Tracer Tests in flooded underground mines

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Key words: tracer test; mine water; abandoned underground mine; microspheres; *Lycopodium clavatum*, club moss spores; Wismut GmbH; Straßberg mine, Niederschlema mine

ABSTRACT: Tracer tests are a common means to investigate the hydrogeological conditions in the hydrosphere. Nevertheless, only few successful tracer tests in flooded underground mines have been described. In two flooded German underground mines tracer tests with club moss spores (*Lycopodium clavatum*) and microspheres had been conducted by the use of the LydiA technique. Both times, effective velocities between 1 and 8 m min^{-1} could be calculated and a good hydraulic connection between the mines' parts investigated could be proved.

1 INTRODUCTION

Tracer tests in groundwater hydrology are a common tool to evaluate groundwater flow, transport processes, recharge and mixing processes, or sources of contamination (Käss 1998). Numerous tracer tests in the past proved the methods, tracers and tools to be reliable and, after careful investigation of the hydrogeological situation, are broadly accepted by both, scientists and authorities (Pascaly 1997).

Though, tracer tests have been widely used in aquifer investigations, only few cases are known, where tracer tests in flooded underground mines had been conducted. Yet, the negative impacts of acid mine drainage or drainage of heavy metals from flooded mines can be tremendous (Younger & Adams 1999, Geller 1998, Baake & Degner 2000, Harries 1990; Ellison 1994). Therefore, especially in Germany, the need for reliable tracer techniques in underground mining became aware at the same time as the flooding of many large East German underground mines began 10 years ago. In the meantime, two EU research projects (PIRAMID, ERMITE), take advantage of the knowledge gathered in Germany. While PIRAMID, prior to installing passive treatment systems, needs knowledge of the decreasing pollution load after mine flooding, ERMITE needs reliable tools for establishing regional guidelines based on European Mine Water Regulations.

This paper briefly describes two artificial tracer tests in East German underground mines and compares the results of both tests. The 1995 test was conducted in one of the deepest European underground mines: the Niederschlema/Alberoda Uranium mine; the 2000 test took place in the GDR's most important flourspar mine: the Straßberg/Harz mine.

2 AIMS AND SCOPES OF TRACER TESTS

All tracer test are used to evaluate the flow regime within porous, fissured or karstified aquifers. One of either, the connectivity between injection and sampling points or the velocity of ground water mostly are to be investigated by the means of artificial tracer tests (Käss 1998). Compared to mine waters, ground water is usually low in mineralisation and lacks of aggressive substances that could destroy artificial tracers. Therefore, a broad range of tracers can be uses for artificial tracer tests (Arbeitskreis "Human- und ökotoxikologische Bewertung von Markierungsmitteln in Gewässern" 1997, Käss 1991, 1998, Aley & Fletcher 1976, Davis 1994 b).

In flooded underground mines, the conditions compared to ground water tracing being different, similar demands on tracer tests are made: evaluation of flow velocity, connectivity, and mass transport

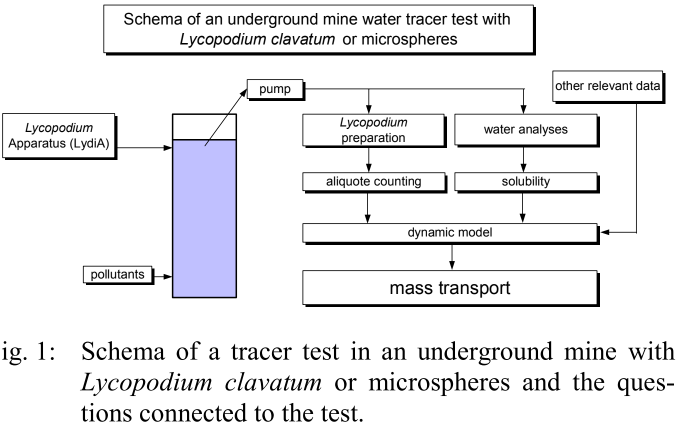

Fig. 1: Schema of a tracer test in an underground mine with *Lycopodium clavatum* or microspheres and the questions connected to the test.

