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Technical Article

Mine Water Tracing – A Tool for Assessing Flow Paths in Flooded Underground Mines

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Abstract. A tracer test developed for hydrodynamic investigations has been successfully tested in German underground mines and the results of one of those tests are reported on here. The objectives of the test were to investigate the kind and rate of flow within a flooded mine. At each sampling point, coloured spores were injected using a *Lycopodium* apparatus. Beginning one day after injection, two samples were collected per weekday at each sampling point. A considerably good recovery rate of 2 % was obtained. The mean velocity of the mine water within the investigated part of the mine was 2.6 m min^{-1} and the different parts of the mine proved to be hydraulically well connected with each other. It appears that the hydrodynamic system within the flooded mine is dominated by convective flow from deeper parts of the mine to higher ones.

Key words: abandoned underground mine, Erzgebirge, Germany, Harz, hydrogeology, *Lycopodium clavatum*, microspheres, tracer test, Wismut GmbH

Introduction

Mining can cause significant ground or surface water pollution (Allan 1995; Singh et al. 1995; Veselić 1995). Major problems in the mining industry include acid mine drainage (AMD), the dissolution of heavy metals, which occurs during and after operation (Harries 1990; Salomons et al. 1995), and the prediction of mine water rebound (Younger and Adams 1999). Different control options have been used to minimize remediation costs and the impacts of mining on the environment. These generally focus on either ameliorating the problem at its source or manipulating the path of the water (Loxam 1988). Fernández-Rubio et al. (1987) and Garga et al. (1983) have discussed possible ways of reducing the source by installing technical barriers. Examples related to manipulations of the path are described by Amacher et al. (1993), Koopman and Rash (1990), Sobolewski et al. (1995), Heyne (1995) and Banks et al. (1997).

Sammarco (1995) describes some of the difficulties in evaluating the hydrodynamics of flooded mines. Few tracer test studies in flooded mines have been published. Most of those that have been published were oriented to either pollution of the aquifer or radioactive waste disposal and not the mine water itself (Skowronek and Zmij 1977; Abelin and Birgersson 1985; Kull 1988; Nordstrom et al. 1989; Cacas et al. 1990; Sumioka 1991; Birgersson et al. 1992; Horn et al. 1995). Investigations in flooded mines were described by Merritt and Angerman (1972), Goldbrunner et al. (1982), Aldous and Smart (1987), Davis (1994), Wolkersdorfer et al. (1997a, b) and Wolkersdorfer and Hasche (2001).

This paper deals with an in-situ tracer experiment conducted in 1995 at the abandoned and flooded Niederschlema/Alberoda uranium mine in Saxony/Germany. It describes a method for conducting tracer experiments in highly contaminated mine water using a specialized tracer probe. The results of the test provide possibilities for optimising remediation methodologies, as for example, using the test results to determine the best location for dams to control mine water flow. In this paper, only the technical details and results are summarized. A more detailed description of preparation and sampling methodology can be found elsewhere (Käß 1998; Wolkersdorfer et al. 1997a, b).

The test case

The Niederschlema/Alberoda uranium mine is located 28 km southwest of Chemnitz in a densely populated area of Saxony/Germany. It is nearly 2000 m deep and consists of 62 main levels with 54 shafts connecting the different levels of the mine. The length of the mine workings totals 4150 km with a total volume of $36 \cdot 10^6$ m^3 (Büder and Schuppan 1992; Gatzweiler and Meyer 2000). Detailed descriptions of the geological setting and the hydrogeochemical conditions can be found elsewhere (Schuppan et al. 1994; Wolkersdorfer 1994; Wolkersdorfer 1996b; Meyer et al. 1998). Remediation plans for the Niederschlema/Alberoda mine include treatment of the discharged water as soon as the water table reached the Markus-Semmler dewatering adit, which originally was scheduled for 2003 (Bundesminister für Wirtschaft 1993; Gatzweiler and Mager 1993; Gatzweiler and Meyer 2000), but occurred in 2000. This illustrates how difficult it is to define in advance the hydrogeochemical, thermal, and hydrodynamic processes that will occur during the flooding of a mine. In fact, after three years of hydrogeological investigations (hydrogeochemical analyses and physico-chemical measurements) in the Niederschlema/Alberoda mine, it was unclear why the chemical composition of mine water was very similar, even in very distant shafts and depths. Therefore, the main objective of the tracer test described in this paper was to investigate the kind and rate of flow within a large part of the flooded Niederschlema/Alberoda mine. The working model for the development of the tracer test, based on the results of the hydrogeological investigations, was that there is convective flow within the shafts and that all shafts are hydraulically connected through the adits. On the basis of a first tracer test in mid-1992 (Wolkersdorfer 1996a), a second test was conducted at the end of 1995.

