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Out of Pile Ballooning Tests on Zircaloy Cladding—The Effect of Heat Transfer on Failure Strain

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Abstract

An experimental programme of ballooning tests on alpha-phase Zircaloy PWR fuel cladding has been recently completed which was designed to demonstrate the interactions between heating method, heat transfer and clad strain characteristics. The results obtained provide a suitable data base for testing the current understanding of the ballooning phenomenon and predictions made using the RODSWELL code. This model was specifically developed to investigate such interactions and hence to identify the loss-of-coolant-accident (LOCA) conditions in which ballooning may be important. Tests were also done at higher temperature to provide basic data and to define the limits of significant ballooning.

1. Introduction

Over the past few years the importance of the influence of the experimental heat transfer conditions on the failure strain of ballooned Zircaloy cladding has been realised. The RODSWELL computer code was written to model the interaction between the heat transfer and straining processes in order to identify the conditions under which significant coolant blockages might be expected. In a previous paper [1] the code was described and the results of some applications given. The results obtained suggested that the nominal surface heat flux at the cladding could be used as a simple parameter together with the failure time or temperature ramp-rate to predict the failure strain. Although the RODSWELL predictions are in broad agreement with the trends in the published data on ballooning tests, in general the heat transfer conditions used in such tests are not well documented so until now it had not been possible to test the model fully.

The experimental programme of ballooning tests described here was designed to demonstrate the variability of failure strain with temperature, heating method and heat transfer from the cladding surface. The intention was to provide a consistent data set (same Zircaloy material and internal components, same experimental rig) which could be used to test the current understanding of the factors determining clad strain, test the modelling capability of the RODSWELL ballooning code, clarify areas where further modelling is required and provide suitable data to assist such developments. The heat transfer conditions were chosen to give nominal heat fluxes covering the range possible in "real" accidents to enable predictions of those conditions leading to large balloons to be checked. The temperature range of the tests considerably exceeded that expected for "design basis" accidents so that the limiting conditions for significant ballooning could be defined.

2. Experimental Programme

The experimental rig and test procedure have already been described in detail [2] so they will be only briefly summarised here.

A fuel-rod simulator (0.4 m long, 9.5 mm diameter) consisting of Zircaloy clad boron-nitride pellets which can be heated directly by Joule heating of the clad or indirectly by means of an inner tantalum rod, is mounted within a stainless steel flow shroud. The shroud tube can also be heated directly (to 1073 K). Cooling is by a controlled flow of superheated steam covering the range 0.2 - 3 g/s (inert gas can also be used). Thermocouples are attached to the internal heater rod, the cladding and the shroud at (typically) three axial levels. Coolant flow, rod and shroud power and coolant temperatures are also measured throughout a test. Nominally constant temperature and temperature ramp tests have been carried out, the times to fail being determined by the rod internal pressures chosen. By varying the coolant flow, the shroud heating and the rod pressure it has been possible to cover about a factor of ten range in clad heat flux and a factor of 100 in failure time. The mean circumferential strain and its axial distribution were measured for all specimens. In addition, all specimens were sectioned at the burst position to enable the circumferential distribution of strain to be determined as well as the oxidation layer thicknesses and microstructure, where appropriate.

3. Results and Analysis

The tests done were divided into three groups according to the Zircaloy phase present at the test temperature: alpha phase (< 1090 K), beta phase (> 1250 K) and mixed phase (1090 - 1250 K).

3.1 Group I tests

The objectives of the first group of bursting tests was to test the ballooning/heat transfer modelling of the RODSWELL code. This model assumes that for alpha-phase Zircaloy the local strain at the point of rupture of a ballooned tube is very high and is a constant. The measured total strain depends on the distribution of strain around the circumference which for an internally heated tube depends primarily on the temperature distribution.

The pellet stack within the fuel-rod or simulator is assumed to be eccentric, just touching the clad at one side. For an internally heated rod this side of the clad will be the hotter. It is further assumed that when straining starts this side of the clad remains in contact with the pellets because of the so-called "hot-side-straight" effect. This effect arises because of the anisotropic creep properties of alpha-phase Zircaloy which causes axial shortening of the clad relatively more on the more highly strained side with resultant bowing towards the heater rod. A circumferential temperature gradient is thus established which increases as the balloon develops by cooling of the opposite side of the clad, localising the strain and limiting its final measured value.

