THE COLLAPSE OF HEAT EXCHANGER TUBES WITH OVALITY AND SIMULATED DEFECTS

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SUMMARY

The heat exchanger tubes of a Pressurised Water Reactor Steam Generator form part of the boundary between the primary and secondary circuits of the reactor, and from a safety point of view it is important that no gross breach of this boundary occurs at any time. Normally the tubes are subjected to a net internal pressure and the failure of a tube or tubes is monitored and remedial action can be taken. However, should a loss of coolant accident occur in the primary circuit of the reactor, these tubes are subjected to external pressure.

An experimental program has been carried out on typical P.W.R. heat exchanger tubing with two objectives; firstly to investigate the collapse pressure of the tubes with varying amounts of initial tube ovality, secondly to simulate tube defects which might be expected to occur during operation.

The defects were artificially induced to simulate:

1. Longitudinal tube cracking;
2. fretting at tube supports;
3. erosion;

and were produced by means of a 60°V groove machined longitudinally partially through the wall of the tube, spark erosion, and chemical thinning, respectively.

The collapse of the oval tubing is compared with the theoretical limit using plastic limit analysis theory and a geometric idealisation of an oval tube, taking into account the effect of elastic changes in ovality prior to collapse.

The collapse of the tubes containing deliberate defects are compared with the theoretical strength of the original tube, and also with the limiting theoretical local membrane stress at the reduced wall section. The effect of varying the length of defect along the tube is also considered, and it is found that with a limited length of defect, considerable support is obtained from surrounding material in the unimpaired part of the tube.

Collapse is of a ductile nature, and in no instance did the defect propagate through the wall of the tube, although some partial propagation and slight extrusion into the bore of the tube occurred in one instance as shown on a micrograph of the section.

The findings are also of interest in situations where any ductile tube is subjected to external pressure in its normal operational state.

1. Introduction.

Heat Exchanger tubing is usually pressurised on at least one side, and often on both sides. When the pressure or differential pressure is external to the tube, the tubing is vulnerable to collapse. The collapse of tubes subjected to external pressure has been studied many times before both theoretically and experimentally and is well documented [1] [2] [3] [4]. Classical work such as that of Timoshenko [1] deals with the problem of collapse due to elastic instability and uses a modified elastic modulus for tubes with thicker walls, where the collapse pressure cannot be calculated from elastic considerations alone. Heise et al [4] have shown that a good correlation exists between theory and tests for thick walled tube where the theoretical collapse pressure is assumed to be reached when the outer surface yields, and the plastic buckling formula is:-

$$P_{cr} = f_y \frac{t}{R_o} \quad (1)$$

Actual collapse pressures were in many cases somewhat higher than theoretical predictions. For thin tubes, correlation with theory based on elastic instability is less reliable, and scatter in the results is mostly attributed to defects in the thick tubes and ovality in the thin tubes. Lohmeier et al [5] have investigated the collapse of ductile heat exchanger tubes of an intermediate thickness in which ovality of varying magnitude was deliberately introduced into the tube geometry and collapse pressures compared with theory based on plastic collapse of the tube, assuming the formation of plastic hinges.

A logical sequel to such work is to deliberately introduce artificial defects into samples of heat exchanger tube and to study the collapse of such specimens. Typical flaws may be due to tube manufacture, mechanical handling during the steam generator manufacture, stress corrosion cracking, erosion and fretting.

The object of this paper is to consider the effects of such defects, to carry out further tests on the deliberate ovalisation of tube, and to determine the relative factors of safety.

The defects simulated are not exhaustive, nor considered in combination. It follows that these tests cannot be construed to demonstrate the complete integrity of the heat exchanger pressure boundary, particularly since effects such as vibration, fatigue, seismic forces and tube to tubeplate interactions have been ignored. Nevertheless such tests are of interest in any situation where tubes are externally pressurised.

A typical P.W.R. steam generator inconel tubing was chosen for the tests, nominally 0.875 inches O/D by 0.05 inches wall thickness.

The tests were carried out on tube as commercially produced at room temperature and because the strength and elastic modulus vary little between room temperature and design temperature (650°F) and further because irradiation effects are negligible, these tests should be fairly representative of actual operational conditions.

