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ATOMIC ENERGY
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L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

VERIFICATION OF A MECHANISTIC MODEL FOR THE STRAIN RATE OF ZIRCALOY-4 FUEL SHEATHS DURING TRANSIENT HEATING

Vérification d'un modèle mécanistique pour déterminer le taux d'effort des gaines pour le combustible Zircaloy-4 au cours d'un chauffage transitoire

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Résumé

Un modèle mécanistique de taux d'effort pour Zircaloy-4, appelé NIRVANA, a été mis à l'essai relativement à des expériences où des gaines de combustible sous pression ont subi des contraintes au cours de complexes situations de température, d'effort et de temps. Les mêmes situations ont ensuite été examinées pour déterminer l'accroissement possible des contraintes calculées par suite des variations dans les dimensions, dans le contenu chimique et dans les propriétés mécaniques que permettent les spécifications relatives aux gaines de combustible. On a constaté que ces variations pourraient probablement modifier plus ou moins les contraintes prévues par un facteur de deux par rapport à la valeur moyenne. Les résultats expérimentaux se sont situés exactement dans cette marge.

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ABSTRACT

A mechanistic strain rate model for Zircaloy-4, named NIRVANA, was tested against experiments where pressurized fuel sheaths were strained during complex temperature-stress-time histories. The same histories were then examined to determine the spread in calculated strain which may be expected because of variations in dimensions, chemical content and mechanical properties which are allowed in the fuel sheath specifications. It was found that the variations allowed by the specifications could result in a probable spread in the predicted strain of plus or minus a factor of two from the mean value. The experimental results were well within this range.

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INTRODUCTION

In order to determine the effect of a postulated reactor transient, one must have a method for modelling fuel behaviour. One part of any such model must be a description of the thermal-mechanical behaviour of the Zircaloy fuel sheath. The computer sub-routine NIRVANA (1) performs this function for CANDU* reactor analyses. This sub-routine models the strain rate of Zircaloy as functions of stress and temperature and integrates these functions over time. Several deformation mechanisms which operate in each of the phase fields (α, $\alpha+\beta$, β) of Zircaloy, and the micro-structural changes (recrystallization, work hardening, phase transformation) which occur, are described. These equations were developed from a variety of tests, both transient and steady state, which were designed to provide specific data (2-9). Subsequently, transient tests, both in temperature and stress, have been used to verify the resulting model.

This paper compares the strain measured on a fuel sheath after a temperature and pressure transient with that calculated by the model for the same transient. It then examines the magnitude of the difference between measured and calculated strain that one might expect either due to an inadequate knowledge of the transient history or due to material variables resulting from the fuel sheath manufacturing processes.

THE MODEL (NIRVANA)

The model (1,10,11) describes the behaviour of unoxidized Zircaloy-4 (i.e. tests in vacuum or inert gas). The creep processes considered include thermal dislocation creep, athermal dislocation glide, diffusional creep (grain or phase boundary sliding) and phase transformation strain. The total creep rate is obtained by adding these separate components. Work hardening, recovery, recrystallization, grain growth and the α to β phase transformation are modelled dynamically. The driving force for deformation is the effective stress (stresses caused by all loads minus the back stresses caused by the instantaneous dislocation network). Since Zircaloy is anisotropic, the effective stress is calculated from the applied stresses using the formulation of Hill (12). The measurement of the appropriate anisotropic factors has been documented previously (4).

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* CANDU - Canada Deuterium Uranium

EXPERIMENTAL PROCEDURE

The tests were performed by the Canadian General Electric Company and the results were sent to the Chalk River Nuclear Laboratories (CRNL) of Atomic Energy of Canada Limited for analysis. Test specimens had nominal dimensions of 240 mm long, 15.24 mm diameter and 0.42 mm wall thickness. They were heated by an internal electrical heater and pressurized with helium. Segel and Hunt (13) have reported the difficulties encountered in analyzing earlier verification tests done in 1974. Small errors in the recording of the temperature or pressure history can result in a large variation in the predicted strain. As a result, in the latest series of tests, done in 1978, the thermocouple and differential pressure readings were monitored by a mini-computer capable of recording 30 data points per second. Up to 4000 points were stored before being dumped onto magnetic tape. Dumps required about 7 seconds and were therefore arranged to take place during periods of predictable behaviour such as thermal dwells or cooling. Measurement accuracy on the temperatures, obtained using 36 AWG chromel-alumel thermocouples, was calculated to be ±7°C at 1200°C (0.6%) and on the differential pressures ±0.022 MPa (roughly 5 to 10% of the values used).

A total of 23 specimens were tested. Temperatures were recorded at three axial planes 50 mm apart. Four general thermal cycles were used:

1. Ramp to about 1000°C, then cool.
2. Ramp to 1000°C. Cool to 500°C. Ramp to 800°C. Hold. Cool.
3. Ramp to 700°C. Hold. Ramp to 1000°C. Hold. Cool.
4. Ramp to 1000°C. Hold. Cool.

Post-test strains were measured at each of the three thermocouple planes. Because of axial temperature gradients in the specimens, we obtained three different thermal histories and three different strains from each specimen. The history data was processed onto punched paper tapes which were sent to CRNL for analysis.

