THE ANALYSIS OF PRESTRESSED CONCRETE PRESSURE VESSELS WITH WIRE WOUND PRESTRESS

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SUMMARY

The paper presents new information comparing certain important features of vessels prestressed by conventional linear tendons and using tendons wound into channels on the external surface of the structure. Stress analyses for both configurations are compared and points of design are identified which have special significance in wire wound vessels. The subjects discussed include the design treatment of stress concentrations and tensile stress zones, the local effects of wire wound bands and factors affecting the distribution of stress through the thickness of the vessel walls. The prestress level in the central region of the end caps of vessels prestressed by external windings is discussed, and the effects of construction sequence and vessel operation on the stresses in this area are assessed.

The paper goes on to consider some aspects of overload conditions which have special bearing upon the design of wire wound vessels. The treatment of potential liner leakage and ultimate pressure adopted in the forthcoming British Standard Specification for prestressed concrete pressure vessels for nuclear reactors is described and appraised.

The strength of a vessel may be limited by the possibility of local failure. Certain examples of this are discussed and recommendations made for their treatment. These include the postulate of horizontal shear failure at the junction of cap and barrel, failure by extrusion of part of the vessel wall between winding bands, cap failure in the shear mode and a statement of the authors' approach to some of these questions.

Components of vessels may also be stressed by wire winding and the design criteria adopted in the design of such a component for the Hartlepool and Heysham boiler closures are described and discussed.

As a natural sequel to the comparisons offered in the paper, an attempt is made to reassess the efficiency of designs prestressed by wire wound and linear tendons, in a new discussion and quantitative appraisal of both styles. It is concluded that wire wound tendons show significant economies over corresponding linear tendons, and that when consequential economies are considered the choice of this method as a standard feature of high pressure primary containment vessels appears likely.

1. INTRODUCTION

A number of papers have been published describing various aspects of the design and development of wire wound vessels. References [1, 2, 3, 4 and 5.] In this paper the authors discuss some specific features which they feel to be of significant importance. The points referred to arise mainly from the designs of the Hartlepool and Heysham vessels, (Fig. 1), but many of them are equally relevant to single cavity vessels.

2. STRESS CONCENTRATIONS

All pressure vessels incorporate some features which give rise to local high stresses in the structure. These may be due to sharp changes of geometry, the presence of penetrations, concentrated anchorage loads from prestressing tendons and similar items. Another transient form of stress concentration can arise in concrete adjacent to the vessel liners when their temperature rises during start-up of the reactor system; and subsequently when operating changes occur which effect the liner cooling system temperatures. In wire-wound multi-cavity vessels, disturbances of the stress field in the vessel walls due to the boiler pods and gas ducts are of special significance in that their treatment may determine some of the key dimensions of the vessel.

It is impracticable to make a satisfactory detailed mathematical analysis of the majority of stress concentrations in a pressure vessel - particularly for those cases where temperature affects the deformation of the concrete and the loads applied to it, or in the case of tensile stresses where cracking of the concrete may be caused. For example; whilst the overall deformation of penetrations may not be greatly affected by the presence of small local tensile stress zones in the adjacent concrete it has been shown experimentally that neither the short nor long term strains local to such zones are accurately predicted by analysis.

The authors consider that the treatment of stress concentrations should be based largely on engineering judgement, taking due account of relevant analysis work and research. Each local stress condition and its treatment demands individual consideration. It is necessary to take account of both the complexity of the prevailing stresses and the local geometry of the structure. Where concrete is contained or is restrained from deformation by its shape, or where triaxial compressive stress states exist, credit may be taken for these factors in assessing the acceptability of the stresses. Higher local stresses may also be acceptable if they can be shown to be either transient or notional or occuring only at a single point. The fundamental requirement is to demonstrate that any high local stresses which may occur are not detrimental to the short or long term behaviour or safe performance of the vessel and to be satisfied and that significant structural liner movements and strains can be adequately predicted and are within acceptable limits.

Fig. 2 illustrates the distribution of hoop stress across a horizontal section of the vessel at the centre line of the boiler pod. It may be seen that although the average stress across the section is acceptable the stress gradient increases steeply adjacent to the boiler penetration and would theoretically lead to a very high peak stress at the liner. A further example of stress concentration in podded style vessels occurs where the pods are wide over the top section of their length where the pod closures are located. This narrows the ligament of concrete between the pods and the outside surface of the vessel. Cap prestress is applied by wire winding bands located in this area which consequently experiences high compressive hoop stresses combined with local flexual effects due to the contact pressure of the winding bands, (Fig. 3). Since these compressive stresses are not significantly relieved by pressurisation of the vessel, there can be high concrete creep deformations with consequent effects on the design of the closure seals and securing bolts. Compensating liners and reinforcement may be required to control these.

