A SUSPENDED STEEL PRIMARY SODIUM TANK FOR A COMMERCIAL FAST REACTOR IN A STRONG CONTAINMENT

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SUMMARY

In the safety case for commercial fast reactors (CFR), it is evident that containment can play an important part in providing protection against accidents that have a finite probability of leading to energy release from the core. In the case of reactors having integral primary plants contained in a tank, it is attractive to consider strengthening the concrete shielding in the roof and side walls by prestressing in order to provide the containment.

The concrete containment walls must be kept at a suitably low temperature and protected by thermal barriers against the contained sodium at a temperature of about 400 °C.

Suspending a steel membrane tank within a strong vault from its roof, so that the main thermal insulation consists of an inert-gas filled gap between tank and vault liner, appears to be a possible proposition.

The tank must be attached to the roof liner by an impermeable weld. The sodium level is at about 4 m from the welded junction. Above the sodium is inert gas at an intermediate (but indeterminate) temperature. Insulation of tank and liner in the gas space is possible, but the likelihood of deposition of sodium frost, if the roof liner and tank upper portions are cool, are important questions. Constructionally, the weld between roof liner and tank must be made before pre-stressing, so that the weld is circumferentially compressed after pre-stressing. Choice of an operating temperature for the junction higher than the temperature at which it was constructed also leads to circumferential compression. These compressions lead to both hoop and bending stresses in the tank wall, as also does the "free" expansion of the tank at the level of the sodium.

The paper gives the results of some typical stress explorations in the upper regions of the tank. The importance of the temperature gradient in the tank wall at the junction is illustrated: important reduction of bending stress at the junction can be achieved by local suppression of gradient. Further reduction can be achieved by local tapering of the tank wall thickness. Further substantial reduction can be achieved by introducing a horizontal "flexing plate" a short distance below the junction, the vessel load (i.e. mainly the weight of the contained sodium) being carried by flexible links. This device has the effect of making the stresses at the junction almost invariant with sodium temperature; the temperature variable stresses below the junction are relatively small.

The stress results obtained are briefly assessed in relation to the available design codes.

1. Introduction

The type of reactor under discussion in this paper follows the general style of the Phenix and Dounreay Prototype Fast Reactors. An illustration of the style at about 1000 MW(e) is given in Figure 1. In considering protection against whole core disassembly accidents, the use of the biological shielding of the primary circuit of this reactor type as a high energy containment is, by inspection, attractive. It is known from the work on gas cooled reactors that pressures higher than those expected in a fast reactor accident can be contained by prestressed concrete structures.

The design basis of the present analysis is the use of a thin stainless steel membrane tank to contain the primary sodium during normal operation. This tank is welded to the underside of the roof in order to provide a structure which contains in a leak-tight manner not only the sodium but also the inert cover gas above it. The external space around the sides and base of the tank is filled with inert gas and contains thermal insulation which, together with cooling means, maintains the concrete structure at an acceptable temperature of 80°C. or less.

For the roof structure, insulation is also required. This insulation is immersed in the cover gas, which will circulate slowly due to the effects of thermal convection and will be saturated with sodium vapour. This insulation will be formed of spaced layers of stainless steel foil. The temperature of the steel lining of the underside of the roof is important since formation of sodium frost could destroy the thermal resistance of the insulation. Either the layers below 100°C must be sealed or a higher temperature must be chosen for the steel lining so that any sodium vapour which penetrates only condenses to the liquid state and can be drained away. If that solution is chosen, the steel lining must be backed by a layer of temperature resistant high thermal conductivity concrete.

The thin steel tank is not expected to play an important part in a whole core disassembly accident. However, the junction with the roof lining must remain sound for the normal operational life of the plant. The purpose of the investigation here reported is to consider the stress system in the vicinity of the junction and the major factors that influence it.

2. Stress analysis

2.1 Design Variables

For the purpose of study, it is convenient to divide the parameters influencing the stress condition of the vessel into those which are mainly externally imposed and those which are mainly under the control of the designer of the steel vessel. In the former class there are:

i) Vertical height of cover gas volume.
ii) Temperature, frequency and magnitude of temperature change.
iii) Magnitude of prestress-induced strain at the vessel/roof junction.
iv) Temperature of vessel/roof junction.

