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8010 & 8072 DISCUSSION

Foyers pumped storage project:

Planning and design

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Construction

D. D. LAND & D. C. HITCHINGS

Messrs Lander *et al.*

We would like to draw attention to the necessity of justifying pumped storage schemes in terms of system economics and in relation to energy conservation, some four units of power being taken from the system for every three returned. The need for economic design at Foyers was further accentuated by an unfavourable distance : head ratio of 18:1 compared with the other four large British pumped storage schemes at Craigroyston (2·7:1), Cruachan (3·9:1), Ffestiniog (4·4:1) and Dinorwig (5·4:1). Fortunately there were some favourable aspects at Foyers. It was well placed geographically in relation to power supply and load: both upper and lower reservoirs were in existence and needed little special attention.

2. Foyers entered commercial service in October 1974, and up to January 1978 running time has comprised 18% generating, 17% pumping and 3% spinning: 38% overall as against the 35% estimated in the design. Design generating load factor was 15%, whereas for the last 3 years the actual factors achieved have been 12%, 19% and 18%, while changes of operating mode have averaged 4000 annually. The on site efficiency of one set generating 150 MW has been measured at 94·7%, a 2% improvement on guarantee, while pumping also showed a marginal improvement. Overall turnround efficiency on the grid connection at Inverness, 29 km away, is a very satisfactory figure of 77%.

3. Maintenance of tunnel lining has cost £12 500, £500 and £9000 in the three years of running, considerably more than would be expected of a conventional hydro power scheme. The reasons are many: some are mentioned in the Paper; others may arise in discussion.

Messrs Land and Hitchings

The conditions in which the work was carried out were extremely wet and uncomfortable. The contract employed 500 men for well over 4 years, including the period of the 3 day week and the national strike of builders.

5. The 3 day week was not observed at Foyers and no men stopped working during the strike. The only problems resulted from delays suffered by outside suppliers. It was

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to the great credit of the staff and operatives that the work went so smoothly and that so little time was lost on the original pre-tender programme of the Client.

Mr D. J. Miller, South of Scotland Electricity Board

It is true that pumped storage is complementary to nuclear generation both in financial terms (nuclear has high capital cost and pumped storage has low capital cost) and in operation. It does not mean, however, that pumping must be carried out with nuclear generated power. In Scotland most of the generation is coal fired and burns about 75% of all Scottish coal that can be produced economically. Growth must come from nuclear energy, but additional nuclear generation will tend to reduce the load factor of operation of the coal-burning plant and this is contrary to the aim of maintaining a level coal consumption. Pumped storage has the effect of maintaining coal consumption because it increases the loading on the coal burning plant by pumping at night.

7. It is also sometimes said that pumped storage has a low efficiency and is therefore counter-productive in energy conservation terms. This is misleading because operating coal burning plant at a reduced load factor produces a reduction in thermal efficiency. This drop can be as much as 25%. This is the same sort of loss in efficiency as with pumped storage. Pumped storage also avoids the stopping and start-up costs of a large turbo-generator, which can be as much as £7000 to £10 000 per start/stop cycle.

8. The requirement for good access to the station influenced aspects of the design. The North of Scotland Board had experience of the Cruachan Station, with four units two-thirds of a mile underground, where great difficulties were faced with access during plant erection. The layout of Foyers sought to mitigate this and influenced the decision towards the shaft type of station. Better access was certainly provided by this for the erection of the plant.

9. Other measures, such as providing a horizontal opening above the turbine casing and below the generator, so that the runner could be removed without disturbing the generator itself, were also made. The rotor of the generator was in fact assembled down the shaft, thus avoiding the need for very large lay-down spaces. While this operation was going on, the generator was also being wound in the shaft, held up by jacks. The starting method is unique, avoiding the necessity for a separate motor and incidentally easing access problems.

10. The Paper metions difficulties with water erosion. Certainly the water velocity in the tunnel is rather higher than most pumped storage schemes, being some 10–15% greater than that recommended by the civil engineering Consultants. I should like to ask whether it was thought that with remedial works the problem will be mitigated, or whether there are any other measures that can be taken to reduce erosion in the future.

Mr J. A. Baines, James Williamson and Partners

Pumped storage power stations in the UK fall into three types: the conventional surface power station, typified by Ffestiniog, the underground caverns as at Cruachan and Dinorwig, and the Foyers type with surface building but with the machinery located in deep shafts. The choice on any site depends on plant capacity, head, topography and geology.

