LydiA – A NEW METHOD FOR TRACING MINE WATER

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ABSTRACT

One of the largest Saxonian uranium mines, the polymetalic Niederschlema/Alberoda deposit in the Erzgebirge (Ore Mountains), has been flooded since 1991 due to economic and environmental reasons. As only little was known about the hydrodynamical, thermal and hydrogeochemical processes while flooding the mine, numerous consultant works have been done on these subjects. Even then the hydrodynamical conditions during the flooding have only been outlined in general.

Based on the results of a first tracer test with *Lycopodium clavatum* in mid 1992 a second one was conducted at the end of 1995. The objectives of the test were to investigate the quality and rate of flow within a large part of the flooded mine to predict the mass flow of the pollutants. Hence four insertion and two sampling points were chosen. At each sampling point coloured spores were inserted by using a newly developed insertion apparatus: LydiA (***Lycopodium*** **Apparatus**). Beginning one day after insertion, at each sampling point 2 samples per weekday were taken. Out of the samples an aliquot amount of material was counted and resulted in a reasonable good recovery rate of 2 %.

It could be shown, that the mean speed of the mine water within the investigated part of the mine ranges between 3 and 8 m min^{-1} and that the different parts of the mine are hydraulically well connected with each other. Therefore it is highly assumed that the pollutants within the flooded mine are transported by convective flow resulting in a transport from deeper parts of the mine into higher ones.

The newly developed insertion and sampling technique was successful and can be used for similar test elsewhere.

INTRODUCTION

As a consequence of mining the surroundings of a mine undergo severe anthropogenic changes by which the ground- or surface water might be polluted (Allan 1995, Singh et al. 1995, Veselič 1995). Environmental, economic or political reasons may cause the closure of underground or open pit mines all over the world which often results in the treatment of mine water.

One of the main problems in the mining industry are acid mine drainage (AMD) or the drainage of heavy metals, which occurs during and after operation (Harries 1990, Norton 1990, Salomons et al. 1995). For minimising the remediation costs and the impacts on the environment, different control options have been developed and successfully carried out. Applying the Source-Path-Target

Methodology, there are, asides removing the target which often cannot be taken into account, principally two control options: reducing the source or manipulating the path (Loxam 1988).

Fernandez-Rubio et al. (1987) or Garga et al. (1983) discuss possibilities of reducing the source by installing technical barriers, and examples relating to manipulations of the path are described by Amacher et al. (1993), Koopman & Rash (1990), Sobolewski et al. (1995), Norton (1992), and Heyne (1995). A remediation plan considering manipulations of the path to be the best solution for decreasing environmental impacts, be it a treatment plant or a wetland, can mostly be improved by options for reducing the source as well.

In the past, technical barriers in underground mines were put up considering safety guidelines or technical reasons (e.g. Scott & Hays 1975, Biaglow 1988, Banks 1994), because little was known about the hydrodynamic regime in the flooded mine. Sammarco (1995) describes some of the difficulties in evaluating the hydrodynamics of flooded mines. No case, to our knowledge, is reported, were tracer experiments in flooded mines were carried out to evaluate the optimal place for a technical barrier. Nearly all tracer tests linked to mine water problems were related to either pollution of the aquifer or radioactive waste disposal and not the mine water itself (Skowronek & Zmij 1977, Abelin & Birgersson 1985, Kull 1987, Nordstrom et al. 1989, Cacas et al. 1990, Sumioka 1991, Birgersson et al. 1992, Horn et al. 1995).

This paper deals with an in-situ tracer experiment at the abandoned and flooded Niederschlema/Alberoda uranium mine in Saxony/Germany. It describes a new method for conducting tracer experiments in highly contaminated mine water by the means of a tracer sonde (LydiA). The results of the test provide new possibilities for optimising the outcome of the Source-Path-Target Methodology and therefore diminish the costs of remediation strategies. As this paper deals with the advantage of the LydiA method for environmental studies in flooded mines, technical details and results will be outlined in general only. A more sophisticated description of preparation and sampling can be found in the literature (Käß 1992, Wolkersdorfer et al. 1997).

