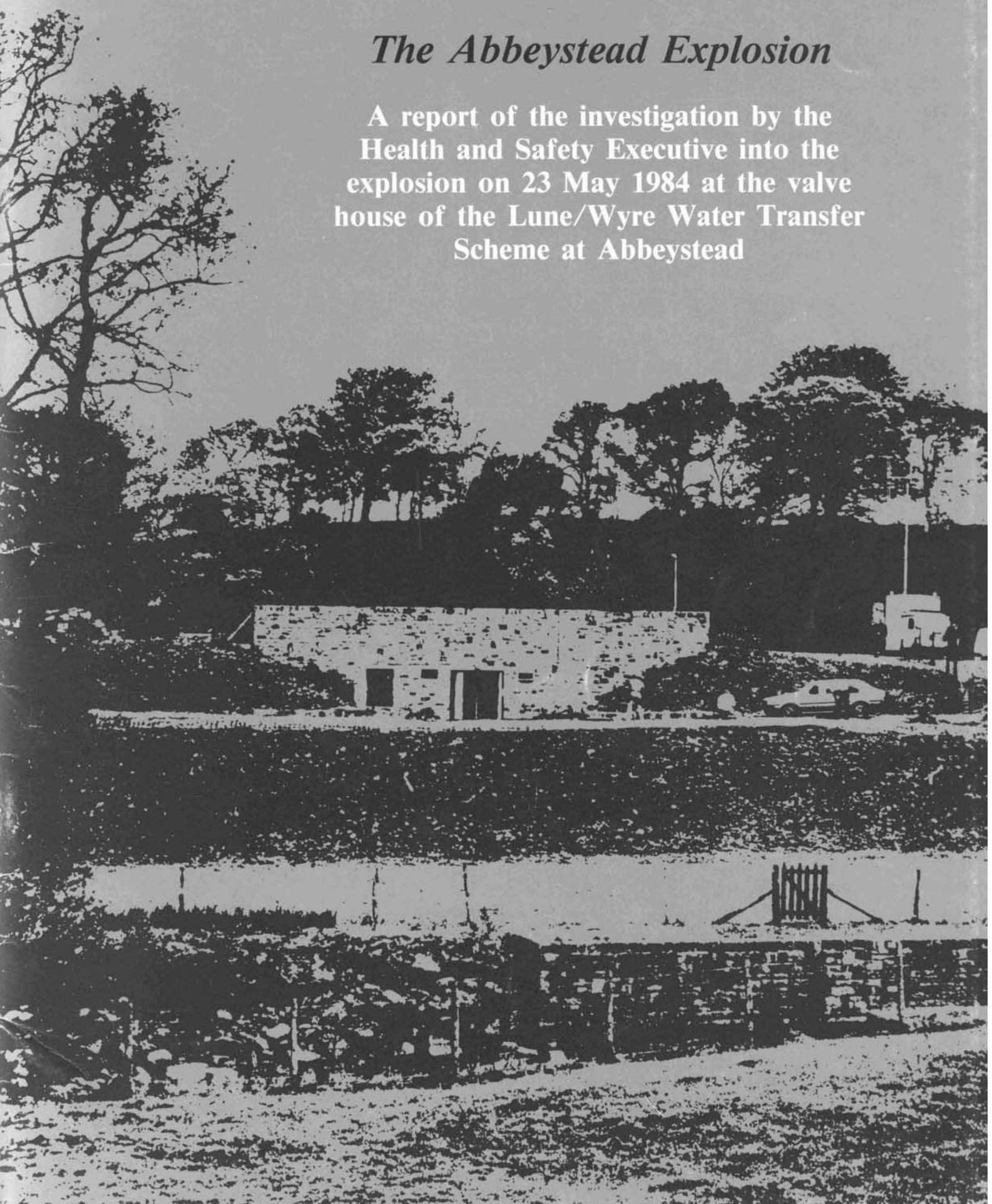
Health and Safety Executive

The Abbeystead Explosion

A report of the investigation by the Health and Safety Executive into the explosion on 23 May 1984 at the valve house of the Lune/Wyre Water Transfer Scheme at Abbeystead



View looking towards the north-west corner of Abbeystead Valve House after removal of damaged roof beams

Health and Safety Executive

A report by HM Factory Inspectorate

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HER MAJESTY'S STATIONERY OFFICE

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Introduction

In the evening of Wednesday 23 May 1984, a group of 44 people including 8 employees of the North West Water Authority, was assembled in a valve house set into a hillside at the outfall end of the Lune/Wyre Transfer Scheme at Abbeystead.

The visitors, mainly from the local Parish of St Michaels on Wyre, were attending a presentation being part of a programme to allay local residents' anxieties on the effects of the installation on the winter flooding of the lower Wyre Valley.

As part of this presentation, water was to be pumped over the weir regulating the flow of water into the Wyre. Shortly after pumping commenced, with the visitors congregated in the valve house which was virtually underground, there was an intense flash, followed immediately by an explosion causing severe damage to the valve house. Sixteen people were killed; no one escaped without injury from the valve house.

The Health and Safety Commission directed the Health and Safety Executive to investigate and to make a special report in accordance with Section 14(2)(a) of the Health and Safety at Work etc Act 1974.

The Lancashire Conjunctive Use Scheme
Design and construction

1 A proposal to establish a water supply link between the Rivers Lune and Wyre was approved in 1971 by the water undertakings which later merged to form the North West Water Authority (NWWA). It was to be part of the Lancashire Conjunctive Use Scheme, which was designed to meet the expected water supply requirements of the area. A well known firm of consultants specialising in water supply systems, Binnie and Partners, advised on the practicability of the scheme and was later commissioned to design the scheme.

2 Design and preparatory work went on from 1971 to 1975. Because of the outstanding scenic beauty of the area it was decided that everything practicable should be done to minimise the effect of the scheme on the landscape, and to forestall possible objections from local residents, landowners, and environmentalists. Angling interests led to a decision to abandon of an original intention to chlorinate the water entering the system. Other design considerations were the security of the installation and protection of valves against freezing in Winter. Taken together these led to the decision that the proposed valve house building at Abbeystead should be largely underground. As a result of the care taken to preserve the environment, no serious objections were raised when a public enquiry was held by the Department of the Environment in 1974. Planning approval was granted in April 1975 without major conditions, and tenders for construction were invited.

3 Prior to the commencement of tunnelling, enquiries made by the designers of the tunnel suggested that information available on the geology of the area was limited, current Ordnance Survey geological maps being based on surveys made in the 1870s. The data obtainable was summarised in documents which were supplied to prospective tunnellers by the designers of the scheme. The tunnel was to be driven through upper carboniferous strata of the millstone grit group, with lengths at both portals through superficial Pleistocene deposits of more regent age.

4 Consideration was given by the designers to the possibility of obtaining further useful information on the geology of the area by drilling bore holes along the line of the tunnel, but only a few were actually drilled, all of them in the vicinity of the ends of the tunnel. Their main purpose was to establish the nature of the ground at points where there would be little ground cover for the tunnel. It was decided that it would not be economically viable to drill sufficient bore holes to the depth necessary to establish conditions along the whole length of the tunnel. The basis for this decision is understood to have been the designers' extensive experience of work on other tunnels where numerous bore holes were sunk, with results of limited value. An independent specialist on site investigations concurred with this view, although an official of the Institute of Geological Science (now British Geological Survey) consulted at the design stage expressed surprise that there was to be no bore hole along the tunnel line. His concern was primarily that there might be a major in-rush of water during construction, rather than that gas might be encountered.

5 No anxiety appears to have been felt at the design stage about the possibility of flammable gases being encountered during tunnelling. Although the conditions of contract required the concentration of flammable contaminants to be kept below 10% of the lower explosive limit and measuring instruments to be provided, these conditions are claimed by the designers to be routine.

6 The contract for construction of the Wyresdale tunnel and Abbeystead valve house was awarded to Edmund Nuttall Limited, who commenced work on site at the end of 1975. The designers of the schemes, Binnie and Partners, acted as Resident Engineers and the North West Water Authority maintained a close liaison with the work by appointing one of its technical staff as Project Engineer.

7 No serious problems were encountered during the driving of the tunnel. Although traces of flammable natural gas were detected, the contractors and consulting engineers appear to have regarded the tunnel to be gas free by normal tunnelling standards. There was a considerable inflow of water through the tunnel walls, although less than had been feared. This inflow continued even after the concrete lining of the tunnel had been completed, and at a late stage in the construction work the ground water entering the tunnel through cracks and porosities in the walls measured at 13.5 litres/sec (1.16 megalitres/day). An inflow of water into deep tunnels is not unusual as the ground water surrounding them may be at much more than the pressure inside the tunnel. If water flowing through a tunnel is at lower pressure than the ground water an inflow through the tunnel walls can be expected even when the tunnel is full of water. It is not then a cause for concern as the inflow augments the water supply.

8 Construction work on the Lune/Wyre link was completed in the Spring of 1979 and water was first pumped through it in June 1979. The responsibilities of the consultants and contractors on the site ended on the 15 December 1980.

The layout of the scheme

9 The Abbeystead Outfall Station, the Wyresdale Tunnel and the Lune Pumping Station form the Lune–Wyre transfer link of the Lancashire Conjunctive Use Scheme. The Scheme is a water supply project aimed at meeting an anticipated increase in demand for water in the North Western region.

