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MODELLING OF GEOTHERMAL RESOURCES WITHIN ABANDONED COAL MINES, UPPER SILESIA, POLAND

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ABSTRACT

The geothermal power potential of abandoned, water filled coal mines in the Upper Silesia region was evaluated by two different modelling approaches. The heat exchange between 20-40 °C warm water filling the typical mine and the surrounding rocks was simulated using the TOUGH numerical code and program HEAT MINE, developed specifically for this project. Sensitivity analysis shows that the geometry and depth of the mine as well as the thermal properties and permeability of surrounding rocks control the thermal power which may be obtained from the mine. Predictions of the temperatures decline in the mine reservoir, in response to heat extraction at the surface, were made assuming a total mine volume of 1,000,000 m^3 and an average radius of mine openings of 0.5 m. The predictions show that it should be possible to extract heat at a rate of about 20 MWt from the whole mine with a temperature decline of 7-8°C over a period of 50 years. The modelling indicates that a large amount of geothermal energy may be obtained from the coal mines of Upper Silesa in an economical and environmentally friendly way.

1. INTRODUCTION

Coal-mining is one of the most important branches of industry in Poland. The main Polish coal-field is located in the Upper Silesia region (South-central Poland, Figure 1), where coal is extracted from Upper Carboniferous deposits in 54 mines. Coal mining has been going on for many decades and some of the mines have already been closed down due to coal seams having been totally exploited. At present there are plans to shut down additional 6 coal mines before the year 2001 and in 36 coal mines exploitation will be partially discontinued (Figure 2). The abandoned mines are partially filled with sand during closing down procedures and flooded by water. Water in the underground spaces deep in the mines will, in a short time, approach the temperature of the surrounding rock massive,

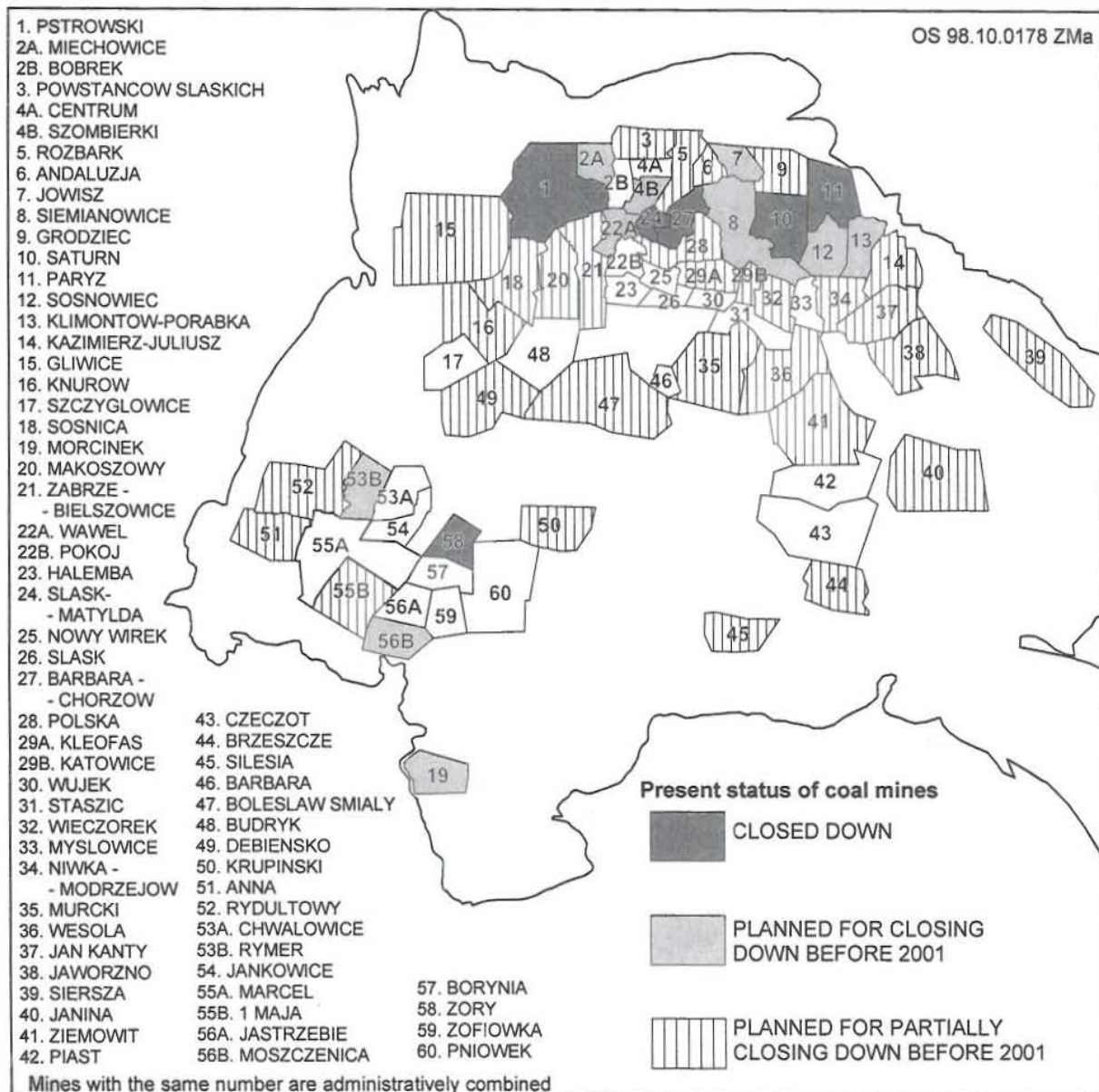FIGURE 1: Location map of the Upper Silesian coal basin in Poland

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1. PSTROWSKI			
2A. MIECHOWICE			
2B. BOBREK			
3. POWSTANCOW SLASKICH			
4A. CENTRUM			
4B. SZOMBIERKI			
5. ROZBARK			
6. ANDALUZJA			
7. JOWISZ			
8. SIEMIANOWICE			
9. GRODZIEC			
10. SATURN			
11. PARYZ			
12. SOSNOWIEC			
13. KLIMONTOW-PORABKA			
14. KAZIMIERZ-JULIUSZ			
15. GLIWICE			
16. KNUROW			
17. SZCZYGLOWICE			
18. SOSNICA			
19. MORCINEK			
20. MAKOSZOWY			
21. ZABRZE -			
- BIELSZOWICE			
22A. WAWEL			
22B. POKOJ			
23. HALEMBA			
24. SLASK-			
- MATYLDA			
25. NOWY WIREK			
26. SLASK			
27. BARBARA -			
- CHORZOW			
28. POLSKA	43. CZECZOT		
29A. KLEOFAS	44. BRZESZCZE		
29B. KATOWICE	45. SILESIA		
30. WUJEK	46. BARBARA		
31. STASZIC	47. BOLESLAW SMIALY		
32. WIECZOREK	48. BUDRYK		
33. MYSLOWICE	49. DEBIENSKO		
34. NIWKA -	50. KRUPINSKI		
- MODRZEJOW	51. ANNA		
35. MURCKI	52. RYDULTOWY		
36. WESOLA	53A. CHWALOWICE		
37. JAN KANTY	53B. RYMER		
38. JAWORZNO	54. JANKOWICE		
39. SIERSZA	55A. MARCEL	57. BORYNIA	
40. JANINA	55B. 1 MAJA	58. ZORY	
41. ZIEMOWIT	56A. JASTRZEBIE	59. ZOFIOWKA	
42. PIAST	56B. MOSZCZENICA	60. PNIOWEK	

Mines with the same number are administratively combined

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Present status of coal mines

CLOSED DOWN

PLANNED FOR CLOSING DOWN BEFORE 2001

PLANNED FOR PARTIALLY CLOSING DOWN BEFORE 2001

FIGURE 2: Distribution of coal mines in the Upper Silesia Region

which has an average thermal gradient of about 33°C/km. This volume of water is a potential source of low-enthalpy geothermal energy.

The Upper Silesia region is the most polluted area in Poland because of the coal-mining and steel industry. The Upper Silesia is also the most densely populated region in Poland due to the concentration of heavy industry located there. The region, therefore, needs cleaner energy sources. The abandoned mines are one of the possible sources of such energy. Filled with water and often located directly below cities and towns, they can take on a new role as a source of warm water in the Upper Silesian coal basin. Furthermore, coal mining is expected to expand to depths of 1000-1200 m underground in the near future. At such depths, the rock temperature varies between 38 and 50°C, and large-capacity cooling and airconditioning systems will be installed for removing heat from mine workings by air and water. This heat should be utilized at the surface.

This report evaluates the possibility of extracting heat from abandoned coal mines by calculating the amount of heat that can be extracted from the mines, taking into account the heat transfer between the mine water and the surrounding rocks. The report is only the first step towards determining the

feasibility of exploiting thermal energy from abandoned coal mines. Further investigation of the economic and technical aspects are necessary.
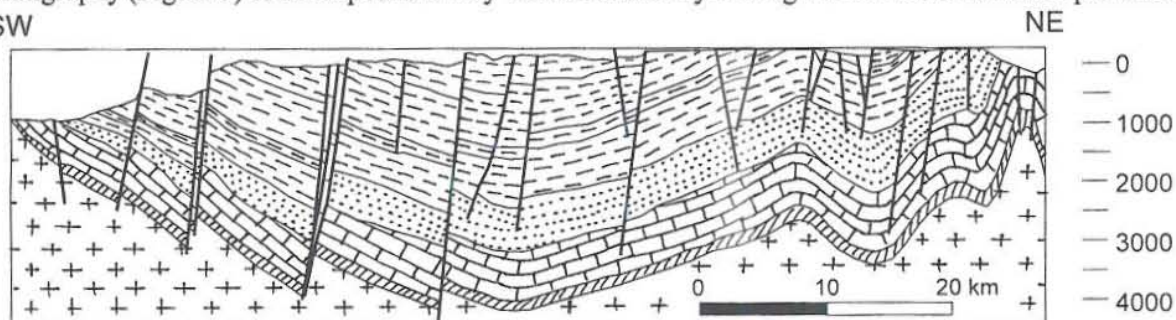
1.1 Previous applications

Geothermal heat in mines has been well known in Poland for many centuries. The first note was made in 1528 when the "Arch-bishop of Upsal" visited some Polish salt mines where he found that "the workmen were naked, because of heat" (Jessop, 1990). At the beginning of this century measurements of temperature were carried out in wells connected with coal mining in Upper Silesia, probably the first such measurements carried out in Europe (Karwasiecka, 1996).

