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DISCUSSION

Hartlepool Power Station: major civil engineering features

F. W. COATES & R. S. TAYLOR

Professor A. L. L. Baker, Imperial College

I was delighted to see that Taylor Woodrow are now winding wire to give circumferential confinement. The very first pressure vessel tested in Britain was designed with that concept: that was back in the 1950's, and it was tested at Stockport. It was designed with a winding system to avoid congestion of anchorages, and with ordinary vertical prestressed cables. But at that time there was difficulty with the winding machine as the friction caused high temperatures, and destroyed the ductility, and in some cases the strength of the wire. I assume that Taylor Woodrow have done research, to get over those earlier difficulties. It would be interesting to know a bit more about that point.

72. Working temperatures are now higher. Does that mean that there is some risk, if insulation breaks down at any point, of the concrete attaining higher temperatures than hitherto? In some of the vessels at hot spots where insulation has partly broken down, temperatures up to, I believe, 180°C have been reached. I would be interested to know more about the insulation, and the security provided against excessive heating of the concrete, and also to know whether Taylor Woodrow have made triaxial creep temperature tests on concrete because that needs doing. Work on this has started at Imperial College and at Swansea.

73. The day could well come perhaps when there will be a hot spot at some critical section of a vessel and the stress displacement laws of the concrete over a long period as a result of the creep effects will not be known precisely; I believe that not only are there creep effects, but some reduction in strength. Tests have shown[5] that if axially unconfined concrete is loaded at about 60% of the normal short-term ultimate stress, it will eventually fail. That leads me to conclude that with higher temperatures, which increase the creep and therefore the displacements that take place, there will be greater axial displacement in a cylinder and that will lead, with high Poisson ratio values, to greater radial displacements. Greater radial displacements will produce extensions, which will cause the beginning of splitting of the concrete, which is the beginning of failure.

74. This needs to be fully investigated and proved. The long-term effect may be considerable weakening of the concrete. It may not matter much if it is in a triaxial condition where the whole piece of concrete is confined in three directions, but nevertheless it would be as well to know what is going to happen to the concrete so that if necessary one can repeat the computer calculation and know exactly whether danger is close and whether to shut down the reactor. I should like to see this precautionary research carried out, not only for pressure vessels, but also for containments in the North Sea for hot oil. The problem is similar: temperatures are not as high but in the same way the long-term effects on the concrete are unknown.

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Mr J. B. L. Faulkner, W. S. Atkins & Partners

Before joining my present firm I was fortunate to have had the opportunity to be closely associated with managing the first five years of the design and construction of this project, and have since had a further two years to review the experience. I wish to comment on two things: the station layout and the philosophy adopted on two features of the design.

76. The layout of the integrated building is, I believe, the most compact and economical arrangement yet devised for a power station of this size. It is an excellent example of how the best features of design, layout, prefabrication and site construction can be combined by preplanning and close co-ordination of all the many branches of the engineering profession involved. It was designed to allow construction of the four main units of the integrated building, and the installation of the associated plant, to proceed independently, thus preventing delays occurring in one section affecting the others. Unfortunately, even this in-built flexibility in programming and application of resources could not cope with the design changes imposed.

77. On design, I feel that this Paper illustrates well a particular worry of mine which I would be interested to know if others share. Are engineers in danger of equating safety with complexity? In this case there are two examples of straightforward design and construction solutions being changed, delayed and complicated in the search for greater safety. Far be it from me to decry this seeking for safety (particularly in a nuclear station close to a centre of population) but has the end result really achieved the objective? For instance, a feature of the shaft foundations considered to be advantageous at the time of tender was that it allowed the bedrock condition to be inspected before the shafts were concreted. In the event the situation that arose was that the rock was not just inspected, it was so closely inspected, tested, sampled and thought about that programme delays occurred, and additional resources had to be deployed. This resulted in the most impressive and intense concentration of civil engineering plant in a small area that it has ever been my privilege to see.

78. In § 9 it is stated that in the site investigations bored in situ piles were tested—successfully if I remember correctly. In hindsight maybe a more conventional bored in situ pile solution with a specified minimum penetration into bedrock, combined with load testing and good quality control, might well have produced just as satisfactory a foundation design with much less difficulty.

