Discussion

The Chairman opened the discussion by mentioning a few points which interested him. One was the slide showing trees growing out of the puddle trench; he felt it would interest Mr Tattersall, who had had experience of drying puddle at Chingford reservoir. The use of the puddle round the reservoir was similar to what had been done in gasholders round London in previous years. The reservoir had ended up by being almost like a gasholder, but the gasholder had a number of timber supports carrying the light steel dome when it subsided. It was interesting to see that at Cleadon a large number of supports had to be erected and a complete dome had been built in timber, as shuttering, only to be replaced by the permanent dome in concrete.

Some years previously the Chairman had investigated a reservoir at Easington for Mr Ruffle's Company where there had been some "rat-holes" and subsidences in the bottom, and there had been a difference of opinion on whether the cause was mining subsidence or cavernous limestone underneath. Mr McLellan had dealt with the matter by using a rubber lining, and the Chairman hoped he would describe his experience in the following discussion, since it was related to the problem of mining subsidence mentioned in the Paper.

Mr A. G. McLellan (Engineer and General Manager, Sunderland and South Shields Water Company) explained that the general picture in the Water Company's area of supply should be painted against a background of mining subsidence. Of the Company's twelve service reservoirs seven had been open reservoirs, and of those seven, six had been constructed in a similar manner to the one at Cleadon, using puddle clay as the water-retaining medium. They were in fact "Hawksley" reservoirs. They had done their job remarkably well over the years. The reservoir at Cleadon was slightly less than 100 years old. The idea had been that the puddle would move and take up any movement caused by mining subsidence, which had in fact occurred.

The first decision required had been whether to interfere with the puddle clay or to adopt some form of roof which had no intermediate supports. With a circular reservoir the second alternative led automatically to a dome, but not necessarily to a concrete dome. A metal dome might have been used. However, from the point of view of cleanliness and freedom from infection the concrete dome had much to commend it.

It could not be assumed that because mining subsidence had taken place it would not recur, or that because the coalmining authorities had said "It is extremely unlikely that we shall take coal out of that seam" any likelihood of their doing so was past. It was therefore necessary always to bear in mind the possibility of mining subsidence under structures in a coalfield until it was known that every seam had been completely worked out, or unless one took the expensive step of buying all the seams in the neighbourhood of each structure. That point had to be considered in relation to the expense of covering a reservoir.

The reservoir at Cleadon was important, especially at night, for balancing supplies to the South Shields area. In view of the considerations to which he had referred, the decision was taken not to puncture the floor of the reservoir. Whether or not that had been the easy way out might be proved during the current year, since in the case of the next reservoir to be covered the floor was to be punctured because no other kind of unsupported roof could be carried by the walls of the reservoir. In making good the punctured floor, however, expensive precautions would be necessary.

Could the Authors subdivide their figure for the cost of construction (about £25,000) and say how much of that had been due to the supports (the tubular scaffolding), and how much to the shuttering? Circumstances had made the work expensive. Only one use of the shuttering had been possible and it had been carefully and elaborately fixed. Even the question of suitable aggregate had been difficult—it was a bad part of the country for good aggregates. Therefore if the Authors would subdivide the cost of construction it would bring out the great cost of the shuttering and its supports.

The men on the job had taken an intense interest in the work, which had contributed markedly to the high degree of workmanship obtained.

Professor A. L. L. Baker (Professor of Concrete Technology, Imperial College of Science and Technology) observed that many good reasons were given in the Paper for using the dome, but probably one reason had been omitted, namely, the love of every engineer of designing and building a large-span dome.

Referring to the quality of the concrete, he said the standard deviation of the cubes had been good but the strength rather low. Presumably that had been due to the local aggregate, which was apparently rather poor. He asked how the reinforcement had been spliced in the ring beam and whether the joints were staggered so that not more than one splice occurred at any section, which was probably the ideal way of splicing the steel in a ring beam. Why had the ring beam not been prestressed? It seemed to have been a good case for prestressing. Would the Authors consider that the risk of cracking would be reduced or, if cracks did occur, that their width might be reduced slightly, if any kind of deformed bar had been used instead of ordinary smooth bars?

With regard to the detail design of the ring in relation to the shell, whilst he was sure that by longer and more careful study the answer would be apparent, would the Authors say whether or not the eccentricity of the horizontal reaction from the ring had been decided in such a way as to reduce the radial bending in the shell to the minimum? Presumably there had been some reason of that kind for the fairly high eccentricity of the horizontal reaction from the ring beam.

He had been interested in the method devised by the Authors and given in Appendix I of assuming hinges and using rotations as unknowns to determine the radial bending moments. Did the Authors consider that if the shell had been made thinner and therefore more flexible the moments would have been less and whether, with those calculations for the hinge rotations, the rotations could have been small enough to be easily taken up by local plasticity, so that it would not have been necessary to thicken the shell quite so much and yet a satisfactory solution obtained?

He noted that it had taken 22 days to lower the supports. In the case of a much smaller dome (60–70 ft in diameter), which Professor Baker had designed in South Africa, the shuttering had been lowered by loosening wedges, as the Authors had done, first of all making them hand-tight and then slackening them gradually to take the load off the shuttering. It had been calculated that the man who had to do the job had to walk several miles over the scaffolding. It was quite a big part of the operation of construction.