RESULTS

Out of the 23 tubes tested, 4 ruptured and 2 ballooned without rupturing. Because of the non-uniform strain in the balloon, there is a triaxial stress resulting from the local curvature. Since the model assumes all pressurized tubes have a 2:1 hoop:axial stress ratio, modified by the materials anisotropy, stress introduced by the curvature resulting from the formation of a balloon is not calculated. Analysis of previous results (2,6,7) showed that variations in strain along the length of a pressurized Zircaloy-4 fuel sheath become large after about 10% average strain. Therefore, 10% has been arbitrarily selected as the maximum strain to which the model should be applied. Beyond 10% strain we assume that ballooning, and hence non-uniform strain, has started and the model should no longer accurately predict the experimental strain. On this basis, predicted strains greater than 10% are considered to indicate a high probability of rupture. Table 1 shows that large strains, and therefore probable failure by this criterion, are predicted for each of the 6 specimens which showed significant ballooning or rupture. Calculated values marked "rupture" on the table signify that the model stopped calculation, with unrealistically large strains, before the temperature/time history was completed.

Analysis of the results for the remaining 17 tests is given on Table 2. The second column of this table shows a schematic of the temperature cycle. Some of these were quite complex. However, in most cases there were two temperature peaks. The third column lists the peak temperatures at the three measurement planes listed in the fourth column. The fifth column lists the measured diametral strain, converted to true strain ($\varepsilon = \ln(1+e)$), for the designated plane of measurement and the sixth column lists the true strain calculated for the history appropriate to that plane, by the model. The seventh column gives the ratio of the predicted strain divided by the measured strain. Assuming that any prediction has an equal probability of being either higher or lower than the measured value, plotting the ratios from column 7 of the table will give a skewed distribution. However, the natural logarithm of the ratios will be symmetrically distributed (i.e. $\ln 1/3 = -\ln 3$). A logarithmic normal distribution of the ratios was therefore assumed for the statistics and the average and standard deviation for the 51 data points were calculated using this assumption. The final two columns of Table 2 show the calculation of the average and standard deviation of the ratios. The average ratio (predicted/measured strain) was 1.46 with a standard deviation of 1.42. The theoretical normal curve defined by these two figures is shown on Figure 1. From this curve, 68% of all calculated strains should fall between 1 and 2 times the measured value. Eighty-four percent of the calculations will be equal to or greater than the measured strain and 16% will be less.

The earlier experiments (13) were re-examined using the current version of the model. The results are included on Table 3. The scatter is greater, (standard deviation = 1.71) as was expected, because of a lack of a record of the fine detail of the histories. The importance of such detail, which was established by the original analysis of this data, was the reason for the computer monitoring of the 1978 experiments.

DISCUSSION

Two questions which will be considered are, how reliable are the calculations based on the current set of experiments, and what scatter should be expected when using the model to calculate behaviour for general reactor transients?

The input data for these experiments were the tube dimensions at the planes of measurement and the temperature and pressure histories. Dimensional measurements are usually considered to be normally distributed about the true value. We shall therefore consider them to be correct, on the average. The history data, temperature and pressure, are recorded electronically and depend on the accuracy of the measuring device plus that of the associated circuitry. The possibility of a systematic bias in the data must be considered. The probable errors were calculated to be $\pm 10\%$ on pressure and $\pm 0.6\%$ on temperature. Since the mean ratio of the predicted/measured strain was 1.46, only positive errors in measurement were investigated. Table 3 shows the results. A 10% reduction in pressure reduced the average ratio to 1.11, but had no effect on the spread. Decreasing the temperature reduced both the average ratio and the standard deviation. However, to reduce the average ratio to 1.0 and to obtain the minimum scatter in the results, requires a temperature reduction of 1.95%, more than three times the probable error in the data. The fact that the average ratio of 1 and the minimum standard deviation occur with about the same fractional reduction in the temperature history is probably fortuitous. The 1974 data also gave a minimum standard deviation with a reduction of 1.9% in temperature, but in this case the average ratio was reduced well below 1.0.

Besides errors in the input data (i.e. history), there are other potential errors inherent in the model. In the general case, these result from the variations necessarily allowed in the manufacturing specifications. These potential errors are the ones of most concern in assessing the effect of postulated transients on real reactor fuel.

The manufacturing specifications define the dimensions, chemical composition, grain size, mechanical properties in specific tests, and allowable flaw size. Thus, a study was made to examine the effects of the extremes in the specifications on strain predictions. The standard cases were taken as the mid-point of each specified range. Calculations were done for a ramp at $25°C \cdot s^{-1}$ to temperature followed by an isothermal hold for 100 s. Differential pressures were picked to give calculated strains in the range of 4-5% at seven temperatures from 600°C to 1200°C in 100°C intervals. In this way the influence of each variable could be examined as a function of temperature. No data is currently available on the effect of flaw size, however, the other variables were all examined.

The effect of dimensional variability was investigated by comparing the strain ratios calculated from the maximum diameter and minimum wall thickness (15.19 mm x 0.45 mm), and the minimum diameter and maximum wall (15.29 mm x 0.37 wall) with the standard values (15.24 mm x 0.41 mm).

The chemical elements most likely to affect the behaviour are oxygen and tin. It was assumed that the model describes the behaviour of material with the median compositions of 1200 ppm oxygen and 1.45 wt% tin. The factors which could change are the individual strain rate equations and the location of the two-phase $(\alpha+\beta)$ field. Burton et al. (14) suggest the α-phase strain rate may be expressed by

$$\dot{\varepsilon} = \dot{\varepsilon}_o \exp(-3.42C) \qquad (1)$$

where $\dot{\varepsilon}_o$ is the strain rate with zero oxygen and C is the oxygen content in wt%. They also found that in the β-phase, oxygen has little effect until the solubility limit is reached. The α-phase strain rate equation in the model was multiplied by factors obtained from equation 1 for compositions of 900 and 1500 ppm oxygen. The temperatures used in the model for the phase boundaries $(\alpha/\alpha+\beta/\beta)$ were modified by the amount composition changes of ±300 ppm oxygen make to these boundaries on the equilibrium Zr-O phase diagram.