THE TEST CASE

The Niederschlema/Alberoda uranium mine is located 28 km south-west of Chemnitz in a densely populated area of Saxony/Germany. It has a depth of nearly 2000 meters and consists of 50 main levels with more than 50 shafts connecting the different levels of the mine. The length of the mine works sums up to 4150 km (Büder & Schuppan 1992) and the total volume to $36 \cdot 10^6$ m³. For 45 years the mine has been operated by the SDAG Wismut, a Sowjet-East German Company.

Following the mine's closure by the Government of East Germany in 1990, the controlled flooding of the mine began in January 1991 and will be completed as early as 2003. While the mine water circulates through the open mine works, it will be enriched in various elements, some of them being toxic to both, humans and the environment. Consequently, the up to date remediation plans for the Niederschlema/Alberoda mine include treatment of the discharged water as soon as the water table will reach the water-adit Markus-Semmler (Bundesminister für Wirtschaft 1993, Gatzweiler & Mager 1993).

At the beginning of the flooding only little was known about the hydrogeochemical, thermal, and hydrodynamic processes during the flooding. Hitherto numerous consultant works and a Ph.D. thesis have been undertaken on these subjects, but the hydrodynamic conditions during the flooding and within the water body have only been outlined in general (Wolkersdorfer 1996b, Merkel & Helling

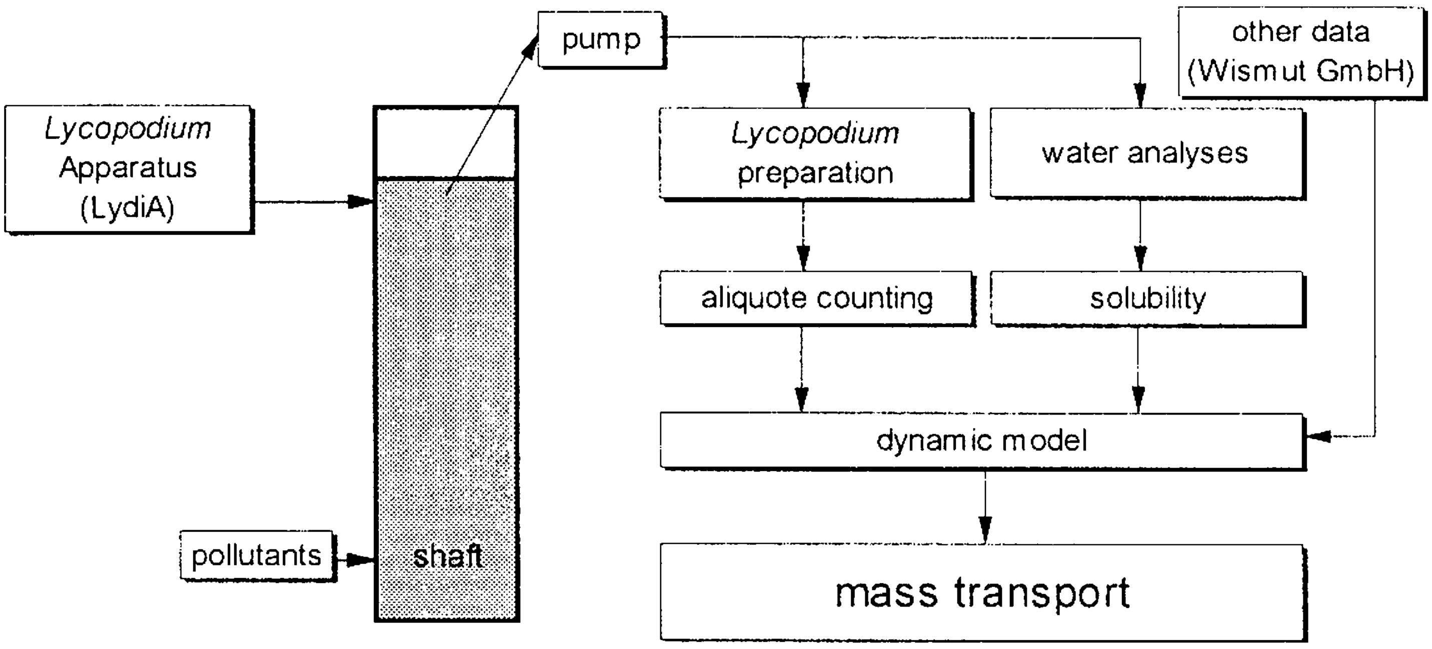

Figure 1: Schema of the tracer test with *Lycopodium clavatum* and the questions connected to the test.