Mr W. E. J. Budgen (Chief Engineer (London), Twisteel Reinforcement Ltd) agreed with Professor Baker that every engineer obtained more satisfaction from designing a structure of the character of that under discussion than by designing something more humdrum. Usually the engineer's instincts in that direction had to be slightly subdued by the necessity to advise his client that such plans tended to be expensive. They had therefore been extremely fortunate when they had been asked by the Sunderland and South Shields Water Co. to design the structure at Cleadon in that that Company decided that the inadvisability of interfering with the puddle clay floor rendered a large-span structure desirable.

It had been thought at first that timber would not be available for shuttering and various schemes had been worked out by which the soffit could have been formed using flat steel plates. Fortunately, when the time came for construction timber had been available, and that enabled the soffit to be formed very accurately and thus maintain the calculated weight within very close limits. The good workmanship of the men on the site, together with adequate supervision, had resulted in a structure which was all that a reinforced concrete structure should be.

It had been realized that an almost unique opportunity would arise at one period, when the whole of the completed structure would be supported on shuttering subject to no loads and that that shuttering would gradually be removed. That seemed to provide a valuable opportunity to obtain some idea of the correlation between calculated and observed stresses. With the co-operation of the Sunderland and South Shields Water Company a fairly extensive testing procedure had therefore been devised and many hundreds of strain-gauge readings had been taken. However, the effects of temperature, as had frequently been found previously when doing similar tests on shell roofs, defeated the object in view, and while it had been hoped that there would be many data to add to the Paper as a result of those tests, in fact those results which had been obtained were not felt to be worth including.

The tests had, however, taught two lessons. The first was that when contemplating building a large dome of that type it was advisable to build it during a period of rising temperature. The second was that whilst much of the elaborate analysis was interesting to the mathematically inclined designer, it was of little use so long as it neglected the important influences in reinforced concrete design of the shrinkage of the concrete and the effect of temperature.

Mr G. P. Manning (a Consulting Engineer in private practice), referring to the relative permanence of reinforced concrete and aluminium domes, asked whether either of the Authors could show him a 3-in.-thick reinforced concrete slab, constructed on a slope similar to the sloping part of the Cleadon dome, which had stood exposed to the weather for more than 15 years without showing some of its reinforcement. In other words, was the Authors' estimate of the permanence of their structure based on experience or on hope? If he had to choose on grounds of permanence alone between two structures, on the one hand a 3-in.-thick reinforced concrete dome designed and specified by the average British designer and built by the average British contractor, and on the other hand an aluminium dome of the Hamman type, with 16-gauge sheeting, he would certainly choose the latter.

The permanence of reinforced concrete depended largely on the correct positioning of the reinforcement, and the only way to ensure that was to design, specify, and provide special spacers for each particular job. The time-honoured method of shoving a block of sand and cement under the steel could not be relied on. Mr Manning showed a slide of some asbestos-cement spacers and remarked that it would be of interest if the Authors would give a sketch of the spacers designed and used for the work at Cleadon.

The cost of a Hamman-type aluminium dome of the size of the Authors' dome would be about £14,500, and its weight about 35 tons, compared with 640 tons for the Authors' dome. Would the Authors say how much the existing walls had settled under the new load?

Had the Authors considered eliminating the edge effects by prestressing the thrust ring? Mr Manning did not suggest that they should have prestressed it, but he would like to know if that had been considered and, if it had, the exact reasons for not doing so. He believed he was correct in saying that all the calculations in the Paper were based exclusively on loading symmetrical about the main vertical axis of the dome.

Mr Manning showed a slide of the first long-span aluminium dome ever to be constructed. The stresses in that dome under the partial loading shown were known; it carried about 25 lb/sq. ft over half its area. Would the Authors say what stresses that type of loading would induce in the dome at Cleadon? How much of the upper surface of the dome had actually been shuttered? The Authors said that the reinforcement in the ring beam was "butted." Did they mean butt-welded?

Mr Manning showed a slide of the Hamman dome nearest in size to that described by the Authors. It was 151 ft in diameter and cost about £12,600. The Hamman type of dome could be constructed without emptying the reservoir and without putting any supports in the water.

Mr C. A. Serpell (Deputy Engineer, Sunderland and South Shields Water Company) said that on p. 266 three possible causes of pollution were given, which in fact constituted the three main reasons for covering the reservoir at Cleadon, but there was another reason which had occurred to him. The Authors mentioned that the water which entered the reservoir from the well had a fairly constant temperature of 55°F. Now the Water Company had a number of burst mains every year, and in the months of December, January, and February the frequency of those bursts was 100% above the average. From that it was deduced that when there was a period of frost an increase in the number of burst mains could always be expected. One possible explanation was that the water in the open reservoirs cooled, and then cooled the main, and that that cooling of the main was just sufficient to cause the fracture. With the thermal protection afforded by the roof the water should be kept at a more constant temperature, and it was hoped that maintenance of an even temperature would reduce the number of burst mains. Unfortunately, sufficient information was not yet available, because the problem was masked by the vagaries of burst mains due to mining subsidence, so that it would be some time before a definite conclusion could be reached on whether or not the covering of the reservoir would have that added advantage.