10 Figure 1 shows in diagrammatic form the layout of the Scheme, which allows for the supply of water from

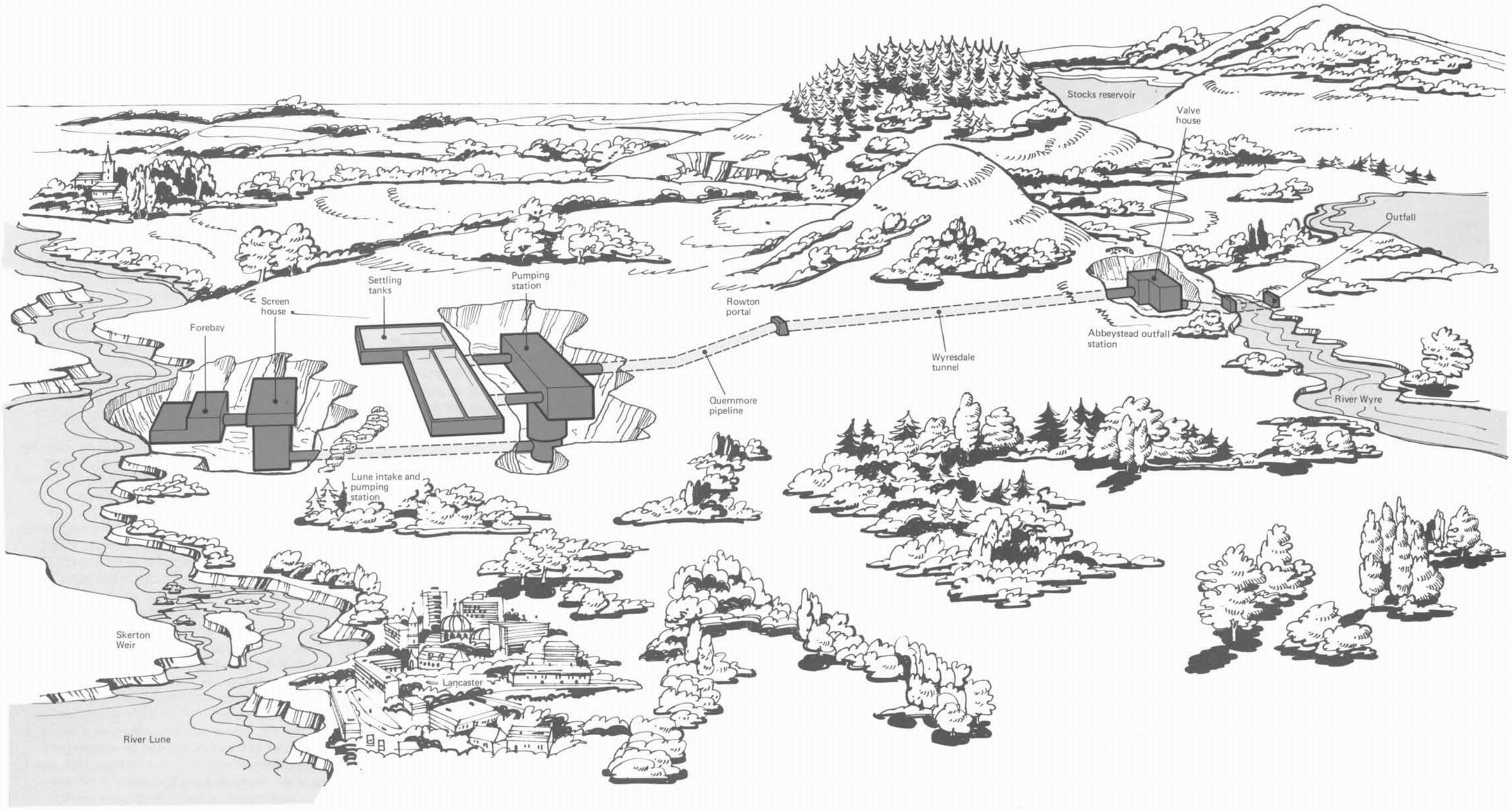


Figure 1. General layout of Lune/Wyre water transfer scheme

existing impounding reservoirs, by extraction from the River Wyre at Garstang and from boreholes sunk into the Fylde Bunter sandstone. On occasions during the year there is insufficient water in the River Wyre to satisfy abstraction requirements and on these occasions it is intended that if sufficient water is available in the River Lune it should be transferred to the River Wyre and subsequently abstracted downstream at Franklaw. It is the Lune–Wyre transfer portion of the Lancashire Conjunctive Use Scheme with which this report is concerned and the Wyresdale Tunnel, and Abbeystead Valve House in particular. (See Fig 1.)

11 The Lune–Wyre transfer link comprises the Lune Intake and Screenhouse, the Lune Pumping Station, the Quernmore Pipeline, the Wyresdale Tunnel and the Abbeystead Outfall Station.

12 The water intake for the transfer link is situated approximately 150 metres upstream of Forge Weir near the village of Halton on the River Lune. A short pipe leads from the intake bays to the Screenhouse where any coarse debris is screened out and from there the water flows by gravity along a tunnel 750 metres long to the Pumping Station.

13 The Lune Pumping Station is sited in Quernmore Park. Six low lift pumps lift the water up to ground level, where it is retained in settling tanks to allow any sediment present to settle out. From the settling tanks the water flows over weirs into a balancing tank prior to transfer to the River Wyre. A further six pumps installed on the floor of the pumphouse can deliver a nominal 545 Ml/day of water into the Quernmore Pipeline, but the maximum amount the NWWA is permitted to abstract from the Lune is 280 Ml/day.

14 The Quernmore Pipeline runs for a distance of 5 kilometres from the Lune Pumping Station to the entrance to the Wyresdale Tunnel at Rowton Portal. The pipeline is approximately 1800mm in internal diameter, and is of welded steel construction. It is buried at a shallow depth and follows the contours of the landscape. Automatic air valves at all high points allow air to escape when the line is being filled and allow air to enter when the line is being emptied. Wash-outs (drain valves) at each low point allow the pipeline to be emptied of water.

15 From Rowton the water is conveyed from the end of the pipeline to Abbeystead Outfall Station through Wyresdale Tunnel, which is 6.6 kilometres in length. The tunnel is concrete lined and has a finished internal diameter of 2600mm. At each end of the tunnel there is a length of a few hundred metres with a steel lining, this being to strengthen the tunnel where the depth of the cover is relatively small. This strengthening lining is not necessary under current operating conditions but is designed to allow operations at greater water pressure in a later stage in the development of the scheme. The tunnel rises a vertical distance of 5.5 metres up a very gentle gradient between Rowton and Abbeystead, the highest point in the line being at the end of the access branch at Abbeystead. (See Fig 2.)

The Abbeystead Outfall Station

17 Abbeystead Outfall Station is situated about 47m from the river bank in a rural area of the Wyre Valley about 10 kilometres South East of Lancaster. When the Wyresdale Tunnel reaches Abbeystead it is continued by two branches of 2600mm diameter concrete-lined steel pipeline, as illustrated in Fig 2. The access branch extends to the tunnel entrance chamber where it terminates in a blank flange. Near the end of the access branch the tunnel is vented into a buried vent chamber. As there are no intermediate access points along the length of the tunnel from Rowton to Abbeystead this is the main vent point/air intake for the whole length of the tunnel. Within the vent chamber eight air valves fitted above the pipeline allow air to escape while the line is being filled with water and to enter while the line is being emptied. The air valves are located within a concrete-lined chamber 4.4m × 3.6m × 2.15m high which is set into the ground and roofed with earth-covered concrete beams to form an underground chamber with no ventilation to the open air. An 800mm diameter steel vent pipe which is permanently open leads directly from the vent chamber to the valve house, so effectively venting the tunnel into the valve house. This vent pipe runs almost horizontally into the valve house where it curves downwards to discharge just above the grid floor level. There is also a small drainpipe from the vent chamber discharging into the valve house. As can be seen in Fig 2, the discharge branch diverges from the side of the access branch and runs at a downward gradient under the lower part of the valve house and on beneath the River Wyre, terminating in a blank end under the far bank. The discharge branch continues beneath the river solely to allow for any future extension of the scheme. A 200mm diameter washout pipe runs from the discharge branch to an outfall chamber on the near bank of the river. This pipe is fitted with a valve which can be opened to allow drainage of the discharge branch of the tunnel, but is intended to be kept closed in normal operation. There are also 100mm diameter circulation pipes extending back from the dead ends of both branches of the tunnel and discharging into one of the distribution chambers in the valve house.

17 From the crown of the discharge branch below the dry room of the valve house the water is conveyed through two 1000mm diameter steel pipe bends (known as 'lobster backs') and discharged into two discharge chambers in the wet room of the valve house (see Figs 3a and 3b). The lobster backs discharge water below the water level in the chambers and are submerged when the chambers are full. A third lobster back, connected to the discharge branch, consists of 800mm diameter steel pipework discharging into a nearby hollow in the surrounding field, and is intended as an emergency discharge line. The three lobster backs are fitted with butterfly valves with controls located in the dry room. For normal running the control valve on the emergency discharge lobster back is kept closed and the control valves on the other two lobster backs are kept

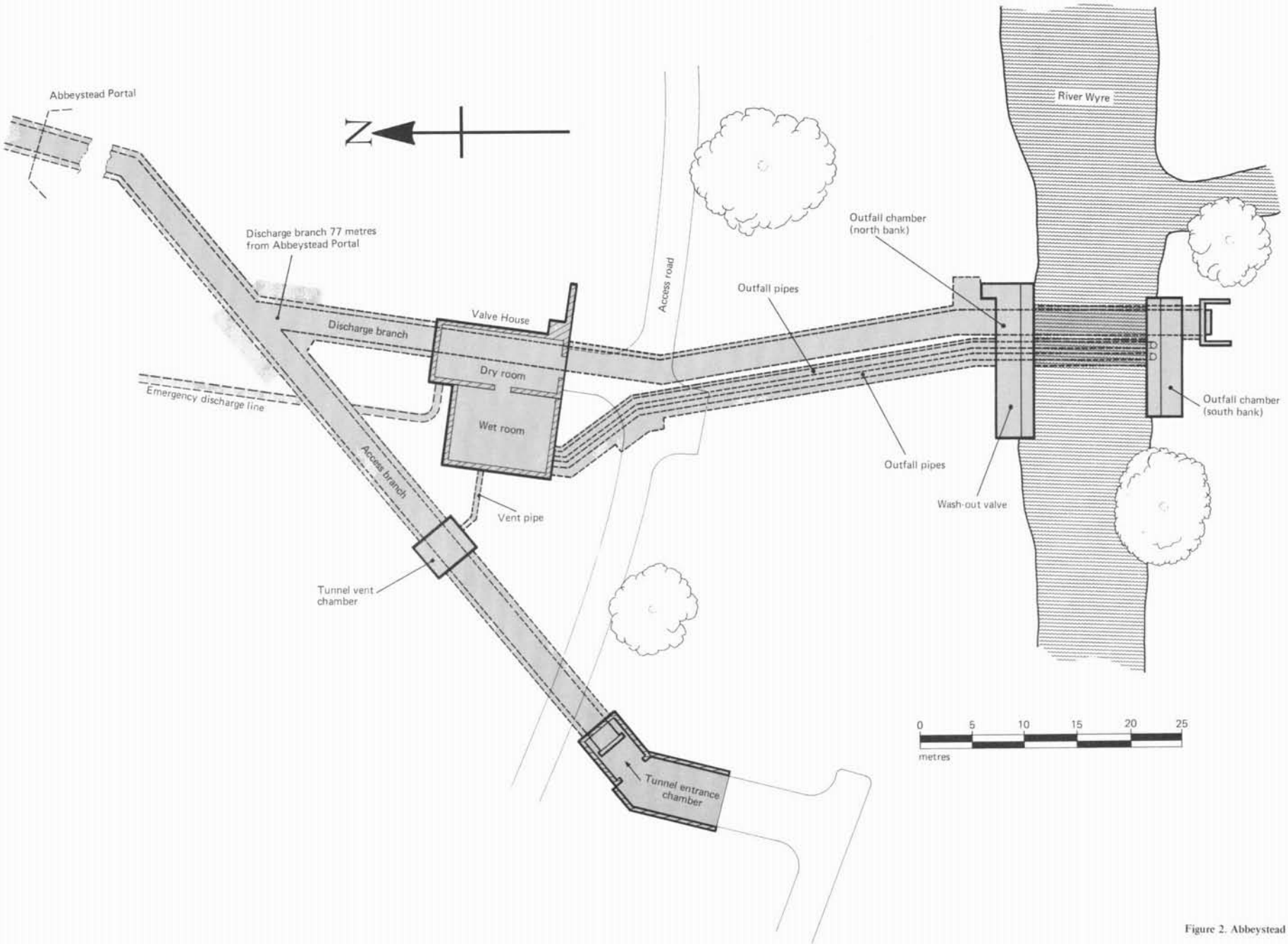


Figure 2. Abbeystead Outfall Station

open. There is an air valve similar to those in the vent chamber on each of the lobster backs venting air just below floor level in the wet room.