The question is how far stresses across the sections, as illustrated in the above examples, should be regarded as field stresses complying with normal permissible limits, and how far they should be regarded as local concentrations to which higher permissible limits can be applied. The authors consider that about 10% of the section can be allowed to rise to stress levels above the normal limit and up to a maximum of twice the permissible field stress. The theoretical high peak immediately adjacent to the pod can be ignored since it is a point peak stress only, reducing at sections either side, and which will also reduce due to creep.

Fig. 4 illustrates local tensile areas caused by the presence of boiler liner anchorages in an area of concrete where the stress is otherwise compressive. In this case analysis showed that any cracking of the tensile zone would be unlikely to propagate. Nevertheless it was decided to control these tensions by the provision of reinforcement.

Fig. 5 shows how local tension in the zones immediately beneath bands of wire windings may cause marked local perturbations of longitudinal stress close to the surface of the vessel. It was decided that the "ripple" effect could not endanger the structure and would be satisfactorily controlled by the reinforcement already provided close to the vessel surface to deal with tensile strains due to shrinkage.

When the vessel and boilers are brought into operation the liner temperature rises rapidly and a high compressive stress gradient is set up initially in the concrete close to the liner. Such stresses may reduce quickly because of creep, but later, when the temperature is lowered, the resulting contractile strains may cause local cracking of the concrete. Since the thermal stress history of concrete adjacent to the liner is difficult to predict, and since concrete in this region is also subject to irradiation, nuclear heating and high shrinkage effects, it must be assumed that the first few inches of concrete at the liner will be cracked. Liner anchorages should therefore be designed to pass through and be embedded beyond this region in a reinforced zone.

The greatest disturbance of field stresses occurs within the standpipe area where the structure acts as a composite of steel tubes and concrete, and where a multitude of local stress concentrations exist within the concrete ligaments. Fig. 6 gives the results of a finite element analysis for a typical standpipe configuration assuming equal and unequal biaxial stress fields. The results of such analyses should be treated with caution since they depend heavily on the simplifying assumptions which are made regarding such effects as temperature and the degree of bond between the standpipe surfaces and the concrete. The authors consider it more satisfactory to treat the standpipe area as a zone of solid concrete with a modified 'E' value and verify its overall behaviour by means of research [5] [6].

3. TOP CAP ZONE

When wire wound tendons are used, prestress in the caps of a cylindrical vessel is transmitted from the external surface of the structure and through the full thickness of the vessel walls before reaching the central zone of the caps. The function of prestress in the top cap area is to control the operating stresses in the concrete so that the effects of cracking or creep do not give rise to short or long term deformations that would be unacceptable to the fuelling route and to ensure that an adequate factor of safety is always available. It is therefore of special importance to see that there are no features of the design or construction which could lead to a loss of prestress in these central zones.

The problem is especially acute in the top cap where the close pitch of the standpipe penetrations, which have very efficient cooling systems, makes the central zone particularly responsive to changes of standpipe temperature. It is possible for the bulk temperature of the central zone to change within hours, whereas a change of liner temperature elsewhere in the vessel would take many weeks to permeate through the vessel walls. Rapid cooling of the standpipe zone is particularly significant where prestress is applied remotely and no tendons actually pass through the cap zone. Tensile stresses of some 400 to 700 lb/sq.in. (2.76 to 4.82 N/mm^2) can result from a cooling system fault in which the temperature of the standpipe zone falls rapidly. Under operating conditions this leads to net tensile stress in the cap over approximately 50% of its depth. In such a situation, although the residual prestress is sufficient to prevent a shear plug failure, considerable cracking of the concrete might occur and a thorough survey would be needed before re-commissioning the vessel. The standpipe cooling system controls must therefore have high reliability.

Difficulties can also arise where the design incorporates large plant penetrations within the cap area. If the liners of such penetrations offer too high a level of compensation they can so increase the rigidity of the annulus in which they lie that this attracts an unduly high share of the prestress at the expense of the central area. These penetrations are sufficiently large to be incorporated in a local three dimensional analysis which should include a study of the effects of the penetration liners.

