BASIS OF DESIGN OF LINERS FOR PRESTRESSED CONCRETE PRESSURE VESSELS, AND PRACTICAL EXAMPLES OF THE APPLICATION OF THE DESIGN BASIS

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ABSTRACT

This paper reviews the duties of a liner and the imposed conditions it is called upon to withstand. Materials for construction and design concepts are considered. The various strains and restraints imposed on the liner are examined and the way in which they can produce interaction forces between the liner and the concrete vessel described. The distribution of these forces between liner attachments, the local redistribution of liner strains because of the deformation of these attachments under these loads, and the effects of liner buckling are considered.

Having established the basic liner design to satisfy the operating conditions, the effect of various methods of construction on the overall cost and construction programme are discussed. Reasons are given for the various methods of construction used for the liners designed and built by Whessoe Ltd. and mention made of service experience.

1. GENERAL BACKGROUND TO LINER DESIGN CONCEPTS

Whessoe's association with liners dates back to the late 1950's. At this time in the United Kingdom consideration was first being given to the use of pre-stressed concrete pressure vessels instead of steel pressure vessels to house gas-cooled nuclear reactors, thus removing the restrictions on size and operating pressure imposed by the steel vessels. This development also gave the important bonus of increasing the ultimate safety of the reactor pressure circuits. As manufacturers of the steel pressure vessels Whessoe could well appreciate the logic of these arguments, and upon consideration resolved to move with and assist this change rather than to resist it, therefore becoming intimately involved in the development of liners and other components for concrete reactor pressure vessels from the earliest formative stages.

From the outset it was accepted that some form of lining for the cavities of the concrete vessel was essential in order to render the vessel impermeable to the contained gases. Having accepted the necessity for providing a lining it soon became obvious that if it were made from suitable materials to a suitably robust design it could serve a number of other purposes during the construction and operation of the power station. Amongst the more important supplementary purposes can be listed :-

a.) To serve as a foundation upon which the insulation and cooling systems needed to protect the concrete vessel from high temperatures and excessive temperature gradients could be built.

b.) The transference of loads from the contained fluid and from components housed within the pressure vessel into the concrete structure of the pressure vessel.

c.) To serve as internal shuttering for the concrete vessel.

d.) To give early weather protection and a controlled environment for the construction of the reactor core and other components to be housed within the pressure vessel.

It is against this background that the various possible forms of liner must be considered. An inevitable initial thought was that the cheapest way of making the concrete vessel impermeable was to apply a coating of some impermeable substance. Such a coating would not have fulfilled the supplementary purposes listed above even if a material capable of withstanding severe irradiation without significant deterioration could have been found. With equal inevitability, attention then turned to using some form of metallic liner. The choices opened up are the inter-related ones of the type of metal to be used and the basic design concept of the liner.

Consideration was given to many different design concepts. For example should the liner be constrained to follow the movements of the inside surfaces of the concrete vessel intimately or should it follow these movements only in a gross sense and "float" relative to the vessel surface locally. In the case of a nuclear reactor with its many penetrations through the pressure vessel wall a partially "floating" liner would have given rise to gross strain accumulations near the penetrations and the possibility of failure of the material or a weldment under cyclic conditions. A second alternative for investigation was whether the distortion should be absorbed by direct compression and perhaps some buckling of the material itself, or by absorbing the movement in some form of convolution. Whilst convoluted liners have found some applications in the cryogenics industry the complexity of shape of the cavities of reactor vessels makes it exceptionally difficult, if not virtually impossible to utilise this concept.

The problems of insulating the concrete vessel would be greatly reduced if the insulation could be protected from the high pressure gas by the liner, thus sandwiching the insulation between the liner and the concrete vessel. The attractions of such a scheme were obvious and merited careful attention, but various factors combined to prevent the development of such a liner. Perhaps it is sufficient to say that the exposure of the liner to the hot gas increases by a large multiple the restrained cyclic thermal expansions imposed on it, and the need for the liner attachments to pass through the insulation would impair the ability of the liner to strain in intimate register with the inside of the concrete vessel. These factors would combine to subject areas of the liner to strain cycling over quite unacceptable ranges. The design of the cooling system would also have become exceedingly complex.

In retrospect there is a seeming inevitability in the progression towards the now universally accepted concept of a cool liner intimately linked to the inside surface of the concrete vessel, which absorbs strains in direct membrane straining with perhaps some small contribution from buckling. Such a design lends itself to construction in mild steel, a familiar well proven and relatively inexpensive material, which when used in this temperature range exhibits the useful phenomenon of yielding, a phenomenon which serves to limit the possible build up of forces on the liner attachments.

2. BASIS OF DESIGN

Having established the concept, it is necessary to develop a basic design and to demonstrate that this design is suitable for the conditions it is called upon to withstand.

Liners are subject to straining from dimensional changes to the cavity of the concrete vessel and thermal restraint. The dimensional changes are caused by such factors as concrete shrinkage, prestressing of the vessel, creep of the concrete, and changes to the shape of the vessel caused by operating pressures and temperatures. Thermal restraint strains result from changes to the bulk temperatures of the liner and of the concrete from the time at which the concrete was cast against the liner.

The basis of design was evolved from the realisation that these liner strains must be produced by forces interacting between the liner and the concrete vessel. In general the overall strains are fed in by bearing forces on some form of liner corner unit. Other liner attachments feed in the forces necessary to produce strain gradients in the liner and the force differences necessary to produce similar strains in adjacent sections of the liner which resist straining to differing degrees. It is the analysis of these forces which gives the basis of design for the general areas of the liner, consideration of the other areas such as corner details areas around penetrations or at the attachments where the loads from internal reactor components are transmitted to the concrete vessel can be considered on an individual basis.

The force needed to produce a given level of strain in a section of the liner is dependent upon :-

a.) The thickness of that piece of material.
b.) The properties of that piece of material, particularly its yield point.
c.) The initial deformations in that region in any form which would encourage buckling as compressive strains are applied.

These are all variables dependent on either the consistency of the material as supplied or the quality of workmanship of the completed liner. Having established the limits of these variables the maximum out of balance force which could arise between adjacent pieces of the liner can be assessed.

Information on the forces needed to produce given overall strains in initially imperfect panels has been built up from numerous tests carried out on simulated sections of liners in biaxial straining rigs such as that shown in Fig. 1, and supplementary tests on families of initially deformed struts. This information has also been correlated with analytically determined relationships between load and strain, and families of non dimensional graphs produced. The biaxial straining tests also enable the "pull-out" loads generated as the liner tie backs restrain the buckle to be measured. It was also realised that in transmitting interaction forces the liner attachments would themselves deform causing a local redistribution of strain and a sharing of the load with adjacent attachments.