12. When Foyers was at the early stage of development, my firm was associated with such a choice in connection with a pumped storage project in South Africa. After careful consideration of an underground station in what was rather unfavourable geology, the final selection there, a four machine station, was a Foyers type arrangement, this time with two machines in each shaft. In the course of the further development of this station, my staff were considerably assisted by the Foyers experience, and we are indebted to the Authors and their organizations in this respect.

13. The long term integrity of concrete tunnel and shaft linings in hydro schemes is of crucial importance and certain problems have been encountered during operations both at Foyers and on other projects; for example, in the tailrace tunnels at Cruachan

and the high pressure shafts at Ffestiniog, where the pumped storage operating regime imposes more arduous conditions than on conventional hydro schemes.

14. On all these schemes there is no doubt that a great deal of attention was given to the design and testing of concrete mixes for hydraulic linings. Factors controlling mix design for such concrete include workability, ease of pumping, compactability and rate of gain in strength for early stripping. These are vital short term aspects. Durability, strength, and resistance to attack by aggressive water are vital long term factors.

15. Notwithstanding the attention given to these, the ultimate integrity of the linings depends on the quality of workmanship as applied by the skill and experience of the labour, design of the shutter, reliability of the placing machinery, avoidance of cold joints, prevention of surface grout loss and solution of drainage problems.

16. With the benefit of research into and experience of other schemes, it may be of interest to refer to some of the measures taken to achieve good results in the large scale concrete linings in the tunnels and shafts of the Dinorwig pumped storage project. At Dinorwig, water velocities are comparable to those at Foyers, but the frequent changes in operating modes may create even more onerous conditions.

17. With regard to mix design, a concrete mix containing 388 kg/m^3 of cementitious material has been adopted at Dinorwig with ordinary Portland cement and selected pulverized fuel ash, mixed in the proportion 3:1. Full scale trials, using the shutters to be adopted on the job, were called for in the contract, but for cost reasons it was decided to use other sections of work without the hydraulic tunnels as trial areas. This proved to be invaluable, revealing considerable scope for improvement in plant disposition and workmanship techniques for future operations.

18. Training courses were held in conjunction with the Cement and Concrete Association for the benefit of leading hands, foremen, gangers, inspectors and engineers. The contractor is carefully training the workforce to be engaged on this work, and it is hoped that smooth operating cycles and techniques will be assisted by the avoidance of potential labour demarcation difficulties.

19. The shutter for tunnel linings to be used at Dinorwig is of Italian design. Intensive technical discussions are still in progress, particularly for the complicated tunnel intersection and manifold areas. The invert form of the shutter is of rigid steel construction, incorporating vibrating screeds used transversely on temporary runners, with purpose made stop ends and side forms designed with individual moveable strips for flexibility and ease of stripping. The vault shutter is basically a curved hinged structure supported on a rigid self-propelled rail mounted gantry, also with flexible stop-end provisions.

20. All major erection and travelling systems are hydraulic and can be operated by one person. Special attention has been given to the number, location and size of access hatches to ensure easy placing, inspection and thorough compaction of concrete. Experience has shown that the crowns of tunnels can be more successfully filled using built in clip-on port connections for pumped concrete, to be used in sequence as the pour advances, rather than the traditional slick pipe. Eight of these, each with its own pressure relief valve, are built in to the shutter length of 10 m. Anchoring and strutting systems to cope with uplift forces are also provided as essential elements in creating a rigid though easily assembled shutter. Curing of the lining surface after stripping will be by splayed membrane.

21. The conclusion was reached at an early stage that better results would be achieved in the Dinorwig circumstances by the use of a positive displacement pump coupled to a hydraulic boom for supplying concrete, particularly to the critical crown zone of the lining, rather than by the use of a pneumatic placer.

22. The sequence of placing will be established and adhered to with the aim of ensuring the build up of layers sufficiently rapidly to preclude cold joints, which initiate erosion problems.

23. In wet areas proper drainage facilities will be installed in advance and sufficient standby equipment will be located close to the works in cases of breakdown.

24. Given human and mechanical fallibility, it is inevitable that some repair work will be necessary, but it is hoped that this will be minimized. Techniques of repair start with meticulous inspection and must be followed by proper cutting back of defects to sound material with fresh concrete properly bonded in keyed joints to the original, using mesh reinforcement and tested bonding agents where necessary. Cavity grouting where possible of pre-plotted potential voids must be carefully undertaken.

25. I should like to ask if the water at Foyers was unduly aggressive and, if so, were any special measures considered necessary? What factors determined the 36 m length of the D shaped tunnel shutter? Were any difficulties encountered in dealing with water or otherwise whilst concreting within the shaft slipform shutter?