(Fig. 1). On the whole, a flooded underground mine can be compared to a karstic aquifer. Therefore, the trace techniques used and the problems discussed there, should apply here as well. Whereas in karst water tracing, both, injection and sampling points are close to the water table, the tracers in underground mines usually should be investigated as deep as possible under the water table and sampled close to the water table.

Due to the mine water's chemistry at the Niederschlema/Alberoda mine (Wolkersdorfer 1994, 1996) and the Straßberg mine (Winkler 2001, Hasche 2001) only a small range of artificial tracers could be used.

By establishing a new tracer technique (LydiA technique), it was possible to fulfil the demands on an underground tracer test and to overcome most of the problems described by Dechant (1960).

Whilst in the Niederschlema/Alberoda mine, dyed club moss spores (*Lycopodium clavatum*) were used, microspheres proved to be a reliable tracer for mines water investigation at the Straßberg site.

3 PREVIOS TRACER TESTS IN UNDERGROUND MINES

3.1 *Literature review*

As already stated by Davis (1994 b), "significant literature on the use of tracers" for mine water related problems is hard to locate. From the 57 papers listed in his bibliography, none especially deals with mine water tracing. To our knowledge, one of the first tracer tests within an underground mine was published by Skowronek & Zmij (1977). Goldbrunner at al. (1982) conducted a tracer test within an alpine magnetite mine, Aldous & Smart (1987) in a coal mines and Davis (1994 a) within a lead zinc mine. A possible reason for this small number of published mine water tracer tests might be, that many tracer tests in underground mines were not or only partly successful (Davis, 1994 a). Not before 1996 a technique was described to trace mine water in flooded underground mines (Wolkersdorfer 1996). Since then the previous methods had been improved and published elsewhere (Wolkersdorfer et al. 1997 a, b, Wolkersdorfer & Hasche 2001). So far, successful tracer tests in flooded underground mines were conduced in the Niederschlema/Alberoda mine (1994, 1995), the Königstein mine (1999, pers. comm. Käss) and the Straßberg/Harz mine (2000). In all these tests solid tracers (club moss spores, microspheres) were used due to the chemical composition and/or acidity of the mine water investigated.

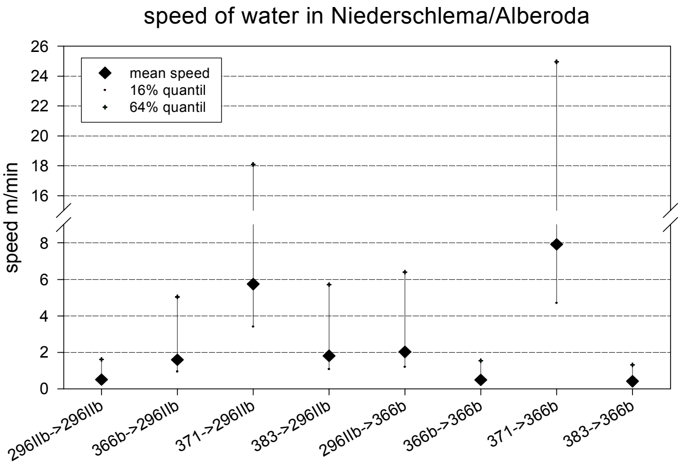

Fig. 2: Mean speed of the flooding water in the Niederschlema/Alberoda mine calculated for each injection and sampling location.

3.2 *Niederschlema Test case*

3.2.1 *Objective*

45 years the Niederschlema/Alberoda Uranium mine had been operated by the SDAG/GmbH Wismut to produce Uranium. Located 28 km south-west of Chemnitz/Saxony, the mine was under the deepest European mines (2000 m deep) with some 50 shafts and 50 working levels. The total length of the workings sums up to 4150 km and the mines volume to $36 \cdot 10^6$ m³ (Büder & Schuppan 1992, Meyer et al. 1998). Due to economic and political reasons the mine's flooding began in January 1991 and will be finished in 2003 (Gatzweiler, & Meyer 2000).