Information on the load carrying capabilities and deformations under loading of various forms of liner attachments has been obtained from tests on such items as studs, groups of studs, fins and cooling pipes. The tests took the form of transmitting loads from a section of liner plate into a concrete block through the attachments and measuring the resultant deformation. For simplicity of loading the tests were carried out on a "mirror image" basis with a central load fed from two liner plates into two blocks of concrete. The method of testing is illustrated diagrammatically on Fig. 2, and at Fig. 3 is given a photograph taken after chipping away some of the concrete to reveal the amount of deformation which had been withstood successfully by typical liner attachments.

A factor which exerts a considerable influence on the design of any particular liner is the pitch of the cooling water pipes needed to give the required thermal performance of the cooling system. The pitch of the liner ties must of necessity be related to the pitch of the cooling pipes and is frequently twice or three times the nominal pitch of the cooling pipes.

The sequence of designing and justifying the basic design of a liner is :-

a.) From a knowledge of the required cooling pipe layout, and guided by the experimental results postulate a probable design, defining :-
    i) Thickness and permissible range of material properties of liner.
    ii) Layout and pitching of ties, cooling pipes and other liner attachments.
    iii) Permissible local deviations from perfect shape of the liner.

b.) Analyse this design to check such items as :-
    i) That the possible loadings in the plane of the liner on all the various attachments are within permissible limits.
    ii) That the pull out loads on liner attachments are within the allowable values.
    iii) That the buckling of the liner does not create problems with other components such as internal insulation.
    iv) That the amount of strain cycling to which local areas of the liner could be submitted is within acceptable limits.

    If necessary one or more of the parameters listed in (a.) above would be modified and the analysis repeated until all requirements are satisfied.

c.) If necessary, make a test specimen incorporating the final design features and test them in a biaxial straining rig as a final demonstration that the actual liner would behave in the manner predicted by the analysis.

By way of example the following typical but rather simplified design cases are given.

CASE 1 FORCES WHICH CAN ARISE WITHIN A LINER PLATE.

The greatest build up of forces within the body of a plate would arise if one initially buckled region were to be bounded by an infinite number of similar regions which were perfectly flat or exhibited favourable curvature to resist buckling. The weakest form of initial buckle is a long ridge running parallel to the cooling pipes as illustrated in Fig. 4. As compressive strains are applied to the system strains will tend to accumulate in the weakest (buckled) panel, the build up being limited by the resistance to distortion of the liner attachments bounding this region.

Experimental work has shown that over their useful operating ranges the various liner attachments exhibit a sensible linear relationship between deformation and force transmitted. This can conveniently be expressed as a "stiffness" characteristic of the particular attachment.

The summation of the forces transmitted by the attachments at one side of the buckle must be equal to the differences between the force needed to produce the nominal strain in a perfect region of the liner remote from the buckle and the force needed to produce the actual strain in the buckled panel. As the actual strain in the buckled region is dependant upon the deformation of the liner attachments the calculation becomes iterative. The magnitude of this force difference 'F' is illustrated on Fig. 5.

And

$$F = \sum_{n=1}^{n=\infty} ky_n + \sum_{n=1}^{n=\infty} k'y'_n$$

If one set of liner attachments offer much less resistance to distortion than another set, then a conservative but reasonably accurate solution can be obtained by disregarding the contribution of the less stiff attachments and basing the calculations upon a finite number of the stiffer attachments. In practice it would be satisfactory to analyse the liner shown on Fig. 4 by disregarding the contributions of the liner ties and considering only the contributions of five cooling pipes on each side of the buckled region.

From an actual case the following parameters can be taken :-

Nominal liner thickness	0.5 in. (0.4375 in. corroded)
Pitch of cooling water pipes	5.4375 in.
Maximum yield stress of material	19.5 tonf/in^2
Youngs Modulus of material	12.950 tonf/in^2
Initial height of buckle	0.0625 in.

By iterative methods assuming different values for the final strain level across the buckled panel until a satisfactory load balance is obtained the following results were obtained.

Design strain in directions of cooling pipes = 942×10^{-6}

Design strain in direction normal to cooling pipes = 1362×10^{-6}

When considering plane normal to cooling pipes

Equivalent equi-biaxial strain

$$= \frac{e_1 + ve_2}{1 + v}$$

$$= \left(\frac{1362 + (0.3 \times 942)}{1.3} \right) \times 10^{-6}$$

$$= 1265 \times 10^{-6}$$

Equivalent equi-biaxial strain in buckled region = 1337×10^{-6}

Maximum load on cooling pipes = 0.22 tonf/inch run

This represents an average bearing pressure of less than 500 lbf/in^2 on the concrete into which the pipes are set, which is well within normal limits. Tests have shown that loadings of a much greater magnitude could be resisted without the possibility of failure of either the concrete or the cooling pipes and its attachment welds. The shear loads generated in the liner ties when subject to a similar amount of distortion is also well within acceptable limits.

The actual strain level reached in the initially buckled region means that the increase in height of the buckle would be approximately 0.05 inches which is acceptable from the viewpoint of the performance of the internal insulation. Tests show that the pull out loads on the liner ties would also be well within acceptable limits.

CASE 2 FORCES WHICH CAN ARISE AT THE BOUNDARIES OF A LINER PLATE.

Calculations are carried out in a similar manner to Case 1, but in assessing the maximum loadings which can build up a further factor must be taken into account. This is the possibility that a plate of minimum thickness with the minimum permissible yield stress may be adjacent to a plate of maximum thickness with the highest permissible yield stress.

Fig. 6 gives typical load strain curves for various categories of liner regions, and comparison of this figure with Fig. 5 shows that this additional factor can cause very much larger forces to build up. These forces can become too large to be fed into the liner safely by the cooling pipes and on current designs the butt welds in the liner plates are bounded by continuous fins. These fins exhibit much greater "stiffness" than the cooling pipes and consequently feed in a large proportion of the required force, with a relatively smaller contribution from the cooling pipes. With a suitable design of fin the loads on the cooling pipes can be kept down to acceptable values and the peak strains in the weakest panels minimised.

CASE 3 LOAD TRANSMISSION AT LINER CORNERS.

The loads necessary to compress the liners and attachments such as cooling pipes in an overall sense are fed in by the liner corner assemblies. A particular design of a liner corner unit based upon a solid round corner bar is illustrated on Fig. 7.

As forces build up on the corner bar it beds into the surrounding concrete slightly. This movement results in strain redistributions and deformations of the liner attachments near to the corner bar. As a result these liner attachments feed in part of the loads. In designing the liner corner region it is then necessary to consider notonly the bearing pressures on the concrete surrounding the corner bar, but also to establish that the loads transferred to all other liner attachments in the region of the corner are within acceptable limits. These loadings are illustrated in Fig. 7 and the calculations are carried out in an analogous manner to Case 1, having determined the "stiffness" of the corner bar experimentally.