Mr G. G. R. Argent, Merz and McLellan

Having participated in the project on the electrical and mechanical works, I would comment on one or two aspects where the civil engineer and the mechanical engineer overlap. A central and dominating issue involving both is the hydraulic design which determines the overall station performance and the economics of a scheme.

27. In §§ 16–21 of Paper 8010 the importance of the method of pump starting to the design of the surge chamber is indicated. This may have been overemphasized. Once the surge chamber performance has been generally established on the basis of normal and unavoidable emergency conditions, including tripping in the pumping and generating modes, there remains the question of allowable time intervals for those sequences which could be controlled, and in a sense are refinements with economic overtones.

28. One of the sequences was pump starting. The main method of invertor starting each pump in succession had no interaction with the surge chamber; however, it was found that the back-to-back starting method, available as an alternative, involved certain restrictions. The relevant case was pump starting after both sets had been tripped while generating at full load. Owing to the influence on the residual surges of the flow to the driving set, it was necessary to allow the surges to decay so that on pump opening the upsurge limit would not be exceeded. Originally it was intended to use a 'watered' back-to-back start; however starting with the runner of the driven set in air required less flow to the driving set and hence involved less delay before pump opening could be allowed.

29. With the pump starting methods employed, simultaneous starting is not possible. There is one set of static variable frequency converter equipment which starts both machines in sequence, and in the back-to-back mode obviously with just two machines it has to be one at a time. Simultaneous opening of both pumps was not allowable for the surge chamber adopted, because the upsurge limit would have been exceeded. Whether the simultaneous opening of pumps should be allowed, or is desirable, depends on the operational requirements, the economic benefits of increased pumping, system control, and probable higher capital cost for the surge system. For Foyers the delay on opening up the second pump from spin pump is quite short at $1\frac{1}{2}$ min, and the control scheme incorporates a timer to prevent simultaneous opening.

30. The adoption of a throttle and expansion chamber appears to have been linked with the question of opening two pumps, whether simultaneously or in succession. Regardless of any specific case a throttled chamber would be preferred rather than a simple surge chamber. The throttle assists the damping effect of the low pressure tunnel, so essential for pumped storage plant where quick mode changes are desirable.

31. It is implied that some changes were made during the tender adjudication period in relation to pump characteristics (§ 19). It would be more correct to say this was due to results of pump turbine model tests during the tender adjudication period which made changes in surge chamber design possible. This is simply because the quantity/head characteristic proved to be more favourable than had been anticipated at the preliminary stage.

32. On draft tube design it is suggested in § 39 that the throated bend may not have been absolutely essential. The description 'throated bend' implies some restriction,

whereas in practice the bend usually involves a slight relative increase in area. The conventional design of draft tubes with flattened bends originated from attempts to minimize the depth of excavation and thereby ease the problems of the civil engineer.

33. Large spans can be avoided by the use of splitter walls if their need is recognized early enough. Instead of heavy reinforcement of the concrete around the draft tube, presumably to cater for groundwater pressures when dewatered, the draft tube could be designed to support such loadings instead of simply serving as a liner. Again these requirements can be met if their need is anticipated.

34. Reference is made to the crane capacity in § 42. A safe working load of 220 tons was anticipated at the project stage based on the estimated weight of the generator-motor rotor, knowing that other major items such as the main valves would have a lesser weight. In the event the successful tenderer offered a generator-motor having a rotor weight of 255 tons but with rotor assembly in situ. Consequently the crane capacity was determined not by rotor handling but by the lifting of the main valve which required a safe working load of 85 tons.

35. In discussing the gates in the lower control works in § 46 the Authors question the suitability of the design for emergency closure. Does this refer to closure against the small flow due to the burst or leak in the machine shaft mentioned in the preceding sentence or to closure against a larger flow such as maximum flow when pumping?

36. The Steenbras scheme referred to by Mr Baines is a 180 MW scheme for the city of Cape Town. The site is about 56 km SE of Cape Town and straddles the Hottentots-Holland mountain range. The upper reservoir is also used for domestic water supplies to the city and has been formed by a new dam upstream of the original reservoir. The lower reservoir is formed by an embankment dam on the lower slopes of the mountain range. The two reservoirs are linked by a low pressure tunnel, surge chamber, concrete lined shaft and steel penstock. A static head of about 290 m is available.

37. As at Foyers, the power station comprises two machine shafts and a surface building. Each shaft is 20 m in diameter and 42 m deep and accommodates two 45 MW, 600 rev/min reversible sets. The civil and main plant contracts were placed in March 1975 and commissioning of the first set is planned for October 1978. The last set is due to be in service in May 1979.

