PWR CLAD BALLOONING

The effect of circumferential clad temperature variations on the burst strain/burst temperature relationship

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SUMMARY

By experiment, it has been shown by other workers that there is a reduction in the creep ductility of Zircaloy 4 in the $\alpha + \beta$ phase transition region. Results from single rod burst tests also show a reduction in burst strain in the $\alpha + \beta$ phase region. In this report it is shown theoretically that for single rod burst tests in the presence of circumferential temperature gradients, the temperature dependence of the mean burst strain is not determined by temperature variations in creep ductility, but is governed by the temperature sensitivity of the creep strain rate, which is shown to be a maximum in the $\alpha + \beta$ phase transition region.

To demonstrate this effect, the mean clad strain at burst was calculated for creep straining at different temperature levels in the α, $\alpha + \beta$ and β phase regions. Cross-pin temperature gradients were applied which produced strain variations around the clad which were greatest in the $\alpha + \beta$ phase region. The mean strain at burst was determined using a maximum local burst strain (i.e. a creep ductility) which is independent of temperature. By assuming cross-pin temperature gradients which are typical of those observed during burst tests, then the calculated mean burst strain/burst temperature relationship gave good agreement with experiment.

The calculations also show that when circumferential temperature differences are present, the calculated mean strain at burst is not sensitive to variations in the magnitude of the assumed creep ductility. This reduces the importance of the assumed burst criterion in the calculations. Hence a temperature independent creep ductility (e.g. 100% local strain) is adequate as a burst criterion for calculations under PWR LOCA conditions.

1. INTRODUCTION

Experimental investigations into PWR clad ballooning have, in general, commenced with a single-rod testing programme before progressing to multirod assembly tests. Numerous single rod burst test (SRBT) programmes have been undertaken to determine the fundamental parameters which control the ballooning behaviour of PWR fuel rods. Results of such tests have shown that when the mean strain at burst is plotted against burst temperature, there is a pronounced dip in the burst strain in the $\alpha + \beta$ phase region. This kind of behaviour is shown in Fig. 1. for ORNL SRBT data reported by Chapman (1). Curves A and B in Fig. 1 denote the upper and lower scatter bounds, respectively, of the correlation of mean strain at burst with burst temperature.

The most common explanation of this behaviour in the $\alpha + \beta$ phase region is that the presence of the β phase in the α matrix reduces the creep ductility of the material. For example, Rosinger et al. (2) have developed a burst criterion which has been used to show a correlation between burst strain and burst temperature under conditions of uniform straining. This has a dip in the burst strain in the $\alpha + \beta$ phase region which implies a reduction in creep ductility.

Rosinger et al. (2) have considered uniform straining with no circumferential variations in clad temperature. But measurements by Chapman et al. (3) have shown that considerable circumferential clad temperature differences occur during ORNL SRBT which are typically in the range 40-80°C. The presence of temperature differences results in strain variations around the clad. Therefore a mean strain at burst may be calculated from a knowledge of the strain variations. The strain variations are determined by the cross-pin temperature difference and the strain rate temperature sensitivity. Thus the mean strain at burst will be governed by the temperature difference and the temperature sensitivity of the strain rate and will not necessarily be controlled by the creep ductility. It is shown that for a given temperature difference across the clad, the strain variations are greater in the $\alpha + \beta$ phase region and this leads to a reduction in the mean strain at burst.

Using the NNC code MAXWEL (4), calculations were made which assume circumferential temperature differences which are typical of those observed during ORNL SRBT (3) and also assume a creep ductility, i.e. a local failure strain, which is independent of temperature. The predictions of the variation of mean strain at burst with burst temperature were compared with results from ORNL SRBT (1). The ORNL SRBT were chosen for comparion because the scatter bounds of the test results could be attributed to variations in the cross-pin temperature gradients which were measured and reported (3). To investigate the importance of the assumed burst criterion, the calculations were repeated using a temperature dependent local burst stress failure criterion which effectively produces local failure strains which vary with temperature with a dip in the $\alpha+\beta$ phase region.

2. SCOPE OF ANALYSIS

The NNC code MAXWEL (4) is able to calculate the circumferential clad strain distribution due to creep when there is a cosinusoidal temperature variation around the clad and a pressure difference, P_B, which remains constant during straining. The clad circumference is divided into a number of discrete segments for which the temperature and strain of each segment is calculated. The clad temperature distribution is specified by the cross-pin temperature difference, ΔT, and the maximum temperature at the hotspot, i.e. the burst temperature T_B, at the rupture segment. The input values of ΔT, T_B, and P_B which were assumed in each calculation are shown in Table I.