The Authors had referred to the choice of material, which lay between aluminium, prestressed concrete, and the shell concrete which had in fact been adopted. For the aluminium roof there had of course been a magnificent precedent in the form of the Dome of Discovery, but that had been intended from the beginning to be a temporary structure. It was felt that the possibility of corrosion had not been fully determined, and that there would be some risk of the corrosion of a permanent structure in aluminium. The prestressed concrete design which had been considered had been visualized as being made with pneumatic mortar, and they had been uneasy about it on two counts. First, no data were available on the behaviour of prestressed concrete under conditions of mining subsidence; secondly, from a number of jobs which had been inspected there had been a doubt about the consistency of pneumatic mortar as applied to a large structure of the type in question. The estimated costs of those alternatives being at that time roughly comparable, it had been decided to adopt the shell concrete roof.

The Authors referred to the additional dead load on the wall, equivalent to $1\frac{1}{4}$ ton/ft run. With all those reservoirs which had been roofed over by a single-span roof, whether it was a dome or a roof over a rectangular reservoir, the crux of the problem was the strength of the gravel puddle on which the wall was founded. That was a question which had been considered in every case. At one of the larger reservoirs which they were at present investigating the extra loading which would be put on the gravel puddle had decided them against the single-span roof; it would mean taking too great a risk. The dome, of course, was ideal in that it loaded the wall uniformly all round, whereas with a barrel-vault or rectangular roof there were concentrations of load at certain points round the perimeter which made the problem of the bearing strength of the puddle clay rather more complex.

The Authors referred to the freedom from cracks of the structure. Mr Serpell considered it could fairly be claimed that for its size it was remarkably free from any kind of cracking.

Mr F. Tattersall (New Works Engineer, Metropolitan Water Board) remarked that it was not the first time that the Sunderland and South Shields Water Co. had adopted rather an unusual solution to a problem. Another of their reservoirs had been rubber-lined, which was, he believed, the only one of its kind.

A dome had many apparent advantages for a structure of the kind in question. He had recently been considering a somewhat similar job, with a span of about 120 ft, but a dome would be difficult to justify economically on the basis of the costs given at the end of the Paper. The costs were very high and, judging by the experience of the Metropolitan Water Board, were perhaps $2\frac{1}{2}$ times as high as the average cost of a flat slab roof which was much more heavily loaded, being asphalted and covered with 18 in. of earth.

The Authors said that the roof became free of the shuttering during construction. If that happened would it not be possible to construct a dome of the type in question by shuttering it in stages, as would be done in the case of an ordinary flat roof? If it were shuttered in rings, by the time that two or three rings had been constructed the first ring would be free of the shuttering, which could then be taken off and used for the next ring. Any further information which could be given on the proportion of the cost represented by the shuttering would be welcomed.

The Chairman had mentioned the drying out of the puddle clay which had occurred at Chingford. The Metropolitan Water Board had had a great deal of experience of puddle. In one case there had been trees about 40 ft from a puddle wall, with 3-in. roots going right through the puddle wall. The effect of the roots on the puddle was that they extracted water from it and the puddle shrank and dried. In addition, the roots might provide a direct path of leakage.

He would not consider the fact that otherwise they would have to interfere with the puddle floor as a reason for deciding to construct a dome. More than one of the Metropolitan Water Board's reservoirs, which had been constructed basically in a similar way to that at Cleadon, had leaked and had had to be repaired. Many of their reservoir roofs were covered with puddle, but most of those roofs now leaked and were having to be repaired. In those cases, of course, the puddle had been exposed to drying. He knew of cases where puddle used in the floors of reservoirs had deteriorated, but even where that was not so he would not consider that a sufficient reason for deciding upon any particular type of roof construction. Mr Tattersall was interested to find that the Sunderland and South Shields Water Co. thought otherwise.

He would like to know the nature of the ground underneath and outside the Cleadon reservoir. In many of the cases where the Metropolitan Water Board had puddle there was London Clay underneath and it did not really matter whether the puddle leaked or not. If there were narrow bands of puddle outside the walls they would not now regard that as a good form of construction.

What was the real function of the weepholes provided in the walls at Cleadon? If their purpose was to let water in to relieve hydrostatic pressure, where did the water come from? Did it come out of the puddle, or between the puddle and the wall? In any case, the wall should be capable of withstanding the hydrostatic pressure.

On the question of settlement, another method worth considering would have been to make the roof entirely of precast members and then asphalt it. Asphalting was quite cheap on a job of that kind and did not add more than about 1*s*/sq. ft to the price. It should have been possible to deal with settlement quite satisfactorily with a roof constructed entirely of precast members and then asphalted.

Referring to the question of temperature, Mr Tattersall said the Metropolitan Water Board had areas which were supplied by river water, where the temperature fell almost to freezing-point in the winter, and also areas supplied by well water at a constant temperature of 52°F. The water in Cleadon reservoir would probably not be cooled very much, and he would be surprised if in future the Sunderland and South Shields Water Co. had any trouble with burst mains if their water was initially at 55°F. In the Metropolitan Water Board it was the practice to mix well water with the river water where possible because the higher temperature was quite enough to prevent bursts occurring on any substantial scale.

The Chairman remarked that the question of lining and of watertightness was always interesting. Mr McLellan had used rubber in his repairs. At that time I.C.I. had been advocating polythene or one of the plastic sheets which could be ironed together. The Chairman did not know whether that had yet been used in such cases.