After intensive laboratory studies, a first tracer test with coloured club moss spores (*Lycopodium clavatum*) was conducted in 1992. This test, due to a lack of experiences in underground mine tracer tests, followed the procedures used in karst water tracing as summarised in Wolkersdorfer et al. (1997 a, b). Though tracers were found in the samples, the method used proved to be unsuitable in the rough conditions of an underground mine: the filter nets were blocked quickly by suspended matter and the wooden frame destroyed by microbial activities. Therefore, the method had to be improved and, finally, resulted in the 1995 tracer test. At the four dif-

Tab. 1: Mean composition of the mine water in the Straßberg mine during the time of the tracer test (May 30th—July 27th 2000) in mg L^{-1}. Li: < 0.1 mg L^{-1}, NO_3: < 0.5 mg L^{-1}; *n*: total number of samples analysed.

Shaft	*n*	Na	K	Ca	Mg	Fe	Mn	Cl	SO_4	HCO_3	F
No 539	15	22	2	56	21	21	12	28	198	64	5
Flour	11	15	2	140	29	22	6	17	387	77	8
Glasebach	9	14	5	178	32	10	13	17	385	184	7

ferent locations within the mine tracers were injected and sampled thereafter at two places at the mine water's surface. A total of 3096 g of spores were used (nile blue A: 804.2 g; safranine T: 805.3 g; malachite green: 722.6 g; crystal violet 764,0 g) by lowering the *Lycopodium*-Apparatus (LydiA) to the predetermined depths.

3.2.2 *Results and conclusions*

Within a 10 day period a total of 15 samples were collected and the tracers analysed after sample preparation in the laboratory. An estimated recovery rate of 2 % was obtained and 16,653 spores found in the filter nets. Based on the 15 %, 50 %, and 84 % quartiles of the travelling time, a mean velocity of 1…8 m min^{-1} could be calculated (Fig. 2).

From the tracer test's results it became clear, that all investigated parts of the mine were hydraulically well connected and that the bulkheads seem to be hydraulically ineffective. Furthermore, the test revealed that the similar chemical composition of mine water in far apart shafts is due to a good convective mixing of the mine water.

3.3 *Straßberg/Harz test case*

3.3.1 *Objective*

Similar to Niederschlema/Alberoda, the Straßberg flourspar mine (Fig. 3) stopped mining in 1991, due to economic and environmental reasons. Today, the mine is owned by the GVV (Gesellschaft zur Verwahrung und Verwertung von stillgelegten Bergwerksbetrieben mbH; Company for remediation and utilisation of abandoned mines Ltd; Kuyumcu & Hartwig 1998) and conventional water treatment is used to clean the water to reasonable standards.

On May 31st 1991, by stopping the drainage water pumps, the Straßberg and Glasebach underground pits started to be flooded. Between July 1992 and August 1998, accompanying in-situ temperature and conductivity measurements within the No 539 shaft and the Fluor shaft (310 and 147 m deep, respectively), clearly showed that a stratification within the water body was taking place (Kindermann 1998, Rüterkamp & Messer 2000). In the Fluor shaft, 3 water bodies, being separated from each other at the 2nd (328 mHN) and 5th (243 mHN) levels, established. Only 2 water bodies, separated by the 4th (357 mHN) level, could be recognised in the No 539 shaft. Evidence for the stratification were differences in temperature, conductivity, and metal-concentrations between each of the water bodies, the uppermost always low, the lowermost with an increased contamination by iron, manganese, and sulphate. Mean values for the mine water during the tracer test are given above (Tab. 1).