3. ECONOMICS OF LINER DESIGN.

A liner is a steel fabrication designed to accept cyclic straining, generally in compression. In this it differs from pressure vessels and steel structures, which are designed to transmit forces in the most economical manner. For vessels and structures any economies in plate thickness or section size tend to be reflected directly in savings of overall cost, and the benefits of any improvements in the design basis which make such savings possible are immediately apparent.

However, reductions in liner thickness necessitate reductions in the pitch of the various attachments and hence an increase in their numbers. A reduction of thickness also increases the problems and difficulties of building the liner within the permissible limits of distortion.

The economic choice of liner thickness thus tends to become a matter of appraisal and judgement rather than a matter of precise calculation. The choice of liner thickness is influenced by the pitch of the cooling pipes insofar as they define liner regions and determine the pitches of liner ties. The thermal performance of the cooling system is also of course affected to some degree by the liner thickness.

Economies can accrue from improvements in the detailed design of individual liner attachments, but major cost savings must come from improved methods of construction. The real basis of judging the economics of liner construction is not the cost of the liner itself, but rather the addition to the total cost of the power station by the inclusion of the liner. On this basis it is frequently sound economics to build the liner by unusual, and at first sight, expensive, methods if by so doing the construction of the remainder of the power station can proceed largely unimpeded. This aspect is expanded upon in the next section of this paper.

4. APPLICATION OF THE DESIGN BASIS.

In addition to considerations of basic design to meet performance requirements attention must be given from the outset to methods of construction which ensure that the liner can be built and inspected to high standards of quality and to determine the impact of the liner construction programme upon the construction of the power station as a whole.

The performance of the liner when being compressed has a critical dependance upon its actual local shape, and the methods of building must be such that local distortions are avoided or minimised. The quality requirements for the liner can perhaps be summarised as conforming to high quality pressure vessel work and close attention is needed at the design stage to ensure that each component and each weldment can be produced and inspected to the required standards. The liner plate material is subject to ultrasonic examination to ensure that liner attachments do not lose effectiveness by being welded to sections of liner plate containing gross laminations.

It has always been appreciated that the building of the liner should have as little impact as possible on the construction operations on the concrete vessel itself. Experience has emphasised the critical dependance of other construction operations, not only those on the concrete vessel outside the liner but also those on the reactor items within the liner, on the liner construction work proceeding smoothly and to programme. The dependance of so many other operations upon liner construction means that economic construction of the power station as a whole can necessitate unusual methods of construction for the liners themselves.

The practice of prefabricating the liners and then moving very large sections weighing hundreds of tons into final position is well established and has been used by Whessoe from the earliest liners. By this means construction of the liner, and construction of the bottom section of the concrete vessel can proceed in parallel and the placement of concrete for the walls of the pressure vessel can commence as soon as the liner has been positioned. Fig's. 8 and 9 illustrate moving in operations on a typical cylindrical liner and the lower half of a spherical liner.

The early liners and their cooling systems were built up on site from individual small components, but with a growing understanding of the distortion problems which arose during liner construction, particularly when the cooling pipes were welded on, Whessoe were able to develop designs and manufacturing techniques which enabled the liners to be constructed from large shop built panels. This enabled more of the work to be carried out under established shop conditions with technical back-up resources more readily available should the need arise. These and other factors combined to give a greater reassurance that the construction programme would be met. This method of building was first used and worked extremely well on the Hinkley Point 'B' and Hunterston 'B' power stations and it is our intention to continue to use this system whenever it is applicable.

The liner panels are built on frames which are designed to fulfil a number of purposes such as :-

a.) To maintain the shape of the panels during shop manufacture.
b.) To provide transport cradles to avoid damage to the panels when in transit to site.
c.) To provide handling frames so that the panels can be lifted and positioned without damage.

d.) When linked to adjacent frames to provide a structure to hold the panels during site assembly and welding of the panels into the complete liner.

e.) To stiffen the liner during the move in operations.

f.) To resist concrete forces as the concrete vessel is cast against the liner.

g.) To serve as scaffolding within the vessel.

The method of construction is illustrated by Figs. 10 and 11 which show the layout of the workshops during the building of liner wall panels and the erection of these panels on site.

In the cases of Hinkley Point 'B' and Hunterston 'B' the entire liner top complete with standpipes and other branches was prefabricated and joined to a massive temporary structure, designed to resist the deadweight of the steelwork and the weights of the initial lifts of concrete. At the appropriate stage of construction when the concrete wall of the vessel had reached the appropriate height and when all large components had been lifted into the reactor cavity, the entire top assembly was lifted into position. Having linked the liner top to the liner wall the concreting of the top of the vessel could proceed. The lifting in of this structure is illustrated on Fig. 12.

The liner contracts undertaken to date by Whessoe and its licencees are shown on Table 1, which summarises the construction methods used or which will be used. The table also shows that the earlier liners are now in service and are giving every satisfaction.

5. CONCLUDING REMARKS.

The period covered by our paper marks the transition from the era of basic conceptual design of liners to an era of increasing understanding of the detailed behaviour of liner components and of increasing refinement in the analysis of liner designs. We feel that this paper is worthwhile if it has served to provide a background against which specific design problems can be viewed, and if it has served to illustrate the firm foundations upon which current design methods have been built.

The lined, pre-stressed concrete pressure vessel has first found large scale application in the field of gas cooled nuclear reactors and rather simpler versions have been used for containment vessels for other reactor systems. The concept is not, however, limited to these uses, and it is hoped that many other applications can be found in the nuclear and other industries. The paper has emphasised the long and continuing involvement of Whessoe Ltd. with steel linings for concrete pressure vessels but emphasis should also be given to the confidence of the Authors that their companies will long continue to be involved in the manufacture of liners, whatever the applications may be. Whessoe Ltd. has a long established involvement with the oil, chemical, gas and capital plant industries generally, and when to this strength is added the all round strengths of Whessoe's licencees for liners, Steinmuller G.m.b.H. of Germany and Kawasaki Heavy Industries of Japan our future involvement in liners for concrete pressure vessels seems assured.

6. ACKNOWLEDGEMENTS.

The Authors wish to express their gratitude to the Directors of Whessoe Limited, of Steinmuller G.m.b.H. and of the Nuclear Power Group Ltd. for permission to publish this paper. They also wish to acknowledge and thank all their colleagues whose combined efforts made possible the advancements in the understanding of liner behaviour and in methods of liner design reviewed by this paper.