The dyed-spore tracing method

Different methods can be used for tracing the movement of water, including the dyed-spore tracing technique (Gardener and Gray 1976; Käß 1998). After comparing the advantages and disadvantages of each method (Table 1), the dyed-spore tracing technique with *Lycopodium clavatum* (club moss) was chosen for the Niederschlema/Alberoda mine. Coloured microspheres have also been used successfully as tracers within flooded underground mines (Käß pers. comm; Wolkersdorfer and Hasche 2001).

Lycopodium was first described as a tracer in the Austrian Dachstein-region (Mayr 1953) and is commonly used in karst water tracing (Käß 1998). Although the fundamentals of this procedure are well established, the main problem is to avoid contamination of the water during injection or preparation of spores. Unfortunately, the method described by Dechant (1976) and Dechant and Hacker (1986), who injected the spores by the use of a spore-suspension, is unsuitable for exact injection in specified depths of flooded shafts in an abandoned mine. In addition, the sampling procedures and *Lycopodium*-nets described in the literature (Maurin and Zötl 1960) proved to be unsuitable within the mine as the plankton nets that are usually used for collecting spores, were blocked by suspended material and affected by microbacterias within few days (Wolkersdorfer 1996a). Therefore, a new tool and technique had to be developed: the ***Lycopodium*-A**pparatus (LydiA) method.

method	disadvantages
radioactive isotopes	isotopes already in the radioactive mine water could interfere with the tracers injected; the use of tritium (^3H) could prevent age determination of the mine water; permit by authorities in question
dyes	interaction between dye and mine water observed
salts	huge amounts of salts necessary as mine water is already loaded with most ions that could be taken into account; density effects could disturb the hydrodynamic situation
solid tracers	Special pumps and filters necessary; time consuming counting

Table 1. Disadvantages of the tracer methods taken into account for the Niederschlema/Alberoda tracer test

Description of the LydiA method

Two components constitute the LydiA method: the *Lycopodium*-apparatus and the filter system, both of which are suitable for the rough conditions of a mine. The *Lycopodium*-apparatus is a particularly constructed probe that hermetically encloses the mechanical tracer. It is lowered with a cable winch to the appropriate depth and remains there during the whole duration of the test. LydiA can be filled with the dry tracer in the laboratory and then injected into the water unopened, so that contamination by the tracer is prevented (Figure 1). A chemical lock and the makeup of LydiA ensure that the tracer will be completely released into the mine water in 6-48 hours, depending on the mine water temperature (30 °C: 6-10 hours; 12 °C: ca. 48 hours). Out of eight in-situ-tests and eight laboratory tests, the chemical lock failed to open only twice, when the operator assembled the probe inappropriately due to changed experimental conditions. During these tests it could be shown, that LydiA and the dry filling of the spores prevents clumping of the tracer at the moment of its release into the water. Over and above, only minor floating of spores could be observed. Thus, the use of LydiA avoids two negative characteristics of spore tracer tests: clumping and floating.