The effect of tin on the α-phase strain rate equations was calculated from Luton's data (5) in the manner described in Appendix I. No data could be found on the effect of tin content on β-phase creep. The effect was therefore assumed to be zero. The movement of the two-phase field was obtained, as for oxygen, from the equilibrium phase diagram for the compositions of 1.20 and 1.70 wt% tin. For each of the above composition changes, both in oxygen and tin, the ratio of predicted strain to the standard case strain was calculated. The same procedure was used to examine the effects of the other variables.

The effect of grain size was treated more arbitrarily. The specifications only require that the average grain size be no greater than 10 μm, with no individual grains greater than 25 μm. For the purposes of this analysis, it was assumed that the grain size could be increased and decreased by a factor of about 2 from the "nominal standard case" and still meet the specification.

The specified mechanical properties are in terms of mechanical strength and ductility. These are achieved by the fabrication process. Two aspects were considered, the initial dislocation density (work hardening and recrystallization resulting from the final fabrication processes) and the mechanical anisotropy. Other work (9) has shown that the tube currently being used in our experimental program is about 50% recrystallized. Since recrystallization occurs rapidly at 700°C, the as-fabricated dislocation density only has an effect in the case of the ramp to 600°C. For this temperature, a change of ±10% in the initial back stress changed the ratio of predicted/standard strain by about 10%. Anisotropy of the mechanical properties, on the other hand, has an influence throughout the α-phase range, i.e. up to about 900°C. The method used to measure the anisotropic factors has been described elsewhere (4). Considerable spread has been found in the measured values of the three tensile anisotropic factors required by Hill's model (13). Whether this spread reflects a true variation between different tube batches or is the result of the measuring technique is currently being investigated. From the data currently available, the average and standard deviation of each of Hill's factors F, G and H were calculated for both as-received and fully recrystallized tube. The effect on the standard cases of ±1 standard deviation from the mean values was calculated.

The effects of each of the above variations are listed in Table 4 and shown graphically on Figure 2. The tolerance on dimensions has the greatest effect throughout the whole range. The mechanical properties (primarily anisotropy) and the tin content have a large effect in the α-phase temperature region but above 900°C they are negligible. Oxygen has little effect over the whole temperature range. Grain size has a very large effect in the two-phase region because of its effect on the grain boundary sliding component. This component, in very fine grain material, was also responsible for the large effect at 600°C. Over the rest of the temperature field the effect of grain size on the overall strain was small.

If one assumes that each of the effects discussed above follow a normal distribution about the mean value, one can calculate the probable distribution of the combined effects. This was done by taking the square root of the sum of the squares of the individual contributions. The resulting probable limits are shown on Figure 2 by the heavy lines. Thus, for any arbitrary thermal cycle, one may expect the calculated strain to lie between slightly less than ½ and slightly more than 2 times the real value that would have been measured, solely because of the tube variability allowed by the specifications.

The fuel sheaths used in the two sets of verification tests, those done in 1974 and in 1978, were each time taken from a single batch. Thus manufacturing variables such as composition and mechanical properties should be similar for all tubes within each test group. These may contribute a systematic bias to the mean value but should not affect the standard deviation. Dimensions do vary between tubes within the same batch, however, and errors in their measurement could contribute to the spread in the data.

Within each of the two groups of tests, each of the following factors could produce a systematic bias:

1. Chemical composition
2. Mechanical properties
3. Dimensions
4. Temperature measurement
5. Systematic error in the original data to which the model is fitted (particularly with reference to temperature control)

Factors number three and four could also produce random scatter. The systematic difference in mean value between the two groups could be the result of any of the above.

Measurement of tube dimensions prior to mechanical testing involves well proven techniques. The probability, and magnitude, of systematic errors should be small. The effect of such errors on the standard deviations for these tests was not calculated, therefore, but must remain as a possibility. Temperature was examined. For both sets of data, 1974 and 1978, a systematic decrease in the temperature history of 1.9% gave the best fit as shown by a minimum in the standard deviation of the results. This could be a consequence of either of factors 4 or 5 above. The mean ratio for the 1978 data was reduced from 1.46 to 1.03 and for the 1974 data from 1.10 to 0.70. These results are well within the probable range defined on Figure 2. Thus, a systematic error in either the measurement of temperature or the modelling of its effect is a definite possibility.

The effect of ignoring the detail of the temperature history on the random distribution of the results is shown dramatically by the difference in standard deviation between the two data sets. In the 1974 tests the temperature histories were taken from strip chart recordings. As a result, the temperature history input to the model omitted considerable detail. The standard deviation was large. The 1978 tests, because of the mini-computer, provided fine detail in the temperature history and in spite of some very complex transients (see column 2 of Table 2) the standard deviation was much reduced compared with 1974. Thus, we can conclude that the model NIRVANA is capable of calculating reasonable strain values for tubes which undergo strain by the variety of mechanisms dictated by the different metallurgical regimes covered in these experiments. The reason for an apparent systematic bias of 1.9% in temperature is not known. It may be due to either a systematic error in temperature measurement or to an over emphasis of the effect of temperature in the equations which are used in the model.

The temperature dependent terms used in the model are mostly in the form of activation energies for the various processes. Activation energies are notoriously difficult to measure with precision. They are, therefore, a likely source of the apparent temperature discrepancy between the tests and the model.

CONCLUSIONS

1. The high temperature creep of Zircaloy-4 is well represented by the mechanistic strain rate model used in the computer subroutine NIRVANA.

