Fracture 1977, Volume 3, ICF4, Waterloo, Canada, June 19 - 24, 1977

# A STUDY OF CONDITIONS LEADING TO FRAGMENTATION ON FAILURE OF ZIRCONIUM ALLOY PRESSURE TUBES

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## INTRODUCTION

In the Steam Generating Heavy Water Reactor (SGHWR) a number of cylindrical channels of seamless Zircaloy-2 tubing serve a similar function to that of the steel pressure vessel in a PWR or BWR system. The primary safety argument for these pressure tubes is similar to that adopted for steel pressure vessels in that pre-service and in-service inspection is used to ensure that defects have not grown to a size which will lead either to stable leakage or to initiation of a fast failure [1]. However in the case of a pressure tube a fast failure of a tube might be acceptable from safety considerations provided that it did not result in damage to other tubes. To a large extent this would be dependant upon whether fast fracture was accompanied by fragmentation or, more acceptably, by ductile opening out of the tube. Conditions likely to promote fragmentation are understood only in a qualititative sense. For example it is expected that the more brittle the metal the greater the likelihood of fast fracture resulting in fragmentation. Zirconium alloy pressure tubes are known to be enbrittled by hydrogen which can be absorbed during service and precipitated as zirconium hydride [2]; neutron irradiation can enhance the embrittling effect of hydrogen [1,3]. It has also been shown that high strain rates can promote brittleness in Zirconoum alloys [4,5]. High stored energy in a pressurized vessel is likely to promote fragmentation at failure [6]. This could arise from either high failure pressures or the use of a pressurising medium of high compressibility. Crack branching could also lead to fragmentation; a low crack resistance or stress concentrating defects could allow crack branching to occur. The work described here was undertaken to quantify failure conditions resulting in fragmentation in Zirconium alloy pressure tubes and more particularly to develop a test piece capable of being irradiated, which would correlate with the behaviour of tubes.

## PRESSURE TUBE BEHAVIOUR

Tests have been made on 30% cold drawn Zircaloy-2 pressure tubes, 130mm internal diameter, and 5mm wall thickness, and also on ZrNb alloy tubes 130mm internal diameter and 4mm wall thickness. The latter were heat treated to obtain coarse and fine grain structures to give a wide range of behaviour. Most of the specimens were pre-hydrided to give hydrogen concentrations up to 400ppm. The tests were made on 460mm lengths of tube which were pneumatically pressurised to failure. Axial, partial thickness defects having a V section were machined in the outer surface. Axial defects were used because this is the most likely orientation of defects which could be present in a reactor tube, and also the orientation in which

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MS158

defects could have the most damaging effect. Defect depths were selected to obtain ligament failure at pressures around 7MPa while a defect length of 180mm was chosen to ensure that fast fracture would occur after ligament snap through. The end seal design was such as to provide no hindrance to the petalling of the specimen after fast fracture. The results for Zircaloy specimens are summarised in Figure 1 which shows the failure pressures for specimens containing 150, 280 and 400 ppm of hydrogen. Specimens which fragmented following fast fracture are shown as closed points and specimens which did not fragment are shown as open points. Although the number of results available is limited it is possible, for each hydrogen concentration, to define a boundary, as showen, between the pressure-temperature conditions which produce fragmentation and those which do not. High pressure-low temperature conditions favour fragmentation while under low pressure-high temperature conditions the specimens merely petal open following fast fracture. SGHWR operating pressures are close to 7MPa and Figure 1 shows that for hydrogen concentrations up to 400ppm fragmentation would not occur at temperature above 120°C. Figure 2 summarises the results for ZrNb alloy specimens. Fine grained material with 400ppm hydrogen present has given results similar to Zircaloy specimens hydrided to this level. The few results available for the coarse grained material confirm the severe embrittlement expected with this material when hydrogen is present [7]. In the non-hydrided condition fragmentation at 7MPa would only occur at temperatures below about 80°C while with 400ppm hydrogen present fragmentation could occur at temperatures up to approximately 240°C.

Before testing many of the specimens were marked on the outer surface with a grid of axial and circumferential lines. The local curvature was measured at the inter-sections of the grid lines and the measurements repeated after testing. The difference between the two readings represented the local permanent bending deflection produced by the petalling following fast fracture. For specimens which did not fragment the deflection was found to be approximatley constant axially, but varied circumferentially, minimum values occurring adjacent to the defect and maximum values at a position about π rad around the circumference from the defect. Figure 3 shows the circumferential variation of deflection for a typical specimen.