79. Somewhat related thoughts occur to me regarding the problem of the boiler closures. In § 47 it is acknowledged that the originally accepted steel compression dome design was changed at the insistence of the safety authorities. The result is a design of *high* safety, but extreme complexity in calculation, detailing, materials, instrumentation, cooling and other features. Whether it is of *greater* safety I believe is questionable, particularly bearing in mind the many additional in-built and complex features, each in itself requiring detailed consideration and in many cases protection. Not only has this change been a major contributor to the time lost on the programme; it has also cost many millions of pounds in design and manufacture costs and many more millions in consequential costs of delay and lost output from this as yet uncompleted station. While trying not to be wise after the event, is the final concept of these boiler closures really the optimum design solution when all the factors are balanced and considered?

80. Project management of a situation such as this becomes a nightmare. Factors completely outside the project manager's control affect the whole progress of the job. It seems particularly unfortunate in the case of Hartlepool that a very carefully considered design and construction method and programme was rendered ineffective by design changes and material problems. The Authors have my sympathy—but also my best wishes that this major work of engineering be brought speedily into what I am sure will be successful operation.

Mr P. F. Mead, John Mowlem and Co. Ltd.

The Authors are to be congratulated on the way in which they have concentrated on the problems of the contract and their engineering solutions.

82. I should like them to give more detailed information on the method of shaft raising, which is a new technique. Was a sump required in which to install the equipment necessary to thrust up the shaft from the tunnel? Can drilling be resorted to in conjunction with up-thrust? If not, is there any danger of rupturing the soil layers, allowing ingress of water and scour leading to instability?

83. Could the Authors please comment on the time aspect. Normally when the shaft is drilled down from the surface the work is concurrent with tunnelling: with the upthrust method this cannot start until the tunnel is completed.

Mr R. E. D. Burrow, Taylor Woodrow Construction Ltd.

I was closely associated with the design of the Hartlepool pressure vessels.

85. I should like to comment on Professor Baker's remarks. The Hartlepool vessels—in common with all others—are designed with conservative basic stresses which hardly exceed the normal values of uniaxial stress used in everyday civil engineering; in the very few locations where they do, it is not difficult to demonstrate that the benefits which come from the triaxiality provide more than adequate compensation. So there has never really been any anxiety concerning the long-term behaviour of these structures with the stress levels which have been used in the concrete.

86. However, one hopes that for the future it may be possible to go to much higher levels of stress, and indeed I am engaged in a design at the moment where the working pressure of the vessel is 69 N/mm^2, which is well above the uniaxial strength of the concrete. Here the effects of triaxiality are absolutely fundamental to the viability of the design. Valuable work has been done by a number of workers to establish how much benefit can be obtained in such circumstances.

87. I do not know of any current work concerned with creep and deformations in concrete under triaxial loading at elevated temperatures, although I am aware that studies are being made to establish what kind of work is within the practicable range of research.

88. The other point on which I should like to comment is the remark of Professor Baker concerning the early wire-wound vessels and the problems of maintaining accuracy of tension. The wire winding system used for those applications was based on the drawing of wire through a die, and the stress was obtained by a combination of the force required to draw the die and the cooling of the wire after drawing. When one considers the many variables involved in that situation, it is not surprising that it was difficult to control the forces within tolerances of ± 10 or 15%. Professor Baker is right in saying that the machine which Taylor Woodrow has developed paid very special attention to that particular feature.

89. It is of course outside the civil engineer's responsibility to deal with the design of the insulation. This particular problem must have caused the British Nuclear Design and Construction Ltd (now the Nuclear Power Co. (Whetstone) Ltd) a great deal of concern and anxiety. The safety of the insulation is indeed important but the circumstances which were referred to, in which insulation is locally ineffective, causing temperatures to rise in the adjacent concrete, were investigated by the Central Electricity Generating Board. I would like to ask whether the Authors can give any information about the work carried out by the CEGB, in which, in my understanding, they demonstrated that quite substantial temperatures (as high as 250°C locally in the vessel concrete) caused no distress whatever to the concrete in those zones, and appeared not to have affected the structure in any significant way at all.

Mr M. J. West, Oscar Faber and Partners

The load under the reactor which is taken down to the Bunter sandstone is very great indeed. Have any significant movements in the rock away from the reactors, say near a gas turbine house, been found due to the significant load?

Professor A. D. Ross, King's College, London

The matter of hot spots has been introduced into this discussion and, of course, there have been hot spots in earlier vessels. But my belief is that the first hot spots to be identified were viewed with disproportionate concern and that, provided they are truly local, they will not cause trouble. This has been confirmed in operational experience of earlier vessels and, more directly, in experiments[6] in which a simulated hot spot was imposed on a representative prestressed concrete structure. Subsequent detailed examination demonstrated that only a small volume of concrete adjacent to the heat source had been affected. If whole areas of insulation were to be detached, then of course trouble would be expected.