For a particular burst temperature, a pressure difference was chosen using a P_B against T_B relationship derived by Rosinger et al.(2) for a heating rate of 25 °K/sec. This relationship, shown in Fig. 2, was used so that the calculations could be compared with ORNL SRBT results (1) which were made with comparable heating rates of 28-30 °K/sec.

Values of ΔT (40°C and 80°C) were chosen to be consistent with the range of circumferential temperature differences (40-80°C) observed during ORNL SRBT (3).

The assumed temperature dependence of the strain rate of Zircaloy 4 clad is derived in Appendix I and shown in Fig. 3. Fig. 3 shows that for a given value of ΔT, the difference in strain rate (and hence strain) across the clad is greatest in the $\alpha + \beta$ phase region where the gradient of the strain rate with temperature curve is highest.

In order to determine the mean strain at burst, a local burst criterion is specified at the rupture segment. Two different burst criteria were assumed. Firstly, a constant value for the maximum local strain at burst, ϵ_{MAX} = 100%, was used to represent a temperature independent creep ductility. Secondly, a temperature dependent creep ductility was simulated using a temperature dependent local burst stress. This is described in Appendix II. The simulated temperature dependence of the creep ductility is shown by the calculated values of the maximum local strain at burst (ϵ_{MAX}). These values, if specified as local burst strains would have produced the same mean strains at burst (ϵ_{MEAN}).

3. RESULTS - COMPARISON OF THEORY WITH EXPERIMENT

The results of the calculations were compared with ORNL SRBT data reported by Chapman (1).

Fig. 4 compares the results of calculations for ΔT = 40°C with the upper bound curve for the experimental data shown in Fig. 1. For the calculations using the local burst stress criterion, the corresponding maximum local burst strain, which would have produced the same mean strain at burst, is shown in Fig. 5.

Fig. 6 compares the results of calculations for ΔT = 80°C with the lower bound curve for the experimental data. Fig. 7 shows the variation with burst temperature of the maximum local strain at burst for the calculations assuming a local burst stress criterion.

Fig. 4 and 6 both show that the theory is in generally good agreement with experiment. Both theory and experiment show a gradual increase in mean burst strain with burst temperature in the α phase region, with a reduction in the $\alpha + \beta$ phase region, then rising steeply to a maximum in the β phase region. A comparison of the results in Figs. 4 and 6 show that larger ΔT's result in smaller values of the mean strain at burst.

The curves in Figs. 4 and 6 show a slight displacement between theory and experiment. This may be due to the fact that the calculations were performed assuming a fixed clad temperature distribution.

In the experiments, the specimen temperatures were ramped and although most of the strain occurs as the burst temperature is approached, the effective straining temperature would be somewhat less than the measured burst temperature. If the effects of temperature ramping were taken into account in the creep strain calculations, the calculated mean strains at burst would occur at slightly higher burst temperatures. This would produce better agreement with experiment.

4. DISCUSSION

It has been shown that the temperature dependence of the mean burst strain derived from SRBT can be predicted from a knowledge of the circumferential temperature variation and the temperature dependence of the strain rate without invoking a dependence of creep ductility on the temperature. This can be explained by considering the effects of circumferential temperature variations which lead to localised straining at the hotspot. An increase in strain localisation leads to a reduction in the mean strain at burst. The degree of strain localisation is controlled by the circumferential temperature difference which leads to strain differences due to the temperature sensitivity of the strain rate. Fig. 3 shows that the temperature sensitivity of the strain rate has three distinct levels in the α, $\alpha + \beta$, and β phase regions. It is greatest in the $\alpha + \beta$ phase region where the lowest mean burst strains occur, and least in the β phase region where the mean burst strains are at a maximum.

Comparison of the results of calculations assuming a creep ductility (i.e. a local burst strain) which is independent or dependent on temperature, show close agreement. This emphasizes that when circumferential temperature gradients are present the mean strain at burst is not sensitive to the dependence of creep ductility on temperature even though there may be a reduction in the creep ductility in the $\alpha + \beta$ phase region as shown in Fig. 5 and 7. It might even be argued that an apparent dependence of creep ductility on temperature in "isothermal" creep tests could be explained by the presence of temperature variations resulting in strain variations in the specimen.

Variations in strain due to temperature differences also make the calculated mean strain at burst somewhat insensitive to the magnitude of the assumed local burst strain. This reduces the importance of the assumed local burst criterion in the calculations.

Hence in the presence of circumferential temperature variations, a temperature independent maximum local strain burst criterion is adequate for the calculation of mean strains at burst under PWR LOCA conditions.