Designers are becoming increasingly aware that to build vessels economically it is desirable to make provision for possible changes of construction sequence and programme. This is particularly desirable in complex areas of the vessel incorporating substantial plant components, and where the sequence and logic of the construction programme may have to be changed to accommodate alterations in the design or late delivery of items.

In the top cap of the vessel, for example, it is desirable to construct the standpipe area and barrel walls independently leaving a narrow annulus between the two which is finally cast to complete the structure. When this method is followed, care must be taken to minimise prestress loss effects caused by induced tensile strains or cracking resulting from heat of hydration effects. A similar situation arises in any sequence in which a large infill pour of concrete is cast within a matured and continuous outer ring. Hydration heating can be reduced by using low heat cement, cooling the infill through built-in pipes (expensive) or by casting the infills in shallow lifts.

Fig. 7 indicates the variation of maximum and bulk temperature of a typical 3' - 0" (0.914m) wide infill with increasing height of infill. A typical temperature analysis for a 2' - 0" (0.61m) high infill cast with low heat cement concrete is shown in Fig. 8. Laboratory experiments and full scale site mock-up trials indicate that a bulk heat of hydration shrinkage contraction of 8.5 microstrain per $^{\circ}$C occurs. For a 2' - 0" (0.61m) high infill this leads to built-in tensile strains which can give rise to high local prestress losses. For an infill it is therefore desirable to control the heat rise such that the heat of hydration cycle of the concrete can be accomplished without cracking. This will allow built-in strain relief by creep, hence minimising any prestress loss effects.

4. DESIGN CRITERIA

The British Standard Specification for Prestressed Concrete Pressure Vessels for Nuclear Reactors, which is now in course of publication, requires two hypothetical ultimate loadings to be examined. In the first of these the liner is assumed to remain intact and the vessel structure is required to have a minimum ultimate strength of 2.5 times design pressure. In the second case, the liner is assumed to have ruptured so that gas pressure is applied to the cross sectional area of the vessel concrete as well as to those surfaces of the vessel which receive gas pressure under normal operating conditions. In making this calculation the pressure is assumed to diminish linearly from that in the main cavity to atmospheric at the outside of the vessel. The ultimate strength of the structure using these assumptions must be at least 1.5 times design pressure. This second calculation may be waived if it can be shown satisfactorily that liner integrity against significant leakage at a pressure up to 1.5 times design pressure is guaranteed.

The specification recognises that the ultimate pressures implied in these calculations are hypothetical figures and are only a convention expressing the reserve of strength in the structure. The actual maximum pressure in the vessel is controlled by extensive reactor safeguards and cannot exceed a defined maximum safety valve accumulation pressure of 1.1 times design pressure. In addition the standard allows the designer to propose alternative design criteria based upon limit-state considerations where these are more appropriate. This form of examination is particularly useful when considering failure modes in which the strength of the structure or area is not sensitive to reduction in the strength of the constituent materials.

Three examples of this may be mentioned:-

Fig. 9 illustrates a potential local failure mode in which a pyramoidal segment of the vessel wall opposite to a boiler pod is assumed to extrude outwards between two bands of wire windings. With the concept of a global load factor it is required to show that this form of failure cannot occur below a hypothetical pressure of 3.0 times design pressure. At such a pressure, the vessel concrete in the vicinity is likely to be in a state of biaxial tension, cracking will have occurred and the notional segment will be contained only by the strength of the steel components passing through or supporting it, plus the effects of any "aggregate interlock" which can be justified on the postulated failure planes. Such a calculation gives a very pessimistic assessment of the true safety of the area since it obscures the fact that part of the global safety factor represents an allowance for the degradation of the materials of the vessel.

If the global factor is treated as having two parts: a totally different situation is apparent, typically it might be assumed that partial factors are as follows:-

a) Partial factor applicable to loading:-

γ_l = 1.5 to 2.0 (depending upon circumstances)

b) Partial factors to allow for loss of strength in the materials:-

γ_{ms} = 1.15 (applicable to steel components)

γ_{mc} = 1.66 (applicable to concrete)

With this approach, at a required ultimate pressure of say 1.50 times design pressure, biaxial compression is still present in the area under consideration, a significant shear strength can be allowed at the failure planes and the capacity of the structure to resist the factored pressure is seen to be ample. This example also emphasises the necessity of appreciating the character of the failure mode. In this case, the local capacity of the vessel to resist failure appears high at design pressure and moderate overloads, but reduces rapidly once the compressive prestress in the area approaches zero and the concrete approaches a state of biaxial tension.