TABLE 1

Contracts Undertaken by Whessoe Ltd. and their Licencees

Station	Station Builder	Liner Builder	Reactor Type	Vessel Layout	Method of Building Liner	Notes
OLBURY (U.K.)	T.N.P.G.	WHESSOE	Magnox 2 x 300 MW	Cylindrical (Annular Boilers)	Site from Small Components	First reactors to be housed in P.C.P.V's. in U.K. R1 on power since late 1967.
WYLFA (U.K.)	N.D.C. (formerly E.E. Co.)	WHESSOE	Magnox 2 x 590 MW	Spherical (Annular Boilers)	Site from Small Components	R1 on power early 1971.
DUNGENESS 'B' (U.K.)	A.P.C.	Rectification only *	A.G.R. 2 x 660 MW	Cylindrical (Annular Boilers)	-	* Whessoe responsible for some rectification work on original liners and supply of some new sections of liner.
HINKLEY POINT 'B' (U.K.)	T.N.P.G.	WHESSOE	A.G.R. 2 x 660 MW	Cylindrical (Annular Boilers)	Shop Built Panels	Liners complete, power station construction continues.
HUNTERSTON 'B' (U.K.)	T.N.P.G.	WHESSOE	A.G.R. 2 x 660 MW	Cylindrical (Annular Boilers)	Shop Built Panels	Liners complete, power station construction continues.
HEYSHAM (U.K.)	B.H.D.C.	WHESSOE	A.G.R. 2 x 660 MW	Core Cavity plus Boiler Pods	Combination shop built panels and small components — Shop built boiler pod liners	Construction now under way.
WESTFALEN (GERMANY)	B.B.K.	STEINMULLER	T.H.T.R. 300 MW	Cylindrical	Shop built Panels	Contact awarded, engineering work in progress.
(JAPAN)	F.A.P.I.G.	KAWASAKI HEAVY INDUSTRIES	A.G.R. 660 MW	Cylindrical (Annular Boilers)	Shop built Panels	Design report being prepared.

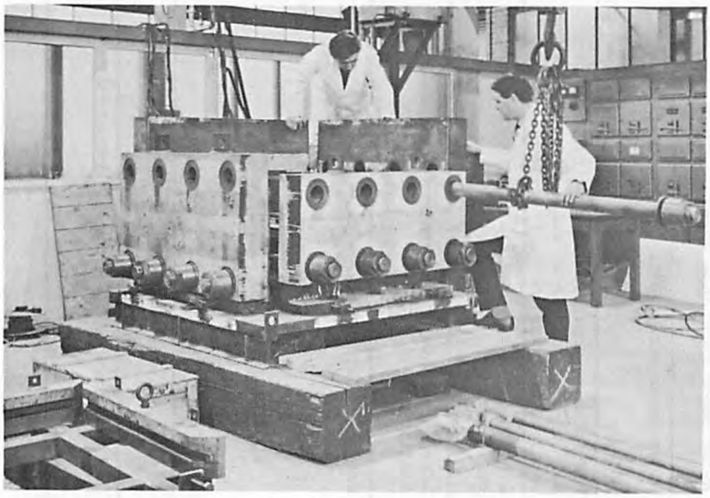

FIG. 1 - ASSEMBLY OF BI-AXIAL PLATE STRAINING RIG.

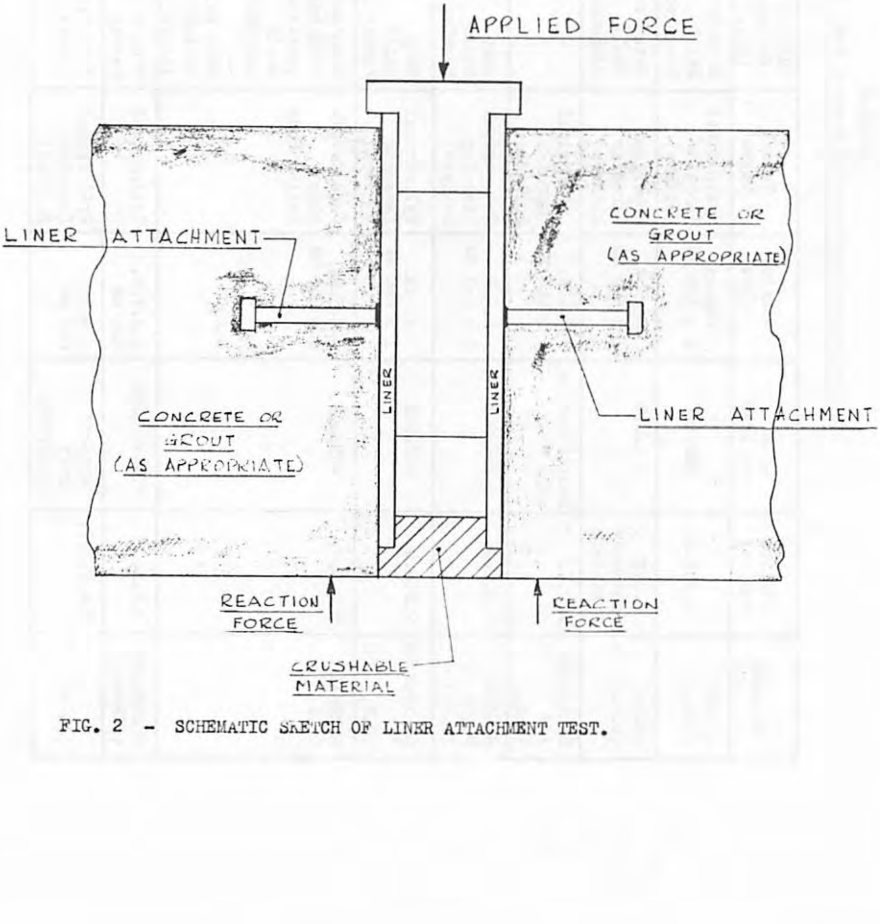

FIG. 2 - SCHEMATIC SKETCH OF LINER ATTACHMENT TEST.