In a recent paper [1] RODSWELL calculations were reported which predicted that the failure strain should correlate with the nominal surface heat flux and failure time under approximately isothermal straining or with the nominal gap flux (surface flux plus thermal inertia term for clad heating rate) in a temperature ramp situation. For these tests the nominal heat flux can be obtained from the measured rod power prior to the start of the deformation test itself.

It is noteworthy that the range of rod power required to achieve the desired clad temperature for the different flow and shroud heating configurations corresponds very well to the range of gap heat fluxes of interest in the ballooning phase of "real" accidents. Thus the typical 5% decay heat for a LB-LOCA corresponds to 600 - 800 W for the 0.4 m long specimen tested here and is well simulated by the high flow/heated shroud test. The low flow/heated shroud test is equivalent to about 1% decay heat typical of a SB-LOCA steady state or the LB-LOCA during adiabatic heating (when $\sim$ 80% of the power is used in raising the fuel pellet temperature). Finally the high flow/unheated shroud configuration represents the peak flux achieved during the temperature turn around during the reflood phase of the LB-LOCA.

Fig. 1 shows the measured failure strains as a function of total heat flux derived from the measured rod power in the indirectly heated clad bursting tests. The times to fail in the nominally isothermal tests and the nominal temperature ramp rates for the ramp tests are indicated in parentheses by each point. Included also are the results of the in-pile bundle experiments MT3 and MT4 as reported by Mohr and Hesson [3] which were simulations of the "turnover phase" and "adiabatic phase", respectively of a LB-LOCA. These are seen to be in very good agreement. Predicted curves summarizing RODSWELL calculations are shown for comparison. The trend of the measurements is seen to be in good agreement with the shape of the predicted curves but the observed strains are in general higher than predicted and also the expected reduction of strain with increased failure time is not found. There are two probable explanations for the under-prediction of the failure strains. Firstly the "hot-side-straight" effect assumed in the calculations is associated with a fully eccentric heater and should predict the maximum temperature gradients and minimum failure strains possible. Secondly the presence of the heated shroud in some tests will reduce the heat flux from the clad as ballooning proceeds, thus decreasing the circumferential temperature gradients and allowing a higher strain at rupture. It can be seen in Fig. 1 that it is these results which are those most underpredicted. The reason for the lack of confirmation of the predicted variation with time is not completely clear, although a contributory factor is thought to be the existence of residual temperature gradients from the heating-up phase which were not considered in the model predictions. However, the discrepancy is not large compared with the heat flux effect itself.

Also shown in Fig. 1 are the results for the directly heated specimens. These have failure strains significantly higher than the indirectly heated samples at high heat fluxes, confirming findings from other sources (e.g. Hindle [4], and Chung and Kassner [5]). The reason is that the temperature gradients caused by ballooning now tend to reduce any initial non-uniformity in creep rate because of the more rapid cooling of the larger surface area on the more highly strained side of the cladding. Although this fundamental mechanism is clear the actual simulation by the model has turned out to be much more complex than for the indirect heating situation. Whereas it has been shown [1] that with indirect heating the pellet/clad eccentricity dominates in determining the temperature non-uniformities, the same does not apply with direct heating. Here the pellets merely act as a damper on the clad temperature changes during ballooning because of their thermal capacity although they can also cause cold spots on the cladding during the initial heating to the test temperature. Thus other sources of non-uniform creep must be studied. These include clad wall thickness and material property variations as well as non-uniform heat transfer characteristics. Analysis of the many possibilities is still in progress.

It is noted that at zero surface flux the temperature gradients disappear in both heating methods and the failure strains should become equal to that found in external (furnace heating) tests. It can be shown that typical wall thickness variations are sufficient to account for the observed finite failure strains in this case.

3.2 Group II and III tests

The aims of the Group II and III tests were to provide data in the temperature regions where the material properties are complex and improvements in the modelling were thought to be necessary, and to confirm that burst strains are generally low under relevant conditions. The anisotropy of Zircaloy creep decreases rapidly once the pure alpha phase temperature is exceeded, thus removing the main source of the difference between direct and indirect heating. Circumferential temperature gradients are even more important in limiting failure strains in the mixed phase region so to demonstrate the maximum ballooning, the majority of tests were done with low power direct heating. Both inert and oxidising atmospheres were used to help development of the oxidation/creep interaction model.