In order to keep proper working conditions in a mine, the mine workings must be cooled by air, which is pumped out at the rate of thousands of cubic metres per minute. The air at the top of ventilation shafts has a temperature near 20°C during the cold season. This warm air could be used for space heating. In Polish mines, some experiments to using warm mine air for the heating of greenhouses and miner's bathrooms have been carried out in the past (personal communication, Gliwice coal mine staff). In that case, there was a problem with contamination in the air (methane, carbon oxide and carbon dioxide). At present, warm mine air at a temperature of about 20°C is used as an input source for heat pumps installed in one of the Polish coal mines.

Another example of utilization of heat from mines in heat pumps is reported by Jessop (1995) in Springhill, Nova Scotia, Canada. A flooded former coal mine at Springhill contains about 4,000,000 m^3 of water, which is recovered at the surface at a temperature of about 18°C. Water is drawn from the mine by several wells and reinjected into the mine at a certain horizontal distance as well as at a different depth. The maximum depth of the Springhill mine is about 1350 m and a maximum temperature of 26°C can be expected at the deepest levels in view of an average thermal gradient of 15°C /km. Energy capacity of all the water in the mine is estimated to be 250×10^{12} J or 70 GWh, assuming a temperature drop of 15°C. Water is used as input for heat pumps for heating and cooling industrial buildings. Thus, during the cold season heat energy is extracted from the mine, whereas during the warm season waste heat from the cooling of buildings is put into the mine. Therefore, the water in the mine acts as storage for heat energy. Estimates show that using the mines in this way can be economically competitive to using conventional sources of energy. There are also clear environmental benefits in reduced carbon dioxide emissions.

1.2 Geological setting

The Upper Silesian coal basin (USCB) is one of the units of the Paleozoic platform north of the European Alpine system. The coal basin was developed in Upper Carboniferous as coal-bearing sediments. The stratigraphy (Figure 3) of the deposits is very well examined by mining works and numerous exploration

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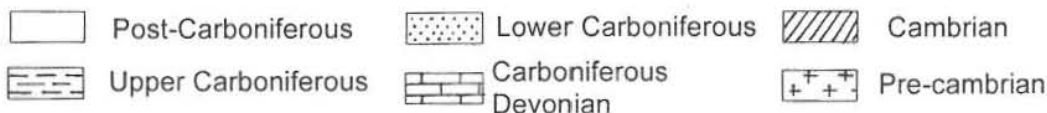| | Post-Carboniferous | | Lower Carboniferous | | Cambrian |
| | Upper Carboniferous | | Carboniferous Devonian | | Pre-cambrian |

FIGURE 3: Geological cross-section of the Upper Silesian coal basin (Kotas, 1995)

boreholes The hydrogeology and geothermics have also been investigated by the coal-mining industry. The basin consists of coal-bearing molasse deposited in a foredeep of the Moravian-Silesian foldbelt of the Variscian system (Kotas, 1995). The basin was subjected to strong subsidence which was compensated by an influx of clastic material. This was followed by folding of the basin at the onset of flysch deposition. The sequence of coal-bearing deposits, reaching 8,000 m in thickness, is divided into two parts. The lower part consists of paralic coal-bearing sediments, developing concordantly from marine siliclastic deposits and is called the Paralic series. The thickness of the series is variable and ranges from about 200 m in the eastern part of basin to nearly 3,800 m in the western part. The upper part of the coal-bearing sediments was deposited after a sedimentary break and is, in general, composed of continental deposits developed as three separate series.

Upper Silesian sandstone series: Sandstones and conglomerates are the main deposits in this unit, which reaches a thickness of 1100 m in the western part of the coalfield. Thick coal seams make up about 9% of the stratigraphic column.

Siltstone series: Fine grained sediments (siltstones, claystone) are about 80% of the series, which reaches a maximum thickness of 2,000 m and is reduced to nearly 150 m in the eastern part of the coal field. Coal seams constitute 5-7% of this unit.

Cracow sandstone series: Coarse-grained sediments (more than 70% of the series) with subordinate siltstones and thick coal seams. The maximum thickness of the preserved portion of the series is estimated to be about 1600 m.

The coal-bearing rocks of the USCB are mostly covered by younger deposits. Some outcrops occur only in the central part of the basin. The thickest (up to 1000 m) sedimentary cover is located in the southern parts of the area and consists mostly of claystones and siltstones with low permeability, formed during the Micoene. These deposits act as cap rock formations for the geothermal fluids in the sedimentary basin. In the southern part of the USCB, positive thermal anomalies have been identified beneath the Miocene cover.

The USCB is divided into three different tectonic units. The western part is a sub-meridian fold belt up to 20 km wide, with two major overthrusts and several different fold systems. The largest and central part of the basin is occupied by a tectonically disturbed zone which is characterised by normal and normal-transcurrent faults trending NNE-SSW and WNW-ESE with throws up to 1200 m. In this zone the strata dip 0-15° and form large wide folds. At the eastern border of the basin a block tectonic zone is localized.

The hydrogeological properties of the sedimentary rock formations within the USCB have been investigated as a part of an exploration research done for the coal mining industry. In the 2,200 m deep section investigated, several aquifers have been found, mainly in sandstones (Różkowski, and Wagner, 1988). The average porosity of the deep aquifers varies between 5 and 15% and the average permeability between 0.14 and 17 mD decreasing with depth (Table 1). Mineralization of water from Carboniferous aquifers is variable and depends on the depth of aquifers and the type and thickness of overlaying rocks. In parts of USCB without a thick cover of cap rocks, the mineralization of water is low and generally increases with the depth of the aquifers. In deep, closed aquifers under thick series of overlaying sediments, paleo-waters have very high mineralization and contain 40-250 g/dm^3 of chlorides.

TABLE 1:   Hydrogeological properties of Upper Carboniferous sandstones of the Upper Silesian coal basin (according to Różkowski and Wagner, 1988)

Formation depth range (m)	Porosity (%)		Permeability (mD)	
	min - max	average	min - max	average
Cracow sandstone series, 700-1000	1.07 - 28.86	14.64	0.05 - 208.59	16.46
Siltstone series, 610-1635	1.0 - 21.26	9.44	0.002 -77.0	1.337
Upper Silesian sandstone series, 1022-1860	0.05 - 16.17	5.31	0.001 - 5.1	0.177
Paralic series 1137-1967	0.05 - 15.19	4.98	0.002 - 2.5	0.143

2. GEOTHERMICS OF THE UPPER SILESIAN COAL BASIN (USCB)

2.1 Thermal properties

The temperature distribution within the USCB has been studied for the last 30 years because of its importance for mining operations. Temperatures within coal mines have a significant influence on the working conditions of miners underground, as well as on the thermo-mechanical properties of rocks around mine workings. The highest air temperature in mine headings allowed by Polish mining rules is 28°C, in order to ensure optimal working conditions. Underground temperatures in the USCB can be simply characterised by a geothermal gradient varying a few degrees from an average value of 33°C/km. On the basis of temperature logs, isothermal maps have been prepared at intervals of 250 m for levels between 250 and 1500 m below sea level (Karwasiecka, 1996) and areas of both positive and negative thermal anomalies have been identified. The positive anomalies have geothermal gradients of up to 40°C/km, whereas negative thermal anomalies have gradients of about 23°C/km.

FIGURE 4: Depth in m to a temperature of 40°C within the Upper Silesian coal basin

On the basis of published data, maps of depths to constant temperatures were prepared by the author in 1996. Figure 4 shows a map of the depth to a temperature of 40°C within the USCB. Temperature anomalies (both negative and positive) correlate with terrestrial heat flow measurements in the Upper Silesia region. Six measurement points of the terrestrial heat flow (Plewa, 1994) are in the range 54-74 mW/m². The highest values were measured in the southwestern part of the basin where temperatures are relatively high.