In respect of these variables, the objective of design study is to explore how they may be allowed to alter in the direction of greatest benefit to other aspects of design without damage to the vessel.

In the latter class there are:

i) Shaping of temperature gradient along the vessel.
ii) Choice of basic vessel thickness.
iii) Choice of thickness distribution.
iv) Choice of materials and their distribution in the neighbourhood of the junction.
v) Within limits, choice of geometry in vicinity of junction.

2.2 Method of analysis

As the objective of the work was to explore the factors important to design and not precisely to compute the stresses in a pre-determined embodiment, it was decided in the interests of speed and economy first to undertake a survey by hand calculations on uniform thickness geometries. The important variables having been determined, limited finite element analysis was undertaken on more complicated embodiments within the range of interest disclosed by the survey.

The hand calculations were based on specific solutions of the well known equations for elastic deformation of an axi-symetrically loaded thin uniform cylinder:-

$$\frac{R^2t^2}{12(1-\sigma^2)} \frac{d^4u}{dx^4} + U = R\alpha\theta \qquad \text{equation (1)}$$

$$T = E\{\frac{u}{R} - \alpha\theta\} \qquad \text{" (2)}$$

$$p = \frac{E}{1-\sigma^2} \frac{t}{2} \frac{d^2u}{dx^2} \qquad \text{" (3)}$$

where R = cylinder radius, t = cylinder thickness, E = Young's Modulus, σ = Poisson's Ratio, T = circumferential membrane stress, p = axial bending stress in outer fibres. U = radial displacement, x = axial dimension θ = local temperature.

Equation (1) is readily solved explicitly if θ is expressed as sine and cosine functions of x. For the purpose of this analysis, two series of solutions were derived based on first terms only, namely:

$$\theta = \theta o \sin \frac{\pi x}{2L} \qquad \text{equation (4)}$$

$$\theta = \frac{\theta o}{2} \{1 - \cos \frac{\pi x}{L}\} \qquad \text{" (5)}$$

Where θo = the temperature difference between sodium pool and junction with roof, L = the length over which the temperature gradient is developed. Solutions were derived for the cylinder length containing the temperature gradient, joined to the lower portion of the vessel at uniform temperature. This lower portion was treated as a semi-infinite cylinder.

Two geometric styles were considered a) with the tank joined directly to the underside of the roof b) with a horizontal flexing plate joining the lower tank portion, the weight of which is carried by straps, to an upper portion of reduced diameter.

In the latter case, for the flexing plate, the well known formulae for the symmetric bending of circular flat plates were also used. The two styles are shown in Figure 2.

Cases of variable thickness, variable material and more complicated temperature distribution were then treated by a finite element analysis, but still as elastic cases. The computer programme used was 'GENSH', which is a finite element program for the elastic small displacement stress analysis of thin axi-symmetric shells. The element used is a tapered cone with a node at each end and three degrees of freedom at each node. The freedoms are axial and radial displacement, referred to this axis of symmetry, and axi-symmetric rotation.

Allowing for the rigid body freedom parallel to the axis of symmetry there are five freedoms available to describe displacement patterns. Using the natural stiffness method, these have been chosen to be constant strain along the line joining the nodes and constant, linear, parabolic and cubic distributions normal to this line. The strain-displacement relationships for the element have been obtained using the usual assumptions of thin shell theory that radial and shear stresses may be ignored. The stress distributions are a combination of membrane and bending. Further examples of the use of the program are given in references (1) and (2).

2.3 Principal dimensions and loading conditions

The vessel is taken to be fabricated from Tp 316 steel and to be 360 ins. (9.1 m) radius. For the purpose of initial assessment, the general vessel thickness is taken to be ¾ ins. (19 mm). This thickness is influenced by considerations of constructibility rather than primary stress; the weight of sodium in the tank is about 3000 tons and the primary membrane stress therefore only 4000 p.s.i. (27.5MN/m^2). The sodium level is 160 ins. (4.06m) below the roof; this is the maximum length over which a pool-to-roof temperature gradient can be generated.

The normal operating condition in the sodium pool is 400°C. This may rise during transient faults to 450°C and be reduced fairly frequently by as much as 200°C for operational reasons. 500 cycles through 200°C. and 10^4 cycles through 50°C. have been conservatively used as a basis of assessment.