1995). Main objective of the tracer test described in this paper was to investigate the quality and rate of flow within a large part of the flooded mine to predict the mass flow of the pollutants. Already in 1991 a tracer test was considered and the Wismut GmbH entrusted one of the authors (C.W.) with establishing a program for a tracer test, which will be suitable for the special conditions in the mine water (Figure 1). The working model for the development of the tracer test was, that there is convective flow within the shafts and that all shafts are connected hydraulically through the adits. Based on the results of a first tracer test in the mid of 1992 (Wolkersdorfer 1996b) a second one was conducted at the end of 1995.

Detailed descriptions of the geological setting and the hydrogeochemical conditions have been described elsewhere (Schuppan et al. 1994, Wolkersdorfer 1994, Wolkersdorfer 1996a).

THE DYED-SPORE TRACING METHOD

Many different methods can be used for tracing the movement of water. So far, the techniques conducted include dyes, chemicals, radioactive materials, bacteria, electrolytes, and mechanical tracers, thereunder the dyed-spore tracing technique (Gardener & Gray 1976, Käß 1992). Subsequent to comparing the advantages and disadvantages of each method, the reasons being more or less equal to those specified by Gardener & Gray (1976), the dyed-spore tracing technique with *Lycopodium clavatum* (club moss) was chosen to be applied in the Niederschlema/Alberoda mine.

This technique was first described for tracing karst water flows in the Austrian Dachstein-region (Mayr 1953) and is commonly applied in karst water tracing (Käß 1992). Although the fundamentals of this procedure, like colouring or recovering the spores, are well known, the main problem is to avoid contamination of the water during insertion or preparation of spores. One possible method for contamination free insertion is described by Dechant (1976) and Dechant & Hacker (1986), but it is unsuitable for exact injection in specified depths of flooded shafts in an abandoned mine. Over and above, the sampling procedures and *Lycopodium*-nets described in the literature (Maurin & Zötl 1960) proved to be unsuitable within the mine (Wolkersdorfer 1996b). Therefore a new tool and technique had to be developed: the *Lycopodium*-Apparatus (LydiA) method.

DESCRIPTION OF THE LydiA METHOD

Two components constitute the LydiA method: the *Lycopodium*-apparatus and the filter system, both being suitable in the rough conditions of a mine.

The *Lycopodium*-Apparatus is a particularly constructed sonde, which hermetically encloses the mechanical tracer. As an advantage, LydiA will be tracer filled in the laboratory and inserted into the water unopened, so that the water is to all prevented from being contaminated by the tracer. A chemical lock and the makeup of LydiA ensure that the tracer will be completely released into the mine water within 6…10 hours after its contact with the warm mine water (temperature: 35 °C). Out of four in-situ-tests and eight laboratory tests the chemical lock failed to open only once. As could be shown, the reason was a wrong assemblage of the sonde by the operator due to changed experimental conditions. Thus the reliability of the chemical lock is certainly higher than the observed 93 %. LydiA will be lowered with a cable winch to the appropriate depth and remain there during the whole duration of the test. Because the sonde will be patented, no more details on its design can be given here.

Compared to karst waters, mine waters contain high amounts of fine suspended material. Therefore, in karst water tracing, relatively untroublesome net constructions, even for long sampling intervals, are suitable. Nevertheless, it might be advantageous to install a coarser net (1…2 mm) in front of the fine *Lycopodium*-net (25…30 µm) to prevent the *Lycopodium*-net from being blocked or destroyed (Bauer 1967 cited after Käß 1992). Suspended material in mine water blocks the nets in quite a short time, as has been shown by the 1992 tracer test in the Niederschlema/Alberoda mine (Wolkersdorfer 1996b). Consequently a modified filter-installation had to be developed.