18 When a discharge chamber is full, the water flows over a weir, each discharge chamber supplying 2 of 4 distribution chambers. A little water can also enter the distribution chambers through the 100mm diameter circulation pipes leading back from each of the dead ends. Four outfall pipes convey the water from the distribution chambers to outfall chambers on both banks of the river. Outfall pipes 1 and 3 feed the outfall chambers on the near bank and pipes 2 and 4 run beneath the River Wyre and feed the far bank outfall chambers. The final discharge into the river should therefore be reasonably uniformly distributed between both banks in normal operation. The discharge ports from these outfall chambers are permanently open. The downstream chamber on the near bank is supplied with water from the washout valve referred to in paragraph 16, and when the valve is opened water from this chamber enters the river through the five discharge ports at the downstream end of the outfall.

19 The construction of the Valve House at Abbeystead was of reinforced concrete and it was predomi-

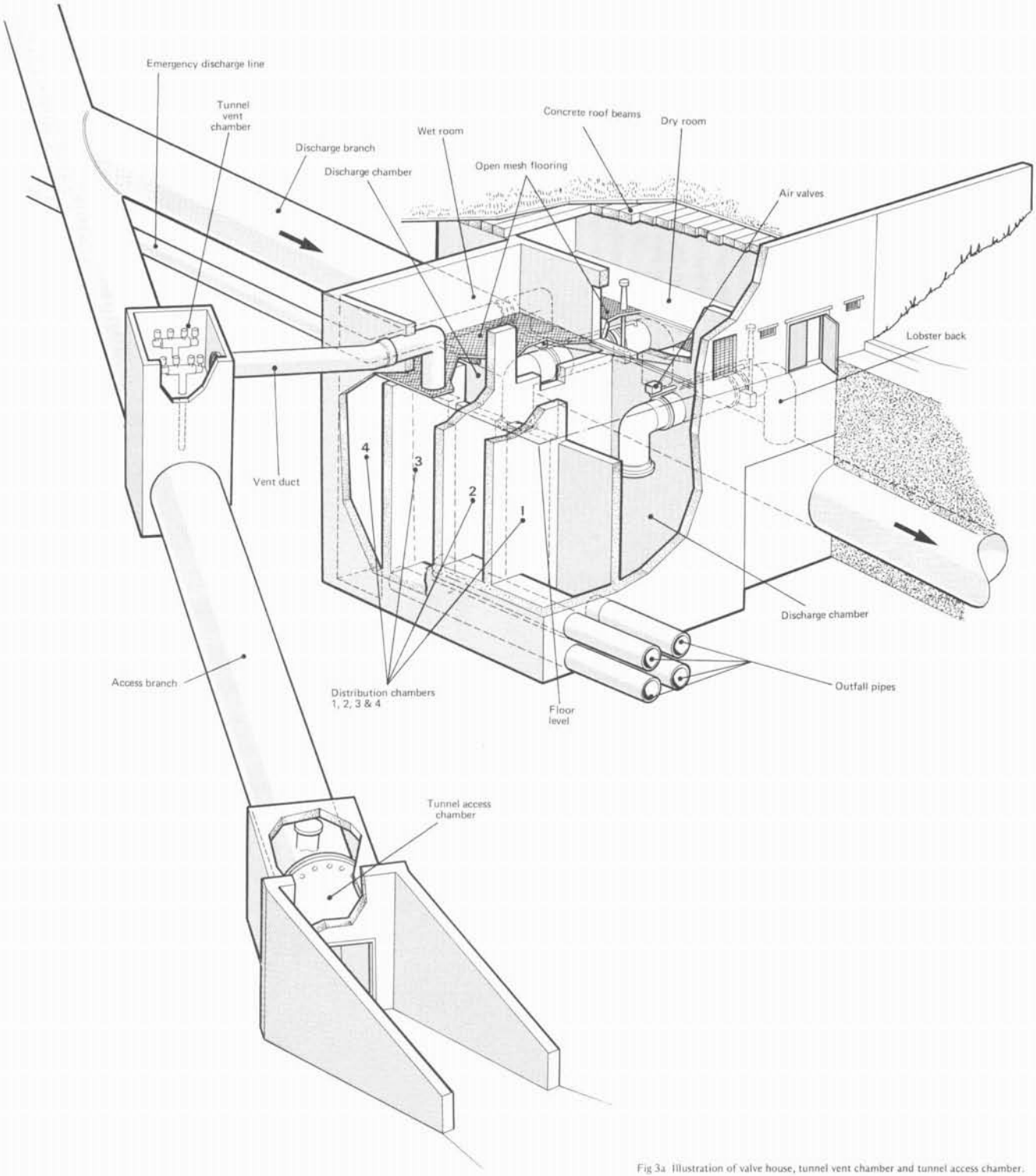
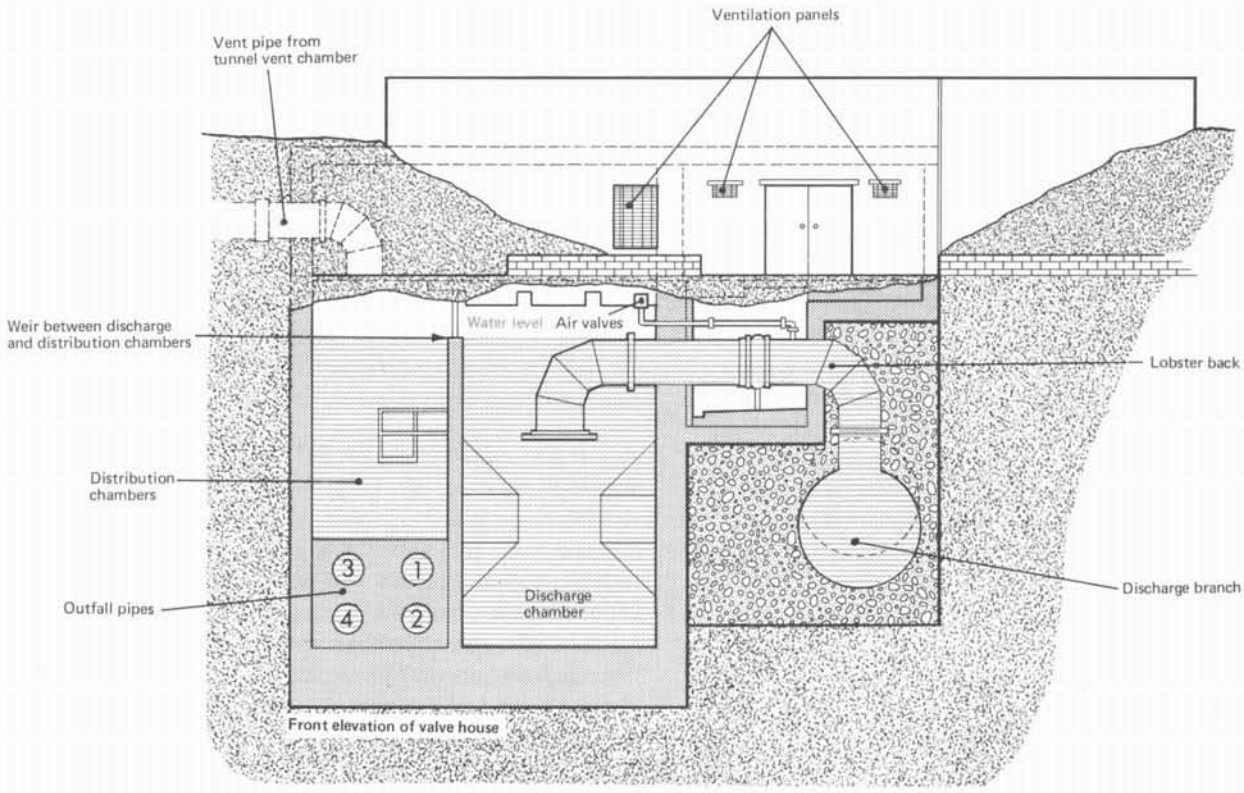
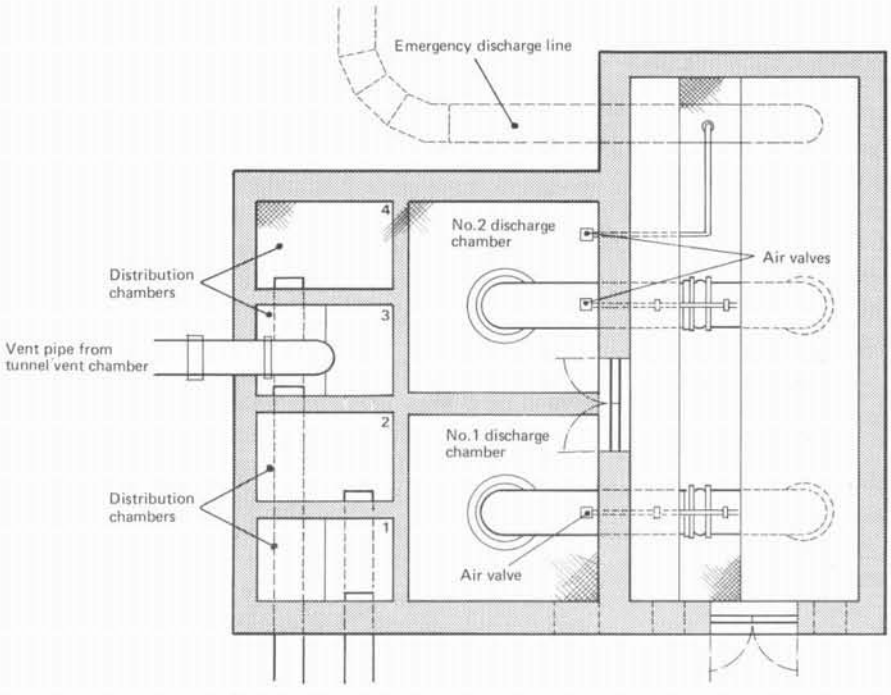


Fig 3a Illustration of valve house, tunnel vent chamber and tunnel access chamber.





Plan of valve house with roof and floor omitted for clarity

Fig 3b Valve House

nantly underground, only the wall at the entrance side being above ground. The roof consisted partly of solid concrete and partly of precast concrete beams 400 × 450mm in cross-section, and was overlaid with a waterproofing treatment and a layer of top soil and turf.

20 Entry to the Valve House from outside was through substantial outward opening double doors on to an intermediate floor above the tunnel and the discharge chambers. These doors led into a room 12.5m long × 5.15m wide and 2.5m high known as the dry room, which was directly above the discharge branch of the tunnel. The dry room housed the controls for the water valves on the lobster backs, instruments and a toilet compartment. It had a floor consisting partly of solid concrete with an inset section of steel mesh over the valve pits. A second pair of substantial double doors in an internal dividing wall opened from the dry room into a room known as the wet room. This room was 9.50m long × 7.50m wide by 2.50m high and occupied the whole area above the discharge and distribution chambers. Its floors consisted entirely of steel mesh panels carried on joists 8.30m above the bottoms of the discharge chambers.

21 Ventilation for the wet room was provided by a single louvred ventilation panel measuring 1410 by 880mm set in the outside wall. There was no mechanical ventilation. In the dry room, air was admitted through a 600 × 330mm louvred opening set near the top of the outside wall. A small electric fan extracted air through metal trunking from below the floor at the rear of the room, where the instruments were situated, and discharged through a separate louvred opening identical to the inlet. In the dry room there were also two small tubular electric heaters which were normally kept switched on.