2. The average ratio of predicted/measured strain for experiments where a detailed history was recorded was 1.46 with a standard deviation of 1.42.

3. The calculated strain is very sensitive to temperature. A reduction of 1.9% in the temperature gave the best fit to the data. Whether this apparent systematic error is caused by errors in measurement of the absolute temperature or by the temperature fits to the data used in the model is at present unknown.

4. The calculated strain is much less sensitive to the pressure history, a reduction of 10% in pressure only reducing the predicted/measured strain ratio from 1.46 to 1.11.

5. Variation of the oxygen content within the range allowed by the material specifications should have little effect on the predicted strain.

6. Variation of the tin content within the range allowed by the material specifications should have some effect on the predicted strain at α-phase temperatures but little effect above 900°C.

7. Variation of mechanical properties, primarily the anisotropic factors, can affect the predicted strain in the α-phase by nearly a factor of two.

8. Grain size variation primarily affects strain predictions at temperatures in the two-phase region, because of its effect on grain boundary sliding.

9. Dimensional variations, within the range allowed by fuel sheath specifications, can affect the predicted strain by nearly a factor of 2 over the whole temperature range.

10. The probable range of calculated strain about the true value, resulting from contributions from all the variables permitted in the fuel sheath specifications, is slightly more than a factor of two.

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TABLE 1

HIGH STRAIN SPECIMENS

Test No.	Plane of Measurement	Measured True Strain %	Ruptured	Calculated True Average Strain %
7	1 centreline	26.70	yes	rupture
	2 + 50 mm	11.43		rupture
	3 - 50 mm	3.08		8.54
7A	1 centreline	measurement	yes	17.59
	2 + 50 mm	not		rupture
	3 - 50 mm	possible		3.56
8B	1 centreline	14.32	no	4.05
	2 + 50 mm	27.93		34.86
	3 - 50 mm	2.13		3.79
8C	1 centreline	15.01	no	22.83
	2 + 50 mm	23.49		rupture
	3 - 50 mm	2.61		3.92
8E	1 centreline	6.48	yes	17.92
	2 + 50 mm	45.45		rupture
	3 - 50 mm	1.50		2.34
8G	1 centreline	burst	yes	24.91
	2 + 50 mm	6.81		no data available
	3 - 50 mm	3.11		4.39

TABLE 2

CGE 1978 STRAIN RATE EQUATION VERIFICATION TESTS

Test No.	Thermal Cycle	Peak Temperatures °C	Plane	ε_m Measured Diametral True Strain	ε_p Predicted Diametral True Strain	$\frac{\varepsilon_{p(predicted)}}{\varepsilon_{m(measured)}}$	$\ln(\varepsilon_p/\varepsilon_m)$	$(x-\bar{x})^2$
		986.8 860.9	1	3.23	3.87	1.20	0.1808	0.0398
1A		1011.2 867.1	2	4.84	5.06	1.05	0.0445	0.1127
		909.1 810.0	3	0.77	1.18	1.55	0.4353	0.0030
		1035.0 865.3	1	3.14	4.79	1.53	0.4223	0.0018
1B		984.4 869.4	2	4.12	4.84	1.17	0.1611	0.0480
		927.8 833.1	3	1.14	2.06	1.81	0.5917	0.0447
		959.6 870.0	1	3.34	3.46	1.04	0.0353	0.1190
2A		992.7 886.6	2	5.20	5.67	1.09	0.0865	0.0863
		897.4 802.6	3	0.51	0.97	1.90	0.6429	0.0690
		966.3 875.7	1	3.83	3.58	0.93	-0.0675	0.2004
2B		991.0 878.2	2	5.48	4.78	0.87	-0.1367	0.2672
		907.4 826.3	3	1.19	1.75	1.47	0.3857	0.0000
		974.9 907.5	1	3.51	3.59	1.02	0.0225	0.1279
3A		998.8 936.8	2	5.63	7.04	1.24	0.2147	0.0274
		916.7 839.5	3	0.77	2.19	2.84	1.0453	0.4424

TABLE 2 (continued)

CGE 1978 STRAIN RATE EQUATION VERIFICATION TESTS

Test No.	Thermal Cycle	Peak Temperatures °C	Plane	ε_m Measured Diametral True Strain	ε_p Predicted Diametral True Strain	$\varepsilon_{p(predicted)} / \varepsilon_{m(measured)}$	$\ln(\varepsilon_p/\varepsilon_m)$	$(x-\bar{x})^2$
		1016.3 947.3	1	5.18	9.28	1.79	0.5831	0.0412
3B		1026.6 955.0	2	7.14	13.01	1.82	0.6000	0.0483
		961.7 893.7	3	2.70	3.20	1.18	0.1699	0.0442
		972.9 814.3	1	1.64	2.01	1.22	0.2034	0.0313
4A		1013.9 818.7	2	2.34	2.57	1.10	0.0938	0.0820
		914.7 761.9	3	0.58	0.92	1.59	0.4613	0.0066
		953.1 820.9	1	1.24	1.76	1.42	0.3502	0.0009
4B		970.9 841.8	2	1.95	2.15	1.10	0.0976	0.0799
		890.2 772.1	3	0.19	0.54	2.84	1.0445	0.4413
		724.8 1010.2	1	4.04	5.78	1.43	0.3582	0.0005
5A		722.3 1002.5	2	3.99	5.03	1.26	0.2316	0.0221
		669.1 968.4	3	2.24	2.42	1.08	0.0773	0.0917
		708.6 1010.9	1	2.31	7.76	3.36	1.2117	0.6914
5B		709.6 995.5	2	2.12	5.33	2.51	0.9219	0.2934
		675.2 982.7	3	1.59	3.68	2.31	0.8392	0.2107

