Mining Science and Technology, 12 (1991) 89–96
Elsevier Science Publishers B.V., Amsterdam

An investigation of water flow paths and tracing techniques undertaken at Littleton Colliery

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(Received March 6, 1990; revision accepted April 24, 1990)

ABSTRACT

Eyre, J.M., 1991. An investigation of the water flow paths and tracing techniques undertaken at Littleton Colliery. Min. Sci. Technol., 12: 89–96.

As a result of changes in the pattern of flow of underground water associated with Littleton Colliery, a series of investigations were carried out to study the pattern of water flow in the north-west of the Cannock Chase Coalfield, of which Littleton is a part.

The likely consequences of any change or termination of pumping operations had to be determined. Indications were that "live" connections for water courses existed and that pumping operations could be consolidated. It was decided that a tracing survey would be carried out to determine both the magnitude and effects of the increased flow rate. A hitherto untried method of tracing the passage of water through mine workings was chosen.

This paper sets out to explain the techniques and results of the survey.

Introduction

Littleton Colliery, Central Area, British Coal is situated on the north-eastern rim of the Cannock Chase Coalfield (Fig. 1). It lies adjacent to numerous old mine workings which have physical and potential connections to the Colliery on its western and southern boundaries [1]. As collieries within this coalfield have closed, water has gravitated via these workings towards Littleton. As a result, pumping schemes were set up at the sites of the former West Cannock 5's and Mid Cannock collieries.

The workings at West Cannock 5's lie to the rise side of Littleton Colliery. Pugh [2] concluded that, if pumping was ceased immediately after the closure of West Cannock

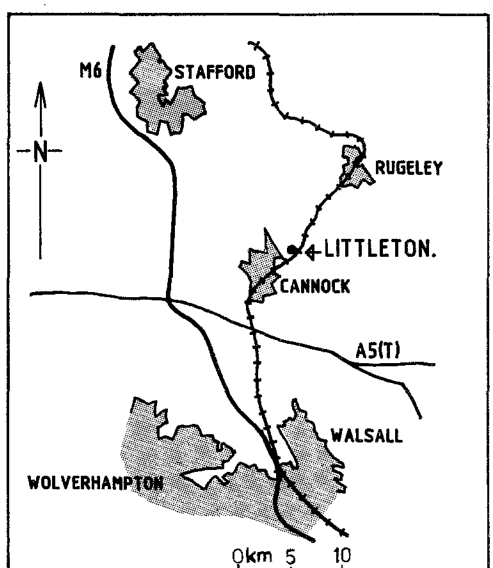

Fig. 1. Location of Littleton Colliery.

5's, the water would build up a hydrostatic head of 198 m. In view of the direct connections between Littleton and the West Cannock collieries there were several points at which water could have gained access to Littleton's main horizons (Fig. 2).

A pumping scheme was introduced at West Cannock 5's upcast shaft together with facilities for water to gravitate by pipes from workings inbye of the Littleton/West Cannock 5's connection (hereafter called The Connection) as described by Slatcher [3].

In May 1987, a change in the normal pumping cycle at West Cannock 5's upcast shaft was noticed. Following checks on the rate of rise in shaft water level it was assumed that an obstruction on the N.W. loco road had effectively isolated the pump lodge. Closed circuit television (CCTV) surveys, showed that water was also entering West Cannock 5's pumping shaft under pressure at its contact with the baseof the Trias. In addition, the base of the shaft was showing evidence of deterioration.

It was necessary to determine whether there was a flow path along the N.W. loco road since, in the event of cessation of pumping at West Cannock 5's (7273744 l/week—1.6 million gallons/week), the water could reverse its flow. In order to determine the effectiveness of the apparent blockage a tracer had to be introduced into the mine water.