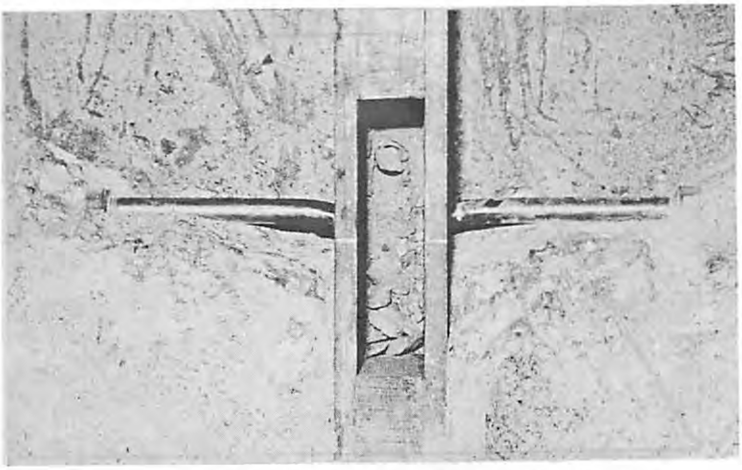

FIG. 3 - LINER STUD ATTACHMENTS AFTER LOAD DEFORMATION TEST.

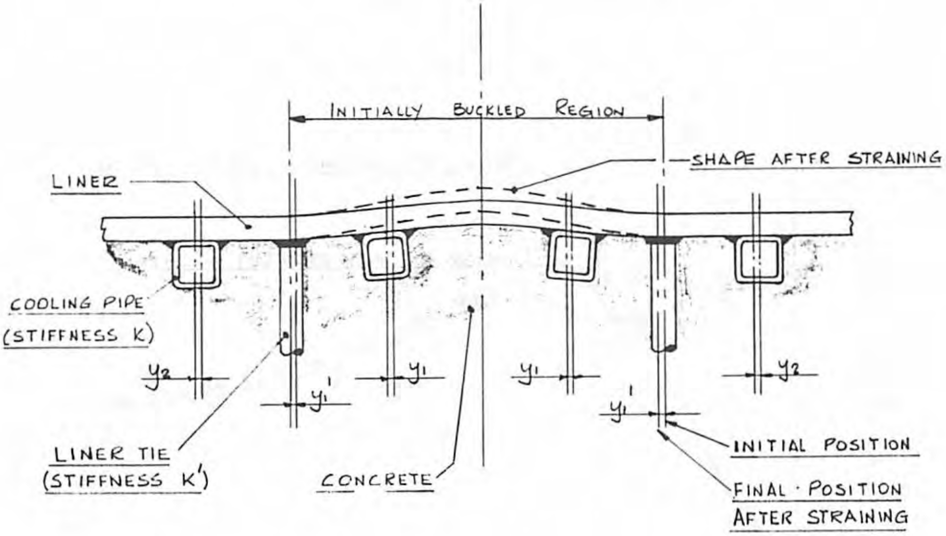

FIG. 4 - CROSS SECTION OF LINER SHOWING INITIALLY BUCKLED REGION.

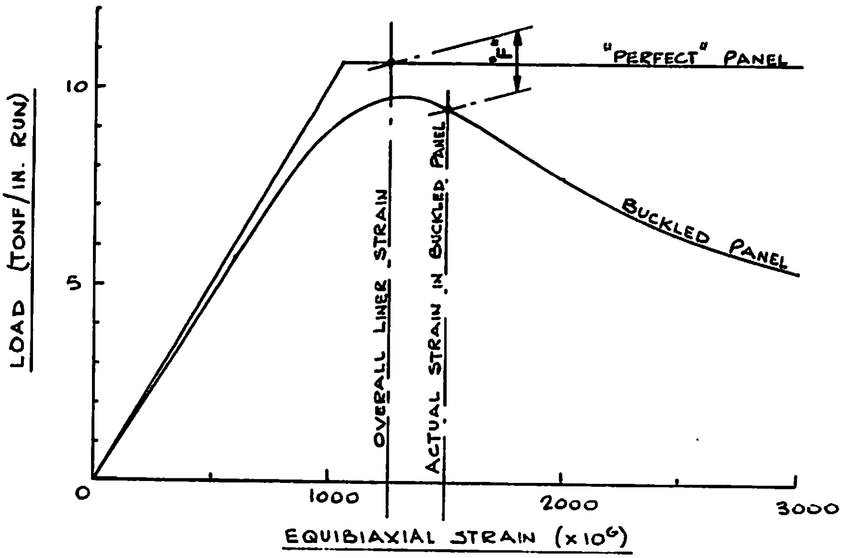

FIG. 5 - MEMBRANE FORCES IN LINER PLATE.

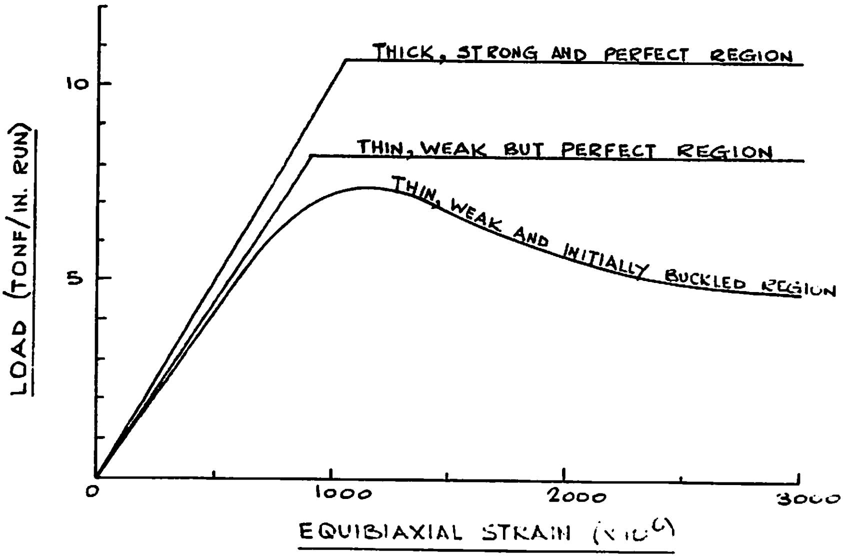

FIG. 6 - TYPICAL LOAD STRAIN CURVES FOR VARIOUS REGIONS OF THE LINER.

