Paper No. 6443

Some contributions from nuclear power to engineering practice†

by

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Discussion

Sir George McNaughton (formerly Chief Engineer, Ministry of Housing and Local Government), observing that the Paper dealt entirely with pressure vessels and biological shields, said that in no other part of nuclear work could a major failure have such disastrous results. It was pointed out in § 3 that nuclear engineering called for a much more scientific approach than that normally given to conventional engineering problems. Presumably, the tremendous potential danger to the population had demanded this very close scientific study.

79. While accepting the theory given in the Paper with regard to pressure vessels, Sir George wondered whether there was any possibility that there would be some loss of the "strength characteristics" of the steel after it had been subject to irradiation for a period of, say, 20–50 years. Certain materials, when subjected to irradiation, changed their characteristics completely.

80. In any large mass concrete structure cracking usually occurred at some place—often at the join between one day's work and the next. In the reactors he had seen there had been no sign of cracking anywhere. How had it been avoided?

81. The Author had referred to the most interesting idea of a prestressed combined pressure vessel and shield. In such a structure, could the temperature rise in the concrete result in the prestress in the steel being raised so substantially as to become dangerous?

82. Wherever ducting or piping ran into or joined up with a heavy structure fracture could easily occur if special precautions were not taken. Fig. 2a showed large ducting passing through the prestressed concrete vessel and apparently no such special provision had been made. How had the danger been obviated?

83. In a nuclear power station there were a large number of tremendous weights, many of them unequal, all over the site. This must result in unequal settlement. How was it possible to avoid, sooner or later, fracture in the ducting or cracking of the valves? Those responsible seemed certain that this would not happen, but it was difficult to understand why it did not.

Mr Stanley Gill (Senior Design Engineer, Nuclear Power Division, Simon-Carves, Ltd) said that his colleagues and he had been engaged during the past 5 years, often in consultation with the Author, on concrete pressure vessel designs similar to that described in the Paper. This work had led in 1959 to the design, construction, and successful testing by his company of a scale model. This model incorporated the typical concrete pressure vessel arrangement in which the ends of the cylindrical walls were closed by domes convex inwards. The springings of the domes were restrained by diaphragm slabs. The domes were in contact with an infilling of structurally inert concrete which transferred the loading to the domes and which offered a suitably shaped surface to the membrane for ease of fabrication and erection. The grouping of cable ducts in threes enabled the holes, which simulated gas duct entries, to be avoided. The circum-

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† Proc. Instn civ. Engrs, vol. 17, pp. 121–136 (Oct. 1960).

ferential prestress had been applied not by horizontal cables but by the Preload wire-winding method. The wires had been wound on to the wall and prestressed by being drawn through a die as the Preload machine moved round the structure. Several layers of wire were necessary, and these were wound in bands above and below the gas ducts and increased locally to compensate for the omission at the gas duct openings.

85. The test had been extremely successful. With a working pressure of 150 lb/sq. in., a design pressure of 200 lb/sq. in., and a test pressure of 250 lb/sq. in., the concrete had cracked audibly at 300 lb/sq. in. At a pressure of 555 lb/sq. in. the membrane had failed and the cracked concrete had permitted the escape of water faster than the pressure could be increased, although the prestressing wires and the vertical cables had still been quite sound. This illustrated the principle to which the Author had referred, that in effect the whole vessel could act as a safety-valve and allow the escape of pressure without doing any real damage to the elements that gave the vessel its strength. The operators of concrete pressure vessels were likely, however, to insist in future upon replaceability of vertical and horizontal prestressing elements, and in consequence the wire-winding systems did not appear to have a future in this application. In some ways this philosophy was difficult to understand, for the wound steel was remote from irradiation and temperature.

86. Mr Gill then put a number of questions to the Author. In § 59 reference was made to the fabrication and testing of the lining. Would the Author discuss the programme implications of fabricating and testing the lining in situ on the concrete substructure or on a separate prefabrication apron?

87. In § 60 the merits of gas-cooling and water-cooling were discussed. Would the Author give his views on the two systems and explain why he considered gas-cooling unattractive? Could he also give some details of the water treatment necessary, as mentioned in § 61?

88. If the cables remained ungrouted from replacement considerations, what steps did the Author recommend against corrosion of the prestressing wires?

89. The use of mild steel in the design of prestressed concrete pressure vessels had been proposed in order to increase the ultimate load of the vessel, to distribute surface cracks evenly, and to reinforce against indeterminate stresses at points of discontinuity. Would the Author give his views on the validity of this approach?

90. Finally, would the Author discuss briefly the virtues and means of applying the prestress on the outside of the wall, and state what he considered to be the optimum cable size to suit this arrangement, for a pressure similar to that given in the Appendix?

Professor A. L. L. Baker (Professor of Concrete Technology, Imperial College of Science and Technology) observed that the outstanding problem requiring discussion concerned the security of pressure vessels, and here the civil engineer was faced with new and perhaps more unpredictable factors than usual which were significant in regard to design. The pressures were known, but to what extent could they be used as a criterion of the design of a structure that might suddenly and accidentally be overheated or overloaded to an uncertain degree?

92. Civil engineers were accustomed to design important structures, such as a bridge, for which the value of a suitable working load could be determined without great difficulty; this value could then be used in conjunction with a load factor of between 2 and 4. The explosive failure of an atomic pressure vessel would be a more serious matter than the collapse of a bridge. A load factor of about 3 for a pressure vessel in relation to the normal working pressure (i.e. an ultimate resistance pressure of about 3 times the working pressure), in conjunction with a temperature having an appropriate margin of safety, should be adequate provided that all risk of structural weakness or overloading that might lead to explosive pressure had by some means been avoided or eliminated.

93. The case of a thick steel vessel seemed to demand: (i) relief and prevention of excessive pressure by infallible safety devices; (ii) perfect relief of welding stresses throughout the vessel, and elimination of all causes of brittle failure; and (iii) complete

safeguards against accidental overheating of the steel to a temperature at which its strength would be seriously reduced. In the Appendix to the Paper details were given of the gas temperatures and cooling requirements for prestressed concrete vessels, which suggested that accidental overheating of the lining or undercooling of the inside of the vessel could be critical factors in regard to failure. Would the Author say more about this point in terms of probability? A designer responsible for the strength of the vessel should perhaps be more concerned with these factors and should be given more detailed information, so that he could be certain that adequate provision had been made, in addition to a nominal load factor in relation to the working pressure. As the Author had pointed out, the position in regard to a prestressed concrete vessel was different from that of a steel vessel. Accidental overload might cause some cables to yield and eventually the lining to leak, with a resultant dissipation of pressure. The concrete could protect the cables against overheating, but excessive heat would weaken the concrete. However, only the domes at the ends were in compression, and the dome stresses need not be high.

94. Referring to the design in Fig. 2a, since security was completely dependent on anchorages Professor Baker would have liked a greater bond length to take up the thrust from the dome at the top. It was not clear how the vertical cables cleared the ducts. Would the Author explain how that was done? The idea of bringing the ducts out between the end of the barrel and the dome-springing was a good one, but there should be close binding in all sections of high concrete compression.

95. In the Simon-Carves-General Electric pressure vessel the duct bands were reinforced so that failure would take place in the bands first. This provided an additional safety device and ensured that the initiation of a failure would be gradual and thus lead to a dissipation of pressure. Internally there were a number of details which reduced the stresses at the corners. The crack pattern after the vessel had been tested to a pressure of 555 lb/sq. in. was good, and there was no indication of very wide cracks at any section. Professor Baker believed that the concrete, even in this state, would act as an effective biological shield.