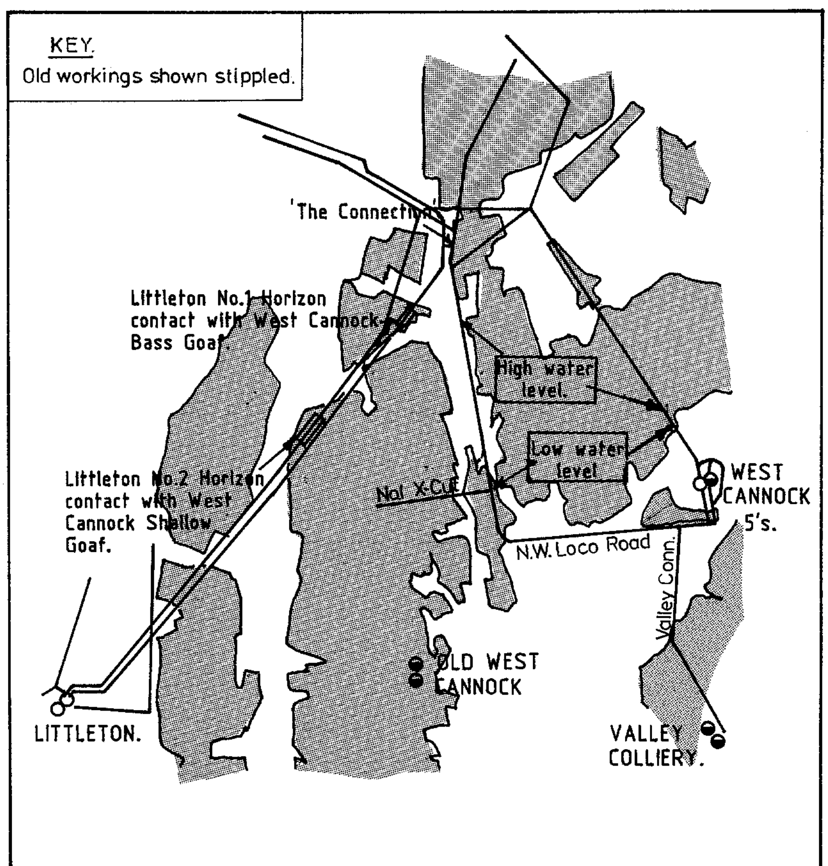

Fig. 2. Plan showing the extent of old workings at Littleton and West Cannock 5's Colliery with details of key points associated with the water regime.

The potential flow paths from The Connection (Fig. 2) are:

(1) Along the N.W. loco road, then via No. 1 Crosscut and old Shallow goaf onto No. 2 Horizon at Littleton.

(2) Along the N.W. loco road and 9850' Horizon to West Cannock 5's pit bottom.

(3) Along the N.W. loco road and 9850' Horizon through the dam/stopping between West Cannock 5's Valley loco road to Mid Cannock.

If the trace was introduced at The Connection it was estimated that the results of the survey would become known within the following periods:

Flow Path *1* 2 months.
Flow Path *2* 2–4 days.
Flow Path *3* 1–3 weeks.

In order to cope with the extra water expected at Littleton it was imperative to determine all the possible flow paths. It was therefore proposed to shut down the pumps at West Cannock 5's and allow a head of water to build up to a level which would provide potential for free flow to Littleton so that flow paths could be defined.

Water tracing

The water industry states that, in order to be useful as a marker, any tracer must exhibit the following characteristics [4,5]:

(a) In the local environment, concentration levels of the tracer should not be larger than trace amounts (and preferably absent), since high background concentrations make the subsequent analysis of samples unnecessarily complex. Not only is it difficult to show significant increases above background levels but, in addition, the higher the background level the greater the amount of tracer that has to be added for increases to be detected, thereby raising the cost.

(b) Any tracer must be:

(1) readily available in sufficient quantities;

(2) non-toxic, in both its concentrated form and when distributed in the environment (especially when the water to be tested is used in a potable supply);

(3) unchanged or inactivate whilst in the environment (ideally it should be possible to recover all the tracer that was originally put in);

(4) cheap (particularly relevant where large quantities are required);

(5) compatible with routine monitoring programmes.

(c) There should be a cheap, rapid and reliable method for assaying the samples. Any such method should be quantitative and capable of accommodating large numbers of samples.

A comparison of tracers has been made by Cole, Nixon, Norton and Stanfield [6] based on traditional tracing techniques which can be classified as chemical, physical and radiological. However, growing environmental awareness and new legislation has brought the use of some of the tracers examined into question.