No matter, if the mine water will be actively pumped or flows out passively through a water adit, a filter system proved its worth. Based on experience and experiments a filter system with three plastic parts used in sewage disposal (DN 150, DIN 19534, DIN Deutsches Institut für Normung e.V. 1979) and two nylon nets fixed between them, was used. Both nets (335 µm, 30 µm) were quadratic in size with side lengths of 270 mm. To obtain adequate test results, the nets and the filter system have to be cleaned, removed and collected on a regular basis (Wolkersdorfer et al. 1997). None of the fine nets were used twice, therefore contamination due to inaccurate cleaning of the nets could be reduced to a minimum. Another reason for changing the nets at every sampling is, that under the rough conditions in the mine, cleaning of the *Lycopodium*-nets might be a problem and thus should be shifted to the laboratory.

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 reduces the time for the counting of spores significantly (Käß 1982). Unfortunately, as a case of spectral overlaps, no more than three fluorescent colours at one single test can be utilised (Smart & Smith 1976, Käß & 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 were conducted based on the procedures described by Brown & Ford (1971), Käß (1992) and own investigations.

A significant question before conducting a tracer test is the amount of spores needed for best results. Various formulas are given by Käß (1992), all of them being suitable for an open water system with one ore more swallets or springs (Brown & 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:

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

m: total mass of spores, g

V: volume of enclosed fluid, m^3

r: recovery rate of spores, % (not more than 2…5 %)

q: pumping capacity, L min^{-1}

So far, no reports are given on toxic effects of coloured spores (Käß 1992), however, investigations on possible health hazards are currently undertaken at the German Umweltbundesamt, Berlin (Umweltbundesamt 1996).