22 The designers of the tunnel have expressed the view, which has been confirmed by enquiries to Water Authorities, that no other installation in Great Britain incorporates all the characteristics of the Wyresdale tunnel and Abbeystead Valve House. The specific characteristics which appear to have been of importance in relation to the Abbeystead explosion were:

(a) All the contents of the tunnel, both liquid and gaseous, discharged into a room with limited natural ventilation.
(b) Water passed through a concrete lined tunnel, i.e. a tunnel not designed to be watertight.
(c) Ground water from the strata surrounding the tunnel leaked in rather than tunnel water leaking out.

Operations prior to 23 May 1984

23 Water was first transferred through the Lune–Wyre Link and discharged at Abbeystead on 25 June 1979. Since then the system has remained operationally available, except when it was drained for inspection and maintenance in September 1979. Operational control was at first vested in the Ribble Division of the North West Water Authority, but following a reorganisation in 1983 control passed to the Ribble District of the new Northern Division Supply and Treatment Department.

24 Demand for water has proved lower than was forecast when the Scheme was planned, so less use has been made of the Lune–Wyre Link than was expected. Records show that between 1 January 1983 and the date of the explosion, pumping took place on 246 of the 509 available days, and there was no pumping for several weeks on a number of occasions. The maximum quantity of water pumped in any one day was only 87 megalitres, as against the 280 megalitres/day which the Authority is permitted to extract from the Lune.

25 It was a feature of the design that during the standstill periods the tunnel would remain full of water, so long as all washout valves through which it could be drained were kept closed and no leaks developed. Indeed, providing there was no drop in the inflow of ground water which was known to enter through the tunnel walls, there should normally have been a continuous flow of water at all times over the weirs in the Valve House and out into the river through all the discharge ports, even if no pumping of water was taking place.

26 The Manual of Operating Instructions provided by the designers of the Scheme indicates that the washout valves at Abbeystead and Rowton Portal should be opened periodically to flush out 'dead water' from the system. No interval between openings is specified but the practice of flushing out monthly was adopted originally by the NWWA. Normally this was done while pumping was in progress, when opening of the washouts would have no noticeable effect on levels of water in the system. Any significant opening of a washout valve while pumping was not in progress might have resulted in partial drainage of the tunnel, but when the valve was re-closed, the system should soon have been re-filled by the inflow of ground water, and flow through the valve house should have restarted.

27 A period of 25 days continuous pumping was completed on 6 May 1984, this being the last time the system was used before the explosion occurred. Towards the end of that period of pumping, routine visits were paid to the Abbeystead site by the Group Superintendent who was operationally responsible for it, and by his assistant, both of whom normally visited about once a month. Throughout the pumping period and the subsequent 17 days before the explosion, routine calls were also made by an operator who normally visited the site for about 1 to 2 hours weekly to keep the plant and installations clean and tidy. The same operator was responsible for the monthly attention to the washout valve referred to above, but it was not a specified part of his duties to check the water flow in the valve house during his weekly visits.

28 The last routine visits to the site prior to the explosion were paid on the day on which it occurred, 23 May 1984. The operator paid his weekly visit around 1.00 pm, and at about 2.15 pm a technician from the Authority's River Division called to check the calibration of a meter installed in the dry side of the valve house. Neither of them went into the wet room where water is discharged, to check the flow of water at the weirs.

29 Except when the routine visits referred to in the previous paragraph were being paid, the Abbeystead installation was normally unattended at all times. There was no operational need for any person to be present when pumping was started or stopped. A number of parties of visitors had been shown round the valve house, since the commissioning of the Scheme, some while pumping was in progress, but it has not been possible to establish whether or not pumping had ever commenced while visitors were present.

30 During the construction of the Wyresdale tunnel and the Abbeystead outfall, HM Factory Inspectorate inspected the civil engineering and construction work on a number of occasions. After the scheme had become operational the Factory Inspectorate made a general inspection of the Abbeystead outfall installations in July 1981. Records of these visits make no reference to the presence of flammable gases.

The events of 23 May 1984

31 Between 6.30 pm and 7.00 pm on the fine, dry evening of 23 May 1984, a party of 44 visitors assembled at the Abbeystead Valve House. Thirty-six of the visitors were residents of the village of St Michael's-on-Wyre, about 15 miles away, where there had been concern that floods in the village during recent years might have been aggravated by water pumped into the Wyre at Abbeystead. The other 8 members of the party were employees of the North West Water Authority. Six of them were members of the technical staff concerned with the operation of the Lancashire Conjunctive Use Scheme, who were to act as guides, the other 2 being office workers who were to assist with refreshments.

32 When the visit began no water was being pumped, and none had been pumped for 17 days, but it was intended that pumping should take place during the visit for demonstration purposes. After giving an introductory talk outside the entrance to the Valve House, the North West Water Authority's District Supply and Treatment Manager gave orders over a telephone installed in the dry room for a pump to be started at the Lune Pumping Station at the supply end of the Lune–Wyre Link. A pump which had a nominal capacity of 37.5 Ml/day was switched on at about 7.12 pm and pumping of water from the balancing tank at Quernmore into the tunnel began. Meanwhile, the visiting party had split up. Some people went into the Valve House, others down to the nearby riverbank where the water outfall from Abbeystead entered the Wyre through the rows of discharge ports on both banks of the river. Visitors who went to the riverbank saw that water was flowing from only a few of the discharge ports, at the downstream end of the outfall on the near bank of the river, i.e. those fed by the washout valve in the discharging branch. Those who went into the wet room of the valve house noticed that there was no flow of water into the discharge chambers, and that the water levels in the chambers were well below the weirs.

33 When no water had flowed into the Valve House after about 10 minutes a second telephone call was made to the pumping station by the District Manager and an order was given for a second, variable speed pump to be started, to double the rate of flow to 80 Ml/day. By then almost all the visiting party had gone inside the Valve House.

34 Just before 7.30 pm, when water had still not started to flow into the Valve House, an explosion occurred inside the House. Every member of the visiting party was either killed or injured, many of them suffering severe burns. Eight people died at the scene and the death toll rose eventually to 16, including 3 of the North West Water Authority Officials who were acting as guides. Substantial damage was caused to the Valve House. Part of the earth-covered concrete beam section of the roof was lifted by the explosion and collapsed into the valve house, causing some of the more serious injuries. The collapsing beams broke through the steel mesh flooring of the wet room and some of the injured fell into the water in the chambers below.

35 The explosion was heard by a number of people in the surrounding countryside, some of whom reached the scene of the accident within 10 minutes and attempted to help survivors, at some risk to themselves. The emergency services were alerted within 5 minutes, but their stations were several miles away, and it was 7.48 pm when the first ambulance arrived on site, followed almost immediately by the other emergency services.

36 The first flow of water into the valve house was noticed by some of the survivors several minutes after the explosion, probably between 7.40 and 7.50 pm. At that time the pumps were still running, and they continued to run until the pump operator at Lune Pumping Station telephoned Abbeystead to check on the water flow at about 7.50 pm. A local resident answered the telephone and told the operator that there had been an explosion. Suspecting a hoax the operator telephoned to the main control room at Franklaw Water Treatment Works for confirmation and it was not until 8.05 pm that the pumps were switched off. Rescue operations continued throughout the night until about 6.00 am, when all known visitors had been accounted for. HM Inspectors of Factories (HMFI) from North West Area and the North West Field Consultant

Group were on site by 1.30 am on the 24 May and established contact with the emergency services and the management of NWWA, before commencing their investigation.

37 A first inspection of the interior of the Valve House was made early on 24 May 1984. At that stage much of the roof had already been removed by the rescue services but it was possible to see that several of the large concrete beams forming part of the roof had collapsed inwards and that most of the beamed section of the roof had been lifted from its supports. The damage was greatest in the wet room where a number of roof beams had fallen onto the steel mesh floor and broken through sections of it into the discharge and distribution chambers below. One of the roof beams in the dry room had also collapsed onto the floor between the entrance to the Valve House and the doorway to the wet room. The internal doors and their surrounds had been blown out of position, as had the louvred ventilation panel for the wet room which was found later on the opposite bank of the river. Signs of smoke and flame were very limited, except in a small area just inside and to the left of the main entrance, where there were clear signs of burning near a partially buried cupboard. Elsewhere the walls appeared quite clean except for adherent fragments of what seemed to be burnt clothing and slight spatterings of bitumen-like material in places. The general effect was consistent with an explosion of a gas-air mixture having occurred inside the Valve House. There were also clear signs of a similar explosion in the nearby vent chamber, its earth-covered roof having sustained severe damage.

The investigation

Preliminary findings

38 In the initial stages of the investigation attention was directed towards a number of potential explanations for the explosion, in addition to the presence of naturally occurring methane. These included the possible storage of liquefied petroleum gases or flammable liquids in the Valve House, entry into the Valve House of commercial gas or other flammable substances leaking from pipelines in the area, the electrolytic generation of hydrogen in the tunnel and terrorist activity. It soom became apparent that most of these potential explanations could be eliminated but one or two were thought to merit some further investigation.

39 The position of all relevant pipelines in the area was established and with the assistance of the British Gas Corporation all gas lines were checked and tested, no evidence being found of any leakage which might have reached Abbeystead Valve House. Neither was there any evidence of the storage of gas cylinders on the premises, but a 5 gal drum buried by fallen debris in the area where fire damage had been noticed just inside the Valve House entrance proved to have contained a very small quantity of petroleum spirit. This drum was situated close to a small wall-mounted tubular heater, which could have raised its temperature, and there was some evidence that the contents had ignited and burst the drum. The drum was examined by experts from the North West Field Consultant Group of HMFI and the Health and Safety Executive's Research Laboratory Services Division (RLSD), who concluded that the petroleum spirit was likely to have been vaporised and ignited by the heat generated by the explosion. Accordingly the drum was discounted as a possible source of the explosion. The strong probability which emerged was that the explosion had been caused by the ignition of gas, likely to be mainly methane, which had accumulated in a void in the tunnel, and that the pumping of water had displaced flammable gas from the tunnel into the Valve House.

40 Although other possibilities were kept in mind, subsequent investigation centred on the following questions.

(a) How, when, and to what extent had a void arisen in the tunnel?
(b) What were the nature and source(s) of any gases present in that void?
(c) How had the gas been transferred to the Valve House?
(d) How and where had the gas been ignited?

All these lines of enquiry are considered separately below.

A void in the tunnel

41 The Lune–Wyre Link was designed to run full of water during pumping and to remain full with the pumps switched off. In these circumstances no significant void could exist in the tunnel during normal operation. If the integrity of the system was maintained and none of the washout valves along the tunnel line was open, water should never have been below weir level in the Valve House, and providing the inflow of ground water into the tunnel was at its normal level, there should have been a small continuous outflow of water over the weirs in the Valve House and through all the 52 normal discharge ports on both banks of the river.

42 The evidence from victims of the explosion indicated that no water was flowing into the discharge chambers in the Valve House and that the water level in them was approximately 1 metre below the weirs prior to the explosion. The only water flowing into the river was from the five downstream discharge ports on the near bank of the river, i.e. the ports supplied only from the washout valve at Abbeystead.

43 An outflow of water from the five downstream outfall ports alone could occur only if the washout valve on the near bank of the river was at least partially opened. The low water level and absence of flow at the weirs indicated that the water level in the system had fallen sufficiently for water to have ceased to flow

through the lobster back discharge pipes. This suggested that the washout valve was sufficiently open to drain off more than the inflow of ground water into the tunnel. This would have resulted in the creation of a void, the size and speed of development of which would depend on the difference between the rate of inflow into the tunnel and of outflow through the washout, assuming that there was no substantial leakage elsewhere in the system.