96. In regard to possible designs of the future, he had always felt that quite apart from the problems of efficient construction and using recognized methods and so on, which of course made things very much easier and cheaper, the ideal form of a pressure vessel would be that of a rugger ball, ovoidal, with a net of prestressed high-tensile steel cables externally over the casing. The casing should be made of blocks of slate concrete, i.e. concrete made from waste slate which was available at small cost by the million tons in North Wales. This had been tested for strength and it had been found that blocks made from this slate would take 12,000 lb/sq. in. across the laminations. That seemed to be a very strong type of block. Slate also stood up to heat very well, holes could be drilled through it, and it had a high hydrogen content. In this way, the great dumps of slate in North Wales could gradually be disposed of. He would not discuss the design further, but it would provide cables that were completely external, completely protected against excessive heat and irradiation, and that could be inspected at any time and replaced if necessary.

Professor Kurt Billig (Taylor Woodrow Construction Ltd) observed that the Paper was extremely timely, and especially that part of it which dealt with the future development of reactor structures in the form of prestressed concrete pressure vessels. He proposed to comment on the problems raised by the use of prestressed concrete for pressure vessels, some of which were mentioned in the Paper.

98. The most important factor in the application of prestressed concrete to pressure vessel design was the behaviour of such a structure under thermal loads. It was known that in this case thermal loads were as important as internal pressure and prestressing loads, and sometimes they might even outweigh them. It had therefore become necessary to pay much more attention to the thermal properties of concrete, such as specific heat, conductivity, and thermal movement, about all of which relatively little was known. From what was already known, however, it appeared that the influence of the

type of aggregate used was much greater on the thermal properties of concrete than on the strength properties.

99. As a direct consequence of the importance of thermal loads and of the fact that concrete had poor thermal conductivity, the problem of cooling became of major importance. Assuming that the inner face of the concrete vessel was lined by steel plates, say 1 in. thick, the Author had suggested that a thermal insulation in the form of a multi-layered assembly of deformed stainless-steel foil should be used, such as that currently employed to protect pressure vessels made of steel. The alternative suggestion was the provision of piping through which cooling water was circulated. The pipes would be placed at a distance of approximately 1 ft–1 ft 6 in. from the inner face of the concrete vessel, i.e. at the place where maximum heat was generated. For advanced reactors even such provisions might not succeed in reducing the temperature gradient through the concrete walls to the 50–60°C gradient for which biological shields were designed at present. With an efficient cooling system, the temperature gradient through the concrete walls might possibly be lowered to, say, 80–100°C, and this should be quite admissible with a satisfactory arrangement of mild-steel reinforcement in the prestressed concrete walls.

100. The next major problem was that of the gas-duct connexions to the pressure vessel. Because of the large discontinuities involved, these were probably the most vulnerable points in the whole structure. Assuming that fuel charge and discharge took place at the top of the reactor, there should be no difficulty at all in providing the inlets and outlets of the cooling gas in the bottom dish of the reactor vessel. To ensure a gradual temperature fall from the core towards the pressure vessel, a coaxial arrangement of the ducts for the incoming and outgoing cooling gas was likely to be adopted, such as had already been employed in the A.G.R. (advanced gas-cooled reactor) prototype and was shown in the Author's proposal.

101. Another major problem was the effect of the temperature difference between the steel lining at the internal face and the adjacent concrete. At Marcoule this problem of compatible deformations had been solved by an intimate connexion of the steel plate with the concrete wall, which had been achieved by providing a great quantity of steel lugs and structural steel connexions. An efficient cooling of the steel lining would go a long way towards a satisfactory solution of this problem and towards ensuring the structural integrity of the vessel.

102. In the Marcoule type of prestressed concrete pressure vessel, and in the present designs in Britain, the prestressing cables were all positioned at a considerable distance from the inner face and were well protected from the effects of irradiation. Nevertheless, to provide more flexibility in the layout of the cables for future designs the irradiation effects on high-tensile steel wires should be investigated. During such irradiation experiments the test specimens should be kept at a high stress, such as 60–70 tons/sq. in., to simulate realistically their state in the actual structure.

103. Finally, the effect of long-term exposure of concrete to elevated temperatures and irradiation should be investigated. Certain data already available indicated that no danger should arise from this source. As the Author had already indicated, research on the last two questions was already in hand, and it was believed that by 1961 some results should be available.

Mr T. C. Waters (Chief Structural Engineer, United Kingdom Atomic Energy Authority) said that in § 59 it was stated that the steel lining would carry no load during service, but he believed that it would have quite a busy time. If the lining was completely built in, as it should be, and if after initial prestressing the concrete compressive stress was 2,200 lb/sq. in., then (assuming $m = 15$) the lining would become prestressed in compression to 33,000 lb/sq. in., which was fairly close to yield. At working pressure, and ignoring for the moment temperature differentials, the concrete would have a residual compressive stress of 1,200 lb/sq. in., so that the lining would have a residual compressive stress of 18,000 lb/sq. in. Assuming that, as suggested in the Paper, there was a temperature gradient of 70°C, there would be a temperature differential of approximately 35°C between the temperature of the lining and the mean concrete temperature, so there would be an additional compressive stress of 12,400 lb/sq. in. in the lining, which when added to the 18,000 would result in a compressive stress of 30,400 lb/sq. in. That was a very significant working stress and would determine the design of the lining. The Author had specified a test pressure of 15 lb/sq. in. on the unsupported lining. At what stage in the construction programme would he make this test?

105. One or two speakers had already commented on the cooling of the vessel. In § 60 water-cooling within the vessel was recommended. The problem would be to ensure that the lining was uniformly at the temperature of the concrete inside face. This assumed a surface temperature drop at the inside face of the steel lining and no temperature drop at the interface between the lining and concrete. This would be very difficult to achieve, but any surface temperature drop at this interface would accentuate temperature stresses in the lining and might possibly cripple it by buckling. Mr Waters believed that the French method of secondary gas-cooling, with its attendant difficulties of pressure balancing the two circuits, would be more reliable.

106. With regard to the gas ducts, the Author's design left a horizontal band, and eight vertical bands, each approximately 7 ft wide without reinforcement. Heavy shear stresses would be generated in this area, owing to the lateral transfer of pressure-loading and of direct temperature thrusts. One-third of the space for longitudinal reinforcement was lost in this area.

107. In § 72 the Author had concluded that there was almost no technical limit to what could be done with a prestressed concrete vessel. Mr Waters believed that there were technical limitations which could be summarized as: (i) temperature gradient limitations; (ii) size and pressure limitations imposed by strain discontinuity problems; and (iii) size and pressure limitations imposed by space considerations for cables and anchorages.

108. In § 72 also the Author had referred to cables and anchorages developing 1,000 tons/ft run of barrel, and to the equivalent thicknesses of cylindrical and spherical steel pressure vessels. It was important to pause here and consider what was being said, because there seemed to be a comparison of engineering standards with present normal building standards. Those who had knowledge of the design of steel pressure vessels would be aware that, whether he liked it or not, a factor of safety of 4 on the ultimate tensile, or approximately 2 on the yield, was imposed on the designer, i.e. 7 tons/sq. in. in tension for material having an ultimate tensile of 28 tons/sq. in. The factor of safety in building construction for high-tensile wires used for prestressing purposes was approximately 1·4 on the proof stress and 1·6 on the ultimate tensile. In Mr Waters's opinion those low factors would be unacceptable for nuclear reactors.