Another case is the postulate of horizontal shear failure at the junction of cap and barrel. This failure mode is of interest since its occurrence could initiate a liner failure. No rigorous calculation of this case can be made since the structure is in a cracked condition and key compressive zones of concrete are loaded beyond the elastic range. In approximate terms, failure can occur when pressure loading on the cap of the vessel (Fig. 10b) is sufficient to overcome the vertical prestress on the section under consideration. It is also affected by the position and direction of the failure plane at the cap/barrel junction and the balance of circumferential prestress which is available to control radial movement of the barrel after separation has occurred. Whilst it is clearly necessary to provide enough vertical prestress and a safety margin which is sufficient for operating purposes and to prevent this failure mode, it is unnecessary to cover pressures equivalent to a global safety factor of 2.5 or 3.0 when a realistic partial factor applicable to the loading is probably much lower.

Corresponding considerations apply to the failure mode expressed in Fig. 10a. If the cap design is related to an ultimate load capacity of three times design pressure, this may lead to a greater cap thickness and circumferential prestress than would be necessary if the design were assessed using separate partial factors applicable to the loading and material properties.

5. WIRE WOUND BOILER CLOSURE

Safety authorities throughout the world are placing increasing emphasis on the integrity of closures to major penetrations of the vessel whose failure might lead to excessively rapid depressurisation of the gas circuit.

The closures used for the boiler pods of the Hartlepool and Heysham vessels [3] have a high level of structural redundancy provided by the use of two systems of wire wound prestress: - an "active" system, comprising layers of stressed wire, which maintains the closure effectively free of tensile stresses under normal operating conditions. Further layers of wire are wound, at nominal tension forming a "passive" wire reinforcement system capable of providing a load factor of three without assistance from the stressed windings. The level of stress in the "passive" windings is set so that after concrete creep during the design life of the closure the passive windings are still in contact with the closure.

The closure is secured to its supporting flange by 48 bolts, stressed to provide a preload across the seal face of 1.3 times the design gas pressure load. Some of this prestress is applied through the closure concrete, but most is transmitted directly to the seal flange through the unbonded bolt tubes (Fig. 11). The proportion of load sharing can be controlled by adjusting the projection of the loose collars above the top bearing ring. The use of bolt tubes in this way reduces the effects of concrete creep on the bolt prestress and hence minimises the relaxation of preload across the seals. In addition, the elasticity of the bolt tube ensures that actual lift-off of the closure from the seals under overload conditions will not occur until a factor well above 1.3 (2.2 for the Hartlepool closure).

The closure was proportioned and initially assessed using axisymmetric analysis of an equivalent model; and was verified by extensive testing to loads in excess of six times the design pressure [7]. A full size mock-up has been made of the closure to establish concreting and assembly techniques and also to test the wire winding system. The central penetration was instrumented at three levels with strain gauges attached to the bonded liner. Readings were taken as layers of active and passive wire were wound on and the hoop strains as recorded and as predicted by the analysis are shown in Fig. 12. This demonstrates that the simplified analysis technique adopted is valid for general assessment of the behaviour of the closure and that the prestress is satisfactorily transmitted to the central area of the closure through the narrow ligaments of concrete.

With the background of development research and design carried through for the design of the Hartlepool closures, the authors believe that design criteria can be rationalised for future designs to give an even more economic solution.

6. ANALYTICAL AND ECONOMIC COMPARISON

Some of the peculiarities arising in the design of wire wound vessels have already been referred to. Most important in practical terms, however, are the increased simplicity and economy of construction which result from the use of wire winding. This has a number of intrinsic advantages over alternative methods for prestressing nuclear or other large pressure vessels, among which are the following:

(a) It is possible to provide very high intensities of prestress in a very compact arrangement.

(b) There is no loss of efficiency in the tendon system arising from frictional losses.

(c) The outside surface of the vessel can be kept free of the heavy anchorage ribs, or their equivalent, which are required to accommodate the tendon exits and anchorages when conventional tendons are used.

(d) The walls of the concrete vessel are not congested by large concentrations of horizontal prestressing ducts, and it is therefore easier to construct the vessel and to maintain a consistently high quality in the placing and compaction of the concrete.

(e) There is a considerable saving through the omission of anchorages and the reduction in the quantity of prestressing steel required to achieve a given prestress.

(f) Since the winding bands provide a uniform radial force around the circumference of the vessel their effects can be represented simply and precisely in the analysis.