Specimens which fragmented had significantly smaller permanent bending deflections than specimens which did not fragment. Results for a typical specimen are included in Figure 3. Examination of the fragmented specimens indicates that in general the position π rad from the defect is a favoured site for cracking. This is particularly so for specimens which produced only 2 fragments.

It is probable that fragmentation results from the rapid bending which occurs during petalling. The bending moment is such that the inner surface is under tension while the maximum bending moment will be at π rad from the defect. It would seem likely that if a critical stress, strain, or strain rate is reached at the inner surface during petalling then long, shallow, axial cracks would initiate and propagate through the wall to create fragments. Since specimens which fragment have smaller permanent bending deflections than the specimens which do not fragment, it is unlikely that the criterion for fragmentation is strain dependent.

The specimens were pressurized pneumatically so that the stored energy available for petalling after fast fracture was a function of the tube failure pressure. The effect of stored energy as a variable has not been

investigated but it is expected from previous work that if the pressurised volume had been reduced by the use of a filler block ising had been hydraulic, then the available energy would be reduced. In this event the rate of petalling would be reduced with a probable effect on the fragmentation behaviour.

## SMALL SPECIMEN STUDIES

Analysis of the tube specimens after tests indicated several features that would be required of a small specimen test to permit a correlation with the tube tests. These were that the specimen should be un-notched, deformed in a bending mode, and that the strain rate should be rapid and variable. Accordingly the specimen adopted was a curved strip cut from the circumferential direction of pressure tubing. This was 12.7mm wide, 55mm overall length and had the thickness of the parent tube. The tests were made on a variable velocity impact tester designed and built for the purpose. The specimen rests on an anvil and is impacted by a projectile having two loading points. The specimen is thus subject to 4 point loading so that the region between the two centre loading points ($\sim 2.5$mm long) is bent uniformly. The projectile is fired from a chanber which is pressurized with nitrogen. In the loaded position the projectile locates in a sealing ring at the tip of the guide tube and is restrained by a bomb release type of mechanism. When the chamber is pressurised to the required level the release mechanism is actuated by means of a solenoid, and the projectile accelerates down the guide tube to strike the specimen. The impact velocity is governed by the chamber pressure.

Series of tests have been made on all the materials examined in the tube studies and in addition on Zircaloy-2 specimens irradiated in the Dounreay Fast Reactor at 300°C to fast neutron doses in the range $3.2 \times 10^{23}$ to $8.6 \times 10^{24}$ n/m$^2$(Ni). The tests were carried out at temperatures in the range 20° to 300°C, and for each material condition several tests were made at each temperature to determine the minimum impact velocity required for specimen fracture. Figure 4 shows an example of the results obtained and is for Zircaloy-2 specimens containing 400ppm hydrogen. A boundary can be drawn between conditions which result in fracture and those for which the specimen bends without fracture. Thus a relationship is established between the minimum impact velocity for fracture and test temperature. Figure 5 summarises the results obtained for Zircaloy-2 specimens and illustrates the effect of irradiation. It must be noted that the relationships established are particular to the test conditions adopted. A change in the mass of the projectile or the specimen dimensions for example, would probably change the relationship.

Deflection measurements were made on some of the bend specimens after test to determine the degree of bending. Figure 6 is typical of the results obtained and shows the effect of impact velocity on the deflection of heat treated ZrNb alloy specimens (fine grained). At each temperature there is a critical impact velocity above which the specimens fracture, the critical velocity increasing with increasing test temperature. For each temperature the specimen deflection is a maximum at the critical velocity and decreases at both higher and lower velocities. The behaviour is closely analogous to that observed with the petalling pressure tubes. It is noticeable however that the bend specimens tolerate greater degrees of bending before fracture than the corresponding tube specimens. It is also observed that anticlastic bending occurs in the bend specimens. This is associated with the Poisson effect which causes thinning of longitudinal fibres at the tension side of the bend specimen and thickening of longitudinal fibres at the compression side. The result is that the specimens bend across the width in the high bending moment region, the tension side becoming concave and the compression side convex. This deformation does not occur in the tubes and indeed could not because of the very large effective width (ie 460mm). Thus for equal amounts of bending a higher longitudinal stress would develop in the tension surface of the tubes during petalling than in the corresponding bend specimens. This could account for the difference in the degree of bending at failure observed in the two types of test.

## CORRELATION BETWEEN TUBE AND SMALL SPECIMENS

In correlating the two types of test a difficulty is that different parameter are measured. However it is considered that the strain rate at the surface under tension during bending is the important variable that is common to both types of test. Several tests have therefore been made with strain gauges on the inner surface of the specimen. These tests have shown that there are linear relationships between tube failure pressure and mean strain rate and between the impact velocity of bend specimens and mean strain rate. It is therefore possible to obtain a correlation from the tests by relating the failure pressure for fragmentation of tubes with the corresponding impact velocityfor fracture of bend specimens. The correlation is shown in Figure 7.