TABLE 2 (continued)

CGE 1978 STRAIN RATE EQUATION VERIFICATION TESTS

Test No.	Thermal Cycle	Peak Temperatures °C	Plane	ε_m Measured Diametral True Strain	ε_p Predicted Diametral True Strain	$\frac{\varepsilon_{p(predicted)}}{\varepsilon_{m(measured)}}$	$\ln(\varepsilon_p/\varepsilon_m)$	$(x-\bar{x})^2$
6A		1020.2 997.9	1	6.53	8.77	1.34	0.2949	0.0073
		1033.1 1004.8	2	6.92	10.10	1.46	0.3781	0.0000
		989.4 975.8	3	2.73	4.58	1.68	0.5174	0.0188
6B		1009.3 1011.9	1	5.27	8.40	1.59	0.4662	0.0074
		1018.3 1015.6	2	5.41	9.02	1.67	0.5112	0.0172
		989.5 972.2	3	2.14	3.16	1.48	0.3898	0.0001
7B		992.0	1	4.10	11.15	2.72	1.0005	0.3848
		976.7	2	3.39	7.63	2.25	0.8113	0.1858
		934.4	3	1.65	3.17	1.92	0.6530	0.0744
7C		989.0	1	4.30	10.80	2.51	0.9209	0.2924
		973.2	2	4.48	7.39	1.65	0.5005	0.0145
		935.7	3	1.80	3.29	1.83	0.6031	0.0497
8A		992.5	1	1.83	2.20	1.20	0.1841	0.0385
		948.4	2	1.60	1.63	1.02	0.0186	0.1308
		906.3	3	0.59	0.81	1.37	0.3169	0.0040
8D		1020.9	1	4.64	7.90	1.70	0.5321	0.0231
		1005.4	2	6.25	6.86	1.10	0.0931	0.0824
		929.4	3	1.28	2.09	1.63	0.4903	0.0121
8F		1110.5	1	4.72	3.86	0.82	−0.2011	0.3379
		1103.7	2	6.10	3.81	0.62	−0.4707	0.7240
		1033.0	3	2.44	2.62	1.07	0.0712	0.0955

$\bar{x} = 0.3802$ $\sigma = 0.3480$

N = 51 $\overline{\varepsilon_p/\varepsilon_m} = 1.46$ $= 1.42$

TABLE 3

EFFECT OF VARYING INPUT PRESSURE OR INPUT TEMPERATURE

	Average $\varepsilon_p/\varepsilon_m$	Standard Deviation of $\varepsilon_p/\varepsilon_m$
1978 Data		
Data as recorded	1.46	1.42
Pressures reduced 10%	1.11	1.41
Temperature reduced 1.5%	1.08	1.33
Temperature reduced 1.9%	1.03	1.28
Temperature reduced 2.0%	0.98	1.30
1974 Data		
Data as recorded	1.10	1.71
Temperature reduced 0.5%	0.98	1.66
Temperature reduced 1.0%	0.87	1.62
Temperature reduced 1.9%	0.70	1.56
Temperature reduced 2.5%	0.60	1.67

TABLE 4

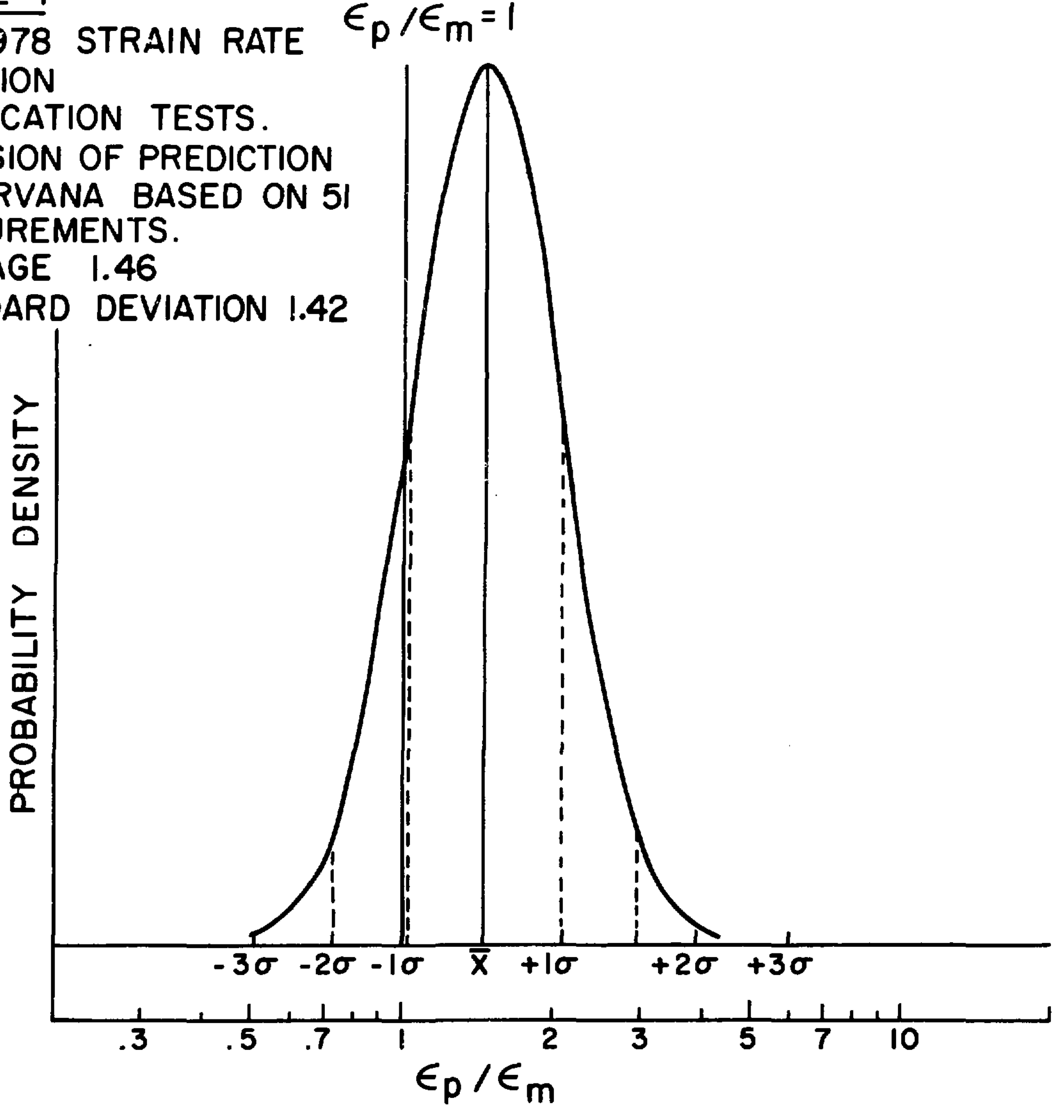
EFFECT OF VARIATIONS WITHIN THE TUBE MANUFACTURING SPECIFICATIONS ON PREDICTED STRAINS