The radial strain at the junction of tank-to-roof imposed by the prestressing of the concrete is 600×10^{-6}. This value covers the expected creep of the roof structure. This strain can for practical purposes be assumed invariant.

The temperature of the junction is an important variable from the point of view of insulation design. It is assumed that the aim is to operate the roof lining above the reactor at 110°C., falling to say 70°C. in the vault. It is assumed initially that the junction is operated at 70°C, (giving rise to a limited sealing problem) having been constructed at 20°C.

2.4 Basis of assessment

The calculated stress conditions have been assessed against the ASME Boiler and Pressure Vessel Code Section III. For the secondary stresses involved in this type of loading, the allowable stress intensity value is 50,000 p.s.i. (345MN/m^2). The allowable fatigue stress for 10^4 cycles is 60,000 p.s.i. Thus it can be seen by inspection that no thermal fatigue problem is likely to exist if the code value stress intensity is not exceeded, even taking into account such stress concentrations as might exist.

Because of axi-symmetry and the consequent suppression of anticlastic curvature, an axial bending stress p is accompanied by a circumferential bending stress σp. In the regions of high stress, where bending is dominant, the stress intensity is therefore the greater of p or $p(1-\sigma) + T$.

3. Results

3.1 Simply supported tank

The influence of temperature gradient taken by itself is illustrated for a reference temperature difference of 400°C. for a uniform thickness tank in Figure 3. Note that the maximum hoop membrane stress does not occur at the junction. The curves show the extreme importance of controlling the gradient so that it is as near zero as possible at the junction, and also that the gradient must be controlled over a very considerable length of the vessel.

At the junction itself, in absence of gradient, the prestress-induced strain is 600×10^{-6} and the temperature-induced strain (due to 50°C.) is 900×10^{-6}. These strains induce respectively 18,000 p.s.i. ($124 MN/m^2$) and 27,000 p.s.i. ($186 MN/m^2$) hoop membrane compression and 32,500 p.s.i. ($225 MN/m^2$) and 48,800 p.s.i. ($340 MN/m^2$) axial bending stress.

Thus with any practicable length over which the gradient is controlled, allowable code stress values will be exceeded, though it can be argued that the prestress-induced stresses should be considered as constructional stresses and not as operational stresses under the code.

Detailed plots show that the regions of high bending stress are extremely localised, indicating that considerable reduction from the above stress levels should be obtainable by varying the thickness of the vessel near the junction. Figure 4 shows the stresses due to prestress and those due to temperature effects (junction plus gradient). The effect of junction temperature is reduced by interposing an inconel section between the 316 vessel and the roof lining, which will be mild steel. The case illustrated is the best of a range studied, though not necessarily an optimum. Temperature stresses are well within those allowable under the code, and even combined prestress-induced and temperature-induced stresses do not greatly exceed the Code allowable.

However, inspection of Figure 4 shows that compressive membrane stresses exist over a considerable portion of the vessel. These stresses might lead to vessel buckling. Exact calculation has not been attemped, but an assessment has been made against the' uniform hoop membrane compression that would exist at buckling due to external pressure on a cylinder of about the length over which the compressive hoop membrane stress due to thermal gradients is significant. The conclusion of this assessment is, that the possibility of buckling cannot be excluded. (In this assessment, all causes of hoop membrane compression must, of course, be taken into account). Should, in practice, even a modest axial temperature gradient exist at the junction, this will increase the compression and hence the risk of buckling.

3.2 Tank with flexing plate

The principal objective of the design is to separate the stress effects of temperature gradient from those of prestress and junction temperature level by means of a relatively flexible flat plate. The radial width of the plate is limited by reasons of economy and its thickness, for ease of construction, must not be too different from that of the tank material. The objective of optimisation is to choose the upper cylinder length and flat plate thickness so that close balance of stresses in all parts is achieved. With the upper cylinder and plate at constant temperature, it is necessary to maintain a cosine distribution in the lower tank in order to avoid excessive rotation of its upper edge. Figure 5 shows the stresses finally achieved with optimum dimensions and taper at the junction. Stresses everywhere are low and the hoop membrane compressions, in particular, are insignificant in the lower cylinder. Buckling in the upper cylinder, which is short and well-supported at both ends, is not to be feared. Even at the very point of junction, the stress intensity due to both prestress and junction temperature is well below that allowed by code.