The correlation is not ideal, being sensitive to temperature however it is considered to be adequate to permit a reasonable assessment of the fragmentation behaviour of irradiated tubes. Thus using the results for irradiated Zircaloy-2 bend specimens containing 10 and 150 ppm hydrogen (see Figure 5) estimates can be made from Figure 7 of the predicted critical pressure for fragmentation of the corresponding tubes. The predictions are shown in Figure 8. This indicates that irradiation has an embrittling effect but at the end-of-life a reactor pressure tube would contain less than 150ppm hydrogen [8] and therefore if a failure by fast fracture did occur the tube would not fragment at temperatures above 130°C. This is well below the operating temperature (282°C).

## CONCLUSIONS

1. Tests on Zirconium alloy specimens have indicated that the tendency to fragment after fast fracture increases with increasing degree of embrittlement, arising for example from increasing hydrogen concentration, neutron irradiation, and strain rate or from decreasing temperature.

2. Following fast failure by propagation of an axial defect, pressure tubes petal open at high bending rates. This results in high tensile stresses at the inner surface. Fragments may be produced if cracks initiate at the surface and propagate through the thickness.

3. Specimens tested under conditions giving high strain rates in bending have been used to estimate the effect of irradiation on fragmentation. The results of these tests have shown many similarities with results obtained from tube specimens.

4. A correlation between the two types of test has been used to predict the behaviour of irradiated SGHWR pressure tubes. This indicates that Zircaloy-2 tubes having the end-of-life embrittlement arising from neutron irradiation and hydrogen absorption would not fragment following fast fracture at reactor operating temperature and pressure.

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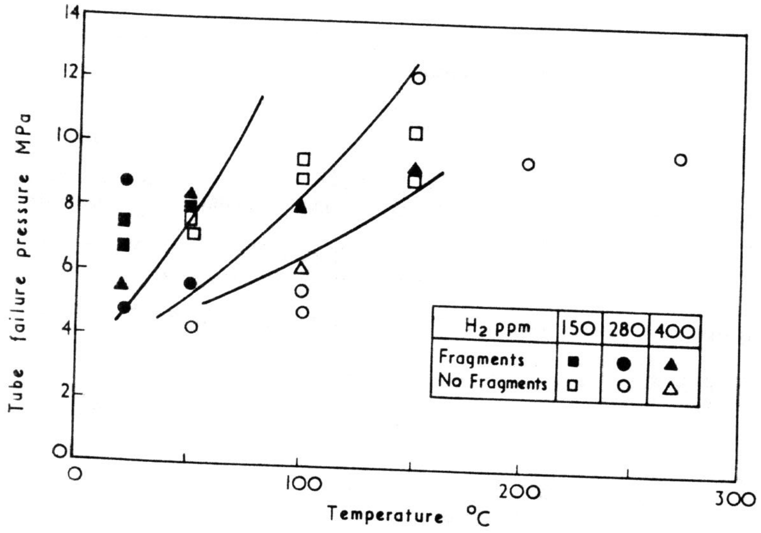

Figure 1 Effects of failure pressure and temperature on fragmentation of Zircaloy pressure tubes

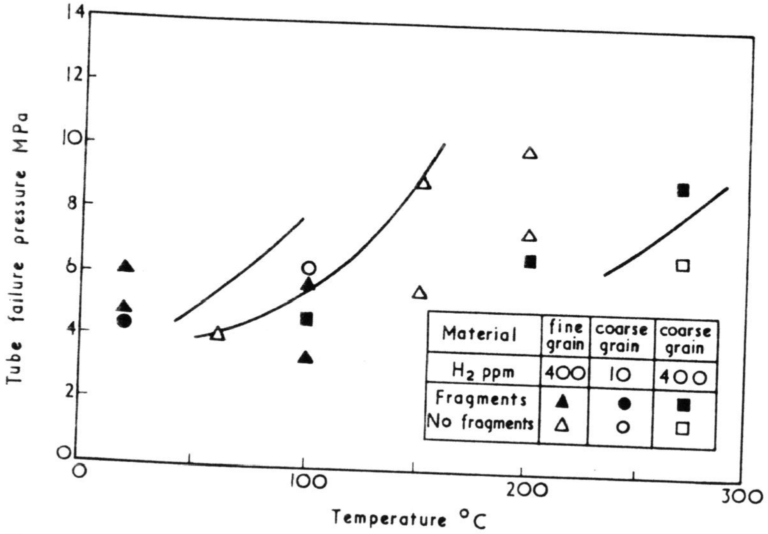

Figure 2 Effects of failure pressure and temperature on fragmentation of heat treated Zr.Nb alloy pressure tubes

