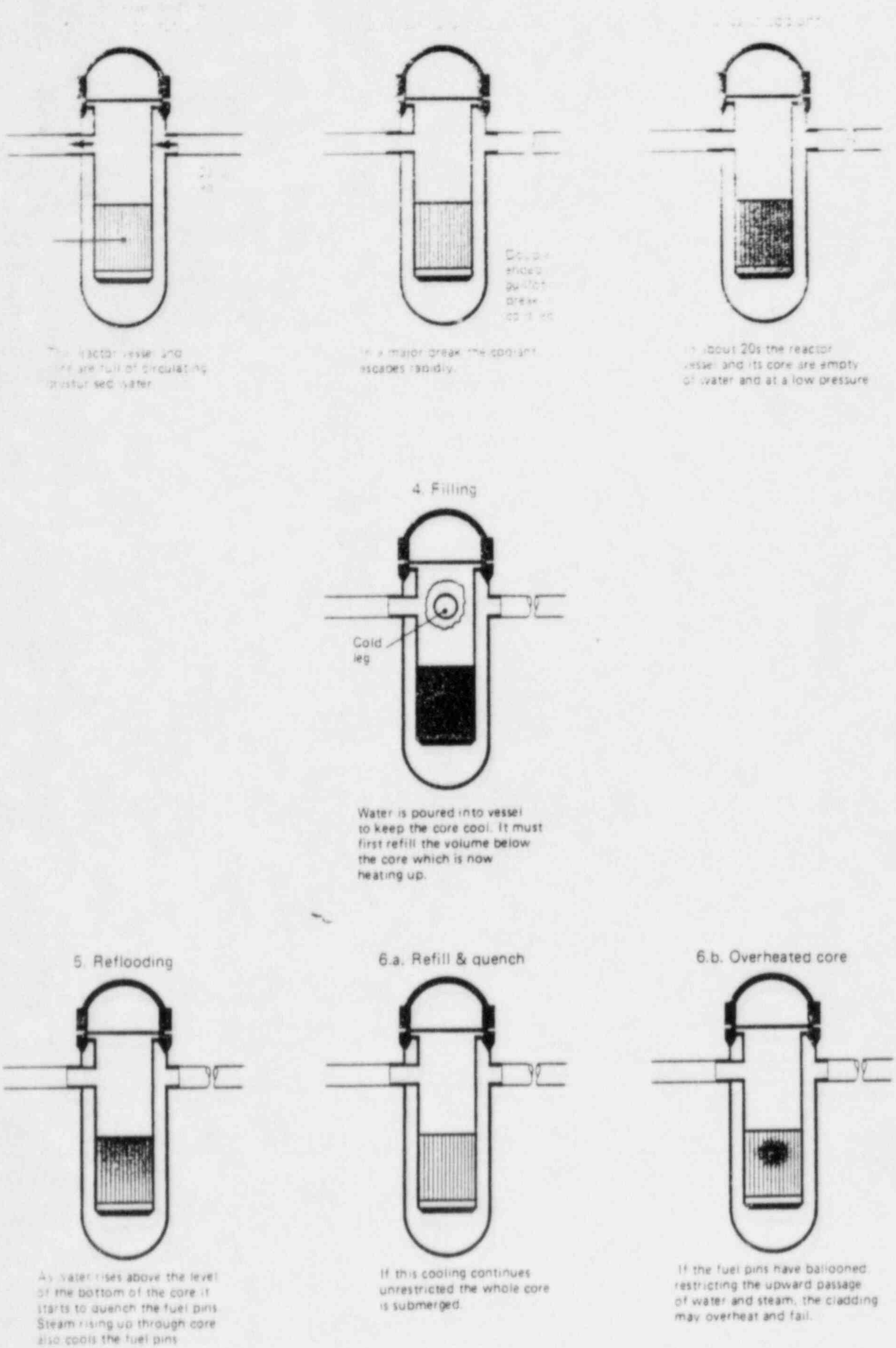

FIG 1 Sequence of events in a PWR LOCA

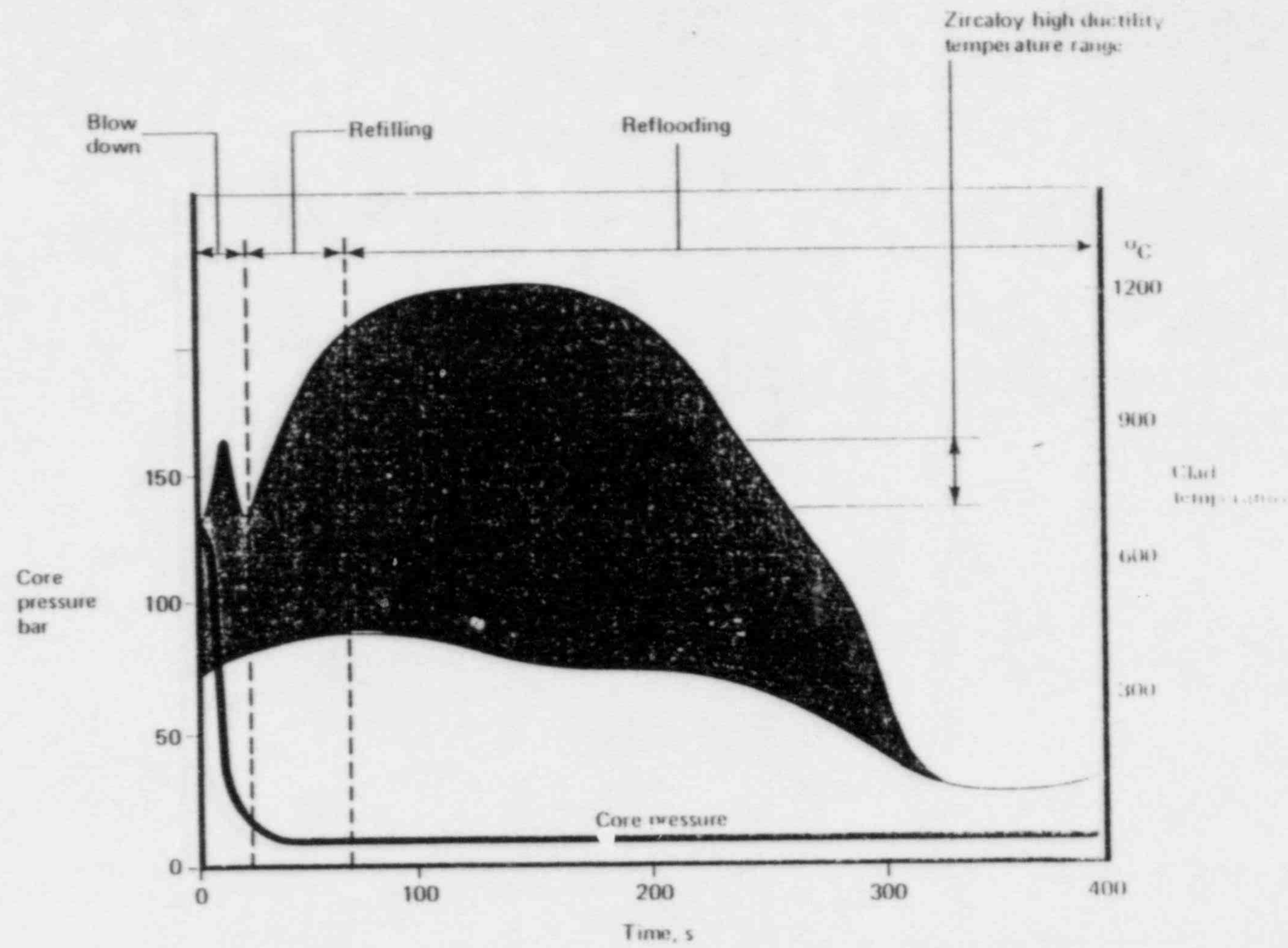