Mr R. S. Jenkins (Partner of Ove Arup & Partners) remarked that circular domes had been talked about for many years, and he believed that there had been some German methods of introducing spiral curves at the edge in order to bring the edge stress to match that of the ring beam without departing from the membrane theory. The work described seemed an obvious case for a prestressed concrete ring beam, and he also would like to ask why that had not been used.

With regard to Mr Manning's contribution, it seemed to Mr Jenkins that the case for a light dome had been very powerful. The Authors stated that under the wall the puddle was reinforced with gravel, but the weight of the dome must surely be increasing the pressure on that region considerably, and only time would show whether it was going to stand up to it. Another good reason for an aluminium dome was that it was cheaper.

Mr Manning had said that he had worked out equations 1(a) and 1(b) in the Paper many years ago. Mr Jenkins pointed out that they had been worked out long before Mr Manning's time, but he thought that the Authors had been quite right to put them down, and also to give the next equation although it often appeared in structural theory, because they were all part of the Paper and of the necessary background.

Mr A. G. McLellan, speaking again, referred to Mr Manning's remarks about cover to reinforcement and the use of aluminium for domes. Mr Manning had said that allowances must be made for what could be obtained from workmen when designing cover. Mr McLellan suggested, on the other hand, that it was possible to get within $\pm \frac{1}{8}$ in. That had been done on the Cleadon roof and in the case of at least six other works which they had carried out recently. In one case the contractors had said that they were asking for machine-tool precision in the placing of reinforcement, but they had insisted on it and found that the men took a greater interest and did it satisfactorily. The contractors had agreed afterwards that it was not a costly business.

Mr Manning had shown an interesting slide of the interior of an aluminium dome, which showed exactly what Mr McLellan did not want to see inside the dome at Cleadon, with all the nooks and crannies to harbour insects, etc., which it was undesirable to have near a potable water supply. The Company's Mill Hill reservoir, which had been lined with rubber, was not entirely germane to the present issue but, since the Chairman had referred to it, Mr McLellan would say that although it had been expensive it was undoubtedly economically justifiable.

Reference had been made to the possible use of polyvinyl chloride instead of rubber. The Water Company had experimented for many months with P.V.C. in all thicknesses and in all sizes and shapes. Under workshop conditions a good joint could be obtained by hot ironing, but that could not be done under the damp site conditions, where it was necessary to think in terms of several thousand square yards. The Research Department of I.C.I. had, at the time, tried to find a solution to the problem of making a continuous lining by the welding of the joints. Not being able to do it with P.V.C. the Water Company had turned to rubber, and the net result had been that to line the reservoir, which had been on the point of being written off as an asset, had cost £70,000. A new 12,000,000-gal reservoir might well cost about £240,000. That was a defence against any charge of extravagance in that respect.

The Chairman, from knowledge of the Mill Hill reservoir, had asked about the "rat-holes" and what had been done about them. There had been no rat-holes under the reservoir which they had lined; the floor had been punctured with about 200 borings to establish that. The so-called "rat-holes" were under the reservoir yet to be repaired and they had been caused by the scouring away of lenticular pockets of sand in the clay foundations by the escape of water through the cracks in the structure.

Mr Bernard Whitteron (a partner in the firm of Howard Humphreys & Sons, Consulting Engineers) said that the question of the insulation of the roof had been mentioned, and he wondered if the Sunderland and South Shields Water Co. had any information on changes of temperature, because such information was difficult to obtain.

Had the question of an aluminium or concrete domed roof created any difficulties in obtaining planning permission? He understood that all such proposals had to be submitted to the County Planning Officer, who might perhaps suggest that a dome would look rather incongruous.

In Fig. 5 there appeared to be no distribution bars to the top steel. If that was so it would be interesting to know the reason. On p. 274 the Authors said that "To eliminate the crowding of the reinforcement the bars were butted, with the joints staggered." Mr Manning had already referred to that point and Mr Whitteron would welcome fuller details.

Lastly, he assumed that no waterproofing was applied but that reliance was placed entirely on the density of the concrete to obtain satisfactory watertightness.

Mr G. P. Manning, speaking further, said he had omitted to point out that when designing aluminium domes the first thing he had done had been to put adjusting screws on both ends of all the members, with a ball joint. He did that before working out any sections, stresses, or spacings. That was the best way to deal with edge effects and problems of that type, namely, to avoid them.

Professor A. L. L. Baker, in a further question, asked the Authors whether they had considered using a flat slab roof, probably with columns spaced at about 15-ft centres, the roof being 8 or 9 in. thick and the columns supported on a similar raft in the floor. That form of construction had been used during the 1939–45 war for tanks where there had been considerable relative settlement, and a tank of that type was very flexible.

*** **Mr B. P. Pritchard** (Engineer, Preload Ltd) observed that the use of a dome roof led to a substantial saving in concrete (or pneumatic mortar) and reinforcing steel, compared with a more conventional flat-slab or beam-and-slab construction. With the present shortage of steel, the latter economy should prove attractive. Furthermore, if the dome was intended as a covering to a water-retaining structure, as in the present case, other advantages ensued, namely:—

(1) The air space between the water and the curved underside of the dome provided a good insulating medium, eliminating the usual earth cover associated with flat roofs.
(2) The absence of roof columns ensured an even distribution of pressure on the floor and subsoil of the structure—an important factor in the watertightness and efficiency of that floor.