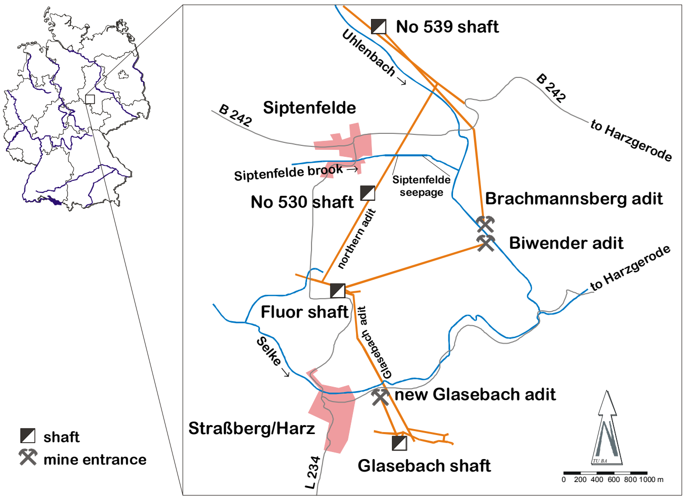

Fig. 3: Location of the Straßberg mine in the eastern Harz mountains and its main galleries and shafts.

As the water has to be treated, the best location for the treatment plant has to be established. Especially in the view of a decreasing water pollution, a passive water treatment plant becomes an interesting alternative to conventional treatment. Currently, near the Fluor shaft, a pilot passive treatment system is investigated and will be developed (Winkler 2001). From the chemical composition of the mine water, it was not clear, how the water flows within the three parts of the mine and were the source of the mine water's contamination could be. Therefore, and for predicting the future mine water composition, a tracer test (Tab. 2) had to clarify the hydrodynamic situation. Furthermore, on the tracer test's results the final position of the treatment plants will be chosen.

3.3.2 *Results and conclusions*

Club moss spores were only detected at the Fluor shaft and the Glasebach shaft. Based on the ratio of the water pumped and the water flowing out of the

Tab. 2: Injection points, depth in shafts, and injection times of the 6 tracers used. Add 40 hours to the times marked with an asterisk, as LydiA (*Lycopodium* Apparatus) opened approximately 40 hours later.

Injection points (depth)	Tracers	Quantity	Injection time
No 539 shaft (92 m)	microspheres „blue“, 15 µm	40 mL	June 5th: 14:44 *
No 530 shaft (ca. 20 m)	microspheres „orange“, 15 µm	40 mL	June 5th: 9:50—10:13
Fluor shaft (247 m)	microspheres „red“, 15 µm	40 mL	June 5th:12:18 *
Fluor shaft (247 m)	spores „malachite green“	264.9 g	June 5th: 12:18 *
Fluor shaft (247 m)	spores „saffron coloured“	279.5 g	June 5th: 12:18 *
Glasebach shaft (4 m)	microspheres „green“, 15 µm	40 mL	June 5th: 8:11 *

three shafts, the recovery rate is as high as 6 %.

Within the Flour shaft, 2.5 days and 6 days after tracer injection significant tracer peaks can be seen (Fig. 4). The maximum is reached very quickly, whilst the peaks are tailing out within 2 days. From the injection point to the water's surface, the spores have to flow 238 m, thus the mean effective velocity calculates to 0.1—0.2 m min^{-1} (Tab. 3).

In the Glasebach shaft, 10.5 days after tracer injection a clear peak exists and another, smaller one, only 3 days after tracer injection. Between the injection point in the Fluor shaft and the detection point in the Glasebach shaft, the tracer had to travel 3.180 m at the shortest pathway. Taking into consideration the two peaks and the shortest travel distance, the mean effective velocity calculates to 0.2—1.2 m min^{-1} (Tab. 3).

From the microspheres injected in the No 539, No 530, Fluor, and Glasebach shaft, only the microspheres from the No 530 and Fluor shaft could be detected, the recovery rate being nearly 100 %. It cannot be excluded that the LydiAs lowered into the No 539 and Glasebach shaft did not open properly due to a blockage by the shaft installations.

In the Fluor shaft, microspheres from the Fluor shaft arrived 1 day and from the No 530 shaft 13 days after tracer injection. As already observed, the peak sets in very quickly and tails out within 1.5 days. Based on the shortest distances of 238 m and 1,773 m, the mean effective velocities are 0.1—0.2 m min^{-1}.