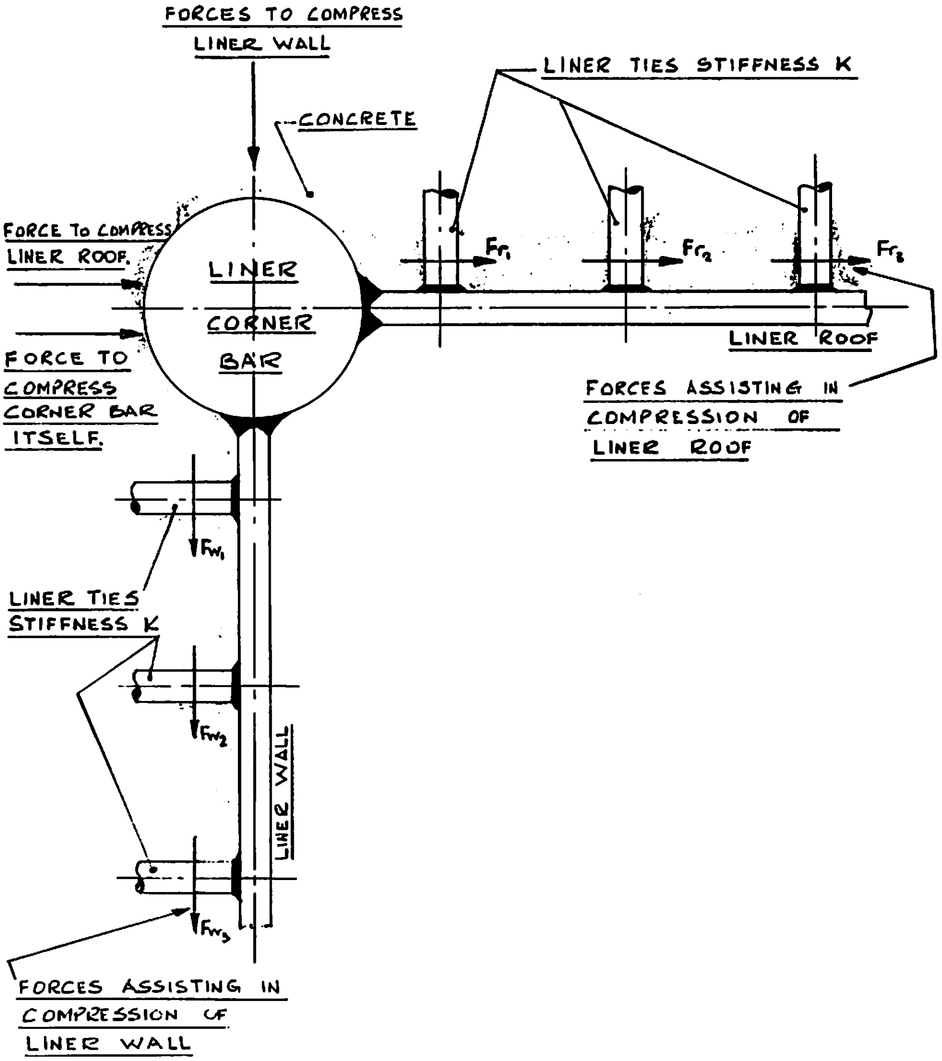

FIG. 7 - FORCES ACTING AT LINER CORNER BAR.

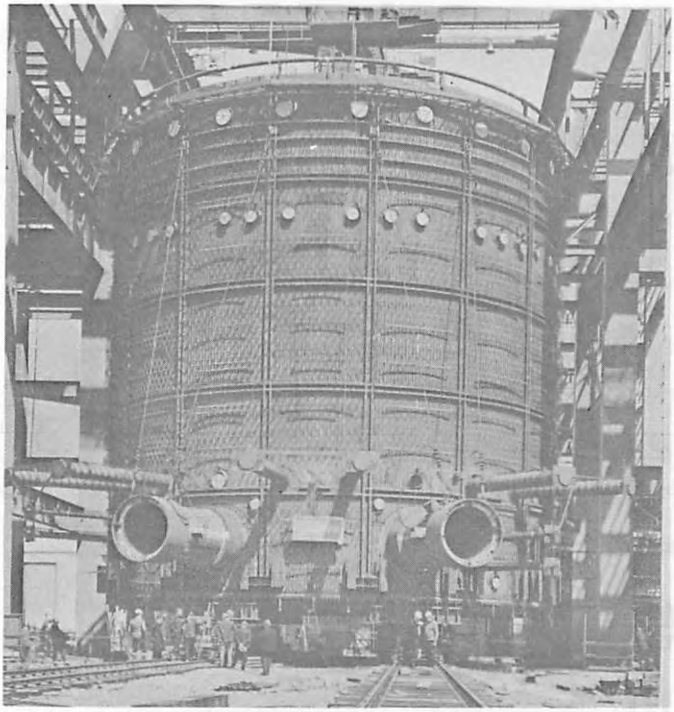

FIG. 8 -

ROLLING A HUNTERSTON 'B' LINER INTO POSITION.

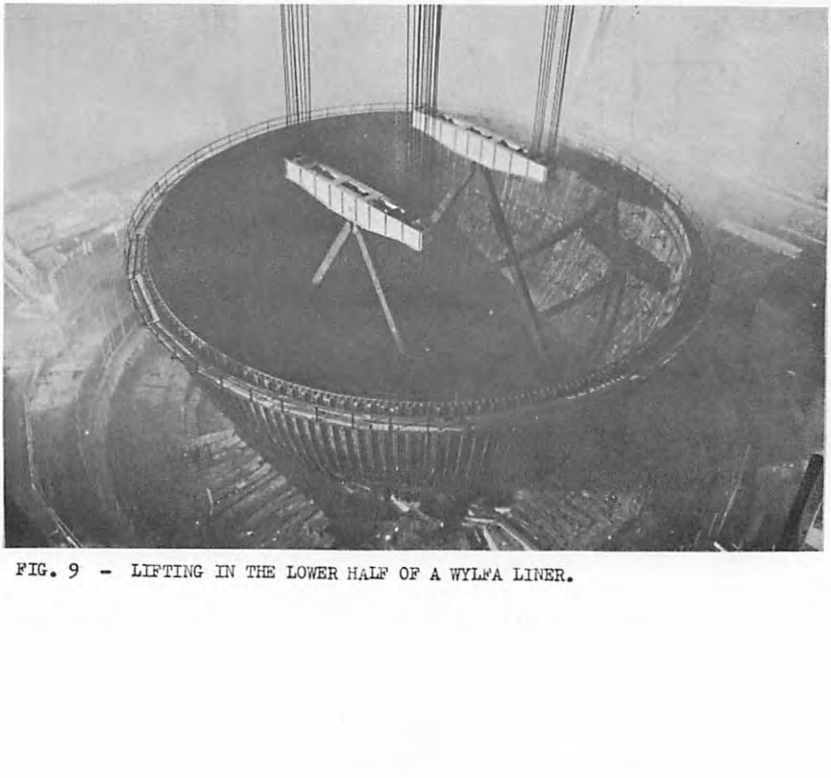

FIG. 9 - LIFTING IN THE LOWER HALF OF A WYLFA LINER.