FIG. 2 Typical core pressure and rod temperature range during a LOCA in a PWR

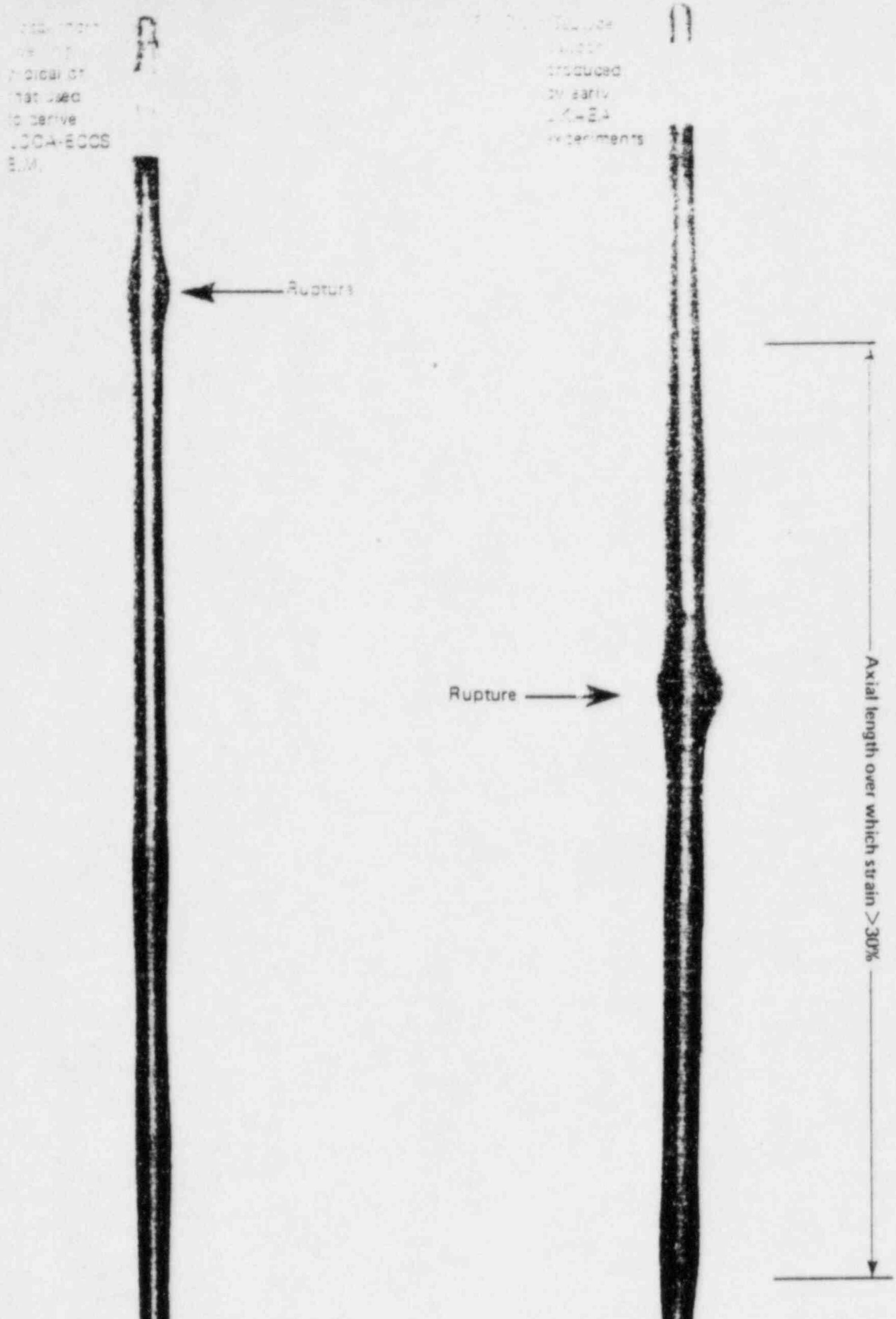

FIG. 3 Typical results