2. Defects Considered.

Heat exchanger tubes manufactured in accordance with the ASME boiler and pressure vessel code, section II, have strict tolerances on material composition, dimensions, material properties and surface condition. The maximum ovality permitted is 1.71% but in practice is unlikely to reach this figure. (The average value of the batch of tubes for this test work being about 0.2%.) In addition, good surface finish, scratch free, is required by the code. Thus gross ovality, greater than permitted by the code, is unlikely

to be found in a steam generator in any quantity. However, ovality over any length greater than the critical length, which is only a few tube diameters, (see section 3) can result in collapse almost as easily as ovality over an infinite length. Accordingly, specimens are ovalised for lengths greater and less than this critical length.

Other defects considered are scratches, part wall penetration cracks, general thinning of the tube wall, and local wall thinning for half the circumference, as would be anticipated due to fretting at tube supports.

All defects were taken to a depth of at least one third the wall thickness and in the case of the local spark erosion, up to 60% of the thickness. It is worth noting that flaws of greater than 20% wall thickness are detectable by the eddy current technique. The USAEC Regulatory Guide 1.83 [6] specifies that the inservice inspection equipment for steam generator tubes shall detect penetration of 20% or more of the minimum wall thickness.

3. Outline of Test Programme.

Tests were carried out to collapse pressure on tube specimens, firstly, as manufactured and secondly on specimens deliberately ovalised over lengths of 3" and 8". The ovality was introduced by means of a hydraulic press, and ovalities of up to 5% were induced. No evidence of flats, where the tube contacted the press, was discernable by visual examination. It is assumed that the small plastic deformation introduced by this method does not significantly add to the strain hardening induced in the tube during the manufacturing processes.

A critical length of tube exists above which end supports have a negligible effect on the collapse pressure. This critical length has been the subject of many investigations. Carman [2] suggest the empirical relationship:-

$$L_{cr}/2R = 6 \quad (2)$$

Cook [3] gives the following relationship based on experiments.

$$L_{cr} = 1.73 \sqrt{\frac{(2R)^3}{t}} \quad (3)$$

which in this case gives an $\frac{L}{D}$ ratio of 5.8.

More recently Heise et al [4] have suggested a value of:

$$L_{cr}/2R = 8 \quad (4)$$

Clearly the 3" ovalised length is below the critical length and represents local damage to a tube where the surrounding tube assists in resisting collapse. The 8" length is nearly ten times the mean tube diameter, and represents ovality over an unlimited length of tube. The original specimens, and details of geometric measurement positions are shown on Figure 1.

In order to simulate partial through-wall cracks, some specimens were machined with longitudinal grooves of 60° V section as shown in Figure 2. These grooves were 8" long and varied in depth up to 40% of the wall thickness. The point of the tool making the groove was made as sharp as possible.

General thinning of the wall was simulated, again over an 8" length, chemically, by means of immersion in Aqua regia (50% concentrated nitric acid, 50% concentrated hydrochloric acid) until the required wall thinning was achieved. The rest of the tube was protected with a plastic coating. A maximum of one third of the wall thickness was removed in this way. The resulting tube surface was quite rough with an average CLA value

of 120 μ inches.

In order to simulate local fretting by tube supports a number of tubes were spark eroded over half their circumference by a $\frac{3}{4}$ " axial length, as shown in figure 3. Up to 60% of the wall thickness was removed in this way. Here again the eroded contour was rough with a CLA Value of 190 μ inches.

In the grooved and spark eroded specimens, the simulated flaws were randomly placed circumferentially, i.e. without reference to the slight ovality which was detectable on most specimens. It was anticipated that for the amount of ovality occurring on as-manufactured tube, the local geometry around the flaw would dominate the mode of tube collapse and that original ovality would hardly affect these results.

A schematic diagram of the test rig is shown in figure 4. The test chamber is designed to accommodate tubes of 12 inch free length and to withstand pressures of up to 6000 p.s.i. at room temperature. A light oil (Shell Tellus II) is used as the working fluid. The test chamber is pressurised by an air-hydro pump. An accumulator of large capacity is installed in the hydraulic circuit which acts as a reservoir and maintains pressure in the test chamber during the collapse process.

The tubes to be tested are mounted in the chamber on two tubular end inserts and sealing fittings which isolate the inside and the outside of the tube from each other and from atmosphere.