To examine the analytical differences between hoop prestress from linear tendons and from wire winding the authors compared a representative vessel with linear hoop tendons and an equivalent wire winding system. The vessel was analysed on the basis of BBRV 145/7mm tendons in the locations shown in Fig. 13. This led to the hoop prestress (transfer) stress distributions also shown in Fig. 13. Wire winding bands were then applied to the outside surface of the barrel such that essentially the same hoop stress values were achieved at the barrel liner and in the centre of the caps. The comparisons were performed on a simple axisymmetric analytical basis with no account taken of the heat exchanger and blower penetrations and with the effective modulus of the standpipe zone assumed as unity.

Fig. 14 shows the comparison between the hoop and radial stresses in the barrel and caps of the vessel for the two systems of applying hoop prestress. As may be expected the hoop stresses are very similar, but the radial stress which is at a peak at the outside surface of the vessel for wire winding does not reach a peak until well into the vessel with the conventional linear tendons. This is a significant advantage for a wire wound vessel since penetrations at full circuit pressure can be located as close to the outside surface as shielding requirements will allow.

The salient quantities for the two prestressing systems are expressed graphically in Fig. 15. It is clear that there is considerable economic advantage in choosing wire winding. In addition there will be valuable time saving due to being able to clear the barrel of the complex arrangement of circumferential ducts.

7. CONCLUSIONS

In this paper the authors have attempted to isolate a number of problem areas which though applicable to some extent in all pressure vessels are particularly relevant to wire wound vessels. Most of the problems concern areas where mathematical analysis is only of limited assistance and they all emphasise the need for the designer to recognise the limitations of the data available to him. Where uncertanties remain he must assess the practical implications of these and if necessary arrange his design to reduce, or eliminate, their significance.

The particular detailed design problems associated with wire wound vessels have been successfully solved and it is clear that wire wound construction can provide vessel styles which are appropriate to all the major gas cooled reactor types which are under development at the present time. Multiple-cavity wire-wound vessels have already been incorporated in several proposals for high temperature helium cooled reactors using either steam cycles or direct gas turbine cycles. Variations of the same style are envisaged for several process heat applications and for a gas cooled fast reactor. Another form of wire wound vessel offers a valuable means of constructing a high capacity containment for the commercial L.M.F.B.R. Thus the vessels at Hartlepool and Heysham appear to be the fore-runners of a long line of future single and multi-cavity vessels based on wire winding.

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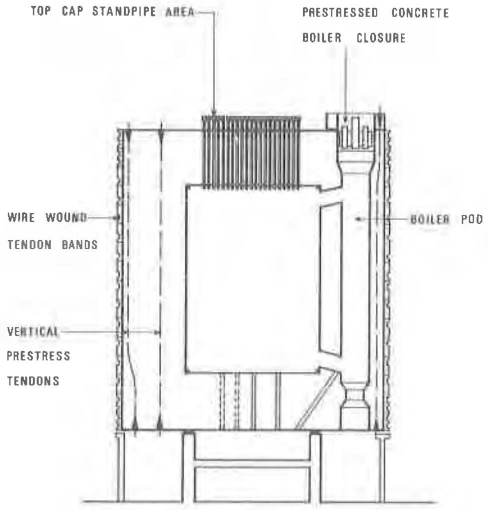