FIGURE 5: Heat conductivity of sedimentary rocks in the Upper Silesian coal basin

The main influence on the distribution of temperature in the USCB is the widely varying thermal properties (Figure 5) of the sandstones, siltstones, claystones and coal deposits. Sedimentary rocks exhibit different thermal properties in directions parallel and perpendicular to the stratification. This anisotropy can lead to a difference in heat conductivity in the range of 30%, measured in different
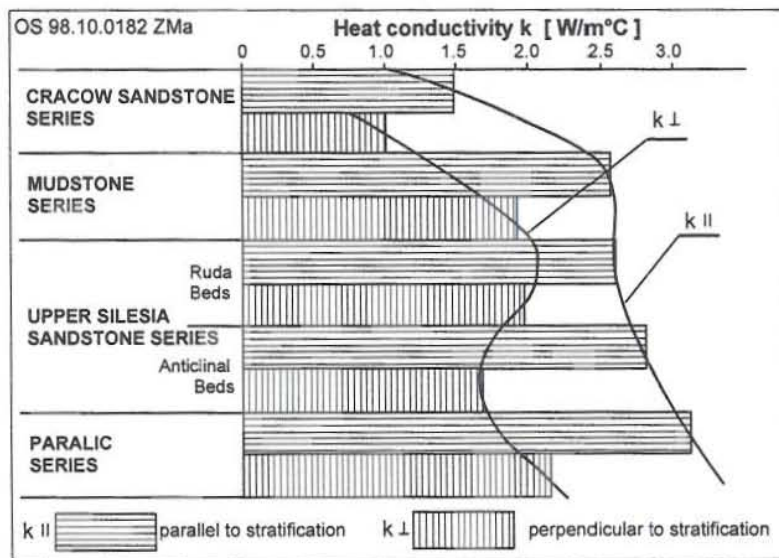
FIGURE 6: Average heat conductivities for lithological units of
Carboniferous within Upper Silesian coal basin
(Chmura and Chudek 1992)

directions. On the basis of these values and analysis of sedimentary profiles, the heat conductivity of lithostrati-graphical units has been evaluated (Chmura and Chudek 1992, Figure 6). The heat conductivity of sedimentary formations in the USCB rises with depth due to increasing geostatic pressure, rock temperature and increasing compaction and cementation of the rock.

Some anomalies can be observed in connection with tectonic features in the USCB. Faults act as zones of good vertical permeability and along them cold water infiltrates from upper aquifers. However, some upflow of warm water along other faults has also been observed.

2.2 Temperature measurements

Before geothermal potential of the mines can be modelled, the temperature conditions in the rocks surrounding the mines must be evaluated both in the natural state as well as during cooling by air ventilation. Temperature data from exploration boreholes as well as from the mines are available in the form of temperature logs and underground temperature measurement points (Figure 7). The accuracy and interpretation of both types of data is discussed below.

Regular temperature logging of exploratory wells has been carried out for many years in Upper Silesian coal basin. More than 600 wells have been logged, but only in a few cases to depths greater than 2000 m. The accuracy of the temperature measurements is variable and depends on the time allowed for temperature stabilization after drilling. This is in the range of 50-500 hours, with an average of 120 hours. In some cases, time allowed may have been insufficient for temperature conditions to become fully stabilized. Thus, temperature measurements in the form of continuous logs may have some errors.

FIGURE 7: Temperature logs and underground
temperature measurement points,
Upper Silesian coal basin.

In most of the coal mines, underground temperature measurements are carried out on a

regular basis. The temperatures are measured in order to detect hazardous temperature conditions, especially at exploitation levels deeper then 450 m. Isothermal maps of the undisturbed rock temperature are prepared for different levels of the mine, in order to predict the temperature increase of the mine air due to heat transfer from rock mass to the mine.

In order to measure the undisturbed temperature of the rock mass, underground temperature measurements are commonly carried out at freshly excavated mine walls. The optimal conditions for data collection are in the mine headings which usually progress faster than the cooling front in the rock mass can migrate. The temperature is measured with termistors after a few hours of stabilisation at the bottom of 2-3 m deep holes drilled perpendicular to the tunnel wall. Due to the short time allowed for stabilization, the accuracy of the data is only about 0.5°C. Additional experiments and tests have been carried out on automatic and continuous temperature measurements in the mine headings to enable permanent monitoring of temperature changes in rocks surrounding the mine workings (Chmura et al., 1992).

More than 2000 points of underground temperature measurements from the Upper Silesian coal basin were compiled by the author in the years 1997-1998. Temperature measurements will soon become available from mine levels excavated at deeper levels, up to 1000-1200 m.

On the basis of underground point measurements in a mine, a three dimensional temperature field can be determined. Figures 8 and 9 show the spatial distribution of point measurements and the interpolated temperature field for the Morcinek coal mine as an example.
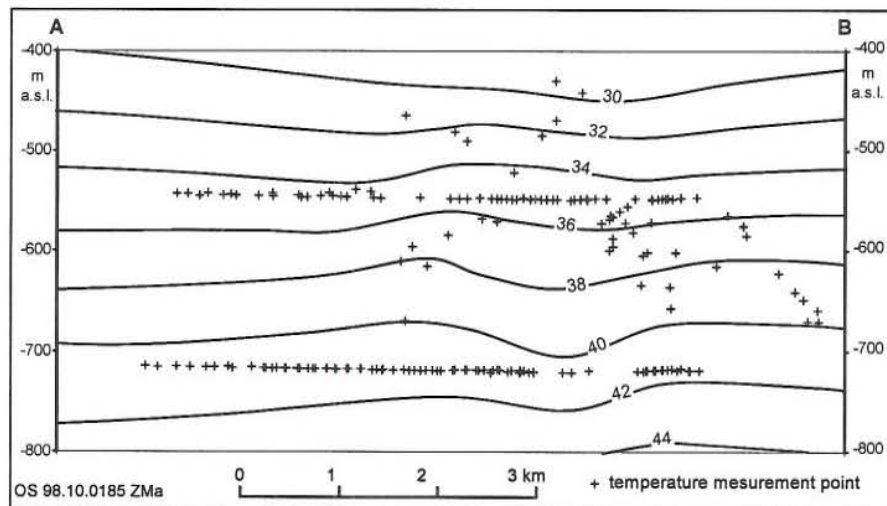

FIGURE 8: Temperature map at 720 m depth level in the Morcinek coal mine, Upper Silesia

FIGURE 9: Temperature cross-section through the Morcinek coal mine (location on Figure 8)

3. OVERVIEW OF UPPER SILESIA COAL MINES

3.1 Coal mining

At present coal is being extracted from the Upper Carboniferous formations in the area of USCB in 54 mines (Figure 2). The deepest coal seams being exploited are located at a depth of about 1000 m under ground. In the near future some of the mines will be deepened to depths of 1000-1200 m. The total amount of coal extracted in the USCB is 100 million tons per year, with an average value of 2 million tons per mine. Extraction of 2 million tons of coal per year leaves about 1.5 million m^3 of voids. The mine openings are treated in two main ways after excavation. One is simply to allow the spaces to collapse. When the supporting pillars have been removed the roof starts to cave in, and in a few weeks or months unsupported roofs reach the floor. A zone of cracks and fractures, up to about 5 times thicker than the extracted coal bed, is thereby created in the roof rocks. Another method is to backfill the openings with waste rock or sand for support. The filling material is compressed by the falling roof. This method is used to prevent subsidence at the surface. In either case the open spaces vanish and are replaced by a backfilled material forming aquifers of variable porosity and permeability. Coal mining is carried out using the longwall system in which coal is extracted at coal face ranging in length from several tens to several hundreds of metres. To support this mining system, it is necessary to dig a few kilometres of passages at each level as well as drifts, airways and water drainage tubes. In every mine there are several tens of kilometres of passages, which are protected against collapse by roof-supporting beams.

3.2 Water management

Water management is necessary to keep the coal mines dry. The water flowing into the mine from the surrounding rocks is collected by a net of drainage openings existing around exploitation levels and is pumped out of the mine. The total inflow of water to the mines in the USCB is estimated to be 952,000 m^3 per day (Goszcz and Rogoz, 1991) corresponding to an average value of about 220 l/s per mine. This waste water is removed by pumping and conveyed to the rivers. Since it has a concentration of NaCl of about 13 g/l, 12,400 tons of NaCl are released into rivers each day. The rate of water inflow varies from mine to mine, ranging from several thousands to hundred of thousands of m^3 per day, depending on the lithology of the surrounding rocks. The inflow is higher in sandstone-dominated formations than in claystone or siltstone-dominated formations. The water comes from deep aquifers as well as from shallow groundwater reservoirs and is mixed during the removal precesses. Thus, the temperature and mineral concentration of water measured at the surface gives average values. Several water temperature measurements were carried out by the author during visits to coal mines in USCB in 1996-1997. As an example, the water leaking from the tunnel wall at a depth 520 m had temperature 28°C and the waste water released to the river had a temperature of 20°C. This shows that part of the heat energy is removed from the mine with the water extracted.

3.3 Ventilation

Ventilation is used for cooling and airconditioning the mine passages as well as for removing methane gas from the mine. The ventilation system works by drawing air out of the mine through upcast shafts. The airflow enters the mine through exploitation shafts. During its course through the maze of mine openings it removes heat from the mine and its temperature rises to 20-28°C.

Approximately 60% of the total amount of heat energy released from a mine during the mining cycle is derived from surrounding rocks. The rest comes from mining machinery and electric power installations. The heat is transferred from the surrounding rocks to air in the tunnel by conduction and convection. Oxidation of coal and other minerals (mainly sulphides) is also an important source of heat in coal mines.

A simple estimate of the amount of heat energy that can be extracted from a coal mine system can be made on the basis of the temperature and volume flux of air drawn through upcast shafts. For example in the Staszic coal mine 60,000 m^3 of air are pumped out of the mine each minute. The average air temperature at the top of the ventilation shafts is 18°C. The average annual temperature of the air drawn into the mine is 9°C. The following equation can be used to estimate the heat energy:

$$Q = K c V \Delta T \qquad (1)$$

where K = Proportion of heat derived from the rocks, 0.6;
      c = Heat capacity of air, 0.0012 $MJ/m^3°C$;
      V = Flow rate of air, 1,000 m^3/s;
      ΔT = Temperature difference, 9°C.

The result is 6.5 MW. The total amount of heat extracted from the coal mines in the Upper Silesia area, which is consequently wasted, can be estimated by multiplying this value by the number of coal mines in the area.