Chemicals and fluorescent dyes are still used successfully and are the most common technique. They are cheap and easy to handle, and the results can be seen and measured in situ. Concern has been raised recently that some dyes have carcinogenic properties and may cause discolouration and tainting of the flesh of fish. The technique is only really suitable where the waters to be tested are of high clarity. In addition, the effectiveness of some dyes is diminished by sunlight. Furthermore, the longer the distance between the point of insertion of the tracer and the point of detection, the greater the concentration of element required, with a consequent increase in cost.

Radioactive tracing has long been established as an accurate, reliable and flexible tracing technique. The isotope Bromide 82

(KBr) is commonly used, with concentrations maintained below that of the Derived Drinking Water Concentrations limit (< 12.5 kBq/1), typically 2 kBq/1. Permission to use radioactive tracers is strictly controlled by licence to specialist bodies from the Radiochemical Inspectorate of the Department of the Environment. Whilst only a small amount of tracer would need to be added into the water, the low levels of radiation would require measurement at each sample point using sensitive scintillation counters. Some specialist teams, such as the Water Resources Centre, are willing to conduct such exercises and if immediate results and high quantitative accuracy are required then the costs may be justified.

However, an alternative to these traditional techniques has come to the fore in recent years; that of microbiological tracing. First introduced in 1897 to study groundwater movements it lapsed into disuse until the mid 1950's when its potential was recognised as an environmentally sound, convenient, flexible and inexpensive technique. Microbiological tracers can best be described as living microorganisms which are easily identifiable above low background levels in water samples. The most suitable of these micro-organisms for tracing applications are thought to be bacteriophages (phages), which are parasitic organisms dependent upon a specific host bacteria for replication. One significant advantage is that it is possible for tracing exercises to be performed where several different phages are used simultaneously and the results can be obtained by plating a single water sample with the different specific hosts.

A phage is completely harmless and dormant until its introduction to the host bacteria in the laboratory, where the effect of multiplication can be seen in the consequent lysis of the host bacteria. As many as 3000 phage particles (plaques) per cell can be observed (Fig. 3).

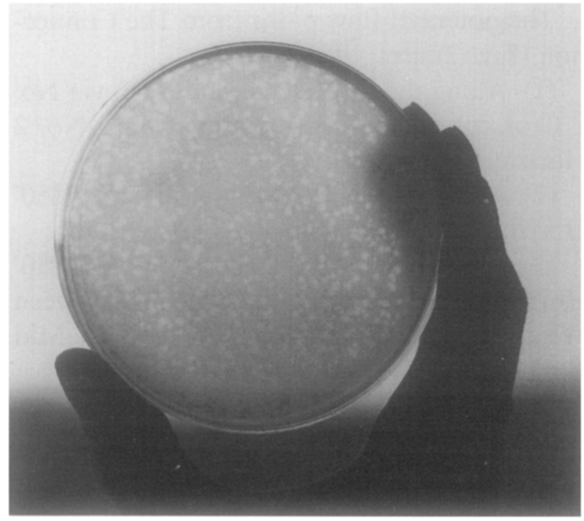

Fig. 3. A good example of Plaque growth.

As a result of these considerations the tracing element chosen for use in the Littleton survey was bacteriophage. This offered many advantages over the traditional methods, not least of which was due to the fact that the discharge water from West Cannock 5's fed directly into a well-stocked series of fishing pools in a Country Park. The surface Triassic sandstones are used locally for potable water extraction with the nearest borehole being less than 1 km from the discharge point. Furthermore, the time period between introduction of the phage to recovery of positive sample was likely to be extensive and, given the poor water quality obtained at Mid Cannock, a tracer which had durability and stable qualities was required.

Whilst documented tests in rivers and near surface groundwater exercises [4,5] had found phage to be a suitable tracer, its use in mine workings and deep underground systems had not previously been tested. Much interest in the findings of the survey was therefore expressed.

Phage can be produced relatively easily in a laboratory and sample types and dosages were calculated and ordered. As described in [7] they can be grown in high concentrations of between 10^{12} and 10^{14} plaque forming units per ml (pfu/ml) making it inexpensive to generate, there is no need for specialised equipment. No health restrictions on the dosage are required. Samples can also be stored for long periods (up to 4 years) without significant deterioration, if kept in cool dark conditions ($-20\,^{\circ}$C in 50% glycerol). Short-term storage at $4\,^{\circ}$C is acceptable, without significant loss.