92. The facility to withdraw and replace a boiler has often been claimed as one of the merits of the podded vessel. However, in my view, a major advantage is that a particular core diameter can be accommodated in a main cavity of smaller diameter than in other integrated designs which require the room to tuck the boilers into the main cavity beside the reactor. The shears in the cap around the circumference of the cavity arising from the gas pressure are thus less severe and more easily accommodated in the slab thickness.

93. In the first Magnox stations incorporating prestressed concrete pressure vessels the spacing of the standpipes was such that it was possible to pass radial tendons directly through the pilecap. The spacing in the standpipe array in the AGRs is much closer so that this is not possible and all the radial prestress in the cap must be applied around the periphery. This feature presents no particular problem or difficulty, but an easier shear condition is a welcome bonus especially when considering the effects of differential temperatures and long-term thermal creep.

Mr M. J. Tomlinson, Wimpey Laboratories Ltd.

My organization was concerned with the site investigations for the power station. The Authors mentioned the difficulties experienced in sinking the exploratory shaft at the site investigation stage which led to the adoption of the drilled shaft foundations described in the Paper. These difficulties were concerned with the water under artesian pressure in the middle sands and gravels. Trouble in sinking the shaft through this layer was expected. Two sets of bored wells and submersible pumps, one set to dewater the Bunter sandstone and the other to dewater the middle sands and gravels, were installed in a ring around the shaft. The set which was operating within the sandstone worked very effectively and reduced the water head considerably. But the draw-down in the middle sands and gravels, because of their silty character, was very slow indeed.

95. The CEGB at the time was pressing for early completion of the shafts because the tender date was getting very close and the information from plate bearing tests in the sandstone was needed for the design of the reactor foundations. The result was that the shaft was sunk at rather too great a rate. Sufficient time was not allowed for the head of water to be lowered in the middle sands and gravels. The result was that the inevitable happened: the water blew up in the bottom of the shaft. That in turn caused the ground surrounding the partly completed shaft to settle, causing a dragdown on the segments of the shaft and circumferential cracking of the segmental lining. There was a safety consideration as well as difficulties in sinking, and it was realized by the CEGB that the time which would then be taken to complete the shaft sinking down to the sandstone would be too great, the tender date would be passed, and the information then would be too late to be of value. So rather reluctantly the shaft sinking was abandoned.

96. The designers of the foundations had instead to rely on the laboratory values of the deformation modulus to assess the settlements under their design bearing pressures. It would appear from the settlement records in the Paper that the modulus values as obtained by the laboratory tests at the site investigation stage, and confirmed by later tests in the shafts, gave a reliable basis for estimating settlement of these foundations.

97. Trouble in sinking the access shaft for the outfall tunnel was also mentioned. Considering the difficulties in sinking the exploratory shaft, it is rather surprising that the shaft for the tunnel was sunk by what appear to be orthodox sinking methods; I gather from the Paper that men were operating within the shaft, and that the shaft was being dewatered as it was sunk. The trouble may have been concerned more with water pressure from the middle sands and gravels than with the isolated layers of sands within the boulder clay. Perhaps more information could be given on that point. Did the Authors consider sinking the shaft as a grabbing operation with the caisson full of water, so that the problems of instability due to the layer of water-bearing sands and gravels would have been avoided?

The Chairman, Sir Norman Rowntree

I have been concerned with the construction of a fairly large water pumping station which had to be put underground for amenity reasons in very poor (waterlogged) ground conditions. Given that two of the major problems were the support to the reactors from the sandstone upwards and the lifting gear that is needed above ground, would both have been resolved if the reactors had been below ground, which would have shortened the supports from the sandstone and made it possible to lift them from ground level?

Mr R. J. Bridle, Department of the Environment

The problem of safety assessment is of great interest and the Authors could possibly have dealt with choice of location and design on a wider basis.

100. There are two components in the choice. First, the problem of assessing the risk of failure or the risk of passing some other limit state; the second component is the assessment of the economic consequences of failure. The economic consequences depend greatly on the location of the power station. With regard to location the comparison of population densities within certain radii are interesting, but it would be relevant to hear how these figures are related to the economic consequences of various scenarios arising from exceeding various limit states.

101. It would also be interesting, perhaps more interesting than the wide discussion that has taken place on stress distribution, to hear what limit states were taken into account and how the design was disposed to ensure that as various loadings increased a particular category of failure was predetermined for each loading condition.