There remained only the economy of the roofing medium, and the figures quoted in the Paper were hardly encouraging. In that connexion it was interesting to record the case of a dome of similar proportions, built as the roof to a 2,000,000-gal service reservoir at Paisley, Scotland. The dome diameter was 143 ft with a rise of 17 ft 10½ in. Dome construction was begun about 2 months after the Cleadon commencement and was completed in less than 6 months, compared with Cleadon's 15 months. The cost per square foot was approximately half that of Cleadon. In fact, the whole reservoir structure was completed for less than the cost of the Cleadon dome. To emphasize that point, it should be stated that the structure consisted of a 143-ft-dia. reinforced pneumatic mortar floor, and an 18-ft-high, 143-ft-dia., 9¼-in.-thick prestressed pneumatic mortar wall, with its foundation, besides the dome and dome ring.

The main shell of the Paisley dome was of 3-in.-thick pneumatic mortar, reinforced with wire mesh as B.S. 123. The peripheral dome ring, 2 ft 0 in. deep by 1 ft 0 in. wide, was monolithic with the reservoir wall. Both dome ring and wall were of pneumatic mortar and were prestressed circumferentially by a proprietary wire-winding system. The dome ring was prestressed by 170 wires, each carrying a design tension of 1·21 ton. It should be noted that the Paisley dome had to be designed for a live load of 40 lb/sq. ft compared with the 15 lb/sq. ft used at Cleadon.

The Authors stated that a system employing prestressing and sprayed concrete (pneumatic mortar) was considered and then rejected. That was unfortunate since both prestressing and pneumatic mortar offered special advantages over normal reinforced concrete in dome construction.

Pneumatic mortar was especially suited to the lightly loaded smaller diameter domes where the very small design thickness required could be satisfactorily placed. Several 2-in.-thick domes, up to 64 ft dia., had been constructed in Britain in the past few years, and it was hard to imagine their construction in reinforced concrete, especially in terms of compaction and construction joints. Pneumatic mortar, of course, obtained excellent compaction from its high-pressure placing and was well adapted to the forming of efficient

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*** This and the following contribution were submitted in writing after the closure of the oral discussion.—Sec.

construction joints. It had the further advantages of easier placing, lighter construction loading on the underlying formwork, and a low shrinkage characteristic. The factor of high strength, also present, was incidental, since only moderate stresses occurred in those dome shells.

Prestressing, *via* a peripheral dome ring, had become a very common feature in shallow dome construction. Many hundreds had been prestressed by the wire-winding system alone, mainly in North America. Its advantages over the reinforced concrete peripheral ring dome could be listed as follows:—

(*a*) The direct stresses for a correctly designed prestressed dome were always compressive. Cracking was eliminated, and full use could be made of the most advantageous property of the concrete—its high compressive strength. Dome-ring proportions were smaller, especially in the large diameters.

(*b*) Edge moments in a prestressed concrete dome were considerably less than with its reinforced concrete counterpart, owing to the balance between the dome self-weight and a part of the prestressing reaction. Edge thickening and bending reinforcement were consequently reduced.

(*c*) Another feature of some importance was that prestressing at the peripheral ring tended to lift the shell off its supporting formwork, which simplified form stripping. In comparison, the normal reinforced concrete dome required special attention at stripping. Care had to be taken to avoid dangerous loading conditions when the formwork was being lowered and removed. The shell had to be let down as uniformly as possible.

A further point made by the Authors concerned the lack of knowledge of the behaviour of prestressed concrete under conditions of mining subsidence. Of course, if that was meant to apply to domes, the lack of such information extended to reinforced concrete in a similar manner. Theoretically, at least, the advantage once more lay with the prestressed solution, which was more resistant to edge disturbance than its reinforced concrete counterpart. A degree of subsidence resistance could easily be incorporated by the winding of extra prestressing wires.

Subsidence implied a removal of part of the support under the edge ring, and several prestressed domes had been specially designed and built for a similar loading condition—where the support was provided by columns. A striking example of that type of structure had just been completed in Havana, Cuba. That dome, 6 in. thick, had a diameter of 294 ft and was supported on a combined beam-dome ring 5 ft 3 in. deep by 3 ft 3 in. wide, wound with nine hundred 0·141-in.-dia. wires, each carrying a 1,650-lb. design tension. The structure was supported on twenty-four columns, giving clear dome-edge spans of 39 ft. However, the dome edge and ring had been designed to span twice that distance, in the event of subsidence rendering any column ineffective.

Mr R. M. Davies (Aluminium Development Association) remarked that the Paper demonstrated very effectively that the dome was still of great practical value today as a roof structure, although it had originated in ancient times.

The advantages of using aluminium as a structural medium at Cleadon might not have been fully realized—an aluminium alloy dome for the reservoir could have been erected more quickly than the reinforced concrete dome and at lower cost.