Suspended material in mine water blocks the commonly used nets described by Bauer (1967) in quite a short time (Wolkersdorfer 1996a). Consequently, a filter-installation for preventing the nets from blocking was developed. This filter system consists of three plastic pipes and two square nylon nets fixed between them. Both nets (mesh sizes: 335 µm, 30 µm; Hydrobios Kiel) have side lengths of 270 mm. To obtain adequate test results, the nets and

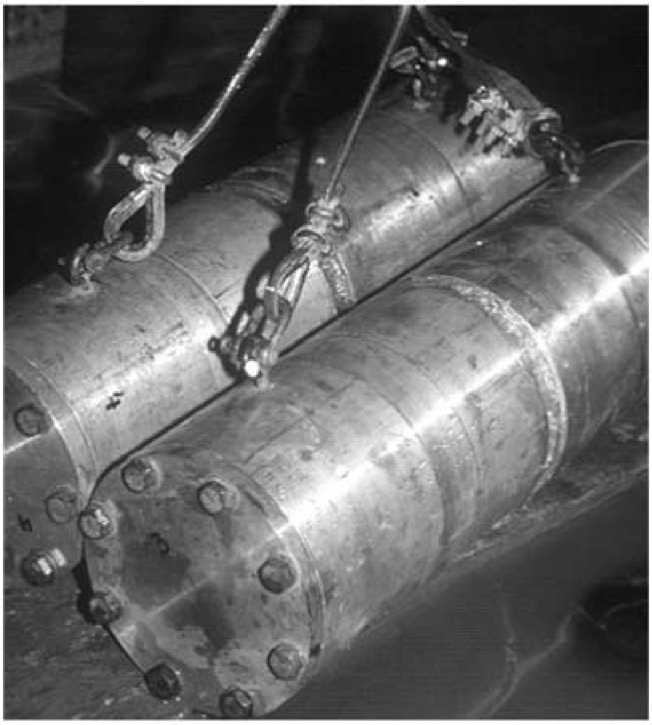

Figure 1. Photograph of two LydiAs before being lowered into a flooded shaft. The chemical lock can be seen in the middle of each LydiA

the filter system have to be cleaned, removed, and collected on a regular basis. None of the fine nets were used twice: this eliminates contamination due to inadequate cleaning of the nets.

The 1995 tracer test: implementation

Preparation of *Lycopodium clavatum*

For the tracer tests, six non-fluorescent dyes were chosen, although the use of fluorescent spores would have reduced the time for the counting of spores significantly (Käß 1982). Unfortunately, due to spectral overlaps, no more than three fluorescent colours can be used in a single test (Smart and Smith 1976; Käß and Reichert 1986). Another disadvantage is that fluorescent dyes might be destroyed by the chemical composition of the mine water (van Berk, pers. comm). Preparation and colouring of spores with azo dyes (Table 2) were conducted based on procedures described by Brown and Ford (1971), Käß (1998), and our own work. Results of investigations by the German Umweltbundesamt clearly show that coloured spores or microspheres are non-toxic (Arbeitskreis "Human- und ökotoxikologische Bewertung von Markierungsmitteln in Gewässern" 1997).

Dye	C.I.	Injection point	Injection depth	Injected mass, g
safranine T	50240	296 II b	-639 mNN	805.3
malachite green	42000	366 b	-639 mNN	722.6
nile blue A	51180	371	-652 mNN	804.2
crystal violet	42555	383	-397 mNN	764.0

Table 2. Details of the *Lycopodium* spores injected. Due to a failure of the crystal violet probe, the crystal violet tracer was injected 2 m below the mine water surface. mNN: meters above sea level; C.I.: Colour index

A question that must be addressed before conducting a tracer test is the amount of spores needed for best results. Various formulas are given by Käß (1998), all of which are suitable for an open water system with one or more swallets or springs (Brown and Ford 1971; Atkinson et al. 1973), but not for a more or less closed system in a partly flooded mine with active water pumping. The following empirical formula gives a good approximation of the spores needed for a tracer test in a quasi-closed system (the formula given in Wolkersdorfer et al. [1997a,b] is faulty, as r stands in the denominator instead of the numerator):

$$m = \frac{1}{55000}\frac{V \cdot r}{q}$$

where m: total mass of spores, g; V: volume of enclosed fluid, m³; r: recovery rate of spores, % (2-5 %); and q: pumping capacity, L min^{-1}; units of constant: L g m^{-3} min^{-1}.