5. CONCLUSIONS

(1) There is good agreement between theoretical predictions of burst strain and reported single rod burst test results. This has shown that the mean burst strain/burst temperature relationship is dependent on the magnitude of the circumferential temperature difference and the temperature sensitivity of the creep strain rate rather than on the variation of creep ductility (i.e. local strain at burst) with temperature. Because the temperature sensitivity of the creep rate in the $\alpha + \beta$ phase region can be shown to be greater than in the α or β phase, there is a reduction in the mean strain at burst in the $\alpha + \beta$ phase region.

(2) When circumferential temperature differences are present, the calculated mean strain at burst is not sensitive to variations in the magnitude of the assumed creep ductility at burst. This reduces the importance of the assumed local burst criterion in the calculations. Hence a maximum local burst strain (e.g. 100% local strain) is an adequate burst criterion for the calculation of mean burst strains under PWR LOCA conditions.

6. REFERENCES

1. R.H. Chapman. "Multirod Burst Test Program Quarterly Progress Report, "July-December 1979". NUREG/CR-1450, ORNL/NUREG/TM-392.

2. H.E. Rosinger, R.J. Neitzel & F.J. Erbacher "The Development of a Burst Criterion for Zircaloy Fuel Cladding under LOCA conditions". Res Mechanica Vol II (1981) 91-107.

3. R.H. Chapman, J.L. Crowley, A.W. Longest & E.G. Sewell. "Effect of Creep Time and Heating Rate on Deformation of Zircaloy-4 Tubes Tested in Steam with Internal Heaters." NUREG/CR-0343, ORNL/NUREG/TM-245, Oct. 1978.

4. P. Barlow "Clad Ballooning During a PWR LOCA - A Study of the Differences in Local Clad Strain due to Contact Effects." NNC(W) PWR/R395, December 1981.

5. H.E. Rosinger, P.C. Bera, & W.R. Clendening. "Steady State Creep of Zircaloy-4 Cladding from 940-1873 °K". Journal of Nuclear Materials 82 (1979) 286-297.

6. B. Brzoska, G. Cheliotis, A. Kunick, & G. Senski. "A New High Temperature Deformation Model for Zircaloy Clad Ballooning under Hypothetical LOCA Conditions" Trans. 4th Int. Conf. Structural Mechanics in Reactor Technology, C 1/8, San Francisco, USA, 1977.

APPENDIX I

The uniaxial creep strain rate, $\dot{\varepsilon}$, is given by the Norton equation:-

$$\dot{\varepsilon} = A\,\sigma^n \exp(-Q/RT) \qquad (1)$$

where A is the structure parameter, σ is the uniaxial stress, n is the stress index, Q is the activation energy, R is the absolute gas constant, and T is the absolute temperature. This expression must be modified in order to derive the hoop strain rate, $\dot{\varepsilon}_\theta$, of a pressurised tube. This is given by the following expression (Ref. 2).

$$\dot{\varepsilon}_\theta = \frac{A(H+(F+G)/4)^{(n-1)/2}}{(F+G)^{(n+1)/2}}\,(H+F/2)\;\sigma_\theta^n\;\exp(-Q/RT) \qquad (2)$$

where F,G and H are the anisotropy coefficients and σ_θ is the hoop stress. The values of A, n, Q/R, F, G, H which are assumed for the α and β phases of Zircaloy 4 are:-

PHASE	T °K	(Ref 5) A $MPa^{-n}sec^{-1}$	Q/R °K	n	(Ref 2) F	G	H
α	$T \leq 1100$	2000	34200	5.32	0.934	0.374	0.192
β	$T \geq 1250$	8.1	17100	3.79	0.5	0.5	0.5

If an Arrhenius plot of the hoop strain rate against temperature is made for a typical hoop stress as in Fig. 3, the curves in the α and β phase regions are straight lines with slope - Q/R which are well defined by experiment. The behaviour in the $\alpha + \beta$ phase region is less well known. However the strain rate must increase between 1100 °K and 1250 °K and the straight line interpolation may be taken as the simplest representation. Even so it can be seen that however the interpolation is made, the average slope of curve in $\alpha + \beta$ phase region must be greater than in the α or β phase region. For high values of stress (greater than 750 MPa), the slope in the $\alpha + \beta$ phase is less than in the α phase. But typical values of stress observed in SRBT are much less than 750 MPa. Hence it may be concluded that under PWR LOCA conditions, the strain rate temperature sensitivity is greatest in the $\alpha + \beta$ phase region and least in the β phase.