Mr D. A. Harries, Tarmac International Ltd

The shaft layout for the sets at Foyers is a very attractive solution to the problem presented by the excavation of an underground machine hall at that site. The Authors have demonstrated how flexible such a layout proved to be when there were serious delays on the no. 2 shaft making it possible to push on with no. 1 and avoid a serious delay to the commissioning date.

39. Would the Authors consider the shaft layout for a similar station in competent rock? Is there an upper limit for installed capacity when large machine halls might be more economical in competent rock than a shaft layout. Obviously, there must be some disadvantages in the shaft layouts from the mechanical and electrical point of view and it would be interesting to hear what these are.

40. I assumed that ICE conditions of contract were used but Paper 8010 suggests that the power of the Engineer was diminished on this contract and financial matters were outside his jurisdiction. If this was the case, I should like to ask the Authors how this worked in practice, particularly having regard to any changes in methods of working and the additional costs which the Contractor so obviously incurred as a result of these changes. Underground construction calls for particularly close co-operation between the Engineer and Contractor, and the arrangement at Foyers does not appear to satisfy this condition. I consider it important to maintain the independent function of the Engineer.

41. I note that critical path planning was used on site. From my own experience the preparation of networks can often become an end in itself, and it would be interesting to have any comments from the Authors on lessons learned.

42. There appears to be some lack of agreement between the two Papers as to whether or not the ground conditions at Foyers had been adequately predicted in the area of the high pressure tunnels. From a description of the Contractor's methods on the shafts and in the vicinity of the X intersection, one can only assume that the ground conditions were not fully anticipated. I am not too sure what the Contractor means by too much reliance being based upon the results from the trial shaft.

43. Steel arch supports were required over a length of 290 m on the drive from Glen Liath to the upper control works. Was any estimate made by the designers for temporary arches and, if so, how were these figures derived, and how did they compare with actual experience?

44. On the shorter section of the low pressure tunnel no steel arches were required except at the portal. Why then did the Contractor decide to drive this tunnel in two stages? I cannot take literally the comment made in Paper 8010 concerning the viability of the project if the trial shaft had been sunk on the centre line of no. 2 shaft. Despite the increased cost of the works which I suspect is mainly due to inflation, I am sure the Client is happy with his 18% load factor. I cannot believe that the project would have been abandoned if the actual ground conditions had been known at the time of the estimate.

45. Would the Contractor offer an opinion regarding his own choice of plant for the low pressure tunnel? Would this choice have been better suited to the works as constructed?

46. I notice there is a reference to lifting of invert concrete. Presumably this was caused by lack of cohesion between the sub-invert concrete and the main slab. Was the invert fully mucked prior to placing the sub-invert slab? In Paper 8010 the Authors state that a moderately dished horseshoe form of invert could have obviated this problem, and either this or a circular tunnel could have been driven at little extra cost. I agree about the cost for a moderately dished invert but not for a circular tunnel, which would have cost very much more to construct. I think that this particular problem will always be present where a sub-invert concrete is placed. The solution may lie in not mucking the invert at all, and I should be interested to hear comments on this point.

47. The description of the grouting of no. 2 shaft is very interesting. More about the flocculating agent which was successfully employed would be helpful.

Mr A. Watson, Robert Watson and Co. Ltd

My comments relate to the steel pressure linings. Steel pressure linings are not common. Before the Foyers scheme my firm had carried out a number of surface pipelines but we had never lined a tunnel.

49. On the recommendation of the Main Contractor we went to California to see extensive works of this type on a scheme for bringing water from the north of that state to Los Angeles and we gained some benefit from examining the difficulties that they had encountered and the methods they had adopted.

50. Because of the size of the pipes (4·6–5·9 m dia.) they could not be transported and a complete fabrication yard was set up on site. Whilst it might have been possible to deliver half plates rolled to diameter, it was decided to roll the pipes on site because longitudinal welds tend to produce peaking, and for pipes joined in a tunnel, true roundness is essential. Further details of fabrication methods are given elsewhere.[D1]

51. Another advantage of site fabrication is that sections can be welded to the maximum length consistent with getting round bends in the tunnel. Pipes 12 m long and weighing as much as 40 t were installed. This, of course, presented some problems, particularly when they had to be lowered down a 1 : 1½ slope and assembled into a curve. Assembling, positioning and welding the pipes down the very steep section leading to the turbines was not helped by the conditions in that particular section where the rock was badly broken and extremely wet.