44 There appeared to be a number of other factors which might have contributed to a void in the tunnel, for example a decrease in the water inflow, faulty washout or air valves along the line, incorrect opening of those washout valves or failure to close them, abstraction of water during the prevailing dry weather by unauthorised opening of washout valves, or leakage from the system as a result of structural faults or damage. A detailed internal examination of the tunnel was clearly essential. It had already been drained back to just beyond Rowton Portal when a washout valve there was opened in the course of the rescue operations, but before it could be entered great caution had to be exercised because of the risk that flammable concentrations of gas might still exist or arise.

45 Assistance was sought from HM Inspectors of Mines and Quarries who have knowledge and experience of work in methane-rich atmospheres, and of the Mines Rescue Service of the National Coal Board. Scientific staff from the HSE's RLSD which incorporates the former Safety in Mines Research Establishment, also joined the investigating team at this stage, and continued to play an active part throughout the investigation.

46 When the tunnel was first entered, the presence of methane was soon detected at levels rising to 2% of the atmosphere at 1.5 km from the access point at Abbeystead. Although the methane concentrations were below the lower flammable limit of 5%, they were above the level at which work would be permitted in coal mining practice, so before the investigation inside the tunnel could continue it was necessary to ventilate the tunnel thoroughly. The large blank flange at the end of the access branch of the tunnel at Abbeystead was therefore removed and with the assistance of the National Coal Board, who made available a large extraction fan and the services of an experienced mine ventilation engineer, a satisfactory extraction ventilating system was installed within a few days and progress could be made with the internal examination of the tunnel.

47 A visual examination of the inside of the tunnel revealed no major defects in the lining. Inflows of ground water through fissures and porous areas were noted at various points in the concrete lined centre section, but measurements of the total inflow using a temporary weir at Rowton indicated that it was of the same order as the flow when the tunnel was taken into use, i.e. approx 1 megalitre/day (11 to 12 litres/sec).

48 Various 'tide marks' were seen on the walls of the tunnel at the Abbeystead end. It was at first thought that they might indicate water levels at different times and in different operating conditions. A number of theories were advanced to account for some of these tide lines but no explanation has been found for them which contributes to the picture of events in the tunnel leading up to the explosion. Another curious observation was that stalactite-like pendant growths had formed at certain points which would be expected to be permanently submerged. It was at first suggested that these growths could not form under water and so a large void must have existed for long periods. This theory was rejected after research by the Commonwealth Mycological Institute established that the growths could form under water.

49 'Tide marks' were also found in the washout chamber at the river outfall and these were thought to indicate water levels at differing settings of the washout valve. The results of tests based on water levels in the washout chamber carried out during the investigation are reported in greater detail in para 94.

50 While water sampling and investigations into the pattern of water flow in the tunnel were being carried out by Inspectors from North West Field Consultant Group, parallel enquiries were going on into the operating procedures followed by the NWWA, particular attention being paid to use of the washout valve at Abbeystead. The interviewing of NWWA staff directly concerned with the operation of that valve revealed that the practice of opening it periodically, as recommended in the Operating Instrutions, had been abandoned early in 1980. This change followed excessive silting up of the dead-end under the river at Abbeystead which led to severe discolouration of the river when the valve was opened.

51 Early in 1980 it is understood to have become the practice to open the washout valve, probably 1½ to 2 turns of the spindle whenever pumping was in progress, and to allow the discharge of water through the washout valve to continue until pumping ceased, at which stage the washout valve was closed. After a few months, when pumping through the Lune–Wyre came under remote control from Franklaw Treatment Works, the method of using the washout was changed again. It is said to have been left permanently 'cracked open', from then onwards, whether pumping was in progress or not. The setting described as 'cracked open' appears to have been about three-quarters to one turn of the washout valve from the fully shut position. It has not proved possible to establish who authorised the changes in the procedure for using the washout valve at Abbeystead. No documentation relating to the changes has been produced, and no guidance on their potential effects appears to have been sought from the designers of the system.

52 It seems probable that the changes were introduced by NWWA operating staff who saw no reason

for referring them to a higher level in the organisation for approval. If this had been done the possibility of partial drainage of the tunnel might have been recognised, and it may well be that the procedures would have been modified to prevent any potential loss of water. No evidence has come to light to suggest that the presence of flammable gas in the tunnel had been envisaged by anyone concerned with the operation of the scheme.

53 With the washout valve open approximately one turn, water was found by the plant operators at the time of change of procedure to continue to flow over the weirs in the Valve House and out through all the outflow ports, including the washout ports.

54 Initially, following the change in procedure, it was the practice for the operator to check the flow over the weirs when he paid his routine weekly visit to Abbeystead Outfall, but with the passage of time and an eventual change of operators, the regular checking of flow over the weirs was abandoned and only the flow of water from the outfall ports at the river was checked. The operator who carried out the checks from November 1983 until the explosion has stated that he saw water flowing from the end five outfall ports supplied by the washout valve whenever he checked, but he is uncertain about the flow of water from the remaining ports. The fact that an absence of flow from these remaining ports indicated that water was not flowing over the weir was not appreciated by him. None of the more senior members of the surviving NWWA staff who visited the site occasionally noticed water flowing from only the end five outfall ports.

55 Information on the flow of water through the outfall ports into the river was also obtained from two independent witnesses not in the employment of the NWWA, one of them an angler who fished regularly over the Abbeystead stretch of the Wyre and the other a local gamekeeper. Both these witnesses have stated that there were occasions when no water was flowing into the river through the outfall ports. In particular, the gamekeeper reports visiting the outfall very regularly for a few weeks before the explosion and seeing no water runing. The angler, who was fishing the river when the explosion occurred, reports walking down the riverbank on the opposite side to the Valve House about 1½ hours before the explosion and noticing water coming out of about four jets at the downstream end on the Valve House bank of the river, i.e. the outfall ports supplied by the washout valve. He also noticed a similar situation on the weekend before the explosion. About two weeks before the explosion he saw no water flowing into the river on two nights.

56 The evidence of the angler referred to in the previous paragraph confirmed that of several survivors of the explosion. It appeared to establish beyond reasonable doubt that immediately before the explosion occurred, and probably for some days before that, water had been flowing into the River Wyre only through the outfall ports supplied by the washout valve. This would indicate the absence of any flow over the weirs in the Valve House that was reported by several survivors of the explosion. The absence of any flow into the river reported by both the witnesses referred to in the previous paras is harder to explain but is considered below in para 59.

57 The fact that water was flowing only from the washout ports did not necessarily establish that there was a substantial void in the tunnel, but this was clearly indicated by the lapse of time between the starting of pumping on 23 May and the arrival of water in the Valve House some time after the explosion. If the void had resulted solely from a loss of water at the Abbeystead washout the maximum void would have arisen when the water in the tunnel was only just flowing into the discharge branch. The water level would then have reached the tunnel crown approximately 291m from the Abbeystead portal and a void of approximately 1425m^3 (1.425Ml) would have existed.

58 The size of any void could have been increased if any of the other washout valves along the line of the pipeline between Quernmore and Rowton had been opened, either officially or by persons seeking to extract water for their own purposes during the dry spell preceding the explosion.

59 The opening of these valves could also have led to the absence of flow at Abbeystead described by the witnesses referred to in para 56 above. Enquiries into this possibility proved fruitless, however, and no information has come to light suggesting that any such unauthorised abstraction occurred during the standstill period before the explosion.

60 The probability appeared to be that the primary cause for the creation of a void was the departure from the instruction in the operating Manual represented by the leaving of the Abbeystead washout valve partly open. Providing that valve was set in the position described as normal by the NWWA employees concerned, it would not in itself have drained off sufficient water to create a void. There is a possibility that a leak somewhere in the system may have contributed to the drainage (and could also have led to a complete stoppage of the water flow at Abbeystead) but no significant leak has been identified and it seems unlikely that any exists. It follows that the washout valve was set in a more open position than had been described as normal, or that there had been unauthorised interference with the operation of the system. No evidence of interference has been found.

Nature and source of the inflammable gas

61 The first positive evidence of the presence of methane was obtained from the analysis of water samples taken when the tunnel was drained down at the Rowton end soon after the explosion. These samples were found to contain concentrations of dissolved methane of from 5 to 9 mg/litre. Samples of

water taken from the pipework between Rowton and Quernmore were found to contain less than 0.5 mg/litre, so it was inferred that any source of methane was unlikely to be in the Lune to Rowton part of the system, or in water extracted from the Lune.

62 Methane was detected in the atmosphere when the Abbeystead end of the tunnel was first entered two days after the explosion and tests were carried out with a methanometer. With no ventilating plant installed, the concentration of methane in air reached 2% about 1.5 km from Abbeystead, 5.2 km from Rowton Portal and it appeared that most of the methane was likely to be originating somewhat nearer the Rowton end than that point.

63 Methane is a flammable gas which, if confined, can give rise to an explosion. A combustible mixture of flammable gas and air can exist only between certain limits known as the lower and upper flammable (explosive) limits. A mixture below the flammable limit is too weak to burn and a mixture above the upper flammable limit is too rich to burn. The flammability limits for methane are 5% and 15% by volume in air.

64 Although traces of other gases were detected they were not present in significant quantities in the tunnel atmosphere, so subsequent investigation was centred on identifying the source of methane, and the way in which it had entered or been generated in the tunnel. Initially there appeared to be two likely hypotheses which will be referred to subsequently as the biological and geological theories: the methane may either have been generated in the tunnel by anaerobic decomposition of organic matter in the water, or it may have entered the tunnel from fissures in the surrounding strata through cracks or porous sections of the tunnel wall. There was also the possibility that a mixture of methane from both sources was present.

65 Considering first evidence for the biological theory; there were deposits of blackish watery sludge several inches deep along the bottom of the tunnel, and in the dead end dipping below the river what appeared to be a large deposit of sludge had built up at a point just beyond the inlets to the lobster backed pipes supplying the Valve House. When the dead end of the tunnel was subsequently pumped out, the water content of this sludge was found to be high and the total mass of solid matter relatively low. The sludge was regarded as one potential source of methane. Another was a wet slime which had been deposited on the tunnel walls. Advice on their methane-generating potential was sought from the Rowett Research Institute of Aberdeen, whose sampling and subsequent culture growth revealed the presence of methanogenic organisms. Their research also indicated, however, that the quantity of methane likely to have been generated could not be expected to be sufficient to create the explosive atmosphere which had existed.

66 To check the validity of the geological theory of the origin of the methane it was necessary to establish the age of gas samples from the tunnel. Samples were taken from the atmosphere at various points and submitted to the Isotope Measurements Laboratory at Harwell for radio-isotope dating. The results indicated that the methane was ancient (i.e. in excess of 20 000 years old) and so must be presumed to be mainly of geological origin. The possibility of a mixture of methane of different ages could not be excluded, but the result of the Rowett Institute tests described in the previous paragraph suggested that the content of recent biological methane was low.

67 Water entering the tunnel by leaking through the walls, and water lying in and flowing through the system was also tested and analysed. At normal temperature and pressure, methane is not very soluble in water, but if the pressure in the surrounding strata was high its solubility would be raised significantly. Samples of water entering the tunnel taken at various points showed methane contents ranging from a trace up to 40 mg/litre. As this water entered the tunnel and was exposed to a lower ambient pressure some of the methane would be given off immediately as gas, particularly where the solution was super saturated and if discharge was into a length of tunnel not full of water. If the tunnel was full of water, methane bubbles would be likely to form in the crown of the tunnel and would tend to move up the slope, much of it dissolving in the water, and eventually enter any void existing in the Abbeystead end of the tunnel. Thus the methane content of the tunnel water would be raised by the methane-rich inflow, as was suggested by the samples of tunnel water taken during the draining of the tunnel and at later stages in the investigation.