Isothermal Temp.	Calculated Strain for Standard Conditions	1. Effect of Oxygen, 1200 ppm Used as Standard Value: 900 ppm		2. 1500 ppm		3. Effect of Tin, 1.45wt% Used as Standard Value: 1.20 wt%		4. 1.70 wt%		5. Effect of ±10% Variation in Back Stress due to Dislocation Network: -10%		6. +10%	
°C	ε_s%	ε_p%	$\varepsilon_p/\varepsilon_s$	ε_p%	$\varepsilon_p/\varepsilon_s$	ε_p%	$\varepsilon_p/\varepsilon_s$	ε_p%	$\varepsilon_p/\varepsilon_s$	ε_p%	$\varepsilon_p/\varepsilon_s$	ε_p%	$\varepsilon_p/\varepsilon_s$
600	4.80	5.33	1.11	4.35	0.91	7.24	1.51	3.40	0.71	5.24	1.09	4.37	0.91
700	4.24	4.63	1.09	3.90	0.92	5.96	1.40	3.16	0.74	4.24	1.00	4.24	1.00
800	4.47	4.95	1.11	4.06	0.91	6.61	1.48	3.18	0.71	4.47	1.00	4.47	1.00
900	5.15	4.33	0.84	4.82	0.94	5.19	1.01	4.83	0.94	5.15	1.00	5.15	1.00
1000	4.47	4.19	0.94	3.60	0.80	4.48	1.00	4.15	0.93	4.47	1.00	4.47	1.00
1100	4.16	4.04	0.97	4.28	1.03	4.12	0.99	4.21	1.01	4.16	1.00	4.16	1.00
1200	4.24	4.06	0.96	4.40	1.04	4.18	0.98	4.30	1.01	4.24	1.00	4.24	1.00

Isothermal Temp.	Calculated Strain for Standard Conditions	7. Effect of Variation in Anisotropic Factors by ± 1 Standard Deviation: Minimum		8. Maximum		9. Effect of Dimensions: Minimum Diameter Maximum Wall		10. Maximum Diameter Minimum Wall		Effect of Grain Size: Grain Size x 2		Grain Size ÷ 2	
°C	ε_s%	ε_p%	$\varepsilon_p/\varepsilon_s$	ε_p%	$\varepsilon_p/\varepsilon_s$	ε_p%	$\varepsilon_p/\varepsilon_s$	ε_p%	$\varepsilon_p/\varepsilon_s$	ε_p%	$\varepsilon_p/\varepsilon_s$	ε_p%	$\varepsilon_p/\varepsilon_s$
600	4.80	2.68	0.56	8.48	1.77	2.55	0.53	10.71	2.23	4.00	0.83	8.91	1.86
700	4.24	2.45	0.58	7.19	1.70	2.71	0.64	7.59	1.79	4.12	0.97	4.93	1.16
800	4.47	2.45	0.55	8.01	1.79	2.71	0.61	8.57	1.92	4.36	0.98	5.10	1.14
900	5.15	5.15	1.00	5.15	1.00	4.13	0.80	6.70	1.30	2.92	0.57	23.34	4.53
1000	4.47	4.47	1.00	4.47	1.00	2.78	0.62	7.97	1.78	4.44	0.99	4.63	1.04
1100	4.16	4.16	1.00	4.16	1.00	2.21	0.53	8.22	1.98	4.15	1.00	4.26	1.02
1200	4.24	4.24	1.00	4.24	1.00	1.96	0.46	9.11	2.15	4.24	1.00	4.30	1.01

FIGURE 1

CGE 1978 STRAIN RATE EQUATION VERIFICATION TESTS. PRECISION OF PREDICTION BY NIRVANA BASED ON 51 MEASUREMENTS.
AVERAGE 1.46
STANDARD DEVIATION 1.42