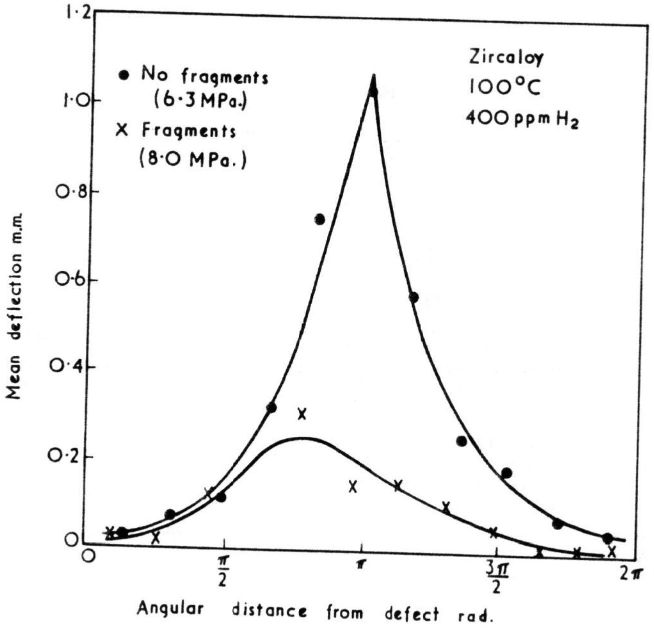

Figure 3 Variation of mean permanent bending deflection (over 25mm span) around the circumference of Zircaloy pressure tubes after fast fracture

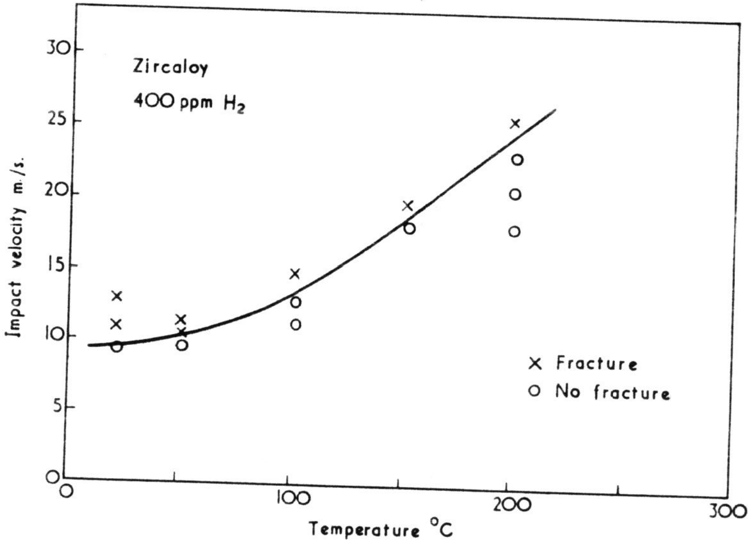

Figure 4 Effects of impact velocity and temperature on fracture of Zircaloy bend specimens

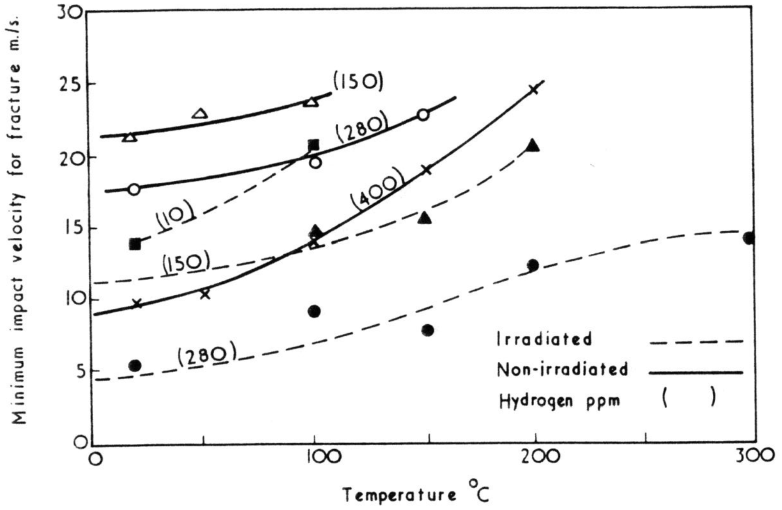

Figure 5 Minimum impact velocity for fracture - temperature relationship for Zircaloy bend specimens