52. It must be obvious that extremely careful co-ordination is required between main contractor and the lining subcontractor, since the process of installing and welding

pipes and retreating while the concrete work is done needs planning almost on an hour to hour basis.

53. One difficulty that was certainly not appreciated arose in seal welding the plugs after grouting had been completed. Although there should not have been much water pressure because of the drainage tunnel, there was certainly sufficient to penetrate the threads in the screw-in plugs and the steam produced by the heat of the weld caused small blow holes which subsequently leaked. In practice it was better to caulk the joints rather than weld them, and this proved to be a satisfactory alternative.

54. Whilst the high pressure linings were by far the greatest proportion of the job and certainly the most dramatic, it must be observed that the low pressure crossing of Glen Liath required just as much ingenuity and possibly greater skill. Here the plate was thinner and the pipes of larger diameter and a sliding expansion joint had to be fabricated without the luxury of any machining facilities.

55. I am interested to hear comments on the integrity of the concrete lining; would a greater use of steel lining prove to be the answer?

Mr A. R. Murray, Sir Alexander Gibb & Partners

I should like to comment a little on a point a previous speaker has made about lifting of the invert. My firm has recently had a similar experience on a job in New Zealand. There the lining is of a 10 in. modified D section and failure is taking place where there is high rock cover and much in-flow of water. Failures have been discovered after contact grouting. To overcome the problems the grouting arrangements have been revised and the grout pressure carefully controlled. As quickly as possible after the contact grouting, relief holes are being drilled through the invert.

57. I would imagine that at Foyers the invert lifting was in the high pressure section where there is considerable rock cover and the possibility of the build-up of ground water pressure. This is a matter which has been a source of difficulty in the past and will continue to be so in the future. I would be interested if the Authors could give some further details of their problem, how they overcame it and perhaps, in retrospect, to say what they would do in the future to prevent such an occurrence if they had to deal with similar circumstances.

58. The other matter that has been raised is that of erosion, and again perhaps the Authors could give their views on what they would do in the future to prevent or diminish erosion problems that could arise.

Mr I. W. Hannah, Central Electricity Generating Board

I should like to ask a specific question on the extent of geological investigation for the considerable tunnelling that was achieved in poor rock conditions. In the Dinorwig project, where the rock is more competent than that described in the Papers, we have employed a considerable number of geology specialists to introduce some science into the art of rock tunnel support.

60. The usual rock material investigations have been supplemented by measurement of existing stress and strain during excavation. In an extensive experiment the full span of the Dinorwig machine hall was constructed to allow instrumental readings to be taken throughout, and this was finished by relaxing the tension in the prestressed tendons.

61. I should like to ask the Authors how much geological investigation they undertook at Foyers, on which there appears to be a slight discrepancy of views between the two Papers. Equally, what weight do they attach to theoretical and experimental aspects and the views of those more intimately concerned with the rock.

Mr J. W. Cowie, James Williamson and Partners

The Authors show an anti-vortex wall at the headworks. I would be most interested to hear how the arrangement has performed in practice.

DISCUSSION

Mr W. P. Wright, Boving and Co. Ltd

A recent review of filling and emptying rates for buried penstock shafts, on projects with which I have been associated, has revealed that the allowable rates at Foyers are relatively slow. Some rates are higher where the penstock is steel-lined throughout.

64. Whenever a penstock has to be dewatered, for whatever reason, the emptying and filling times have to be added to the work time in order to arrive at the total outage time. On pumped storage schemes the outage time is always at a high premium, since the practice on conventional schemes to store water is not valid.

65. Could the Authors say, in the light of the above remarks, if consideration was given on economic grounds to having a steel-lined penstock at all levels below that of the low pressure tunnel.

66. The form of draft tube bend adopted (§ 39) follows that of conventional plants, where the shape has been evolved in order to achieve the most economic manufacturing costs, whether in concrete or steel, for the water surface, commensurate with no detrimental effect on machine efficiency.

67. However, on pumped storage plants with relatively deep submergence it could be that a more complicated geometrical shape, circular at all sections at right angles to the water flow, might well result in a more economical design, when the complete cost is taken into consideration. Such a change, if contemplated, would have to be investigated very early on, in order to allow efficiencies to be guaranteed and subsequently demonstrated at the model and perhaps prototype tests.

68. The existing design, as stated, stems from conventional plant, and the rectangular shape has not been found in any way to be detrimental to the hydraulic efficiency of the turbine.