4. Design Aspects

Success of the design in practice depends on accurate control of temperature gradients. Uncertainty and possible variability with time of heat transfer coefficients inside the vessel and of insulation performance indicate, that this control will be very difficult to achieve by adjustment of external heat transfer coefficients from a flow of low temperature gas. Furthermore, a large volume flow will be required and the necessary numerous penetrations of the concrete containment would be difficult to close in the event of a core energy release. Gradient control by a pumped liquid at the required temperature is therefore preferred, a large excess of insulation being provided inside the vessel. This design style is particularly important near the junction.

The cooling system must be developed to aim for guaranteed uninterruptability. However, should loss of cooling occur despite this, there is increased time for lowering the sodium temperature if the radial heat flow is made low and the cooling system in contact with the vessel is at the required temperature and of significant thermal capacity

5. Conclusions

The design of a suspended steel tank in a prestressed concrete containment appears feasible for a large pool-type sodium cooled fast reactor primary circuit, assessed against conservative stress criteria. Careful design of the junction between tank and structure is required and the cooling system, in conjunction with insulation provisions, must give accurate control of temperature gradients.

Desirably, the insulation should everywhere operate above sodium freezing point. The design described achieves this aim except over a very limited region, in which internal insulation must be carefully sealed against sodium vapour ingress.

6. Acknowledgments

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7. References

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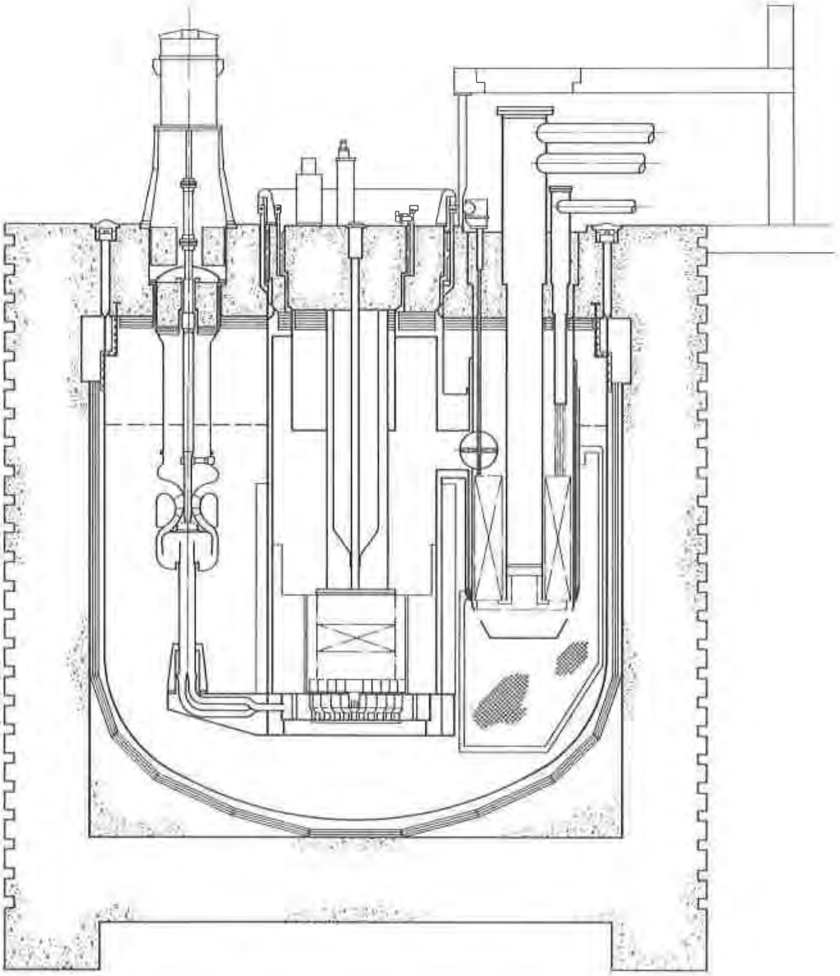