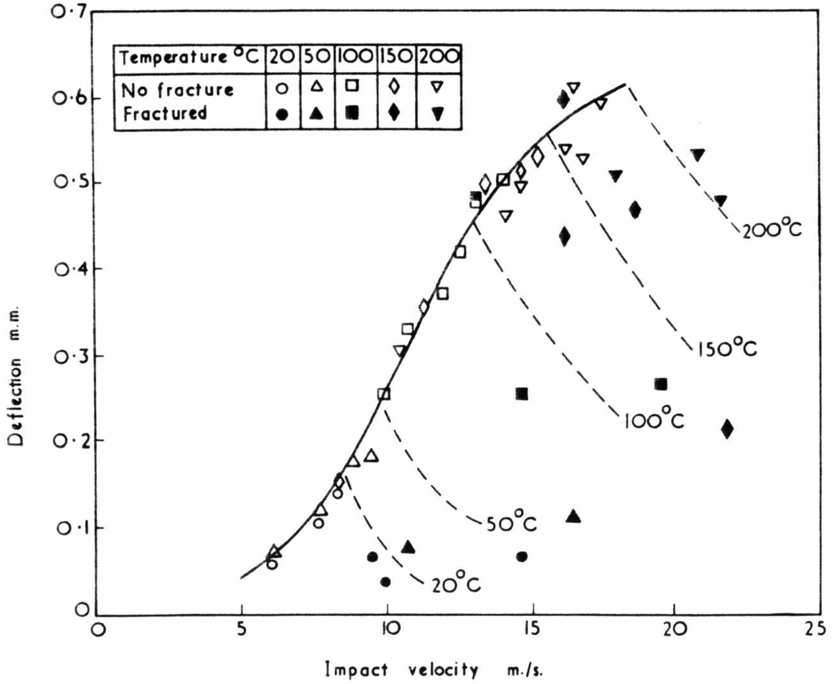

Figure 6 Effect of impact velocity and temperature on permanent bending deflection (over 11.2mm span) of heat treated Zr.Nb alloy bend specimens

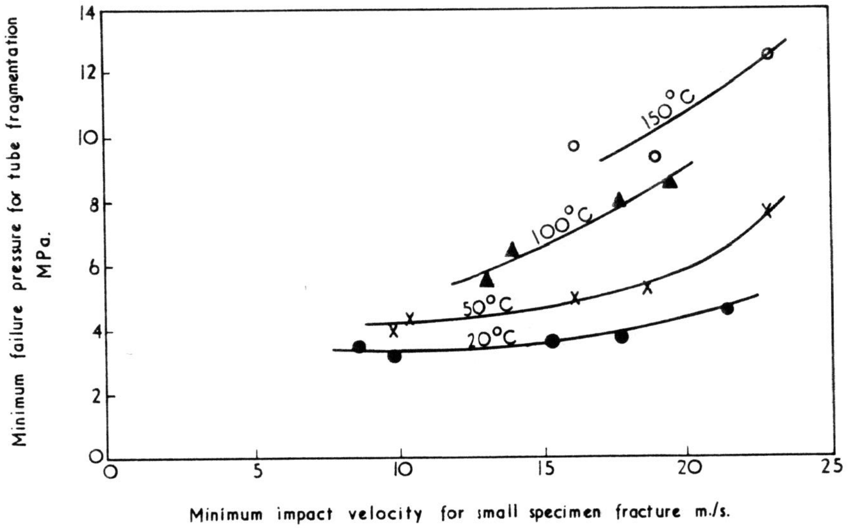

Figure 7 Correlation of results for tubes and bend specimens

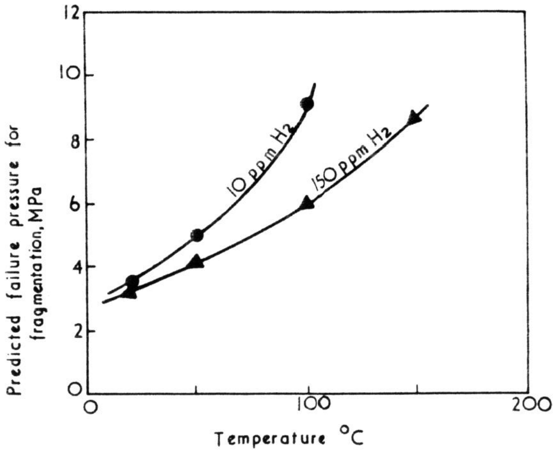

Figure 8 Fragmentation behaviour of irradiated Zircaloy pressure tubes predicted from Figure 7