68 The visible flow of water into the tunnel was entirely in the concrete lined section. The main inflow occurred well beyond the end of the steel lined sections of the tunnel at a distance of between approximately 4.2 and 5.7 km from Rowton Portal (1.0 and 2.5 km from the Abbeystead end). In that area several small jets of water could be seen emerging from the tunnel wall and there were also clear signs of more diffuse leakage. Because of difficulties in sampling and measuring the amount of ingress water it was not possible to estimate how much methane was entering the tunnel dissolved in water.

69 Measurements of low concentrations of methane in air extracted from the empty tunnel by the ventilation system installed during the investigation indicated that the total quantity of methane entering or being given off in the tunnel at that time was $0.001 m^3$/sec. This was the only measurement of the total quantity of methane in gaseous form that it was possible to carry out. It must be regarded as only approximate, because of the limitations in measuring both low concentrations of gas and the volumetric air flow.

70 It was concluded, following the completion of all the tests described and a detailed inspection of the

tunnel, that the flammable gas which was present was almost entirely methane and was mainly of geological origin. Most of it was leaking through the tunnel walls in solution in water between 4.0 and 5.5 km from Rowton Portal, where it had already been established that the tunnel was likely to have been full of water prior to the explosion.

71 Efforts were made to reconcile these findings on the geological origin of the methane with information which had come to light about conditions prior to and during construction of the tunnel. Present knowledge of the geology of the area, based partly on surveys carried out by the British Geological Survey during the driving of the tunnel, is shown diagrammatically in Fig 3c. It will be noted that the tunnel may have passed through the top of a sandstone anticline, a structure resembling an inverted dome, at about 4 to 4.5 km from Rowton (2.2 to 2.7 km from Abbeystead), this being in the area where the greatest levels of methane in ingress water have been measured. Truncated limbs of other anticlinal structures, in the form of bands of sandstone, also cross the tunnel in other areas where water is entering the tunnel in quantity. The sandstone anticline and bands are likely to act as aquifers through which water can flow in the strata, possibly carrying methane from a distant source in solution.

72 Local inhabitants have reported that the presence of methane near the surface of the ground in areas near Abbeystead has been known for many years. This appears to have been biogenically produced methane of the marsh gas or 'will-of-the-wisp' variety rather than the methane of ancient origin detected in the tunnel during the investigation. Methane has also been detected in the spoil heaps at Abbeystead and Rowton made up of materials excavated during construction of the scheme but the significance of its presence is difficult to assess. The spoil is a mixture of material excavated at various points, some perhaps near normal ground level. Some of it is known to have been contaminated during the construction period by organic substances, including diesel oil which might now be giving off methane. Finally, results of a borehole which indicated some presence of hydrocarbons, sunk by Place Oil & Gas in 1966 some 3 km from the line of the tunnel (the Whitmore borehole) had been lodged with the British Geological Survey under 'commercial in confidence' cover, but were not available.

73 During driving of the tunnel a good deal of ground water was encountered although less than had been feared. Evidence of the presence of flammable gas during tunnelling is far less clear. Although Draeger gas detectors were provided, as required by the contract, they were evidently used to a very limited extent. They can in any case give only a qualitative indication of the presence of natural gas because of the sensitivity of the indicator tubes to other gases known to have been present at the construction stage. Tests are known to have been done on 10 occasions, all of them between May and October 1977. The tunnel ventilating plant was in operation during all but one of these tests. The results of all these tests have been traced and examined. Three showed indications of the possible presence of natural gas in small quantities, so advice on their interpretation was sought from the manufacturers of the measuring instrument. HSE's investigating team concluded that the results of the tests could not be taken to give a reliable indication of either the presence or absence of methane in the atmosphere of the tunnel at the time the tests were carried out.

74 No incidents involving naturally occurring flammable gas are known to have occurred during construction, although the tunnel was driven by drilling and explosive blasting, the electrical plant used was not flameproof, welding and cutting was done during the installation of the steel linings at each end of the tunnel, and a fire involving a transformer occurred inside the tunnel near the Rowton Portal without any indication of the ignition of unexpected gases. At one stage of the construction, a dead end extended for about 1 km beyond the ventilation trunking at the Rowton end of the tunnel, reaching as far as the section where the highest methane levels have been measured in ingress water during the investigation. No incidents were reported to have occurred in this dead end, although some of the potential means of ignition referred to above are said to have been present in the unventilated length. Largely on the strength of this experience, members of the staff of the designers and of NWWA present during the construction, believe that it is extremely improbable that methane could have been entering the tunnel then, to even a fraction of the present extent. But the tunnel was normally well ventilated and in the absence of comprehensive testing for flammable gas, it is impossible to reach a firm conclusion on the basis of their observations and any inferences drawn from them.

75 A former employee of the contractor, who worked as a ganger in the tunnel, has reported that on three occasions he suffered headaches which from previous mining experience he associated with the presence of methane. However, it has proved impossible to correlate his recollection of the places where his headaches occurred with surviving records, or with the existing pattern of water and gas ingress in the tunnel. Headaches often result from other types of fumes which are encountered during tunnelling or from oxygen deficiency in poorly ventilated conditions.

76 Experts on relevant aspects of geology have been consulted and various theories have been put forward to explain the presence and nature of geological methane in the strata and its mode of migration into the tunnel. On the evidence available, it has not proved possible to reach any firm conclusion. Advances in geological knowledge which have arisen from the widespread search for oil and gas in this country in recent years, have introduced one new factor, which would not have been recognised when the tunnel was designed,

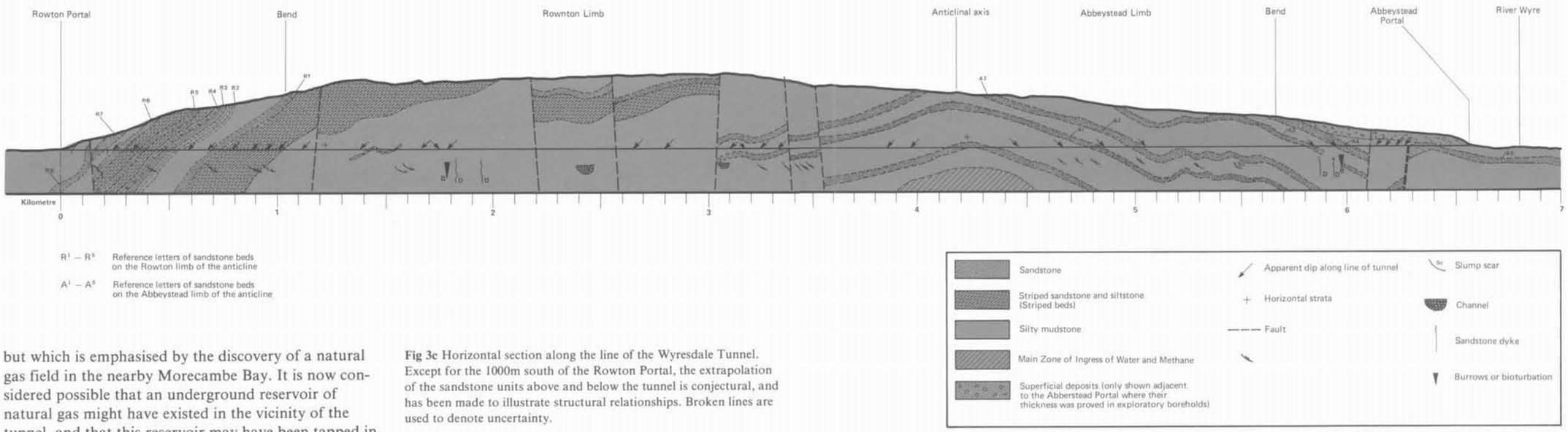


Fig 3c Horizontal section along the line of the Wyresdale Tunnel. Except for the 1000m south of the Rowton Portal, the extrapolation of the sandstone units above and below the tunnel is conjectural, and has been made to illustrate structural relationships. Broken lines are used to denote uncertainty.

but which is emphasised by the discovery of a natural gas field in the nearby Morecambe Bay. It is now considered possible that an underground reservoir of natural gas might have existed in the vicinity of the tunnel, and that this reservoir may have been tapped in some way as a result of changes in the ground water channels in the strata initiated by the driving of the tunnel. There is also a possibility, suggested by major differences in the chemical analyses of water inflows at different points, that more than one source of methane-containing water exists and that the sources function in different ways. The explanations for the existence of methane which have received consideration are in simple terms.

(a) Continuous emission of methane of the firedamp type familiar to miners and its transfer by ground water in Wyresdale Fell.
(b) The existence of a low pressure methane reservoir in Wyresdale Fell.
(c) The existence of a high pressure methane reservoir in Wyresdale Fell.
(d) A flow of methane, mainly in solution, from a deep high pressure source possibly at some distance from the tunnel.
(e) In association perhaps with one of the above, the existence of a pocket of methane which was largely discharged on the night of the explosion.

77 Because of the uncertainty which now exists, both as to the presence of methane at the time of the design and construction of the tunnel, its source and the likely pattern of its production at the time of the explosion, now and in the future, the North West Water Authority is sponsoring further geological investigation in the area surrounding the tunnel.

The method of entry of gas into the Valve House

78 It was established at an early stage in the investigation that a substantial void existed in the tunnel on 23 May 1984. The atmosphere in that void could have been transferred to the Valve House in several ways. Providing the standing water level in the discharge chambers was above the level of the outlets of the lobster backs in the chamber, as indicated by the evidence of the survivors, the primary routes for the flow of air and gas would be from the tunnel, through the eight air valves in the vent chamber near the Valve House, and then via the 800mm diameter vent pipe from the vent chamber into the wet room of the Valve House. The secondary route would be through the air valves on the lobster backs and directly into the wet room. Some air/gas might also pass into the wet room through the drain pipe from the vent chamber which discharges into one of the distribution chambers, and also through the circulation pipe at the access dead-end of the tunnel beyond the Valve House, but the quantities would be relatively small. The main flow of gas would be through the air valves in the vent chamber.

79 The air flow could be in either direction; from the tunnel into the Valve House, or vice versa. While the tunnel was draining, air from the outside atmosphere would be drawn into it through the air valves in the vent chamber and the Valve House, which fresh air could enter through the ventilation louvres in the external wall. While the water was standing, the movement of air might be in either direction, depending on atmospheric conditions, but it would probably not be of great significance. Once pumping restarted air/gas would be displaced from the tunnel as the level of water rose in it and would pass through the air valves in the vent chamber and on the lobster backs.

80 When the water level rose sufficiently to seal the lobster backs, the flow of air/gas through the valves on them would cease and the flow would continue only through the valves in the vent chamber. The faster the rate of pumping the greater would be the rate of flow of air/gas, which would fill the vent chamber and pass through the large vent pipe into the valve house.

81 There appeared, therefore, to be an easily identifiable gaseous flow mechanism by which any flammable atmosphere inside the tunnel could be transferred to the Valve House, although it was difficult to predict accurately the exact distribution of flow, between the different routes.