Installation of LydiA

Four injection and two sampling points were chosen for the 1995 tracer test, and the sampling points were equipped with mini-piston-pumps (Pleuger Mini-Unterwasserpumpe, Pleuger Worthington GmbH/Hamburg; Figure 2). Injection and sampling points were selected to cover as much of the mine water system as possible. The aim of the tracer test was to find the reason for the chemical similarities in even distant shafts and to test the reliability of the bulkheads installed. Therefore, based on the conceptional hydrodynamic model of the mine, the injection points were chosen to be as far apart as possible and in one case (shaft 383) separated from the overall flow by bulkheads at each level. At the injection points, each LydiA was carefully mounted and slowly lowered into the shaft to the pre-selected depth.

Unlike conventional injection techniques in karst water tracing, the successful injection with the LydiA method cannot be observed directly. Successful opening of the chemical lock can only be determined at the end of the tracer test. However, LydiA is now equipped with a clock to precisely determine its opening time.

Sampling and sample preparation

The sampling interval depends on such factors as sediment load (Gardener and Gray 1976), estimated flow rate, distance between injection and sampling points, the mine's operational sequence, and costs. Therefore, the intervals range from 0.5 to 48 hours and very few general recommendations can be given (Atkinson 1968; Gardener and Gray 1976; Hötzl et al. 1976; Maurin and Zötl 1960; Smart et al. 1986; Wolkersdorfer et al. 1997a). However, based on the experiences of the 1995 tracer test described here, a test in the Straßberg/Harz mine in Germany in 2000, and in the Georgi Unterbau mine in Brixlegg, Austria in 2001, sampling intervals of at least 12 hours (2 samples a day) are needed for a reliable interpretation.

All the *Lycopodium*-nets have to be rinsed and carefully stored in plastic bags or glass containers. Due to the high amount of Fe-oxihydrates and suspended material, EDTA (Idranal 2, Merck) as suggested by Käß (1998), was added prior to filtering and counting. Unfortunately, if too large an amount is used, EDTA forms small, long crystals, covering the filters after drying, which seriously interferes with the mechanical counting process. No interference of the spores with the Fe-oxihydrates was observable and has also not been described in the cited literature. For the Straßberg and Brixlegg tests, therefore, oxalic acid was used instead, giving excellent results.

After drying, the filters (8 µm cellulose nitrate filters, 50 mm ∅; Sartorius/Göttingen) were fixed between 2 glass plates and provided with a grid for counting the spores. Two persons should do the aliquot counting of the filtered samples to minimize errors in colour recognition and to improve the statistical significance of the aliquot counting. In future tests, the time consuming manual counting of the particle tracers must be improved by automatic image recognition and/or laser induced scanning microscopy.

Results

The results of the 1995 tracer test are presented in Figure 3 and Table 3. Spores of each injected colour

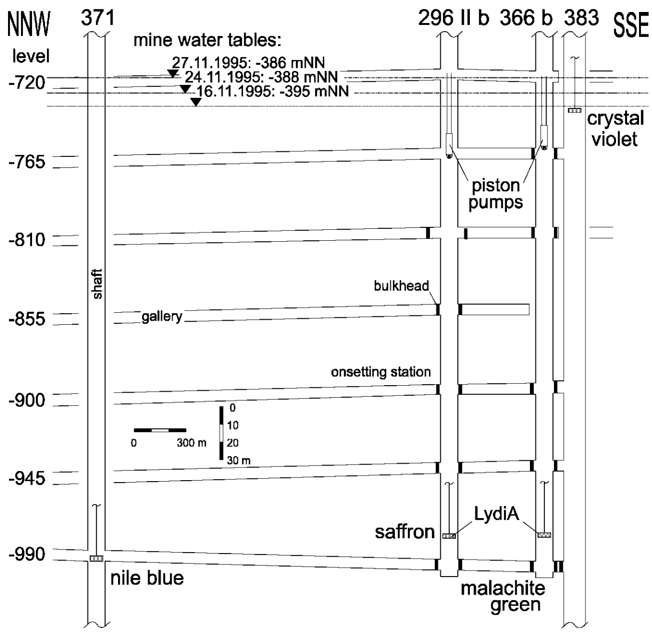

Figure 2. Geometric details of the 1995 tracer test in the Niederschlema/Alberoda mine. Only a small portion of the mine in which the tracer test was conducted is shown. mNN: meters above sea level; the levels are given in meters below the main dewatering adit (Markus-Semmler-Adit). Sampling points: piston pumps; injection points: nile blue, saffron, malachite green, crystal violet. Due to a failure of the crystal violet probe, the crystal violet tracer was injected 2 m below the mine water's surface