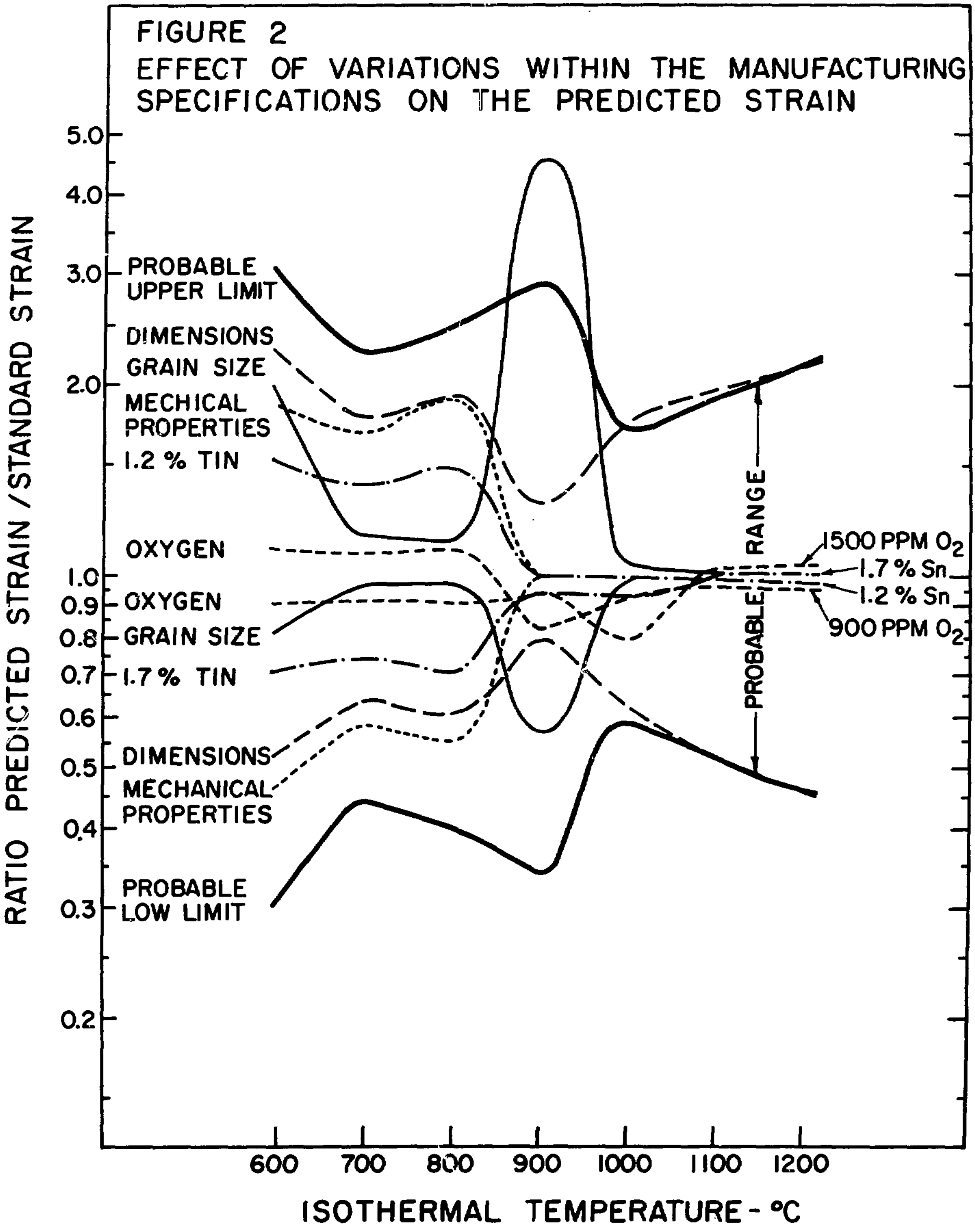


FIGURE 2
EFFECT OF VARIATIONS WITHIN THE MANUFACTURING SPECIFICATIONS ON THE PREDICTED STRAIN
RATIO PREDICTED STRAIN /STANDARD STRAIN
5.0
4.0
3.0
2.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
PROBABLE UPPER LIMIT
DIMENSIONS
GRAIN SIZE
MECHICAL PROPERTIES
1.2 % TIN
OXYGEN
OXYGEN
GRAIN SIZE
1.7 % TIN
DIMENSIONS
MECHANICAL PROPERTIES
PROBABLE LOW LIMIT
PROBABLE RANGE
1500 PPM O_2
1.7 % Sn
1.2 % Sn
900 PPM O_2
600
700
800
900
1000
1100
1200
ISOTHERMAL TEMPERATURE - °C

APPENDIX I

Effect of Tin Content

The effect of tin content on the strain rate of zirconium has been reported by Luton (5). At a steady state stress of 100 MPa one gets the following values of temperature corrected strain rate:

Composition	Zirconium	Zr-0.7 wt% Sn	Zr-3 wt% Sn	Zr-5 wt% Sn
$\dot{\varepsilon}\exp(Q/RT)$	$2.3(10^{11})$	$5(10^{13})$	$1.6(10^{12})$	$3(10^{13})$

These results are plotted on Figure I-1. The specified range in tin content for Zircaloy-4 is 1.20 to 1.70 wt% with a mean value of 1.45 wt%. The following assumptions will be made:

1. The curve shown on Figure I-1 is not dependent on stress.

2. The results are not a function of temperature.

3. The temperature corrected strain rate may be expressed by

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

   where Q and n have the mean value (i.e. that used in the code NIRVANA) throughout the range and all variability may be lumped into the constant A.