109. He noticed that the proportioning of circumferential and longitudinal cables was in the ratio of 4:1, but, taking account of frictional losses for the former, the proportions might have been expected to be nearer 2·5:1. Would the Author comment on this?

110. On the subject of economics, the Author had stated that there would be a direct saving in capital costs and running costs, but this did not appear to have been established. The comparative economics of a steel pressure vessel inside a normal concrete biological shield, as against a leak-tight lining within a prestressed concrete pressure vessel, could not be determined in isolation. This was only part of a very large item of highly specialized plant and equipment for power generation in which economy of layout, running costs, and capital costs assumed their appropriate importance.

111. It was of interest to consider the concrete biological shield as it was at present used and to take as an example the advanced gas-cooled reactor that had already been mentioned. This was at present under construction and so far as the civil engineering work was concerned had been nearly completed. The biological shield carried the whole of the reactor primary circuit and provided part of the containment boundary; it also carried the whole of the refuelling floor, with its plant and equipment, and all the plant and control rooms round the reactor. Few restrictions had been imposed on the

reactor designer for his plant layout, his cooling system, and his fuelling arrangements. This multiple use of the normal concrete biological shield was the yardstick against which to compare the relative merits of the prestressed concrete pressure vessel. With regard to the concrete thicknesses shown in the Paper, Mr Waters would have expected the walls to be not 7 ft 9 in. thick but at least 9 ft. Would the Author comment on this?

112. In Mr Waters's view insufficient discussion had been devoted to the complex structural problems, and undue optimism had been expressed regarding the ease with which they could be solved. He thought the Author's statement of economic factors in favour of a prestressed concrete pressure vessel was a little rash and should be accompanied by a good many reservations, which could be resolved only by detailed analysis and a greater understanding of outstanding problems.

Mr I. P. Haigh (Research Engineer, Sir Alexander Gibb and Partners, Consulting Engineers) said that about 8 months previously he had been asked to make a review of the use of ultrasonic methods for testing welds. He had made a number of inquiries of well-known fabricators of pressure vessels and pipelines, and also of some structural engineers. The pattern of the replies that he had received was quite clear. Many of these engineers were using ultrasonic methods for checking laminations in plates, and some were experimenting with the testing of welds. Two problems, however, emerged from almost every answer: one was the interpretation of the ultrasonic record; the other was the question of keeping some form of record. Both those points had been mentioned by the Author. The engineer for whom Mr Haigh had been making those inquiries had not been satisfied with these very practical and obvious conclusions, and had asked him to make further inquiries of the Atomic Energy Authority and of others.

114. These later inquiries had led to much the same sort of pattern in many cases, but there had been some exceptions, and one of them was the Atomic Energy Authority. As a result of this, and of a visit which he had made to Risley and to the Metallurgical Laboratory at Culcheth, a very clear explanation of these differences emerged. With perhaps one or two exceptions, only the firms that had had contact with the work of the Atomic Energy Authority regarded ultrasonic methods as suitable. At Culcheth, where he had met Dr Hanstock and Mr Godwin, the problems under study that he had been shown were precisely those two problems that had appeared to be a stumbling-blocks, i.e. the problem of the autographic record and that of interpretation. He had been disappointed to find that the whole of this work had been condensed into two sentences (§ 19) in the Paper. Would the Author enlarge on that aspect of his work?

Mr P. J. Fox (Messrs Kennedy and Donkin, Consulting Engineers) referred to that part of the Paper dealing with steel pressure vessels. The Author had pointed out, he said, that for the reactor vessels at present under discussion the risk of creep failure had been eliminated by maintaining the shell temperature of the pressure vessel well below the temperature of the outlet gas from the reactor core, and that this had been done either by means of internal insulation or by allowing some of the cooler inlet gas to bypass the core and pass over the vessel shell. In the latter case it was usual to rely on the core pressure drop to drive this cooler gas over the shell. The cooling requirement, when the reactor was up to normal temperature, was almost independent of reactor load, but the core pressure drop and therefore the flow of cooling gas were very dependent on the reactor load. The Author had emphasized the need for the integrity of this cooling supply, and it was important to bear this interdependence in mind when considering the integrity of the cooling system under all conditions.

116. A problem in the design on which the Author had not touched was that of the support of the reactor core within the vessel. The geometry of the core support was normally a rectangular grillage, whereas the sphere geometry was circular. This gave rise to an uneven load distribution from the rectangular grillage on to the circular boundary. When the vessel was being supported by a number of individual brackets the problem was to transfer this uneven load distribution to those brackets in such a way that within reason they shared the load equally. If this was not done each individual bracket had to be designed to take the maximum of the uneven load distribution.

117. The Author had given some details of the methods that could be and were being adopted for post-commissioning inspection of reactor pressure vessels. In view of the fact that the Paper had been written some time previously, and since this topic of post-commissioning inspection had recently been given prominence by Major-General Joslin of the Ministry of Power, during the discussion on a Paper[12] by Pemberton and Crossley at the Institution of Mechanical Engineers, would the Author comment on what it was now considered reasonable to include and what methods were still being developed?

Mr R. E. Strickland (Lecturer in Nuclear Power, Mechanical Engineering Dept, Imperial College of Science and Technology) referred to the Author's belief that a concrete pressure vessel could be considered safer than a steel vessel. There were two small points with regard to which it might be considered less safe. One was the use of water-cooling near the steel lining; systems using steel pressure vessels cooled externally by air were safer in this respect. The second was the use of the insulation attached to the membrane lining, which was also sometimes used with a steel pressure vessel. Any failure of the insulation in a prestressed concrete pressure vessel would probably result in more serious damage than it would in a steel pressure vessel.

119. With regard to the temperature rise in the concrete due to gamma-heating, would the Author give a figure in whatever units were most appropriate and state whether it was given with or without a boron-steel shield? If it was without, would there be any saving, from the safety point of view, by having a boron-steel shield inside the vessel?

120. The Author had shown a most interesting arrangement incorporating the boiler units inside the reactor pressure vessel, but what arrangements were envisaged for the inspection of these units?

Mr D. R. Berridge (Reactor Design Engineer, Central Electricity Generating Board) was concerned lest the Author's emphasis on the safety of the concrete vessel, particularly against catastrophic failure, should carry the unintentional implication that the steel vessel was unsafe. There was a very long history of development, manufacture, and safe use in service of steel vessels, and their possible modes of failure were well understood. The Paper made it clear that all the known modes of failure of steel vessels had been taken into account in the design of steel reactor vessels. Although experience of the effects of irradiation on steel was necessarily limited very careful measurements would be made on irradiated specimens within reactors, which those who were co-operating in this work were confident would give them advance warning of any undue deterioration of the material itself. This would enable the vessel to be taken out of service before it reached an unsatisfactory condition. Therefore, all that was possible had been done to make the steel vessel safe; and if steel vessels did fail it must be for some reason that the designers had failed to appreciate; the same possible criticism could clearly be levelled at the concrete vessel.

122. The concrete vessel was likely to be a more complex structure than a steel one bearing in mind the need for sealing, cooling, insulation, and so on, and although it might be free of the risk of catastrophic disintegration it was perhaps rather more liable to suffer minor failures that would either reduce its availability or even render it unfit for further service.