The failure strains are plotted in Fig. 2 as functions of time and temperature. The points to note here are:

- a general reduction of failure strain with temperature above 800^{o}C, particularly in oxidising conditions, and leads to very low strains for all realistic accident conditions with temperatures of 900^{o}C or greater;
- an increase in strain at low strain rates for the inert atmosphere tests at temperatures of 850 and 900^{o}C. This can be attributed to superplasticity and can be predicted by the RODSWELL model which was based on early Zircaloy 2 data [6];
- low strain-rate superplastic deformation can lead to large ballooning strains also in indirectly heated cladding in low steam flow at temperatures as high as 870^{o}C. Such conditions (long time, low heat flux, quasi-isothermal) are not relevant for a LB-LOCA but may arise in the wider range of scenarios possible in "beyond design-basis" accidents.

3.3 Axial distribution of strain

In addition to the ballooning failure strain itself a further point of interest is the axial extent of the strained portion of the cladding because this affects the probability that balloons in neighbouring rods can interact to produce a blockage. Hindle [4] has demonstrated that axially extended balloons can be formed in directly heated alpha-phase Zircaloy tubes over a wide range of temperatures and rod pressures provided the temperature is quasi-steady-state and the time to fail is greater than 30 - 50 seconds. The stabilising mechanism is again thought to be the better cooling of the more highly strained portion of the tube which reduces the strain rate giving extra time for strain elsewhere. The effect is predicted to increase with surface heat flux and time and considerable stabilisation of strain is expected under the two higher heat transfer conditions with negligible effect with the lowest heat flux. Fig. 3 shows the actual measured strain distributions for the three situations. The stabilisation pattern is seen to follow the expected trend with heat flux but once again the predicted effect of time is not apparent. It is noteworthy that the more stable the ballooning process the lower is the failure strain, particularly for the "realistic" indirect heating.

Axial distributions of strain for the Group II tests with low heat flux are shown in Fig. 4. Here the low stability observed for alpha-phase Zircaloy is again seen at short times to failure but lower strain rates give much more extended balloons. This again can be attributed to the superplastic strain mechanism which dominates at low strain rates and temperatures near to 900°C and has a very low stress and temperature sensitivity. This is confirmed by the 950°C tests in which the maximum strain at low strain rates is found in bulges away from the peak temperature position indicating a minimum strength at about 900°C. This strength minimum was also found in the early tests on Zircaloy 2 [6] on which the current creep model was based. In the steam atmosphere the strain at temperatures of 900°C and higher are too low to be of concern in blockage studies. However, the indirectly heated specimens at 850 and 870°C show that it is possible to produce stable, high strain balloons by this mechanism in "realistic", although rare, accident conditions.

4. Concluding Remarks

On the basis of the experimental results and supporting modelling calculations the following observations and conclusions can be made:

The test results for alpha-phase Zircaloy confirmed the expected difference in clad failure strain between direct and indirect heating. They also confirmed current ideas and modelling predictions on the effect of clad heat flux on circumferential temperature gradients and on the failure strain and its distribution in indirectly heated cladding. They did not confirm the expected influence of failure time in reducing failure strains in indirectly heated rods and increasing them in directly heated ones. This has been partially explained by the effect of other stochastic variables and the investigation is continuing. The work has confirmed that the maximum strains under "realistic" accident conditions are to be expected at temperatures near to 800°C under conditions of low surface heat flux such as that during the quasi-adiabatic phase of the LB-LOCA or a quasi-steady-state phase late in a SB-LOCA. These strains are expected to be localised axially, thus reducing the potential for coolant channel blockage. A possibility for more stable ballooning due to superplasticity has been demonstrated for a narrow range of temperature under the rather unlikely combination of conditions of long time to fail, low heat flux and constant temperature.

References

[1] LAVAL, H., CASADEI, F., JONES, P.M., "Modelling of azimuthal effects arising from interaction between clad deformation and heat transfer under LB-LOCA conditions", Nucl. Eng. Design, 79 (1984) 267-276.