Mr G. M. Binnie, Binnie and Partners

The decision to house the reversible pump/turbines in deep shafts was an excellent solution to a difficult problem. In § 37 of Paper 8010 it is stated that below a heavily reinforced concrete collar the shaft lining was of reinforced concrete 1 m thick. Was the Contractor able to excavate the shafts to full depth before constructing the reinforced concrete lining from the bottom upwards, or did the concreting follow the excavation downwards in stages during the excavation of the shafts?

70. The cross-section of the power station (Paper 8010, Fig. 7) shows two overhead cranes, one of 85 tons and the other of 10 tons capacity. The rotor was erected at the bottom of each shaft (§ 42). From the 85 ton crane, the length of suspension for the pump/turbine casing scales approximately 45 m and for the rotor approximately 35 m. With such long suspensions, was the 85 ton crane able to be used satisfactorily for erection purposes or was additional temporary cranage provided at the bottom of each shaft during the erection period?

Messrs Lander *et al.*

Several speakers have raised the matter of high maintenance costs on pumped storage works. A number of reasons are given in the Paper, but there is another that can be put forward. In a straight hydro-electric plant the machine causes vibrations in the water column; these are quite quickly damped out by the fresh water flowing from the upper reservoir to the machine. In the pumping mode the machine vibrations exist in the water column possibly all the way up to the upper reservoir; thus the concrete lining of shafts and tunnels is subjected to high velocity, high pressure water with a superimposed high pitch vibration.

72. **Mr Harries** asks whether we would consider a shaft type station in competent rock. The short answer is yes. We reported in favour of such a layout for a scheme in Australia a few years before Foyers, so having considered shafts twice and built them once we would probably look at shafts first, with their ease of access and early start on machine erection, and then see if other forms had anything better to offer.

73. We have found no major disadvantages although travel up and down and between shafts is more tedious than for a cavern type station. However, this is more than counterbalanced by the problem of communication to and from the surface workshop of a cavern type station such as Cruachan.

74. Several speakers raise the matter of the ground not being as anticipated. That is true, conditions in the second shaft were much worse than anticipated from the trial shaft; however, I think we got more value from the trial shaft than from more borings. Naturally we would have liked more borings but time and money did not permit and in the event our troubles arose from isolated lenses of bad ground which might well have been missed by extra boreholes.

75. Mr Harries asks whether no. 2 shaft being so very bad would really have affected the project go-ahead. In 1967 it was very touch and go, costs were looked at very hard indeed and the operational beauty of pumped storage was not then fully appreciated.

76. **Mr Binnie** raises two points. In the machine shafts we specified that linings should follow closely on excavation and the Contractor did exactly that. The surge shaft and chamber, in better rock, were excavated in full before lining. The long suspension under the 85 t crane gave no trouble in machine erection and only the usual jacks were required in the base of the machine shafts.

77. **Mr Cowie**'s question concerning the vortex wall is interesting. The upper control works were designed initially in a conventional manner with a deck running from the shore to the screens, the intention being to provide screen cleaning gear if necessary. As part of an economy exercise the deck and head wall above the screens were omitted in the belief, proved correct in operation, that the screens would be self-cleansing. The original design had been model tested and no tendency to vortex formation had been revealed. The revised design was also model tested and disclosed alarming oscillations in the approach channel and vortex formation at the screens. Replacement of the head wall on the model restored stability and in operation there has been a minimum tendency to vortex formation.

78. Concerning the invert of the low pressure tunnel, **Mr Harries** suggests that lifting of the invert concrete was caused by lack of adhesion between the sub-invert concrete and the main slab. This is undoubtedly true and it is at least possible that no trouble would have arisen if the invert had been placed in one operation, thereby eliminating the horizontal construction joint. The rock invert was fully mucked and meticulously cleaned before the sub-invert was placed. We have no evidence at all that the integrity of the sub-invert has been affected. In places where the invert lifted and had to be stripped off, the sub-invert showed no signs of distress or movement. An invert slab placed on an unmucked invert would be susceptible to damage from groundwater pressure unless an adequate drainage system incorporating a filter layer between the slab and unmucked invert were provided. Such a drainage system would probably result in a significant loss of water.

79. The invert pressure relief drainage system evolved during construction. The Contractor provided a longitudinal gravel filled construction drain in the centre of the sub-invert to facilitate concreting of the walls and crown. This drain was initially cleaned and filled with concrete when the invert slab was poured and pressure relief holes were drilled to rock at 50 ft centres along the centre of the invert. Trouble was subsequently experienced with the invert lifting. The density of relief holes was then increased and the central drain was incorporated as a permanent feature of the works. At the Mhor Portal in Glen Liath the drainage system was modified to minimize leakage from the tunnel where the rock cover was small. Here the pressure relief holes were sealed.