Analytical procedures for the samples are simple and fast with results being available within 4 hours. Observations are made of the effect of a sample of water on a "lawn" of host on an agar culture plate. Any phage within the sample specific to that host will cause lysis of the bacteria resulting in clear areas of the lawn, called plaques. A count of the number of plaques indicates the density of the phage in the sample.

Some potential areas of concern were identified prior to commencement of the survey which related to:

(a) the variable mortality of the phage;

(b) the stability of the phage within the underground environment;

(c) the phage's capacity for adsorption into the environment;

(d) practical problems of cross-contamination between sampling and analysis.

Factors (a)–(c) were tested for in bench mark tests prior to the start of the survey. These samples were also used as control samples during the survey period. Factor (d) could be largely overcome by ensuring that the personnel used to carry out the dosage injection were different from those taking the water samples. Only factor (c) remained as an unknown quantity, since the technique had never been attempted in this type of environment.

The survey

A scheme was agreed with the Severn Trent Water Authority (STWA) in December 1987 to carry out the analysis of water samples and to provide the necessary phage. Since the phage is highly specific in its relation to the host it was possible to use two different strains of phage host (*Serratia marcesens* and *Estereichia Coli*) in conjunction, without affecting their isolation and individual identification. The tracing exercise would require monitoring of the same potential flow paths and makes of water but in two consecutive operations without cross-contamination.

The first injection of phage into the inspection manhole at The Connection was made on 11th January 1988, when 500 ml of phage specific to the host *Serratia marcesens* (at a concentration of 5.6×10^{12} pfu/ml) was used. This would establish whether a flow path existed along the N.W. loco road to West Cannock 5's pumping shaft via the 9850' Horizon.

Since an obstruction was thought to exist along this route, only low velocities of water were expected. It was considered prudent to "flush" water regularly through The Connection pipe. As a result, approximately 1136,500 l/week (250,000 gallons/week) were diverted along the loco road.

Daily samples of mine water (500 ml bottle) were taken at West Cannock 5's discharge point and on Littleton No. 2 Horizon. Samples were collected and stored in refrigerated conditions at the colliery before being collected for weekly analysis by STWA. A study of the pumping figures for the schemes appeared to indicate a free flow from The Connection to West Cannock 5's pumping shaft.

A single positive phage trace was recorded on 5th February 1988, from the West Cannock 5's sample which was subsequently assumed to be a rogue result caused by contamination. In view of the seemingly inordinate delay it was thought that the tracer could have been missed if it had flushed through in the first few days. Alternatively, it was possible that the phage was trapped in the loco road due to a combination of an obstruction, a lower than expected flow rate, the ebb and flow effect of discontinuous pumping and dilution of the phage by dispersion. It was therefore hoped that by repeating the injection with an increased dose that detection would be accomplished. For this reason a further 1000 ml of the same phage strain at a similar concentration level was added into the inspection manhole at The Connection on 9th February 1988. Additionally, on 11th February the pumping levels at West Cannock 5's were raised to reduce the spasmodic pumping periods. Subsequent samples of West Cannock 5's discharge water were taken from a large collection barrel sited immediately beneath the outflow pipe. This allowed a proportion of the daily discharge to be contained for sampling.

Sampling for the first tracing survey was halted in April 1988 and preparations were made for the second survey. This involved the injection of a different phage strain directly into the base of West Cannock 5's shaft. Samples of water were then taken at The Connection, No. 2 Horizon and Mid Cannock pumping station.

The maximum pumping level at West Cannock 5's was raised to 36.6 m B.O.D. to permit the following:

(1) To prove the effectiveness of the flow along the N.W. loco road. At a level of 37.5 m B.O.D. water should reverse its flow from West Cannock 5's to The Connection.

(2) To prove that the arrangements at The Connection could handle the maximum anticipated flows whilst still retaining the option of recommencing pumping at West Cannock 5's shaft.

(3) To increase the head of water on the Valley loco road "dam" to 10 m and at the No. 1 Crosscut stopping to 7 m, thus testing their effectiveness.

(4) To observe the rate of rise of water in West Cannock 5's shaft from sump level to the reverse flow level (critical level) of 37.5 m B.O.D.