APPENDIX II

A temperature dependent creep ductility was simulated in the calculations using a temperature dependent local burst stress failure criterion. This criterion has been used in the case of uniform straining by Rosinger et al.(2) The application of the methods used by Rosinger et al. to the present work is described as follows:-

Rosinger et al. (2) have considered the case of uniform deformation of a thin walled tube of initial radius, R_o, and initial thickness, t_o, under constant differential pressure, P, and temperature, T. The hoop stress, σ, is related to the hoop strain, ϵ, according to the equation

$$\sigma = (PR_o/t_o)(1+\epsilon)^2 \qquad (3)$$

The burst stress is related to the uniform burst strain, ϵ_B, by equation (3) which becomes

$$\sigma_B = (P_B R_o/t_o)(1+\epsilon_B)^2 \qquad (4)$$

σ_B can be determined using an empirical relationship between burst stress and burst temperature, T_B, developed by Brzoska et al. (6). The burst strain can then be calculated from equation (4) provided the burst pressure, P_B, at the burst temperature is known. Rosinger et al. have used an infinite strain rate criterion to determine the burst time which fixes the values of P_B and T_B for different pressure and temperature histories. Using a value of P_B obtained in this way, equation (4) gives a mean burst strain which varies with the pressure history and heating rate. The P_B/T_B correlation for a heating rate of 25 °K/sec. is shown in Fig. 2 which was taken from Ref. 2 (Fig. 5). This correlation was used in the present work to enable the theoretical predictions to be compared with the results of ORNL SRBT reported in Reference 1, which were made with comparable heating rates in the range 28-30 °K/sec.

Rosinger et al. (2) have suggested that the uniform burst stress criterion described above can be adapted for use as a local burst stress criterion in the case of non-uniform straining. This can be achieved by assuming that in an asymmetrically straining tube, rupture occurs at the same local stress as in a uniformly straining tube under the same pressure having the same temperature as the rupture segment. If the hoop strain of the rupture segment at burst is ϵ_{MAX} and the mean strain is ϵ_{MEAN} then the burst stress at the rupture site is given by the equation

$$\sigma_B = (P_B R_o/t_o)(1+\epsilon_{MAX})(1+\epsilon_{MEAN}) \qquad (5)$$

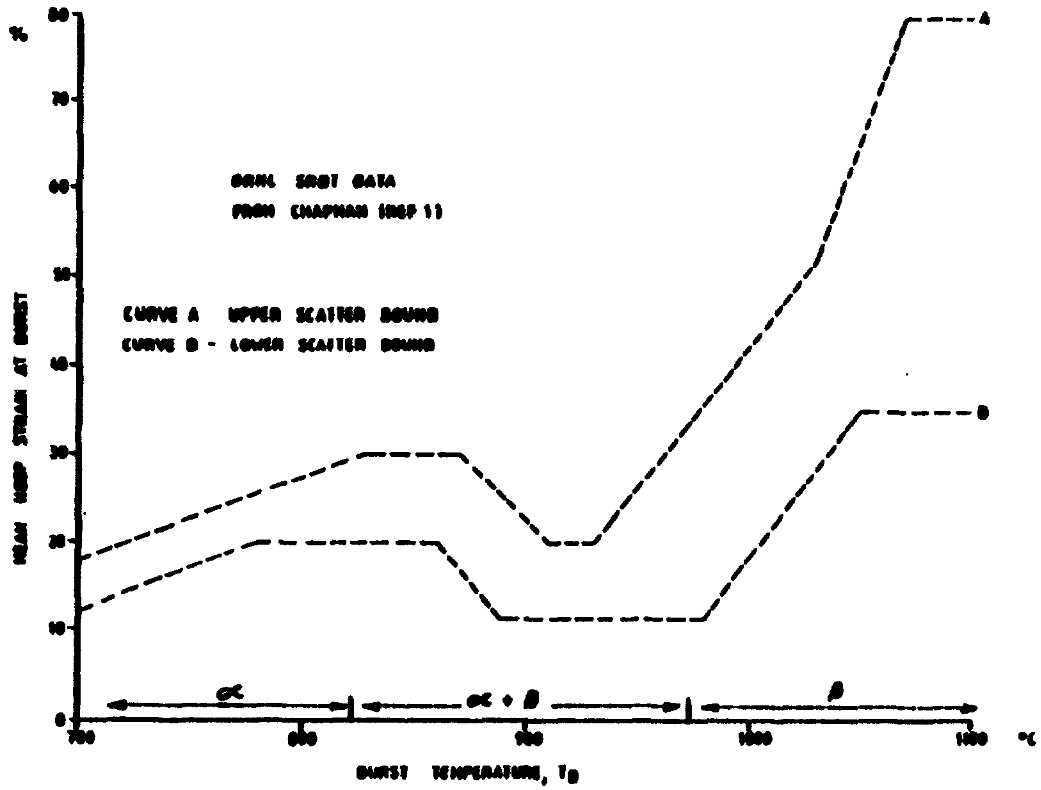
In the MAXWEL calculations, the σ_B/T_B correlation by Brzoska et al. (6) and the P_B/T_B correlation calculated by Rosinger et al. (2) were used with equation (5) to determine the values of ϵ_{MAX} and ϵ_{MEAN} at burst.