Source of ignition

82 From the evidence of survivors it is clear that the explosion originated in the wet room of the Valve House, when between 15 and 20 people were in that room. Their individual recollections vary in detail, but there is a common thread of a flash probably around the floor level near the north-west corner of the wet room, followed by a blast of burning gas through the doorway into the dry room and out through the main entrance doors of the Valve House. Six of the eight bodies recovered from the scene of the explosion were found in the wet room and there was a preponderance of structural damage in that same area.

83 The probable mode of ignition of the gas cloud has received careful and detailed consideration but a precise source has not been established although a number of possibilities have been identified. In a room where electrical equipment was not intrinsically safe, flameproof or pressurised, and where over 40 people, some known to be smokers, were present, ignition by one means or another was highly probable if an explosive atmosphere arose.

84 The electrical equipment in the wet room where the explosion originated, consisted solely of weatherproof light fittings and their associated circuitry, all instruments, heaters, switches and other electrical gear being in the outer dry room. The whole installation was subjected to thorough examination by one of HM Electrical Inspectors of Factories and specimens of the light fittings and other items of electrical equipment were later examined and tested in the HSE's laboratories. Their reports indicate that there were no faults in the electrical equipment that were likely to have provided a source of ignition. A possibility exists of sparking caused by current tracking between damp terminals but there were no positive signs of it having occurred. The measured operating temperatures of the lamps, including the two large floodlights installed beneath the grid floor in the wet room and of the tubular heaters in the dry room were well below the temperature at which ignition of methane could occur.

85 Items of smoking equipment have been recovered from the Valve House, and although they might have been there before the day of the explosion, it is possible that some of them were the property of the visitors on 23 May. A lighted cigarette or pipe might not ignite methane but the use of a cigarette lighter or match would. One survivor reports seeing a man lighting a pipe some minutes before the explosion, and it would not be surprising if several people lit cigarettes or pipes during the rather lengthy wait for water to come through the system. No blame could rest on anyone who did, for visitors were not warned against smoking in the Valve House, the NWWA not having envisaged that a flammable atmosphere could arise there.

86 Another possible source of ignition which cannot be excluded is the spark discharge of static electric charges built up on clothing. A report by HM Electrical Inspector indicates that the removal of a garment made of synthetic fibre by a person inside the wet room might possibly have generated sufficient energy to initiate the explosion.

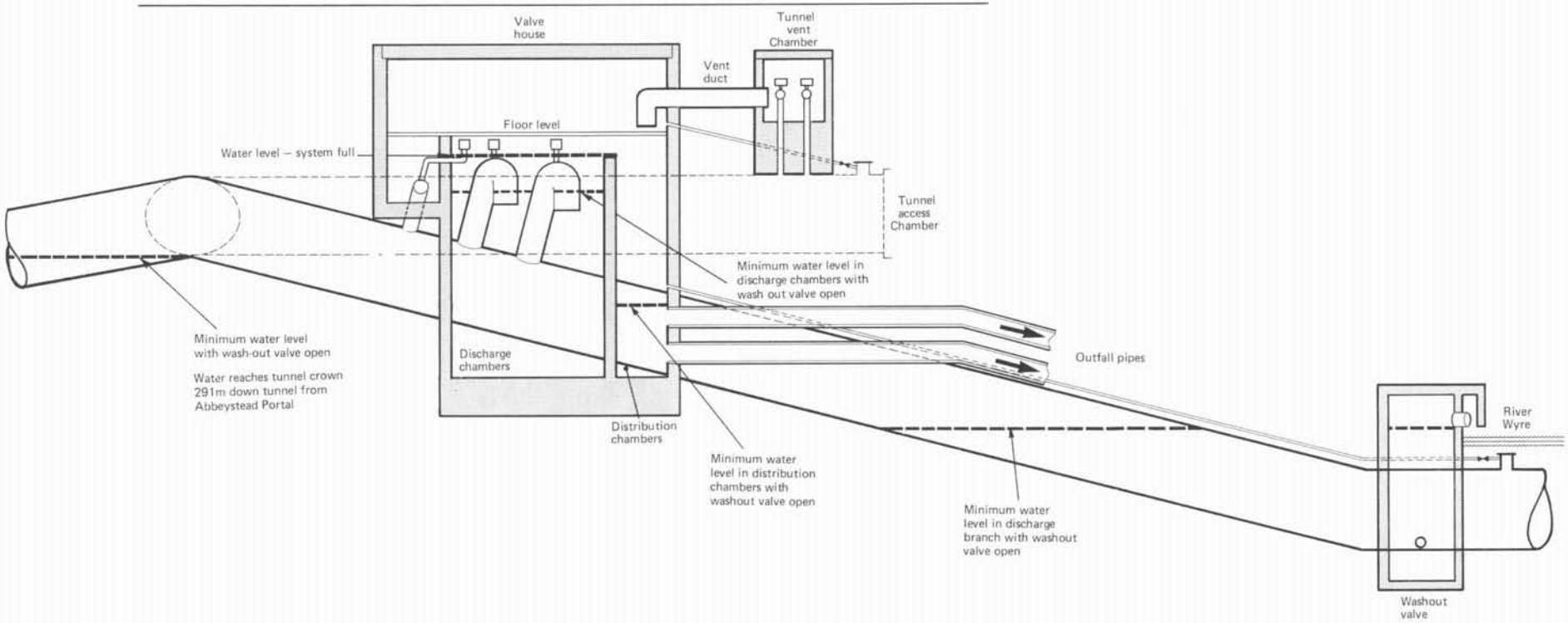


Figure 4 Abbeystead
Schematic arrangement of outlet works showing water levels

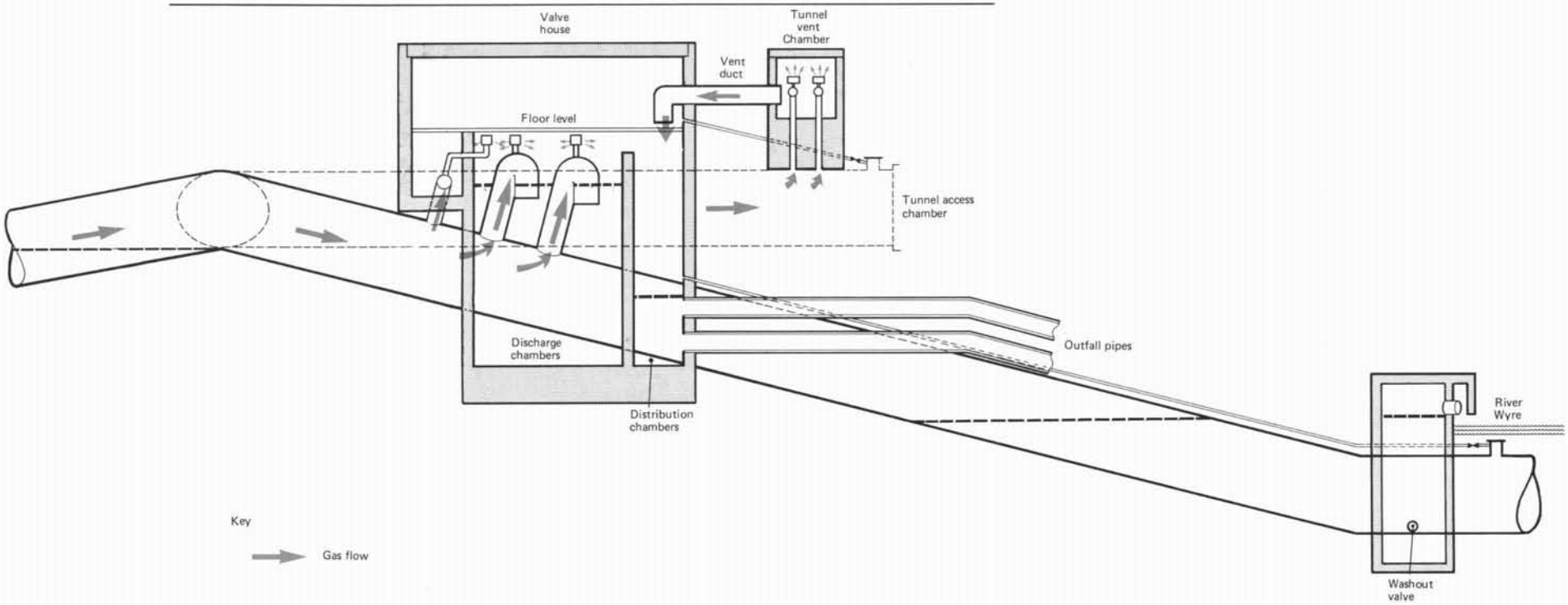


Figure 5 Abbeystead
Schematic arrangement of outlet works showing gas flow

Testing the theories — a simulation of events

87 As a result of the investigations a likely scenario seemed to have been established for the explosion, so it was decided to put it to the test by staging a simulation of the events prior to the explosion. The system would be re-filled with water and left standing for the same period as it stood before 23 May, and then pumping at the same rate as on the night of the explosion would be re-started under test conditions.

88 After all those concerned with the various aspects of the investigation had been given a final opportunity to carry out any further tests considered necessary inside the tunnel, preparation for the simulation began early in July.

89 Temporary roofs were erected for the Valve House and vent chamber and new ventilation louvres and internal doors were fitted to replace the ones severely damaged by the explosion. Inside the tunnel, and in the Valve House and vent chamber, sampling points for gas and water were installed and connected to remotely situated measuring instruments. The tunnel ventilation fan installed during the investigation was disconnected and the blank flange and the manhole cover at the access end of the tunnel at Abbeystead were replaced. After all personnel had been withdrawn to a safe distance and all foreseeable sources of ignition eliminated, pumping was recommenced in mid July for the first time since the explosion.

90 The equivalent of two fillings of the system was pumped through it to flush out the water which had been stagnant in the pipeline end of the Lune/Wyre link since the time of the explosion and to reproduce so far as was practicable the conditions when pumping ceased on 6 May 1984.

91 After re-filling, pumping was stopped with all the washout valves in the system closed and locked off. Water continued to flow over the weirs in the valve house as a result of ground water entering the tunnel. This inflow had been measured by checking the flow over a weir at Rowton Portal while the tunnel was empty. It was found to be 0.9 to 1.1 Ml/day, a rate of flow similar to that measured when the tunnel was commissioned. A subsequent measurement of water flowing from the washout ports at Abbeystead indicated that with the tunnel full the inflow was only 0.69 Ml/day, a reduction of about 30% and a more recent measurement following wet weather was 0.79 Ml/day.

92 On the morning of 23 July, the washout valve at Abbeystead was re-opened one full turn, which was the extent to which it had been the practice to open it prior to the explosion, according to the NWWA employees most directly concerned. Within a few minutes the flow of water over the weirs ceased. The only flow into the river was from the 5 end ports at the downstream end of the outfall on the near bank, the ports supplied through the washout valve. This was the condition observed by witnesses immediately prior to the explosion.

93 The flow of water over the weirs did not recommence, but within a short time the level of water in the discharge tanks stopped falling and settled only inches below weir level. A gauge installed at the access end of the tunnel indicated that the level in the system had settled at just above the level of the tunnel crown, at that point which meant that the system was still effectively full of water. In these circumstances no void would have developed in the tunnel, the outflow of water through the washout being balanced by the inflow of ground water through the tunnel walls.