Mr Davies was surprised at the statement on p. 266 that aluminium was not used for the project because doubts were felt about its resistance to corrosion. With regard to external conditions, suitable aluminium alloys correctly installed had very good resistance to maritime atmospheres and would provide an indefinite life without maintenance and without painting. That had been shown by the tests of the American Society for Testing Materials and also by experience both before the 1939–45 war and since.

The present extensive application of aluminium alloys in shipbuilding and the fact that small boats made from aluminium alloys as long ago as the early 1930s were still in use, although unpainted, should dispel doubts about how the appropriate alloys performed even under severe marine conditions. The results achieved in that field showed that the corrosion resistance could be of a high order.

With regard to the inside of the dome, the amount of chlorine present in the water was, of course, extremely small and the concentration in the atmosphere would be insufficient to have any appreciable effect on the aluminium alloy, particularly if the interior was well ventilated. In the case of reservoir domes already in service, there was no evidence of any interaction having taken place.

The use of aluminium alloy domes was not confined to reservoirs, and roofs of that type had already been used with success in industrial areas for covering oil tanks and sugar storage vessels.

It was possible that the Authors might not have had experience of the durability of aluminium for roofing purposes. One example was the cupola of the Church of San Gioacchino in Rome which was covered with aluminium in 1897; another was the Rheinbahn Station, Dusseldorf, which was roofed with aluminium in 1929. In both cases, the metal was found to be in good condition when examined in recent years. Another example of durability, perhaps better known, was the cast figure of Eros in Piccadilly Circus, erected in 1893. That had been examined several times and after the coating of dirt had been cleaned away no pitting had been found on the metal surface.

It was perhaps not unreasonable to expect that an aluminium dome for a reservoir would have a similar expectation of life.

With regard to considerations of weight, the load imposed on the wall surrounding the reservoir by an aluminium-alloy dome would be a very small proportion of the load imposed by the reinforced concrete structure described. That would seem to be a useful attribute since the load on the gravel puddle below the masonry wall would consequently be kept to the minimum, with reduced risk of disturbance and leakage. In the event of mining subsidence repair work would be rendered easier and, because of the inherent elasticity of the metal, the dome itself would not be so liable to fracture as one of concrete.

The construction of the reservoir dome in reinforced concrete appeared to have been a lengthy process entailing elaborate scaffolding and considerable usage of timber for shuttering. The use of scaffolding was not, of course, entirely eliminated in the erection of an aluminium dome, but a much smaller amount was required.

The experience which had been gained with aluminium alloys in past years, and recent developments in their use, had now made it possible for aluminium to be employed with advantage in a wide range of applications. Unfortunately, there had been occasions in the past when technical advice in the selection of alloy had not been sought and simple precautions against bimetallic action had not been taken. In some of those instances the material had not had the success that it should have had and the impression created had been undeserved.

Mr Ruffle, in reply, said that the trees to which the Chairman had drawn attention were not so close to the reservoir as they perhaps appeared to be in the photographs; none were nearer than 20 ft from the wall. Although it was well known that the roots of trees had caused trouble elsewhere, no harmful effects had so far been found at Cleadon.

In reply to Mr McLellan and to Mr Tattersall, the subdivision of the cost of the construction was as shown in Table 4.

He agreed with Professor Baker that the average strength of the concrete was low. He was not sure why, but it had been about 400 lb/sq. in. lower than he had expected. It had been known from other jobs in the district that the average value would in any case be considerably lower than that indicated by the curve in Road Note No. 4. The strength requirements for the design had nevertheless been met.

Mr Manning had raised the question of the permanence of aluminium compared with that of concrete. Mr Ruffle was confident that if the concrete were inspected after 15 years there would be no signs of rusting. The cover on the concrete had been very carefully maintained by, as Mr Manning had surmised, the use of blocks of sand and cement. (They were shown on one of the photographs.) There had been constant checking and inspection during the concreting operations.

20

TABLE 4

		£
Scaffolding (including sole bearers, barrow runs, etc.)		6,212
	£	
Shuttering: Materials	1,703	
Labour	6,336	
		8,039
Steel fixing		2,544
Concreting: Materials	2,241	
Labour and plant	4,518	
		6,759
Other permanent work		2,032
Total cost of construction		£25,586

No settlement of the walls had been detectable on a recent check.

The concrete had a compacting factor of 0·91, which had made it possible to place the concrete on the slope of the dome quite satisfactorily and to compact it adequately without top shuttering.

Mr Tattersall had compared the cost unfavourably with that of a slab roof and had suggested that it was 2½ times the cost of a flat slab roof. In Mr Ruffle's experience that was not so. Recent tender prices suggested that the cost was perhaps 1½, not 2½, times the cost of a slab roof. Nevertheless, he was not prepared to suggest that the structure would be suitable for a new reservoir. At Cleadon it had been used for the reasons given, which were not necessarily applicable to other reservoirs.

The puddle clay in the reservoir had been in good condition, despite its age. It was absolutely essential that the puddle should remain in good condition because, unlike the reservoirs referred to by Mr Tattersall, Cleadon reservoir was founded on magnesian limestone. If failure of the puddle occurred, it would quickly lead to very serious leakage. In point of fact the reservoir had withstood successfully, without leakage, considerable movement caused by mining subsidence.