FIG 1 – VERTICAL SECTION THROUGH HARTLEPOOL/HEYSHAM PODDED STYLE PRESSURE VESSEL

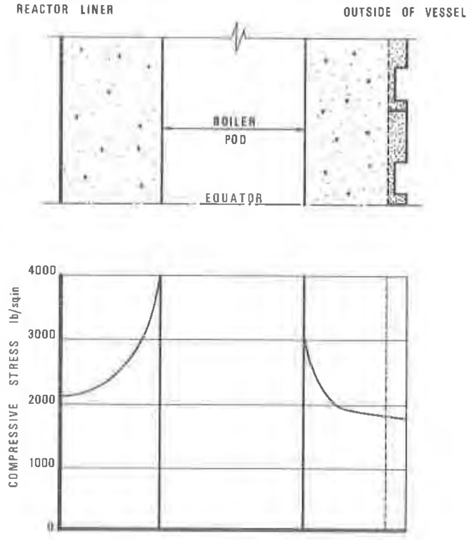

FIG 2 – HOOP STRESS DISTRIBUTION THROUGH BARREL WALL ACROSS ℄ OF BOILER AT EQUATOR LEVEL PRESTRESS LOAD ONLY

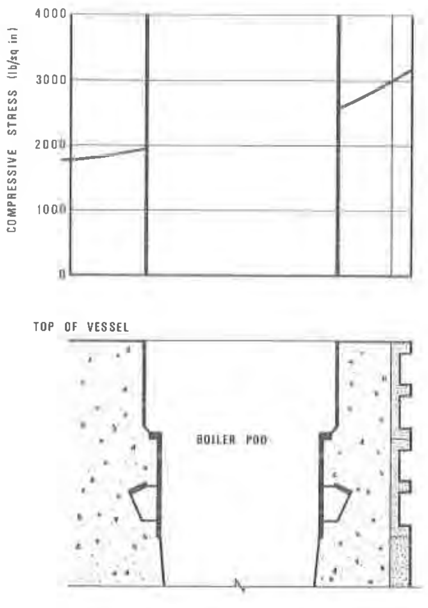

FIG.3 – HOOP STRESS DISTRIBUTION IN LIGAMENT BETWEEN BOILER POD & OUTSIDE OF VESSEL PRESTRESS LOAD ONLY

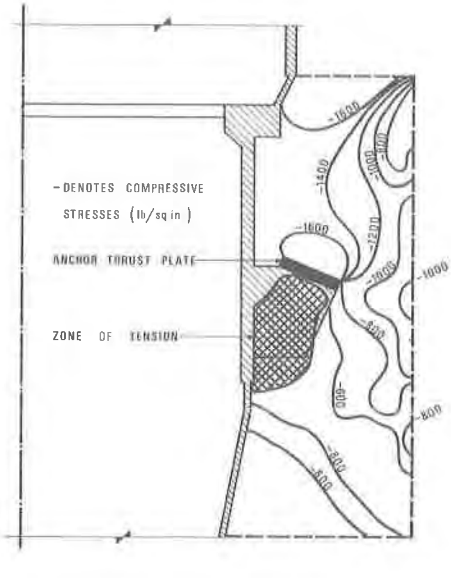

FIG 4 – STRESSES ADJACENT TO BOILER LINER ANCHORS AT BOILER CLOSURE FLANGE POSITION. LATE LIFE OPERATION

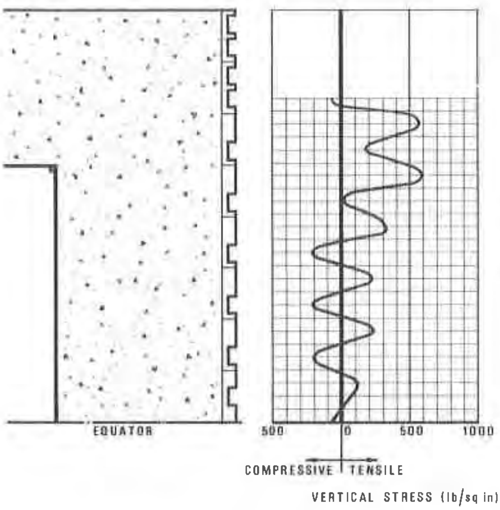

FIG 5 – VERTICAL STRESSES ON OUTSIDE SURFACE OF VESSEL UNDER EARLY LIFE OPERATING CONDITIONS

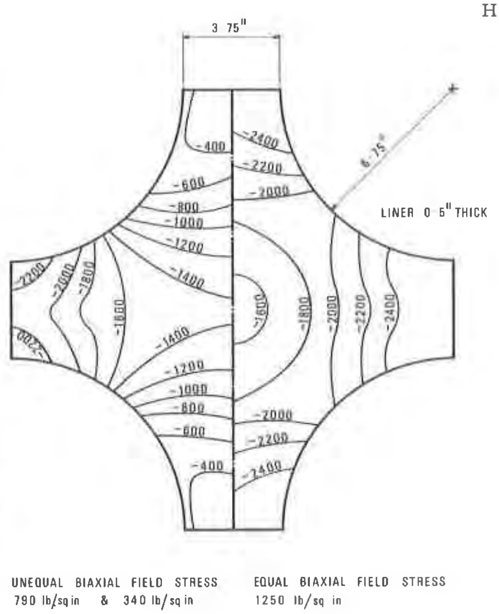

FIG 6 – DISTRIBUTION OF COMPRESSIVE STRESSES IN STANDPIPE CONCRETE LIGAMENTS UNDER THE ACTION OF EQUAL AND UNEQUAL BIAXIAL FIELD STRESSES