During ventilation and cooling the air takes up heat from the tunnel walls and induces heat flux into the tunnel from the surrounding rocks. Complex heat transfer by conduction and convection occurs in the cooling zone around the tunnel, between the tunnel wall and undisturbed rock mass away from the tunnel. The radius of this zone depends on the temperature difference and time as

FIGURE 10: Temperature distribution around a mine working at 1030 m depth in the Halemba coal mine (Chmura et al., 1988)

well as the thermal properties of the rocks. Figure 10 shows an example of temperature distribution in the cooling zone observed at a depth of 1030 m in the Halemba coal mine (Chmura et al., 1988)
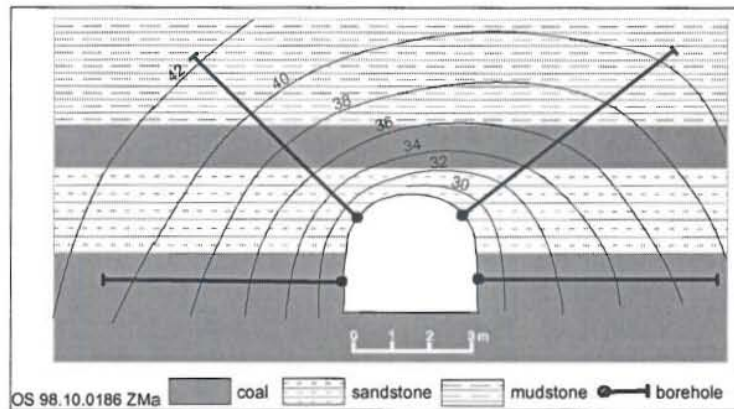
4. MODELLING OF GEOTHERMAL RESOURCES

Abandoned coal mines have a significant, but little studied, potential as a source of geothermal energy. This potential arises primarily from the heat energy stored in the rock formations surrounding the mine and not from the heat content of the body of water filling the mine after closure. This is easily demonstrated by a simple calculation in comparison to the amount of heat removed from the mine by ventilation (see above). In this calculation the water filling an abandoned mine with volume 1,000,000 m^3 will yield 62,700 GJ of thermal energy when cooled 9°C. At a rate of 6.5 MW it would only take 72 days to extract this energy.

The purpose of this chapter is to present a model of the heat exchange between the water in the mine and surrounding rocks. This make it possible to give a realistic estimate of the thermal power potential of abandoned coal mines.

4.1 Modelling approach

The modelling was carried out using the parameters of a typical Upper Silesian coal mine. The parameters and assumptions of this model are the following:

Geometry: Four vertical shafts (two main exploitation shafts and two ventilation shafts); several exploitation levels at variable depths, down to a maximum depth of 1000 m, variable dimensions of mine workings (length and radius); areal extent of coal mine 15-50 km^2; total volume of mine 500,000 - 1,000,000 m^3.
Thermal properties: Heat conductivity and thermal diffusivity specified for each level; thermal properties for the vertical shafts found by averaging values for the exploitation levels.
Temperature distribution: Calculated for every level on the basis of the temperature gradient in the mine area.

A two-step approach was taken in the modelling. In the first step, the heat exchange between water in a mine tunnel and the surrounding rock formations was investigated using an advanced numerical program code TOUGH (Pruess, 1987) which takes into account both the conductive and convective aspects of the heat transfer. The sensitivity of this process to changes in geometry and thermal parameters of the model tunnel was investigated.

In the second step the model was expanded to simulate the thermal output of a whole mine. For this purpose a special simulation program HEAT MINE was written. It is based on a simple analytical model of the heat exchange, which does not take convective heat transport into account.

4.2 Numerical modelling using TOUGH

The TOUGH program is a multi-dimensional numerical code for simulating coupled transport of water, vapour, air and heat in porous and fractured media. TOUGH is an acronym standing for "transport of unsaturated groundwater and heat". It is a member of the MULKOM family of multi-phase, multi-component codes, which is being developed at Lawrence Berkeley Laboratory in California, primarily for geothermal reservoir applications (Pruess, 1987). The numerical approach is based on the finite difference method, which permits simulation of one, two or three dimensional systems. This formulation easily handles both regular and irregular grid block geometries. The differential equations are solved simultaneously by using Newton-Raphson iteration and a direct solution technique.
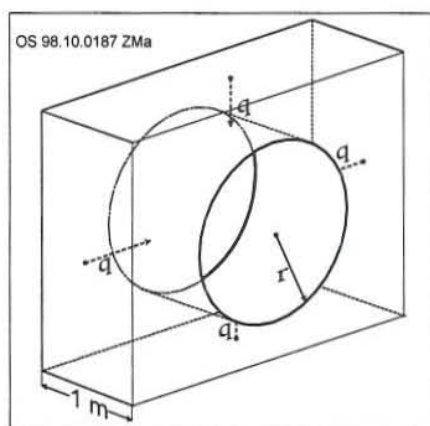

FIGURE 11: Model of a mine tunnel for heat exchange calculations

A two-dimensional grid was prepared for numerical modelling of the heat flow around a cylindrical mine tunnel in a 1 m thick vertical slice of rock (Figure 11). In order to avoid influence from the boundaries of the model the tunnel was placed in a 1,000 m high and 700 m wide grid (Figure 12). The radius of the water-filled tunnel can be changed during the simulation in the range 0.5-1.5 m. The grid consists of two basic parts, an inner and outer block. The inner block is formed by a fine grid of 52 elements with gradually increasing volume. The small size of the elements in the inner block is required for an accurate simulation of the heat flow close to the tunnel. The outer block consists of 69 elements with dimensions of 100x100x1 m. Two additional elements determine the boundary conditions of the model at the top and bottom of the grid.

The grid is divided into three main domains water, rock and boundary blocks. The physical properties of the elements in each
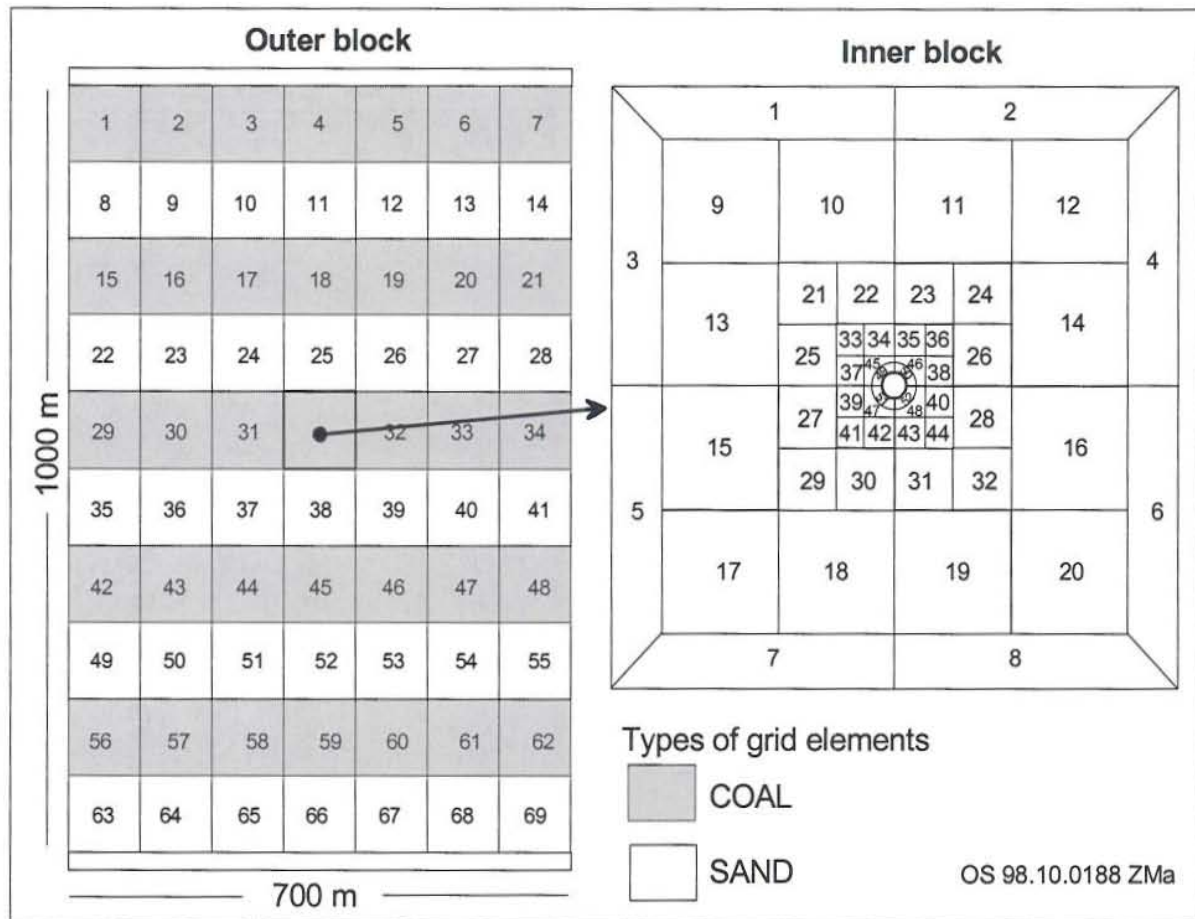
FIGURE 12: The grid used in numerical modelling of the heat exchange between
the water filling the mine tunnel and the surrounding rocks

domain are presented in Table 2. Two rock types are used, SAND and COAL. Their properties follow
average properties of rocks in the Upper Silesian coal basin . SAND represents lithological units
dominated by sandstones, and COAL lithological units with coal seams, claystones and siltstones, which
have relatively lower permeability and heat conductivity. The two types of rock are intercalated in the
model to simulate the sedimentary stratification of the Upper Silesian coal basin. The permeability of
the rocks is anisotropic and two different values are therefore given for the vertical and horizontal
directions. WATER is simulated as a rock with a porosity of 99%, permeability of 100 D, and heat
capacity and thermal conductivity of water. Boundary blocks BOUND are very thin layers at the top and
bottom of the model. They have a very low permeability which does not allow flow of fluid into or out
of the model.