reached the sampling points, indicating the proper opening of the chemical lock and a hydraulic connection between the 4 injection and 2 sampling points. Even from shaft 383, which should have been separated from the rest of the mine by bulkheads, tracer reached the sampling points, indicating a malfunction of the bulkheads. The recovery rate was about 2 % (2367 spores safranine T, 3956 spores malachite green, 2622 spores nile blue A, 7708 spores crystal violet).

As evidenced by two blind samples, which contained small amounts of coloured spores (296 II b: n = 123, 366 b: n = 384), contamination could not be completely eliminated (Wolkersdorfer et al. 1997a). Fortunately, there were significant differences between the number of spores in the blind samples and the first set of test samples (296 II b: n = 1346, 366 b: n = 2134, Table 3). Therefore, it was possible to evaluate the results and calculate the velocity of the mine water (Schulz 1992) flowing through the flooded shafts and adits, based on an opening time of 8 hours for LydiA. The maximum velocities (first tracer arrives at sampling point) range between 0.5 and

8 m min^{-1} and the average velocities (maximum of the tracer distribution) between 0.1 and 0.8 m min^{-1}. Each of the maximums belongs to an injection and sampling point were the tracer mainly had to flow through adits, whereas the minimums correspond to passages were the tracer mainly flew up- or downward through a shaft.

Based on the test results, the following mine water velocities can be calculated: in the adits, a maximum of 8 m min^{-1} and a mean of 0.8 m min^{-1}; in the shafts, a maximum of 0.5 m min^{-1} and a mean of 0.1 m min^{-1}. The overall average of the maximum mean velocity in the flooded mine is calculated to be 2.6 m min^{-1}.

Conclusions

The tracer test with *Lycopodium clavatum*, carried out in the Niederschlema/Alberoda uranium mine, proved that the injection and sampling techniques ("LydiA method") can be used in the rough conditions of an underground mine. Nevertheless, good results can only be obtained after intensive hydrogeological investigations. Eventually, the test proved that there is a good hydraulic connection between the shafts and adits and indicated that convective flow is actively transporting the contaminants.The method is also a good means for evaluating hydrodynamic conditions in a mine. Thus, prior to the planning of remediation strategies or numerical simulations, the LydiA method is a relatively cheap and reliable tool for decision making. Over and above that, the method may be used to characterise the water flow in underground water storage systems.