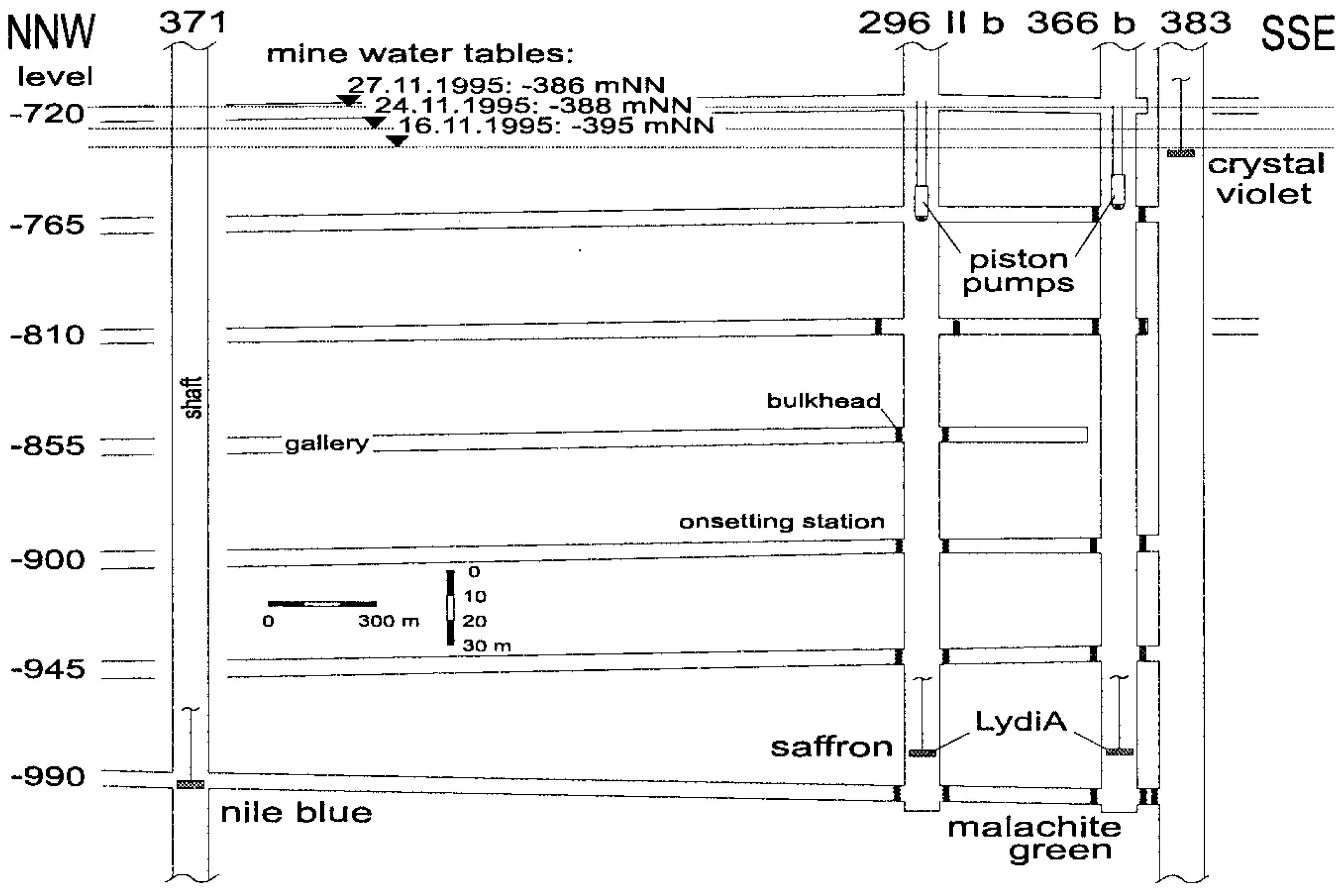

Figure 2: Geometric details of the 1995 tracer test in the Niederschlema/Alberoda mine.

Installation of LydiA

Four injection and two sampling points, the latter equipped with mini-piston-pumps (Pleuger Mini-Unterwasserpumpe, Pleuger Worthington GmbH/Hamburg), were chosen for the 1995 tracer test (**Error! Reference source not found.**). Injection and sampling points were selected to cover as much of the mine water system, as possible. At the injection points each LydiA was carefully fixed to a mount and slowly lowered to the pre-selected depth in the shaft.

Contrary to conventional injection techniques in karst water tracing, the successful injection with the LydiA method cannot be observed directly. Certainty of a successful opening of the chemical lock will therefore not be achieved until the end of the test.

Sampling and Sample Preparation

The sampling interval depends on a few factors like accuracy of determining arrival times, sediment load (Gardener & Gray 1976), estimated speed of the mine water, the mine's operational sequence, and the costs. Therefore the intervals range from 0.5 hours to 48 hours (Table 1) and hardly no general recommendations can be given. However, after the experiences of the 1995 tracer test in the Niederschlema/Alberoda mine, it seems reasonable to use sampling intervals between 4 and 8 hours (3 to 6 samples per day).

Table 1: Sampling intervals for tracer tests with the dyed-spore tracing method from different sources.

Sampling interval	Author
0.5 to 25 hours	Atkinson 1968
48 hours	Gardener & Gray 1976
6 to 24 hours	Hötzl et al. 1976
2 hours	Maurin & Zötl 1960
24 to 48 hours	Smart et al. 1986
3 to 44 hours	Wolkersdorfer et al. 1997

All the *Lycopodium*-nets collected during the duration of the 1995 tracer test (14 days; colours: safranine A, malachite green, nile blue, crystal violet) were rinsed and carefully stored in plastic bags. Due to the high amount of Fe oxides and suspended material, edetic acid (Idranal 2) as suggested by Käß (1992), was added prior to filtering and counting. After drying, the filters (8 µm cellulose nitrate filters, 50 mm ∅; Sartorius/Göttingen) were fixed between two glass plates and provided with a grid for counting the spores.

The aliquot counting of the 15 filtered samples was done by two persons, to minimise errors in colour recognition and to improve the statistical significance of the aliquot counting. From each filer two quarts were counted and the results for each colour recorded (Table 2).