4. We may describe the effect of tin on the temperature corrected strain rate by an equation of the form

$$\ln[\dot{\varepsilon}\exp(Q/RT)] = a + b\,(\%\ \text{tin}) \qquad \text{I-2}$$

From Figure I-1 we have values of the temperature corrected strain rate at 0.7 and 3% Sn. This gives us the two equations (from equation I-2)

for 0.7% Sn $\quad \ln[5(10^{13})] = a + b\,(0.7)$

3% Sn $\quad \ln[1.6(10^{12})] = a + b\,(3.0)$

$$\ln\left[\frac{5(10^{13})}{1.6(10^{12})}\right] = b\,(0.7 - 3.0)$$

$$b = -1.496$$

$$a = 32.59$$

APPENDIX I continued

$$\exp(Q/RT) = \exp\,[32.59 - 1.50\,(\%\ Sn)]$$

$$\therefore\ \dot{\varepsilon} \equiv A \exp\,[32.59 - 1.50\,(\%\ Sn)]\ \exp(-Q/RT)\ \sigma_*^{\,n}$$

From the standard equation used in the code NIRVANA, A is defined for 1.45% Sn. From this we have

$$A \exp\,[32.59 - 1.50\,(1.45\%\ Sn)] = 1.884\ (10^4)$$

$$A = 1.164\ (10^{-9})$$

Therefore, for 1.2% Sn, $A \exp\,[a-b\ \%\ Sn] = 2.741\ (10^4)$

1.7% Sn, $A \exp\,[a-b\ \%\ Sn] = 1.295\ (10^4)$

thus the strain rate equations equivalent to equation (I-1) for the two compositions are:

1.2% Sn $\quad \dot{\varepsilon} = 2.741(10^4)\ \exp\,(-34730/T)\ \sigma_*^{\,5.3}$

1.7% $\quad \dot{\varepsilon} = 1.295(10^4)\ \exp\,(-34730/T)\ \sigma_*^{\,5.3}$

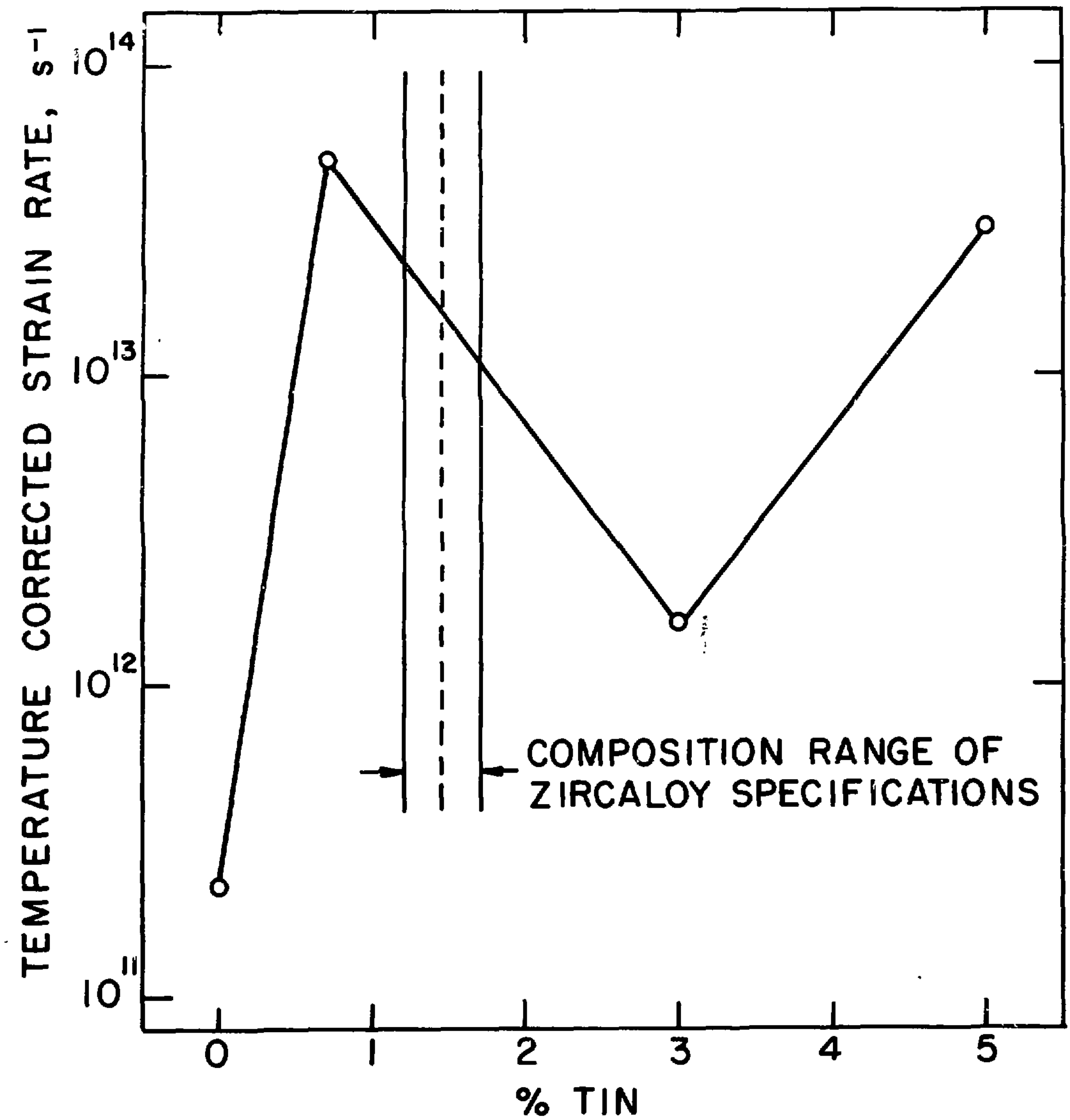


FIGURE I-1
EFFECT OF TIN ON THE TEMPERATURE CORRECTED STRAIN RATE

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