TABLE I

INPUT VARIABLES FOR MAXWEL CALCULATIONS

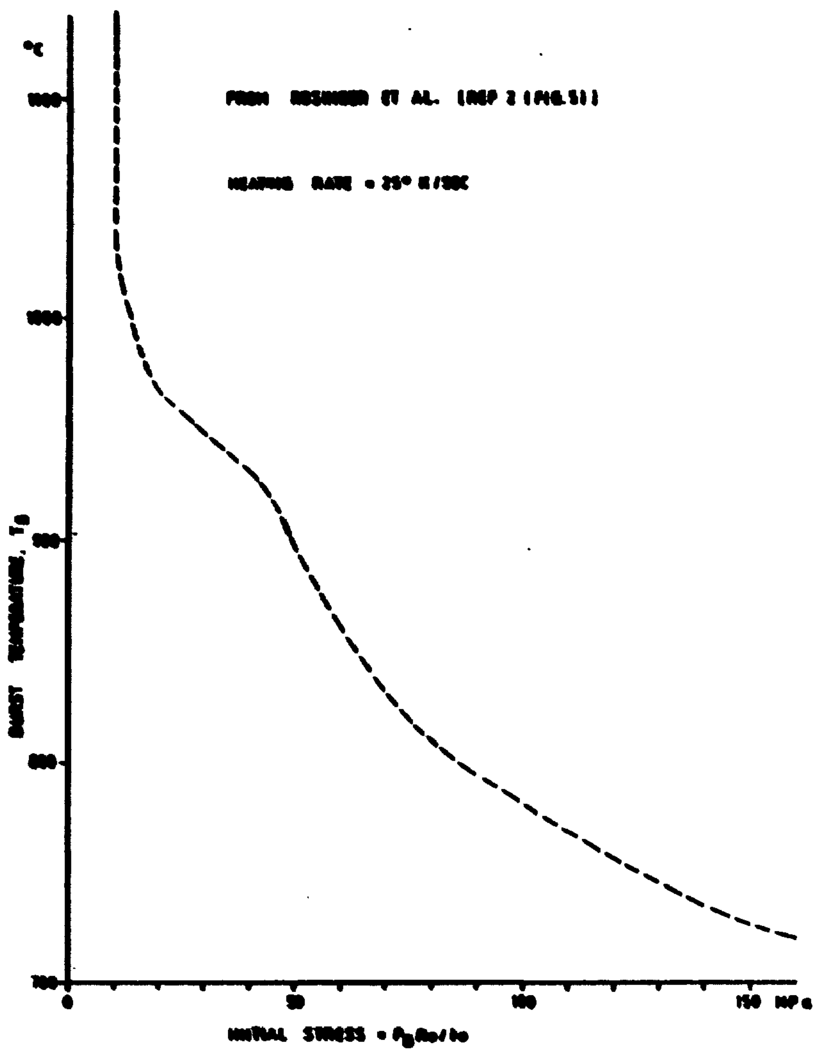
CASE NUMBER	ΔT °C	T_B °C	Initial Hoop Stress - MPa $\sigma = P_B R_o / t_o$
1	40	720	160
2	40	820	75
3	40	845	70
4	40	872	60
5	40	919	45
6	40	966	20
7	40	993	15
8	40	1019	12
9	40	1120	10
10	80	740	135
11	80	820	75
12	80	840	70
13	80	892	50
14	80	939	35
15	80	986	15
16	80	1013	12
17	80	1039	10
18	80	1060	10
19	80	1140	10

Note : For a given value of T_B, the value of P_B was derived from Fig. 2.