TABLE 2: Properties of elements used in TOUGH 2 numerical modelling

Domain		Porosity (%)	Permeability (mD)		Density (kg/m³)	Thermal conductivity (W/m°C)	Heat capacity (J/kg°C)
			Vertical	Horizontal			
Water		99	1.0×10^6	1.0×10^6	1000	0.58	4180
Rocks:	Sand	8	4.0	9.0	2650	2.00	1000
	Coal	2	1.0	3.0	1800	1.50	1000
Bound		5	0.001	0.001	2650	1.50	1000

TABLE 3:   Temperature conditions in the model for different depths

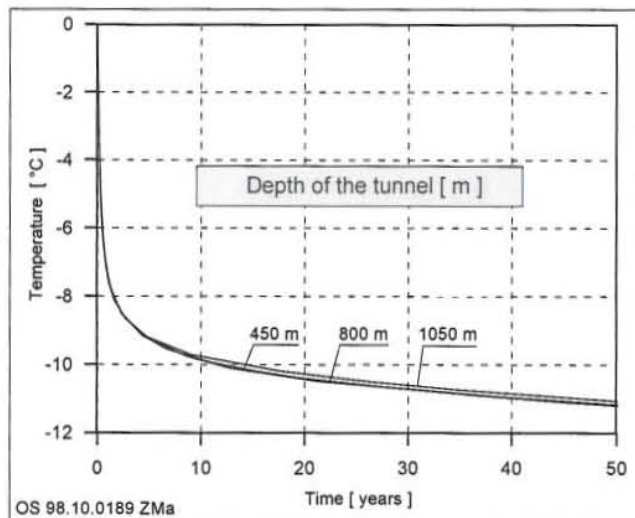| Depth of tunnel (m)	Temperature (°C)			Pressure (bar)		
	Tunnel	Top	Bottom	Tunnel	Top	Bottom
450	23.3	8.0	42.0	49.0	1.1	110.0
800	35.2	20.0	54.0	87.1	38.1	147.0
1050	43.7	28.4	62.4	114.3	65.3	174.2

FIGURE 13:   Temperature drop in the tunnel for different tunnel depths and a heat extraction rate of 5 W/m³

The temperature drop in the tunnel, in response to heat extraction from the water filling the tunnel, was simulated using this model and parameters given in Table 2. The heat extraction rate assumed was 5 W/m³ and the simulations started with the water in the tunnel at ambient temperature. This was done for three different tunnel depths by imposing boundary conditions on pressure and temperature at the top and bottom of the model corresponding to hydrostatic pressure and a regional temperature gradient of 33°C/km (Table 3). The heat flow up through the model then becomes approximately 0.06 W/m² which agrees with the average value measured for the USCB. The time period for the simulation was 50 years.
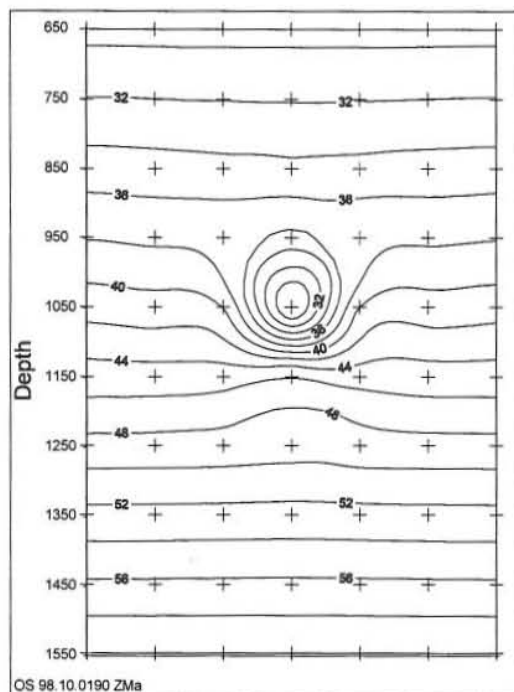
Figure 13 shows the temperature change inside the tunnel for different tunnel depths. The temperature curves are almost the same indicating that the heat transfer from the rocks to the water is not sensitive to tunnel depth. Therefore, in the following simulations only one tunnel depth, 450 m, was used in the calculations. This depth is the most common depth of coal mining in the Upper Silesian coal basin. The distribution of temperature in the model is shown in Figure 14 in a vertical cross-section. The tunnel was placed, in this case, at the depth 1050 m. An inspection of the heat and mass flow in the model, which were calculated as functions of time, shows that the temperature field is affected by convection around the tunnel.

The model presented above is only two-dimensional and should in future be expanded to three dimensions and to incorporate data from underground temperature measurements and lithological profiles.

FIGURE 14:   Temperature distribution in the model after 50 years of heat extraction from the tunnel at a rate of 5 W/m³

4.3 Sensitivity analysis

Numerical modelling has provided information on the mechanism of heat transfer between water in the mine
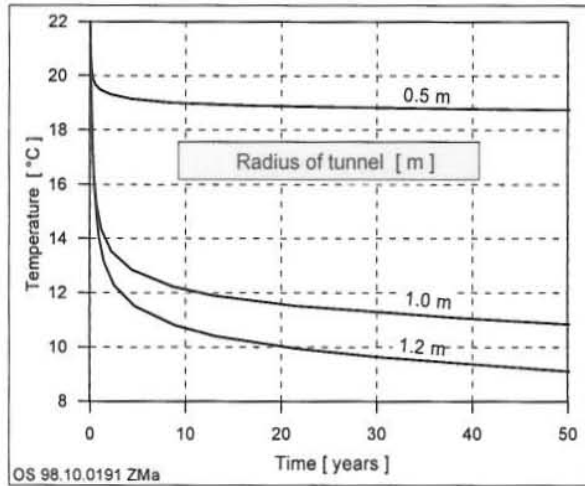
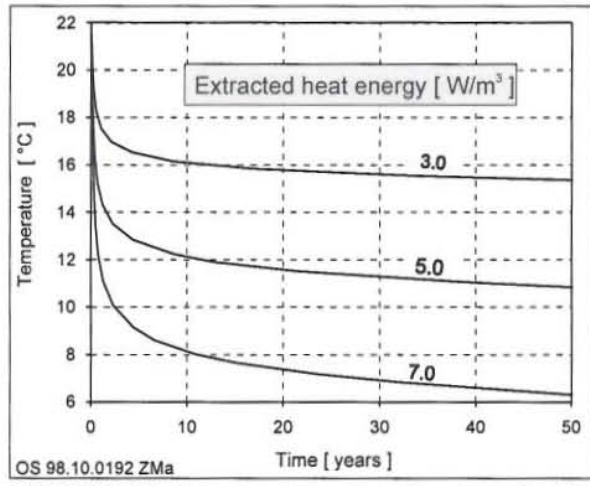FIGURE 15: Temperature drop in tunnels with different radii

FIGURE 16: Temperature drop in a tunnel with a radius of 1 m for different rates of heat extraction

and surroundings rock. The influence of different parameters on the temperature of the water in the mine tunnel is shown in Figures 15-18.

Figure 15 shows the temperature drop during 50 years of extraction of 5 W/m³ from tunnels with different radius. Comparison of the three curves shows that cooling of the water is the lowest for tunnels with a small radii. This can be explained by the dependence of the relationship between area and volume of the tunnel on the radius. It is relatively high for a radius of 0.5 m and decreases with increasing radius.

Figure 16 shows the temperature drop for different heat extraction rates (with the same radius of tunnel). On the basis of such a graph, the amount of heat that can be extracted from a mine with known average dimensions of mine openings can be estimated.

Figures 17 and 18 show how the temperature drop in the tunnel depends on thermal conductivity and permeability, assuming a tunnel radius of 1 m and heat extraction rate of 5 W/m³. The cooling rate decreases significantly with increasing permeability and thermal conductivity.

As was mentioned above, the depth of mining spaces does not influence the heat exchange in the mine in a major way. However, the thermal conductivity and permeability which change with increasing
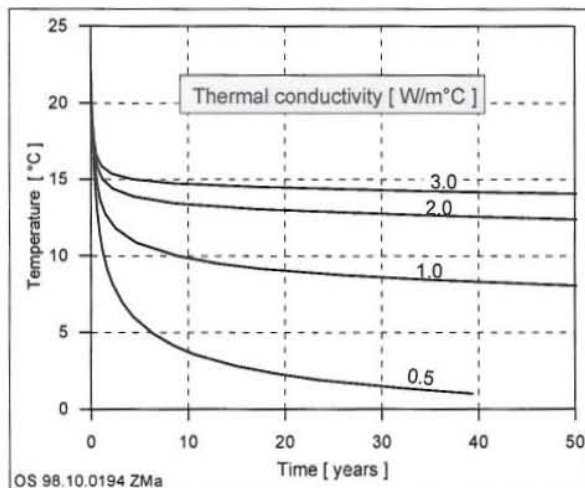

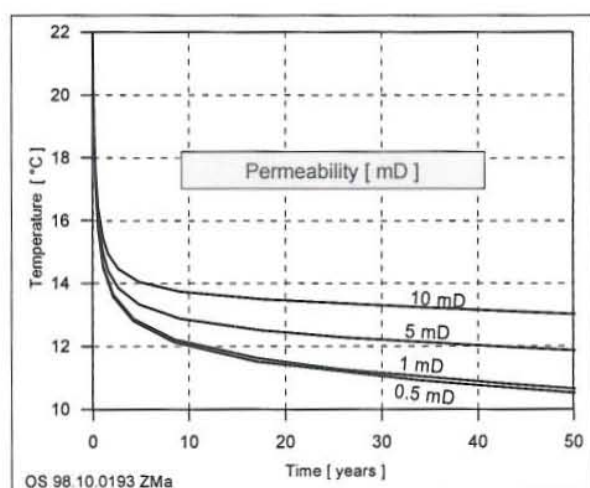FIGURE 17: Influence of thermal conductivity of rocks on temperature drop in the mine

FIGURE 18: Influence of rock permeability on temperature drop in the mine

depth, will control the heat transfer to some degree. An additional effect of depth is rising formation temperature. This may be important after a long period of exploitation when a high temperature drop is expected. The influence of other rock properties such as density, heat capacity and porosity has also been investigated by modelling, but the results indicate that they are not very important.