Following cessation of pumping, the critical level was reached in only 1 week. The original estimate was 30 days, which therefore appeared to confirm an underground blockage. As a result it was agreed to pump West Cannock 5's shaft water down to sump level in order to introduce the second phage tracer, then allow the water level to rise and flush the phage away from the shaft. In the second trace, 750 ml of phage specific to the host bacterium *Estereichia Coli*, at a concentration of 7×10^{13} pfu/ml was introduced on 19th April 1988. Due to the depth of the shaft (220 m) and the ingress of Trias water from the shaft wall, the tracer could not be poured directly from the surface, instead the phage had to be lowered into the base of the shaft before releasing it. Following trials of various devices the most successful method consisted of an eccentrically weighted plastic container which spilt out its content only when it hit the water. The container was in turn lowered by a graduated cable from the shaft top. Daily samples were then taken at The Connection, No. 2 Horizon and Mid Cannock.

On 25th April, an increase of water into the inspection manhole at The Connection was seen on the CCTV monitor. This was subsequently proved to be coming from the direction of West Cannock 5's shaft. By 27th April, the pump at West Cannock 5's remained standing and water continued to flow towards The Connection.

From the behaviour patterns of the water flow between 19th and 27th April, it appeared that any roof fall along the N.W. loco road had been breached or surmounted. This would help explain why the phage from the first tracing exercise failed to reach West Cannock 5's shaft. If all the water previously pumped at West Cannock 5's had now made its way to The Connection, the existing arrangements at Littleton had proved capable of handling the increase. This amount of water would only have to be dealt with during treatment of West Cannock 5's shaft until the Trias water had been sealed. Thereafter the quantity would reduce to the volume of the West Cannock 5's outbye underground water make. In order to determine whether West Cannock 5's water was flowing to any other location, a further phage trace specific to *Estereichia Coli* was injected into West Cannock 5's pit bottom on 5th May 1988. The water then rose to reach critical level by midday on 11th May, when water was noted to be flowing into The Connection manhole. On 17th May, positive phage traces were detected in the samples taken on Littleton No. 2 Horizon. The phage was identified (*Serratia marcesens*) as that injected into The Connection in January/February 1988. This was subsequently confirmed by further positive samples taken on 18th May at both No. 2 Horizon and The Connection. On 23rd May a sample of West Cannock 5's water also revealed traces of the initial phage, a total of 139 days survival time.

The first positive phage traces from the shaft injection were detected on 26th May at the following locations:

(1) West Cannock 5's discharge point;
(2) The Connection;
(3) Littleton No. 2 Horizon.

This proved the suspicion that water would find its way onto No. 2 Horizon despite there being no evidence of an increase in water make along that Horizon.

Water sampling continued for some weeks to discount the possibility of a flow path to Mid Cannock. Despite repeated positive results at all other locations, no trace was found at Mid Cannock. It can be assumed that either all the phage had been missed in the samples or that an insufficient head of water was exerted on the Valley loco road "dam".

Conclusion

Further deterioration of the shaft wall at the base of West Cannock 5's shaft was observed in the video camera survey carried out when the minimum sump level was reached. This increased the desire to establish an alternative course of action to pumping at that shaft. The tracing survey had established:

(1) Water flow from The Connection to West Cannock 5's pumping shaft via the N.W. loco road and 9850' Horizon and the reverse.

(2) Water flow from West Cannock 5's pumping shaft to No. 2 Horizon via 9850' Horizon and No. 1 Crosscut.

(3) No connection for water from West Cannock 5's to Mid Cannock.

(4) The suitability of bacteriophage tracing in an underground mining environment.

From the results of the tracing survey it was concluded that the resultant extra water flow at The Connection could be accommodated with only minor amendments to pipework. Proposals for the closure of part of No. 2 Horizon would require the incorporation of drainage provisions for the small quantity of West Cannock water. As a consequence, a decision was taken to seal and treat the West Cannock 5's pumping shaft. Works were commissioned in July, 1988. Following successful completion of the works, pumping at Littleton and Mid Cannock was continued without difficulty and in the knowledge that the water flow is controlled by an efficient and effective scheme.

Acknowledgements

The author wishes to thank members of British Coal and Severn Trent Water Authority staff and his former colleagues for their valuable contributions and permission to publish this paper. The views expressed are those of the author and are not necessarily those of British Coal.

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