The specimen chamber is pressurised to any desired value by means of the hydro-pump via valves 1 and 2. The two valves are then closed and the pressure inside the tube is released via a quick acting electro-pneumatic valve. Both the inside and the outside pressures are monitored by pressure transducers connected to a U/V recorder.

The test chamber was pressurised initially to a value conveniently below the estimated collapse pressure. This pressure was maintained on the tube exterior for 5 minutes, and then raised by 100 p.s.i. and held for a further 5 minutes. This procedure was continued until the tube collapsed.

The tube material was Inconel 600, to a Swedish specification, equivalent to the A.S.M.E. specification SB-163-61T. The mechanical properties of the material are as follows:-

Yield point	45200 p.s.i.
Tensile strength	101,800 p.s.i.
Elongation	72%.

4. Results.

It was observed during the tests that in some cases collapse occurred after a noticeable time delay. (up to 3 minutes at the held pressure). This is unlikely to be a rig effect because the volume occupied by the tube in the elastic state is virtually constant, and further because of the accumulator in the pressurising system maintaining uniformity of pressure.

Because of the small increments in pressure towards the collapse point (between 1% and 1.8% of the total collapse pressure) it is believed that the change in ovality due to plasticity in the outer fibres thus increasing the moment at the plastic hinges, is almost offset by strain hardening of the material, so that the onset of collapse is slow. The fact that the specimens taking the longest to collapse were those ovalised for the

subcritical 3" length, so that the spread of plasticity was axial as well as circumferential, supports this view.

4.1 Collapse Pressure v. Ovality.

Theoretical upper and lower bound curves of plastic collapse assuming an idealised "oval" consisting of two semicircles joined by two short straight lines, and the formation of plastic hinges, assuming a linear elastic - perfectly plastic material, have been deduced by Lohmeier et al [5]. It is not intended to reproduce this theory in full here, but for convenience figure 5 shows the idealised tube cross section and the location of assumed hinge points.

The upper bound collapse pressures were obtained by equating the external work to the internal plastic work during an infinitesimal motion of the mechanism. The hinge plastic work is governed by the flow rule associated with the yield diagram which specifies that the ratio between the rotation and extension or compression shall correspond to a normal to the yield curve. See [5].

The lower bounds were found from equilibrium satisfaction for the given choice of plastic hinges and observation that yield is exceeded only over the flat region. Since the equilibrium relations are linear, lower bounds were calculated by multiplying the upper bound collapse pressure by the appropriate "centre of flat" moment ratio which reduces to the yield curve.

Two more collapse pressures can be determined for the same idealised shape; one based on the initial ovality and another based on the final ovality taking elastic deformation prior to collapse into account.

Figure 6. shows the comparison of experimental and theoretical results, where the theoretical upper and lower bounds take elastic deformation prior to collapse into account. These are preferred because the experimental points should be closer to these curves than those based on initial ovality only.

The elastic ovality has been calculated by the approach of Timoshenko [1]:-

$$e_t = \left(1 + \frac{q_y}{q_{cr} - q_y}\right) \quad (5)$$

$$\text{where } q_y = \frac{1}{2} \left\{ \frac{f_y t}{R} + \left(1 + \frac{6R}{t} n\right) q_{cr} - \left[\left(\frac{f_y t}{R} + \left(1 + \frac{6R}{t} n\right) q_{cr} \right)^2 - \frac{4 f_y t}{R} q_{cr} \right]^{1/2} \right\} \quad (6)$$

$$q_{cr} = \frac{E}{4(1-\nu^2)} \left(\frac{t}{R}\right)^3 \quad (7)$$

$$n = \frac{e D}{4} \quad (8)$$

Rather than presenting the results in terms of collapse pressure v. percentage ovality, they are presented in terms of $\frac{PR}{f_y t}$ v. percentage ovality.

This enables a comparison to be made of tubes manufactured from different materials.

Actual thicknesses, thickness to diameter ratios and average ovalities for tubes nominally round, i.e. not deliberately ovalised, were used in the determination of the experimental points. It can be seen from the figure that there is a reasonable agreement between the theoretical curves and experimental points.

The effect of slight ovality on the as-manufactured specimens is noticeable, and again agrees fairly well with the experimental curves.