Fig. 1 - Typical 1000 MW(e) Pool-type Reactor

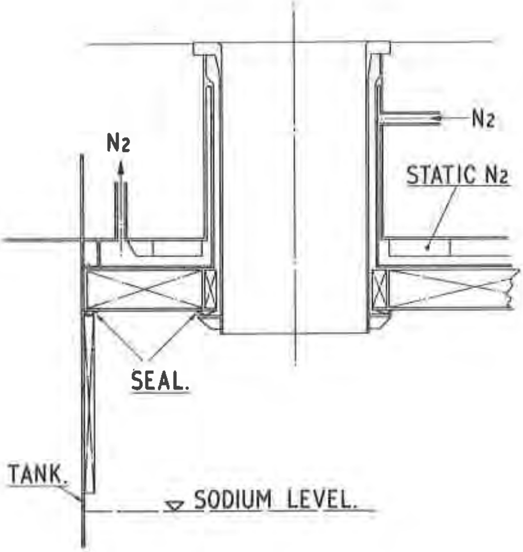

Fig. 2a - Arrangement of Simply-suspended Reactor Tank

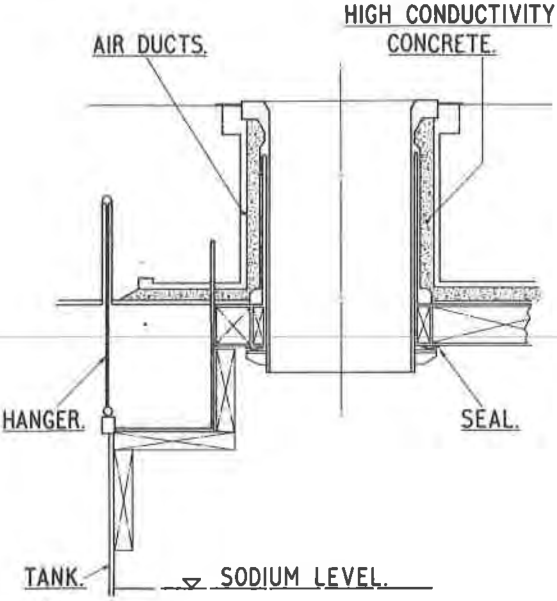

Fig. 2b - Àrrangement of Strap-supported Reactor Tank with Flexing Plate

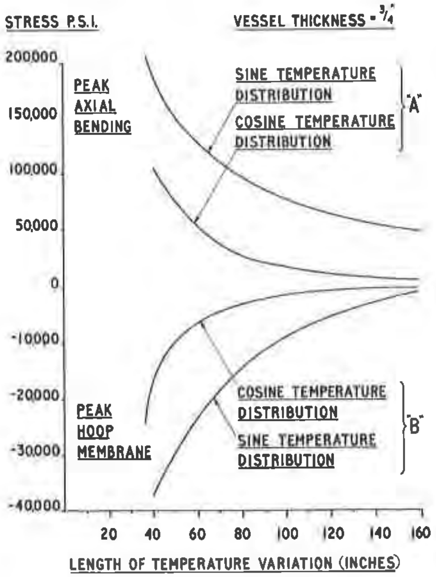

Fig. 3 - Peak Stresses in Simply Suspended Uniform Thickness Tank due to Temperature Gradients Only

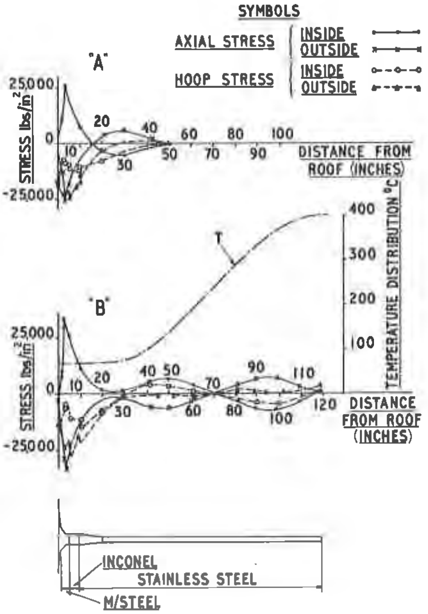

Fig. 4 - Stresses in Simply Suspended Tapered Tank due to Prestress of Containment Structure (Top) and Temperature Gradient (Bottom)