123. Mr Berridge believed that the arguments that favoured the concrete vessel on the grounds of safety were inconclusive and possibly misleading. On the other hand there was a very good prospect that such a vessel would be attractive economically, and its development was therefore to be encouraged.

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[12] H. N. Pemberton and Edward Crossley, "Inspection of primary circuits and reactor pressure vessels of nuclear power plant". Proc. Instn mech. Engrs, vol. 175 (1961), Separate No. 4. Discussion by Major-General S. W. Joslin.

Mr James C. Simmons (The English Electric Company Ltd), commenting on the design study of a prestressed concrete pressure vessel, said that having established that the scheme was structurally feasible and secure, the internal insulation and the cooling were of paramount importance. In the water-cooled vessel described in the Appendix the loss of heat by thermal heating of the concrete represented about 13 MW. The corresponding loss in electrical output would be about 4 MW, of a total electrical output of about 300 MW. This loss was about three times that from a reactor pressure vessel of the Calder Hall type.

125. The design proposed the use of an internal insulation consisting of 6 in. of dimpled stainless-steel sheet. From some very approximate figures he had estimated that this might cost more than £100,000. It would be interesting to hear more about the economics of the insulation and the thermal heat losses.

126. He would ask two further questions. First, how was it intended to take up the thermal movements in the coaxial ducting? He assumed that an arrangement such as that used for the A.G.R. at Windscale would not be possible with the prestressed concrete design study, and that it would be very difficult to use a conventional hinged bellows unit arrangement with the coaxial ducts. Secondly, was the proposed leak test on the lining of the vessel likely to be of any value? Presumably such a test would be at a relatively low pressure, for it would be carried out before the concrete was placed, and it was doubtful whether such a test would give any guide to the behaviour of the lining under the operating pressure.

The following contributions were received in writing.

Mr Brian Severn (Civil Engineer, Simon-Carves Ltd) observed that in §§ 50–53 the Author had discussed design for temperature gradient in a slab constrained to remain flat (or equally, in a cylindrical wall). This problem had also been described by Bonsall[13]. The results of such calculations depended very much on the initial assumptions, and widely differing conclusions on the effect of reinforcement could be drawn from reasonable alternative premises. The assumptions regarding the modulus of elasticity of concrete and the effect of tensile strength in the concrete were particularly significant.

128. Considering the simple example of a linear temperature gradient through such a slab having tensile reinforcement at the cooler face only, the neutral axis depth for any percentage of reinforcement was readily determined by elementary bending theory. For this purpose a value must be assumed for the modular ratio, and the tensile strength of concrete was conventionally taken as zero. However, if account was taken of the tensile stress in concrete, up to the assumed tensile strength, then the neutral axis position could be calculated if the reinforcement stress was assumed (the limiting case of interest was for maximum permissible working stress). The neutral axis having been located, the stresses for a given temperature difference, or the maximum temperature difference for limiting acceptable stresses, were readily computed by using the coefficient of thermal expansion of concrete.

129. First, supposing concrete to have no tensile strength, the following values were assumed:—

Modular ratio		$m = 15$
Coefficient of thermal expansion of concrete		$\alpha = 11 \times 10^{-6}/°\mathrm{C}$
Young's modulus for steel		$E_s = 30 \times 10^6$ lb/sq. in.
Permissible tensile stress in reinforcement		$p_{st} = 20{,}000$ lb/sq. in.
Permissible compressive stress:		
in concrete	(*a*)	$p_{cb} = 1{,}000$ lb/sq. in.
and alternatively	(*b*)	$p_{cb} = 1{,}500$ lb/sq. in.

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[13] William Bonsall, "Stresses in reinforced concrete shields for nuclear reactors". Proc. Instn civ. Engrs, vol. 16, pp. 259–270 (July 1960).

The permissible temperature difference varied with reinforcement percentage according to curves 1(a) and 1(b) in Fig. 3. However, with high-grade concrete, or for a rapidly established temperature gradient, it might be appropriate to employ a lower value for m. Curves 2(a) and 2(b) showed the lower permissible temperature differences if $m = 8$. It was interesting to note that resistance to temperature gradient was improved by increasing reinforcement up to the "economic percentage", but thereafter diminished.

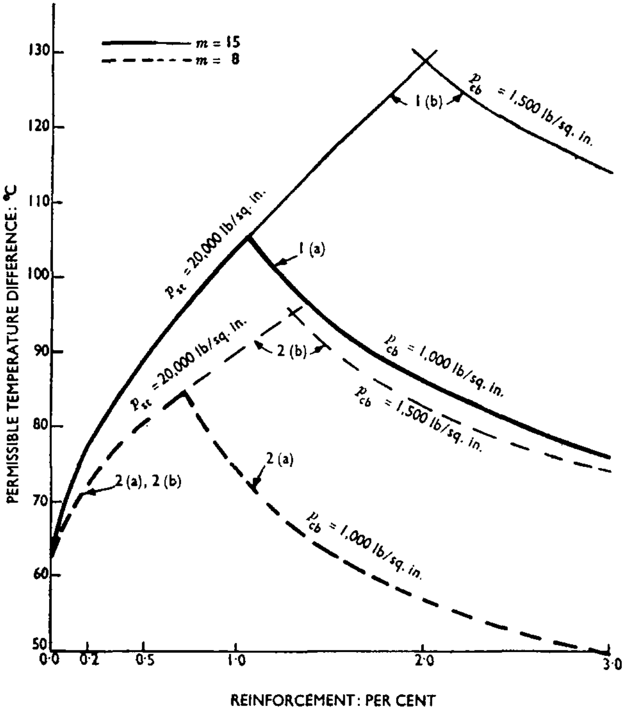

FIG. 3.

130. Assuming that concrete was uncracked by tensile stress up to a limit of 500 lb/sq. in., corresponding curves 3 and 4 could be plotted as shown in Fig. 4. This might be supposed to give a truer picture. On this basis, resistance to temperature gradient was only slightly improved by adding reinforcement, within the usual range of percentages. Even assuming no reinforcement, some 70–80°C temperature difference appeared to be acceptable, the criterion then being a degree of cracking corresponding to fully stressed reinforcement at the cooler face.

Mr I. W. Hannah (Development Engineer, Simon-Carves, Ltd) noted that in § 54 the Author had mentioned creep as a factor of considerable importance in thermal stress calculations. From the results of a limited experimental programme on slab and beams subjected to modest linear temperature gradients across their depths, it appeared that an abnormal shrinkage due to the temperature conditions was also of importance. This effect was naturally more noticeable in small specimens than in massive shields.

132. The slab experiments had been intended to simulate the restraint condition described by the Author in § 53. However, with slabs 7 ft 6 in. × 3 ft, and 6 in. deep, loaded with a central, constant bending-moment section 3 ft long, the maintenance of the restraint by mechanical loading had not been practicable since the initial deformation due to temperature had been rapidly reduced by differential shrinkage. It had been necessary to investigate the deformations of the specimens due to temperature, to shrinkage and to mechanical loading in the opposite sense, independently.

133. In order to examine this behaviour over a longer period, beams 10 ft long by 10 in. deep by 6 in. wide were tested in identical pairs. One such beam was subjected to a constant heat input on the upper face and the deformation due to the gradient established was recorded. After the deformation pattern had been established, both beams were simultaneously equally loaded to a predetermined maximum fibre stress and maintained in that condition for 2–3 months. Again, the deformation characteristics of both the heated beam and the control beam were recorded to indicate the relative creep values. The experimental rig was shown in Fig. 5, facing p. 192.