The weep-holes through the wall were intended to keep water away from the back of the wall during emptying of the reservoir, so reducing the inward thrust. The cross-section of the wall was such that it would not be safe from either sliding or overturning if there were full inward hydrostatic pressure. In a copy of the specification, dated 1860, there was a clause headed "Drain-holes": "That *at every* 6 *feet in length, or thereabout*, and every 2 feet in height, or thereabout, a hole of the height of a course of stones, and three-fourths of an inch wide, shall be left entirely through the side-walls for the purpose of draining off any water which may happen to lodge between the wall and the puddle." It was conceivable that a certain amount of water could reach the back of the wall via the interstices and joints in the limestone masonry.

Mr Jenkins was right in saying that the loading on the gravel puddle had been considerably increased. The gravel puddle was in good condition, and the increase of 20% in the loading, applied after the many years during which it had stood and reached equilibrium with the loading of the wall itself, was not likely to cause any trouble.

In reply to Mr Whitteron, the Authors had no information on the insulating effect of the roof. Undoubtedly it would help to maintain the initially constant temperature of the water. Conversely it was to be expected that the water would tend to keep the temperature of the concrete in the shell lower in summer than it would be otherwise and rather higher in the winter, thus reducing the effect of the seasons, the time of day, and the weather on the expansion and contraction of the dome.

No criticism of the dome had been made by the planning authority who had stated that town planning approval was not required for that type of development. The dome was actually in a sheltered position and was not prominently in the public eye. But apart from that, it was difficult to imagine that anyone would take exception to the dome, which was entirely functional and yet not unpleasing in shape.

Mr Whitteron was correct in assuming that the density of the concrete was relied on to maintain the watertightness, and Mr Ruffle was sure that no rainwater seeped through. The underside of the dome was often wet, but that was due to condensation.

Professor Baker had suggested a flat slab roof constructed on a raft above the puddle clay. That had been considered, but Mr Ruffle had thought that it would be difficult to ensure reasonably even settlement on the soft puddle. Furthermore a concrete raft over the floor would render the puddle inaccessible in the event of severe ground movement necessitating its repair. The stepped floor of the reservoir (Fig. 5a) would complicate the construction and it was probable that the cost would be more than that of the dome.

Mr Tottenham, in reply, referred to the suggestion by Professor Baker, Mr Manning, and Mr Jenkins that a prestressed concrete ring-beam might have been advantageous. There were, of course, many advantages to be derived from prestressing, the principal one being the elimination of hoop tension for normal loading conditions. However, the effects of variations in temperature between the shell dome and the ring-beam would not be reduced by prestressing and experience with other forms of shell construction indicated that they might be of considerable importance.

Moreover, it was felt at the time that insufficient data were available concerning the effect of mining subsidence on prestressed concrete structures and that there were two good reasons for adopting ordinary reinforced concrete. The first of them was that the distribution of steel in the ring-beam and the shell would give good crack control in the event of uneven settlement. With a prestressed ring-beam good control would be achieved only if either there were additional unstressed reinforcement distributed throughout the section, or the prestressing wires were distributed and had a good bond to the concrete. Distributing the wires would be complicated and good bond difficult to ensure.

The second reason was that settlement of a portion of the ring-beam might, in the case of prestressing, cause the neutral axis to move so far to the compressed face of the beam that the prestressing force would cause bursting of the concrete.

Professor Baker had asked whether the reason for the fairly high eccentricity of the shell on the ring-beam was to reduce the radial bending moments. Mr Tottenham agreed that by raising the springing level the line of action of the resultant of the forces T_2 and N_2 passed more closely to the centroid of the ring-beam, and thus reduced the tendency of the beam to twist. The main considerations were, however, practical ones. Had the springing level been lower there would have been an upstanding portion to the ring-beam which would have complicated the casting of the beam. Also the draining of the rain-water from the dome would have necessitated an opening in the beam which would have been undesirable.

Professor Baker had also raised an interesting point concerning the possibility of reducing the edge moments by allowing for a small amount of plastic rotation in the edge zone. The plastic rotations would, indeed, be small, even if the edge-zone moments were reduced to zero. The method of analysis outlined in Appendix I of the Paper permitted the "plastic" analysis of that type of structure. For example, the first four equations of Table 2 could be solved by taking the moments as zero, and checking the rotations at the hinges by using equations (12). The value of E, which determined the strain due to hoop tension, should, for safety, be taken as that of concrete. Alternatively, the moments could be given some definite value to suit the reinforcement detail, the first four equations solved, and the rotations then checked. In the case of the Cleadon dome, however, such a method would not have been advisable, for cracking was to be minimized and the absence of insulation on the outer surface of the dome would give rise to daily thermal movement which, if associated with plastic deformation, might prove harmful. Should a smaller dome be required where external insulation were to be provided it would be interesting to design it by some such plastic method and to observe its behaviour.

In reply to the requests by Professor Baker, Mr Manning, and Mr Whitteron for more details of the ring-beam reinforcement, the main bars were simply laid end to end, the positions of the ends being staggered within each of the three vertical rings of reinforcement. Thus the ends of the bars forming one hoop of reinforcement were effectively "spliced" by a bar in the same vertical band but some distance away. It was thought that that system would give a maximum chance of consolidating the concrete around the reinforcement. It was not considered necessary to provide distribution reinforcement in the top of the dome near the springing.