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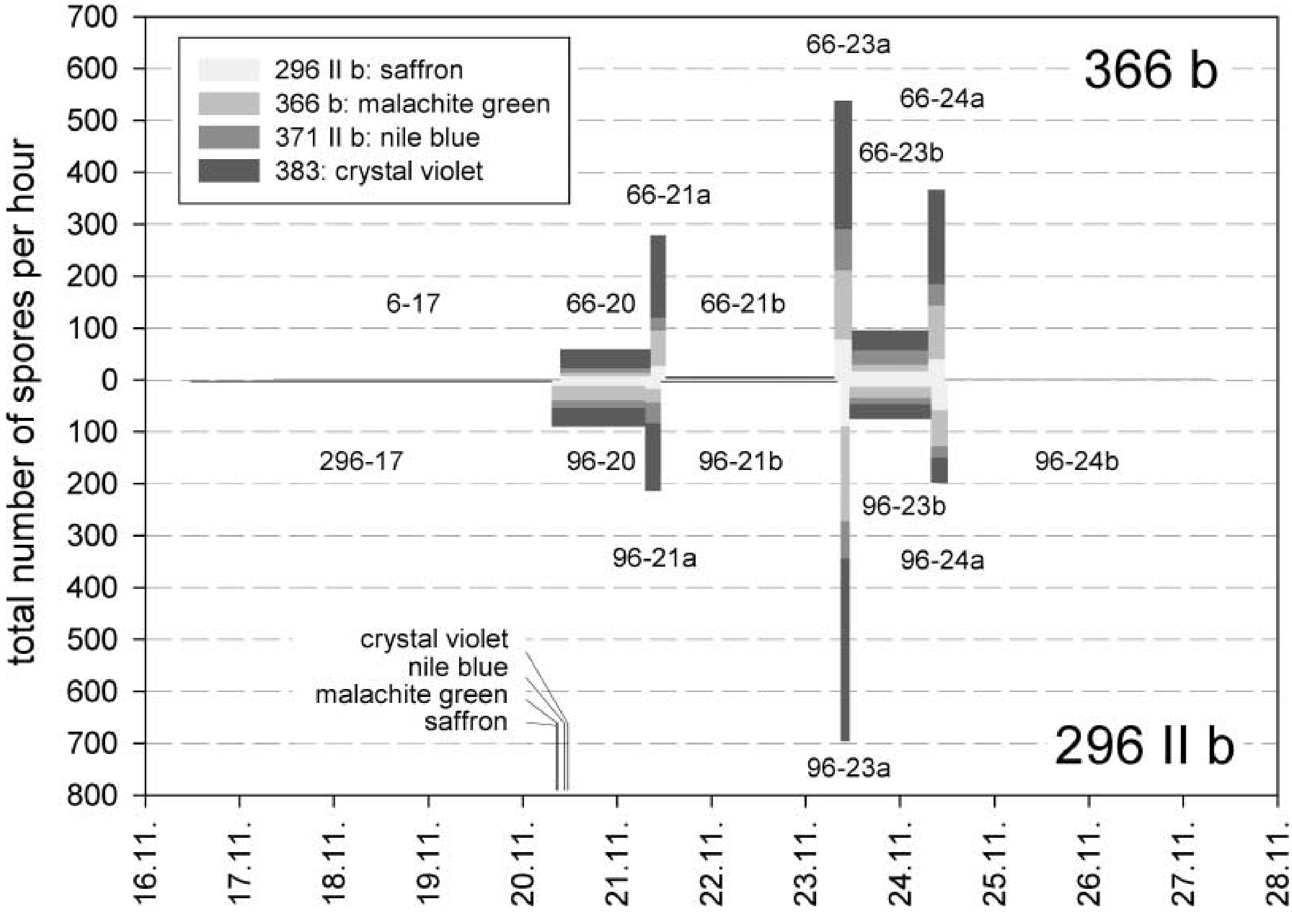

Figure 3. Results of the 1995 tracer test in the Niederschlema/Alberoda mine given in spores per hour for the whole duration of the test. The width of each box represents the sampling interval. Also shown, between the 20th and the 21st, are the injection times of the four LydiAs

Sampling point	sample	safranine T 296 II b	malachite green 366 b	nile blue A 371	crystal violet 383	pumping time, hours
296 II b	296-17	1	26	24	72	72:54
	96-20	174	160	188	824	22:50
	96-21a	96	244	82	564	3:32
	96-21b	60	80	40	106	42:58
	96-23a	354	598	358	1112	4:30
	96-23b	322	254	522	752	19:16
	96-24a	172	452	180	784	4:20
	96-24b	38	12	16	38	67:45
spores, sum		1217	1826	1410	4252	
Distance, m		216	776	2159	736	
366 b	6-17	30	30	132	192	91:59
	66-20	260	670	352	852	23:47
	66-21a	70	100	164	518	3:59
	66-21b	28	58	34	82	44:54
	66-23a	254	526	206	1008	2:52
	66-23b	266	454	230	602	20:44
	66-24a	242	292	94	202	4:12
spores, sum		1150	2130	1212	3456	
Distance, m		780	220	2723	172	
spores, total		2367	3956	2622	7708	—

Table 3. Results of the Niederschlema/Alberoda tracer test for all injection and the two sampling points. Given are the numbers of spores counted in each sample and the total of all spores as well as the pumping times (this equals the sampling intervals) as well as the distances between injection and sampling points

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