4.4 Heat exchange simulation program HEAT MINE

The numerical modelling above was concerned only with a small part of the huge system of the mine openings, which, in reality, are located at different depths and in different kinds of rocks. In addition, the dimensions of the openings not only vary from place to place, but may also change after closing down the mine. It would be difficult to prepare a TOUGH model of such a complicated system.

In order to estimate the thermal power potential of a whole coal mine a new simulation program, HEAT MINE, was prepared as a part of this project (Figure 19).

The program simulates the heat transfer between the rock walls and the flooded mine workings, as a function of time, on the basis of the geometry of the mine, the thermal properties of rocks as well as the rate of heat extraction from the mine. The simulation takes into account only heat transfer by conduction. The program is divided into three modules:

Mine geometry: The model of the mine has four vertical shafts. Input parameters are the depth and diameter of the vertical shafts, the number of levels and, at each level, the length and diameter of the mine workings. On the basis of these parameters, volumes of separate parts of the mine are calculated as well as the total volume of the mine.

Rock properties: The input parameters in this module are the heat conductivity, heat capacity, density and geothermal gradient in the host rock. Different rock properties can be used for different levels of the mine. In the present implementations of the program, the geothermal gradient is assumed constant for the whole mine and is used to calculate the undisturbed rock temperature at different levels in the mine. In future implementation it would be useful to allow the geothermal gradient to vary from place
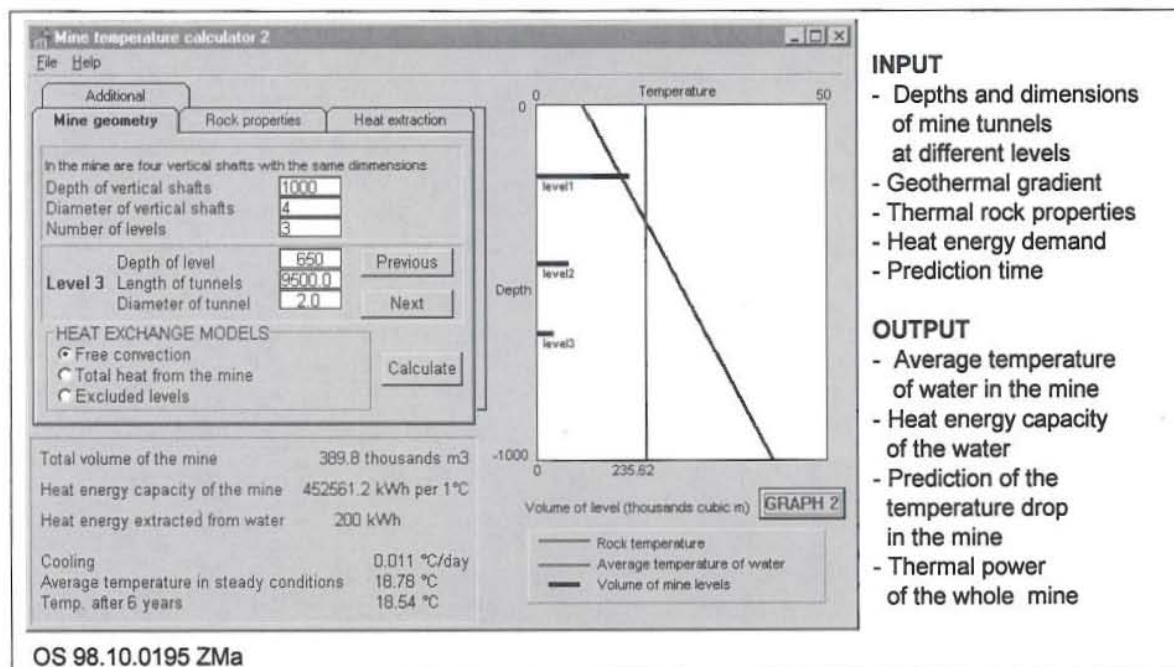

FIGURE 19: Interface window of the simulation program HEAT MINE

to place in the mine.

Heat extraction: Input parameters in this module are the average rate of heat extraction from the mine, at the surface (kWh), the period of simulation (years) and the number of days per year when heat is extracted from the mine. Parameters related to the use of heat pumps, such as the flowrate of mine water into the heat pumps and the temperature drop and efficiency of the heat pumps, will be added later.

Program HEAT MINE calculates the heat transferred between rocks and water by using equations for heat transfer between a hollow circular cylinder and an infinite medium surrounding it. The equations were developed as "important in connection with [...] cooling of mines" (Carslaw and Jaeger, 1959).

The heat flux, q [W/m] at the surface of a 1 m long tunnel (Figure 11) is for small values of time t (at/r^2 <<1), given by

$$q_s = 2\pi k \left(T_r - T_w\right) \left[\left(\pi \frac{at}{r^2}\right)^{-\frac{1}{2}} + \frac{1}{2} - \frac{1}{4}\left(\frac{at}{r^2\pi}\right)^{\frac{1}{2}}\right] \tag{2}$$

and for large values of time t (at/r^2 >>1), by

$$q_s = 4\pi k \left(T_r - T_w\right) \left[\left(\ln\left(4\frac{at}{r^2} - 2\gamma\right)\right)^{-1} - \gamma\left(\ln\left(4\frac{at}{r^2} - 2\gamma\right)\right)^{-2}\right] \tag{3}$$

where γ = Euler's constant 0.5772;
q_s = Heat flux [W/m];
k = Heat conductivity [W/m°C];
T_r = Undisturbed rock temperature [°C];
T_w = Temperature of water in tunnel [°C];
a = Thermal diffusivity of rock [m²/s];
t = Time [s];
r = Radius of tunnel [m].

An example of calculations using these equations is presented in Figure 20. The graphs show the heat flux in a 1m long tunnel with a temperature difference between rocks and water of 8°C.

On the basis of the input parameters above, the program simulates the heat output from the mine during a given time period. The point of intersection of the two curves was used to determine the range for validity of the equations.

When a mine is abandoned, it gradually becomes filled with water. Assuming fairly vigorous convection, the water temperature will become similar throughout the mine. At first, rapid temperature changes will occur, as the temperature of the tunnel walls adjusts to the
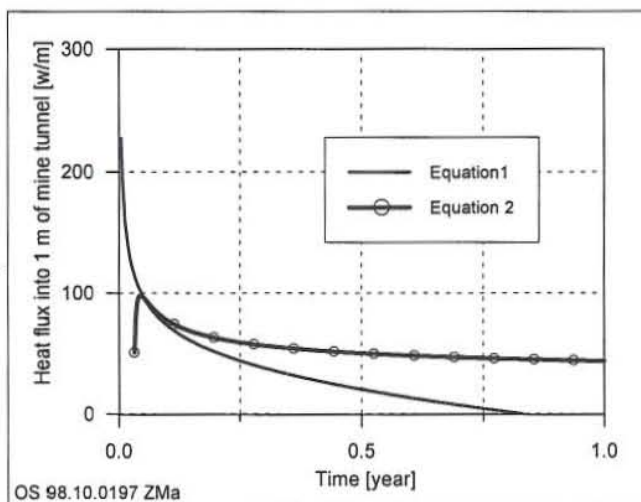

FIGURE 20: Heat flux calculated for 1 m of mine tunnel with temperature difference 8°C and radius of tunnel 1m

water temperature. Gradually, however, a new steady-state will be established. During this state the average temperature of the water filling the mine will stabilize at a value determined by the balance between steady heating of the upper part of the mine and steady cooling of its lower part. In the program HEAT MINE the calculations are started from an idealized initial state as follows. The rocks surrounding the mine are assumed to be totally undisturbed by the mining operations with an undisturbed formation temperature up to the tunnel walls. At each depth the mine is assumed to have been filled with water at the formation temperature at that level. This body of water is then assumed to have been mixed instantaneously to reach a constant temperature determined as a volume weighted average of the temperatures at each level.

The energy budget of the mine can be described by the equation:

$$Q_{in} = Q_{out} + Q_{ext} \tag{4}$$

where Q_{in} and Q_{out} are heat fluxes [W] through the total surface area of openings in the mine, into the water from the surrounding rocks and from the water into the rocks, respectively, and Q_{ext} is the heat extraction rate at the surface [W].