80. **Mr Murray** refers to problems experienced with invert lifting in a modified D section high pressure tunnel in New Zealand. The trouble at Foyers was restricted to the low pressure tunnel though it must be remembered that this tunnel is subjected to a head of 60 m. The high pressure tunnels have circular sections and have not been affected. In retrospect, an arched monolithic invert would compare with the flat

invert in construction cost and have considerably more resistance to damage by back pressure.

81. **Mr Harries** questions the allowance in the bill for steel arches. In the low pressure tunnel it was a nominal allowance as we had no reason to expect that the number of steel arches used would be as high as it turned out to be.

82. Messrs **Miller, Baines, Watson** and **Murray** have raised questions on the erosion of concrete tunnel linings of pumped storage schemes. On both the Foyers and Cruachan schemes we have found that erosion has been more severe and has occurred more quickly than on any of our conventional hydro schemes. Defects became apparent at Foyers after less than a year's operation. At Cruachan, numerous cavities were found (largest 30 ft long × 18 in. × 18 in. extending back to rock) after 6–7 years' running. It would appear that the flow regime picks out any defects (substandard concrete etc.) outstanding after construction and it is essential to repair these areas as they appear and to keep on top of them. The incidence of defects at Foyers has reduced with time as a result of the repair programme, but it may well be a continuing item throughout the lives of the Foyers and Cruachan schemes, leading to heavier maintenance budgets than for conventional schemes.

83. There are a number of different ways in which the performance of these concrete linings could be improved. Although concrete specifications previously adopted for conventional schemes were used at Foyers and Cruachan, it is thought that a higher strength, better quality concrete is necessary for pumped storage. This will require tighter concrete specifications, better mix designs and closer site supervision. We have doubts about the use of pneumatic placers and would prefer to pump the concrete with both internal and surface vibration. Shutter bay lengths should be chosen so that placing can be completed in one shift and serious consideration given to the provision of standby plant.

84. Although these measures should lead to significant improvement in concrete performance, surface protection to the concrete could be worth while if the present trend to higher velocities and more onerous operating conditions continues in the future. 'On-surface' treatments, such as painting, are of doubtful value but treatments which penetrate the surface may well afford enhanced resistance and improved hydraulic characteristics. Low viscosity epoxies have been successfully used on some of the scour aprons of recent Danube barrages for this purpose.

85. At least five years' full load running experience is required before the performance of a lining can be assessed. From the operational side, it is suggested that the design and operating objective should be to provide linings which require inspection only once every five years (as for conventional hydro tunnels) and maintenance every ten years. (Maintenance has been done every year since the Foyers scheme was commissioned in 1974.) The alternatives to superior concrete linings are to accept more frequent and greater maintenance or to adopt a more conservative approach to operating requirements which become increasingly onerous. Where there are still doubts about the ability of concrete to meet the duty (e.g., at bifurcations where severe turbulence is expected) steel linings should be considered although the financial penalty is high.

86. The water at Foyers is not aggressive and has a pH of 7·4. We considered painting the tunnel linings with bitumastic paint as adopted in the past on some conventional schemes but after undertaking a detailed study we came to the conclusion that it was not worth while. This decision has been supported by the fact that, in the odd areas where paint has been applied (albeit in rather unfavourable conditions), it has been stripped off.

87. In answer to **Mr Argent**, the gates of the lower control works were designed to close against the flow arising from a 4 in. dia. burst on the high pressure side or 9 in. dia. burst on the low pressure side of the machine.

88. **Mr Harries** questions the value of critical path planning on the project. Reports on design, manufacture, construction and installation were sent each month to our mechanical and electrical Consultants, who processed this data and produced an up-

dated miniaturized Level 1 network on one sheet with the three most critical paths defined. The network was accompanied by a trend sheet giving the position on all the most important current activities and a commentary on the overall position and critical sections as well as potential courses of action to recover delays. These documents were used as a basis for discussion of how problems could be overcome and deciding project policy at the monthly project management meeting. Actions were implemented through design and site meetings and the Level 1 programme was revised during the following month to take account of actions taken. Communications were very short and management of the project most effective as was proved by results—progress was held up for 8–9 months on no. 2 machine shaft by severe water problems but the first machine went into service within six months of the Contract date of the original 5 year programme.