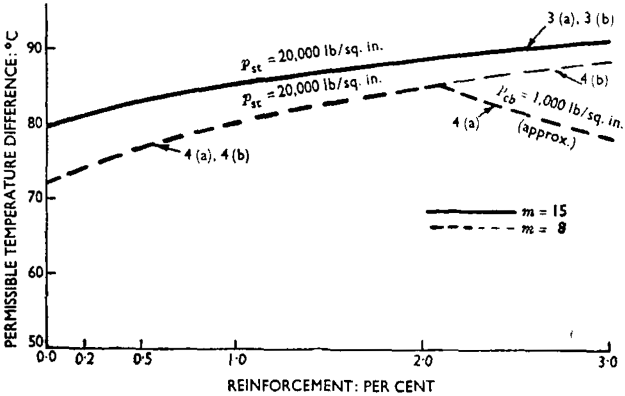

FIG. 4.

134. The deformation characteristics of a typical pair of unreinforced beams of gravel aggregate concrete were shown in Fig. 6, together with a theoretical prediction based on simple bending theory and on concrete characteristics as determined by standard tests.

135. The difference between the actual deformation and the predicted values was most pronounced and was thought to arise from several contributing factors, all of which required much more experimental verification:—

(*a*) The modulus of the heated beam, determined in flexure, was found to be considerably below that of the unheated control beam.

(*b*) The heated beam displayed considerably greater creep than that at ambient temperature.

(*c*) Perhaps most important of all, differential shrinkage substantially reduced the deformation due to temperature. It was of interest to note that the maintenance of a constant electrical heat input throughout the tests led to a steadily increasing value of temperature drop through the beam, as shrinkage reduced the conductivity of the concrete.

136. The work had been restricted to about twenty tests. Had the Author noted any similar characteristics in the work referred to in § 54?

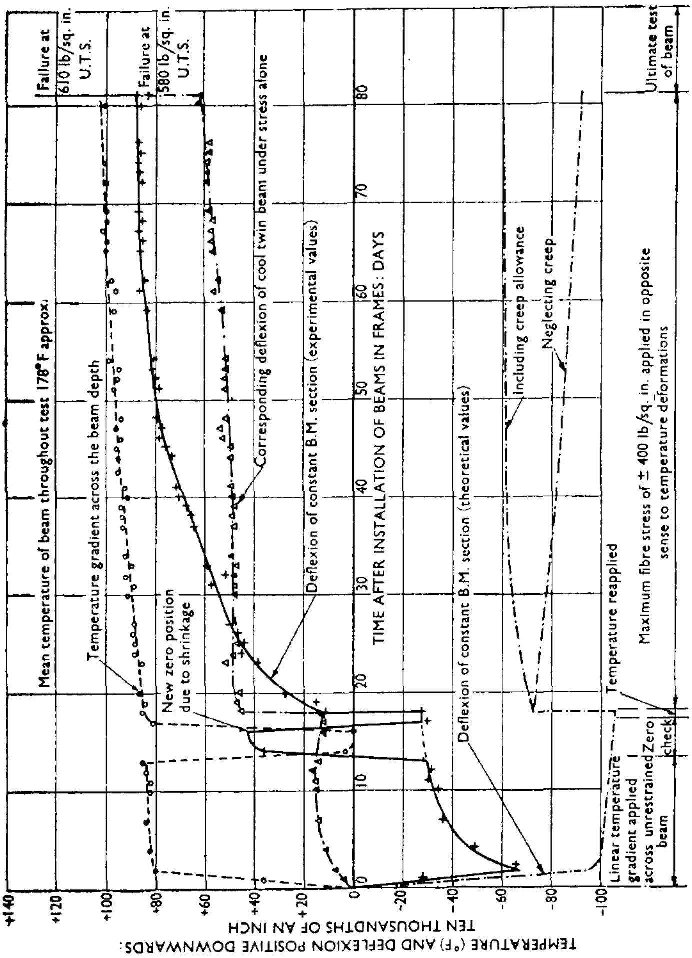

FIG. 6.—BEAMS MADE OF GRAVEL CONCRETE: LONG-TERM DEFLEXIONS

137. The behaviour of a reinforced section after cracking should be more predictable, but in the particular case of reactor shields the percentage of steel provided was likely to be of the order of 0·1–0·2%, which might well be insufficient to allow normal reinforced concrete behaviour.

Dr S. C. C. Bate (Senior Principal Scientific Officer, Building Research Station, Dept of Scientific and Industrial Research) observed that the Paper drew attention to the need for information on the behaviour of prestressing steel under the conditions that would exist in a prestressed concrete pressure vessel. It was clear that, in addition to being subjected to irradiation, the steel would be maintained at a temperature somewhat greater than that in normal structures. With this need for information on the effects of irradiation and temperature in mind, the Building Research Station, in close collaboration with the United Kingdom Atomic Energy Authority, had begun to investigate the influence of these conditions on the relaxation of stress in stressed specimens of hard-drawn steel wire, made in Britain for prestressed concrete.

139. The limitations on the size of specimens for exposure in materials-testing reactors provided considerable problems in the development of a compact testing rig. The form of rig ultimately adopted consisted of six individual tubes, each containing a stressed wire, which were fitted within a water-cooled aluminium block with cooling gas circulating between the tubes and the block, the whole assembly being less than 4 in. in diameter. Each of the tubes in the rig was tapped at both ends, at one end with a right-hand thread and at the other end with a left-hand thread, to receive suitable bolts which were drilled longitudinally and fitted with barrel-grip anchorages for anchoring the wire. The wire specimens, which were 18 in. long, were stressed by gripping the tube and rotating the end bolts simultaneously. The stress in the wire was determined from its frequency of vibration. The earlier rigs were designed for use with wire of 12 S.W.G., but with slight modifications it was found that wires of 0·2 in. dia. could be stressed and vibrated satisfactorily. So far, one series of test specimens had been exposed to irradiation, and results were being analysed; preparation was being made for further series of exposure tests.

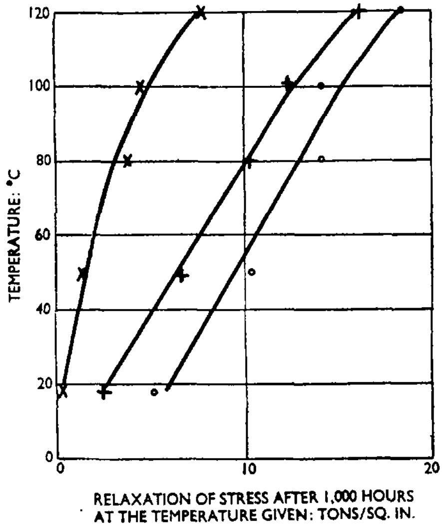

FIG. 7.—EFFECT OF TEMPERATURE ON RELAXATION OF STRESS IN DIFFERENT MAKES OF 0·2-IN.-DIA. WIRE STRESSED INITIALLY TO 70% OF ITS TENSILE STRENGTH