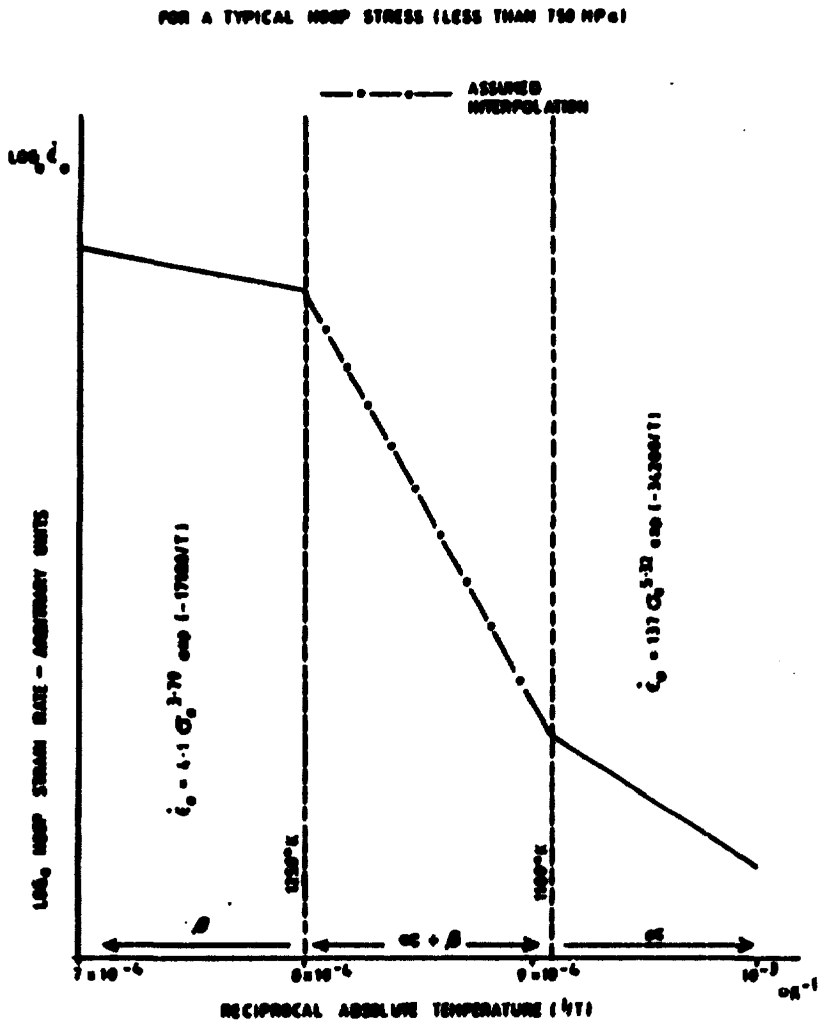
ORNL SRBT DATA - FROM CHAPMAN (REF1)
CORRELATION OF MEAN BURST STRAIN WITH BURST TEMPERATURE.

FIG. No. 1



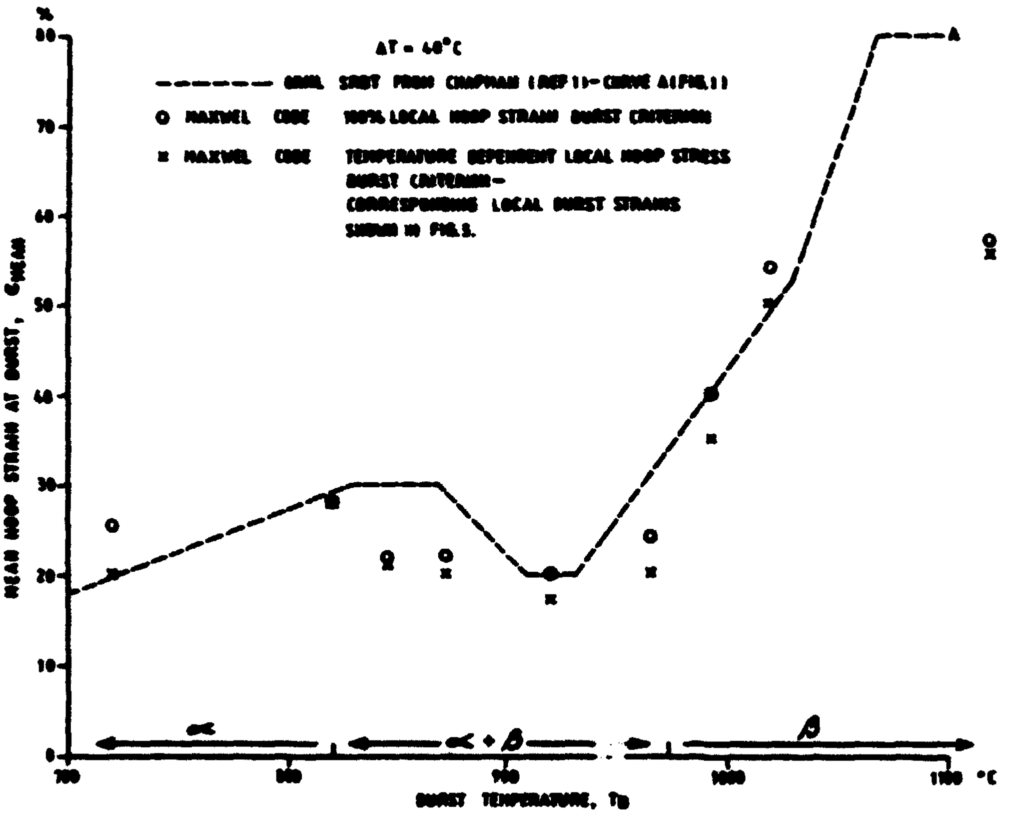
PREDICTION OF BURST TEMPERATURE Vs INITIAL STRESS
-FROM ROSINGER ET AL.(REF 2(FIG.5))