89. In answer to **Mr Hannah**'s question regarding the extent of geological investigation and its value, the Institute of Geological Sciences, Edinburgh, were the geological advisers. The geologist assigned to the project visited site on average once a month and when any major geological problem arose. The geological interpretation of the conditions at Foyers was outstanding and enabled the right decisions to be taken on almost every occasion.

90. **Mr Harries** raises a number of points on project management. Foyers was the first occasion on which the Board had appointed an overall project engineer. His main duty was to direct all facets of a multi-discipline project: civil engineering works, mechanical and electrical plant, transmission and—very important—communications. Communications at Foyers are by radio. The power station is controlled by radio from the Group Control at Fort Augustus at the south end of Loch Ness and likewise the hydraulic indications, alarms and other data from Dochfour Weir and Loch Mhor. The main concerns of the project engineer were co-ordination of the design of these different disciplines, control of the Board's operational input, the maintenance of progress to programme and detailed financial control. The Conditions of Contract for the civil engineering works were the ICE Fourth Edition and the Engineer was Sir Alexander Gibb and Partners who maintained their independent function as Engineer throughout.

91. **Mr Wright** asks about the consideration given to the extent of the steel linings. The steel lined sections of the high pressure tunnel were extended into sound breccia (Fig. 2), at which point there was adequate cover for transition to concrete lining. The bifurcation was constructed at this point with closely spaced steel arches and concrete lining. The provision of steel lining beyond this point would have been too costly and entirely uneconomic.

Messrs Land and Hitchings

Mr Argent's comments on the conventional design of draft tubes with flattened bends are interesting, but from the Contractor's viewpoint additional and slightly deeper excavations are preferable to heavily reinforced concrete surrounding a relatively thin-walled steel draft tube with a 6 m wide flat bottom.

93. In reply to **Mr Harries**' queries, the driving of the shorter length of the low pressure tunnel in two stages was not dictated by ground conditions. The high pressure tunnel driving had been delayed by the poor rock in the X intersection, and both plant and tunnelling crews were available for transfer to the low pressure tunnel. The plant was not suitable for driving full face.

94. For the main low pressure tunnel drive the use of different types of muck haulage and loading machines from those accepted for the reasons explained in § 1 of the Paper would have enabled the tunnel to have been driven with a smaller labour force. The number of drilling machines was inadequate and had to be increased.

95. The flocculating agent used in the ground was polyacrylamide, a long chain polymer added to the grout in the proportion of 0·025 lb per hundredweight of cement.

96. **Mr Baines** raises several interesting points on concrete lining with particular

reference to Dinorwig, and two specific queries with regard to Foyers. The length of the shutter used in the D shaped low pressure tunnel was determined by considering the volume of concrete to be placed, the placing rate to enable a length to be completed in one shift, and the stripping, moving, and re-erection time to give the optimum theoretical advance during a week. In the event, the concreting time exceeded one shift duration in lengths of heavy overbreak. A 27 m length of shutter was used in the ribbed section of the tunnel, with a consequent loss of progress.

97. Water control in wet areas was dealt with in advance, but this did not apply to the slipforming of the surge chamber and shaft which were virtually dry excavations. In no. 2 machine shaft, extensive provisions were made to deal with water inflows using hyrib and pipes to duct the water.

98. Apart from the use of a positive displacement pump in lieu of a pneumatic placer, and the length of the shutter, Mr Baines' description of the Italian-designed vault shutter for Dinorwig could be a description of the D shaped shutter used at Foyers, and many other shuttering set-ups used by the Contractor elsewhere.

99. The question of the erosion of concrete tunnel linings was raised by several speakers and has been commented on by Messrs Lander *et al.* The concrete specification used at Foyers was that previously used for conventional hydro schemes with slower water flow velocities, and was not changed for the high flow speeds which are used. There has never been any suggestion that the quality of concrete placed at Foyers was in any way under the required standard, nor that the site supervision or workmanship was at fault.

100. A tighter concrete specification, which might preclude the use of local aggregates, and the use of standby equipment have been suggested. These would add to the cost and it is for the Client to decide on how much additional capital expenditure is justified, and to arrange with the Engineer to specify accordingly. Overruling by the Client of advice to increase the concrete thickness in the crown of the Cruachan tail race tunnel to give more rock cover, and the reduction in the low pressure tunnel cross section made during assessment of tenders for Foyers, suggest that capital cost is the major concern of the Client.

101. The use of pulverized fuel ash depends, to some extent, on the availability of supplies, and for Foyers would have been very expensive and subject to interruptions in supply.

Reference

D1. Welding at Foyers hydro-electric project. *Welder*, 1973, **39**, July, No. 192, 2–9.