The tubes having deliberately induced ovality over the sub-critical length (3") collapsed at significantly higher pressures, as would be expected.

The collapse is completely ductile and the collapsed form is shown in figure 7, which is typical of all oval tubes without defect.

4.2 Collapse Pressure v. General Wall Thinning.

The results of the collapse of specimens in which general wall thinning up to one third of the wall thickness has been carried out, is shown in figure 8. The results are again plotted against $\frac{PR}{F_y t}$ taking the effects of the reduced O/D into account, and further modified assuming an ovality equal to the average ovality (0.2%) of the as-manufactured tubes. It will be seen that the experimental and theoretical results agree very well.

The collapse is again completely ductile and of similar shape to figure 7.

4.3 Collapse Pressure v. Longitudinal V Groove.

The collapse of tubes in which V grooves of up to 40% of the tube wall thickness and 8" axial length have been machined, and are also depicted on figure 8.

Stresses around the groove are complex and not easily calculable. Accordingly, finite element computations have been carried out at each depth of groove, one mesh of which is shown on figure 9. The program used a standard constant stress element developed by G.E.C. Limited, and was an elastic program. A nominal external pressure of 1000 p.s.i. was used, and the results extrapolated up to the yield point of the material. When general yield is reached at the weakened section, the section diametrically opposite is still capable of taking a further bending moment, until collapse occurs. The additional pressure required to cause collapse was calculated by hand and the collapse pressure deduced. The theoretical collapse curve on an elastic - perfectly plastic basis is not linear, and is shown dotted on figure 8.

The collapse in every case is initiated by a crack opening mode, but even in these cases, collapse is almost completely ductile as shown in figure 10, the exception being shown in figure 11, where crack propagation of the .01" and extrusion into the bore is clearly shown on the photomicrograph of the polished and etched section.

One collapsed specimen of this type was repressurised hydraulically to 150 p.s.i. No gross change of shape from the collapsed condition occurred and there was no leakage from the tube.

The experimental points in this case are not a very good fit to the theoretical curve, particularly for the deepest groove. However, the experimental points are well above the theoretical curve at this point, probably due to plastic flow at the weak section caused by the compressive nature of the loading, tending to increase the load carrying capability.

4.4 Collapse Pressure v. Spark Erosion

Here, because the length of eroded tube is well within the critical length of tube as previous defined, and further because the erosion is over half the circumference only, a theoretical collapse pressure is difficult to determine. Considerable axial support of the thinned section is anticipated, with a limited circumferential support from the uneroded half of the tube. The experimental points may be usefully compared with the local membrane yield stress associated with the thinned wall section, and these are again shown on figure 8 (the yield line in this case being chain dotted). In this case the minimum radius is used in the calculations. The experimented points are well above this line particularly for the specimens in which 60% of the tube wall is removed, demonstrating that considerable support from the surrounding tube is, in fact, effected. As expected, the tube collapsed at the weakened part, as shown in figure 12. Again the collapse is completely ductile.

5. Comparison of Safety Factors.

It is interesting to compare relative margins of safety to failure of such tube, used in a PWR steam generator.

Typical operational pressures are as follows:-

Primary side	2250 p.s.i.
Secondary (Steam) side	860 p.s.i.
Differential	1390 p.s.i.

However, following a primary or secondary side containment failure, conditions across the tube boundary change, and the tube design pressure differentials become:-

Primary to secondary	1600 p.s.i.
Secondary to primary	670 p.s.i.

When the differential pressure is internal to the tube bursting pressure must take into account strain hardening effects and tube dilation. Several equations have been proposed for the ultimate pressure, and additional material properties are required for a more precise solution, but using the equation due to Faupel and Furbeck [7].

$$P_u = \frac{2f_2}{\sqrt{3}} \left[2 - \frac{f_2}{f_u} \right] L_n \frac{R_o}{R_i} \quad (9)$$

an upper limit is 9800 p.s.i.

This gives a maximum factor of safety during normal operation of 7.05 with an effective pressure of 1390 p.s.i. inside the tube. After a steam side failure when the differential pressure increases to 1600 p.s.i., this factor reduces to 6.12.

After a primary side L.O.C.A., the collapse pressure with a tube having the maximum ovality permitted by the ASME II code, taken from the theoretical lower bound of figure 6, is 4270 p.s.i. This gives a factor of safety of 6.37.