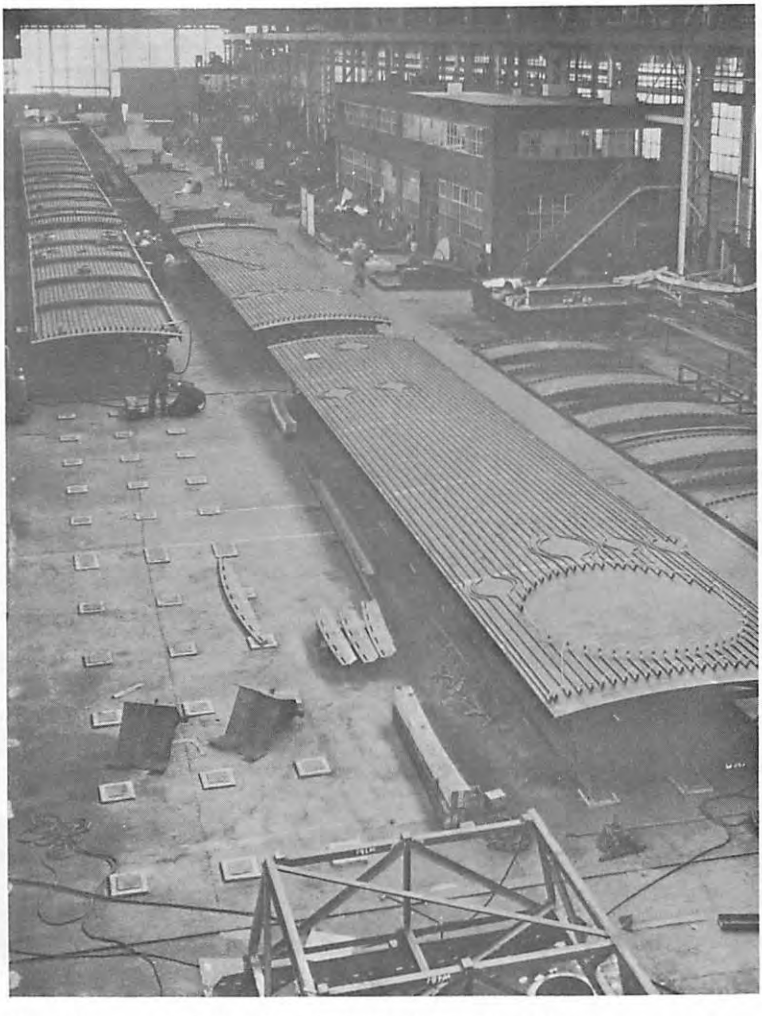

FIG. 10 - WORKSHOP MANUFACTURE OF LINER WALL PANELS.

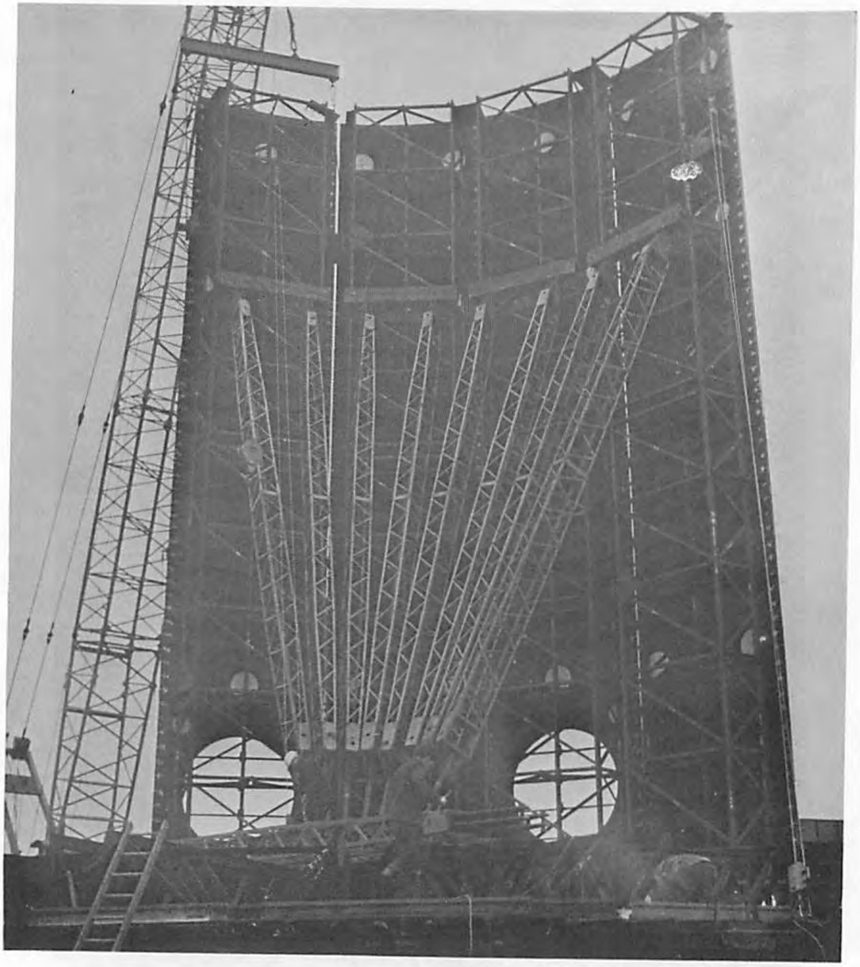

FIG. 11 - ERECTION OF LINER WALL PANELS.