FIG. No. 2



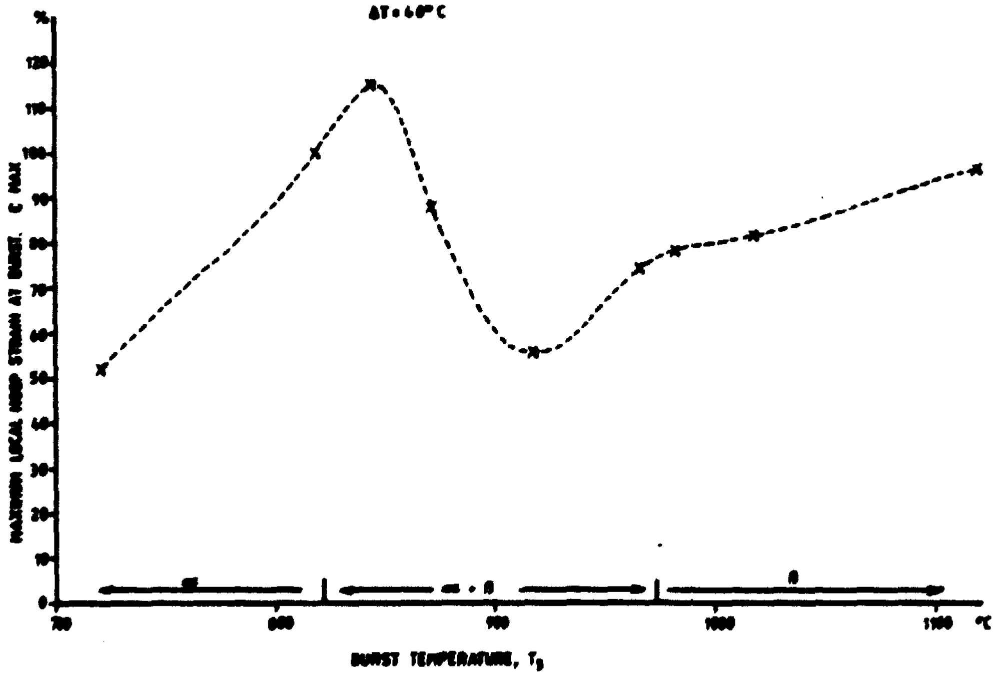
TEMPERATURE DEPENDENCE OF ZIRCALOY 4 CREEP PROPERTIES

FIG. No. 3



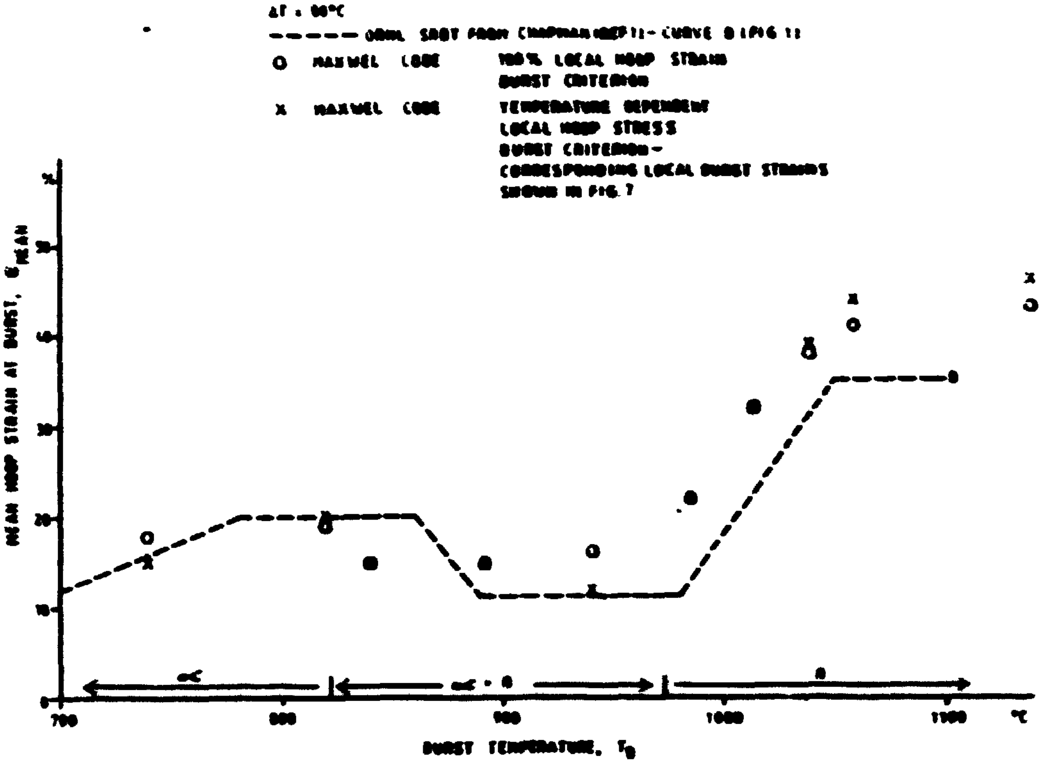
VARIATION OF MEAN STRAIN AT BURST WITH BURST TEMPERATURE
ΔT = 40° C.

FIG. No. 4.



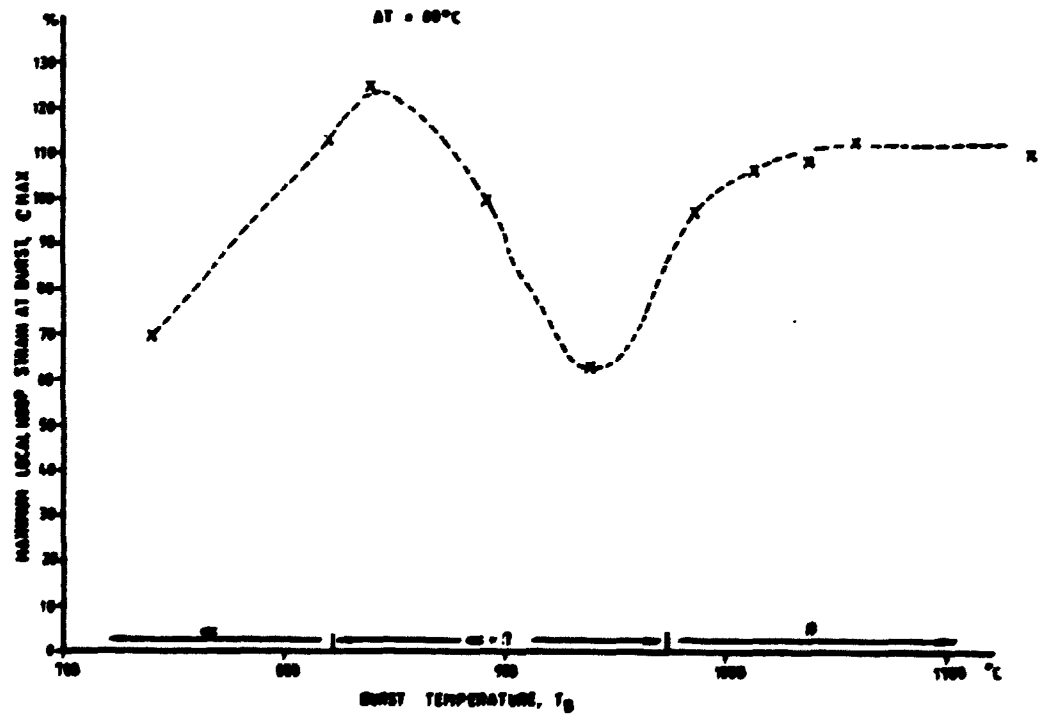
TEMPERATURE DEPENDENCE OF THE MAXIMUM LOCAL STRAIN AT BURST
ΔT=40°C-TEMPERATURE DEPENDENT LOCAL HOOP STRESS
BURST CRITERION

FIG. No.5



VARIATION OF MEAN STRAIN AT BURST WITH BURST TEMPERATURE
ΔT = 80°C

FIG. No. 6



TEMPERATURE DEPENDENCE OF THE MAXIMUM LOCAL STRAIN AT BURST
ΔT = 80°C - TEMPERATURE DEPENDENT LOCAL HOOP STRESS
BURST CRITERION

FIG. No. 7