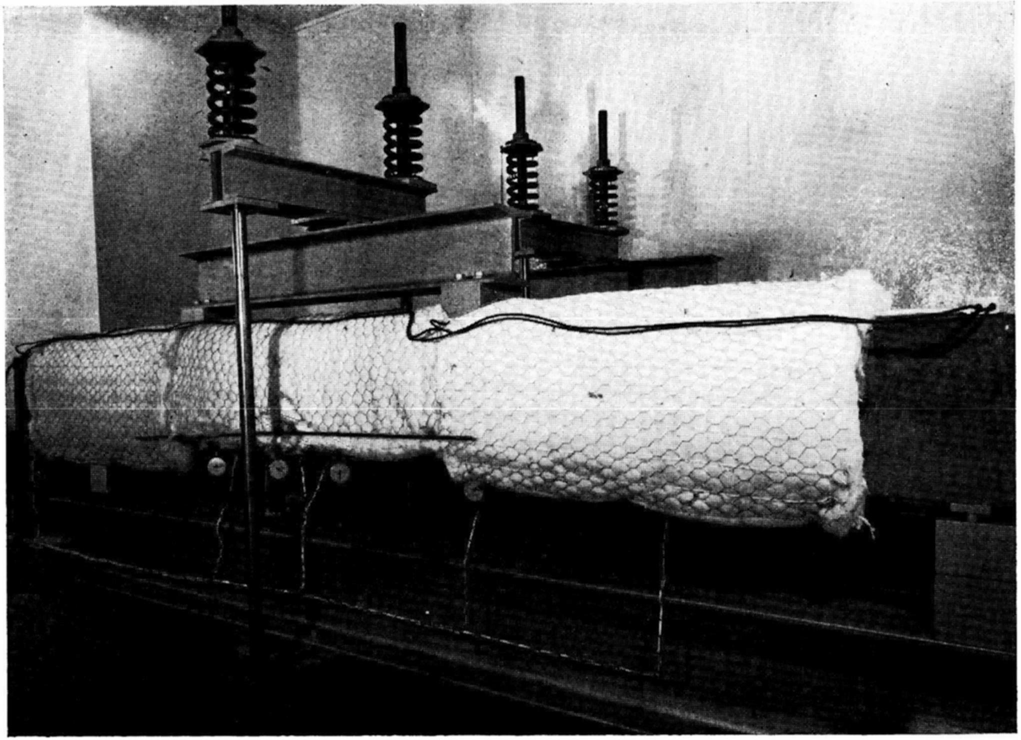

FIG. 5.—EXPERIMENTAL RIG FOR INVESTIGATING THE DEFORMATION CHARACTERISTICS OF CONCRETE BEAMS

140. Preliminary tests in connexion with the irradiation tests showed that the effect of temperature alone on the relaxation of stress in hard-drawn steel wire was somewhat greater than had been expected. An investigation of this effect was therefore started to determine its importance for wires of 12 S.W.G. and 0·2 in. dia. of British manufacture. Stressing rigs similar to those designed for the irradiation tests were being used for the tests, which were being made at temperatures between 18 and 120°C. Since the testing procedure for the examination of the effect of temperature was simpler than for that relating to irradiation, some results showing the influence of temperature on relaxation were available. A selection of these results for several different wires of 0·2 in. dia. was shown in Fig. 7, where the losses of stress given were those recorded from 1 min after stressing, over a period of 168 hours (7 days) at 18°C, followed by a period of 1,000 hours at the temperature given.

141. While the test period was short in comparison with the service life of a pressure vessel, the results showed that the increase in relaxation of stress with temperature was substantial. At temperatures slightly above normal it would be necessary to make an increased allowance for loss of prestress in design, which at higher temperatures, i.e. 100°C, might well be prohibitive for some makes of wire. It seemed likely, therefore, that the positioning of tendons in prestressed concrete pressure vessels would be largely conditioned by the effects of temperature in the surrounding concrete.

Mr A. C. Paterson (Partner, Messrs F. R. Bullen & Partners, Consulting Engineers) believed that the Author's suggestion, that one of the great contributions of nuclear energy to general engineering had been the introduction of a more scientific approach to the conventional engineering problems, would meet with widespread agreement. The impetus given to mechanical and electrical design was perhaps more obvious, but that given to civil engineering design and construction was no less real. He hoped that a freer interchange of information would become possible between those concerned with the civil engineering design of the civil stations for the C.E.G.B. A paper comparing designs submitted by the various consortia for a specific station would be of value.

143. The Author had placed due emphasis on the consequences of failure of the reactor pressure vessel. His remarks also applied to the failure of the main CO_2 ducts, which in some stations would seem to present an additional hazard because the ducts between the tops of the heat exchangers and their reactor appeared relatively exposed to mechanical damage from aircraft. Such an event might seem improbable but could not be dismissed as impossible.

144. The Author had referred to the energy of the compressed gas within the reactor pressure vessel. Would he give his views on the effects of pressure vessel failure on the biological shield? Would shock waves be formed, and if so, what effect would they have on the concrete of the biological shield?

145. On the question of the choice between pneumatic and hydraulic pressure testing, the surrounding of the pressure vessel with water contained within a watertight biological shield would be a neat method of avoiding the overloading of the vessel-support system if a hydraulic test was chosen. Such a solution would, however, impose an additional temporary load over 2½ tons/sq. ft on the foundations within the area of the biological shield.

146. If the pressure vessel was tested without the biological shield's being filled with water to balance the hydrostatic pressure, then not only was the vessel support system overloaded but the stress pattern imposed on the vessel would differ from the pattern under working conditions. The problems associated with obtaining, storing, and handling the large volumes of suitable water necessary for the tests should not be underrated. It would be of interest to know whether a hydraulic test was proposed on any of the stations at present under construction in Britain.

147. In §§ 47 and 48 the Author had described the procedure for determining the "dry density" of the concrete, but had not mentioned the oven temperature at which the cubes were dried. The temperature did of course have a significant effect upon the results; for example, if the cubes were dried at 50°C the water retained might be expected

to be of the order of 15·5% by weight of cement, but if the temperature were 100°C this figure would drop to just more than 13%[14].

148. The current C.E.G.B. specification for civil stations called for drying at a temperature of 100°C, and at this temperature it might no longer be true that a hydrogen content of 0·5% by weight of the final mixture could be achieved by normal engineering practice. Cement in excess of the economical might have to be used in the concrete, but since this also increased the density, the rate of increase in percentage of hydrogen was slow, and it might be more satisfactory to increase the thickness of concrete shielding. Would the Author confirm the figure of 0·5%, since 0·3% had also been mentioned?

149. The "dry density" arrived at by oven-drying the test cubes could be expected to be considerably less than the actual final in-situ density for the following reasons:—

(*a*) The longer the concrete was allowed to cure before heating, the greater would be the percentage of water retained for a given temperature[14]. The cubes described by the Author had been cured for 7 days, whereas the shielding concrete would be cast for possibly 2 years before heat was applied.

(*b*) It was anticipated that water would evaporate much more readily from a 6-in. cube than from a mass of concrete 8–10 ft thick.

The selection of the oven temperature should not be arbitrary but should be related to the anticipated temperature in the shield, and a figure rather less than the peak temperature would seem appropriate.

Mr P. I. Parker (Chief Design Engineer, The Cementation Company Ltd), referring to prestressed concrete pressure vessels, said that the combination into one unit of the shield and the structural element seemed clearly to be the technique of the future. French engineers had led Britain into this field with their reactor at Marcoule.