94 The level of water in the chamber fed by the Abbeystead washout valve was compared with a number of 'tide-marks' noticed on the walls of the chamber. The marks were at 23mm, 35mm, 53mm and 75mm above the bottom level of the outfall ports through which water flowed into the river, and were thought to indicate levels of flow. In particular the HSE investigating team considers that the 53mm mark represents the setting of the washout valve used for several months before the explosion. At this setting the outflow through the washout is believed to have just balanced the inflow of ground water when the valve was set. With the washout valve setting of 23 July, i.e. open one complete turn, the water settled at 44mm above the bottom level. As this was within the range of tide marks it was considered appropriate to maintain the valve setting and observe developments.

95 By 27 July there had been no significant change in water levels, and it was evident that no significant void was going to develop in the system at the existing valve setting in the absence of any unpredictable events. As it was clear that a void had developed between May 6 and 23, it was decided to increase the outflow through the washout sufficiently to ensure partial drainage of the system.

96 Accordingly the Abbeystead washout valve was opened a further $\frac{5}{8}$ of a turn on 27 July, making a total of $1\frac{5}{8}$ turns from the closed position. The level in the washout chamber rose to 70mm above the outfall port level, i.e. 5mm below the highest 'tide-mark' in the chamber. At this setting the water level in the tunnel started to fall and by 8 August a void of considerable size had formed. However, it was thought possible that it was smaller than the void on 23 May, since the water level had been falling for only 12 days since the re-setting of the washout valve, as against a possible 17 days before the explosion.

97 Between 23 July and 8 August methane levels in the system were monitored regularly. The results showed a methane in air concentration of about 9% in the small space between the water level and the crown of the tunnel near the inner end of the void in the access branch at Abbeystead. A representative sample

from this area taken on 7 August was found to contain methane 8%, ethane 0.05%, Carbon dioxide 0.14%. Carbon monoxide 0.0001%, Oxygen 17.80% and Hydrogen 0.01%. Lower methane concentrations of 3 to 4% were recorded in the tunnel nearer the Valve House and in the vent chamber. In the Valve House itself they were generally below 0.5%.

98 On 8 August pumping of water was recommenced, an attempt being made to follow the same sequence of operation as on the night of the explosion, with the same operator controlling the pumps

99 It did not prove possible to duplicate exactly the pumping pattern of 23 May but the overall pumping rate was similar. The exact size of the void which existed on 8 August was the equivalent of 1.38Ml as indicated by the amount of water pumped by the time of the first flow of water over the weir. It has not been possible to establish exactly when that occurred on 23 May but there is strong evidence that it was between 27 and 37 minutes after pumping started. On 8 August the flow started after 35 minutes, so it is possible that the void which existed in the tunnel on 23 May was slightly less than 1.38Ml measured on 8 August, rather than greater as had been thought possible in view of the shorter drainage period referred to in para 86 above. The order of size of the void on 23 May was clear, however.

100 While pumping was in progress the measuring of methane concentrations and water levels in the system continued. After the pumps had run for the same length of time as they ran on 23 May before the explosion occurred, i.e. approximately 17 minutes, the concentration of methane in the atmosphere of the Valve House was approximately 3%. This concentration is non-flammable, the flammable range for methane being approximately 5 to 15%. The concentration in the vent chamber at the same time was approximately 4%, also below the flammable range.

101 A maximum concentration of 7% methane was recorded near the roof of the vent chamber after about 35 minutes pumping. The maximum concentration measured in the Valve House at the same time was 4.80% methane in air, i.e. still just below the flammable limit. It was however, fairly uniform at all the sampling points in the Valve House, all of which were at or above the level of the floor grids.

The simulation ***Comments***

102 The simulation cannot have been an exact one. It was necessary to go beyond what was stated to be the normal setting of the washout valve to create a void, and when pumping was resumed an explosive atmosphere was not created in the Valve House. It did establish that a substantial void could be created by opening the Abbeystead washout valve only slighly more than the reported setting, and that a methane-air mixture would accumulate in that void. Pumping of water would transfer that mixture to the Valve House mainly via the vent chamber and an approximately uniform mixture of air and methane would form above the Valve House floor. The pattern was similar to that thought to have led to the explosion but the concentration of methane was less than had been produced between 6 and 23 May. Possible reasons for this were thought to be differences in the degree of ventilation of the tunnel system, short-term changes in the level of the water table in the surrounding ground as a result of prolonged dry weather during the investigation, or a fall in the 'supply' pressure arising from unknown changes in conditions in the strata. It has also been suggested that a pocket of gas in the ground may have discharged completely into the tunnel on the night of the explosion.

Conclusions

103 The explosion was caused by ignition of a mixture of methane and air which had accumulated in the wet room of Abbeystead Valve House. The methane had been displaced from a void which had formed in the Abbeystead end of the Wyresdale Tunnel during a period of 17 days before the explosion when no water was pumped through the system. When pumping was resumed on 23 May 1984, while the visiting party was inside the Valve House, the water level in the tunnel rose slowly and pushed out the methane and air mixture in the void through the air valves near the end of the tunnel. Most of the air/gas mixture passed through the eight air valves mounted above the access end of the tunnel into a closed vent chamber, from where it flowed through a large open vent pipe into the Valve House.

104 The design of the Lune–Wyre Link was novel in certain respects for the water supply industry. Its most unusual feature in relation to the explosion was the discharge of water and vented air from the tunnel into an enclosed Valve House situated below ground. Although ventilation grids were installed in the external wall of the Valve House, they were not so positioned nor of such a size as to disperse the volume of gas which arose on the night of the explosion. If a water discharge system open to atmosphere had been used, an explosion would almost certainly not have occurred.

105 No source of ignition for the explosion has been positively identified. Thorough examination and testing of the electrical equipment has not revealed any faults likely to have caused ignition and there is insufficient evidence to confirm any of the other explanations which have been considered. Smoking in the Valve House was not prohibited because the likelihood of a flammable atmosphere arising there had not been envisaged.

106 The void in the tunnel was produced by loss of water through a washout valve at Abbeystead which had been left permanently open to minimise silt accumulation in the end of the tunnels beyond the Valve House. A maximum loss of water, approximately

1.5 Ml, was possible through this washout although the evidence indicates that the actual loss at the time of the explosion was between 0.97 Ml and 1.42 Ml. A void of the same order of magnitude would be created in the tunnel, which had been designed to remain full of water at all times, except when drained intentionally for maintenance or inspection.

107 Use of the washout valve in the way described in the previous paragraph was not in accordance with the operating manual provided by the designers of the system. It had been introduced a year or two after the system became operational, apparently without the knowledge or approvel of senior operational and technical staff employed by the NWWA. If more detailed operating instructions had been issued and stricter working procedures followed the change in the use of the washout valve might have been detected, but the possible disastrous consequences of the new procedure would almost certainly not have been recognised by anyone operationally involved.

108 Almost all the methane was of ancient geological origin, although small quantities probably arose from decomposition of organic matter in the tunnel. Most of the methane percolated in through the concrete walls of the tunnel between 2 and 2.5km from Abbeystead, either in a gaseous form or in solution in water under pressure. The fact that significant quantities of methane might be dissolved in water does not appear to have been recognised by the personnel concerned with the design and operation of the Lancashire Conjunctive Use Scheme, and probably not by the water industry generally. Information obtained in the course of the enquiry indicates that it has been widely regarded as an insoluble gas, its solubility under normal atmospheric conditions being very low. References to the presence of dissolved methane in water supply systems have been traced in published literature but they do not appear to have achieved wide circulation, particularly amongst the sections of the Civil Engineering Profession concerned with water supply schemes.

109 On the strength of their experience during the driving of the tunnel, both Binnie and Partners and the NWWA believed, and still believe, that methane was not emerging from the strata in quantities which were significant. During the construction period, some testing for methane was carried out in accordance with standard contract clauses for safety in the construction operation. The results of those tests which were carried out showed on three occasions what might have been very low levels of methane. But the instrument used was susceptible to other gases likely to be present and the readings therefore cannot be regarded as confirming the presence of methane; in addition the majority of the tests were carried out when forced draught ventilation was in operation.

Recommendations

110 The recommendations concerning design, construction and operation are intended to apply to TUNNELLED RAW WATER TRANSFER SYSTEMS which are not of watertight construction. They also apply to closed raw water transfer systems in which methane is liable to be generated. They do not apply to treated water distribution systems using watertight pipes.

Design and construction

111 Systems conveying water should be so designed that any air or gas discharged, either during filling or at any other time, is vented to a safe place in the open air.

112 Where it proves impracticable to comply with Recommendation 1 in a particular case, comprehensive tests should be made to ascertain the nature of any contaminants which might enter the system or be generated in it, and appropriate precautions should be incorporated in the design to deal with them.

113 The controls for washout valves should either be so located that they cannot be operated by unauthorised persons or should incorporate arrangements for the valves to be locked in the closed position.

114 During tunnelling work, sufficient tests should be carried out at frequent and regular intervals to establish the presence or otherwise of flammable gases using instruments able to provide a quantitative reading of acceptable accuracy. On completion, and before the commissioning of any tunnel forming part of a water transfer scheme, further tests for flammable gas should be carried out with no ventilating system in operation. The results of such tests should be recorded and retained; positive results should be reported immediately to the designers of the installation and to the organisation which will be responsible for its operation.

Operation

115 Operators of existing raw water transfer systems should review the possibility of methane being present in the system and, where appropriate, should consult with the designers in assessing the safety of the installation, particularly where significant voids may be formed in the system.

116 Safe systems of work covering all aspects of operation and maintenance should be laid down in comprehensive operational instructions, the observance of which should be monitored by management.

117 The training of operating, technical and supervisory staff concerned with water transfer systems should include measures to ensure that they are made fully aware of the significance of any special features of the installation with which they are concerned, any potential hazards which may be anticipated in the course of operations and the appropriate precautions to deal with the hazard.

General

118 The fact that methane is soluble in water and increasingly so above ambient pressure, and that it can be given off by ground water entering workings, should be widely publicised throughout the civil engineering profession and incorporated in professional training courses.

Action by HSE

119 Following the Abbeystead explosion, HSE wrote to water authorities alerting them to the possible dangers of water transfer and comparable systems where methane may create a risk.

120 Interim advice on the risk of gas evolution at water boreholes has been produced for the guidance of users.

121 Further advice on the wider aspects of methane evolution from ground water is being prepared.

Appendix

The Health and Safety Executive is indebted to the following organisations for producing papers which assisted with the investigation, and in the preparation of this report.

British Geological Survey: Fluid Processes Research Group
Keyworth
Nottingham

Isotopic and Chemical Analyses of Gas and Associated Water. Wyresdale Tunnel.

Commonwealth Mycological Institute
Culture Collection & Industrial Services
Ferry Lane
Kew
Surrey

Investigation of structures of possible biological origin in concrete pipe at Abbeystead.

Rowett Research Institute
Bucksbarn
Aberdeen

Two reports on samples taken from the Abbeystead Tunnel.

Harwell: Low Level Measurements Laboratory

Measurement of Carbon-14 activity in two samples of Ba CO_3 supplied as extracted from CH_4 gas collected at the Abbeystead Pumping Station.

In addition to site investigation work the Research and Laboratory Services Division of the HSE produced the following reports:

Observations on the damage and deductions as to the course of the explosion.

Examination of and tests on electrical equipment.

Identification of the fuel, location of its ingress and simulation of its displacement from the tunnel.

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