When the wall is thinned to 70% of its original thickness, the collapse pressure for tube with typical as-manufactured ovality, is 3710 p.s.i. The factor of safety following a primary side LOCA is now 5.54.

Tubes with cracks and locally fretted areas as studied, give collapse pressures in excess of those due to general wall thinning, for the same remaining wall thickness. Therefore factors of safety following a LOCA are better than 5.54 in these cases.

Tubes with local ovality of 5% (over a 3" length) collapse at 3520 p.s.i. This

results in a factor of safety of 5.25 following a LOCA.

It follows that the factor a safety of 7.05 for a full thickness tube wall subjected to internal pressure reduces to below 5.0 for a tube of 70% of full wall thickness.

6. CONCLUSIONS.

- 6.1 Ovality is an important consideration where tubing is pressurised externally, and can result in substantially reduced collapsed pressures compared with the nominally round tube. Ovality over a length of tube shorter than the critical length, results in a relatively higher collapse pressure than general ovality of the same magnitude over the whole tube. However factors of safety are such that for collapse to occur at operating conditions using tube thicknesses as required by nuclear design codes, the ovality would be excessive. For the deliberately ovalised specimens, the test and theoretical collapse pressures agreed very well and were similar to the results obtained by Lohmeier et al [5] for a similar material of slightly different strength.
- 6.2 Where deliberate defects were introduced into the tube good agreement was obtained between theory and experiment for tubing with general wall thinning. For other types of defect, results showed some scatter, but were surprisingly good, in all cases being better than the general yield stress in the minimum wall section would suggest. This is probably mostly due to two factors; support from the surrounding thicker wall, and the compressive nature of the loading, so that plasticity improves the local geometry at cracks. It is worth noting that the V groove machined in the specimens is probably a conservative approach, because natural fine cracks tend to close up in compression. For the order of defect considered, i.e. up to about one third of the wall thickness, general thinning gives a lower factor of safety than cracks or one-sided local fretting of the same magnitude (in terms of defect depth). This factor of safety is still quite good for the maximum defect considered and although collapse is more probable than bursting for the same pressure, for the particular design pressure differentials across a PWR steam generator, the factor of safety is about the same. However, it does not follow that this would still be the case where operating pressure causes failure, because the wall thickness would be such that instability would be the prevailing criterion for collapse.
- 6.3 For a ductile material, crack propagation is small due to collapse pressure, and for the particular material used in these tests, in no case did a crack propagate through the wall of the tube.

NOMENCLATURE

P_{cr}	Critical pressure
f_y	Yield Stress
t	Tube thickness
R	Mean radius of tube
R_o	Outside radius of tube
R_i	Inside radius of tube
L_{cr}	Critical length
L	Unsupported length of tube
e	Original eccentricity
ν	Poisson's ratio
D	$2R$
L_n	Natural logarithm
P_u	Ultimate pressure
f_2	Lower tensile yield point
f_u	Ultimate strength

References.

- [1] TIMOSHENKO, S.P., "Theory of Elastic Stability", McGraw-Hill Inc., New York 1961.
- [2] CARMAN, A.P., CARR, "Resistance of Tubes to Collapse", University of Illinois Eng. Exp. Stn. Bulletin No. 17, 1906.
- [3] COOK, G., "The Resistance of Tubes to Collapse", (Resumé and Bibliography) Rpt. British Assoc. 1913.
- [4] HEISE, O., ESYTERGAR, E.P., "Elastoplastic Collapse of Tubes under External Pressure", Trans. Amer. Sc. Mech. Engrs. J. Eng. Ind. 1970.
- [5] LOHMEIER, A., SMALL, N.C., BONIN, M.J., GONNET, B., "Collapse of Ductile Heat Exchangers Tubes with Ovality under External Pressure", 2nd Int. Conf. on SMIRT Berlin, Sept. 1973, paper F6/4.
- [6] U.S. Atomic Energy Commission, Regulatory Guide 1.83, "In service Inspection of Pressurised Water Reactor Steam Generator Tubes", June 1974.
- [7] FAUPEL, J.H., FURBECK, A.R., "Translations of Amer. Soc. Mech. Engineers" Vol. 75, 1953.

Note: Please refer to the author for the figures mentioned in the text.