from early UKAEA experiments

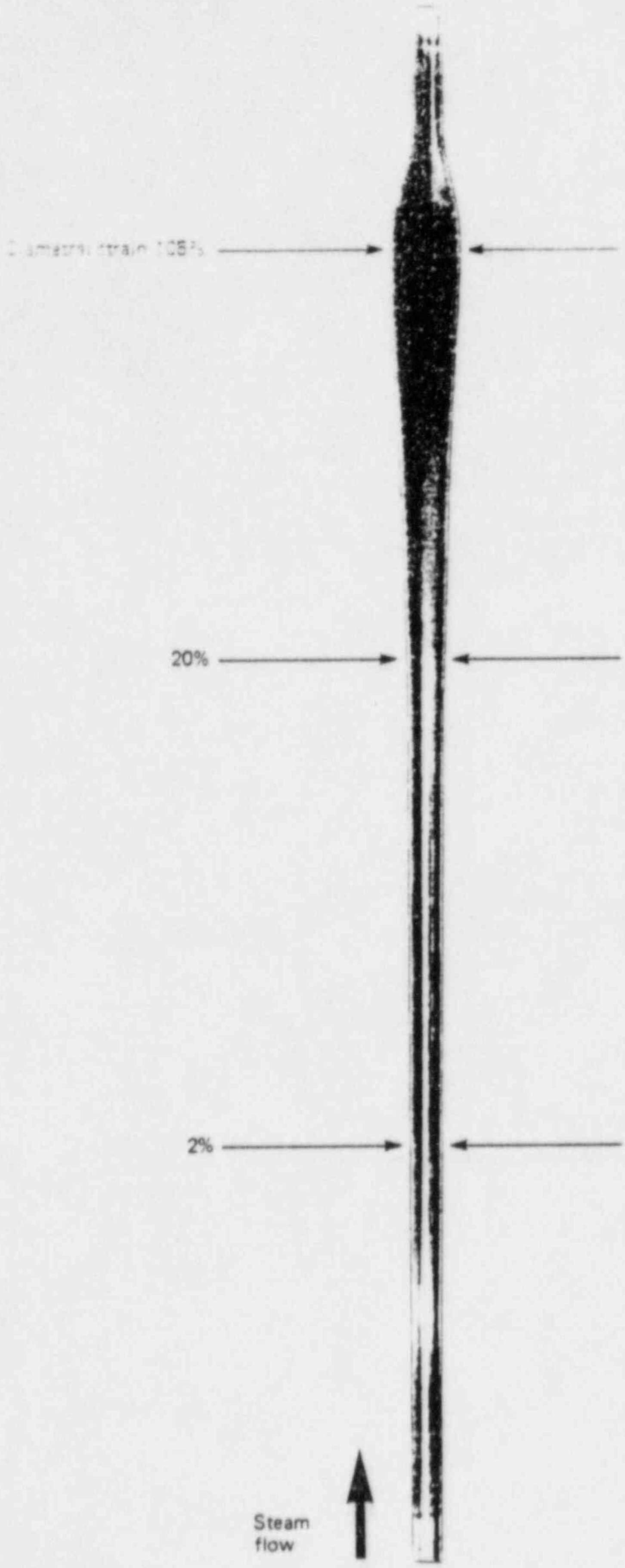

FIG. 4 Effect of steam flow on axial strain profile