151. The Author had stated that, using cables and anchorages commercially available, a net hoop tension of upwards of 1,000 tons/ft of barrel could be developed. It seemed probable that, using large cables of, say, 1,400 tons capacity (as installed at Howden Dam near Sheffield) and placing them in staggered rows so as to provide adequate room for the heads, this intensity of prestress could be substantially increased without any significant departure from present practice and experience. However, for intensities of prestress up to about 1,000 tons/ft, the Author was wise to suggest the use of smaller cables. Apart from the more uniform distribution of load that they gave, experience on prestressed dams had shown that cables of 200–300 tons capacity tended to be the cheapest, bearing in mind the practical difficulties on site of cable handling, homing, stressing, testing, and final grouting.

152. Cables of 250 tons capacity would suitably comprise 126–130 parallel wires 0·2-in. dia. made up on site from coils of normal cold-drawn high-tensile steel wire. Stressing heads of the type used at Marcoule would be of 2 ft dia. and 1 ft 6 in. thick, sufficient to house three jacks and three permanent 6-in.-dia. packs or pedestals. Alternatively, if the cables were not to be removable for inspection, they could be stressed by means of temporary yokes and jacks and anchored permanently with high-grade concrete vibrated into cylindrical or conical openings of about 1 ft dia. and 3 ft deep at their ends. Both systems of anchorage had been extensively used with success and gave an extremely low unit cost for stressing and anchoring.

The Author, in presenting the Paper, drew attention to the advisability of taking the prestressed concrete pressure vessel a stage farther. It was technically possible to make such a vessel large enough to enclose the boilers, as well as the reactor core. He had prepared a design study of such a concept, and he felt that it was technically feasible and could offer important advantages in safety and economy.

154. Replying to Sir George McNaughton, the Author agreed that pressure-vessel steel was affected by irradiation over a long period. There would probably be some

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[14] Raymond Wilson and F. A. Martin, "Water retained in hardened cement pastes". Proc. Amer. Concr. Inst., vol. 31 (1935), p. 272.

change in the yield point and ultimate strength; there was certainly an increase in the transition temperature. It was hoped that sufficient was known to make due allowances in the design. But, as Mr Berridge had mentioned, each vessel contained a very large number of samples of its own materials, subjected to the same temperature and irradiation as the vessel itself, and these could be brought out year by year for examination to make sure that everything was still satisfactory. Cracking in biological-shield concrete had been known to occur, but not to any serious extent. The efficacy of a concrete radiation shield was not reduced by minor cracking, and a good "structural" standard was acceptable.

155. A number of speakers had asked about the possibility of a temperature rise in the concrete, which might cause the stress in the steel to rise dangerously. There did not appear to be any circumstances that could cause a rapid temperature rise, and as had already been explained, the vessel could run for a considerable time on full power, with no cooling at all, before the stresses became serious. Nor did there seem to be anything within the reactor itself that could lead to a very large output of heat until, in fact, the vessel had failed.

156. It was true that the connexion of the ducting to the vessel shown in Fig. 2a was diagrammatic. In detail some provision could and should be made to provide a transition between the rigidity of the concrete and the unsupported duct.

157. The problem of foundation design, to avoid excessive differential settlements, varied according to the nature of the ground, and this was taken into account in selecting the site. The science of soil mechanics must assist the designer in this respect.

158. Mr Gill had thrown some doubt on the Author's suggestion that the cables should be replaceable. After further reflection it was still felt that this was not only a wise precaution, but a positive advantage for which some extra cost would be well justified.

159. It seemed essential that the completed lining inside the finished vessel should be completely free from leaks, but it appeared difficult, although not impossible, to test it at that stage. The Author had therefore suggested that the lining could either be completed and leak-tested, before pouring concrete, or all seams could be radiographically examined shortly after welding, in which case the concreting could be concurrent. The choice seemed to be one for the contractor, taking into account the programming of the work.

160. The choice between gas-cooling and water-cooling for the vessel was not an easy one. With gas-cooling, which must be CO_2 because it was impossible to guarantee complete separation from the reactor coolant, some light construction must be fitted inside the vessel lining to separate the two streams of coolant, which were at very different temperatures. To avoid damage to that light construction the pressure of the two coolants must be balanced; if there was one thing that was likely to go wrong it was any form of automatic pressure-regulating valve. It might be necessary to have a deliberate leak between the two circuits. The vessel coolant gas must of course be brought outside the vessel, so that it could be cooled in some external heat exchanger; any failure in that external system constituted a breach in the pressure vessel, which was an unfortunate and serious weakness in the scheme. Another difficulty was that such a system could not conveniently be adjusted from outside, so that local overheating might occur.

161. On the other hand the water-cooling system could have the cooling pipes embedded in the concrete close to the point where heat was being produced, which seemed sensible. In that arrangement it would also be possible to connect the pipes to the lining by strips of steel welded on, thus providing good thermal paths for the removal of heat from the lining and ensuring that the lining was kept at the same temperature as the concrete. This was important with a material such as concrete, which had a poor thermal conductivity. Such an arrangement of pipes and strips would also serve to bond the lining to the concrete. The removal of heat with water was economic, leading to low running costs. Taking all these factors into account, the Author favoured

water-cooling in spite of its higher capital cost. At the low temperatures involved the treatment of the water to avoid corrosion could follow accepted practice.

162. The prevention of corrosion in ungrouted cables was a problem for the designer to solve. The use of mild-steel reinforcement was also a matter for the individual; it could certainly play a useful part. It was a fact that it might be cheaper to put the cables on the outside of the wall, but there might be the possibility of damage to the cables by some local accident, such as fire.

163. The Author agreed with Professor Baker that an ultimate-load factor of 3 seemed appropriate for a reactor pressure vessel. To avoid misunderstanding it should be remembered that ultimate-load factor meant the ratio of the gas pressure, at which structural collapse occurred, to the working gas pressure, in conjunction with temperatures having an appropriate margin of safety. As had already been mentioned, there could be no significant overheating, and the provision of proper pressure-relief valves could avoid the possibility of significant overpressurization, so that the conditions laid down by Professor Baker could be met.

164. In the sketch design shown in Fig. 2a care had been taken to provide sufficient space for all cable anchorages, and the cables were unbonded; the vertical cables were bent round the gas ducts.

165. The Author agreed with Professor Billig that the effects of temperatures, and temperature gradients, in the concrete were important and relatively novel. Not only did the thermal properties of concrete become important, but they were themselves affected by the temperature at which the concrete was maintained. For instance, some moderately elevated temperature might occur in some particular point of the concrete, and as a result of that temperature the thermal conductivity might be reduced, leading to a further increase of temperature. Mr Hannah had also referred to this matter.

166. It was true that the design of the vessel cooling system was important, and it should be made clear that it was visualized that internal lagging of the vessel would be combined with water-cooling, not as an alternative. In that case it was felt that the general gradient through the wall of the vessel could be restricted to less than 50°C; a conventional elastic-stress analysis would probably indicate that it was economical to do so. A more correct analysis, using better understood concrete properties, would probably tend to optimize at some other temperature gradient. Local temperatures, over limited areas, might well exceed the figure mentioned above.

167. In stating that the lining had to carry no load during service the Author meant that it did not have to sustain by its own strength any applied force. As Mr Waters had pointed out it did have to be subjected to strains to match those of the concrete to which it was bonded. The figures quoted by Mr Waters were a little exaggerated in some respects; for instance, the value of m would be less than 15, and the figure quoted of 1,200-lb/sq. in. compressive stress in concrete, under working conditions, included the effect of temperature gradient. On the other hand a thorough analysis of the effects on the lining over the life of the vessel, using realistic concrete properties, would probably show that the lining was taken past the yield point in compression. This would not seem objectionable, provided that it was not done repeatedly. The Author agreed that such an analysis of lining behaviour was necessary.