Mr Coates and Mr Taylor

Professor Baker's pioneering work in the development of wire wound prestressed concrete pressure vessels is widely acknowledged and his recollections of the first attempts to wire wind a concrete vessel in the 1950s were interesting, particularly the problems encountered with high temperatures arising from friction damaging the wire. In the system developed for Hartlepool and later projects this problem has been completely overcome.

103. The machine moves around the vessel at a maximum speed of 2·1 m/s, and wire is drawn from a horizontal spool mounted on the rear section and passes through a tensioning device. This clamps the wire between a pair of caterpillar type tracks that are driven by a pair of hydraulic motors. Four hydraulic rams fed from the machine's servo pressure system maintain the transverse load of 15t which is sufficient to prevent the wire slipping in the tracks. The tracks are fitted with soft steel pads and cause no damage to the wire. In fact, the wire used on the test rig was wound and released many dozens of times without damage.

104. The load applied to the wire when it is first wound onto the vessel can be precisely controlled. The tensioning assembly is mounted on low-friction trunnions and transfers its load to the machine chassis through two tension load cells. The output signal from these cells is fed directly to a chart recorder and also to an electronic control

unit where it is compared with a preset demand signal. Any difference in signal then actuates an automatic adjustment of the hydraulic circuit and corrects any deviation from the required load. During extensive trials, equivalent to winding more than 1000t of wire, this control system has been shown to maintain wire tension within limits better than ± 445 N at a prestressing force of 24 000 N.

105. Working temperatures for the AGR power stations are considerably higher than for the original Magnox designs using a concrete pressure vessel, and the necessary emphasis on ensuring the maximum integrity of the stainless steel insulation is probably the most important single factor which has delayed the completion of the AGR stations and increased their costs. The problems of designing insulation involving perhaps 40 layers of dimpled stainless steel up to about 150 mm in thickness and ensuring that it will withstand a temperature of 700° C at a high CO_2 gas pressure for a 30 year life without attention are not difficult to imagine.

106. At Hartlepool the liner is cooled on the concrete side by an array of tubes carrying cooling water.

107. Both **Mr Burrow** and **Professor Ross** made helpful contributions on the subject of concrete 'hot spots' originally raised by Professor Baker, and both were closely associated with the design of the Hartlepool vessels. We are fully in agreement with their views. To add a little to the discussion, the importance of a hot spot in a vessel is a matter of scale (how much of the total volume of concrete is affected by the hot spot, whether it is a hot spot or a hot volume) and the restraint to which that particular piece of concrete is subjected. Certainly those hot spots with which we have dealt so far, notably at Wylfa power station, were very carefully investigated. We found values of about 120° C in local areas, but the stress induced by temperature reduced so rapidly with the creep, enhanced by temperature, that there was really no problem. One is in fact more concerned about the recovery of strain after cooling the concrete, that is when the temperature has been removed. Their query concerning CEGB experience is dealt with in Irving.[6]

108. The triaxial behaviour of concrete at normal temperatures has, however, received a great deal of attention, and knowledge of such behaviour has led to the design of the ultra pressure vessel referred to by Mr Burrow.

109. **Mr Faulkner** played a leading role in the design and construction of the project, and we very much appreciate his contribution to the discussion. We certainly share his worry about the dangers of equating safety with complexity, and believe that probably the risk is greatest when increased requirements on the grounds of safety are imposed, for one reason or another, at a very late stage in design or even after construction on site has begun. As a result additional features may have to be incorporated within extremely restricting limits and this undoubtedly contributes to complexity.

110. As mentioned in the Paper, Hartlepool was the first nuclear power station in Britain to be sited close to a centre of population and, quite apart from this aspect, there is no doubt that the requirements for safety at nuclear power stations have grown throughout the years, not only in the British Isles but throughout the world. There are, however, two important aspects of safety, particularly in the field of nuclear power. First, the assumptions upon which any particular design is based must as far as possible be verified through the synthesis of physical observations: second, a design should so far as possible be such that failure of a single component will not affect the safety of the structure as a whole, and in this respect, redundancy contributes to safety.

111. Mr Faulkner referred to the method adopted to construct the foundations and the importance attached to the investigations on the Bunter sandstone at the bottom of the shafts. It was necessary to satisfy all the people concerned that a satisfactory foundation had been achieved without the risk of rock heave and subsequent movement, and undoubtedly this took longer than originally anticipated. We are convinced, however, that the adoption of the alternative very large number of bored in situ piles would not have provided a quicker or more economical solution.