Only Microspheres from the No 530 shaft could be detected at the Glasebach shaft 13 days after tracer injection. All the other microspheres, including those injected into the Glasebach shaft itself, could not be found abundant enough to draw useful conclusions. As the distance between the No 530 and Glasebach shafts is 4,798 m, a mean effective velocity of 0.3 m min^{-1} calculates (Tab. 3).

4 CONCLUSIONS AND OUTLOOK

Tracer tests in flooded underground mines are rare and the tracer injection and sampling techniques used are often insufficient. Due to ongoing mine closures all over the world, a reliable tracer technique, to investigate the hydrodynamic situation, estimate the mass transport and the pollution potential was essential. The LydiA technique proved to be an efficient method in the rough conditions of an underground mine and can be used to trace mine water.

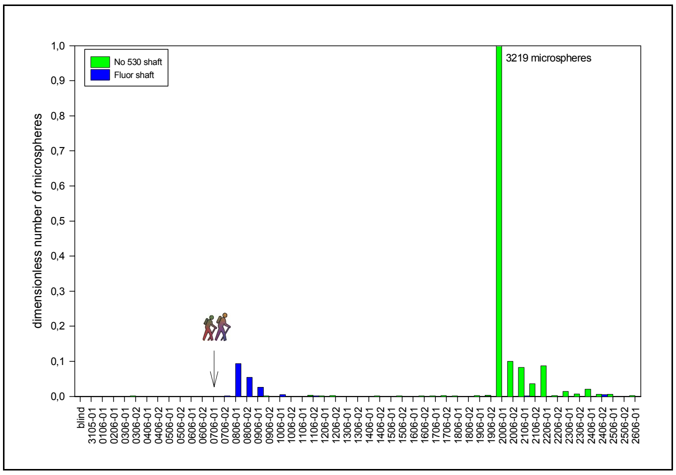

Fig. 4: Breakthrough diagram of the microspheres detected at the Fluor shaft. (max.: 3,219 microspheres). Arrow marks time of tracer injection.

Provided, that careful hydogeological investigations preceded the tracer test, the recovery rate of both, club moss spores and microspheres is high enough to find significant amounts of tracers. Based on the two tracer test carried out so far, it can be assumed, that mine water within the flooded part of a mine roughly has an effective velocity of around 1 m min^{-1}.

In future investigations, the counting of the tracers must be improved and the exact time of LydiAs opening be measured more precisely.

5 ACKNOWLEDGEMENTS

The author would like to thank the Wismut GmbH/ Chemnitz, the GVV GmbH/Sondershausen and the BST GmbH & Co KG/Mansfeld for their support. Thanks to R. Schecke, N. Feldtner, S. Meister, and A. Hasche for their counting of spores and microspheres! Support for the 1995 tracer test has been given by the DFG (German Science Foundation/Bonn) under contract Re 920/1-2 (Univ.-Prof. G. Reik, PhD). The 2000 tracer test was financially supported by the BST Mansfeld, the DFG Graduate School "Geowissenschaftliche und Geotechnische Umweltforschung" (speaker: Univ.-Prof. Dr. B. Merkel) at the TU Bergakademie Freiberg and the EU Project PIRAMID (contract no. EVK1-CT-1999-00021). This paper expresses the views held by the authors and does not necessarily

Tab. 3: Mean effective velocity of mine water in the Straßberg mine. No tracer from No 539 shaft could be detected anywhere.

from	to	tracer	velocity v_{eff}	distance
No 530 shaft	Flour shaft	microspheres	0.1 m min^{-1}	1,773 m
No 530 shaft	Glasebach shaft	microspheres	0.3 m min^{-1}	4,798 m
Flour shaft	Flour shaft	microspheres	0.2 m min^{-1}	238 m
Flour shaft	Flour shaft	club moss spores	0.1 m min^{-1}	238 m
Flour shaft	Glasebach shaft	microspheres	0.3 m min^{-1}	3,180 m
Flour shaft	Glasebach shaft	club moss spores	0.2—1.2 m min^{-1}	3,180 m

reflect those held by the Wismut GmbH, the BST Mansfeld, the GVV, or any authorities involved.

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