Costs

Depending on the use of labour the costs for the workers are the main expenses for a tracer test. The following list is an overview of the costs estimate for the 1995 tracer test (14 days):

mine workers and scientific stuff:	21,400 ECU
stuff for counting of spores:	5,900 ECU
stuff for ding of spores and filling of LydiA:	1,000 ECU
sum stuff:	28,300 ECU
tracer and dyes:	200 ECU
net system:	360 ECU
tools for sampling:	380 ECU
4 LydiAs:	6,100 ECU
sum tools:	7,040 ECU
total:	35,340 ECU

As the counting of spores is very time consuming (approximately one day for a quart of a 50 mm filer), and needs experience, the stuff has to consist of skilled persons. These costs cannot be easily reduced by employing cheap workers, because the whole test relies on the accuracy of counting.

RESULTS

The results of the 1995 tracer test are summarised in Table 2 and presented in Figure 3. Spores of each injected colour reached the sampling points, therefore showing the reliability of the chemical lock. As suspected, the recovery rate was 2 %, consisting of 2367 spores, coloured in safranine T, 3956 in malachite green, 2622 in nile blue A and 7708 in crystal violet.

Evidenced by two blind samples, containing small amounts of coloured spores, contamination could not be fully omitted (Wolkersdorfer et al. 1997). Fortunately, there were significant differences between the number of spores in the blind samples and the first set of test samples. Therefore it was possible to evaluate the results and calculate the speed of the mine water (Schulz 1992) flowing through the flooded shafts and adits. The maximal speeds (first tracer arrives at sampling point) range between 0.5 and 8 m min^{-1} and the average speeds (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 with the passage between them dominated by adits, whereas the minimums correspond to shaft-dominated passages.

It can therefore be stated that the mine water in the adits flows at a maximal speed of 8 m min^{-1} and a mean speed of 0.8 m min^{-1}, the water in the shafts, however, at a maximal speed of 0.5 and a mean speed of 0.1 m min^{-1}. The overall average of the maximal mean speed in the flooded mine is calculated to be 3 m min^{-1}.

Spores from all the injection points reached the sampling sites within a relatively short time of less than 24 hours. **Error! Reference source not found.** shows, that on several onsetting stations bulkheads were constructed to prevent the mine water from circulating. The reason for these technical barriers was to stop the transport of contaminants from its sources in deeper parts of the mine into higher ones. As can be seen by the results of the tracer test, this control option is not effective because the bulkheads were either not correctly constructed or build up at unsuitable places. Furthermore, the test proved that there is a good hydraulic connection between the shafts and adits and the convective flow can highly be assumed.

Table 2: Results of the aliquot counting of the 1995 tracer test with *Lycopodium clavatum* in the Niederschlema/Alberoda mine. time: pumping time in hours and minutes, distance between sampling and insertion points in m.

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
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
sum		1150	2130	1212	3456	
distance, m		780	220	2723	172	
total	–	2367	3956	2622	7708	–

CONCLUSIONS

The tracer test with *Lycopodium clavatum*, carried out in the Niederschlema/Alberoda uranium mine, proved that the new insertion and sampling techniques (LydiA method) can be used in the rough conditions of an underground mine. Therefore the newly developed method is a good tool for evaluating proceedings deduced from the Source-Path-Target Methodology.

In the investigated mine it could be verified that the mean maximal speed in the adits and shafts is 3 m min^{-1} and that the bulkheads on the onsetting stations cannot effective stop the interchange of water. Furthermore, the active transport of contaminants by convective flow was confirmed. To prevent the transport of contaminated water into the anthroposphere and to make the planned treatment plant highly superfluously, the main vertical connections must be plugged as far as possible.

It could be shown, that the dyed-spore tracing method is applicable in tracing mine water and that the method is 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, where areas with no water movement shall be excluded.