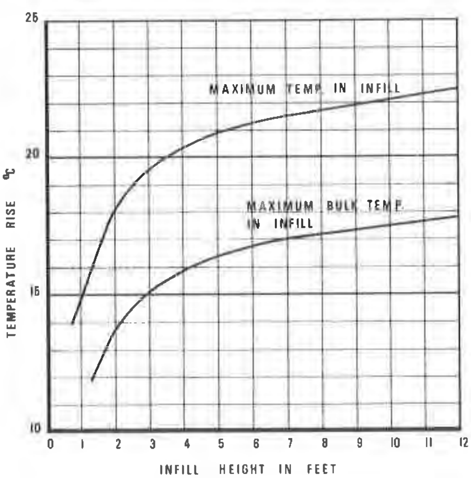

FIG 7 – VARIATION IN TOP CAP ANNULUS INFILL TEMPERATURE WITH INCREASING HEIGHT (INFILL 3 0' WIDE) LOW HEAT CONCRETE

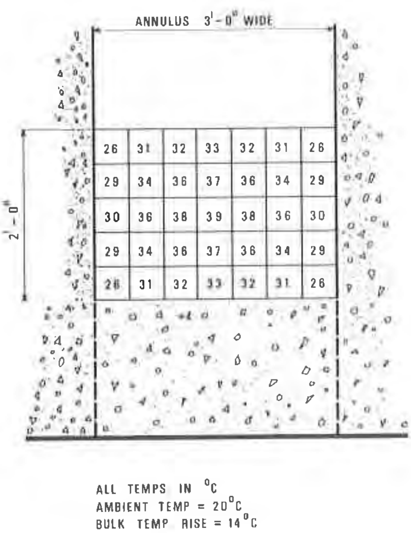

FIG 8 – MAXIMUM HEAT OF HYDRATION TEMPERATURE DISTRIBUTION (L H C) IN 2'-0" HIGH INFILL LIFT

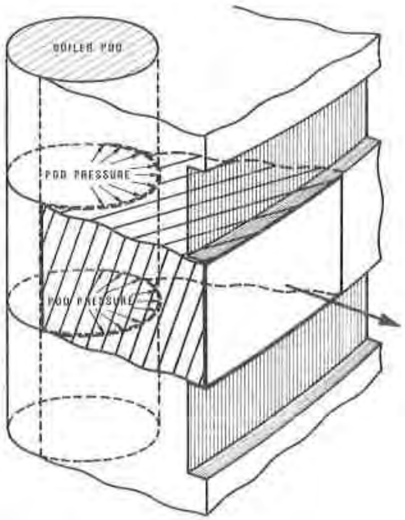

FIG 9 – LOCAL FAILURE MODE WHERE SEGMENT OF VESSEL ADJACENT TO BOILER POD IS EXTRUDED BETWEEN BANDS OF WIRE WINDINGS

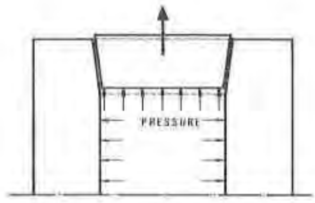

FIG 10a – SHEAR PLUG FAILURE

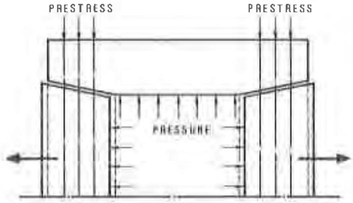

FIG 10b – FAILURE AT JUNCTION OF CAP & BARREL

FIG 10 – SHEAR FAILURE MODES AT CAP & BARREL JUNCTIONS

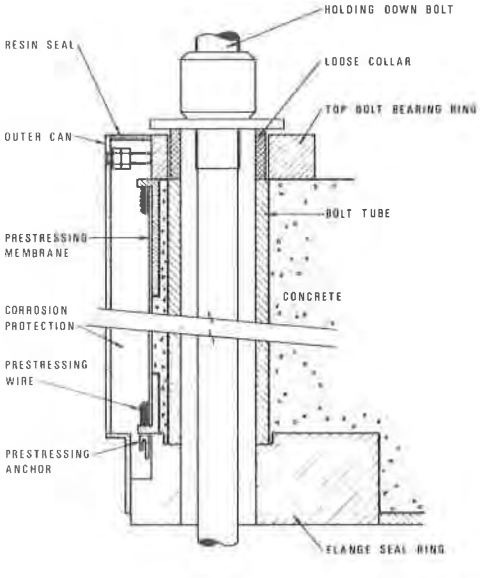