112. With regard to the boiler closures, the safety authorities requirements were for

a closure with a high safety factor, high redundancy and a mainly compressive operating state that would not be subject to a fast fracture mode of failure. From laboratory experiments that Taylor Woodrow had already carried out at the time of the proposed design change it was evident that a wire wound concrete disc would form an elegant and relatively simple solution for a closure meeting these requirements.

113. The complexities were introduced by the necessity of having to pass nine major steam penetrations through the closure together with a number of minor penetrations, and to incorporate an adequate cooling system. The design change was made at a stage when vessel construction had already begun. The prestressed concrete closure itself had to be designed to fit within the confines of already tightly proscribed geometrical parameters of the overall pressure vessel and its boiler penetrations.

114. **Mr Mead** asked about shaft raising. This method was first employed in the construction of the cooling water intake and outfall of Sizewell nuclear power station in 1962, and has since been successfully utilized in a number of similar cooling water and sewage outfall constructions. However, a temporary depression is not required for raising the shafts. Drilling is not resorted to, in combination with the upthrust of the jacks, and in most cases jack capacity has been over provided. The original site for the shaft was through 6–9 m of sand; some 1000 t of jack capacity were provided for, but only 500 tons were required.

115. The extent of displacement of soil sideways depends upon the nature of the soil and the size of the shaft being driven. Certainly there is some sideways displacement of soil which one can pick up on a model scale, but this does not lead to any risk of leakage of water, since the tunnel and the shaft are designed to the appropriate code of practice, CP2007.

116. Quite often it has been possible to use the shaft raising method as an alternative to more conventional means of working off shore involving the use of coffer dams, etc; the method saves both time and money.

117. In reply to **Mr West**, we have no evidence of any significant movement in the rock away from the reactors. The gas turbine house foundations were not carried down to the Bunter sandstone and the question of rock movement does not arise.

118. Looking back, if the ligament size at Hartlepool had been such that we could have passed cables through between the stand pipes in an orthogonal grid, as suggested by Professor Ross in § 93 we would still have gone to wire winding. Considerable experience has been gained over the years with restrained thick slabs on the basis of a considerable number of tests on large specimens of concrete. There is sufficient basic understanding and empirical evaluation of the behaviour of these thick slabs for them to be used with confidence. As mentioned in the Paper, the pile cap area is designed for a higher load factor than the barrel of the vessel (3·0 in the pile cap, 2·5 in the barrel). This is primarily to ensure that the mode of failure of the vessel is predetermined and does occur by failure of the equatorial prestress.

119. **Mr Tomlinson** had considerable involvement with the original site investigations for the power station and described the difficulties with the exploratory shaft very fully. He queried the reference to trouble in sinking the circulating water tunnel shaft. We may have over emphasised the construction difficulties in the Paper. The method suggested by Mr Tomlinson was considered but was rejected because of the uncertainty of obtaining an adequate seal in the boulder clay, and the lack of positive control implicit in open grabbing operations. There were in fact no 'middle sands and gravels' in the area of the shaft as existed on the main power station site. **Sir Norman** mentioned the possibility of sinking the reactors below ground. This is a matter which must be primarily decided on economic grounds in each case, but so far this style has not been adopted in Britain. We have however been involved in interesting exchanges on this topic on the grounds both of nuclear safety and of the general appearance of large reactor structures in areas of outstanding natural beauty!

120. **Mr Bridle** raised the general problem of safety assessment and the choice of location and design. Essentially the safety risk is dominated by the possibility of a

rupture of the main gas circuit which would give rise to a major nuclear release. Hence the prestressed concrete pressure is the essential component for consideration.

121. The vessel was designed before the 'limit state' approach was adopted in CP 110 and it is interesting to recall that several years later the BSI Drafting Committee for PCPVs concluded that there is still insufficient data to allow a limit state approach to be recommended in their standard. The Hartlepool design was based on a conservative permissible stress approach with additional checks to ensure that the vessel did not become vulnerable to pressure induced failure at much higher pressures whether or not the liner retained its leak tightness. Experience with earlier vessels containing Magnox reactors suggests that the sophisticated multiple control instrumentation is well able to limit gas pressure variations to within the designs pressure values. Deterioration of the PCPV is accommodated by the use of annual statutorily imposed inspection and test requirements. All reasonable steps to ensure the continued integrity of the vessel and hence of the station at Hartlepool have therefore been taken and the vessel is regarded as a robust structure well able to undertake its specified function.

122. Site economics for power stations, to which Mr Bridle refers, are very complex and any reasonable discussion of the factors involved is not possible in the space available or indeed, germane to this Paper.

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