The program simulates extraction of heat at a constant rate during time period t by setting the temperature in the water T_w in Equations 2 and 3 equal to:

$$T_w = T_{eq} - \left[\left(T_{in} - T_{out} \right) - T_{ext} \right] \tag{5}$$

where T_{eq} is the initial temperature described earlier, and the incremental temperature changes due to Q_{in}, Q_{out} and Q_{ext}. They are found from the following three equations:

$$T_{in}(t) = \frac{1}{c_w V_{total}} \sum_{j=1}^{n} Q_{in} \Delta t \, j \tag{6}$$

$$T_{out}(t) = \frac{1}{c_w V_{total}} \sum_{j=1}^{n} Q_{out} \Delta t \, j \tag{7}$$

$$T_{ext}(t) = \frac{1}{c_w V_{total}} \sum_{j=1}^{n} Q_{ext} \Delta t \, j \tag{8}$$

where c_w = Heat capacity of water [kJ/kg°C];
         V_{total} = Total volume of the water that is filling the mine [m³].
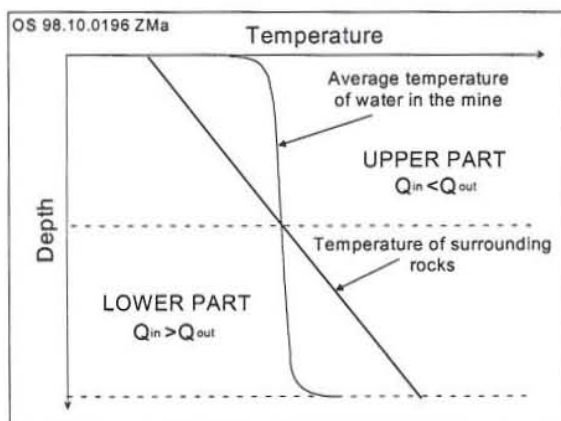

FIGURE 21: Average temperature of mine water in steady-state conditions

The time coordinate is discretized by the equation $t = n\Delta t$, where n is the number of time steps, Δt.

The following three scenarios of heat exchange in the mine are given as options in the program:

Free convection: The whole volume of the water in the mine is mixed due to free convection. The temperature of the water becomes the volume weighted average of the temperature in the upper and lower parts of the mine (Figure 21). The upper part is colder than this average temperature and the rocks surrounding that part are heated by the water. Warm water rises by convection from the lower parts where

steady-state temperature conditions will gradually be reached in the flooded mine. The amount of heat, Q_{in} transferred from the rocks to the water in the deep parts of the mine will equal heat Q_{out} transferred from the water to the rock walls in the shallower parts of the mine, i.e.

$$Q_{in} = Q_{out} \tag{9}$$

In this case all the heat energy provided by the warmer, deeper parts of the mine is lost in the upper part. **Total heat from the mine**: Maximum heat extraction from the mine is achieved when cold water returning from heat pumps at the surface enters the upper spaces of the mine and flows to its deeper parts. Because full convective mixing is assumed in the program, this scenario is simulated by assuming that the temperature of the water everywhere is below the undisturbed formation temperature of the surrounding rocks.

Separation of mine levels: In this scenario, a part of the mine is assumed to be sealed off from the rest of the mine. Free convection is assumed to occur in the sealed-off part and water flowing into and out of the heat pumps at the surface is assumed to be drawn from and returned to this part only. The scenario covers the case in which barriers hindering free circulation are present in the mine, but is mainly intended to be used to simulate planned utilization of the warm lower parts of mines.

The results of simulation by the HEAT MINE program are presented as follows:

Total volume of the mine, calculated on the basis of the mine geometry (two vertical shafts and several horizontal levels represented by a net of cylindrical tunnels).

Heat energy capacity of the mine, i.e. amount of energy which can be extracted from the water filling the mine by lowering its temperature by 1°C. Calculated on the basis of the total volume of the mine, while heat exchange with the walls is neglected.

Cooling temperature: the decrease of temperature per day due to heat energy extraction at the surface, at a given rate, from the water filling the mine.

Average temperature of the mine water in steady-state condition: This temperature changes with time. Here it is calculated 1 year after the flooding of the mine.

Temperature of the water filling the mine at the end of the prediction period.

Program HEAT MINE also draws three graphs showing the results of the simulation:

GRAPH 1 - The mine geometry is shown (Figure 19) as horizontal black bars, one for each depth level, their length being proportional to their volume. The rock temperature versus depth and the temperature of water in steady-state are also shown on the graph.

GRAPH 2 - Temperature curve showing the decline in the temperature of water filling the mine versus time (years).

GRAPH 3 - Thermal output power from the mine versus time.

In conclusion, the program presented here is a simple approximation of the heat exchange process between water in the mine and the surrounding rocks. In future, it will be extended to a more advanced computer application capable of simulating the heat exchange processes on the basis of a three dimensional distribution of temperature and thermal properties in the rock surrounding the mine, as well as parameters of convection of the mine water.

4.5 Evaluation of heat resources

Based on the simulations carried out using the numerical code TOUGH and the simulation program HEAT MINE, it is possible to make a preliminary estimate of the thermal power obtainable from a single, typical coal mine in the Upper Silesian coal basin.
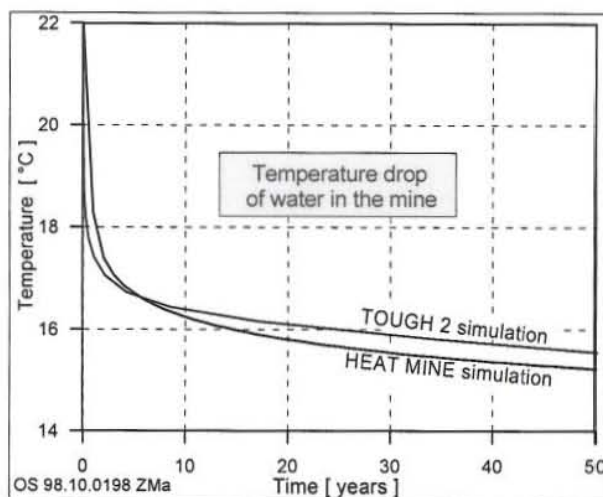
FIGURE 22: Predicted temperature drop in a typical mine calculated by programs HEAT MINE and the TOUGH numerical modelling assuming an extraction rate of 20 MWt

As the sensitivity analysis of the heat transfer conditions in the underground mining spaces showed, the amount of heat transferred to the water in the mine from surrounding rocks depends mostly on the size of the mine openings. After closing down a mine, some of the workings will stay open for some time, but most of them gradually decrease in size through roof sag and collapse. The collapse process creates a zone of smaller fractures and openings around initial spaces which retain more or less the same volume. Thus, the area of contact between water and surrounding rocks will increase and this will improve conditions for heat exchange.

The temperature drop in an abandoned coal mine, predicted by the program HEAT MINE for a 50-year period, in response to a heat extraction at rate of 20 MWt, is shown in Figure 22. The mine is assumed to have a volume of 1,000,000 m^3, distributed at three levels (200, 450 and 650 m) in the form of mine tunnels with a radius of 0.5 m. The thermal properties of the host rocks are the same for all levels, thermal conductivity of 2 W/m°C and thermal diffusivity of 1.1×10^{-6} m^2/s. Warm water from the mine is assumed to be extracted at a constant rate throughout the year, to be cooled in heat pumps and the cooled water to be reinjected into the mine. Figure 22 shows that during the 50-year period the temperature of the water filling the mine decreases from 22°C to about 15°C due to heat extraction. The second curve in the figure shows the results of numerical modelling by TOUGH. In this model energy was extracted at a rate of 20 W/m^3 from a 1 m long mining tunnel with radius 0.5 m, which gives 20 MWt when multiplied by the volume of the mine. The temperature decline during the 50 year period, is almost the same. The small positive difference can be explained by the additional heat transferred by convection in the rocks surrounding the mine-tunnel, not taken into account in HEAT MINE.
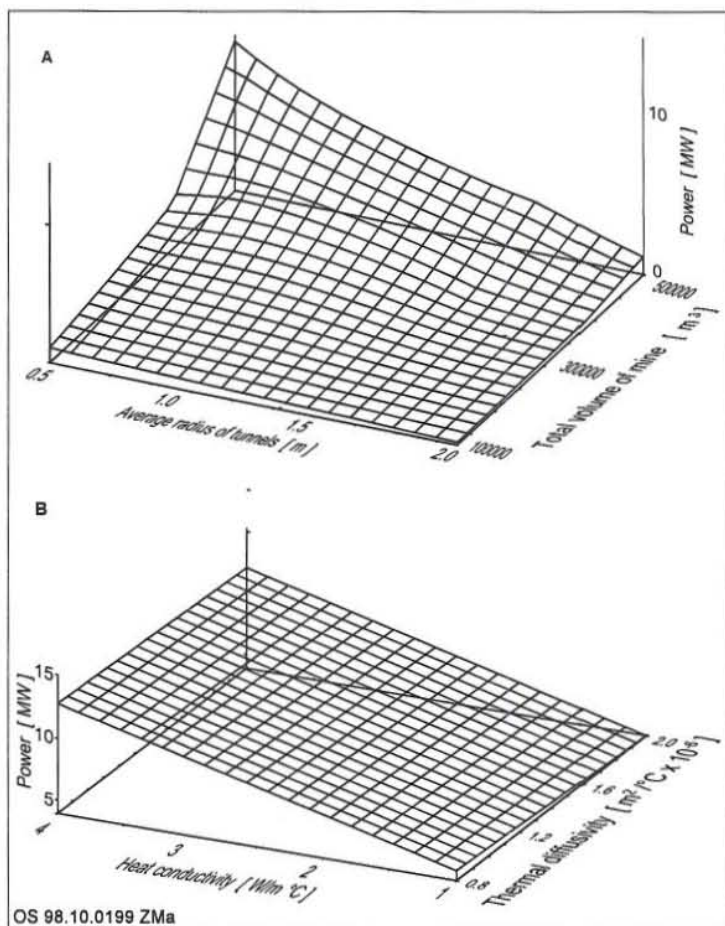
The two block diagrams in Figure 23 show how the thermal power output of the mine, as simulated by HEAT MINE, depends on the geometry of the mine openings (volume-area relationship) and the two thermal rock properties. The output power

FIGURE 23: Influence of a) Total volume and radius of mine tunnels, and b) Thermal rock properties on the heat power of the mine

increases with increasing total volume of the mine and decreasing dimensions of the underground spaces. The figure also shows that thermal conductivity has a significant influence on thermal output power. The influence of thermal diffusivity, which is a function of thermal conductivity, heat capacity and density of the rocks, is much less.