[2] VESPRINI, R., LOMBARDI, L., JONES, P.M., CASADEI, F., "Out-of-pile ballooning and bursting tests on Zircaloy cladding rods with direct and indirect heating", Final Report on Contract N.021 SRI., CEC EUR-report, in press.

[3] MOHR, C.L., HESSON, G.M., "LOCA rupture strains and coolability of full length PWR fuel bundles", Proc. 7th Int. Conf. on Structural Mechanics in Reactor Technology, Chicago, USA, August 1983, Paper C 2/1*.

[4] HINDLE, E.D., MANN, C.A., REYNOLDS, A.E., "The deformation of Zircaloy PWR cladding with low internal pressure under mainly convective cooling by steam", CSNI Specialist Meeting, Espoo, Finland, September 1980.

[5] CHUNG, H.M., KASSNER, T.F., "Deformation characteristics of Zircaloy cladding in vacuum and steam under transient heating conditions", Argonne National Laboratory Report ANL-77-31.

[6] JONES, P.M., GITTUS, J.H., HINDLE, E.D., "CANSWELL: a computer model of clad behaviour during a loss-of-coolant accident", CSNI Specialist Meeting, Spatind, Norway, September 1976.

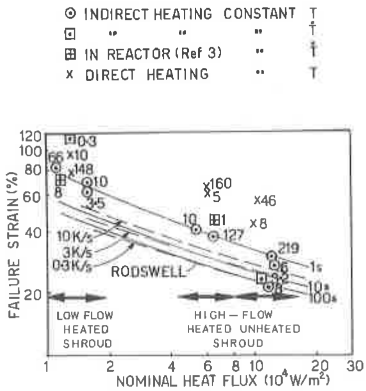

Fig. 1 Comparison of observed and calculated strains for indirectly heated cladding.

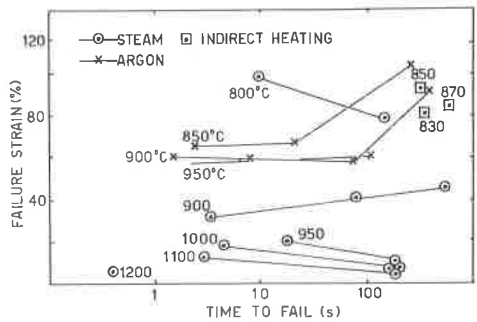

Fig. 2 Observed failure strain as functions of time for high temperature, low heat-flux tests.

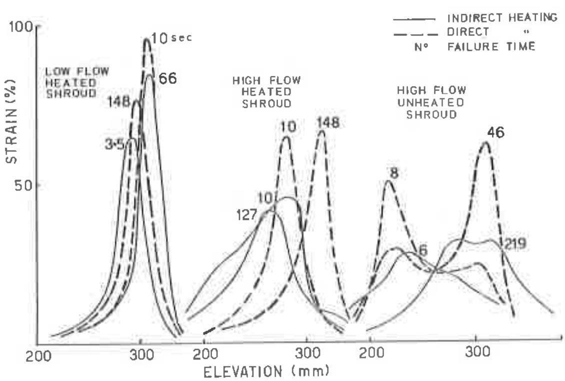

Fig. 3 Axial distributions of hoop strain for the three heat transfer configurations.

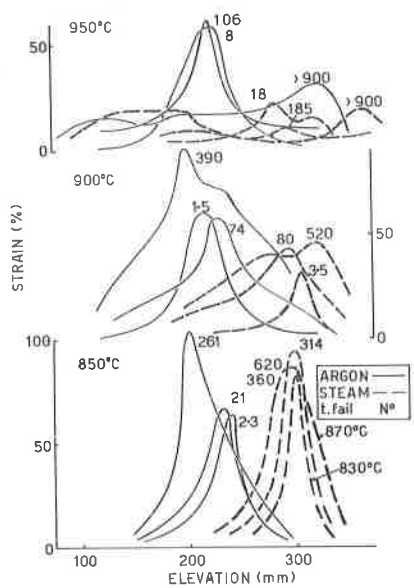

Fig. 4 Axial distributions of hoop strain for mixed phase deformation.