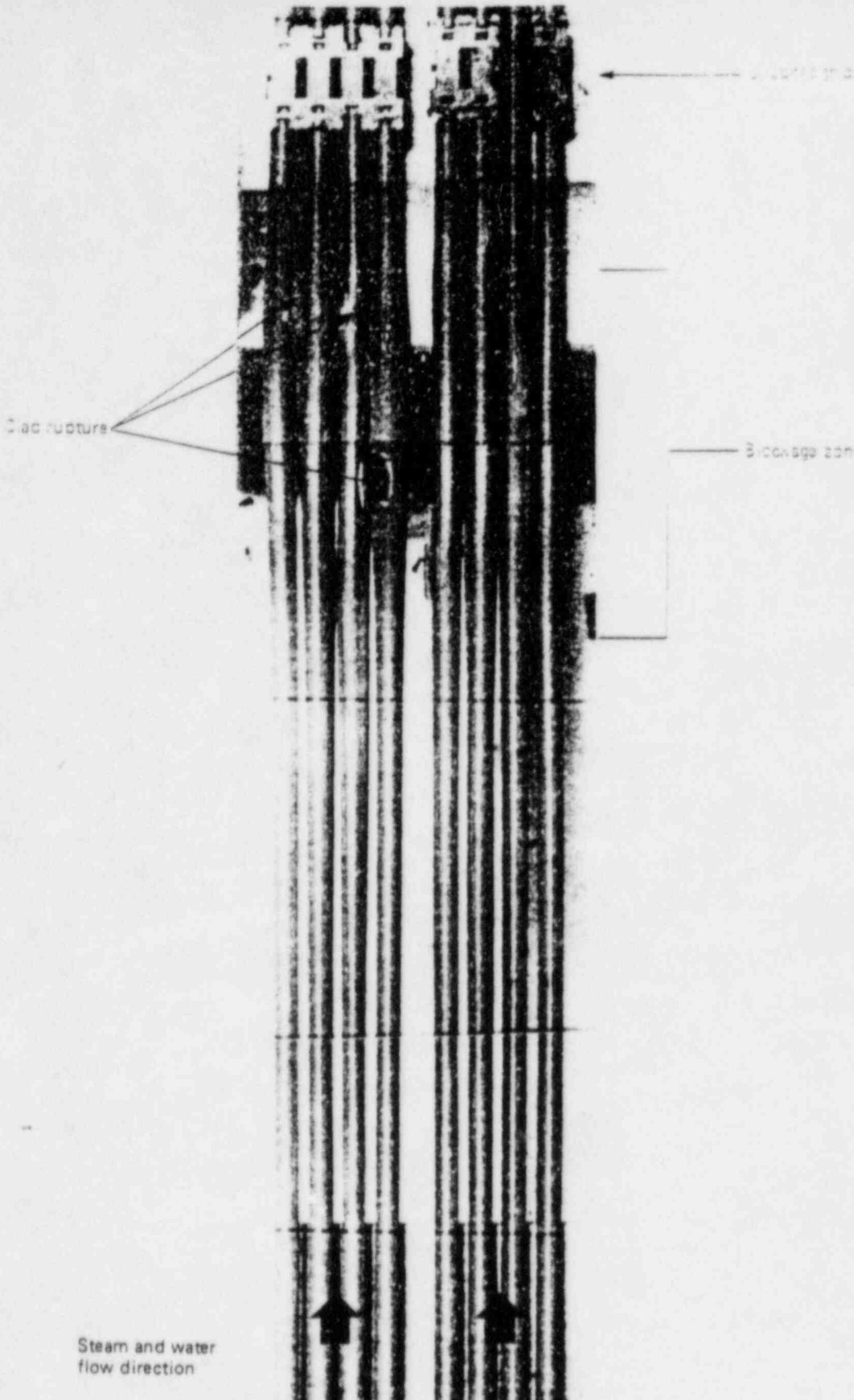

FIG. 5 View of the inter grid span with greatest deformation in the UK sponsored MT3 experiment