There were methods of eliminating edge-effect forces, as suggested by Mr Jenkins, by using a special shape at the shell edge, but those forces were eliminated only for vertical loads. Temperature stresses would not be removed. Mr Manning had suggested that the provision of ball joints and adjusting screws at the edge of the shell would have the same effect. That would be merely a form of prestressing and would only have the desired effect for one particular load. Mr Tottenham could not agree that the best way to deal with edge-effect forces was to avoid them. To him those forces were merely the effect of continuity between dome and ring-beam and were in no manner harmful. They were, in fact, of exactly the same nature as end moments in continuous beams and frames, and presented no greater difficulty in their analysis.

The calculations in the Paper were, as Mr Manning had suggested, entirely devoted to the effect of loading symmetrical about the main vertical axis. In the actual design temperature effects had also been considered. Partial loading had not been investigated, since the self-weight of the dome constituted a large proportion of the design load. Those interested in the analysis of domes under partial loading should refer to the paper by Reissner[7] and the report on model tests by Voss and Peabody.[8]

Mr Manning had also expressed doubts regarding the durability of a 3-in.-thick concrete slab cast on a slope such as that at Cleadon. There were in fact many reinforced concrete shell roofs, both in Britain and on the continent where weather conditions were more severe, which were less than 3 in. thick and were cast with slopes greater than 28°, and yet after more than 15 years showed no signs of corrosion of the reinforcement.

The lifting of the dome from the shutter had led to an interesting speculation by Mr Tattersall. He had suggested that it might be possible to cast a dome in a series of rings and as each ring became free removing the formwork and re-using it again nearer to the crown of the dome. Mr Tottenham did not think that experience of only one dome would be sufficient to justify such a procedure. The reason for the lifting of the dome did not seem to have been convincingly explained as being due to any one particular factor. It might well be that a slight change of circumstances, such as a falling temperature or a long dry spell, might be sufficient to cause the dome to remain seated on the formwork. If that were to occur then the supporting of the thin shell on the ring-beam and another ring of scaffold near to the crown might cause severe local deformations and cracking. It was to prevent such an occurrence that the method of striking of the formwork adopted had been devised.

It would probably have been possible to construct the dome in segments, leaving the segments propped but removing and re-using the formwork for the next segment. The saving in cost on the timber, however, would probably have been outweighed by the added cost of removing and re-erecting the staging for each segment.

The Authors, in joint reply, thanked Mr Pritchard for the details he had given of the dome at Paisley. Reasons for the decision not to adopt the system of construction employing pneumatic mortar had been stated in the Paper and amplified by Mr Serpell in the discussion. Those reasons were qualified in the Paper by "at the present stage in the development of sprayed concrete" and although the choice of material had been influenced by the inspection of some completed structures, the Authors did not wish to imply that there would not be subsequent improvements in the technique of sprayed concrete. The Authors were not yet convinced, however, that the excellent compaction referred to by

[7] References 7–9 are given on p. 301.

Mr Pritchard could always be obtained, nor were they satisfied as to the superiority of sprayed concrete in forming construction joints.

A weakness to which the wire-winding system was subject was the liability of the final sprayed cover on the wires to break bond with the concrete placed earlier, owing to the differences in stress and rate of shrinkage. It was worth noting that the only case of corrosion noted by Hill[9] in his report to the 2nd Congress of the Fédération Internationale de la Précontrainte had occurred in a horizontal cable around a tank which was protected by a gunite coating. The Authors could not agree that the risk of serious damage by mining subsidence was less with a prestressed than with a conventional reinforced concrete design.

It appeared that Mr Pritchard's conception of subsidence was one of local settlements which would result in intermittent support of the ring-beam. Previous experience at Cleadon, however, had shown that owing to the considerable depth of the coal seams, movement, if it occurred, would more likely consist of a large-scale tilting, possibly accompanied by "hogging" of the site as a whole. The Authors were not in any event attracted by the idea of constructing the dome on a series of columns. The advantage of the existing uniform loading of the reservoir wall would be lost and greater expense would be involved.

The case for using aluminium had been ably stated in the communication by Mr Davies. Aluminium was the first material to be considered by the Water Company, which had been in touch with a firm specializing in such work. They had been informed by the aluminium manufacturers that the alloy which it was proposed to use was susceptible to intercrystalline attack under conditions such as might obtain under the roof and they had been advised that painting, comprising zinc chromate primer followed by two coats of aluminium paint, should be carried out. There had been at that time a lack of information concerning the behaviour of aluminium in the somewhat onerous conditions of roofing a reservoir.

The use of aluminium would undoubtedly have made for speedy and economical erection though it was felt that the advantage was with reinforced concrete when the lower cost of maintenance, the smooth soffit, and the greater insulation value were taken into account.

Additional references

7. E. Reissner, "Stresses and small displacements of shallow spherical shells". J. Math. & Phys., Feb. 1946, p. 80.
8. W. C. Voss and D. Peabody, "Thin shelled domes loaded eccentrically". Proc. Amer. Soc. Civ. Engrs, vol. 73, 1947, p. 1173.
9. A. W. Hill, "Report on present practice regarding grouting and anchorages in prestressed concrete in Great Britain". Paper No. 8, 2nd Congr. Fedn Intern. Précontrainte.

Correspondence on the foregoing Paper is now closed.—Sec.