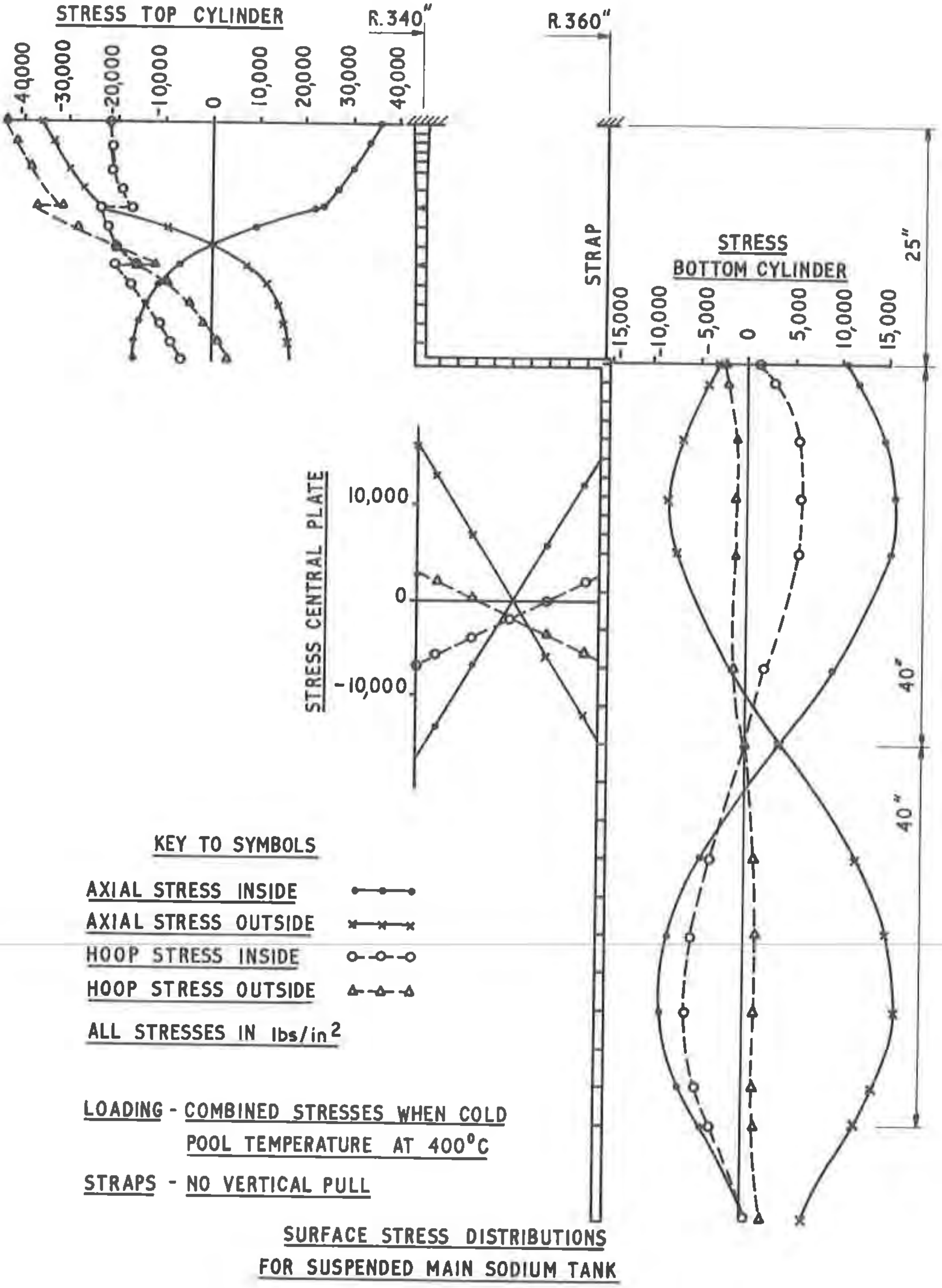

Fig. 5 - Surface Stress Distributions for Suspended Main Sodium Tank