An estimate of a 20 MWt power output from a single mine may seem to be optimistic. However, the high cost of large heat pumps and other technical installation needs for pumping about 0.3 m^3/s of water from the mine to extract 20 MWt, need to be taken into account. Thus, the economics of heat extraction from the mine are probably limited not by the thermal capacity of the mine reservoir but rather by technical and economical aspects.

The simulation presented above assumes a constant rate of heat extraction during the whole year. For Polish climate conditions, space heating is not needed for the whole year. The heating period starts in October and lasts till April. During the summer season, when the demand for thermal power is much lower, inflow of heat from the rocks will restore some of the thermal capacity of the water filling the mine. Additional heat can be supplied to the reservoir from heat pumps at the surface used for cooling purposes. In this case, the temperature of the water flowing from the heat pump outlets will be higher than the inflow of water from the mine reservoir. Reinjecting this warm water amounts to storing heat energy in the mine until needed during the cold season. This can significantly improve the thermal efficiency of the reservoir. This additional heat inflow to the mine reservoir is not considered in this report, but should be included in future investigations of mines as geothermal reservoirs. It will add to the positive results obtained in this report which indicate that abandoned and existing coal mines have a high potential as low-enthalpy geothermal resources.

5. PROSPECTIVE UTILIZATION AND ENVIRONMENTAL ASPECTS

A flooded coal mine in the Upper Silesian coal basin constitutes a reservoir of low-enthalpy geothermal water at a temperature of 20-50°C, depending on depth. In order to extract and utilize the heat energy stored in the reservoir, the water must be drawn from the mine. After the heat has been extracted the water must then be reinjected into the reservoir because of its high mineral content. Another method is to extract the heat energy by a system of loop heat exchangers installed within the mine itself.

Water can be extracted from the mine through wells drilled to deep mine levels. The de-watering installations of the mines, can also be used for this purpose, but after the mine is closed down, they need to be adjusted for this use. A water flow of a few to a few tens of litres per second will be needed to supply the heat pump installations at the surface. The water will be cooled by 10-15°C in the heat pumps and consequently pumped back to shallow levels of the mine through reinjection wells or directly to the vertical shaft (Figure 24B). Water could also be drawn from partially isolated levels deep in the mine (Figure 24A). In this case the temperature of the water will be higher because of limited mixing with
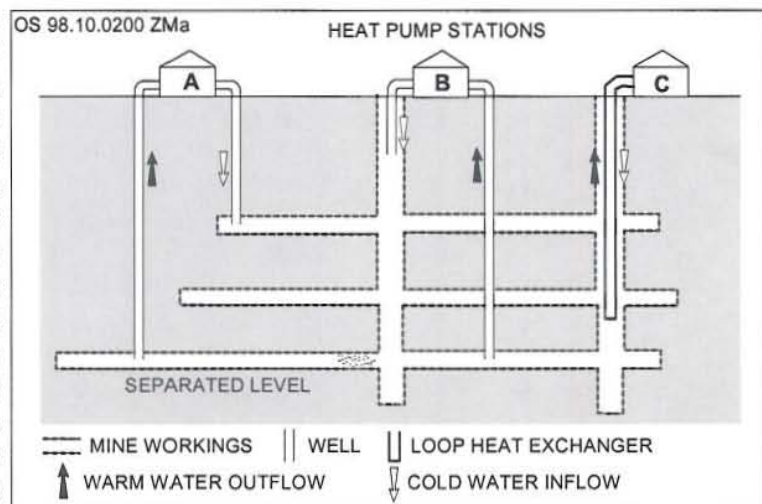

FIGURE 24: Three simplified schemes for the extraction of geothermal energy from abandoned coal mine

colder water from shallower levels. For smaller applications, loop heat exchangers could be placed into the vertical shafts before they are backfilled (Figure 24C). This can significantly limit installation costs by eliminating the need for drilling wells, but results in much lower extraction rates.

Heat pumps using water from mines can be used for different heating purposes. An example of a model installation using heat from mine water, in combination with a conventional boiler, as modernization of a traditional system of local district heating, with a thermal power 8.7 MWt is proposed by Kubski (1996). In this example 50 l/s flowrate of water pumped from the mine is cooled down by 15°C in a heat pump for extraction of 3 MWt of heat energy. Electrical power of the 1.5 MWe for the heat pump is provided by a gas engine with waste heat recovery of 2.3 MWt. Output power of the heat pump is 4.5 MWt with heat pump efficiency equal to 3. The temperature supply of the system is 80°C and its total power output, including gas engine waste heat, equal to 6.8 MWt, which is supplied to the thermal power plant. The remaining balance of 1.9 MWt is produced by a conventional coal boiler. This system saves 78% of the coal otherwise required by replacing part of it by natural gas. The efficiency of a conventional coal burning system is 75%. In a heating system, combined with heat pumps and utilizing warm mine water, efficiency can reach 128%.

Utilization of geothermal energy from mines can be combined with methane burning which is more environmentally friendly than burning coal. Methane is common in coal mines and is often collected from the mine ventilation systems. In the southwestern part of Upper Silesia, there is a coal field where methane is exploited. In that area the greatest thermal anomalies in the region has been localized, with a thermal gradient of 40°C/km. The mining activity can provide warm mine water for heat pump systems combined with methane burning.

Heat pumps utilizing water from coal mines can also be used for space cooling during the summer season. In this case water reinjected into the mine will carry heat from the surface and store it in the mine reservoir. The possibilities of using warm water from mines, for other direct uses, seem to be limited due to the high concentration of dissolved solids in the water. However, a possible use seems to be in snow melting systems for pavements, city squares and parking places.

Utilization of geothermal heat as a clean and renewable source of energy has the potential of becoming a very important part of environmental management in Upper Silesia. In this region the concentration of combustion gases in the air is the highest in Poland. Levels of carbon and sulphur oxides are also high because electrical and thermal power are generated in coal fired power plants which use coal with a high sulphur content. A reduction in the use of this type of conventional fuel will significantly reduce the emission of polluting gases. The use of waste water in heat pumps can improve the water management in the coal mines and reduce the release of salty waste water to the rivers. Furthermore, ventilation air from the mines carries considerable heat energy, and proper use of this heat can also limit the environmental impact of coal mining. However, the environmental benefits of geothermal energy can only be realized in close cooperation with the coal industry and coal mining communities involved. Therefore, informing the industry and the general public in the Upper Silesia region about the potential of renewable energy sources and development within the field of geothermal energy should be given priority.

6. CONCLUSIONS AND RECOMMENDATIONS

The main conclusions of this report are the following:

1.   Abandoned, water-filled coal mines in the Upper Silesian coal basin contain large reservoirs of water at a temperature of 20-40°C. They constitute a significant, but little-studied, geothermal resource.

2.   The thermal power potential of a typical abandoned, water-filled coal mine was estimated using numerical modelling. The utilization was assumed to take the form of pumping water from the mine, heat extraction in heat pumps installed at the surface, and reinjection of the cooled water into the mine. A two-step approach was taken in the modelling. First, the heat exchange between a section of a mine tunnel filled with water and the surrounding rocks was investigated using the TOUGH code, taking both conduction and convection into account. A more comprehensive modelling of the geothermal resources in a simple mine model was then carried out using a new simulation program, HEAT MINE, written specifically for this project.

3.   The modelling indicates that a maximum of 20 MWt can be extracted from a 1,000,000 m^3 volume coal mine over a period of 50 years with temperature drop of 7°-8°C.

4.   Sensitivity analysis of the models shows that the most important parameters influencing the thermal output of an abandoned coal mine are
      - Total volume of mine openings and their surface area;
      - Depth distribution of the volume of mine openings and their surface area as a function of the geothermal gradient.
      - Thermal conductivity and permeability of host rocks.

To fully evaluate the thermal power potential of abandoned coal mines in the Upper Silesia region, more research is required. This research should include:

1.   More accurate studies in the heat extraction process, taking into account:
      - The three dimensional geometries of real mines;
      - The actual temperature field, including both variations of mine scale and the cooling zone around mine openings caused by ventilation;
      - Variations in thermal properties of the host rocks;
      - Convective processes in the host rocks;
      - Nature of fluid convection and heat transfer in backfilled and collapsed mine spaces.

2.   Technical aspects such as comparative analysis of different methods for extracting heat from the mine. Studies of ways to optimize thermal output from the mines through preparations prior to closure would also be useful. As an example, erecting barriers or establishing connections between different levels may increase the thermal output from the mine.

3.   Economic and environmental aspects. The feasibility of using the coal mines of Upper Silesia as geothermal reservoirs depends on the economics of utilization. The economics of different utilization schemes should be estimated and compared. Based on Polish experience, combined use of different kinds of energy sources and cascading use of hot water are attractive options.

4.   Environmental aspects. The environmental benefits of partly replacing existing coal-fired thermal power plants with heat energy derived from coal mines should be studied and quantified as helpful for reduction of combustion gas emissions. This also applies to the expected reduction in the release of brine from the mines into the rivers of the region.

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