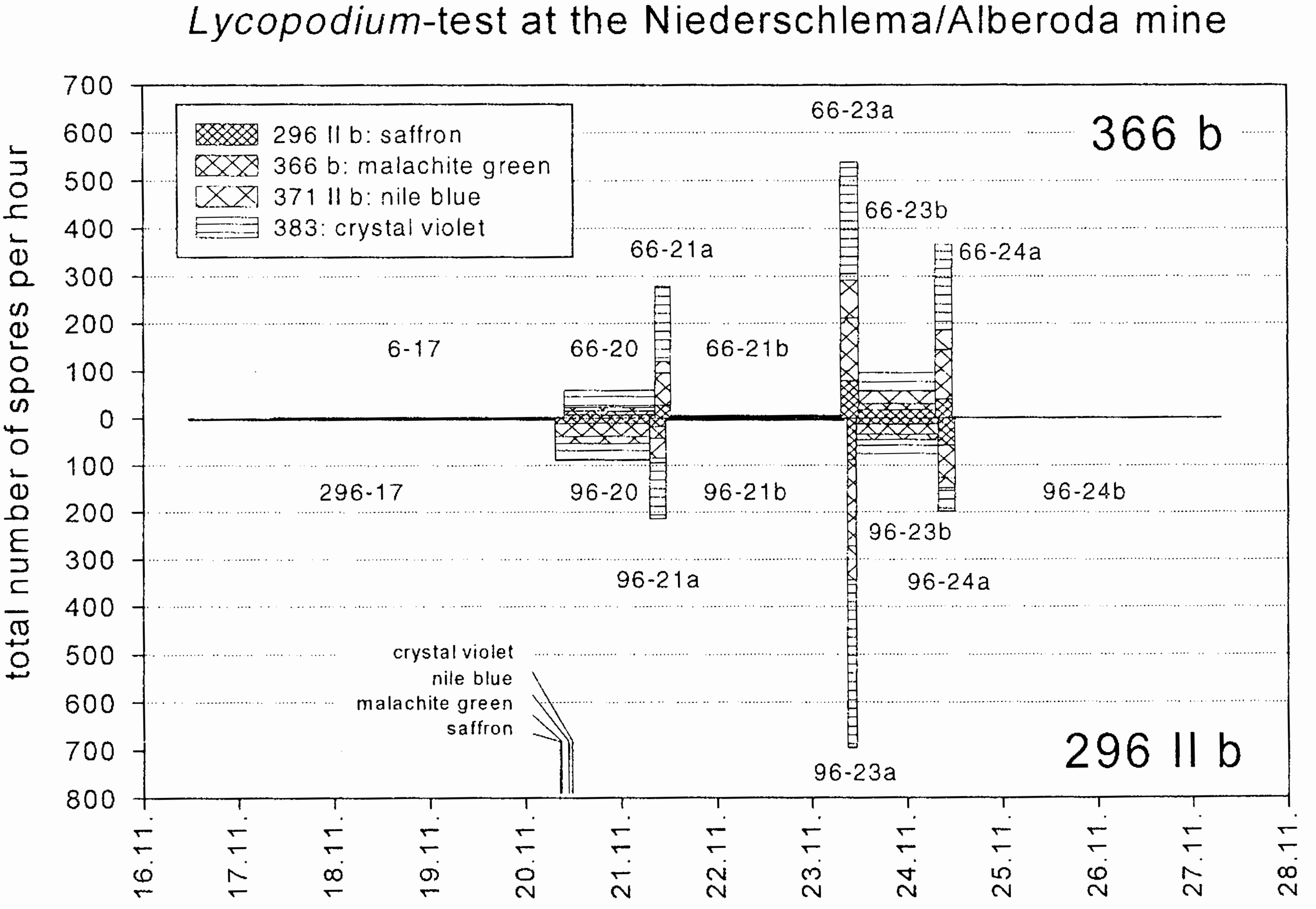

Figure 3: Results of the tracer test in the Niederschlema/Alberoda mine given in spores per hour for the hole duration of the test. The width of each box represents the pumping time as shown in Table 2. Also shown, between the 20th and the 21st, are the insertion times of the four LydiAs.

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