168. Owing to the thickness of the vessel walls, no particular difficulty had been found in dealing with shears in the unsupported areas shown in Fig. 2a. This had been confirmed by model tests.

169. Mr Waters was quite right in concluding that there would be, in fact, technical limits to what could be done with a prestressed concrete vessel; but these limits were a long way off in several important respects, such as size. Development potential was always welcome.

170. Mr Waters had compared, disadvantageously, a factor of safety of 4 for steel vessels against a factor of safety of 1·6 on prestressing cables. The Author felt that it was necessary, as Professor Baker had shown, to talk about ultimate-load factors. The steel vessel designed to a conventional code had a nominal membrane stress limited to one-quarter of the room-temperature ultimate tensile strength of the material. But that

"factor of safety" was eaten into by all the stress concentrations and bending stresses produced at openings and other discontinuities. Not all of these were truly secondary, i.e. removed by yield or creep. It could not be maintained that the ultimate-load factor for a steel reactor pressure vessel was much more than 3, even in its early life.

171. As had already been stated, the Author's opinion was that a concrete vessel should have a designed ultimate-load factor, which could be confirmed by model test, of not less than 3, partly because he felt that a concrete vessel should be in no way inferior to a steel vessel. In that context a "factor of safety" of 1·6 on the prestressing cables had no significance.

172. The ratio of circumferential to longitudinal cables was in fact 2·2:1, as given in the Appendix to the Paper. The thickness of the walls need not exceed 7 ft 9 in. on grounds of structural strength or shielding.

173. When expressing the view that insufficient discussion had been devoted to the complex structural problems, and that undue optimism had been expressed regarding the ease with which they could be solved, Mr Waters must remember that the length of the Paper was limited, and that the subject had received the attention of many competent engineers over a period of several years. Their work should not be dismissed too lightly.

174. Mr Waters had suggested that the economic results were not established. In the Paper some particulars were given of a design study which had been made for a concrete vessel as an alternative to a fully detailed steel vessel; a careful cost analysis had been made and it had been found that there was a saving with the concrete vessel. Similar results had been found independently. It was considered that the design mentioned in the presentation of the Paper, with the boilers in the reactor pressure vessel, would be markedly cheaper than a conventional arrangement.

175. Mr Haigh had referred to the work on ultrasonic examination which the Atomic Energy Authority was carrying out at their Culcheth laboratories. This was part of the development in which several firms were engaged.

176. Work had continued on developing the automatic application of the simple compression wave probe, particularly to difficult configurations, with automatic recording of observations. The ultrasonic examination of butt welds was rapidly becoming important, and here the inclined, reflected, shear wave technique was necessary to locate defects in their probable orientation. The Authority were attempting to develop a multiple probe assembly to make a complete survey of a butt weld automatically, but this was a difficult task, whose success could not be forecast.

177. The assessment of the significance of a defect echo signal was also difficult, particularly if automatic recording was required, and continued consideration had been given to this problem. It remained true that significant extension of ultrasonic examination was taking place within the industry concerned with nuclear power stations, but this to some extent remained confidential at present.

178. As Mr Fox had pointed out, some steel reactor vessels depended for cooling upon the circulation of the cooler inlet gas, making use of the core pressure drop. Creep was of course a very long-term phenomenon, and the occasional reduction of vessel cooling flow, when the reactor was on part load, would not be expected to have any adverse effect. It was true that owing to the lack of symmetry at the margins of a rectangular core support grid the reactions varied. This could be overcome by using a radial support grid. Post-commissioning inspection was mentioned in the Paper. The Atomic Energy Authority were developing strain-gauges which, it was hoped, might give significant information over the life of the vessel.

179. For reasons already given, the Author did not agree with Mr Strickland that the two points he mentioned rendered a concrete vessel less safe than a steel vessel. The total heating in the vessel was mentioned in the Appendix, without a boron shield. Such a shield might be economically justified, but had no influence on the safety of a correct design. The Author's personal view was that inspection of the boiler units was not essential. A burst boiler tube would not hazard the reactor, and could be isolated outside the vessel; and the possible number of such bursts, arising from undetected

defects, was extremely small. Any possibility of general failure arising from corrosion or otherwise should be eliminated by correct design.

180. Mr Berridge had very properly drawn attention to the fact that there was nothing inadequate about the steel pressure vessel, and the Author hastened to endorse that view.

181. It could be questioned whether the concrete vessel was really more complex than the steel vessel. The latter looked simple but functioned in a manner that was very difficult to understand in detail.

182. In reply to Mr Simmons, the Author pointed out that most of the heat removed by the vessel cooling system was produced by radiation in the concrete, and would also be lost from a steel reactor pressure vessel. With the boilers inside the concrete vessel this heat could be trapped in the shield wall between the core and the boilers and fed to the system, thus producing a marginal advantage. The cost of the stainless-steel insulation had been taken into account in the cost analysis already mentioned. The design study illustrated in the Paper was for an advanced gas-cooled reactor scaled up from the Windscale AGR. The leak test on the lining was intended to prove the soundness of the welds; it should not be difficult to develop sufficient strength in them.

183. Mr Severn had drawn attention to the importance of the assumptions made in a theoretical treatment of the effect of thermal gradients in concrete. Fig. 1 had been included in the Paper to provide a lead-in to the subsequent discussion of the concrete pressure vessel. It was accepted that such an analysis was really over-simplified.

184. Other evidence that the effect of thermal gradients required the most careful study had been provided by Mr Hannah's valuable contribution. The striking result of moisture migration, produced by temperature, in reversing the expected deflexion of test beams showed that this effect must be taken into account, although there was at present much uncertainty about the rate at which moisture content would change in the considerable thicknesses under consideration.

185. The work on the behaviour of hard-drawn steel wires under irradiation and under moderate temperatures, which Dr Bate had reported, would provide information vital to the concrete pressure vessel concept. Tribute should be paid to those responsible at the Building Research Station for successfully developing the necessary apparatus to measure the stress in the wires, even after they had been irradiated, and when they could not therefore be handled directly. It should be added that the tests on the effects of temperature, of which some results to 1,000 hours had been given, would be extended to at least 10,000 hours.

186. In reply to Mr Paterson, it could be said that some model experiments had indicated that a burst pressure vessel could produce local shock loads, by gas impingement, on the biological shield. But because the inertia of the shield was high, these did not seem as important as the general build-up of gas pressure within the shield. It seemed that fragments of the pressure vessel could create more severe local effects.

187. A hydraulic pressure test had been proposed for the reactor vessels of a station now under construction in Britain. Such a test had been successfully completed on a reactor vessel being built by a British consortium in Italy.

188. The original intention in suggesting that shield-concrete density cubes should be oven-dried at 100°C had simply been to shorten what was otherwise a rather long drying period. It was agreed that the resulting dried density was rather too low, but it was consistently so. A hydrogen content of the order 0·5% should be ample, and less might be satisfactory. It must be recognized that the basic physics of shielding were extremely complex, and substantial margins should be left in all respects until more experience was available.

189. Mr Parker had been right in saying that a net hoop tension higher than 1,000 tons/ft of barrel could be developed, and it was interesting that he also favoured a cable size of about 250 tons. The Appendix to the Paper gave the proposed cable make-up, and it had been intended that these should be parallel wire cables. However, it must be recognized that the laid cable might be a more competitive arrangement.