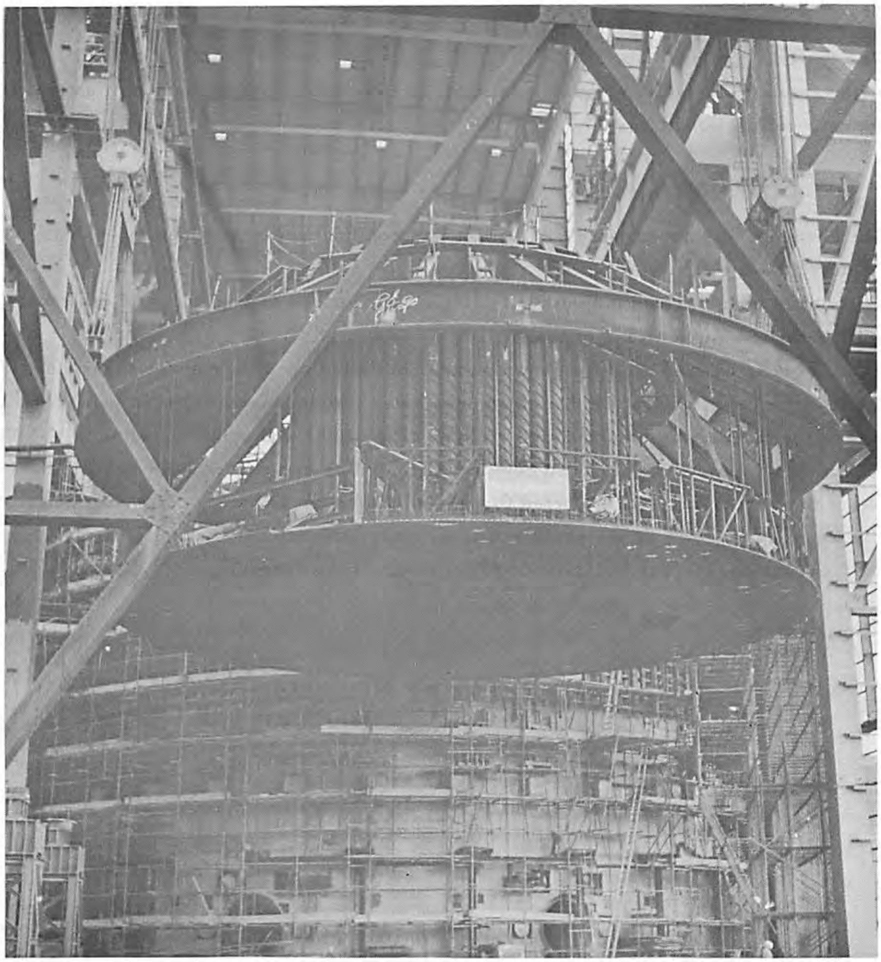

FIG. 12 - LIFTING IN THE LINER TOP, STANDPIPES AND CONCRETE SUPPORT STRUCTURE - HINKLEY POINT 'B'

DISCUSSION

Q I. DAVIDSON, U. K.

1. In the stud deformation tests was the concrete prestressed ?
2. Was the load cycled ?
3. Is the corner bar detail adequate to withstand also tensile strains which might occur under pressure overload conditions ?

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1. The concrete was not prestressed, but it was confined and restrained by a strong steel box, into which it was cast.
2. Tests have been carried out both with single applications of load to large deformations, and with repeated applications of load.
3. Round corner bars of the type shown on are not called upon to transfer significant tensile forces into the liner. If special circumstances arise which cause very high compressive strains in the liner, then compressive yielding of the liner and some "bedding in" of the corner bar may occur. As the imposed compressive strains are reduced the liner in the general region of the corner may be subjected to tensile strain, but the majority of the necessary tensile forces are fed in by the studs and other liner attachments with only a small contribution from the corner bar which tends to lift clear of the concrete.

This case is considered in evaluating the liner design.

GENERAL COMMENTS TO SESSION H 6

C J. MEYER, Germany

Konzeption des heissen Liners.

Der heisse Liner, wie er für Spannbetondruckbehälter von Leichtwasserreaktoren benötigt wird, soll durch folgende Konstruktion verwirklicht werden. Von innen nach aussen kommen der Reihe nach heisser Liner, Isolation, kalter Liner, Spannbeton. Der heisse Liner ist zusammen mit dem kalten Liner durch Anker im Spannbeton gehalten.

Die durch das An- und Abfahren des Reaktors bedingten Temperaturzyklen bewirken im austenitischen Linerblech eine Gesamtdehnung von 5‰. Dazu kommen noch Biegedehnungen aus der Verformung des Liners, der sich zwischen den Bolzen beim Abkühlen von der Isolation abhebt. Durch entsprechende Wahl von Blechstärke und Bolzenabstand können diese zusätzlichen Dehnungen in Grenzen gehalten werden. Auch muss ein Ausbeulen beim Erwärmen verhindert werden.

Das erste Resultat der Untersuchung war die Forderung, dass die Bolzenabstände in Umfangsrichtung nur etwa halb so gross sein dürfen wie in axialer Richtung. Um die Berechnungen zu prüfen, wurde ein Modell untersucht, das einen Ausschnitt aus einer Behälterwand in Originalabmessungen darstellte. Die interessierenden Biegeverformungen wurden bei 8 mm Blechdicke des heissen Liners mit verschiedenen Bolzenabständen gemessen, wobei die maximale Temperaturdifferenz 300°C betrug. Dabei zeigte sich eine weitgehende Übereinstimmung mit den Berechnungen.

C D. COSTES, France

French PCPV program.

We carry out in France a program on prestressed concrete reactor pressure vessels, in coordination between Electricité de France, the Commissariat à l'Energie Atomique and the Société d'Etude des Caissons Nucléaires (SECN) which joins four main civil engineering societies. The purpose of the program is to develop PCPV's for HTGR's and water reactors, for economic and safety interests. The program includes basic studies on materials and calculations, and technological studies in various fields, namely in insulation field.

HTGR insulation studies have been performed with Société Bertin. They include calculation of porous material insulation system with open cells, under natural or forced general convection. Extensive tests have correlated the results. The work is going on with studies on individual materials. For water reactors insulation the bulk of studies applies to hot liner concept. The figure shows the classical solution of cold liner, with internal insulation and mechanical shield, and the hot liner concept, in which the liner is submitted to the coolant temperature. The general structural concrete is at room temperature and is separated from hot liner by a system of cooling coils and by a certain thickness of insulating concrete. The liner is hold by connectors, for instance studs welded on the liner and penetrating into the concrete.

For water reactors with coolant temperatures of about 300°C, we choose an ordinary low carbon stainless steel liner. Good behaviour of such a liner under constant dimension temperature cycling between 50 and 300°C, in current part of the wall, may be predicted from usual fatigue curves and from successful tests we have performed with a plane, edge fixed liner element in a cold steel ring.

The expected advantages of the concept are the following ones:

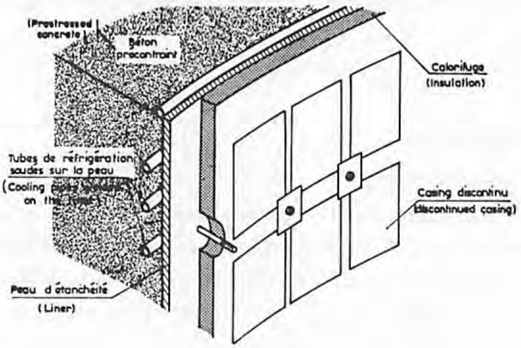
1. One avoids stagnation areas of water, with possibility of pollutants concentration and chemical attack of the liner.
2. The insulation efficiency appears to be good.
3. Economics appear to be attractive.

The risks appear in the following fields:

1. Instability and ratchetting in discontinuities zones.
2. Increased fatigue in stress concentration zones and at connector welds.
3. Accelerated internal corrosion under tensile conditions when cooling the vessel.
4. Corrosion of connectors in hot concrete.

Tests are in progress for that points. Some work is carried out on metallic insulation systems.

Solution "peau froide" ("Cold liner" solution)



Solution "peau chaude" ("Hot liner" solution)