FIG 11 – PRESTRESSING DETAILS OF PRESTRESSED CONCRETE BOILER CLOSURE

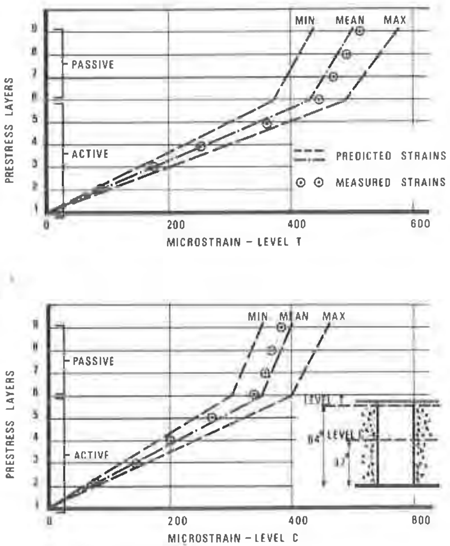

FIG 12 – COMPARISON BETWEEN MEASURED AND PREDICTED STRAINS FOR CENTRAL PENETRATION OF FULL SCALE TRIAL BOILER CLOSURE WITH APPLICATION OF PRESTRESS

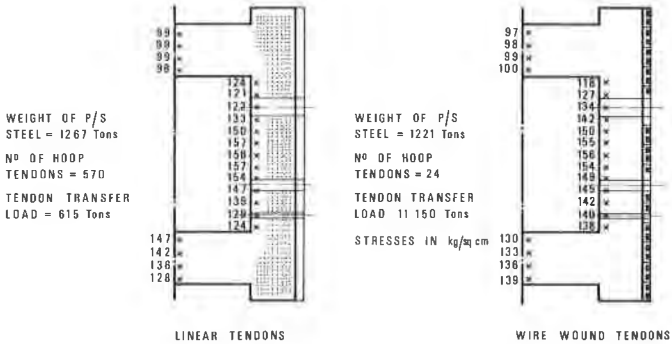

FIG 13 – COMPARISON OF HOOP STRESSES FOR PRESTRESS ONLY ANALYSIS OF A TYPICAL VESSEL USING LINEAR AND WIRE WOUND TENDONS

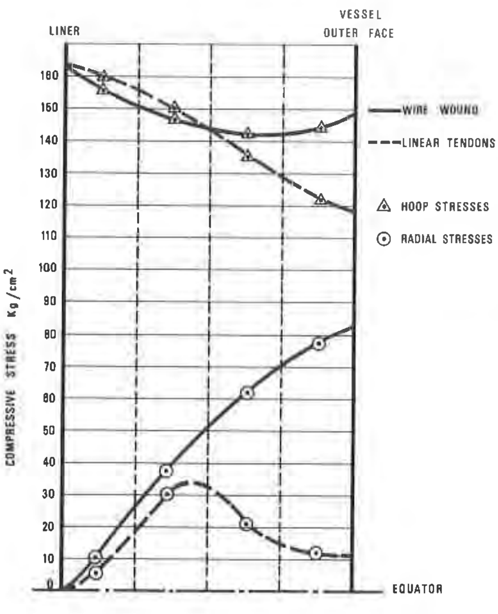

FIG 14 – COMPARISON BETWEEN RADIAL AND HOOP STRESSES THROUGH BARREL WALL OF VESSEL FOR WIRE WOUND AND LINEAR TENDON PRESTRESS

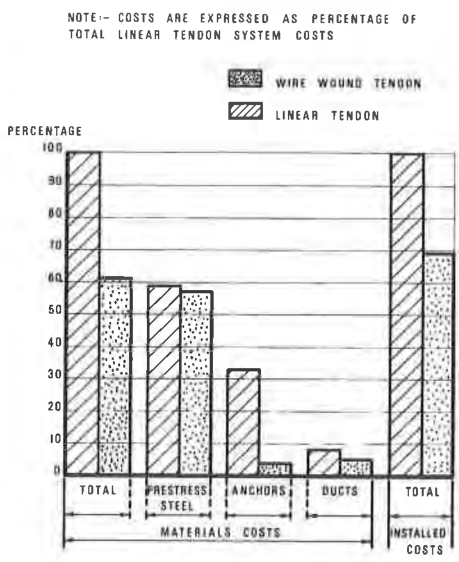

FIG 15 – COMPARISON OF COSTS OF APPLYING CIRCUMFERENTIAL PRESTRESS TO A VESSEL BY LINEAR TENDONS AND WIRE WOUND TENDONS